NBER WORKING PAPER SERIES

CONTRACTING OVER THE DISCLOSURE OF SCIENTIFIC KNOWLEDGE: INTELLECTUAL PROPERTY AND ACADEMIC PUBLICATION

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Working Paper 19560
http://www.nber.org/papers/w19560

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
October 2013

Thanks to Dan Burk, Iain Cockburn, Julian Kolev, Mark Lemley, Michael Riordan, Chris Snyder, Glen Weyl, Heidi Williams and participants at the 2008 Organisational Economics Workshop (Sydney), Workshop on Scholarly Communication (Michigan), Summer Workshop on Industrial Organisation (Auckland), 2009 International Industrial Organization Society Conference (Boston), 2009 Conference on the Patent Crisis (UC Irvine), 2010 NBER Summer Institute and seminars at Northwestern, Colorado, Stanford, Hong Kong, Melbourne, Queensland, the Australian National University, Wharton, Harvard, Toronto, Georgetown, Yahoo Research, Case Western, MIT and Boston. Thanks to Vivienne Groves for research assistance. JG acknowledges an ARC Discovery Grant for financial assistance. FM and SS acknowledge a National Science Foundation Science of Science Policy Grant. Responsibility for all errors lies with us. The latest version of this paper is available at research.joshuagans.com. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

At least one co-author has disclosed a financial relationship of potential relevance for this research. Further information is available online at http://www.nber.org/papers/w19560.ack

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NBER Working Paper No. 19560
October 2013
JEL No. M55,O32,O34

ABSTRACT

This paper provides a theoretical investigation of the tension over knowledge disclosure between firms and their scientific employees. While empirical research suggests that scientists exhibit a 'taste for science,' such open disclosures can limit a firm's competitive advantage. To explore how this tension is resolved we focus on the strategic interaction between researchers and firms bargaining over whether (and how) knowledge will be disclosed. We evaluate four disclosure strategies: secrecy, patenting, open science (scientific publication) and patent-paper pairs providing insights into the determinants of the disclosure strategy of a firm. We find that patents and publications are complementary instruments facilitating the disclosure of knowledge and, counter-intuitively, that stronger IP protection regimes are likely to drive openness by firms.

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I. Introduction

An enduring puzzle in the management of innovation is that many firms fund basic research and embrace practices from open science (such as publishing and conference participation) alongside their more traditional and anticipated development activities. Industry scientists even appear to have internal career paths tied to publishing success (Xu 2007) and career ladders that resemble those in academia with advancement solely through individual technical contributions (O'Mahony and Dahlander 2012). To explain these observations, scholars have hypothesized that open science practices serve as a "ticket of admission" to absorb scientific knowledge from academia, allowing firms to more rapidly reach the frontier and exploit first mover advantages (Rosenberg, 1990; Cohen and Levinthal, 1990). By implication, firms adopting open scientific practices are more productive. However, upon empirical examination, the adoption of open science by firms is found to be negatively correlated with the incomes of scientists at those firms (Stern, 2004). Moreover, patent quality may be negatively correlated with the magnitude of scientific impact of associated papers (Gittelman and Kogut, 2002). This suggests that scientists themselves have a "taste for science" (Merton, 1973; Dasgupta and David, 1994) and that, in fact, firms face costs in engaging in scientific practices. This leaves open a critical question for scholars and for managers of innovation: What types of disclosure practices – particularly with regards to open and closed practices - should firms adopt? And, relatedly, as firms make these disclosure choices what tradeoffs are being made with regards to firm-level competitiveness on one the hand and employee preferences one the other?

The importance of exploring the collection of disclosure practices firms should adopt reframes the question of open science in a broader context. Specifically, while much of the current literature counterpoints open science with "closed" practices such as intellectual property, there exist a wide variety of disclosure strategies that might be pursued. For example, trade secrets are widely used in industry but rarely adopted in academia. Moreover, one of the distinguishing features of science as practiced by industry (compared to that practiced in academic settings) is the greater adoption of mechanisms to protect intellectual property simultaneously. This includes patent protection, which, of course, involves some disclosures but can restrict use, as well as trade secrecy. Indeed, there is an increased incidence of patents being associated with publications of the same underlying research (Murray 2002, Azoulay, Ding and Stuart, 2009) and this incidence is greater for industry than academia (Murray and Stern 2007).

The second of our key questions relates to the contractual relationship regarding disclosure between scientists and the firms who employ them. Studies of scientists' preferences for open science ignore the fact that firms have preferences and these preferences may be at odds with scientists' desire for open publication. Moreover, these studies ignore the fact that scientists may have more complex preferences over the bundle of disclosure approaches – not simply publication. For example, the recent Twitter contract suggests that scientists may have preferences over the use of their intellectual property: the firm provided employees with significant future control rights over the use of their patents including commitments not the use the patents in "troll" situations.[1] A similar commitment to 'open science'-like practices can be observed with IBMs agreement to contribute intellectual property related to open source software. To complicate matters, scientists may have preferences with regards to combinations of disclosure practices. The backlash over the patenting (and publishing) of the Oncomouse discovery in the 1980s demonstrates that (academic) scientists resist attempts to exclude the use of research results through intellectual property protection and generally look with skepticism on practices that allow unfettered commercial exploitation of research (Bok, 2003). Does this imply that industry scientists will be less interested in open science publication practices when they are combined with simultaneous patenting? Put more broadly, what is the negotiation that arises between industry scientists and the firms who employ them with regards to disclosure?

To date, there has been no thorough examination of the drivers of firm adoption of a full range of disclosure practices: open science publication alongside other commercial options including secrecy and intellectual property. Thus, while the empirical studies show that scientists pay to be scientists i.e. pay to engage in open disclosure through publication - in industry settings they cannot explain why some firms adopt those practices while others do not. If one were to take a pure "taste for science" view of the management of scientific workforces, we might expect that in industries were intellectual property protection is weak (and, therefore, less consequential for firms), scientific practices would be more widely adopted as a means of economizing on labor costs. However, open science is most widely found in sectors such as the pharmaceutical industry where intellectual property protection is strong (Cockburn and Henderson 1999; Lim 2000). To account for these apparent puzzles, we propose a theoretical model that takes into account scientist preferences on the one hand and firm concern over disclosure on the other. Thus, we can enable scholars as well as managers to sort out these competing effects and generate hypotheses for future empirical examination of firm approaches to basic research.

One key advance inherent in our approach relates to the relationship between the type of research and disclosure. Some prior treatments have assumed that a simple mapping takes place from organizational context – industry versus academia, to type of research – applied versus basic, to disclosure strategy – patents versus publications. However more recent empirical evidence of universities' growing patent portfolios (Mowery et al. 2004, Jensen, Thursby and Thursby 2010; Sauerman and Stephan, 2010) and the growing contribution to the scientific literature made by industrial scientists (Henderson and Cockburn 1996) suggests that no simple relationship exists between organizational

[1] http://engineering.twitter.com/2012/04/introducing-innovators-patent-agreement.html (accessed 4 Sept 2012).

arrangements and particular disclosure strategies. By recognizing and formally modeling the ways in which one project has the potential to lead to a variety of disclosure outcomes, ours is the first model to endogenize disclosure, thus, enabling us to provide a formal treatment that is closer to industrial research as practiced on the ground, as well as allowing examining how these choices impact on the relationship between scientists and commercial firms who employ them.[2] Our focus on disclosure highlights the various channels through which the research outcomes of *all* projects may, in fact, be disclosed in an environment where it is possible for commercial firms to keep project outcomes secret as well as to patent and publish.

Of equal import is the fact that our theoretical treatment explicitly links disclosure choices made by firms with the preferences of scientists. Our approach is in contrast to other studies that have modeled and empirically examined the relationship between openness and project selection (rather than disclosure) including, mostly notably, Aghion, Dewatripont and Stein (2008), who examined the governance of project direction and the degree of control that funders use to determine project choice (see also Lacetera 2010). Similarly, it has been shown that different incentives – implemented through the length of project funding periods – shape researchers' project selection (Azoulay et al. 2010). Initial team size (Uzzi, Jones and Wuchy 2010) and structures of collaboration also serve as important organizational choices for knowledge production (Haeussler et.al., 2011; Gans and Murray 2013). Jeon and Menicucci (2008) also examine the interplay between scientific and commercial rewards in determining the choice of scientists between industry and academia in labor markets and the welfare consequences of these decisions. Likewise, Sauermann and co-authors have a line of research that uses survey data to explore scientists' interests in both academic and industry-oriented rewards (Sauermann and Cohen 2010; Sauermann and Roach 2013). What these approaches are missing, and what we provide, is formal model that engages with the interaction between scientists' preferences for alternative disclosure-based rewards and the consequences for firm competitiveness of these disclosure strategies.

Our paper has a number of important findings built around a set of empirically-derived assumptions and a baseline model examining a single negotiation over a research project between a scientist and firm. Most importantly, we find two key conditions that generate *complementarity* between decisions to patent and decisions to publish i.e. that resolve the otherwise opposing requirements of scientists and firms on disclosure. First, to the extent that knowledge disclosed in patents and in publications overlaps, then if knowledge is disclosed through one path, the incremental cost to the firm of disclosures through the other path falls. Second, to the extent that a patent can effectively protect the firm from imitative entry facilitated by disclosure, the negative consequences of additional disclosure through

[2] Mukherjee and Stern (2009) look at the broad choice between disclosure and secrecy in a dynamic setting but do not consider the interaction and feedbacks between this and firms' other disclosure options such as patenting.

publication fall. From a managerial perspective, this suggests that firms considering disclosure strategies must not only understand the degree to which these conditions hold but also must develop approaches that allow for disclosure of all types to be highly coordinated. Most important is the finding that the stronger are scientist preferences for publication (e.g., because scientific rewards are strengthened), the greater the incentives to take out intellectual property protection. This stands in distinction to prior literature which suggests that open and closed policies for disclosure within a firm lie in opposition to one another (von Hippel 2005).

Moving beyond our baseline model we consider a dynamic setting with overlapping periods in which of scientists and firms negotiate over research that potentially cumulates from one period to the next. Such a dynamic model allows for a richer examination of scientist preferences (allowing them to care about citations as well as publications) and also greater commercial opportunities (allowing firms to earn revenue from licensing to future projects). The end result is the identification of further complementarities – this time among publication decisions (namely, one cannot generate a citation unless the future researchers also publish) but also inter-temporal substitutability between patent and citation decisions (namely, that a patent may cause future scientists to avoid explicit follow-on research so as to avoid license payments). From a managerial perspective, this suggests that decisions to patent and publish may not be entirely complementary over time and will need to be considered over the dynamic of a particular research and commercialization project, suggesting that sophisticated management of innovation requires, among other things, a highly integrated approach to disclosure strategy and rewards.

II. Disclosure of Scientific Knowledge: Model Elements

The goal of our paper is to develop a theoretical model that examines how firm choices regarding the disclosure rights of their scientists interact with other elements of the firm's commercial and institutional environment; particularly, the firm's decision to pursue formal intellectual property protection. In so doing, we explicitly consider environments where knowledge has both a basic component (of value in academic publishing) as well as an applied component (of immediate use value); that is, to use recent classifications, that research is taking place within Pasteur's Quadrant (Stokes, 1997) named after Pasteur's simultaneous advances in vaccination (a "product" of immediate value) and microbiology (scientific knowledge of value for future generations of innovators). It is in these environments where firm choices over the management of scientists have their greatest salience.

In this section, we consider the broad assumptions underpinning the formal model that follows below and the evidence supporting them. Specifically, we consider the disclosure strategies available to firms (with regard to both published and patented disclosures), the potentially conflicting preferences of scientists and firms over these strategies, and the process by which strategies are chosen or negotiated.

Disclosure Strategies

We consider research projects that generate both a product of immediate commercial value and also scientific knowledge that provides the foundation for future research in subsequent generations and for potential competitors in this generation. For projects of this type, the set of possible disclosure choices faced by firms is comprised of two elements: First, given the production of scientific knowledge of potential interest to future generations, the results from the research project may be *published*. This represents the collection of activities that comprise academic dissemination including publication as well as the presentation of papers that augment the stock of publicly available knowledge (Dasgupta and David, 1994). Second, given the production of immediately useful knowledge, it is possible to file a *patent* application disclosing what precisely is protected. If a decision is made *not* to patent, then this can lead to knowledge being kept *secret*. Taken together, this leads to four disclosure regimes that we term secrecy, open science, commercial science, and patent-paper pairs.[3] We examine each in turn.

Secrecy: It has been observed that, in the absence of incentives for disclosure provided by a range of institutions, knowledge production frequently leads to very limited disclosure and diffusion of knowledge (Mokyr, 2004). Examples abound of inventions that operate under a regime of *secrecy* where for a significant (and perhaps indefinite) time, knowledge created is not disseminated. In seventeenth century England, the Chamberlen family maintained the design of forceps and techniques for their use as a secret for three generations thus ensuring their position as the leading (male) midwives of the era (Radcliffe, 1947). Not restricted to medical innovations nor to product designs, the secret formula for Coca Cola has been retained by the firm as a trade secret rather than being disclosed in a patent.[4] Similarly, Thomas muffins actively maintain secrets to their recipes to protect the approximately $500 million in yearly muffin sales (Neuman, 2010). Examples extend across a variety of industry sectors, from scientific instruments (Moser 2005) to Apple's on-going attempts to control pre-launch information on products such as the iPhone. Indeed, survey analysis by Levin et al. (1987) revealed the surprising importance of secrecy as a form of appropriability in many sectors while Lerner (1994) observed that 43% of all IP litigation involves trade secrecy. Secrecy itself is grounded in a range of institutions including formal trade secrecy law, non-compete agreements (Marx et al., 2009), non-disclosure contracts (Williams, 2010) as well as non-disclosure clauses that are enabled by the inevitable disclosure doctrine within trade secrecy law (Lowry 1988).

[3] It is worth noting that this is the type of disclosure assumed to arise in the endogenous growth literature although not explicitly discussed as such. For example, Romer writes: "The crucial feature of the specification used here is that knowledge enters into production in two distinct ways. A new design enables the production of a new good that can be used to produce output. A new design also increases the total stock of knowledge and thereby increases the productivity of human capital in the research sector." (Romer, 1990, S84)

[4] In recent years several Coca Cola employees have been charged with and found guilty of attempting to steal trade secrets from the company and sell them to Pepsi Co. resulting in prison sentences of up to seven years (http://money.cnn.com/2007/05/23/news/newsmakers/coke/index.htm).

Open Science: The institutional foundations of scientific publication in the academic literature are well established (Dasgupta and David 1994; David, 2008). They provide a clear set of organizational arrangements through which scientific knowledge can be evaluated, certified and disclosed through peer-reviewed journals. Less formally other forms of 'publication' can include presentation at conferences, symposia and the writing of abstracts. More recently, the development of a range of on-line platforms for scientific knowledge has expanded the possibilities for scientists and firms engaging in what we broadly refer to as publication or 'open science.' Researchers are rewarded with reputation and kudos from their peers as well as opportunities for signaling their quality to future employers (Merton 1952, David and Dasgupta 1994, Stern 2004).[5] A line of scholarly research has emphasized the expansion of publishing in scholarly journals, and most importantly for our purposes, the significant contributions to these journals made by scientists affiliated with for-profit firms (see Henderson and Cockburn 1998 and Gittelman and Kogut 2002 for early elaborations of the importance of this disclosure path).

Commercial Science: Governments, long recognizing the potential inefficiencies of secrecy, have developed national institutions allowing for property rights over novel inventive knowledge. The patent system lies at the heart of an institutional system that, among other functions, provides incentives to ensure that knowledge locked within firms or the minds of inventors might instead be disclosed (Machlup and Penrose, 1950; Scotchmer and Green, 1990). This incentive arises as patents can protect firms against imitative competition. First, a broader patent may make it more costly for competitors to enter with work-around products. Second, patents can block entry entirely; albeit in a probabilistic manner (Lemley and Shapiro, 2005). As a *quid pro quo* for such protection, patent holders must disclose knowledge to the level that enables a person "skilled in the art" to replicate that knowledge and potentially build upon it. Substantial empirical evidence illustrates the degree to which firms use patent disclosure strategies and under what conditions (Scotchmer 1995). More recently, this evidence has highlighted the expanding role of patent thickets and other more subtle uses of patent disclosure (Ziedonis 2008).

Patent-Paper Pairs: While the simple comparison between patenting and secrecy or publishing and secrecy provides some insight into the different possible disclosure strategies, this approach ignores a fourth alternative to disclosure through both patenting and publication; a strategy we refer to as *patent-paper pairs* (see Murray 2002). As noted above, for a project to result in disclosure through patent-paper pairs, the knowledge generated in a *single* research project must contribute to both scientific research and useful commercial (technical) applications. If it meets this test, then researchers can disclose their knowledge simultaneously in both institutions; garnering property rights through patents and making the research available to future generations of researchers. In projects of this type, the knowledge actually

[5] Also related are the norms of open source communities (Lerner and Tirole, 2005). Mukherjee and Stern (2009) consider the trade-off between scientific disclosure and secrecy in a dynamic model although they do not explicit model the negotiated outcomes between scientists and funders over disclosure strategy.

revealed in the patent and paper may be more of less congruent: At one end of the spectrum, projects may generate fundamental breakthroughs in respective scientific domains that are disclosed in papers, while the patents cover immediate applications of the knowledge. At the other, it is possible to find examples where the knowledge disclosed through patents and papers is highly congruent; i.e., it is the same knowledge being disclosed.[6]

While the notion of a patent-paper pair may appear to be a peculiar anomaly, in reality, pairs constitute the disclosure choices of private firms (as well as academics) across a range of disciplines. Consider the following examples drawn from the past fifty years of scientific research pursued by industrial scientists in chemistry, physics, biology and computer science in industry and academia:

- William Shockley described work at Bell Labs in his research notebook leading to the patent on the solid state transistor and published breakthroughs on the theory of P-N junctions underlying the transistor (Shockley, 1949).
- Knowledge of how to amplify DNA developed at Cetus Corporation was an important, published scientific discovery (leading to the 1993 Nobel Prize) and also a consequential patented and profitable invention (see Rabinow, 1996).
- Researchers at Microsoft have used patent-paper pairs as a disclosure strategy for advances in computer science including image processing: Patent 7,262,769 (filed 2004) discloses "Systems and methods for optimizing geometric stretch of a parametrization scheme" and the same inventors are authors on a paper at the Eurographics Symposium on Geometry Processing (2004) (Signal-Specialized Parameterization for Piecewise Linear Reconstruction."

Beyond specific examples, the coincidence of patent-paper pairs disclosing knowledge of related consequence has been extensively identified and studied by Ducor (2000), Murray (2002), Murray and Stern (2007) and Huang and Murray (2009). More recent empirical evidence from publications in scientific journals focused on biotechnology and nanotechnology illustrate that for industry authors, the incidence of pairs is 54% and 30% respectively (Fehder, Murray and Stern, 2013).

In the management literature, patent-paper pairs have not been explored as a disclosure strategy. However data on the extensive use of patenting and publication are suggestive of the fact that patent-paper pairs are the preferred disclosure strategy with considerable regularity. For example, among

[6] This feature of patent-paper pairs is illustrated with an example from genetics research focused on a gene known as BLNK (pronounced "blink") found on Chromosome 10. The BLNK gene encodes a B cell linker protein. In simple terms, proteins of this type sit on the surface of B cells and provide bridges between receptors and other proteins, regulating the biological functions of B cells. In 1999, scientists discovered, and published the sequence and function of the BLNK gene in a paper in *Immunity*: "*We describe here the identification of a novel B cell linker protein, termed BLNK, that interfaces the B cell receptor-associated Syk tyrosine kinase with PLCgamma, the Vav guanine nucleotide exchange factor, and the Grb2 and Nck adapter proteins*" (Fu et al, 1998). The researchers also filed patent #5994522 on BLNK proteins describing "the discovery of molecules which interact with either Grb2 or PLC-γ … play a role in the regulation of … signaling pathways are desired. Accordingly, it is an object of the present invention to provide such molecules, termed 'BLNK' proteins, and to provide methods of using such molecules in screening assays." The paper provides no additional disclosure relative to the patent.

researchers identified as disclosing knowledge at leading R&D firms (including DuPont, Merck, Intel and IBM), 10-25% are listed on both patents and publications (Lim, 2004). The dual disclosure strategy of patenting and publishing is also widespread in biotechnology firms (DiMinin and Fabrizio, 2003).

One additional observation is worth making about patent-paper pairs: The decision to pursue both patents and papers cannot be an after-thought but rather needs to be a clearly deliberated strategic choice. The reason for this is the timing requirements with respect to the ability to apply for and be granted a patent: that is, if publications precede patent application filing (by more than one year in the US) then the publication is considered to be prior art and the patent would be invalidated.[7] This suggests that pairs are indeed part of a well crafted disclosure strategy pursued by firms (as well as academics and their technology licensing officers) rather than a strange artifact of modern disclosure.

Preferences

In his work on the reasons behind private firm investments in basic research Rosenberg (1990, p. 169) notes there is a basic tension between the preferences of scientists and those of firms. He writes:

> Many scientists in private industry could honestly say that they are attempting to advance the frontiers of basic scientific knowledge, without any interest in possible applications. At the same time, the motivation of the research managers who decide to finance research in some basic field of science, may be strongly motivated by expectations of eventually useful findings.

While these divergent preferences can be broadly considered to incorporate differences over the types of projects being undertaken (see Aghion, Dewatripont and Stein 2008), they also, centrally, involve divergent views on the types of disclosures generated after project completion. Our model will capture this by assuming that scientists have a preference for disclosure through publication while firms seek to maximize profit. Here we review the literature justifying these assumptions.

Scientists: The institutional norms and career practices of academic scientists emphasize the importance of disclosure through the scholarly literature in the form of publication. To receive credit for the intellectual priority of their scientific discoveries, scientists publicize their findings as quickly as possible but retain no other rights over their ideas (Merton, 1957). More subtly, these rewards – sometimes referred to as 'kudos' – are related both to the significance of the published research relative to the existing literature and to the value, often judged *ex post*, that it adds to the pool of knowledge used by future generations of researchers. In simple terms, rewards are given for publication (a certification of significance) and citation (a certification of eventual relevance).

Publication-based rewards obviously critical to the career concerns of university-based scientists, however empirical evidence suggests that scientists working in industry have similarly strong preferences

[7] Some papers consider a form of interaction between the patent system and publication via the strategy of defensive publication (Bar Gill and Parchemovsky 2003) particularly in settings with patent races (Baker & Mezzetti, 2005; Bar, 2006; Johnson, 2005). There is also a literature on the interaction between scientists' incentives and University technology transfer offices to disseminate patent applications (Macho-Stadler et.al., 2007; Hellmann, 2007).

for publication. As noted earlier, Stern (2004) provides strong empirical evidence that scientists working in the private sector have strong preferences for disclosure through publishing (or presumably through patent-paper pairs although this was not explicitly explored).[8] Moreover, while career paths among scientists in industry are distinctive to those in academia, qualitative evidence suggests that publications and the rewards that come with it serve as important signals of credibility (Xu 2007) and are potentially important signals for promotion and job mobility (Stephan, 2011). This suggests is that even scientists employed in the private sector are motivated by concerns beyond purely monetary rewards.[9] Their career incentives, when coupled with the socialization that arises during their research training, leads them to value their contributions to scientific knowledge and the recognition they garner in this activity (Merton, 1957); that is, they have a 'taste' for disclosure through publication (Roach and Sauermann, 2010).

With regard to scientist attitudes towards formal intellectual property protection, there is no clear norm arise from the institutions of science. Especially since the passing of the Bayh-Dole Act, universities have had strong incentives to patent scientific research for the explicit purpose of encouraging the dissemination of useful research results (Gans and Murray, 2012). At the same time, there has been growing concern amongst scientists and those who study them that the pursuit of IP protection may hinder scientific processes (Heller and Eisenberg, 1998; Nelson, 2004; David, 2008, Murray 2010). While building in an explicit preference against IP protection would be possible in the model below, instead, in the baseline model, we treat scientists as agnostic regarding IP protection itself but, in a dynamic extension, they have concerns when that interferes with scientific norms; particularly, the reward to disclosure that arises through follow-on research and the citation of that research (Murray and Stern, 2007).

Firms: For firms, we assume that they are interested in maximizing profits associated with the outcome of a research project. This means that firms carefully evaluate the consequences of disclosures, not only in granting publication rights to scientists, but also in whether they themselves pursue formal intellectual property protection. In so doing, we abstract away from longer-term arguments that firms may encourage disclosure as a 'ticket of admission' into more academic processes that allow them to quickly move to knowledge frontiers (Rosenberg, 1990; Cohen and Levinthal, 1990). As noted earlier, we justify this abstraction based on the evidence that firms wage practices do not incorporate such a value (Stern, 1994) and that patent quality associated with published results may be low (Gittelman and Kogut 2002). In general, what is critical here is that, all other things being equal, firms would seek to limit the disclosure rights of scientists compared with what the scientists would themselves prefer.

[8] See also Sauerrmann and Roach (2011) who provide insight into these mechanisms in a broader sample.
[9] It is well documented that scientists inside for-profit firms engage in high levels of publication activity: For example, in the period from 1985 to 1997, scientists at Intel produced 665 publications while in the same period scientists at Merck produced over 10,000 publications (Lim, 1999).

Negotiation: In scientific labor markets, this tension between any given scientist and a firm is resolved through negotiation. That negotiation will take into account the disclosure strategy chosen by the firm but also be mediated by the wage the firm pays the scientist. Specifically, as the disclosure strategy moves towards one more favorable to scientist preferences (e.g., open science), the negotiated wage can be lowered (as in Stern, 2004). However, critically, we assume that this cannot go too far. Scientists have limited wealth and so wages cannot be negative. Nonetheless, while in the formal model, this presents a technical challenge, we demonstrate that our main results do not hinge on this particular constraint.

III. Baseline Model

Our baseline model focuses on the nature of the bilateral negotiation between the scientist and the firm. It should be noted that this model is structured to emphasize a scientist working for a for-profit firm (which could be a small entrepreneurial firm or a large organization) rather than for scientists working inside a university whose funding comes from a variety of sources and where norms of publication are strongly established. This allows us to derive clearer insight into the nature of firm disclosure strategies and how it relates to environmental parameters.

Modeling Disclosure Strategies

Consider a single scientist who is matched with a single firm. The scientist and firm engage in ex ante negotiations over the disclosure outcomes of a project. Disclosure, if it occurs, can be achieved through both patenting and publication. Specifically, the scientist and firm negotiate as to whether a project is patented or not – that is, they agree on some $i \in \{0,1\}$ where $i = 1$ if they decide to patent and $i = 0$ otherwise. Choosing to patent with its protective benefits involves a quid pro quo of certain disclosures the minimum level of which is represented by a parameter, d_{PAT}.[10] Similarly, the firm and scientist must agree on how much information to disclose through publication. This is a negotiated choice, $d \in [0, D]$. A choice of $d = D$ represents full disclosure of the project's outcomes. When the firm and scientist choose $d = 0$ we term this 'no publication' whereas any agreed $d > 0$ is considered a publication.[11] Importantly, knowledge in a patent disclosure may overlap with knowledge disclosed through publication. The combinations of choices between patenting and publication give rise to four possible broad disclosure regimes described earlier (see Figure 1).

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[10] Patenting, of course, involves other costs such as those associated with filing and enforcement that can impact on firms and scientists. We normalize these costs to zero but note that their inclusion would serve merely to reduce the returns to patenting and would not change any of the results obtained in this paper.

[11] It would be possible to imagine a situation where publication also required a minimum level of disclosure. Because, as will be argued below, scientists and firms disagree over the degree of publication disclosure but not over patent disclosures, we allow the level of publication disclosure to be a continuous variable with no positive lower bound. Imposing a lower constraint on the level of publication would have the effect of reducing the parameters for which publication might be observed.

Figure 1: Disclosure Strategies

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Publication Rights</td></tr>
<tr><td>$d = 0$</td><td>$d > 0$</td></tr>
<tr><td rowspan="2">Patenting</td><td>$i = 1$</td><td>Commercial Science</td><td>Patent-Paper Pairs</td></tr>
<tr><td>$i = 0$</td><td>Secrecy</td><td>Open Science</td></tr>
</table>

Modeling Scientists and Firms

Scientists are motivated by money (in the form of a wage, w) and scientific kudos that results from publication and citation by other scientists.[12] They are also presumed to be liquidity constrained and so cannot agree to any w where $w < 0$.[13] If they choose to participate in the project, the scientist's utility is represented by $U \equiv w + bd$ where b is the marginal benefit of disclosure in terms of kudos.[14] Non-participation gives rise to a reservation utility of $\underline{u}$. Note that this particular form of utility specification presumes that only disclosures through publication generate scientific kudos and patent disclosures do not matter for scientific prestige and rewards.[15]

Firms provide capital, k, for the scientist's research and pay the scientist's wages, w, (if any). Their profits net of these costs depend upon whether they have a monopoly, earning Π, or face imitative competition, in which case they earn π (< ½Π). Competition occurs if there is entry. The probability that a firm faces entry is a function, $F(i,d) \in (0,1)$ which is assumed to be, differentiable, non-decreasing and strictly concave in d for all (i,d). As will be discussed in detail below, the qualitative properties of $F(.)$ with respect to i are ambiguous. Because of disclosure requirements, d_{PAT}, a patent may be entry promoting rather than entry deterring. Given this, a firm's expected payoff from agreeing to fund a scientist's research is: $V \equiv \Pi - k - w - F(i,d)(\Pi - \pi)$. The firm and scientist, therefore, have conflicting preferences over the level of disclosures through publication.

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[12] This could also be paid in equity but would not change the results that follow.
[13] This is a natural assumption given it is the firm who provides capital for the project. If scientists had independent wealth they could simply choose to provide that capital themselves i.e. exit and 'spawn' a new firm (see Toole and Czarinka 2010).
[14] We opt here for a reduced form of the impact of publication on scientist's utility. It would be possible to explore different mechanism by which this impact occurred from pure intrinsic motivation to a more complex model of career concerns. While these models may yield insights into the behavior of scientists, what matters for the question under investigation here is that the scientist benefits more from publication than does the firm (who here is modeled to prefer less publication, ceteris paribus).
[15] This assumption is made for notational simplicity. If the scientist's utility depended on patent disclosures scientists would be more driven to disclose knowledge using patents. This would not, however, eliminate the conflict of interest between the scientist and the firm over disclosure. Hence, the main qualitative predictions would not change if we represented the utility of the scientist as depending upon publication well as patent disclosures.

Modeling Negotiations

The scientist and firm negotiate over a wage, *w*, and the disclosure strategy (i, d). As noted above, we assume that the scientist has no financial capital and so the wage must be non-negative. We use the Nash bargaining solution to describe the outcomes of this negotiation. Specifically, under that solution, the following problem is solved:

$$\max_{w,i,d} \left(w + bd - \underline{u}\right)\left(\Pi - k - w - F(i,d)(\Pi - \pi)\right) \tag{1}$$

Note that we assume that the scientist and firm have equal bargaining power.[16] To ensure that at least one of *w* and *d* that solve this problem are positive, it is assumed throughout this paper that:

$$\min_i \Pi - k - F(i,0)(\Pi - \pi) > \underline{u} \tag{2}$$

This implies that at least in the best case scenario for profits (i.e., when $d = 0$), those profits exceed the outside utility a scientist could earn.

Holding the disclosure strategy constant, the wage is given by $\max\left[0, \frac{1}{2}\left(\Pi - k - F(i,d)(\Pi - \pi) - bd + \underline{u}\right)\right]$. In this case, notice that the kudos associated with publication lowers the wage received by the scientist. This is consistent with the findings of Stern (2004) that scientist wages within firms are lower if they are allowed to freely publish their research results. Also, note that if disclosure through publication is sufficiently high, wages will fall to zero. The critical level of disclosure that results in zero wages is given by $\underline{d}$ such that:

$$\Pi - k - F(i,\underline{d})(\Pi - \pi) - b\underline{d} + \underline{u} = 0 \tag{3}$$

Given our focus on settings where scientists are employed by a firm, we confine our attention to cases where wages will be positive. Thus, we make the following assumption:

(A1) $D < \underline{d}$

This says that even if all knowledge is disclosed, the left hand side of (3) will be positive implying positive negotiated wages. Below, we demonstrate that this assumption, in fact, does not alter any qualitative results derived although the interpretation would change to environments beyond scientists employment by firms and to where, say, scientists within universities receive commercial funding.

Interaction between patenting and publication

We are now in a position to examine the interaction between patenting and publication decisions arising from a negotiated disclosure strategy. The following proposition states the key result:

Proposition 1. *Under (A1), a necessary and sufficient condition for the negotiated level of disclosure through publication (d^*) to be non-decreasing in the choice of patenting (i) is that* $\frac{\partial F(1,d)}{\partial d} \leq \frac{\partial F(0,d)}{\partial d}$.

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[16] The model could easily be extended to parameterize the degree of bargaining power. Doing so, however, would not change our qualitative results.

The proof of the proposition is in the appendix.[17] To understand what drives it, note that (*i, d*) are chosen to maximize the following joint surplus (a sufficient condition for which is (A1)):

$$bd + \Pi - k - F(i,d)(\Pi - \pi) \quad (4)$$

Observe that the optimal choice of $d^*(i)$ satisfies:

$$\frac{b}{\Pi - \pi} \leq \frac{\partial F(i, d^*(i))}{\partial d} \quad (5)$$

If $\frac{\partial F(1,d)}{\partial d} \leq \frac{\partial F(0,d)}{\partial d}$, this implies that when a patent is taken out, the entry-promoting consequences of greater disclosure are lower and hence, a higher level of disclosure will be negotiated.

There are two broad reasons why it is likely that $\frac{\partial F(1,d)}{\partial d} \leq \frac{\partial F(0,d)}{\partial d}$. The first derives from the very nature of the patent system. Patent protection is designed to block imitative entry. That includes entry based on disclosures. For instance, suppose that $F(.) = (1 - i\rho)\Delta(id_{PAT}, d)$. Here we interpret ρ as the probability that entry is blocked if the firm has a patent and Δ(.) is the entry-promoting qualities of disclosure. It is clear that, in the limit, as ρ tends to 1 (blocking becomes perfect), there are no adverse consequences to disclosure. Thus, if they chose to obtain a patent, the scientist and firm would negotiate maximal disclosure through publication $d^* = D$ as the firm would face no commercial costs from this. More generally, the more effective a patent is in blocking imitative entry, the more likely it is that publication and greater disclosure through publication will be negotiated. Thus, the role of patents in reducing the likelihood of entry has the natural consequence that they insulate the firm from the consequences of actions it may take that would otherwise promote that entry.

A second broad reason why $\frac{\partial F(1,d)}{\partial d} \leq \frac{\partial F(0,d)}{\partial d}$ comes from the possibility that disclosures in patenting and publication are not independent. In particular, those disclosures may overlap. To take an extreme, suppose that the knowledge disclosed in a patent and publication were identical.[18] Then if you were to choose to patent, there would be no additional cost, in terms of an increased likelihood of entry, to publish as well; and vice versa. In this extreme case, the two dimensional choice of disclosure path turns into a single dimensional choice of whether to disclose or not – with only secrecy or patent-paper pairs being observed.

Of course, in reality, patent and publication disclosures may not completely overlap. Suppose that *F*(.) were increasing and concave in total disclosure, $\Delta(id_{PAT}, d)$; here written, $F(i, \Delta)$ to separate out the non-disclosure related impacts of patenting. Under this specification, the marginal cost of publication disclosures would be $\frac{\partial F}{\partial \Delta}\frac{\partial \Delta}{\partial d}(\Pi - \pi)$. The impact of patenting can be seen by considering a 'marginal'

[17] The proof demonstrates that (A1) is not required for sufficiency part of Proposition 1. The impact of relaxing (A1) is discussed in the appendix where we note that a *weaker* condition guarantees the result from Proposition 1.
[18] For instance, the BLNK gene research discussed above.

change in *I*; $\left(\left(\frac{\partial^2 F}{\partial \Delta^2} \frac{\partial \Delta}{\partial i} d_{PAT} + \frac{\partial^2 F}{\partial \Delta \partial i} \right) \frac{\partial \Delta}{\partial d} + \frac{\partial F}{\partial \Delta} \frac{\partial^2 \Delta}{\partial d \partial i} d_{PAT} \right) (\Pi - \pi)$. The first term is negative by the concavity of *F*(.) while $\frac{\partial^2 F}{\partial \Delta \partial i} \leq 0$ for reasons described above. The second term will not reverse this so long as $\frac{\partial^2 \Delta}{\partial d \partial i}$ is not too positive. In fact, it is likely to be negative given overlap in patent and publication disclosures.[19]

This demonstrates that in order for $\frac{\partial F(1,d)}{\partial d} > \frac{\partial F(0,d)}{\partial d}$, not only must the publication and patent disclosures be distinct, but also that their combination must be more entry promoting than their separate contributions. A circumstance such as this could conceptually arise when, for example, a patent discloses a tool or process while a publication discloses a product developed with the patented tool. A case of this type might arise in an area such as chemistry when tools or processes could be covered by patents but when the product is the output of scientific interest. However, it is hard to envision a disclosure strategy of this type that would not also include a product patent (to foreclose imitative entry into the product market) or that would not also require disclosure of the process in the publication to enable other scientists. Thus, while this is theoretically possible, our examination of patents and associated publications suggests that it is unlikely.

Equilibrium Regimes

Having established the drivers of complementarity between patenting and publication disclosures, it is instructive to consider how this translates into observed equilibrium regimes. As noted earlier, in choosing the level of publication the scientist/firm must trade-off the benefits the scientist receives from kudos against the potential for such disclosures to raise the probability of entry. In choosing whether to patent or not, the drivers are all on the firm side of the negotiation. A patent impacts on entry in two ways. First, it makes successful entry more difficult by increasing the probability that such entry is blocked or alternatively making entry more costly as a broader scope patent would require more investment in generating potential work-arounds. Second, the patent can actually facilitate entry through the disclosures made through the patent itself. For this reason, if d_{PAT} is regarded as the minimal level of disclosure

[19] The effect of such overlap can be demonstrated in a reduced form model of learning. For instance, an entrant may need to learn a critical piece of information in order to imitate the firm. Let id_{PAT} and d be the probabilities that the entrant learns that information from each disclosure path. Suppose that with probability, α, patent and publication disclosures provide the same type of information. In this case, the probability that the entrant learns is $id_{PAT} + d - id_{PAT}d$. In contrast, with probability, $1-\alpha$, the knowledge that can be acquired through patent and publication disclosure is distinct. In this case, the probability that the entrant learns is $id_{PAT} + d$. Thus, in expectation, at the time of the entry decision, the probability of learning through disclosure is $\Delta \equiv id_{PAT} + d - \alpha id_{PAT} d$. In this respect, α parameterizes the degree of *congruence* between patent and publication disclosures in terms of their usefulness in assisting entry. Note that: $\frac{\partial F}{\partial d} = (1 - \alpha id_{PAT}) \frac{\partial F}{\partial \Delta} \geq 0$ and that $\frac{\partial^2 F}{\partial d \partial i} = -\alpha d_{PAT} \frac{\partial F}{\partial \Delta} + (1 - \alpha id_{PAT}) \left(d_{PAT}(1 - \alpha d) \frac{\partial^2 F}{\partial \Delta^2} + \frac{\partial^2 F}{\partial \Delta \partial i} \right) \leq 0$ even when $\alpha = 0$.

required to obtain a patent, we can expect that the firm will disclose no more than that minimum.[20] Thus, we cannot say unambiguously whether $F(.)$ is increasing or decreasing in i even if we can say that $F(1,d)-F(0,d)$ is (weakly) increasing in d (because the entry promoting effects of disclosure are smaller if there is a patent). The following proposition summarizes the equilibrium regimes that emerge.[21]

Proposition 2. *Suppose that* $\underline{d} \geq D$. *If* $\frac{\partial F(1,d)}{\partial d} < \frac{\partial F(0,d)}{\partial d}$, *the negotiated outcome is:*

(i) *Secrecy (* $i=d=0$ *) if* $\frac{b}{\Pi-\pi} < \min\left[\frac{\partial F(0,0)}{\partial d}, \frac{F(1,d^*(1))-F(0,0)}{d^*(1)}\right]$ *and* $F(1,0) < F(0,0)$

(ii) *Commercial Science (* $i=1$, $d=0$ *) if* $\frac{b}{\Pi-\pi} \leq \frac{\partial F(1,0)}{\partial d}$ *and* $F(1,0) \geq F(0,0)$

(iii) *Open Science (* $i=0$, $d>0$ *) if* $\frac{b}{\Pi-\pi} > \frac{\partial F(0,0)}{\partial d}$ *and* $F(1,d^*(1)) > F(0,d^*(0))$

(iv) *Patent-Paper Pairs (* $i=1$, $d>0$ *) if* $\frac{b}{\Pi-\pi} \geq \min\left[\frac{\partial F(1,0)}{\partial d}, \frac{F(1,d^*(1))-F(0,0)}{d^*(1)}\right]$, *and* $F(1,d^*(1)) \leq F(0,d^*(0))$.

If $\frac{\partial F(1,d)}{\partial d} = \frac{\partial F(0,d)}{\partial d}$, then in negotiations (with $d^*(1)=d^*(0)=d^*$) publication occurs if $\frac{b}{\Pi-\pi} > \frac{\partial F(0,0)}{\partial d}$ while patenting occurs if $F(1,0) \leq F(0,0)$.

The outcomes of Proposition 2 are depicted in Figure 2. Figure 2a depicts the outcome when there is complementarity between patents and publications as determined by the condition: $\frac{\partial F(1,d)}{\partial d} < \frac{\partial F(0,d)}{\partial d}$. In contrast, Figure 2b depicts the outcome that arises when there is no complementarity with $\frac{\partial F(1,d)}{\partial d} = \frac{\partial F(0,d)}{\partial d}$. This may arise if patent and publication disclosures did not overlap and were independent and if patents had no blocking power against imitative entry. In this case, patenting and publication decisions are independent of one another.

The strength of intellectual property protection

At the heart of the debate regarding the commercialization of science is a concern that intellectual property protection will reduce the amount of disclosure of scientific knowledge – specifically through publication. Our analysis here allows us to examine this question more synthetically in the context of a fully specified disclosure framework, by considering how the strength of intellectual property protection impacts scientist-firm negotiations over the level of publication (as well as the levels of other disclosures).

First, note that under both open science and patent-paper pairs, there is a positive level of disclosure. However, the complementarity between patents and publications would mean that a *higher* level of disclosure through publication would be negotiated under patent-paper pairs than under open science. As an example of the countervailing effect (i.e. when patents require more disclosure and so

[20] As noted earlier, the literature has considered strategic reasons for firms involved in patent races to disclosure more than minimal amounts but this possibility would not change the qualitative results here.

[21] In stating the proposition it is assumed that if the scientist/firm are indifferent between patenting and/or publication, they undertake those disclosures. Once again, we state the proposition for the case where w is guaranteed to be positive. The appendix states conditions that emerge when w may be constrained at zero.

patent-paper pairs are reduced), when the patent disclosure and inventive-step requirements of gene patents were substantially increased in 2001 and the strength of patents was also called into question by the 2000 joint Clinton-Blair announcement[22] on the use of genetic information, publications in the area of molecular genetics from companies such as Human Genome Sciences declined with the shift to greater levels of secrecy absent complementary patent protection for genetic information.[23]

Second, by strengthening intellectual property protection (while holding d_{PAT} constant) – say, by increasing patent scope or improving the probability that entry can be blocked – it is more likely that patenting will be chosen by the scientist and firm. This effect is well-known. However, what the model demonstrates is that this strengthening, both by making patent protection a more desirable option and by insulating the firm from the competitive consequences of disclosure, will lead to greater disclosure through publication. This has broader flow-on benefits in terms of the production of future knowledge.

For a similar reason, an increase in patent disclosure requirements (d_{PAT}) has an ambiguous impact on the degree of disclosure. While it is the case that increasing the disclosure requirements through patenting does reduce the marginal cost of disclosing through publication (and hence, increases the likelihood that a commercial science regime becomes a patent-paper pair regime), it does so by increasing the firm's cost of patenting.[24] In the process, a higher d_{PAT} results in a weakening of the incentives to take out intellectual property protection leading to, in particular, a greater likelihood that secrecy will be chosen over other regimes. Conversely, reducing d_{PAT} makes patenting more likely to be chosen (and so leads to greater levels of disclosure through that pathway) and also, within patent-paper pairs, allows the scientist to negotiate greater levels of disclosure through publication. Thus, this change in IP protection alters the *type* of disclosure that we observe. Nonetheless, we cannot say conclusively whether a change in d_{PAT} would result in an increase or decrease in disclosure.

[22] White House Press Release June 26, 2000, PRESIDENT CLINTON ANNOUNCES THE COMPLETION OF THE FIRST SURVEY OF THE ENTIRE HUMAN GENOME: Hails Public and Private Efforts Leading to This Historic Achievement.

[23] In the period from the founding of Human Genome Sciences in 1993 until the joint presidential announcement in 1999 and the discussions in the USPTO regarding the strengthening of the enabling requirements for gene patents, HGS published over 200 publications and 280 patents with 52 research articles published in 1999 and 77 patent applications (that were subsequently granted). From 2000 onwards, publications have been decline with fewer than 40 publications each year from 2001 until 2004 dropping off again in the period after 2006. In contrast, patent filings increased and with over 100 patents filed each year in the period 2001-2004 and over 70 each year in the years following. We interpret the stable and even growing trend in patents with the decline in publications to be consistent with the view that as patents are potentially (probabilistically) weakened their complementarity with publishing declines and thus the disclosure in publications is lowered. [Data taken from ISI Web of Science and USPTO]

[24] Strictly speaking, what we are concerned with here are disclosure requirements that might assist entry. This could be a simple increase in d_{PAT} or it may be a requirement that patent disclosures should be more like disclosures through publication. Either interpretation gives rise to the same qualitative effects discussed here.

IV. Dynamic Extension

In the baseline model, our focus was on the static impacts of publication and patenting. However, scientists not only value the publication of their knowledge (generating immediate kudos) but also the use and acknowledgement of their discoveries by follow-on researchers. Such future kudos can be thought of as being realized when a publication is cited by scientists in future publications.

There are also prospective future returns for the firm as well. If an innovation is patented, the firm can earn future revenues from licensing the rights to utilize the patent in future research. An issue arises, however, because future scientists and their funders may be concerned that publication and citation of past work might trigger their liability for such payments. Consequently, they may actively avoid citing past research thereby causing a loss in potential kudos for the original scientist. In the long run, if future researchers are impeded by the need to license prior intellectual property from commercial funders, researchers may divert their work away from areas that require citation of existing publications. This will generate a new source of conflict between scientists and their funders regarding current disclosure through publication.

This possibility has received attention recently amongst scientists. Concerns have been raised that patenting of scientific knowledge gives rise to an *anti-commons effect* (Heller and Eisenberg, 1998). This occurs when future scientists fear that patent protection will generate a thicket of licenses, permissions, and other transaction costs, and so avoid building on research where formal intellectual property exits. Murray and Stern (2007) demonstrated that when a paper becomes associated with a patent, its citations drop significantly; indicating that scientists might be avoiding research areas with potential intellectual property issues. Moreover, there is some concern that, either as a result of these measurable effects on future citations, or as a result of the decrease in kudos, scientists may face reputational harm if they patent as well as publish their research. Finally, Williams (2010) demonstrated that researchers on the human genome project avoided building on genes that were covered by intellectual property protection by the private firm Celera.

In this section, we construct a dynamic model designed to evaluate this concern. In contrast to the baseline model, the firm and scientist are assumed to live for two periods and in each time period a new firm/scientist pair is born. In the first period, they negotiate over various terms, research is conducted, and immediate outcomes (profits, patents, and publications) are realized. This corresponds to the static model already examined. In the second period, the next generation of scientist and firm do the same thing. Their choice as to whether there is a publication or not determines the kudos achieved by the previous scientific generation where that kudos only emerges if there is a citation to that previous work. In this situation, however, if there was a patent in the previous generation, the firm and scientist may be required to pay a license fee to the previous generation funder. In effect, negotiations are now three-party; the firm, the scientist and the previous patent rights holder must all agree on the terms and conditions. Thus, our static model becomes a dynamic model with overlapping generations.

To this end, we make several changes to the static model. A first set of assumptions is to continue to assume that (A1)[25] while, in addition, we assume that $\underline{u} = 0$. A second set of assumptions gives the scientist a stake in the future. We do this by incorporating an additional level of kudos from publication, *B*, that is only realized if the scientist publishes and the publication is cited by the next generation. Note that a citation requires actual publication by that next generation. We also assume that firms and scientists share a common discount factor, δ. Thus, a scientist researching at time *t* earns $(b + I_{d_{t+1}>0}\delta B)d_t$ if they have a publication with disclosure d_t that is cited by future generations of researchers.[26]

Third, we make assumptions regarding the impact of patents on future generations. We assume that, if a patent is granted, the patent holder always negotiates with the next generation research team. If these negotiations succeed, there is a transfer of knowledge between generations meaning that no capital costs of research are incurred and a lump sum license fee, τ_t, is paid. If these negotiations fail, then with probability γ, the new generation research team must choose a different research path. Thus, γ is the probability that a patent blocks future research based on past knowledge. In this case, there is no knowledge transfer (future research teams incur the full capital costs, *K*). On the other hand, with probability $(1 - \gamma)$, the new generation at time *t* can, if there is a previous publication with disclosure level, d_{t-1}, exploit the knowledge from that publication in another way, despite failed negotiations. In this event, their expected capital costs becomes $k(d_{t-1})$ where *k* is a decreasing function with $k(D) = 0$ and $k(0) = K$.[27] In this respect, γ corresponds to a measure of the strength of future IP protection.[28]

We make no specific assumption as to whether a past publication is cited or not in the event of a breakdown in licensing negotiations. There is some probability $(1-\gamma)$ that the young scientist/firm pair could proceed with a research path that allows them to exploit the past publication. In that case, one could imagine that they avoid citing the past work as part of a strategy of working-around previous patent rights. One interpretation of this is simply as a desire to remove them as a litigation target by avoiding citation. Another is that the scientist-firm pair changes their research direction in order to avoid directly

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[25] As with the static model, considering the case where *D* is relatively high would do little to change the qualitative results and little additional insight would be gained in relation to the interaction between publications and patents. Moreover, any difference that does exist is of a form that has already been discussed in the static case.

[26] Mukherjee and Stern (2009) posit a similar linkage between current publication and future kudos by making the assumption that scientist utility is increasing in the level of follow-on research that is conducted. The difference here is that we derive more explicitly the implication in terms of primitives in the model so as to examine the impact of patent protection in this environment.

[27] These capital costs are not strictly equipment and infrastructure per se but the non-scientist effort cost in finding another path towards scientific progress.

[28] An alternative way of modeling the imperfection of future IP rights would be to assume that the uncertainty regarding patent enforceability was released prior to any negotiations. This alternative timing is more complex than the one we have chosen and does not appear to result in any additional significant qualitative conclusions.

relying on the past technology while still taking advantage, should the opportunity arise, of scientific knowledge in the publication. Each of these might be regarded as consistent with Murray and Stern's (2007) findings of reduced citation following patent grants. However, the key results below do not hinge on this. Instead, it may be the citation occurs so long as some use of the past publication is made. Nonetheless, when we come to consider whether scientists should own IP, whether a citation occurs or not following a breakdown is of importance.

A final model assumption is that, if no patent is granted, then the previous funder is not involved in future negotiations. If there is no previous publication, there is no transfer of knowledge and the future team incurs the full capital costs, *K*. In contrast, if there is a previous publication, those capital costs are eliminated and the future scientist cites the past researcher, thus, generating kudos.[29] In effect, this is an assumption that no contractual means of transferring knowledge is possible in the absence of a patent. Under secrecy, this means that no transfer occurs[30] while under open science, such transfer occurs and so there is no reason to contract for payment of that knowledge.

To model the three-party bargaining game, should it emerge, we utilize a multi-lateral variant of the Nash bargaining solution. That solution is found by solving the following:

$$\max_{\tau_t, w_t, i_t, d_t} \tau_t (w_t + bd_t + I_{d_{t+1}>0} \delta B d_t - u_t)(V_t - v_t) \tag{6}$$

where the subscript, *t*, corresponds to the generation, *I* is an indicator function taking a value of 1 if a publication occurs in *t*+1 and 0 otherwise, u_t is the scientist's expected utility if no licensing agreement is reached, V_t is the firm's expected payoff should a licensing agreement be reached with the old firm while v_t is the firm's expected payoff in the absence of such an agreement. The outside options of the previous period's firm and researcher are the result of the bilateral negotiation between the scientist and firm as described in the baseline model. Given our assumption here restricting attention to environments where wages are positive, we are able to focus on negotiation outcomes that maximize total surplus. We focus on symmetric dynamic equilibria in which each generation chooses the same disclosure strategy.[31] Before formally characterizing the symmetric equilibria, it is useful to consider each disclosure strategy in turn.

Secrecy. Suppose that each generation chooses $i = 0$ and $d = 0$. Then research capital costs of *K* are realized in every period and each generation of scientist and firm pairs earn their static outcomes; each has a payoff of $\frac{1}{2}\left(\Pi - K - F(0,0)(\Pi - \pi)\right)$ for the first period only. Note that there is no additional

[29] It would be possible to model the savings on capital cost as a function of the level of disclosure. This would not change the model's predictions, however, and so we opt for a simpler equivalence between unimpeded transfer through publication and a transfer alongside a patent.

[30] There are many possible rationales for this but the most salient is Arrow's (1962) disclosure paradox whereby transfer of knowledge requires disclosure of it prior to contracting leaving the licensor open to expropriation.

[31] We do not consider asymmetric equilibria whereby firms and scientists alternate their disclosure strategies from generation to generation or, choose their strategy contingent upon the disclosure strategy of the immediate past generation.

incentive for a single generation to deviate and publish than there was in the static case as this does not earn the scientist any kudos because (as we will show formally below) the future generation has no additional incentive to publish as a result of this. In contrast, there is an incentive to patent since patenting allows the firm to obtain license fees in the future. In the absence of publication, by using the license and corresponding knowledge transfer, the future generation saves capital costs, *k*. In this case, they solve:

$$\max_{\tau_t, w_t, d_t, i_t} \tau_t (w_t - u_t)\left(\Pi - F(i_t, 0)(\Pi - \pi) + i_t \delta \tau_{t+1} - w_t - \tau_t - v_t\right) \quad (7)$$

Of course, in a symmetric equilibrium, $u_t = v_t = \frac{1}{2}\left(\Pi - K - F(0,0)(\Pi - \pi)\right)$. Consequently, assuming no other changes (that is, $d_t = i_t = 0$), the license fee, τ_t, equals *K*/3. In this case, by choosing to patent, current expected surplus changes by $\left(F(0,0) - F(1,0)\right)(\Pi - \pi) + \delta \frac{1}{3} k$. Note that the potential to earn future license fees increases the returns to patenting relative to the baseline model.

Commercial Science. Like secrecy, commercial science does not involve publication, and so if future scientists are not expected to publish there is no additional incentive for the current generation to publish and earn kudos. In contrast to the static model, however, a license fee is both earned and paid. Consequently, the scientist and firm each expect a payoff of $\frac{1}{2}\left(\Pi - \frac{1}{3}K - F(1,0)(\Pi - \pi) + \delta \frac{1}{3} K\right)$. Thus, if $\frac{F(0,0)}{F(1,0)} \geq 1$, the firm and scientist will have an on-going incentive to continue patenting.

Open Science. Like in the case of commercial science, open science does not result in research capital costs, *K*, being incurred by the next generation. In addition, the scientist receives kudos from publications and citations. Foregoing any agreed upon publication disclosure, d_t, would reduce total surplus by $(b + \delta B) d_t$.

Is there an incentive to deviate and patent? Deviating would allow the pair to earn $\left(F(0, d_t) - F(1, d_t)\right)(\Pi - \pi)$ in immediate profits as well as to earn a future license fee of $\tau = \frac{1}{3}(K - k(d_t)(1 - \gamma))$. Thus, compared with the transition from secrecy to commercial science, the transition from open science to patent paper pairs involves a lower license fee. Note that this is in contrast to the static case where the returns to patenting were unambiguously higher when a publication existed.

Patent-Paper Pairs. In patent-paper pairs, the outcome of negotiations is the solution to:

$$\max_{\tau_t, w_t, d_t, i_t} \tau_t (w_t + (b + \delta B) d_t - u_t)\left(\Pi - F(i_t, d_t)(\Pi - \pi) + i_t \delta \tau_{t+1} - w_t - \tau_t - v_t\right) \quad (8)$$

What is interesting is that the scientist's and the firm's outside options are influenced by the publication disclosures of the previous generation. The greater these are, the lower are the gains from trade from reaching a licensing agreement over the use of past IP. Nonetheless, these past decisions do not impact on the choice of publication. In this respect, joint surplus is maximized by publication if and only if:

$$b + \delta B \geq \frac{\partial F(i_t, 0)}{\partial d_t}(\Pi - \pi) + i_t \delta \frac{1}{3} \frac{\partial k(0)}{\partial d}(1 - \gamma) \quad (9)$$

Here, however, in contrast to the baseline model, the cost of publication is higher when there is a patent. Note that, in the dynamic game, $\underline{d}$ is defined by:

$$\Pi - k - F(i_t, \underline{d})(\Pi - \pi) + i_t \delta \tfrac{1}{3}(K - k(\underline{d})(1-\gamma)) - \tfrac{1}{3}(K - k(d_{t-1})(1-\gamma)) - (b + \delta B)\underline{d} = 0 \qquad (10)$$

We are now in a position to prove the analogue of Proposition 1 for the baseline case for the dynamic extension.

Proposition 3. *Suppose that, in equilibrium,* $d_t^* > 0$ *for all t. A necessary and sufficient condition for the negotiated level of disclosure through publication in any period (*d_t^**) to be non-decreasing in the choice of patenting (*i_t*) is that* $\left(\frac{\partial F(1,d)}{\partial d} - \frac{\partial F(0,d)}{\partial d}\right)(\Pi - \pi) + \delta \frac{1}{3} \frac{\partial k(d)}{\partial d}(1-\gamma) \le 0$ *for all d.*

This proposition demonstrates that when $\frac{\partial F(1,0)}{\partial d} \approx \frac{\partial F(0,d)}{\partial d}$, $d_t^*(1) < d_t^*(0)$ so that a choice of patenting is associated with a lower level of disclosure through publication. Substitutability arises because the future licensing revenues from patenting are reduced if there is publication. Absent other factors, if a scientist/firm take out a patent, then commercial returns fall as a result of publication by more than if there was no patent.

Proposition 3 requires that $d_t^* > 0$ for all *t*, because if no publication is expected in one period, this can reduce the returns to publication in previous periods. To see this, first consider the following proposition that fully characterizes the symmetric equilibrium outcomes for the dynamic game.

Proposition 4. *The following represent symmetric equilibria in the dynamic game:*

(i) Secrecy ($i = d = 0$*) if* $F(1,0) > F(0,0)$, $\frac{b}{\Pi - \pi} < \frac{\partial F(0,0)}{\partial d}$*;*

(ii) Commercial Science ($i = 1,\ d = 0$*) if* $F(1,0) \le F(0,0)$, $\frac{b}{\Pi - \pi} < \frac{\partial F(0,0)}{\partial d}$*;*

(iii) Open Science ($i = 0,\ d > 0$*) if* $\frac{b + \delta B}{\Pi - \pi} \ge \max\left[\frac{F(0, d_t^*(0)) - F(1,0)}{d_t^*(0)} + \frac{\delta \frac{1}{3} K}{(\Pi - \pi) d_t^*(0)}, \frac{\partial F(0,0)}{\partial d_t}\right]$ *and* $\frac{\delta \frac{1}{3}(K - k(d_t^*(1))(1-\gamma))}{\Pi - \pi} < F(1, d_t^*(1)) - F(0, d_t^*(0))$*;*

(iv) Patent-Paper Pairs ($i = 1,\ d > 0$*) if* $\frac{b + \delta B}{\Pi - \pi} > \frac{\partial F(1,0)}{\partial d_t} - \frac{\partial k(0)}{\partial d_t} \frac{\delta \frac{1}{3}(1-\gamma)}{\Pi - \pi}$, $\frac{\delta \frac{1}{3}(K - k(d_t^*(1))(1-\gamma))}{\Pi - \pi} \ge F(1, d_t^*(1)) - F(0, d_t^*(0))$.

An example of the equilibrium outcomes are depicted in Figure 3 where it is assumed that $\frac{\partial F(1,0)}{\partial d_t} \approx \frac{\partial F(0,d)}{\partial d}$. Interestingly, there can be multiple equilibria. The existence of multiple equilibria emerges because there is an inter-generational complementarity in publication decisions. Specifically, publication today is only valuable if there is publication and citation tomorrow. Consequently, when $\frac{b}{\Pi - \pi} < \frac{\partial F(0,0)}{\partial d}$, there always exists a 'non-communication' equilibrium involving $d_t = 0$, since future expectation creates no additional incentives for publication today. Note also that the presence of substitutability means that the domains of open and commercial science are wider than in the static case.

The strength of IP protection

In contrast to the previous static model, the dynamic model with licensing demonstrates the possibility that IP protection can impede publication as publication and patents act as substitutes rather than complements in a dynamic context. This phenomenon occurs because publication can reduce future licensing revenues associated with a patent due to the behavior – specifically the research choices - of follow-on firm/scientist pairs. Counter to the static result, this might suggest that a weakening of intellectual property protection can lead to greater levels of publication. To be sure, a reduction in γ reduces the incentives to take out a patent and, to a degree, this expands the domain of open science. At the same time, however, as can be seen from (9), this *increases* the costs associated with publication. Those costs arise because patents cannot perfectly protect future licensing revenues from the adverse consequences of publication disclosures. Consequently, the domain of patent-paper pairs will also be reduced (both in the domains of open and commercial science). The overall dynamic effect, therefore, of a weakening of intellectual property protection is ambiguous. Indeed, in the limit as γ approaches 1 (and patents become perfectly strong), the substitutability between patents and papers disappears and, while there is some degree of multiple equilibria, the conditions under which disclosure occurs become very similar to those in Proposition 2. This suggests that the full equilibrium interpretation of results, that patent protection is associated with a reduction in citations or in a substitution away from building on patented knowledge, is subtle. While moves to limit future licensing (such as preventing reach-through rights or allowing for a research exemption) might appear to address these issues directly, this also changes the disclosure incentives of researchers.

Ownership of IP rights

In the above analysis, firms are assumed to be the owners of patents and hence, are the only party that participates in future negotiations over license fees. This means that firms have no interest in the disclosure decisions of future generations and, indeed, given their hold-up power, only care about future capital costs. But what if scientists, instead of firms, owned IP rights? The impact on immediate entry would be unchanged, but if the scientist had a publication, in licensing negotiations the scientist would care about the publication outcomes of the next generation of scientists. More importantly, scientists might fear that, in the event of a breakdown, they would not be cited and they would not receive their rightful kudos. The implication of this is that, in patent-paper pairs, where this is relevant, the scientist would discount the license fee to take into account the ability of the next generation to hold up the value of their kudos. Indeed, the license fee would become: $\tau_{t+1} = \frac{1}{3}\left((K - k(d_t)(1-\rho)) - Bd_t(1-\rho)\right)$. In this situation, joint surplus becomes:

$$\begin{aligned}&(b+\delta B)d_t+\delta\tfrac{1}{3}\left(K-k(d_t)(1-\rho)-Bd_t(1-\rho)\right)\\&+\Pi-F(1,d_t)(\Pi-\pi)-\tfrac{1}{3}\left(K-k(d_{t-1})(1-\rho)-Bd_{t-1}(1-\rho)\right)\end{aligned} \tag{11}$$

This means that the pair jointly appropriate future kudos of $\delta Bd_t\left(1-\tfrac{1}{3}(1-\rho)\right)$. Thus, the threshold for publication to be chosen as a disclosure strategy would be higher, and consequently, the domains for open science and patent-paper pairs would shrink relative to the case where only the firm owned patent rights. Intuitively, by bringing future kudos to the bargaining table as a valuable item, giving scientists ownership rights would shift some of the value of kudos to future generations. As licensing agreements are accepted, this shift in value is a mere transfer. Nonetheless, the lower appropriation of kudos biases against agreements that involve publication.

V. Conclusions

A far cry from the self-funded gentleman scientist of prior centuries, the production of scientific knowledge is increasingly undertaken in complex organizational settings. Scientist's daily work is structured by funders from a variety of sources including governments, private firms' internal R&D allocation, foundations and philanthropists (Gans and Murray 2012). Within this emerging context, the management of scientific work and the nature of the employment relationships between scientists and their funders is of increasing salience to scholars and practitioners. While the particular nature of technical opportunities at the knowledge frontier matter, these deeply organizational and managerial issues are increasingly understood to mediate the productivity of scientists.

It is within an industrial context – where firms employ highly trained research scientists – that we have explicitly explored the negotiation over disclosure strategies. Using a theoretical approach to this complex set of choices, we examine scientists' disclosure rights and their interaction with the institutional environment facing the firm. By focusing on the tension between scientist preferences for open publication and the concerns of firms that such publication will undermine their ability to appropriate commercial value from their research investments, we were able to analyze disclosure strategies making patenting and publishing decisions meaningfully endogenous and jointly determined. We modeled this tension by considering the negotiations between a single scientist and a single firm over payments, patents, and publication rights. This allowed us to map the primitives of the model (specifically, the value of scientific kudos and the threat posed by disclosures in facilitating imitative entry) into clear outcomes. Overall this approach moves us far from a setting in which disclosure is regarded as exogenous, shaped only by the type of knowledge and the organizational setting. Moreover, it more clearly maps to the daily challenges faced by scientists themselves as well as their managers.

Our principal finding involved an insight into the nature of the intellectual property system and how this drives the interaction between patent and publication disclosure choices that has not been previously identified or highlighted in the literature. While prior work has identified how patenting and publication decisions might be linked for pragmatic and practical reasons (due to prior art rules in the patent system), we showed that these choices interact strategically. Indeed, it is because of the distinctive role of the patent system (in contrast to the system of academic publication) in providing protection over the outcomes of disclosure, that we frequently see patents and publications - patent-paper pairs - as the chosen disclosure regime. This allowed us to not only to contrast the decisions to patent and publish with the decision to keep knowledge secret, but also to examine when choices are made to disclose knowledge in both a patent and a publication.

Our results are as follows. In a baseline model that examined a single negotiation over a research project between a scientist and firm, we found that there is a key condition that generates *complementarity* between decisions to patent and decisions to publish. This condition can be understood in two ways. First, to the extent that knowledge disclosed in patents and publications overlaps, then if knowledge is disclosed through one path, the incremental cost to the firm of disclosures through the other path falls. Second, to the degree that a patent can effectively protect the firm from imitative entry facilitated by disclosure, the negative consequences of additional disclosure through publication fall. Each of these effects implies that decisions to patent and publish are complementary. Consequently, and in counterpoint to traditional arguments, measures that strengthen intellectual property protection (increasing the benefits of patenting) are likely to generate greater amounts of observed disclosure through publication. Conversely, the stronger are scientist preferences for publication (e.g., because scientific rewards are strengthened), the greater the incentives to take out intellectual property protection. This suggests that, not only are some of the recent concerns about the impact of the patent system on academic publication misplaced,[32] but also that policies designed to ‘force disclosures’ (e.g., minimum disclosure requirements in patents) may have the adverse consequence of diminishing patent applications, raising the costs associated with publication and thus lowering disclosure.

Moving beyond our baseline model, we considered a dynamic setting with overlapping generations of scientist/firm pairs whose research potentially builds on one another. A dynamic model allows for a richer examination of scientist preferences (allowing them to care about citations as well as publications) and also greater commercial opportunities (allowing firms to earn revenue from licensing to future projects). The end result is the identification of a potentially important inter-temporal complementarity between publication decisions (namely, one cannot generate a citation unless the future researchers also publish) but also inter-temporal substitutability between patent and citation decisions (namely, that a patent may cause future scientists to avoid explicit follow-on research and

[32] See, for example, Heller and Eisenberg (1998), Bok (2003), Nelson (2004) and Heller (2008).

acknowledgement of past research so as to avoid license payments).

Our contribution links to a wide range of literature that has examined the organization of scientific work in a range of settings. Most centrally, we provide a bridge between the literature that explores the preferences of individual technical employees on the one hand and the firm-level approaches to disclosure on the other. With regards to the preferences of individual scientific and technical employees, the literature has continued to puzzle over the complex and multifaceted preferences held by scientists and engineers trained and deeply steeped in the "academy" and yet engaging in knowledge production in an industrial context (see Stern 2004, Sauermann and Cohen 2010). On the other hand, scholars of R&D management, intellectual property management and innovation have examined patent strategy, trade secrecy and the adoption of open science practices at the firm level (Hall and Ham 2001; Ziedonis 2004). By linking the two approaches and recognizing the fact that firm disclosure strategies are shaped, in part, by employee preferences for disclosure and vice versa, we resolve a number of the paradoxical and seemingly contradictory results in the literature. From a managerial perspective, our results suggests that firms considering disclosure strategies must not only understand the degree to which these conditions hold but also must develop approaches that allow for disclosure of all types to be highly coordinated with their critical employees.

VI. Appendix

Proof of Proposition 1

Using Theorem 4 of Milgrom and Shannon (1994), holding *i* fixed, d^*, the solution to (1) is non-decreasing in *i* if the objective function (at the optimal *w*) satisfies the single-crossing property in (d,i). There are two cases. If the optimal wage, $w > 0$, then the objective function becomes $U+V$ whereas if $w=0$, the objective function becomes $(U-\underline{u})V$. In each case, if $\frac{\partial F(1,d)}{\partial d} \leq \frac{\partial F(0,d)}{\partial d}$, the objective function satisfies the single-crossing property in (d,i).

By Proposition 1, note that when $w = 0$ and $\frac{\partial F(1,d)}{\partial d} \leq \frac{\partial F(0,d)}{\partial d}$, $d^*(1) \geq d^*(0)$. Consequently, if $\hat{d}(1) = d^*(0) < \underline{d}$, then $d^*(0) < \underline{d}$ and wages are zero whether there is a publication or not. Thus, restricted to the $[0, d^*(1)]$ domain, Theorem 4 of Milgrom and Shannon (1994) states that $U+V$ satisfying the single-crossing property in (d,i) is a necessary and sufficient condition for $d^*(1) \geq d^*(0)$.

Suppose that $\hat{d}(1) > \underline{d}$, then if both patenting and publication are chosen, $w=0$, and $d^* \in \arg\max_d (U-\underline{u})V$ holding *i* constant. The derivative of the objective function with respect to *d* is $b\big(\Pi - k - F(i,d)(\Pi-\pi)\big) - (bd-\underline{u})\frac{\partial F(i,d)}{\partial d}(\Pi-\pi)$. Comparing these when *i* is 1 and 0 respectively gives: $-bF(1,d) - (bd-\underline{u})\frac{\partial F(1,d)}{\partial d} > -bF(0,d) - (bd-\underline{u})\frac{\partial F(0,d)}{\partial d}$ or $b\big(F(0,d) - F(1,d)\big) > (bd-\underline{u})\Big(\frac{\partial F(1,d)}{\partial d} - \frac{\partial F(0,d)}{\partial d}\Big)$ which can hold even if $\frac{\partial F(1,d)}{\partial d} > \frac{\partial F(0,d)}{\partial d}$ demonstrating that the marginal cost of *d* can rise with *i*.

Proof of Proposition 2

The condition of the proposition guarantees (by Proposition 2) that $d^*(1) \geq d^*(0)$. Total surplus from each regime (net of $\underline{u}$) is:

- Secrecy: $\Pi - k - F(0,0)(\Pi-\pi)$
- Commercial Science: $\Pi - k - F(1,0)(\Pi-\pi)$
- Open Science: $bd^*(0) + \Pi - k - F(0,d^*(0))(\Pi-\pi)$
- Patent-Paper Pairs: $bd^*(1) + \Pi - k - F(1,d^*(1))(\Pi-\pi)$

Noting that $d^*(i) = 0$ if and only if $\frac{b}{\Pi-\pi} \leq \frac{\partial F(i,0)}{\partial d}$ and comparing these surpluses with one another gives the conditions in the first part of the proposition. The conditions in the second part of the proposition come from noting that when $\frac{\partial F(1,d)}{\partial d} = \frac{\partial F(0,d)}{\partial d}$, then $d^*(1) = d^*(0)$ and $F(0,d) - F(0,0) = F(1,d) - F(1,0)$.

Remark on the zero wage case

Propositions 1 and 2 hold qualitatively and, in some cases, are strengthened when (A1) does not hold and specifically, wages may be zero in equilibrium. First, Proposition 1 demonstrates that, under (A1), $\frac{\partial F(1,d)}{\partial d} \leq \frac{\partial F(0,d)}{\partial d}$ is a necessary and sufficient condition for disclosure to (weakly) increase if a patent is taken out. The following proposition demonstrates when wages are zero, the disclosure can increase with patent protection even if $\frac{\partial F(1,d)}{\partial d} \leq \frac{\partial F(0,d)}{\partial d}$ does not hold.

Proposition A1. *Let* $\hat{d}(i) = \arg\max_d bd - F(i,d)(\Pi-\pi)$. *If* $\hat{d}(1) < \underline{d}$, *then* $\frac{\partial F(1,d)}{\partial d} \leq \frac{\partial F(0,d)}{\partial d}$ *is a necessary* *condition for* $d^*(1) \geq d^*(0)$. *If* $\hat{d}(1) > \underline{d}$ *, then it is possible that* $d^*(1) \geq d^*(0)$ *when* $\frac{\partial F(1,d)}{\partial d} > \frac{\partial F(0,d)}{\partial d}$.

Proof: Note that when $d^* = 0$ (which occurs if $\frac{b}{\Pi-\pi} \leq \frac{\partial F(i,0)}{\partial d}$), in equilibrium, $w > 0$, as this is the only way to ensure the scientist's participation. In this case, the Nash objective functions are:

- Secrecy: $\frac{1}{4}\left(\Pi - k - (F(0,0)(\Pi - \pi) - \underline{u}\right)^2$
- Commercial Science: $\frac{1}{4}\left(\Pi - k - F(1,0)(\Pi - \pi) - \underline{u}\right)^2$

There are two cases to consider of relevance: (i) that $\hat{d}(0) < \underline{d}$ and (ii) that $\hat{d}(0) > \underline{d}$. In the former, the objective function for open science is:

- Open Science: $\frac{1}{4}\left(\Pi - k - F(0,\hat{d}(1))(\Pi - \pi) - \underline{u}\right)^2$

While in the latter it is:

- Open Science: $\left(\Pi - k - F(0,d^*(0)(\Pi - \pi)\right)\left(bd^*(0) - \underline{u}\right)$

The maximized objective function for patent-paper pairs is:

- Patent-Paper Pairs: $\left(\Pi - k - F(1,d^*(1)(\Pi - \pi)\right)\left(bd^*(1) - \underline{u}\right)$

For the case where $\hat{d}(0) < \underline{d}$, the equilibrium outcomes are:

- Secrecy ($i = d = 0$) if $\frac{b}{\Pi-\pi} \leq \frac{\partial F(0,0)}{\partial d}$, $F(1,0) < F(0,0)$ and $\frac{1}{4}\left(\Pi - k - (F(0,0)(\Pi - \pi) - \underline{u}\right)^2 > \left(\Pi - k - F(1,d^*(1)(\Pi - \pi)\right)\left(bd^*(1) - \underline{u}\right)$
- Commercial Science ($i = 1$, $d = 0$) if $\frac{b}{\Pi-\pi} \leq \frac{\partial F(1,0)}{\partial d}$ and $F(1,0) \geq F(0,0)$
- Open Science ($i = 0$, $d > 0$) if $\frac{b}{\Pi-\pi} > \frac{\partial F(0,0)}{\partial d}$ and $\frac{1}{4}\left(bd^*(0) + \Pi - k - (F(0,d^*(0))(\Pi - \pi) - \underline{u}\right)^2 > \left(\Pi - k - F(1,d^*(1)(\Pi - \pi)\right)\left(bd^*(1) - \underline{u}\right)$
- Patent-Paper Pairs ($i = 1$, $d > 0$) if $\frac{b}{\Pi-\pi} \geq \frac{\partial F(1,0)}{\partial d}$, $\frac{1}{4}\left(bd^*(0) + \Pi - k - (F(0,d^*(0))(\Pi - \pi) - \underline{u}\right)^2 \leq \left(\Pi - k - F(1,d^*(1)(\Pi - \pi)\right)\left(bd^*(1) - \underline{u}\right)$ and $\frac{1}{4}\left(\Pi - k - (F(0,0)(\Pi - \pi) - \underline{u}\right)^2 \leq \left(\Pi - k - F(1,d^*(1)(\Pi - \pi)\right)\left(bd^*(1) - \underline{u}\right)$

For the case where $\hat{d}(0) \geq \underline{d}$, the equilibrium outcomes are:

- Secrecy ($i = d = 0$) if $\frac{b}{\Pi-\pi} \leq \frac{\partial F(0,0)}{\partial d}$, $F(1,0) < F(0,0)$ and $\frac{1}{4}\left(\Pi - k - (F(0,0)(\Pi - \pi) - \underline{u}\right)^2 > \left(\Pi - k - F(1,d^*(1)(\Pi - \pi)\right)\left(bd^*(1) - \underline{u}\right)$
- Commercial Science ($i = 1$, $d = 0$) if $\frac{b}{\Pi-\pi} \leq \frac{\partial F(1,0)}{\partial d}$ and $F(1,0) \geq F(0,0)$
- Open Science ($i = 0$, $d > 0$) if $\frac{b}{\Pi-\pi} > \frac{\partial F(0,0)}{\partial d}$ and $\frac{1}{4}\left(bd^*(0) + \Pi - k - (F(0,d^*(0))(\Pi - \pi) - \underline{u}\right)^2 > \left(\Pi - k - F(1,d^*(1)(\Pi - \pi)\right)\left(bd^*(1) - \underline{u}\right)$
- Patent-Paper Pairs ($i = 1$, $d > 0$) if $\frac{b}{\Pi-\pi} \geq \frac{\partial F(1,0)}{\partial d}$, $\frac{1}{4}\left(bd^*(0) + \Pi - k - (F(0,d^*(0))(\Pi - \pi) - \underline{u}\right)^2 \leq \left(\Pi - k - F(1,d^*(1)(\Pi - \pi)\right)\left(bd^*(1) - \underline{u}\right)$ and $\left(\Pi - k - F(0,d^*(0)(\Pi - \pi)\right)\left(bd^*(0) - \underline{u}\right) \leq \left(\Pi - k - F(1,d^*(1)(\Pi - \pi)\right)\left(bd^*(1) - \underline{u}\right)$

Finally, note that the derivative of the Nash objective function (with w = 0) with respect to d can be re-written as $\Pi - k - F(i,d)(\Pi - \pi) - (d - \frac{u}{b})\frac{\partial F(i,d)}{\partial d}(\Pi - \pi)$. As b increases this marginal condition falls indicating that, when w = 0, $d^*(i)$ is non-increasing in b.

This proposition highlights an additional complementarity between patents (and commercial returns in general) and publication that is less obvious but is derived from the formal model. When $\hat{d}(1) > \underline{d}$, when a patent is taken out, the negotiated level of disclosure will be high enough that, in equilibrium, $w^* = 0$.[33] In this case, if a patent is granted, stronger patents increase commercial returns (as $F(1,d) < F(0,d)$). As noted earlier, since wages are zero when there is a publication, the only way this additional surplus can be transferred to the scientist is by allowing more disclosure. Similarly, any policy changes that strengthen patent protection and make patents more likely to be undertaken will make disclosure more likely. Thus, in contrast to concerns that changes (such as the Bayh-Dole Act) would diminish levels of openness and publications, there are stronger incentives to generate published disclosures for commercially funded projects as patent protection becomes stronger and more commercially desirable.

Second, with regard to Proposition 2, we demonstrate that this proposition still holds even when the firm and scientist may negotiate a level of disclosure such that wages are zero in equilibrium. In the appendix, it is demonstrated there that the broad drivers of observed disclosure regimes do not change when $\frac{\partial F(1,d)}{\partial d} < \frac{\partial F(0,d)}{\partial d}$. Interestingly, when wages are zero, the level of publication disclosure (which is necessarily positive in that case) is negatively related to the scientist's benefit from kudos (*b*). Thus, while a higher *b* makes it more likely that the firm and scientist will agree to a positive level of *d*, the negotiated *d* may decline as wages become constrained.

In addition, as noted in the discussion of Proposition 1, the patenting choice of the firm also has an effect on the negotiated level of disclosure. If patenting is commercially desirable, the level of disclosure is higher under patenting. If it is not commercially desirable, the level of disclosure is lower under patenting. Thus, when wages are at zero, the firm and scientist share a common interest in the patenting decision and this drives whether open science actually results in more disclosure than under patent-paper pairs (it may not if patenting is commercially desirable).

In interpreting the distinction between the two cases – one in which wages are zero, and one in which wages are non-zero – it is tempting to characterize the positive wage case as being performed by scientists employed within firms and the zero wage case as on which involves research performed in universities. Indeed, it is certainly true that it is only in universities (and similar organizations) where you see scientists being paid through non-pecuniary means, and for outcomes that are not directly related to a particular project. However, it is equally possible that, for low kudos (or high commercial return) projects university scientists will be directly paid for research (usually termed consulting) even when they have publication rights. Nonetheless, there is a sense in which an extension of this model – say to include the role of publication as a means of monitoring research quality (Garfield 1973) – would lead to a meaningful distinction as to the employment choices of scientists. This possibility is left for future research.

Proof of Proposition 3

As in the proof of Proposition 1, we examine whether the Nash objective function satisfies the single-crossing property in (d_t, i_t). Given that total surplus is maximized, the derivative of the objective function with respect to d_t is: $b + \delta B - \frac{\partial F(i_t,d_t)}{\partial d_t}(\Pi - \pi) + i_t \delta \frac{1}{3} \frac{\partial k(d_t)}{\partial d_t}(1-\gamma)$. A simple comparison on this at $i_t = 1$ versus $i_t = 0$ yields the condition of the proposition.

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[33] While the proposition endogenously derives when wages are constrained at zero, in some environments, such payments may be prohibited. In such cases, the source of complementarity highlighted here will always be present.

Proof of Proposition 4

First, consider the conditions for secrecy. If a scientist/firm pair deviated and patented their research, this would result in a change in surplus of $\left(F(0,0)-F(1,0)\right)(\Pi-\pi)+\delta\frac{1}{3}K$ so long as the next generation (a) agreed to this license fee and (b) did not themselves choose to patent or publish. Note that, in a secrecy equilibrium, $u_t = v_t = \frac{1}{2}\left(\Pi - K - F(0,0)(\Pi-\pi)\right)$ and $\tau_{t+1} = \frac{1}{3}K$. Substituting this into **(7)** yields:

$$\max_{\tau_t, w_t, d_t, i_t} \tau_t \left(bd_t + w_t - \tfrac{1}{2}(\Pi - K - F(0,0)(\Pi-\pi))\right)\left(\tfrac{1}{2}(\Pi - K) - F(i_t, d_t)(\Pi-\pi) + \tfrac{1}{2}F(0,0)(\Pi-\pi) + i_t\delta\tfrac{1}{3}K - w_t - \tau_t\right) \quad (12)$$

As τ_t and w_t are positive, the choice of i_t and d_t is determined by total surplus. Under the conditions for secrecy, increasing either of these reduces total surplus and hence, even if a licensing agreement is signed upon deviation, these choices will not change. Similarly, deviating to publication will reduce total surplus as it assists entry, does not result in kudos (as there is no future publication), and reduces future research capital costs (something not captured by the current generation). Finally, deviating to both patents and publications, increases u_t and v_t but does not otherwise change the drivers of licensing. Hence, it results in a lower return than a move to commercial science alone and is not profitable.

Second, consider the conditions for commercial science. A deviation to secrecy will not change the incentives for the next generation to engage in commercial science (although it will change their costs) and so the condition supporting commercial science is the mirror image of the condition supporting secrecy. A deviation to patent-paper pairs would reduce commercial returns – both immediately and in the future – and not offer the benefit of additional scientific kudos as it would still maximize total surplus of future pairs not to publish. This is also true for a move to open science. Hence, the existence of an equilibrium with commercial science is solely driven by whether $F(1,0) \le F(0,0)$ and $\frac{b}{\Pi-\pi} < \frac{\partial F(0,0)}{\partial d}$.

Third, open science results in disclosure equal to $d^*(0)$ with scientists and firms earning an expected payoff of $\frac{1}{2}\left((b+\delta B)d^*(0) + \Pi - F(0,d^*(0))(\Pi-\pi)\right)$. Secrecy would reduce total surplus if $\frac{b+\delta B}{\Pi-\pi} > \frac{\partial F(0,0)}{\partial d_t}$. In contrast, obtaining a patent increases total surplus by $\frac{\delta\frac{1}{3}(K - k(d_t^*(1))(1-\gamma))}{\Pi-\pi} - \left(F(1,d_t^*(1)) - F(0,d_t^*(0))\right)$ which is negative by the condition of the proposition. Finally, by reverting to commercial science, total surplus falls by $\frac{b+\delta B}{\Pi-\pi} - \frac{F(0,d_t^*(0)) - F(1,0)}{d_t^*(0)} - \frac{\delta\frac{1}{3}K}{(\Pi-\pi)d_t^*(0)}$.

Finally, patent-paper pairs results in a level of disclosure equal to $d^*(1)$. This will be preferred to open science if $\frac{\delta\frac{1}{3}(K - k(d_t^*(1))(1-\gamma))}{\Pi-\pi} \ge F(1,d_t^*(1)) - F(0,d_t^*(0))$ and to commercial science if $\frac{b+\delta B}{\Pi-\pi} > \frac{\partial F(1,0)}{\partial d_t} - \frac{\partial k(0)}{\partial d_t}\frac{\delta\frac{1}{3}(1-\gamma)}{\Pi-\pi}$. Compared to secrecy, patent-paper pairs results in higher total surplus if: $(b+\delta B)d^*(1) + \delta\frac{1}{3}(K - k(d_t^*(1))(1-\gamma)) > \left(F(1,d^*(1)) - F(0,0)\right)(\Pi-\pi)$. Note, however, that if the other two conditions hold, then this holds as well and so is redundant.

Figure 2a: Complementarity

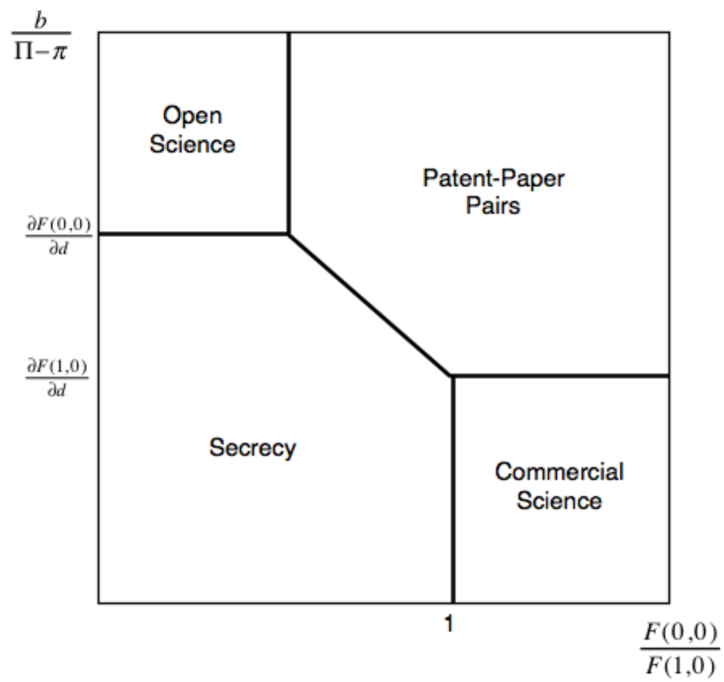


Figure 2b: Independence

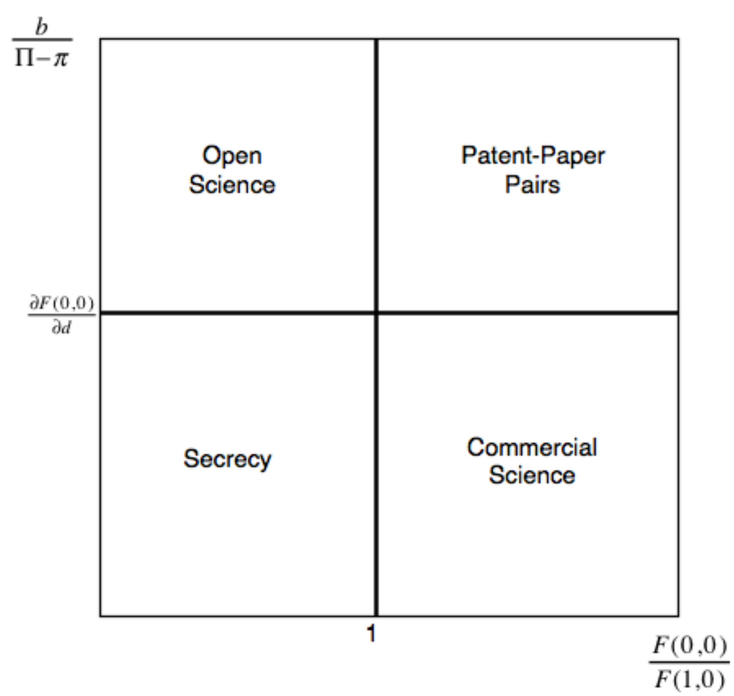
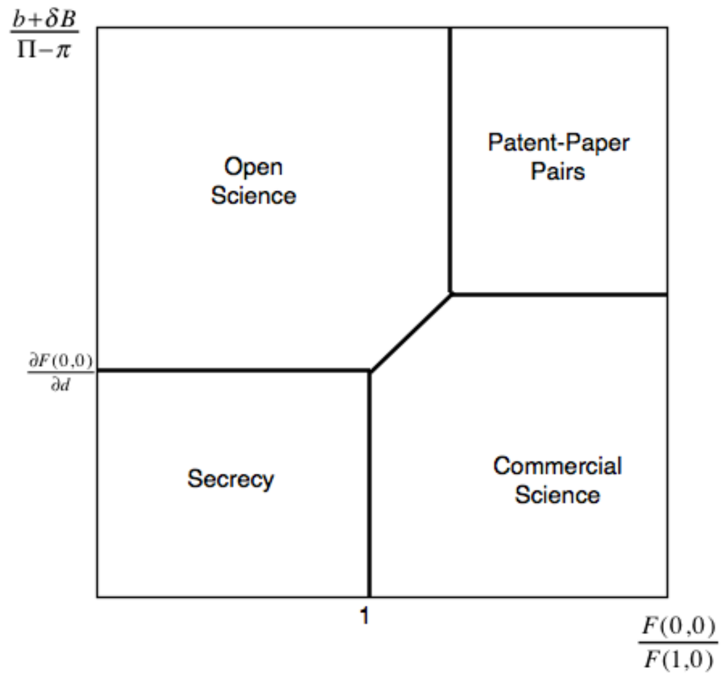


Figure 3: Substitutability



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