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Intellectual Human Capital and the Emergence of Biotechnology: Trends and Patterns, 1974–2006

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***Abstract*—We present an analysis of the trends and patterns documenting the role of intellectual human capital in the emergence of knowledge within both new biotech ventures and incumbent pharmaceutical firms. We leverage individual-level data detailing the publication and citation records for more than 284 000 scientists employed by biotech and pharma firms between 1974 and 2006. During this 33-year time period, these scientists published nearly 1.2 million academic papers that were cited 16.8 million times. Through a detailed analysis of these data, we attempt to gain insights into the similarities and differences between the activity, productivity, and movement of star and nonstar scientists across both biotech and pharma firms over time.**

***Index Terms*—Biotechnology, intellectual human capital, pharmaceutical, star scientists.**

I. Introduction

THE ADVENT of biotechnology ushered in a fundamentally new drug discovery and development process. This scientific breakthrough represented a discontinuity for incumbent pharmaceutical firms, while offering a unique opportunity for start-up biotechnology firms [1]. As is common with most technological discontinuities, individuals played a key role in the development and dispersion of the knowledge underlying biotechnology [2], [3]. Within this setting, scientists that gained expertise through productive research programs became more influential and valuable than their colleagues [2], [4], [5]. These star and nonstar scientists together make up a firm's *intellectual human capital*, i.e., its collection of highly skilled and talented employees, who generally hold doctorates in the sciences. To qualify as a research scientist in this study, the individual must have (co)authored at least one paper published in the open science during the study period.[1]

Following the biotech discontinuity, access to star scientists and their knowledge networks became a prerequisite for both incumbent pharmaceutical companies and biotech start-ups attempting to acquire and assimilate the new knowledge [2]. Although this line of research seems to point to the importance of star scientists, several recent studies have highlighted the important complementary roles nonstar scientists play in this process [4], [6], [7]. The notion that different individuals play different roles in the innovation process has its roots in sociological research that investigates the relationship between a scientist's talent, status, and conformity [8]. Our investigation allows for insight into the motivations that underpin the roles of individual scientists or researchers within a commercial enterprise. Within firms, analysis of the overlap between scientific and commercial opportunities available to researchers provides a fertile ground for investigating the process through which knowledge underlying a scientific revolution (e.g., biotechnology) emerges.

Despite differences in size and strategic focus, both biotech and pharma firms shared a dependence on intellectual human capital consisting of star *and* nonstar scientists at the onset of this scientific revolution. We attempt to highlight some of the similarities and differences between these two types of firms—pharma companies (generally older, larger, and more diversified) and biotech start-ups (generally younger, smaller, and more focused)—and their tendencies to employ intellectual human capital. Such an analysis provides unique insights into the importance of considering the *heterogeneity within intellectual human capital* and the roles that scientists played (and continue to play) in spreading the knowledge underlying biotechnology, not only throughout firms, but also throughout the scientific community as a whole. To examine this heterogeneity, we examine star and nonstar scientists and their complementary roles in scientific inquiry, in addition to the employment decisions of

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[1]Although there are alternative ways to identify intellectual human capital (e.g., through patent analysis), our research reveals that publications are the preferred method to track scientific intellectual human capital in the pharmaceutical and biotechnology industries. Indeed, a scientist must coauthor only one paper in a 33-year time span to be identified in our data; moreover, our discussions with both scientists as well as biotech and pharmaceutical executives suggest that there is a significant reward for publishing in the open science. Moreover, our focus in this project is on the diffusion of scientific knowledge. We therefore needed to track individuals who participated in this process by leaving "forensic evidence" in the form of publications. There was also concern that the method in which individuals' names are put on patents (e.g., often influenced by legal counsel) as inventors may vary significantly between firms [31]. This bias is greatly reduced for the publication process because it relates to the broader scientific community. The journal publications in our data are peer reviewed adding an additional layer of quality control. In general, publications generally precede patents in time, allowing us to capture a firm's intellectual capital more accurately. Finally, there are many more publications than patents, allowing us to track the roles of individuals in knowledge diffusion in a more fine-grained manner. In this sample, the ratio between publications and patents is 16:1 at the firm level.

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biotech and pharma firms with regard to these two populations of scientists.

Despite the importance of considering the heterogeneity of intellectual human capital across both biotech and pharma firms, the majority of prior research has focused on *either* biotech *or* pharma firms, neglecting the interactions between the two. As a result, numerous important questions relating to the roles of intellectual human capital within these types organizations remain. For instance, while Zucker and Darby [2] and Zucker *et al.* [9] assert that star scientists were critical for the incumbent firms' acquisition of biotech knowledge, it remains unknown whether the value of those stars diminished with time or if they even remained employed at the incumbent firms. More importantly, do the star scientists employed by large pharma firms differ from the star scientists employed by biotech firms? Are they equally productive and impactful? Is performance independent of work context? Is there significant movement or overlap between these populations? Furthermore, if there is a significant overlap between biotech and pharma intellectual human capital, what are the trends and patterns in movement between the two populations? It is critical to answer these questions in order to better understand the activity, productivity, and movement of scientific personnel within the commercial setting.

An organization's resource base is a direct result of the collective actions of *individuals.* Within the realm of biotechnology, these individuals are both a source of new knowledge as well as a means by which this knowledge is transferred through organizations and the institution of science itself [2]. Investigating the movement of scientific personnel allows us to analyze the microfoundations of organizational strategy formation. More specifically, these individuals represent the core knowledge resource of science-based organizations. Understanding how and when individuals of differing talent and expertise are employed allows us a glimpse into the motivations and actions of firms attempting to commercialize scientific advancements.

We endeavor to shed light on these fundamental questions by presenting an analysis of the trends and patterns concerning the role of intellectual human capital in biotechnology and pharmaceutical firms. We leverage a longitudinal dataset consisting of the publication and citation records for 284 302 scientists (each of whom we track at the individual level) employed by biotech and pharma firms between 1974 and 2006. During this time period, these scientists collectively published nearly 1.2 million papers that were cited 16.8 million times. Through the analysis of these data we are able to illustrate some similarities between the stars of new biotech ventures and those of incumbent pharma firms. Moreover, we discover that star scientists themselves are not a homogenous group, but exhibit significant within-group heterogeneity. Finally, different types of pharmaceutical firms may employ stars and nonstars differently in their attempts to gain access to external knowledge. We highlight the dynamics of these trends.

II. Intellectual Human Capital and the Emergence of Biotechnology

Building on the foundational research by James Watson and Francis Crick, who established the double-helix model of DNA structure in 1953 [10], [11], a research team led by Stanley Cohen and Herbert Boyer demonstrated the feasibility of genetic engineering through recombinant DNA (rDNA) in 1973 [12]. The importance of their findings stems from their discovery of a set of techniques for "cutting and pasting" different DNA fragments outside the human body (*in vitro*). Subsequently, Georges Köhler and Cesar Milstein [13] discovered monoclonal antibodies in 1975, a second important breakthrough that helped launch the biotechnology revolution.

The emergence of biotechnology presented a new technological paradigm with respect to drug discovery and development for incumbent pharmaceutical companies such as Merck and Novartis [14]–[16]. Unlike traditional drug discovery and development methods, which are largely based on trial and error analyses of chemical compounds [1], [17], advances in rDNA, molecular genetics, and gene sequencing allow researchers to discover and develop new drugs far more efficiently. In addition, a more scientific approach, including genetic engineering, genomics, and molecular biochemistry underlies these new drug discovery and development processes. For example, unlike the well-established method of discovering chemical compounds through random screening, researchers now use rDNA to create living organisms and their cellular, subcellular, and molecular components as a basis for producing new products [2].

The emergence of a large number of start-ups specifically focusing on using this new technology represented a threat for incumbent pharmaceutical firms. In fact, specialization in rDNA discovery became more important to new drug breakthroughs than firm size [18]. The new biotech science challenged traditional drug discovery modes in the chemical paradigm; as a result, the incumbents' existing competencies in upstream R&D were considerably devalued, if not destroyed altogether [19]. Accordingly, Herbert Boyer and venture capitalist Robert Swanson founded Genentech, the first biotechnology company, in 1976. The first new biotechnology drugs reached the market for pharmaceuticals just a few years later in the 1980s. To highlight the economic importance of this scientific breakthrough, the total revenues from drugs based on the new biotechnology worldwide were $78 billion in 2008 [20]. By comparison, in the same year, revenues from the entire U.S. pharmaceutical industry (both biotech- and chemical-based drugs and medicines) was close to $300 billion, with global sales at $750 billion [20].

Confronted with the perils of creative destruction, pharmaceutical firms were faced with the challenge of transforming their upstream research capabilities in order to survive [1].[2] Only a few key individuals held the initial knowledge to this new technology [2]. This discontinuous technological change allows us to investigate how the new biotech knowledge diffused and how different firms accessed this new knowledge. Here we differ from many prior studies, because we not only consider both pharma and biotech firms simultaneously, but also we include an explicit consideration and analysis of nonstar scientists (in addition to star scientists) to provide a more complete picture

[2] A review of more than 100 annual reports for the sample firms revealed that by the early 1980s most of the incumbent pharmaceutical firms were pursuing attempts to innovate within the new biotechnology paradigm.

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of the role of intellectual human capital in the emergence of biotechnology. Moreover, we also consider a longer time period than most prior work, allowing us to highlight the dynamics in this process.

A. Participation in the Open Science

Why do firms allow their scientists to publish their research findings in the open science? The motivations behind firms publishing their internal research in scientific journals have directly and indirectly been linked to the importance of forming ties to the larger scientific community in order to access basic knowledge [2], [17]. To gain membership in these communities, a firm must be actively involved in the creation and dissemination of new knowledge through presentations at conferences and publications in academic journals. Thus, biotech and pharma firms whose members actively participate in this community are more efficient learners and have a higher absorptive capacity than firms outside of this knowledge network [21]. The stronger and more diversified a firm's internal research capability and knowledge base, the better it will be at identifying and absorbing external sources of knowledge [22], [23].

For pharmaceutical firms, these connections to upstream sources of basic knowledge are of critical importance in their efforts to adapt to a more scientific drug design process [24]. By refocusing human capital, forming strategic alliances, and undertaking acquisitions, the old-line pharmaceutical firms have attempted to stave off a Schumpeterian destiny where incumbent firms are replaced by new entrants in the process of creative destruction [1], [25]–[27].

B. Role of Star Scientists

When scientific and commercial opportunities converge, the roles of individuals lie on a continuum between scientific (associated with the creation and dissemination of new basic knowledge) and commercial opportunities (associated with the commercialization of applied knowledge). We suggest that an individual's position on this continuum is in part due to his/her talent. This assertion is due to the fact that within knowledge-based communities, status is accrued via performance in the knowledge generation process (i.e., publication in scientific journals) [28]. While an organizational structure may prescribe certain job tasks, scientists tend to self-select into the jobs they aspire to. In support of this notion, prior research indicates that scientists who want to continue engaging in research will accept some $14 000 less in annual salary to work at an organization that permits them to publish their findings in academic journals, implying that some scientists will "pay" to be scientists [29].[3]

Specifically, *high status* or star actors tend to be confident in their positions within their organization and are thus more likely to deviate from conventional behavior [8]. In particular, star scientists are more likely to pursue more tacit research streams that have a higher risk/reward potential, even if these activities are not directly related to the dominant (commercially driven) organizational research goals. Such pursuits are frequently rewarding for the individual scientist [30], but due to the tacit nature of the generated knowledge, they do not always lead to commercially viable products [31].

Prior research has documented the pivotal role star scientists play for new biotech firms. It points to stars affecting the location of firm entry into new technologies [32] and having a significant positive effect on a wide range of firm-level measures, such as the number of products on the market, publishing propensity, and network connections [9], [33]. As an indication of the "stardom" of these scientists, Zucker and colleagues found that while the 327 stars they identified comprised only 0.75% of the total scientific authors in GenBank, they accounted for 17.3% of the published articles, nearly 22 times as many articles per star as the average scientist. These stars held the main locus of knowledge, at least during the early period of the biotechnology revolution [2], [5], [34], [35].

Though star employees are often more intelligent or creative than the average employee, within biotechnology, it is the star's level of connectedness to both the private and public research sectors that has been shown to be one of its most valuable assets [32], [36], [37]. A high level of connectedness to both upstream and downstream knowledge gives star scientists the ability to identify gaps in the drug discovery, development, and commercialization processes. Moreover, a number of recent studies have highlighted the fact that the value of star employees may lay in their firm- or team-specific knowledge that is not necessarily transferable to other environments [7]. Given these findings, it is critical to understand the role of supporting actors within the organization.

C. Role of Nonstar Scientists

Although nonstar scientists generally attract less attention, empirical research provides some evidence that they play an important complementary role in a firm's innovation efforts [4]. In contrast to star researchers, *middle* status actors (differentiated from *low*-status individuals who are not likely to be employed[4]) do not experience the same level of freedom. Whether due to tenure or talent, these individuals are likely to be more conservative given the tension between their aspirations and fears of disenfranchisement [8]. Based on more pecuniary motivations, middle status or nonstar scientists are more likely to pursue activities that are closely aligned to the commercial end of the scientific-commercial continuum [38].

In contrast to star scientists, nonstar scientists are more likely to pursue research activities that are more codified in nature and thus more likely to result in patents and new products, rather than in publications in the open science literature. In particular, because these individuals are often part of a larger research team, they are likely subject to an element of institutional restriction dictating the direction research projects can go, rather than enjoying freedom to pursue their own research interests [30]. Here, star scientists frequently create the firm's

[3]Note that *all* firms in this study publish in the open sciences. Stern's sample consisted of postdoctoral biologists considering multiple job offers [53].

[4]Zuckerman and Philips [65] suggest there exists an inverted U-shaped relationship between status and conformity, with low-status actors also feeling free to defy accepted practice because they are excluded regardless of their actions.

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exploratory knowledge that nonstar scientists build on to subsequently exploit. Our interviews with scientists confirm that the knowledge conversion process follows this division of labor. The publication process begins with novel research findings being disclosed in publications. If the publication findings are applicable and of commercial interest, a firm then transforms this basic knowledge into more applied knowledge, which is then patented. The final step of the knowledge conversion process is the commercialization of new products and processes. In support for a distinct division of labor in the knowledge conversion process, Furukawa and Goto [6] found that while star scientists are responsible for a disproportionately large number of publications in scientific journals, it is nonstar scientists who translate this tacit knowledge into patents. Nonstar scientists, therefore, transform tacit knowledge not only into codified knowledge, but also into knowledge that is legally protected and can provide a basis for commercial exploitation.

III. Data Collection and Descriptive Statistics

Our analysis is based upon a sample of pharmaceutical and biotechnology firms. For the identification of pharmaceutical firms, we compiled a list of all firms alive as of 1980 based on standard industry classification (SIC) reports and a variety of industry publications.[5] Through this process, we identified 125 incumbent pharmaceutical firms worldwide. We defined an incumbent pharmaceutical firm as a firm that focuses on human therapeutics and was founded prior to the emergence of biotechnology in the mid-1970s. The companies in this sample, including Fujisawa (Japan), Novartis (Switzerland), and Merck (USA), are generally large enterprises with an emphasis on proprietary drug discovery and development. We tracked the sales of 52 sample firms that were not diversified outside pharmaceuticals. These focused pharmaceutical companies represent only 44% of the initial sample, but account for 75% of the total sales for pharmaceuticals worldwide [20].

We completed a similar process for our sample of biotechnology firms. Specifically, we identified all companies in the *BioScan* database that were fully dedicated to commercializing the new biotechnology. We then cross checked this list of biotech firms with those identified as fully dedicated biotech companies in the *Recombinant Capital* database. We included 2324 firms that appeared in both databases. To ensure that our samples were representative of the overall population, we cross checked the firms listed in both databases based on SIC codes.

Following prior research [4], [6], [39], [40], we used bibliometric measures to identify a firm's intellectual human capital. Using our list of biotech and pharma firms, we searched the *Web of Science ISI* database of publications to identify publications (excluding meeting notes and abstracts) that were published between 1974 and 2006, which included a keyword related to science research (excluding social science research and non-human focused research, such as "agricultural") and could be unambiguously connected with one of the firms in the sample. While publication information was available for all of the 125 pharmaceutical firms, given their small size (and often brief existence), we were able to collect complete records for 1308 biotechnology firms (56% of initial sample). This process resulted in a sample of nearly 1.2 million publications from which we collected the following information: author(s), journal name, number of times cited, publication type, keywords, and publication year. Note that we collected publication information beginning in 1974, because the Cohen–Boyer team published their rDNA breakthrough in 1973 [41].[6]

TABLE I
Summary Statistics—Intellectual Human Capital, 1974–2006

						Averages	
Setting	*Scientists**	*Publications*	*st dev*	*Cites*	*st dev*	*Pubs*	*Cites*
Pharma	171,314	672,476	8.12	11,197,293	265.28	3.93	65.36
Biotech	159,772	512,758	7.10	5,588,095	220.54	3.21	34.98
Both	46,784			p-value of t-test**		0.089	0.001

*The total number of scientists is 171 314 (pharma) +159 772 (biotech) – 46 784 (both) = 284 302.
**The indicated t-test tests the difference between the mean number of publications between biotech and pharma scientists ($p = 0.089$) as well as the mean citation count between the two populations of scientists ($p = 0.001$).

We compiled the publication history of each author in the sample as well as the number of forward citations each journal publication garnered (excluding self-citations). This yielded the records of 284 302 authors who, on average, published 3.6 papers each, which were cited 50.7 times by other academic papers. We then tied each author back to the firms in our sample based on affiliations as indicated in the journal article(s). Unlike the norms in the social sciences, where authors tend to note their current employers as organizational affiliation on a journal publication, in the natural sciences authors are required to list the organization where the intellectual property (IP) was generated [4]. This implies that the locus of IP creation and the locus of IP credit are more or less identical in the natural sciences, thus allowing us to more accurately link journal publications to knowledge creation within specific firms. In addition, the time lag between initial article submission and publication in a journal is only about 3–6 months in the natural sciences [42], [43], further strengthening the use of publication data in tracking an author's affiliation accurately.

Given the fundamental differences in size and strategic focus between biotech and pharmaceutical firms, we divided the population of scientists into those who were affiliated with a pharmaceutical firm, a biotech firm, or both. These data are summarized in Table I.

To identify star scientists from the population of publishing authors, we first had to consider the normative question of what it means to be considered a star. Specifically, should stardom be a fairly static measure accounting for lifetime achievement, as Zucker and colleagues have suggested? This notion of "once a

[5]Including: *BioScan* (annual volumes), *Burrill & Company Life Sciences Annual Industry Reports, Compustat, DataStream* (Thomson Financial), *Ernst & Young's Annual Biotech Industry Reports, FIS Mergent,* and *Scrip's Yearbooks on the Global Pharmaceutical Industry*.

[6]The subsequent Cohen–Boyer rDNA patent (U.S. Patent 4 237 224) was granted to Stanford University in 1980, which licensed this new technology widely for a nominal fee. This patent is influential and is often associated with the commencement of the biotechnology movement [15].

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star, always a star" has its roots in sociology literature, where an individual's network and reputation become inextricably linked to his/her identity [44]. In contrast to this static approach stands a methodology that is more dynamic in nature and measures stars based on multiple, shorter time horizons. This method of rolling stardom allows for the identification of individuals who come and go from the star population, rather than being labeled a star for life. Sociological research suggests that the two populations will have a significant overlap given the "Matthew effect" in science [44]. Coined by the sociologist Robert Merton, the Matthew effect suggests that eminent scientists will often get more credit than a comparatively unknown researcher, even if their work is similar; this implies that credit is usually given to researchers who are already famous. We did not expect that we would identify a significant number of stars who rest on their laurels, given the diminished marginal cost of maintaining stardom once it has been achieved.[7] Based on the distributions of publications and citations displayed in Table I, we identified star scientists from our population using the two different methods described in below.

A. Method 1: Overall Stardom Measure

To recognize stars based on the "lifetime achievement" methodology, we followed Rothaermel and Hess [4] by identifying stars as researchers who had a total count of *both* publications *and* citations that was at least three standard deviations above the mean (z-score > 3.0) for the entire period of our study from 1974 to 2006.

We collected and analyzed the data for pharmaceutical and biotechnology firms separately, resulting in a different threshold for a scientist to attain stardom in each sample. To qualify as a star, a scientist must have published more than 28 papers during the study period and be cited at least 861 times when employed by a pharma company, or more than 24 papers during and be cited at least 696 times when employed by a biotech company. Note that the difference in the star publication requirement between biotech and pharma firms is not statistically significant, while the difference between the citation filters is significant ($p < 0.001$). See Table I for a summary.

Based on the intersection between publications and citations, we identified 1071 star scientists employed in pharmaceutical firms, and 432 stars employed by biotech firms. Although we will discuss the overlap between populations more in depth shortly, of the 46 784 (14% of the total) scientists who published under the imprimatur of both a pharmaceutical and biotechnology firms at some point during their career, only 68 (0.15%) were found to be stars in both samples. We calculated the number of nonstar scientists employed by a firm by taking the difference between the total scientists and star scientists. Table II summarizes the data related to identifying the star scientists in both biotech and pharma firms. More specifically, we found that while there is no significant ($p > 0.05$) difference between the impact of biotech and pharma stars relative to publication output, biotech stars have significantly more impact in terms of citations garnered ($p < 0.001$). As would be expected, the scientists who have achieved stardom in both biotech and pharma have a significantly higher impact than those who are stars in only one domain.[8] We will expand more on these "superstars" later on.

TABLE II
SUMMARY STATISTICS—STAR SCIENTISTS, 1974–2006 – OVERALL STARDOM MEASURE

	Stars				*Times more impactful*	
Setting	*#*	*% of total population*	*% of all pubs*	*% of all cites*	*Pubs*	*Cites*
Pharma	1,071	0.63%	10.61%	19.64%	**16.97**	**31.42**
Biotech	432	0.27%	5.34%	14.56%	**19.74**	**53.87**
			p-value of t-test*		**0.092**	**0.001**
Both	68	0.15%	8.40%	17.89%	**55.97**	**119.26**
			p-value of t-test**		**0.001**	**0.001**

*t-test compares the difference between the times more impactful for stars in biotech and those in pharma relative to publications and citation count.
**The two t-tests comparing stars in both fields with those in either pharma or biotech were both significant at the $p < 0.001$ level.

B. Method 2: Dynamic Measure of Stardom

As a second methodology for identifying stars, we employed a rolling window of publication and citation performance. Akin to analysis in patent data [45], we chose to look at a five-year rolling window. This analysis essentially reproduces the one outlined above for the entire panel timeframe in rolling five-year increments. Thus, we identified scientists who had a publication and citation count that was above three standard deviations above the mean *for a specific five-year increment*. For example, to be considered a biotech (pharma) star for the 1974–1978 timeframe, a star had to publish more than five (5) papers and had to be cited more than 164 (436) times. We repeated this process in a rolling fashion, which resulted in 28 possible *star windows* (1974–1978, 1975–1979, and so on) in which an individual could qualify as a star. On average, to become a star for any five-year window, a scientist in the biotech (pharma) population had to publish more than five (5) publications and be cited more than 257 (309) times.[9]

Based on this process, we identified 4817 pharmaceutical and 2257 biotech scientists. For each of these authors, we calculated the number of windows in which the individual was a star. The average number of windows for biotech stars was 2.5, while for pharma it was 4.1. Given our methodology of using a rolling timeframe, it is possible for a scientist to produce the necessary output to be considered a star in one year and receive credit for the five-year window. As our interest is in high-performing scientists (rather than the potential "one-year wonders"), we removed individuals who failed to achieve stardom for at least five windows (which equates to a 9-year time period over the 33-year study period).[10] This final query returned 1223 pharmaceutical and 474 biotech stars.

[7]The notion of why stars experience a decreasing marginal cost of publication is discussed on page 15, in the discussion of the notion of preferential attachment in scale-free networks.

[8]Times more impactful = (percentage of publications or citations)/(percentage of population).

[9]The forward citations themselves were not limited to the five-year window.

[10]Given the rolling nature of this measurement, it is possible for an individual to have one very productive year and be counted as a star in five windows. There were 3594 and 1783 such individuals in pharma and biotech, respectively.

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C. Comparing Methods 1 and 2

By comparing results from the two stardom identification methodologies, we can yield some insights pertaining to the overlap of tenure and productivity. Specifically, we find that 97% (95%) of the biotech (pharma) stars identified using methodology 1 are also identified in the final query of methodology 2. In fact, the average number of *star windows* for the overall stars identified by method 2 is 12 for pharma and 11 for biotech scientists (out of a possible 28 windows). These levels are significantly different from the average for stars in both the pharma (4.1 windows, $p < 0.05$) and biotech (2.5, $p < 0.05$) samples that were selected using only the dynamic measurement procedure. The analysis empirically supports the idea that a Matthew effect in science does indeed exist in the biotech and pharmaceutical publishing arenas. In speculation, perhaps the effect is further enhanced by the lack of tenure structure in the corporate setting, serving to keep scientists motivated to publish. Regardless of the motivation, we find only a handful of scientists in both pharmaceutical and biotech firms who do not maintain their stardom for at least five years after they have reached the threshold for overall stardom (method 1). There is not a significant number of stars based on overall star measure who rest on their laurels, implying that these scientists remain productive even after they attain stardom. Thus the remainder of our analysis uses the overall stardom measure (method 1).

D. Importance of Stardom

The stars in biotech (pharma) firms represented only 0.27% (0.63%) of the population of scientists, but produced 5.34% (10.61%) of all publications and garnered 14.56% (19.64%) of all citations. This made star scientists in biotech 19.74 times more productive in terms of research output and 53.87 times more impactful in terms of influencing other scientists' research. Likewise, star scientists in pharma firms were 16.97 times more impactful in terms of the quantity of publications, and 31.42 times more impactful in terms of quality. It is also interesting to note the pervasiveness of the stars in terms of coauthorship. Sociologists have long argued that given a preferential attachment process, such as the Matthew effect discussed earlier, the network of coauthorship in the sciences follows a scale-free or star-centric network [46]. Such networks have heavy-tailed distributions and are characterized by the fact that some nodes, or hubs, have many more connections than others. These networks as a whole follow a power-law distribution relating to the number of links connecting to a node. In science, the stars serve as hubs. These individuals become sought after coauthors, as their presence increases the reputation of those to whom they are connected, despite the fact that their appearance as a coauthor may marginally diminish the significance of nonstar authors on the paper. In our data, we do see evidence of this effect: despite the fact that the star scientists make up only a very small percentage of the scientist population, in biotech (pharma) 12.7% (26.9%) of all nonstar scientists have coauthored with a star scientist. Prior research supports the notion that the network of citations in mathematics and neuroscience journals is scale-free and governed by a system of preferential attachment [47].

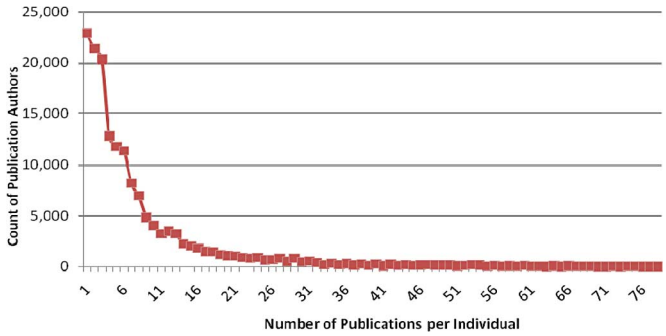

Fig. 1. Distribution of publications, 1974–2006.

As shown in Table II, there was no significant difference ($p = 0.092$) between the impact of biotech *or* pharma firms' stars in terms of the quantity of publication output. There was, however, a significant difference between their impacts in terms of quality, with the stars in biotech garnering more citations ($p < 0.001$). This result is corroborated by comparing the stars from our database with the *ISI Highly Cited Index* (which identifies, as the name suggests, the top-250 most highly cited researchers in 21 subject categories). The individuals in this index are the most highly cited within each respective subject category, and comprise less than 0.5% of all publishing researchers. Unlike our measure, however, this stardom measure only considers forward citations, regardless of how many publications the author may have. This comparison reveals a much higher match between the stars listed in the *ISI Highly Cited Index* and our biotech stars (25%) than our pharma stars (11%). These findings seem to corroborate the research by Zucker and colleagues [9], [32], [35], indicating that many of the best and brightest in academia either founded their own biotech ventures or worked for a biotech start-up. In addition, this pattern of overlap may be due to the fact that biotechnology firms tend to be more focused on their product offering. As a result, scientists in these firms may concentrate on specific subject areas more so than their more diversified peers at pharmaceutical firms, whose expertise is often spread across multiple subject areas. As we illustrate shortly, however, it appears that many of the biotech stars did not move directly from academia to a biotechnology firm, but rather arrived there via a stint at pharma companies.

Our finding that there is no significant difference between the publication impacts of the two star populations provides support for the notion that the distribution of publications in science is relatively fixed. The Lotka-Price Law of scientific knowledge distribution hypothesizes that scientific progress follows an inverse square [48], [49]. In particular, it proposes that the number of scientists publishing n papers is proportional to $1/n^2$. We indeed find that the publications of both biotech and pharma firm authors follow this inverse square distribution. We do not find, however, that journal citations follow a similar fixed distribution. Specifically, we find a much more egalitarian distribution of citations among pharma firm authors than that of the biotech firm authors. Fig. 1 below illustrates the disparate distributions we discovered in our data.

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As we explore further in our discussion of trends and patterns, while a simple analysis of differences between the star populations provides some insights, it is a deeper look at the *dynamic aspects* of these data that sheds the most light on the role intellectual human capital played in the emergence of biotechnology.

IV. Trends and Patterns

Some striking similarities as well as differences emerge when we examine the dichotomization of intellectual human capital between biotech and pharma scientists. The average pharmaceutical firm in our sample employed 220 publishing research scientists per year, while a biotech firms averaged just over 13. It is noteworthy that 46 784 (or 14%) of all authors published under *both* biotech and pharma firms, though of these, 5 237 scientists worked for both types of firms in the *same* year. Although we will investigate the issue of scientist mobility further shortly, looking at the number of organizations our scientists published for reveals that the average nonstar scientist has worked for only 1.3 pharma firms (standard deviation of 0.9) during the time of our analysis, while the average star scientist has worked for 3.4 pharma firms (standard deviation of 1.8). Our data suggest that a star scientist working for a pharma firm is significantly more likely to change jobs when compared with a nonstar scientist. Within biotech firms, however, we do not find a significantly different level of mobility between star and nonstar scientists. In comparison, we find that a nonstar scientist in biotech has worked for an average of 2.5 firms (standard deviation of 1.2), while a star scientist has worked for 4.2 firms (standard deviation of 2.1). While we do not have a baseline for comparing the relative size of these figures, our ex-ante expectation had been that these figures would be higher given recent research pertaining to high rates of mobility among researchers and scientists [50]–[52].

We also expected there would be a significantly higher overlap between the scientists appearing in both the biotech and pharmaceutical databases. The relative magnitude of this number is low given that the careers of the scientists in our sample tend to originate in upstream research institutions and universities. Our ex ante assumption had been that biotech and pharma firms are substitutes in terms of employment in the commercial setting. However, the fact that only 14% of our scientists published in both biotech *and* pharma firms points to some fundamental differences between work environments as well as a general lack of scientist mobility. Indeed, research suggests that small firms, such as many of the biotech companies in our sample, may enjoy advantages over large firms in terms of attracting top talent and motivating high effort by using incentive-laden employment contracts [53]. Given these differences, the intellectual human capital in this study appears to be two *separate* populations of scientists: one consisting of those who are drawn to the high risk-reward opportunities of working for a biotech start-up, and those who prefer the financial stability offered by larger, incumbent pharma firms.

Although these static comparisons shed some light on the characteristics between different scientist populations employed by biotech versus pharma firms, taking a closer look at the dynamic activity of star (see Fig. 2) and nonstar scientists (see Fig. 3) over time reveals additional insights into the ways these different author types participate in the open sciences.

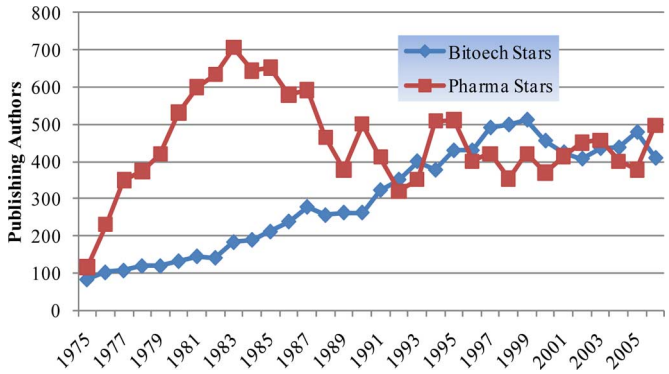

Fig. 2. Star scientist authoring activity, 1974–2006.

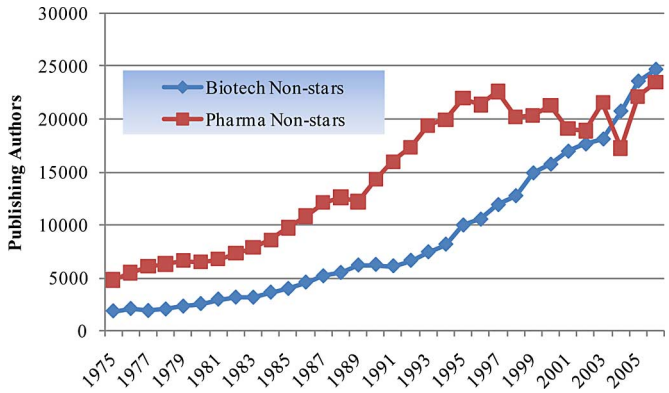

Fig. 3. Nonstar scientist authoring activity, 1974–2006.

Note that in the publication activity of star authors (see Fig. 2), there is a significant spike in star pharma authors between 1979 and 1985. This period is of interest because many researchers consider the Cohen–Boyer patent in 1980 to be the beginning of the commercialization of biotechnology [39], [54]. One potential explanation for this trend is that pharmaceutical firms were anxious to fill empty drug pipelines, and thus jumped on the opportunity that rDNA and other scientific breakthroughs in biotechnology promised.

Fig. 3 illustrates the importance of considering the heterogeneity of a firm's intellectual human capital. The graph depicts the overall trends in the activity of nonstar scientists in biotech and pharma firms. Unlike the case of the star scientists, the trends here generally move upward for both types of firms, a trend that tends to be a function of the size or scale of these firms as they grow over time and develop new biotech capabilities. Once again, the use of intellectual human capital seems to plateau for nonstar scientists in pharmaceutical firms in the latter part of the 1990s, but continues to increase as biotechnology firms expanded their roles into the development and manufacturing of new drug treatments. Taken together, this analysis points to the importance of understanding the heterogeneity present in intellectual human capital. Although the trends revealed by the absolute numbers are interesting, to fully understand this

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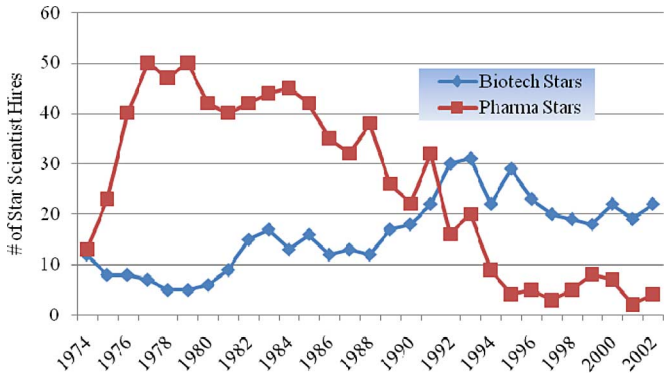

Fig. 4. Star scientists hires per year, 1974–2006.

heterogeneity, we next turn to briefly analyze the trends in the ratio of star scientists as a percentage of total intellectual human capital in both the biotechnology and pharma firms.

In support for the notion that star scientists are employed by pharmaceutical firms to aid in alternative drug discovery and development methods, we investigated each scientist's date of hire (proxied by first date of publication with a firm [39]), as illustrated in Fig. 4. We see a pronounced jump in star scientist hires in the late 1970s through the early 1980s in the pharmaceutical data. Surprisingly, however, the data in the biotechnology sample did not reflect a similar trend. Rather, the hiring of star scientists in biotechnology firms gradually increased over this period, eventually overtaking the pharmaceutical hires by the early 1990s. Although there are multiple potential explanations for these trends, one that is in line with prior research suggests that while stars helped pharmaceutical firms to gain competencies in the new biotech, once these competencies were built, the expense of keeping star scientists employed was no longer a necessity [2]. While this notion puts the star scientists in a passive role, there are many examples pointing to the fact that stars may have left pharmaceutical firms to become a "big fish in a small pond" in the biotech world. Although Zucker *et al.* [32] illustrate that stars are often the founders of biotechnology firms, our data seem to suggest that many of these stars actually come from pharmaceutical firms, rather than directly from upstream research institutions such as universities.

When considering a career move, a tenured professor running a research laboratory may prefer the job security and resources offered by a large pharmaceutical company over the uncertainties inherent in an entrepreneurial biotech venture, especially during the early period of biotechnology. Some anecdotal evidence supports this conjecture. In 1979, Monsanto hired (star scientist) Howard Schneiderman, then Dean of Biological Sciences at the University of California, Irvine. When asked why he left academia for industry, Schneiderman explained: "If you are a red-blooded American who has chosen research as a career, and a guy comes along and says 'Do you have any good ideas for $100 million worth (about $300 million in 2009) of research?' it's a fantastic temptation" [26: 512], [55: p. 510]. Once a scientist adjusts to a commercial setting, he/she is more likely to move back to upstream institutions (e.g., biotech firms or research institutions). Each career move, from a research university to a pharma firm to a biotech firm, minimizes the degree of newness in a new work environment. The traditional and bureaucratic research atmosphere found at many incumbent pharmaceutical firms, as well as the incentives offered by many small research firms to attract top talent [53], may work in tandem to lure stars away from pharma firms and sign on with biotech ventures [56].[11] Finally, as biotechnology overcame early uncertainty and emerged as a viable commercial alternative to discovering and developing new medicines, the allure of being part of an entrepreneurial biotech venture only grew stronger.

To further investigate the trends in movement between pharmaceutical and biotech firms for both star and nonstar scientists, we placed each of the 46 784 scientists publishing as an employee in *both* types of firms at one point in their career into 1 of 12 categories, composed of three broad types depending on star status and employer type at the time of an individual's first publication. Table III summarizes these categories, as well as the percentage of authors within each one.

More than 98% of the overlapping scientists are categorized as type A, meaning that they were nonstar scientists in either sample. Among this type, 57% comprise nonstar scientists who moved from a pharma firm to a biotech venture. Nearly half of type A scientists made this transition in reverse. We posit that the more interesting analysis is found by looking at scientists who were stars in either one or both of our samples. Specifically, type B scientists were identified as being a star in one sample and a nonstar in another. The majority (495, or 58%) of type B scientists comprise scientists who began their commercial careers as star scientists in pharma firms but finished up as nonstar scientists at a biotech firm. These individuals became stars while at the pharma firm and subsequently left for a biotech firm [30]; unlike type C "superstar scientists," however, these individuals did not continue the requisite productivity at the biotech firm to become a star in that population as well. It is possible that type B scientists opted for managerial roles in favor of an active research agenda at the biotech firm. A less favorable interpretation of this finding is that such individuals "cashed in on their reputation" earned at a pharmaceutical company in order to join a biotechnology company [49], [51]. Comparably, only 89 scientists in the overall database (0.19%) made the same transition in reverse order; they began as nonstars at pharma companies and concluded their careers as stars in biotech companies.

Finally, we identified 68 type C "superstar scientists" (0.14% of overlapping scientists) who kept up productivity with both a biotechnology and a pharma firm. All but one of these individuals was also included in the *ISI Highly Cited Index*. Once again, of these individuals, 57% first published (in a commercial setting) with a pharma firm before subsequently moving to a biotech firm and maintaining their star status within the new

[11] An excerpt from the autobiography of Sir James Black, who was awarded the Nobel Prize in Medicine in 1988 and also employed by Wellcome, provides an example of the rationale behind such movement: "The division I took over at Wellcome, however, was remarkable for its traditional, conservative, ways and feudal structures. Entrenched attitudes can absorb reformist efforts like a punch bag" [5: p. 6]. Black eventually went on to establish a small academic research unit at King's College, London.

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TABLE III
SCIENTISTS ACTIVE IN BOTH BIOTECH AND PHARMA FIRMS, 1974–2006

Type	#	%	Initial	Movement	Subsequent	Category Description
A	26,466	56.57%	Pharma Non-star		Biotech Non-star	Non-star in both, Pharma first
A	14,285	30.53%	Biotech Non-star		Pharma Non-star	Non-star in both, Biotech first
A	5,113	10.93%	Pharma Non-star		Biotech Non-star	Non-star in both, Same year
B	89	0.19%	Pharma Non-star		Biotech Star	Non-star in Pharma, Star in Biotech, Pharma first
B	90	0.19%	Biotech Star		Pharma Non-star	Non-star in Pharma, Star in Biotech, Biotech first
B	51	0.11%	Pharma Non-star		Biotech Star	Non-star in Pharma, Star in Biotech, Same year
B	64	0.14%	Biotech Non-star		Pharma Star	Non-star in Biotech, Star in Pharma, Biotech first
B	495	1.06%	Pharma Star		Biotech Non-star	Non-star in Biotech, Star in Pharma, Pharma first
B	63	0.13%	Pharma Star		Biotech Non-star	Non-star in Biotech, Star in Pharma, Same year
C	19	0.04%	Pharma Star		Biotech Star	Star in both, Pharma first
C	39	0.08%	Biotech Star		Pharma Star	Star in both, Biotech first
C	10	0.02%	Pharma Star		Biotech Star	Star in both, Same year
	46,784	**100%**				

context. Investigating these superstars in the aggregate database reveals that they have 56 times more impact in terms of publications and 120 times more impact in terms of citations than the average scientists.

Our analysis of the dynamics underlying affiliation changes by star scientists (in categories B and C mentioned earlier) sheds some light on the mobility of stardom. There are differing streams of thought as to whether a star can carry his value if she changes her place of employment. The work by Groysberg and colleagues [7], [57] suggests that stardom is not likely to be highly mobile, because it is primarily based on firm- or situation-specific attributes such as a star's teammates, culture, available resources, etc. Specifically, these individuals would be classified as type B scientists in the typology mentioned earlier (i.e., stars in one domain but nonstars in another). It is not surprising that the majority (92.6%) of our mobile stars fall into this category. By contrast, Type C scientists were able to transfer stardom across the boundary between pharma and biotech firms. These scientists may represent what recent literature has referred to as "lone wolves" [58], meaning they are productive on their own regardless of work setting. The "lone wolf hypothesis" postulated by Oettl stands in contrast to the "team hypothesis" advanced by Groysberg *et al.* [7], [57]. However, rather than looking at these theories as being mutually exclusive, our analysis reveals that there exists *heterogeneity even among star scientists,* where a small group is likely to be composed of lone wolves, while the vast majority rely on their teams to be highly productive.

To better understand this phenomenon, we investigated the average productivity of star scientists after they had made the switch from pharma to biotech, or vice versa. Specifically, we counted the number of star windows (see description in the methodology section mentioned earlier) a star scientist had following the switch. Our analysis revealed that on average, a pharma (biotech) star scientist who moved to biotech (pharma) had 3.2 (5.4) star windows following the move. This significant ($p < 0.05$) difference indicates that on average, a biotech star who joined the ranks of a pharmaceutical firm remained more productive following the move than a colleague who moved in the opposite direction.

Up to this point, we have been treating all of the pharma firms in our sample as being identical in terms of their use of intellectual human capital. However, there are significant differences in the strategic mindset among different pharmaceutical firms. To account for these differences, we split pharmaceutical firms up into those that specialize in pharmaceutical research (e.g., GlaxoSmithKline, Schering-Plough, or Yamanouchi, which focus primarily on proprietary drug discovery and development) and those that are more diversified in nature (most notably chemical companies like Monsanto or DuPont and consumer products firms such as Johnson & Johnson). Specialized pharmaceutical companies are firms that are active in SIC 2834 (pharmaceutical preparations manufacturing). If a company is active in both SIC 2834 and in SIC 2890 (chemical products manufacturing), e.g., it was coded 0, indicating a higher degree of diversification. More than half of the firms (53%) were fully specialized pharmaceutical companies, and they exhibited a significantly higher rate of biotech-related patents than the more diversified firms (i.e., 9.2 biotech patents per year for specialized firms versus 6.3 annual biotech patents for diversified firms; $p < 0.05$).[12]

Within the setting of biotechnology, we suggest that a firm's level of diversification may influence the extent to which it draws upon different types of intellectual human capital (i.e., star versus nonstar scientists). When confronted with the biotechnology revolution, fully dedicated pharma firms had more at stake than their more diversified counterparts. Therefore, in regard to the relationship between star and nonstar scientists and firm diversification, specialized pharma firms, being earlier and more aggressive adapters to biotech, had a higher proportion of publication output from star scientists. Q1

Fig. 5 depicts the proportion of authorship by star scientists in specialized pharma, diversified pharma, and fully dedicated biotechnology firms. Despite being highly focused on scientific research, the biotech firms in our sample actually had a lower proportion of star authors than either specialized or diversified pharmaceutical firms. One potential reason for this speaks to the role of stars and the different strategic directions for biotech and pharma firms. Specifically, pharmaceutical firms must innovate

[12]The U.S. PTO compiled these data based on all biotechnology patents in the following patent classes: 424 [Drug, bio-affecting and body treating compositions (different subclasses)], 435 [Chemistry: Molecular biology and microbiology], 436 [Chemistry: Analytical and immunological testing], 514 [Drug, bio-affecting, and body treating compositions (different subclasses)], 530 [Chemistry: Natural resins or derivatives; peptides or proteins; lignins or reaction products thereof], 536 [Organic compounds], 800 [Multicellular living organisms and unmodified parts thereof and related processes], 930 [Peptide or protein sequence], PLT [plants].

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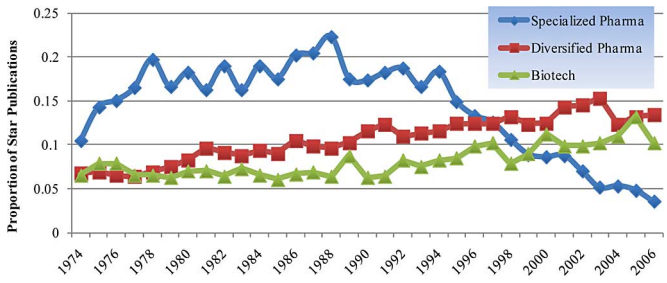

Fig. 5. Proportion of star authorship, 1974–2006.

or perish [1], as their livelihood depends upon the ability to constantly refresh their drug pipelines. This necessity drives their need to retain research visionaries (in the form of star scientists) in the hope that the breadth of their research interests will help stimulate the organization's innovative efforts. By contrast, research suggests that biotech firms are often founded around a single individual or small group of highly talented individuals who are focused on one specific technological application [32]. Given their smaller size relative to pharmaceutical firms, the founders of these biotech firms are likely to be compensated through incentive-based schemas, such as stock options [53]. Based on this model, the end goal for many biotechnology firms is not to continually innovate, but to develop a single technology for the purpose of being acquired by a pharmaceutical firm, or to accomplish an initial public offering [1], [59]. The focus of this business model, therefore, decreases the need and incentive to hire more star scientists; in fact, doing so would actually likely dilute the ownership of the original founder(s).

Within the specialized pharma firms, star scientists created an average of 14.8% of publications. This is significantly different ($p < 0.05$) from the proportion for diversified pharma firms (11.2%) as well as the biotech firms (7.3%). Thus, while our ex ante assumption regarding the activity of specialized pharmaceutical firms is supported, the proportion of star authors in biotechnology firms is significantly lower than either type of pharmaceutical firm and only trends slightly upward. This trend is similar to what we see for diversified pharmaceutical firms, but much different from that illustrated for specialized pharmaceutical firms.

The trend in specialized firms (also supported by the star authorship trend in Fig. 2) may indicate that star scientists became less critical to incumbent adaptation after the knowledge associated with biotechnology became more widespread in the early 1990s [1], [60]. The lower level of star activity in biotech firms may be the result of the different strategic focus we just discussed, or it may be simply due to fewer resources in these smaller firms. An alternative explanation to talent, however, is that biotech firms place less emphasis on publishing than pharma firms, and thus the behavior is either not encouraged or made more difficult for scientists employed by a biotech venture. While it is a possibility, we submit that this explanation is likely not the case when accounting for the differences between biotech and pharma firms. There are several reasons for our stance. First, to be a member of the scientific community, an individual must give in order to get [21]. Thus, active participation within the community, usually in the form of publishing and attending conferences, is essential for remaining in contact with the greater knowledge networks. In support of this, Cockburn and Henderson [54] and Cockburn *et al.* [61] illustrate that for firms to take advantage of public sector research, they must actively collaborate with their public sector colleagues in addition to investing in basic in-house research. Second, a frequent exit strategy employed by many biotechnology firms is acquisition by a pharmaceutical firm [62]. Thus, as a signal of quality, many biotechnology firms will seek to maximize their patent and publication outputs [8].

V. Conclusion

We provide herein a detailed analysis concerning the role of intellectual human capital in the emergence of the new biotechnology for both incumbent pharma firms and new biotech entrants. Our data comprise individual-level publication histories, allowing us to compare and contrast how these different types of firms employ one of their most fundamental resources. We are able to unearth some interesting findings. The most fundamental contribution of our investigation is the importance of *heterogeneity in intellectual human capital.*

We illustrate disparate patterns for star and nonstar scientists in pharmaceutical firms (specifically in specialized pharma firms). It appears that the importance of star scientists peaked in the early to mid-1980s and diminished as the knowledge associated with biotechnology was disseminated through the scientific community. Furthermore, our analysis gives us a better understanding of where these stars go when they leave a pharmaceutical firm. Specifically, we suggest that they tend to move back upstream, either to universities, research institutions, or in our case, biotechnology firms.

Although they are often portrayed as conservative and bureaucratic [63], pharmaceutical firms appear to be critical for the development and progress of science. As our findings regarding mobility between pharmaceutical and biotech firms illustrate, many star scientists first appear in our dataset while employed in pharmaceutical firms. These stars played a central role in determining where and when firms enter the new field of biotechnology, and how successful they were [34]. Therefore, pharmaceutical firms foster the intellectual human capital that may eventually form the basis for a competing biotechnology firm.

Individuals are the central resource of all organizations. Especially for firms in knowledge-intensive industries (e.g., semiconductor, pharmaceutical, and biotechnology), access to the knowledge held by these individuals is critical for their very survival [64]. By drawing upon a fine-grained dataset, we endeavored to increase our understanding of the roles different types of individuals play within an organization, as well as their movement between organizations. This movement is critical because the individuals we study represent the conduits of knowledge transfer and help firms capture knowledge spillovers [65], like those associated with the biotechnology revolution of the early 1980s [33], [65]. We not only reveal and highlight significant

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across-group heterogeneity between star and nonstar scientists, but also significant within-group heterogeneity. Not all stars are created equal. The majority rely on their teams to succeed, while others are able to succeed more or less independent of work and team context.

One of our intended contributions with this manuscript is to provide fodder for future research. Specifically, we feel that there are numerous potential avenues that can further our understanding of issues related to, but not limited to, knowledge diffusion, employee mobility, organizational learning, and the dynamics of network structure. To this last focus, future research may enlighten us regarding the appropriate level of analysis when investigating coauthorship networks. For example, it may be found that different treatment areas (e.g., anemia, diabetes, obesity) have different network structures. In addition, analysis of these networks over time may provide for the ability to identify emerging star scientists that will eventually become the thought leaders in their specific treatment areas.

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QUERIES

Q1. Author: Do we mean for pharma firms?