Essays in the Economics of Technology and Innovation, and Development Economics

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Abstract

In this thesis I study two fields in economics. While my focus is on issues of knowledge and technology diffusion, my work also investigates the proletarianization of attached workers in agrarian economies. Each chapter constitutes a free-standing contribution to the field of the economics of technology and innovation or to development economics.

In Chapter 1, I empirically compare the pattern of knowledge flows associated with university patents to those of firm patents. Specifically, I explore the change in how more broadly university knowledge disseminates to subsequent patent holders and how more broadly patented university innovations draw from different prior art owners. The findings are that university knowledge flows concentrated substantially over the 1980s to resemble more the knowledge flows of firm patents. Moreover, I find the concentration of flows is caused mainly by universities experienced in patenting, suggesting these phenomena are unlikely to dissipate with experience.

In Chapter 2, I theoretically explore why firms leading a research and development (R&D) race sometime choose freely to disclose valuable technology. Disclosing basic knowledge only helps rivals far behind the lead to compete more strongly against the leader's closer and more threatening rivals, thus lowering the latter's incentives to perform R&D; with greater competition, the expected profits of these firms decreases. If disclosure harms close rival more than the leader, technology disclosure benefits the leader.

Finally, in Chapter 3, I propose a theory of the proletarianization of attached labour in agrarian economies. Where farm owners need to motivate worker effort with contingent payments but no institution exists to prevent farmers from cheating workers from these payments, workers may be paid with the use of subsistence plots. This facilitates contracting when farmer reputation is valuable; subsistence plots decrease the farmers' benefit of cheating workers relative to the cost workers may impose in retaliation. Proletarianization occurs as the price of the farmers' principle crop rises and farmers can commit to make more of the contingent payment in cash. The model also predicts workers become pure wage earners instantly once their rights are enforced. Both predictions are consistent with observations of the proletarianization of attached labour.

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Chapter 1

University Patenting: Estimating the Diminishing Breadth of Knowledge Diffusion and Consumption

1.1 Introduction

Amongst the most striking developments on American university campuses over the past quarter century has been the rapid rise of patenting to lay claim to and protect intellectual property associated with novel and practical inventions developed by university researchers. Indeed, in just 13 years, from 1980 to 1993, the number of patents issued annually to US universities increased by 315%, from 390 to 1620.[1] This dramatic shift in academic behavior has been attributed to many factors. Principal among these are developments in the fields of microbiology and computer science, an expansion in the range of patentable matter (e.g., genetically modified life forms, software), the creation of the Court of Appeals for the Federal Circuit, and, most commonly, the passage of the Bayh-Dole Act (1980), which granted universities extensive rights to patent and retain ownership of innovations produced with federal government funding.

Although many observers have characterized the dramatic rise of university patenting as a windfall for the American economy - indeed *The Economist* went as far as describing the Bayh-Dole Act in particular as "possibly the most inspired piece of legislation to be enacted in America over the past half century" and citing university-based innovation as a key factor that facilitated America's industrial renaissance in the 1980s[2] - others have expressed a variety of concerns, most of which can be grouped into one of three categories: 1) a shift in focus from "basic" to "applied" university research,[3] 2) a decline in quality of university inventions, and 3) a decline in the dissemination of knowledge associated with university inventions due to the anti-commons problem.

Surprisingly, given the increasing level of concern over university patenting expressed in both policy circles and the popular press,[4] the evidence to

[1]By comparison, the number of patents issued to other US non-government organizations increased by only 48% over the same time period.

[2]*The Economist*, December 12, 2002.

[3]Notwithstanding Stokes' legitimate grievances with respect to the basic/applied taxonomy (Stokes (1997)), we reference it here since most of the discourse on this topic has characterized research this way.

[4]*New York Times*, August 17, 2001; *New York Times*, January 10, 2002; *The Econo-*

date offers little support for the first two of these concerns. The first concern, that an increased focus on commercialization may induce university researchers to divert their energies away from basic research (Cohen et al. (1998); Henderson et al. (1998)), is predicated on the notion that it is more important for universities to provide basic than applied research. This is because the market is more likely to under-provide basic research in the private sector due to appropriability problems. Yet basic research is important since it is often the basis of subsequent applied research and product development, which in turn is the basis for long run productivity and economic growth.

However, empirical studies that examine whether professors substitute patenting for publishing, a rough proxy for changes in research focus, do not provide evidence of such substitution. Agrawal and Henderson (2002) examine the publishing and patenting output of electrical engineering, computer science, and mechanical engineering faculty at a major research institution (MIT) and present evidence suggesting that these two activities are complements rather than substitutes. Markiewicz and DiMinin (2005) examine the complement-substitute question more directly with data from a much broader sample of university researchers and find similar results. Further still, these findings are not specific to US universities; several studies that examine the patenting-publishing relationship at various European institutions yield similar conclusions (Van Looy et al. (2005) - K.U Leuven in Belgium; Buenstorf (2005) - Max Planck Institute in Germany; Carayol (2005) - University Louis Pasteur in France; Breschi et al. (2005) - various

mist, December 24, 2005; Lieberwitz (2005); *New York Times*, May 5, 2006.

institutions in Italy).

The second concern is predicated on the notion that an increased focus on commercialization may induce researchers to shift resources towards the disclosure and patenting of lower quality inventions (Henderson et al. (1998)).[5] However, evidence presented by Mowery et al. (2004) shows that although the quality of inventions did decline after 1980, this was due to the entry of universities with little patenting experience; it was not due to a general decline in quality of inventions patented by all universities. The implication of this finding is that the estimated decline is likely to be only temporary, while inexperienced universities learn the patenting process and how to most effectively manage their intellectual property portfolio.

Thus, it is only the third concern, relating to how the anti-commons retards the flow of knowledge, that has found traction in empirical evidence. In a study employing a difference-in-differences identification based on patent-paper pairs, Murray and Stern (2005) report findings that although publications linked to patents are associated with a higher overall citation rate, after the patent actually issues, the rate declines substantially (by 9-17%). The authors note that the decline is particularly salient for articles authored by researchers with public-sector affiliations, such as university professors. They interpret their findings as evidence of an anti-commons effect that results from moving intellectual property from the public into the private domain.

Our paper further addresses the third concern: retarding the widespread

[5]The quality of inventions is measured by "importance," reflected by a count of subsequent citations, and "generality," reflected by the dispersion of citations received from patents in different technology fields.

flow of knowledge associated with university inventions. However, where Murray and Stern focus on the decline in the *level* of knowledge flows, we focus on the *narrowing* of knowledge flows to a smaller set of recipients. Specifically, we examine whether, over time and conditional on being patented, university inventions are more likely to be cited by a more concentrated set of subsequent patent owners. Such a finding would reflect the outcome of a change over time in the management objectives of university intellectual property, reflecting less emphasis on the broad dissemination of new knowledge and more towards limiting access, perhaps to maximize private returns to licensees.

Using a Herfindahl-type measure of patent assignee concentration associated with forward citations as a dependent variable and employing a difference-in-differences estimation (taking the difference of the change in concentrations over time between university versus firm patents), we estimate that the university diffusion premium (the degree to which knowledge flows from patented university inventions are more widely distributed across assignees than those of firms) declined by over half between the early and late 1980s. Furthermore, unlike the decline in invention quality that occurred during the 1980s that Mowery et al found to be due to the entry of inexperienced universities (suggesting that this was a temporary phenomenon that would dissipate as professors and administrators gained experience), the increase in knowledge flow concentration we discover is driven by experienced universities; this finding suggests that the phenomenon we identify is unlikely to disappear with time but may actually increase as inexperienced universities become more like their experienced counterparts with respect to the manner in which they manage their intellectual property.

In addition to examining the pattern of knowledge flowing out from these inventions, we also study the pattern of flows into university inventions. We expect universities to draw from a particularly wide set of prior art holders since academia is largely exempt from the anti-commons problem. This problem arises when prior art is widely distributed across different owners and strongly enforced (Heller and Eisenberg (1998); Argyres and Liebskind (1998); David (2001); David (2003); Lessig (2002); Etzkowitz (1998); Krimsky (2003)).

Under these conditions, Cournot's "complements problem" can arise (Shapiro (2001)). Each upstream patent owner prices royalties without coordinating with owners of complementary patents. Without coordination, the marginal cost of utilizing complementary technologies is higher than if all patents were owned by a single agent. Moreover, a larger number of prior art holders may increase transactions costs incurred negotiating the rights to use complementary technologies required to practice the invention.

While firms may consciously conduct R&D with this in mind to minimize exposure to the anti-commons problem,[6] we expect university researchers are largely insulated, for two reasons. First, universities have traditionally been shielded from patent infringement liability by the doctrine of "experimental use exemption" (Eisenberg (2003)). Under this doctrine, otherwise

[6]For example, from the outset of Kodak's efforts to develop its instant photography technology, the firm employed its legal counsel to work along with its R&D engineers to minimize the likelihood that any new technology would infringe on existing Polaroid patents (Warshofsky (1994); Rivette and Kline (2000); Jaffe and Lerner (2004)). In addition, Hall and Ziedonis (2001) and Ziedonis (2004) present evidence suggesting that firms building on prior art that is more fragmented patent more aggressively in order to facilitate cross-licensing and mitigate against potential infringement costs.

infringing activity is permitted if it occurs "for amusement, to satisfy idle curiosity, or for strictly philosophical inquiry."[7] Second, to the extent that university researchers choose their research projects to advance knowledge and only concern themselves with patenting *ex post* – after something they have discovered is shown to work and offer commercial potential – their project selection and prior art decisions will not be influenced by potential anti-commons problems.

However, as university patenting rises during the 1980s, we find that university researchers tend to draw from a more concentrated set of prior art holders. Specifically, our results suggest that the university diversity premium (the degree to which knowledge inflows used to develop patented university inventions are drawn from a less concentrated set of prior art holders than those used by firms) has declined by over half between the early 1980s and early 1990s. Furthermore, similar to the case of knowledge outflows described above, the estimated increase in knowledge inflow concentration is driven by experienced universities, again suggesting that this phenomenon is not likely to dissipate with experience but may actually increase over time.

This finding may reflect a change over time in the manner in which university researchers conduct research. Rather than merely worrying about the patentability of an invention *ex post*, researchers may increasingly plan research projects with an eye toward commercialization. If motivated by

[7]Walsh et al. (2005) present evidence suggesting that university researchers pay little attention to patents protecting research tools and are unlikely to modify their research due to impediments posed by existing patents. These findings are particularly interesting since they are based on data reflecting attitudes after the *Madey v. Duke* verdict of 2003.

pecuniary gains, as evidence reported by Lach and Schankerman (2005) suggests, academic researchers will look forward, anticipating the burden of future licensees, and reason backwards that the value of their intellectual property could be increased if they are able to plan their research approach so as to narrow the scope of prior art holders associated with complementary technologies.

Like Murray and Stern, our findings suggest caution with respect to the increasing tendency to patent university research. However, our findings are quite distinct. Their paper shows the impact of patenting on knowledge dissemination: an overall reduction in the level of knowledge outflows. Our results suggest that, conditional on patenting and controlling for a reduction in overall flow levels, the management of knowledge flows both to and from universities has resulted in an increasing concentration of flows over time.

This behavior seems counter to the stated mandate of most US universities, which is to maximize the dissemination of new knowledge that results from their research. While the welfare implications of our findings are non-obvious - limiting access to new knowledge can be welfare enhancing when the value of doing so to provide the necessary incentives to develop it is greater than the value of that knowledge to those who are denied it (Colyvas et al. (2002); Agrawal and Garlappi (forthcoming)) - our results are consistent with the view that universities are increasingly managing their intellectual property like profit maximizing firms rather than as welfare maximizing public institutions.

These trends in university knowledge flows are important to identify and understand because they have great implications for science policy and economic growth. Precisely because of their non-commercial focus and their welfare enhancing objectives, universities play a unique and important role in the national innovation system (Nelson (1993); Nelson (1996)). They receive extensive government funding to produce basic knowledge that is intended to be widely disseminated.[8] It is in this context that universities have historically contributed to economic growth and welfare (Henderson et al. (1998)). The finding that university knowledge flows are narrowing, at least those associated with patented inventions, throws into question the traditionally conceived arrangement between academia and society.[9]

The remainder of our paper proceeds as follows. In Section 2 we describe the empirical methodology, including our dependent variable, the "fragmentation index," that we use to measure knowledge flow patterns. In Section 3 we describe the patent citation data that we use to construct our measures. In Section 4 we present our empirical results for both knowledge outflows and inflows as well as provide examples to better understand the meaning of the estimated coefficients. Finally, in Section 5, we conclude by offering some possible explanations for our findings and directions for future research.

[8]From 1980 to 1993, universities received approximately $103 billion (constant 1996 dollars) from all levels of government to fund basic R&D. This represents approximately 45% of all basic research undertaken in the US (National Science Board (2004)).

[9]As a current example of a public response to this trend, the National Institute of Health (NIH), a major US government funding agency, recently issued new guidelines urging universities to increase the frequency with which they license genomic, NIH-funded, patented inventions on a non-exclusive, rather than exclusive, basis (National Institute of Health (2005)).

1.2 Methodology

Our empirical objective is to test whether knowledge flows associated with patented university inventions become more concentrated over time. Thus, most importantly, we need to employ an estimation technique that facilitates the clean identification of a change in the concentration of knowledge flows over time that is university-specific. Furthermore, we require an appropriate measure of knowledge flow concentration. We describe each of these in turn.

1.2.1 Estimation

In order to estimate university specific changes in concentration of knowledge flows over time, we analyze data from two distinct periods.[10] We define these as Period 1 (1980-1983) and Period 2 (1986-1989).[11] In order to identify changes in concentration that are university specific as opposed to general changes in flow patterns, we employ a difference-in-differences estimation (taking the difference of the change in concentrations over time between university versus firm patents). In addition, we include control variables to address specific dimensions along which it is plausible that universities systematically patent differently than firms (e.g., inventions that are more important, more basic, or more likely from a particular technology field).

[10] As described in the introduction, we are interested in university-specific changes in the concentration of both knowledge outflows and inflows. Since the estimation procedure is almost identical, we describe the outflows case only and comment in footnotes where the methodology differs for inflows.

[11] In the case of knowledge inflows, we define Period 2 as 1990-1993 since we use backward citations and thus are not restricted by the data set ending in 1999.

Thus, we estimate the following relationship:

$$Frag_p = F(\alpha_o + \alpha_1 D_p + \alpha_2 ERA_p + \alpha_3 D_p ERA_p + X_p \alpha_4 + X_p ERA_p \alpha_5) + \varepsilon_p \tag{1.1}$$

where $Frag_p$ measures the fragmentation of ownership dispersion of patents building upon patent p ("forward fragmentation" of knowledge outflows).[12] D_p is a university dummy variable that takes a value of one if p is assigned to a university and zero otherwise. ERA_p identifies patents that were issued in Period 2 (i.e., $ERA_p = 1$ if patent p was issued in 1986-1989 and zero otherwise).[13] X_p is a vector of variables that control for non-institutional factors that may also affect fragmentation. Finally, ε_p is a mean zero random error.

We use Equation 1.1 to test whether the university dummy explains some of the fragmentation of knowledge flows, $Frag_p$. The sign and significance of $\hat{\alpha}_1$ offers insight into the relationship between institution type and the patterns of related knowledge flows. If $\hat{\alpha}_1$ is such that the marginal effect of the university dummy is positive,

$$F(\hat{\alpha}_o + \hat{\alpha}_1 + X_p \hat{\alpha}_4) - F(\hat{\alpha}_o + X_p \hat{\alpha}_4) > 0,$$

and statistically significant, we will interpret this as suggestive evidence that university knowledge flows are less concentrated than those of firms, at least

[12]Similarly, for the case of knowledge inflows, $Frag_p$ measures the fragmentation of prior art holders upon which patent p builds (backward fragmentation).

[13]For the case of knowledge inflows, the dummy variable ERA_p distinguishes patents that were *applied* for in Period 2 (i.e., $ERA_p = 1$ if patent p was submitted to the patent office in 1990-1993 and is zero otherwise).

in Period 1.[14] This finding would be consistent with our prior beliefs about the differences between university and firm knowledge flows.

To identify how any initial difference in knowledge flows between universities and firms have changed over time, we focus on $\hat{\alpha}_3$, the coefficient on the interaction between the university dummy variable, D_p, and ERA_p. If $\hat{\alpha}_3$ is such that

$$\Big[F(\hat{\alpha}_o + \hat{\alpha}_1 + \hat{\alpha}_2 + \hat{\alpha}_3 + X_p\hat{\alpha}_4 + X_p\hat{\alpha}_5) - F(\hat{\alpha}_o + \hat{\alpha}_2 + X_p\hat{\alpha}_4 + X_p\hat{\alpha}_5)\Big]$$

$$-\Big[F(\hat{\alpha}_o + \hat{\alpha}_1 + X_p\hat{\alpha}_4) - F(\hat{\alpha}_o + X_p\hat{\alpha}_4)\Big] < 0,$$

is negative, we will interpret this as indicating that the change in the difference between university and firm knowledge dispersion over time is negative; in other words, knowledge flows from university patents have become disproportionately more concentrated.

1.2.2 Variables

We construct each of our variables using information found on the front page of the patents in our data. When a patent is issued, a substantial amount of information regarding the innovation embodied by the patent is disclosed including the technology field,[15] the assignee name (i.e., the

[14] In this case, $ERA_p = 0$ because we are analyzing patents in Period 1.

[15] Technology fields are determined by the US Patent and Trademark Office (USPTO) and are analogous to industry classes in an industry classification system such as the Standard Industrial Classification (SIC). Technology classes, however, do not map readily to any one industry because a given innovation can be applied in a wide range of industries. See Kortum and Putnam (1997) for details regarding technology field-industry concordances.

patent's owner), and all prior patents on which the given innovation builds (i.e., prior art citations). These citations are important for our study because they trace the knowledge flows between patents;[16] they may also indicate complementary technologies that may need to be used to practice the new innovation.[17] As such, while a patent grants the assignee the right to exclude others from practicing the invention described in the patent, it does not necessarily grant the owner the right to practice the invention without the permission of cited assignees. Consequently, cited assignees can be used as a proxy for potential licensees. As indicated by Ziedonis (2004) and Rivette and Kline (2000), this is how some IP consulting firms have come to use citations.[18]

[16]We use patent citations as a proxy for knowledge flows. However, citations are not straightforward to interpret in terms of direct knowledge flows, and the signal-to-noise ratio for this measure is therefore likely to be rather low. Patents cite other patents as "prior art," with citations serving to delineate the property rights conferred. Some citations are supplied by the applicant, others by the patent examiner, and some patents may be cited more frequently than others because they are more salient in terms of satisfying legal definitions of prior art rather than because they have greater technological significance. Cockburn et al. (2002) report, for example, that some examiners have "favorite" patents that they cite preferentially because they "teach the art" particularly well. Nonetheless, Jaffe et al. (2002) surveyed cited and citing inventors to explore the "meaning of patent citations" and found that approximately one-quarter of the survey responses corresponded to a "fairly clear spillover," approximately one-half indicated no spillover, and the remaining quarter indicate some possibility of a spillover. Based on their survey data, the authors conclude: "We believe that these results are consistent with the notion that citations are a noisy signal of the presence of spillovers. This implies that aggregate citation flows can be used as proxies for knowledge-spillover intensity, for example, between categories of organizations or between geographic regions" (p. 400).

[17]This point is made in Ziedonis (2004).

[18]These firms use citations to assess potential licensees and to determine what patents are best to renew or to allow to lapse.

Dependent variable

Our dependent variable, a measure of the concentration of knowledge flows, is constructed in the spirit of the "fragmentation index" developed in Ziedonis (2004). Again, we describe only the knowledge outflows measure, or forward fragmentation, $ForFrag_{i,p}$, given that the backward measure, $BackFrag_{i,p}$ is defined analogously using the citations a patent makes rather than receives.

Forward fragmentation measures the ownership dispersion of subsequent patents that cite a focal patent. Specifically, for a patent p issued to assignee i, the fragmentation measure $ForFrag_{i,p}$ is given by

$$ForFrag_{i,p} = \left[1 - \sum_{j \in J} \left(\frac{C_{j,i,p}}{C_{i,p}}\right)^2\right] \frac{C_{i,p}}{C_{i,p} - 1}, \tag{1.2}$$

where J is the set of assignees whose patents cite the focal patent, $i \notin J$, and $C_{j,i,p}$ are all citations made to p by patents belonging to assignee $j \in J$. In Equation 1.2, $C_{i,p}$ is the total number of citing patents referring to patent p that do not belong to i. That is

$$C_{i,p} = \sum_{j \in J} C_{j,i,p}. \tag{1.3}$$

Our fragmentation variable simply measures dispersion as the expected probability that two randomly selected citations made to a given patent refer to citing patents issued to two *different* assignees.[19,20] Consequently, the measure's range of possible values is the unit interval. For patents that have more widely distributed knowledge outflows (i.e., higher fragmentation), the probability that any two sampled citations belong to different assignees will be closer to one. Conversely, the probability of this event will be closer to zero the more concentrated the citing intellectual property is.

To gain a better intuition for interpreting this dispersion index, which is related to the familiar Herfindahl concentration measure, consider the following three examples of focal patents that are each cited by 10 patents (i.e., $C_{i,p} = 10$). First, suppose the focal patent is cited by 10 patents that are all issued to IBM, $J = \{IBM\}$. In this case, citing patents are perfectly

[19]This is a traditional interpretation for dispersion measures of the type defined by Equation 1.2. See Easterly and Levine (1997) for an example of this interpretation in the context of measuring ethnic diversity.

[20]With this interpretation, one can easily understand the fragmentation measure defined by Equation 1.2. Due to the count nature of citations (i.e., too few citations are typically made to make sampling with replacement an appropriate assumption), the conditional probability that two citing patents belong to different assignees, given that one of these two citations is known to belong to assignee j, is

$$1 - Pr(\text{Second citation belongs to assignee } j) = 1 - \frac{C_{j,i,p} - 1}{C_{i,p} - 1}.$$

Consequently, the expected probability that two randomly chosen citing patents belong to different assignees is

$$\sum_{j \in J} \frac{C_{j,i,p}}{C_{i,p}} \left(1 - \frac{C_{j,i,p} - 1}{C_{i,p} - 1}\right) = 1 - \sum_{j \in J} \frac{C_{j,i,p}}{C_{i,p}} \frac{C_{j,i,p} - 1}{C_{i,p} - 1}.$$

It can then be shown that

$$1 - \sum_{j \in J} \frac{C_{j,i,p}}{C_{i,p}} \frac{C_{j,i,p} - 1}{C_{i,p} - 1} = \left\{1 - \sum_{j \in J} \left(\frac{C_{j,i,p}}{C_{i,p}}\right)^2\right\} \frac{C_{i,p}}{C_{i,p} - 1}.$$

The term $\frac{C_{i,p}}{C_{i,p}-1}$ in Equation 1.2 corrects the empirical probability had we assumed that we could sample with replacement. Without this adjustment, our dispersion measure would be biased toward zero. This is the same adjustment recommended by Hall et al. (2002).

concentrated and thus make it impossible for any two citations to refer to different assignees, $ForFrag_{i,p} = 0$. Next, suppose the focal patent receives five citations each from two different assignees. This yields an intermediate measure of fragmentation; the probability that any two of the 10 citations are made by different assignees is approximately half, $ForFrag_{i,p} \simeq 0.556$.[21] Finally, suppose the focal patent is cited once each by 10 different assignees. In this case, it is certain that any two citations will come from different assignees, $ForFrag_{i,p} = 1$.

Control variables

Our identification of university specific fragmentation is based on a difference-in-differences estimation that compares differences in fragmentation over time between universities and firms. This approach is used to "difference out" overall changes in knowledge flow fragmentation that are not university specific. However, it may be the case that identified changes in university knowledge flow fragmentation are the result of certain characteristics of university patents rather than institutional characteristics of universities themselves. For example, it may be the case that the probability of generating a "general purpose" patent increased less over time for universities than for firms and that general purpose patents are more likely to generate diffused knowledge outflows due to their wide applicability. This could appear as a university specific increase in knowledge flow concentration over time, but is actually a "generality" effect rather than an institutional effect caused by a change in the management practices of university intellectual property. Sim-

[21] $Forfrag_{i,p} = (1 - 2(\frac{5}{10})^2)\frac{10}{9} \simeq 0.556$.

ilarly, it may be the case that the probability of generating a biotechnology patent increased more over time for universities than firms and that biotechnology patents are more likely to generate concentrated knowledge outflows. Again, this could appear as a university specific increase in knowledge flow concentration over time, but is actually a biotechnology effect.[22]

We control for these and several other possible confounding effects. Specifically, we control for four invention specific characteristics: 1) generality, 2) technology field, 3) importance, and 4) university science.[23] First, "generality" is constructed using the same citations used to calculate the dependant variable. However, rather than measuring the dispersion of citations received in terms of assignees, this control measures dispersion of citations received across technology fields defined by the US Patent and Trademark Office (USPTO) three-digit technology classification system.[24]

Second, we include technology field fixed effects using dummy variables coinciding with the NBER two-digit technology field classification.[25] Third, we control for invention importance using a simple count of total citations

[22]We acknowledge that universities might manage their entire patent portfolio in a manner that influences knowledge flow concentration. However, our analysis focuses on how universities manage patents individually. For example, over time a university might allocate technology transfer resources more heavily towards a particular field, such as biotechnology. If biotechnology patents generate more concentrated knowledge flows, this would affect our dependent variable but the variance would be captured by the technology field coefficient rather than the coefficient of interest, the one on the university dummy. Thus, we may underestimate the university management effect.

[23]We control for "originality" rather than generality in the inflows case. These measures are similar in spirit.

[24]This measure reflects the extent to which the knowledge embedded in a focal patent is applicable across other technology fields (Trajtenberg et al. (1997)).

[25]Our conclusions are robust to using more disaggregated technology field fixed effects; dummy variables based on the USPTO three-digit technology classification codes do not change our conclusions.

received by the focal patent.[26] Finally, we control for the degree to which a patent is cited by universities as a factor influencing fragmentation. We control for this with a variable representing the share of citations received from university patents. This variable controls for any systematic "university science" effect that might induce innovators to be cited by a smaller (or larger) group of assignees (i.e., universities).

1.3 Data

We collect our data primarily from the NBER patent database described by Hall et al. (2002). This source provides all the raw citation data needed to construct the variables in our samples. In addition, we use the report "US Colleges and Universities-Utility Patent Grants, Calendar Years 1969-2000"[27] to identify all US university patents granted from 1969 to 1999.[28]

1.3.1 Sample construction

Since we ask two different but related questions concerning changes in the concentration of university knowledge outflows and university knowledge inflows, we require two distinct samples. Although the sample construction process used for each is similar, there are a few key differences. Thus, we describe each separately below.

[26]The generality and importance measures, as described in Hall et al. (2002), have been widely used in the patent-based economics of innovation literature.

[27]This source is produced by the Information Products Division, Technology Assessment and Forecast Branch (2002).

[28]When referring to universities, we refer to universities, colleges, polytechnics, other post-secondary institutions, and university consortia.

Knowledge outflows sample

This sample is composed of a subset of all utility patents issued to US non-government organizations by the USPTO.[29] Specifically, we collect patents issued during the periods 1980-1983 and 1986-1989. This results in 241,929 patents. Furthermore, of this set of patents, we only keep those that receive at least two citations since our forward fragmentation and generality measures are undefined for these patents.[30, 31]

Next, turning to the restrictions we apply to citations, we remove self-citations because we are interested in how knowledge flows across agents in the economy.[32] Furthermore, we remove citations received from patents applied for before the focal patent was issued. We do this because we assume that citations from such patents are unlikely to represent knowledge flows due to the secrecy usually maintained during the patenting process. Finally, due to truncation issues, we remove citations that come from patents issued more than 10 years after the focal patent issue date.[33] Consequently, by only keeping patents that receive at least two "allowable" citations, we are left

[29] A utility patent is a patent protecting a process, machine, composition of matter, or an improvement of any one of these things.

[30] This is obvious from the definition of our forward fragmentation measure defined in Equation 1.2.

[31] It is difficult to deduce what bias these exclusions introduce into our results. Other studies that use these measures confront similar problems (e.g.,Mowery et al. (2004)). Thus, it is important to note that our results may only apply to patents that receive at least two citations and, in the case of inflows, to patents that make at least two citations.

[32] A self-citation is a citation received from a patent issued to the same assignee as the focal patent.

[33] Since our focal patents can be issued as early as 1980 and as late as 1989, the earlier patents would have nine more years to accumulate citations if we did not truncate. We choose 10 years since the NBER patent database contains citation data up to 1999. Since we focus on the difference-in-differences estimation, this issue is likely less of a problem, but we truncate the data in case university patents differ systematically from firm patents along this dimension.

with a final sample containing 173,499 focal patents that are, on average, referenced by 7.88 citing patents.

Knowledge inflows sample

This sample is also composed of a subset of all USPTO utility patents issued to US non-government organizations. In this case we collect patents *applied* for during 1980-1983 and 1990-1993. This results in 289,894 focal patents. Next, similar to the outflows sample construction, we remove patents that do not make at least two citations since our dependant variable, $BackFrag$, as well as our measure of originality are undefined for these patents.

Thus, by construction, each focal patent in our sample cites at least two patents. Moreover, as in the earlier case, we only consider citations with particular characteristics. Since we are concerned about potential anti-commons effects on knowledge inflows, we only consider cited patents that can potentially hold-up the utilization of follow-on inventions. Therefore, we focus on cited patents not owned by the focal assignee and that were issued before (but no more than 10 years before) the application of the focal patent. We consider these citations because they are particularly salient in terms of potential for impeding the utilization of a new invention.[34] Removing focal patents that make less than two "allowable" citations, we generate a final sample that includes 201,433 focal patents that, on average, cite 5.79 prior

[34] For example, an IBM patent applied for in 1980 might cite a Texas Instrument patent issued in 1969, an Intel patent issued in 1973, an IBM patent issued in 1978, and an AMD patent issued in 1981. Of these cited patents, we remove all but the Intel patent because it is less than 10 years old and so is likely to remain enforced by the time the focal invention is practiced, and because it is not owned by IBM. Furthermore, unlike the AMD patent, the Intel patent was issued early enough that it could be observed by IBM and thus could have influenced IBM's decision to develop and ultimately patent the focal invention.

patents.

1.4 Data limitations

Though rich, our data has limitations. Most notably, some of the patents in the data do not include assignee information. This is important since our dependent variable, the fragmentation index, is constructed using this information.[35] As described in Hall et al. (2002), 18.4% of all patents in the NBER database have unidentified owners.

However, we take a number of steps to minimize this problem. First, by construction, we only use focal patents for which we have assignee information. Recall that our initial set of patents is drawn from patents issued to US non-government organizations. Thus, only our citing patents may be missing assignee information.[36] Next, since we apply a 10 year window for constructing our backward fragmentation index and older patents are more likely to be missing assignee information, we further limit our exposure to this problem.

In addition, we utilize inventor name data that is also provided by the NBER database.[37] We use this information to obtain a better measure of fragmentation for patents that are cited by more than one unassigned patent. In these cases, we group the unassigned citations by the first inventor of the unassigned patents. For example, if a sampled patent cites two unassigned

[35] For example, when calculating the forward fragmentation measure, we need to know ownership information for the focal patent and for each of the citing patents.

[36] Similarly, for the knowledge inflows case, only our cited patents may be missing assignee information.

[37] The NBER patent database provides the inventor name(s) for all patents issued after 1974.

patents, both with the same first inventor, we treat these two citations as belonging to the same assignee.

Thus, as a result of these measures, only 13.3% of the citations made by our sampled patents are to unassigned patents and only 12.0% of citations received are from unassigned patents. Alternatively, each sampled patent, on average, cites 0.80 unassigned patents and receive 0.85 citations from unassigned patents. Finally, when calculating our fragmentation measure, we assume unassigned patents are not self-citations and that each belongs to a different assignee. However, as a robustness check, we also estimate our key models using fragmentation measures constructed by instead assuming that all unassigned patents belong to a single assignee; our results do not change. In addition, we further check robustness by limiting our sample to only those focal patents that are cited by patents with full assignee information; our results persist.[38]

A second limitation of the data is the absence of ownership transfer information. Our fragmentation measure is calculated based on the assignee identified at the time each patent is issued. However Serrano (2005), finds that the sale and purchase of patents is not uncommon. This would only pose a problem if the likelihood of ownership transfer (specifically the type that would cause a change in fragmentation) changed at a different rate for universities than firms. The literature on this topic is limited and does not indicate whether this is the case. Moreover we do not have access to ownership transfer data to check; thus, we note this as a caveat for interpreting

[38]We similarly check robustness for the knowledge inflows case by limiting our sample to only those focal patents that cite patents with full assignee information, and again our results persist.

our results and an issue warranting further research.

1.5 Results

1.5.1 Summary statistics

We present summary statistics on Table 1.1 confirming the findings of Henderson et al. (1998) that university patents are more important, general, and original than firm patents. Beginning with Panel A, which presents data for the knowledge outflows sample, we see that university patents are more important (they receive more citations) in both Periods 1 and 2. For example, the average university patent receives 35% more citations than the average firm patent in Period 1 and 32% more citations in Period 2. Similarly, university patents are more general in both periods. Turning to Panel B, we see that university patents are also more original, and this difference seems to increase over time.

Next, we consider our variable of interest - the fragmentation index. Beginning with Panel A, we see that knowledge outflows from university patents are more fragmented than their private sector counterparts in Period 1. (We explain how to interpret the difference in index values in Section 1.5.4.) However, this difference seems to disappear by Period 2. Similarly, in Panel B, we see that knowledge inflows to university patents are more fragmented than those to firm patents in Period 1. Again, however, this difference seems to disappear by Period 2.

Table 1.1: Summary statistics, means, standard deviations and difference in means

Panel A: Knowledge OUTFLOWS

	Period 1: 1980-1983			Period 2: 1986-1989		
	University (I)	Firm (II)	Difference (I) - (II)	University (III)	Firm (IV)	Difference (III) - (IV)
Forward Fragmentation	0.902	0.879	0.023	0.861	0.867	-0.006
	(0.187)	(0.223)		(0.214)	(0.216)	
Generality	0.571	0.538	0.033	0.561	0.547	0.013
	(0.332)	(0.361)		(0.316)	(0.338)	
Citations Received	8.620	6.37	2.250	11.650	8.85	2.800
	(10.030)	(5.94)		(13.280)	(10.31)	
University Citation Intensity	0.065	0.013	0.052	0.101	0.018	0.083
	(0.136)	(0.068)		(0.178)	(0.078)	
Observations	1,125	70,699		2,705	98,970	

Panel B: Knowledge INFLOWS

	Period 1: 1980-1983			Period 2: 1990-1993		
	University (I)	Firm (II)	Difference (I) - (II)	University (III)	Firm (IV)	Difference (III) - (IV)
Backward Fragmentation	0.918	0.903	0.015	0.905	0.908	-0.002
	(0.200)	(0.220)		(0.211)	(0.197)	
Originality	0.535	0.514	0.021	0.563	0.515	0.048
	(0.374)	(0.388)		(0.355)	(0.364)	
Citations Made	5.374	4.608	0.766	6.493	6.458	0.035
	(4.767)	(3.574)		(5.726)	(6.383)	
University Citation Intensity	0.050	0.007	0.042	0.090	0.017	0.073
	(0.139)	(0.053)		(0.178)	(0.076)	
Observations	1,212	72,050		4,437	123,734	

Notes: Standard deviations in parenthesis.

Although these statistics are suggestive of a change in university behavior concerning the management of knowledge flows associated with patented inventions, changes in institution-related fragmentation measures could be confounded with changes in non-institutional factors, such as technology field portfolio, as we note in the methodology section above. Thus, we turn next to regression analysis which allows us to control for key invention characteristics.

1.5.2 Regression analysis: dispersion of knowledge outflows

We report the estimated OLS coefficients of Equation 1.1 for the knowledge outflows sample in Table 1.2. Recall that the dependent variable in this case is $ForFrag_{i,p}$. Referencing the fully specified model reported in Column IV, we see from the estimated coefficient on the university dummy that university patents in Period 1 are more fragmented than their private sector counterparts, even after controlling for the importance, generality, and technology field of the invention. We refer to this difference – the degree to which knowledge flows from patented university inventions are more widely distributed across assignees than those of firms – as the university diffusion premium.

Turning to the coefficient on the interaction between the university dummy and the Period 2 dummy (ERA), we see that the university diffusion premium is significantly diminished by the second period. In fact, by comparing the magnitudes of this coefficient with the coefficient on the university dummy (with no interaction), we see that the university diffusion premium measured in Period 1 is reduced by approximately 74% by Period

Table 1.2: Forward fragmentation, OLS and fractional logit regression marginal effects

	Panel A: OLS Regressions Dependent Variable: *ForFrag*				Panel B: Fractional Logit Regression Dependent Variable: *ForFrag*			
	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)
University Dummy	0.037***	0.036***	0.032***	0.031***	0.032***	0.031***	0.028***	0.027***
	5.624	5.444	5.025	4.874	6.636	6.431	5.700	5.575
University Dummy x Era Dummy	−0.026***	−0.025***	−0.024***	−0.023***	−0.022***	−0.021***	−0.020***	−0.019***
	−3.328	−3.197	−3.066	−2.940	−3.618	−3.475	−3.279	−3.160
Citations Received		0.001***		0.001***		0.001		0.000
		4.850		4.106		1.185		0.698
Citations Received x Era Dummy		−0.001***		−0.000***		−0.001		−0.001
		−3.793		−3.712		−1.029		−0.847
Generality			0.090***	0.090***			0.081***	0.080***
			40.33	40.24			34.06	34.19
Generality x Era Dummy			0.008***	0.009***			0.012***	0.013***
			2.828	2.889			3.745	4.101
University Intensity	0.017	0.016	0.001	0.000	0.013	0.013	−0.003	−0.003
	1.448	1.389	0.068	0.021	0.810	0.785	−0.175	−0.189
University Intensity x Era Dummy	0.009	0.009	0.010	0.011	0.009	0.010	0.010	0.011
	0.615	0.661	0.727	0.765	0.499	0.484	0.547	0.561
Tech. Field F.E.	YES	YES	YES	YES	YES	YES	YES	YES
Tech. Field F.E. x Era Dummy	YES	YES	YES	YES	YES	YES	YES	YES
R^2	0.042	0.042	0.064	0.064				
Log Likelihood					−54,028	−54,022	−53,225	−53,223
Observations	173,499	173,499	173,499	173,499	173,499	173,499	173,499	173,499

- Fractional logit regression results are the marginal effects evaluated at the sample mean.
- *** 1% significance, ** 5% significance, * 10% significance
- Robust t-statistics shown.

2. By comparison, other characteristics of university patents, such as their tendency to be more general than firm patents, remain virtually unchanged over this period.

This is our main result with respect to the increasing concentration of knowledge outflows from university patents. We check for robustness in a number of ways. First, we show that the result holds in various specifications of Equation 1.1, which are also reported in Panel A of Table 1.2. We also confirm that the result holds using different procedures for handling unassigned patents.[39] Furthermore, the result holds when we use finer technology class fixed effects based on the USPTO three-digit classification system. Finally, due to the nature of the dependent variable, we estimate Equation 1.1 using Fractional Logit rather than OLS. Again, the result holds. We discuss the details of this next.

Fractional logit

Although coefficients estimated using OLS are straightforward to interpret, this regression method may not be suitable since our dependent variable is an index that only takes values between zero and one. However, due to its linear nature, OLS estimation can yield predictions that are negative or greater than one. Thus, fractional logit regression, as described by Papke and Wooldridge (1996), may be more suitable.

To implement this estimation technique, we assume a logistic functional form for the conditional mean of our fragmentation measure. More explicitly,

[39] Specifically, we treat all unassigned patents as if they are from the same assignee and, separately, we drop all observations for which one or more of the citing patents is unassigned. The result is robust.

we assume:

$$E[ForFrag_p|D_p, ERA_p, X_p] = \frac{\exp\{\alpha_o+\alpha_1 D_p+\alpha_2 ERA_p+\alpha_3 D_p ERA_p+X_p\alpha_4+X_p ERA_p\alpha_5\}}{1+\exp\{\alpha_o+\alpha_1 D_p+\alpha_2 ERA_p+\alpha_3 D_p ERA_p+X_p\alpha_4+X_p ERA_p\alpha_5\}}.$$

Given this assumption, the parameters are estimated by quasi-maximum likelihood estimation, where the quasi-log likelihood, l_p, for a given observation p is:

$$l_p = Frag_p \log\left\{\frac{\exp\{\alpha_o+\alpha_1 D_p+\alpha_2 ERA_p+\alpha_3 D_p ERA_p+X_p\alpha_4+X_p ERA_p\alpha_5\}}{1+\exp\{\alpha_o+\alpha_1 D_p+\alpha_2 ERA_p+\alpha_3 D_p ERA_p+X_p\alpha_4+X_p ERA_p\alpha_5\}}\right\} +(1-Frag_p)\log\left\{1-\frac{\exp\{\alpha_o+\alpha_1 D_p+\alpha_2 ERA_p+\alpha_3 D_p ERA_p+X_p\alpha_4+X_p ERA_p\alpha_5\}}{1+\exp\{\alpha_o+\alpha_1 D_p+\alpha_2 ERA_p+\alpha_3 D_p ERA_p+X_p\alpha_4+X_p ERA_p\alpha_5\}}\right\}.$$

Using this procedure yields estimates that must take values within the unit interval.[40]

Panel B in Table 1.2 provides the marginal effects of each variable specified in Equation 1.1 based on coefficients estimated with fractional logit regressions.[41] Evaluated at the sample mean, the marginal effect of each variable is very close in magnitude and significance to the OLS estimates.[42]

[40] See Papke and Wooldridge (1996) for further detail.

[41] It is important to note that the marginal effects are not simply given by the coefficients estimated in our fractional logit regressions. Since we assume a non-linear functional form for the conditional mean of the dependant variable, we calculate the marginal effects as suggested by Ai and Norton (2003). Furthermore, to remain consistent with the exposition of the OLS estimates, the estimated marginal effects of variables not interacted with the ERA_p variable show the marginal effects these variables had on fragmentation in Period 1. The marginal effect of interacted variables show the change in the marginal effect from Period 1 to Period 2.

[42] Similar results follow when we use double-sided tobit regressions.

Experience and dispersion of knowledge outflows

The rapid rise in university patenting that occurred during the 1980s reflects significant change in the overall landscape with respect to academia's approach to the management of intellectual property. During this period, many universities that did not have a formal technology transfer office established one and created standardized procedures for managing the disclosure, patenting, and licensing process (Mowery et al. (2004)). In addition, much of the increase in patent activity came from "inexperienced" institutions that had been issued few patents prior to 1980.

The increasing role of these inexperienced institutions in university patenting influenced the overall character of the "average" university patent. Indeed, the decrease in importance and generality of university patents over time identified by Henderson et al. (1998) was shown by Mowery et al. (2004) to be due to the entry of inexperienced schools. The implication of the Mowery et al finding is very important; since the measured decrease in importance and generality was due to the entry of inexperienced universities, the effect was likely temporary while these schools learned to manage their intellectual property to become more like their experienced counterparts.

Since our study is similar in spirit to these papers, it is incumbent upon us to also check whether our effect is a result of entry by inexperienced universities. To accomplish this we categorize our university patents in a similar way to Mowery et al. We divide universities into two categories based on their patenting experience prior to 1981. We define: (1) High Experience Universities as those universities obtaining at least 10 patents that were applied for after 1970 but before 1981, and (2) Low Experience Universities as those universities that obtained less than 10 patents that were applied for during the same period.[43] Based on this categorization, experienced universities account for 87% (984) and 72% (1948) of the focal university patents in Periods 1 and 2, respectively.

To examine the effects of experience on knowledge outflows, we run essentially the same regressions as in Table 1.2. The only difference is that we now break apart the university effect according to the level of university experience. We do this by using two university dummy variables that differentiate between universities according to the categories of experience described above.

The regression results in Table 1.3 show that the reduction in the breadth of knowledge from university patents estimated in the prior section is not driven only by the entry of inexperienced universities. In fact, the coefficient on the interaction dummy (High Experience university * ERA) is highly significant. This result suggests that the issue of interest, an increase in the concentration of knowledge flows associated with university patents, is at least partly driven by experienced universities implying that, unlike the decline in importance and generality, this is unlikely to be temporary.

[43]Though our categorization of universities is similar to Mowery et al. (2004), it is not identical. Specifically, we do not distinguish between the less experienced institutions. Whereas Mowery et al delineates between universities with moderate experience (universities that obtained between one to nine patents that were applied for after 1970 but before 1981) and universities without experience (universities with zero patents applied for during this time), we group these two categories into one. Also, our categorization differs slightly for two measurement reasons: (1) we only consider those patents that made at least two citations while Mowery et al considers all university patents; and (2) we include patents applied for by the University of California, Stanford University and Columbia University while Mowery et al excludes these universities.

Table 1.3: Forward fragmentation based on university experience

	Panel A: OLS Regressions Dependent Variable: *ForFrag*				Panel B: Fractional Logit Regression Dependent Variable: *ForFrag*			
	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)
High Experience University Dummy	0.037***	0.036***	0.033***	0.032***	0.032***	0.031***	0.028***	0.027***
	5.350	5.168	4.757	4.604	6.331	6.119	5.428	5.301
High Experience University Dummy	-0.021**	-0.020**	-0.018**	-0.017**	-0.018***	-0.017**	-0.015**	-0.014**
x ERA Dummy	-2.485	-2.354	-2.170	-2.046	-2.649	-2.504	-2.292	-2.179
Low Experience University Dummy	0.033*	0.033*	0.030*	0.030*	0.029**	0.029**	0.026*	0.025*
	1.828	1.801	1.696	1.673	2.158	2.131	1.883	1.863
Low Experience University Dummy	-0.036*	-0.035*	-0.036*	-0.036*	-0.032**	-0.031**	-0.031**	-0.030*
x ERA Dummy	-1.811	-1.795	-1.841	-1.820	-2.039	-2.026	-1.989	-1.960
Citations Received		0.001***		0.001***		0.001		0.000
		4.849		4.105		1.183		0.697
Citations Received		-0.001***		-0.001***		-0.001		-0.001
x ERA Dummy		-3.789		-3.709		-1.027		-0.845
Generality			0.090***	0.090***			0.081***	0.080***
			-40.33	40.24			34.06	34.19
Generality			0.009***	0.009***			0.012***	0.013***
x ERA Dummy			2.833	2.894			3.743	4.098
University Intensity	0.017	0.016	0.001	0.000	0.013	0.013	-0.003	-0.003
	1.448	1.389	0.068	0.021	0.810	0.785	-0.175	-0.189
University Intensity	0.009	0.009	0.010	0.011	0.009	0.010	0.010	0.010
x ERA Dummy	0.601	0.647	0.711	0.750	0.438	0.474	0.537	0.550
Tech. Field F.E.	YES	YES	YES	YES	YES	YES	YES	YES
Tech. Field F.E. x ERA Dummy	YES	YES	YES	YES	YES	YES	YES	YES
R^2	0.042	0.042	0.064	0.064				
Loglikelihood					-54,028	-54,021	-53,224	-53,222
Observations	173,499	173,499	173,499	173,499	173,499	173,499	173,499	173,499

- Fractional logit regression results are the marginal effects evaluated at the sample mean.
- *** 1% significance, ** 5% significance, * 10% significance
- Robust t-statistics shown.

1.5.3 Regression analysis: diversity of knowledge inflows

We turn next to examine the concentration of knowledge inflows. Although the economic forces affecting the concentration of inflows are different from those affecting that of outflows, as we described in the introduction, the econometric approach to identifying changes in concentration is much the same.

We report the estimated coefficients of Equation 1.1 for the knowledge inflows sample in Table 1.4. Recall that the dependent variable in this case is $BackFrag$. Referencing the fully specified model reported in Column IV, we see from the estimated coefficient on the university dummy that university patents in Period 1 are more fragmented than their private sector counterparts, even after controlling for the originality, technology field, and overall number of citations made. We refer to this difference – the degree to which knowledge inflows used to develop patented university inventions are drawn from a less concentrated set of prior art holders than those used by firms – as the university diversity premium.

Turning to the coefficient on the interaction between the university dummy and the Period 2 dummy (ERA), we see that the university diversity premium is significantly diminished by the second period. In fact, by comparing the magnitudes of this coefficient with the coefficient on the university dummy (with no interaction), we see that the university diversity premium measured in Period 1 is reduced by approximately 67% by Period 2. By comparison, another characteristic of university patents, their tendency to be more original than firm patents, does not diminish but rather

Table 1.4: Backward fragmentation, OLS and fractional logit regression marginal effects

	Panel A: OLS Regressions Dependent Variable: *BackFrag*				Panel B: Fractional Logit Regression Dependent Variable: *BackFrag*			
	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)
University Dummy	0.026***	0.026***	0.025***	0.024***	0.023***	0.022***	0.021***	0.020***
	4.414	4.291	4.213	4.131	4.686	4.534	4.429	4.364
University Dummy x Era Dummy	−0.015**	−0.014**	−0.017**	−0.016**	−0.013**	−0.012**	−0.014**	−0.014***
	−2.252	−2.140	−2.528	−2.448	−2.284	−2.136	−2.553	−2.477
Citations Made		0.001***		0.001***		0.001*		0.001
		5.267		3.531		1.709		0.811
Citations Made x Era Dummy		−0.000		−0.000		0.000		0.000
		−0.301		−0.154		0.245		0.255
Originality			0.066***	0.066***			0.060***	0.059***
			34.05	33.83			28.60	28.49
Originality x Era Dummy			0.011***	0.011***			0.012***	0.011***
			4.481	4.236			4.428	4.330
University Intensity	0.006	0.006	0.004	0.004	0.004	0.004	0.004	0.004
	0.452	0.456	0.265	0.269	0.218	0.235	0.218	0.227
University Intensity x Era Dummy	0.016	0.017	0.013	0.013	0.015	0.015	0.009	0.010
	1.056	1.080	0.868	0.887	0.673	0.690	0.450	0.467
Tech. Field F.E.	YES	YES	YES	YES	YES	YES	YES	YES
Tech. Field F.E. x Era Dummy	YES	YES	YES	YES	YES	YES	YES	YES
R^2	0.028	0.029	0.045	0.046				
Log Likelihood					−53,095	−53,050	−52,248	−52,234
Observations	201,433	201,433	201,433	201,433	201,433	201,433	201,433	201,433

- Fractional logit regression results are the marginal effects evaluated at the sample mean.
- *** 1% significance, ** 5% significance, * 10% significance
- Robust t-statistics shown.

is further amplified over this period.

This is our main result with respect to the increasing concentration of knowledge inflows. As before, we check for robustness in a number of ways. First, we show that the result holds in various specifications of Equation 1.1, which are also reported in Panel A of Table 1.4. In addition, we estimate Equation 1.1 using Fractional Logit rather than OLS. The results presented in Panel B are very similar to those generated by OLS.[44] We also confirm that the finding holds using the different procedures for handling unassigned patents described above. Furthermore, the result holds when we use finer technology class fixed effects based on the USPTO three-digit classification system.

Experience and the dispersion of knowledge inflows

For the reasons outlined in Section 1.5.2 above, we must check whether the decline in the university diversity premium measured here is the result of entry by institutions that were less experienced at managing intellectual property. Recall that this issue is important since if the decline is due to the entry of inexperienced universities, the effect is likely temporary while these schools learn to manage their intellectual property like their experienced counterparts.

As before, we define the universities in our data as either high or low experience. Based on this categorization, experienced universities account for 81% (982) and 61% (2694) of the focal university patents in Periods 1 and 2, respectively.

[44]Similar results follow when we use double-sided tobit regressions.

To examine the effects of experience on knowledge inflows, we run essentially the same regressions as in Table 1.4. The only difference is that we again break apart the university effect according to the level of university experience. We do this by using two university dummy variables that differentiate between high and low experienced universities.

The regression results in Table 1.5 show that the reduction in diversity of knowledge sources used in developing patented university inventions estimated in Section 1.5.3 is not driven only by the entry of inexperienced universities. In fact, the coefficient on the interaction dummy (High Experience university * ERA) is highly significant. While the negative coefficient on the interaction coefficient is slightly greater for inexperienced universities in terms of magnitude, it is not significant at the 10% level, whereas the coefficient on the interaction term for experienced universities is significant at the 5% level. Most importantly though, this result suggests that the issue of interest, an increase in the concentration of knowledge flows into university patents, is at least partly driven by experienced universities, suggesting that this is not likely a temporary phenomenon.

Table 1.5: Backward fragmentation based on university experience

	Panel A: OLS Regressions Dependent Variable: *BackFrag*				Panel B: Fractional Logit Regression Dependent Variable: *BackFrag*			
	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)
High Experience University Dummy	0.025***	0.025***	0.024***	0.024***	0.022***	0.021***	0.020***	0.020***
	3.861	3.764	3.682	3.617	4.023	3.901	3.758	3.706
High Experience University Dummy x ERA Dummy	-0.017**	-0.016**	-0.019**	-0.018**	-0.014**	-0.013**	-0.015**	-0.015**
	-2.164	-2.061	-2.430	-2.356	-2.127	-1.993	-2.332	-2.261
Low Experience University Dummy	0.030**	0.029**	0.028**	0.028**	0.026**	0.024**	0.024**	0.024**
	2.228	2.145	2.133	2.078	2.573	2.464	2.545	2.495
Low Experience University Dummy x ERA Dummy	-0.017	-0.014	-0.017	-0.016	-0.013	-0.012	-0.015	-0.014
	-1.008	-0.998	-1.169	-1.124	-1.194	-1.105	-1.403	-1.359
Citations Made		0.001***		0.001***		0.001*		0.001
		5.264		3.529		1.702		0.808
Citations Made x ERA Dummy		-0.000		-0.000		0.000		0.000
		-0.301		-0.154		0.245		0.254
Originality			0.066***	0.066***			0.060***	0.059***
			34.05	33.83			28.59	28.48
Originality x ERA Dummy			0.011***	0.011***			0.012***	0.011***
			4.482	4.237			4.435	4.337
University Intensity	0.006	0.006	0.003	0.004	0.004	0.004	0.004	0.004
	0.446	0.450	0.259	0.263	0.214	0.231	0.214	0.223
University Intensity x ERA Dummy	0.016	0.017	0.013	0.014	0.015	0.015	0.009	0.010
	1.059	1.082	0.870	0.890	0.675	0.691	0.451	0.469
Tech. Field F.E.	YES	YES	YES	YES	YES	YES	YES	YES
Tech. Field F.E. x ERA Dummy	YES	YES	YES	YES	YES	YES	YES	YES
R^2	0.028	0.029	0.045	0.046				
Loglikelihood					-53,095	-53,049	-52,248	-52,234
Observations	201,433	201,433	201,433	201,433	201,433	201,433	201,433	201,433

- Fractional logit regression results are the marginal effects evaluated at the sample mean.
- *** 1% significance, ** 5% significance, * 10% significance
- Robust t-statistics shown.

1.5.4 Interpretation of fragmentation index values

The meaning of the fragmentation index, the basis of our dependent variables, can be difficult to comprehend. Similar to the Herfindahl index, which, although often used in market concentration studies is usually accompanied by more intuitive "four firm concentration ratios," the fragmentation index is complex. This is because many states of the world (e.g., combinations of citation frequencies and assignee distributions) can generate similar values. Although the index is complicated, however, it is important to understand. Throughout most of the discussion so far, we have discussed changes in university knowledge flow concentration in relative terms. In other words, we have discussed the change in the university premium rather than the absolute change in the concentration of university knowledge flows. While the relative change in concentration between periods seems large ($> 50\%$), the absolute change seems small ($< 3\%$). Ultimately, we are interested in whether the change is economically important. To this end, we offer three distinct ways of interpreting the fragmentation index to help the reader develop intuition for comprehending the economic significance of the estimated changes in knowledge flow concentrations.

Distribution of assignees across a single patent

Consider a patent that receives eight citations, roughly the mean number of citations received by focal patents in our sample. Further, suppose these citations are from five different assignees. If three different assignees each cite the patent twice while the remaining two assignees only cite the patent once, then the fragmentation measure equals 0.89.[45] To increase the fragmentation measure by 0.04 (approximately the value of the coefficient on the university dummy) while holding constant the total number of citations, one additional assignee would have to cite the patent. In this case, two assignees would each continue to cite the patent twice while now four assignees would each cite the patent once. With this distribution, the fragmentation would increase to about 0.93.[46]

Distribution of average versus perfectly concentrated patents

Suppose there are two periods in which university patents are issued: Period 1 and Period 2. Further suppose that all Period 1 patents are average in terms of concentration (i.e., they have the average fragmentation value). However, in Period 2, patents are either average or perfectly concentrated (i.e., $fragmentation = 0$). To develop intuition for interpreting the meaning of our estimated coefficients we calculate what fraction of patents must be perfectly concentrated in order to obtain the observed drop in the average fragmentation value from Period 1 to Period 2.

Specifically, we use the fractional logit procedure to estimate the relationship between a patent's fragmentation, $frag_p$, and the same patent's characteristics, (ERA_p, X_p):

$$frag_p = F(\alpha_o + \alpha_1 ERA_p + X_p\beta) + \varepsilon_p.$$

[45] $For Frag_p = \{1 - \frac{2}{64} - 3\frac{2^2}{8^2}\}\frac{8}{8-1} \simeq 0.89$

[46] $For Frag_p = \{1 - \frac{4}{64} - 2\frac{2^2}{8^2}\}\frac{8}{8-1} \simeq 0.93$

Note that, for simplicity, no variable is interacted with the period effect, ERA_p, as was done in the specifications reported earlier. Here we assume the relationship between all control variables and $frag_p$ does not change over time.

To estimate the absolute decrease in fragmentation, Δ, we find the estimated marginal effect of ERA_p. Since ERA_p is a dummy variable that equals one for any patent, p, in Period 2 and zero otherwise, the marginal effect is given by

$$\Delta = F(\hat{\alpha}_o + \hat{\alpha}_1 + \overline{X}\hat{\beta}) - F(\hat{\alpha}_o + \overline{X}\hat{\beta}).$$

Δ is calculated at the sample mean, $\overline{X}$, to remain consistent with the estimated marginal effects found in the main tables above.

Finally, since patents in Period 2 can only have a fragmentation value equal to $F(\hat{\alpha} + \hat{\beta}\overline{X})$ (the "average" level of fragmentation in the Period 1) and zero (perfectly concentrated flows), we need to determine the number of patents, Y, out of a total of T patents in Period 2 that must have perfectly concentrated knowledge flows to cause the change in average fragmentation, Δ. That is, we solve

$$\frac{(T - Y)F(\hat{\alpha}_o + \overline{X}\hat{\beta}) + (Y)0}{T} - F(\hat{\alpha}_o + \overline{X}\hat{\beta}) = \Delta,$$

or

$$\frac{Y}{T} = -\frac{\Delta}{F(\hat{\alpha}_o + \overline{X}\hat{\beta})}.$$

Recalling that in Period 1 all university patents have fragmentation equal to $F(\hat{\alpha}_o + \overline{X}\hat{\beta})$ implies that the propensity of patents with perfectly concentrated knowledge flows increased from 0 to $\frac{Y}{T}$.

Thus, from Table 1.6 we see that our estimated changes imply the following. For the knowledge outflows case, if there are 100 patents in Period 1 that all have the average level of fragmentation, in Period 2 approximately 96 will still have the average level of fragmentation, but four will be perfectly concentrated (i.e., all citations come from a single assignee). For the knowledge inflows case, only one patent will be perfectly concentrated. Clearly, the estimated changes in concentration are likely not the result of perfect concentration (i.e., rather than 4% of the focal patents being perfectly concentrated, a larger percentage might be moderately more concentrated than average) but this simple dichotomy allows for developing intuition regarding the economic implications of our findings.

Table 1.6: Change in propensity of university patents to have perfectly concentrated knowledge Flows

	Backward Knowledge Flows				Forward Knowledge Flows			
	(I)	(II)	(III)	(IV)	(I)	(II)	(III)	(IV)
Period 1 Average	0.921	0.920	0.926	0.925	0.910	0.912	0.911	0.913
Period 2 Average	0.914	0.914	0.916	0.916	0.869	0.869	0.874	0.874
$\frac{Y}{T}$	0.007	0.007	0.011	0.010	0.045	0.047	0.041	0.043

-*Note*: The Roman numerals in the table coincide with the specifications of our regression equations reported above (i.e. in terms of the use of originality and citations made for the knowledge inflows case and generality and citations received for the outflows case.).

Distribution of average firm versus perfectly fragmented patents

In our final illustrative example, we compare university patents to those of firms. Suppose all firm patents have the same level of fragmentation, $\overline{Frag_f}$.

Suppose also that university patents can take two values of fragmentation, either $\overline{Frag}_f$ or one (the latter case implies perfect fragmentation such that all citations come from unique assignees). Our data indicate that the average fragmentation of university patents, $\overline{Frag}_u$, is greater than that of firm patents such that $\overline{frag}_u = \overline{frag}_f + \Delta$ where $\Delta > 0$.

In this example, we ask, given the assumptions described above, what must the distribution of university fragmentation be (i.e., proportion where fragmentation is $\overline{Frag}_f$ versus one) to generate an average level of fragmentation that is Δ greater than that of firm patents? We address this with a simple exercise.

Randomly draw T university patents. Let Y be the number of these T patents with fragmentation equal to 1 and consequently T-Y is the number of patents with fragmentation equal to $\overline{Frag}_f$. Thus, we want to know: What fraction of the university patent sample (i.e., $\frac{Y}{T}$) must have a fragmentation equal to one such that the average university fragmentation is greater than the average firm fragmentation by Δ. That is, what does $\frac{Y}{T}$ have to be such that

$$\overline{Frag}_u = \frac{Y + (T - Y)\overline{Frag}_f}{T} = \overline{Frag}_f + \Delta.$$

The solution is

$$\frac{Y}{T} = \frac{\Delta}{1 - \overline{Frag}_f}.$$

Given our estimates of the coefficients on the university dummy variables and the sample fragmentation means for firm patents, we find the following for knowledge outflows (i.e., forward fragmentation). Initially, in Period 1, university fragmentation is greater by about 0.027 (the estimated value of the university dummy variable in Table 1.2 Column (VIII)) and the sample mean of firm fragmentation is 0.879 (i.e., the sample mean of firm patents in Period 1, shown in Table 1.1). This implies that 22 out of 100 university patents are perfectly fragmented in Period 1 compared to only six in Period 2.[47]

For knowledge inflows, we use the estimated initial fragmentation difference between firm and university patents, which is 0.02 (the estimated value of the university dummy variable in Table 1.4 Column (VIII)) and the sample mean of firm fragmentation of 0.903 (the sample mean of firm patents in Period 1 shown in Table 1.1). Using these values, we calculate that approximately 21 out of 100 university patents are perfectly fragmented in Period 1 compared to only seven in Period 2.[48]

1.6 Conclusion

The dramatic rise in the level of university patenting that occurred during the 1980s has been examined along a variety of dimensions. Ours is the first study to our knowledge that has sought to determine whether the increasing trend towards formal intellectual property protection has restricted the breadth of knowledge flows. Our findings suggest that it has. However, although the magnitude of the decline in dispersion of university knowledge flows is large relative to firms, the absolute changes are modest. Also, im-

[47] In Period 2, the difference in university-firm fragmentation is 0.027-0.019=0.008 and the firm sample mean is 0.867.

[48] In Period 2, the difference in university-firm fragmentation is 0.020-0.014=0.006 and the firm sample mean is 0.908.

portantly, the changes are at least partly driven by universities that were experienced at patenting, suggesting that the identified effect is likely not temporary.

What are the broader implications of these findings? There could be many explanations and we are cautious about pushing too hard on any one interpretation of our results. However, we close by drawing on the literature to speculate about some potential causes to offer context for our findings.

In terms of knowledge outflows, our results suggest that not only might behaviors associated with patenting limit the level of dissemination of knowledge flows as shown by Murray and Stern (2005), these behaviors might also limit the breadth of dissemination. In the university setting, this could occur at either or both of two levels: the technology licensing office and/or the inventor.

To the extent technology licensing offices shift their objective function from dissemination-maximization (leading to predominantly non-exclusive, widely licensed patents) to profit-maximization (leading to predominantly narrowly licensed patents), we would observe a decrease in forward fragmentation, as we did with our sample. It seems plausible that such a shift could occur given that performance metrics for the latter are much easier to measure.

One could also imagine how plausible changes in inventor behavior could result in the findings reported here. Due to the early stage nature of most university inventions, the transfer of tacit knowledge is particularly important for commercial development (likely leading to the creation of follow-on inventions that will also be patented and may cite the original patent). Such tacit knowledge is often most efficiently transferred through direct interaction with the inventor (Jensen and Thursby (2001);Agrawal (2006)). To the extent that inventors become more commercially oriented regarding the management of their intellectual property, and the findings of Lach and Schankerman (2005) suggest this is not unlikely, their tendency to share tacit knowledge with others who are not licensees may diminish.

In terms of knowledge inflows, our results suggest that the breadth of assignees that inventors draw upon in developing their own inventions diminished over time. Although it is difficult to imagine how this could be a direct result of changes in behavior by technology licensing offices, an explanation based on changes in inventor behavior is reasonably straightforward. If inventors become more commercially oriented and savvy over time, they may increasingly look forward and anticipate that, to the extent that future licensees are exposed to anti-commons problems associated with access to complementary inventions, the value of their inventions will be diminished. As such, inventors reason back and plan their research program in a manner that minimizes anti-commons exposure by reducing the breadth of prior art citations. This seems reasonable given that university researchers have been shown to respond to economic incentives (Lach and Schankerman (2005)).

It is important to note that although it is tempting to assume that higher concentrations of knowledge inflows and particularly outflows are welfare reducing, it is not necessarily true. Knowing that knowledge spillovers contribute to economic growth (Romer (1986); Romer (1990)) but also recognizing the importance of exclusivity for creating incentives to commercialize as well as of minimizing cost by limiting exposure to the anti-commons problem, it is unclear how increased concentration of university knowledge flows affects welfare. What is clear, however, is that what we learn from further study of this topic will offer important insight for science policy and economic growth.

Chapter 2

Technology Disclosure Discourages Rival R&D and Defends Leader Profits

"What is available to everyone is of interest to no one." (Bremer (1999))

2.1 Introduction

There is no question, profit maximizing firms take great measures to protect their intellectual property. Often relying on patents or secrecy, firms hope to exclude rivals from key proprietary technologies. They do so largely with the objectives of limiting competition and ultimately preserving profits. It is then surprising to observe that firms often freely disclose research beneficial to society in general and rivals in particular.[1] That is, firms voluntarily place useful knowledge into the public domain where they can not control who uses it or how it will be used.[2]

Examples of technology disclosure abound. IBM regularly discloses great amounts of its research in the pages of *The IBM Journal of Research and Development.*[3] Xerox did likewise in its own journal, *The Xerox Disclosure Journal.* Furthermore, many other firms present their work at conferences and publish in scholarly journals or in fora such as *Research Disclosure.*[4]

What can explain this puzzling behavior? The existing literature addressing free disclosure largely ignores the possible benefits disclosure might have for rivals or explicitly considers such help to be unintended and counter productive for the disclosing firm. This paper in contrast, considers an environment where disclosure is a profitable action exactly because the revealed knowledge helps rivals compete more strongly.

The fundamental insight of this paper is that disclosure renders less exclusive the basic innovation upon which follow-up inventions build and this in turn, affords a firm the potential to manipulate its rivals' incentives. As has been long argued, profit maximizing firms are reluctant to build upon widely accessible inventions. The market power a follow-up innovation can expect is diminished because non-exclusivity of the initial invention lessens

[1]One can infer that the technology disclosed is beneficial because it is often cited as prior art by subsequent patents. That is, the disclosed technology serves as the foundation for subsequent innovation (Baker and Mezzetti (2005); Hall et al. (2002)).

[2]This is essentially the basic definition of disclosure given in the literature (Harhoff et al. (2003); Penin (2004)).

[3]Previously, IBM disclosed in *The IBM Technological Disclosure Journal.*

[4]*Research Disclosure* is a publication service where researchers, scientists, and inventors can establish the state of the art without patenting. For further details please see, http://www.researchdisclosure.com.

the burden of rivals that also seek to innovate. Essentially, less exclusivity erodes the entry barriers to whatever market any subsequent innovation opens. Consequently, firms expect less profits and so have less incentive to incur research and development (R&D) costs needed to innovate.

A lack of exclusivity was thought to be the principle impediment in the development and commercialization of unpatented university inventions and what ultimately led to the 1980 Bayh-Dole Act (Mowery et al., 1999). Furthermore, exclusivity remains an important consideration for incremental innovation. This is why, for example, universities find it necessary at times to license some of their patented innovations on an exclusive basis.[5] Similarly, concerns over exclusivity are also the reason why venture capitalists only tend to invest in the work of start-ups that build on their own patented technologies (Penin (2004)).

Envisioned here is an R&D race in which firms compete to obtain an innovation that gains them access to a new market. Once a firm innovates, the intellectual property is patented to prevent imitation. Though this protection is perfect, the first innovator is not assured to retain her monopoly;[6] competitors can subsequently enter the market as long as they do so with their own original innovation. Consequently, a technology leader is interested in slowing its competitors' progress especially if competitors are close to catching-up. In this paper, technological disclosure subdues the innov-

[5] Colyvas et al. (2002) provides an example in which the University of California licensed one of its major biotech inventions to only 3 firms despite there being more willing licensees. The University of California decided to limit licenses out of concern that further development of this innovation would be discouraged.

[6] A patent's claims protect against any product that "does the same work in substantially the same way to accomplish the same result" (Scotchmer (2004)).

ative zeal of the leader's closest competitor. It does this by revoking the exclusive position and advantage of the leader's main rival. Teaching firms trailing far behind something new pulls them closer to the lead. In turn, the barrier impeding general entry into the market is reduced and the expected reward of front runners is decreased along with their incentive to catch-up to the leader. As long as the damage inflicted on the dangerous competitors off-sets the damage the leader does to herself by helping the most backward firms, disclosure is a profitable action.

Disclosure can be undertaken for four broad reasons. First, disclosure can be used strategically to complement patenting. For example, suppose a firm patents a technology that is the basis for several different new products. However, to produce these new products minor incremental innovations are needed. In this case, disclosure of the incremental innovations makes them unpatentable and thus prevents rival firms from fencing in how the owner of the core technology uses its intellectual property (Cogen and Colson (2001)).[7]

Disclosure can also complement patenting by mitigating the original innovator's threat to hold-up licensees who pursue profitable follow-on innovations (Bar-Gill and Parchomovsky (2003)). Revelation in this case, credibly reduces the original innovator's bargaining power in any ex-post renegotiation. Here disclosure narrows the scope of what the patent protects. This is important because it preserves a licensee's incentives to benefit from developing follow-on innovations and thus makes innovation a desirable un-

[7]Once a technology or innovation is publicly disclosed it becomes "prior art" and can no longer be patented by anybody else.

dertaking.

Second, disclosure may be beneficial by encouraging the wide adoption of an innovator's technology. If the disclosed technology is intrinsically suited to the innovating firm, the technology may confer above normal profits for the firm, despite the wide use by rivals, for longer than what is possible if the technology were protected by a patent; network effects arising from the technology's wide adoption may prevent the emergence of competing technologies that are less suited to the disclosing firm (Harhoff et al. (2003)). Also, wide adoption may trigger beneficial consumption networks.[8] Finally, wide adoption can also benefit by allowing upstream suppliers to take advantage of scale economies to produce better inputs, based on the new technology, at lower average costs. If the benefit of lower cost and better inputs exceed the effects of greater competition by rivals, disclosure can be profitable (Harhoff et al. (2003)).

Third, firms may disclose in order to bolster their reputation. In terms of the firm's reputation, disclosure of new technology might be used to signal innovativeness and future profitability that, in turn, is meant to attract creditors (Anton and Yao (2003)).[9] In terms of employee's reputation, allowing employee to publish and gain notoriety may be needed, along with pecuniary rewards, to motivate researchers and to recruit high quality researchers (Penin (2004)).

[8]For example, with the technology more freely available, competitors may produce complementary products that increase the demand for the original technology (Penin (2004)).

[9]Penin (2004) also suggests that disclosure might help pharmaceutical companies gain reputation within the Food and Drug Administration that hastens market approval for their products.

Finally, disclosure can be used advantageously by firms racing to obtain a patent or to enter a market. Disclosure may serve as discouraging news to competitors involved in an R&D race. In an R&D race, the progress of each firm may be secret and so participants determine their optimal research intensity based on their beliefs about the standings in the race. As such, firms may be strong competitors because they believe they are in strong contention to win. However, once a firm discloses and competitors realize how far they trail in the race, these trailing firms rationally lower their R&D efforts and become weaker competitors (Gordon, 2004).

Disclosure may also be used within the context of an R&D race as a means to manipulate the position of the finish line. Following Parchomovsky (2000), the literature emphasizes the novelty requirement of patentable invention.[10] In this context, disclosure augments the prior art and pushes forward the patent finish line. Lichtman et al. (2000), Baker and Mezzetti (2005), and Bar (2006) provide several examples of how extending a race can benefit a firm. In these papers, a technology leader may wish to extend the race in order to increase the expected costs of finishing for all participants and thus induce the exit of some trailing rivals. Conversely, trailing firms are shown to be able to buy themselves time to catch-up to the leader by disclosing and prolonging the race.

This paper contributes to the last branch of the literature by articulating how a technological leader can use disclosure to manipulate the standings and incentives of rivals in an R&D race. The contributions are made in

[10]Briefly, a patentable innovation must represent a considerable advancement in the state of the art that is in the public domain, prior art. This requirement is analogous to what is expected of publishable academic work.

three ways.

First, the existing literature has a focused view of the interaction between the innovation process and the patent system. Implicitly, it assumes that there is only one way to innovate or to produce a new product and that, consequently, only one patent can be issued. These assumptions are extreme given that often there is more than one way to solve the same problem and that firms can design around pre-existing patents.[11] In contrast, this paper adds to the literature by focusing correctly on what a patent actually protects, the particular innovation rather than the market power the patent might yield. In this way, the environment allows for legitimate market entry by rivals after the first patent is issued. Consequently, even after it patents, the technology leader has an incentive to seek additional ways to protect its market power.[12]

Second, the existing literature also largely ignores the possibility that rivals might benefit from disclosure.[13] Assuming away disclosure's potential external benefits is troubling and contradicts expectations. If, as is argued by the literature, technological disclosures augments the prior art, the knowledge in the public domain, how can it not also enable at least some

[11] In terms of multiple ways to invent, Gillette found seven different ways to build its *Sensor* razor blade (Rivette and Kline, 2000). Furthermore, in terms of designing around patents, it is now more apparent that Schick successfully designed around all *Mach3* patents when developing its multi-blade razor, the *Quattro*. On January 15 2004, Judge Patti B. Saris of the Boston District Court denied Gillette's plea to impose a preliminary injunction on sales of the *Quattro*. The judge denied the injunction by indicating Gillette was "not likely to succeed in its claims" that the *Quattro* infringes on Gillette technology; that is, Schick is not likely to infringe on Gillette patents (*New York Times* January 16, 2004).

[12] In this respect, disclosure is complementary to patenting.

[13] Lichtman et al. (2000) is an exception as the positive spillovers of disclosure are recognized.

opponents to compete more strongly?

Allowing disclosure to help rivals get ahead, as suggested to be possible by Eisenberg (2000), is another way this paper extends the literature. It makes the literature consistent with examples such as IBM's race to develop semiconductors utilizing copper interconnections between circuit elements. As Lim (2000) describes, IBM, the clear leader in the field, freely disclosed much of its research. The net effect was that late starters, such as Motorola, AMD, and VLSI Technology, were able to build off of IBM's free technology and beat earlier starters, such as AT&T/Lucent and Hitachi, to the new market for copper plated semiconductor chips.

Finally, this paper extends the literature by considering an interesting R&D race. Similar to the existing literature, this paper borrows from the R&D race literature, mainly Fudenberg and Tirole (1983), Harris and Vickers (1985), Grossman and Shapiro (1987), and Judd (2003), by modeling a multi-stage R&D race that introduces the concept of leadership and aspects of dynamic R&D rivalry. However, this paper goes further by considering a race between more than just two competitors. This expands the space for strategic interaction in an insightful way. Only with more than two competitors is one able to explore how a firm can play its rivals against each other by disclosing technology.

This paper is most closely related to Agrawal and Garlappi (forthcoming) and Mazzoleni (2005) in emphasizing the significance of exclusivity to develop innovations. However, in this paper, I consider the role of exclusivity in motivating disclosure rather than in sponsoring university research or in rationalizing university patenting. More importantly, however, this paper differs by highlighting how a technology leader can exploit the asymmetric effects of disclosure for the end purpose of manipulating its rivals' incentives.

The remainder of the paper is structured as follows. In Section 2.2, I start by describing the model. I then outline, in Section 2.3, the subgame perfect Nash equilibria of the game and the general conditions under which these equilibria hold. In Section 2.4, I illustrate the existence of profitable disclosure in equilibrium. I then discuss the forces behind profitable disclosure in Section 2.5 before concluding the paper in Section 3.5 with a discussion about competition and innovation.

2.2 The model

Three identical, risk-neutral firms, respectively named, the Leader, Challenger and Dawdler, race, in discrete time, to enter a newly created product market. These firms seek entry to earn profits in each period they produce. Bertrand competition in differentiated products and with joint profit dissipation characterizes the market. Monopoly profits, for example, would be twice duopoly profits if prices remained constant. However, with higher market power under monopoly, profits are more than double duopoly profits. Here monopoly, π_m, duopoly, π_d and oligopoly, π_o, profits are related by $1 = \pi_m > 2\pi_d > 3\pi_o > 0$.[14]

Before entering the market, however, firms must first obtain an innovation that will make production feasible. Innovation is modeled as a step-by-

[14]Monopoly profits are normalized to 1. Oligopoly refers to the case when three firms produce. Finally, to focus on the main insight of this paper, the product market is not modeled except to say that profits are the outcome of the symmetric Nash equilibrium of Bertrand competition in differentiating products.

step process where successful completion of an initial step, research phase α, yields an intermediate result essential for a subsequent research phase, research phase Ω.[15] Furthermore, research is costly and its outcome is uncertain. To complete successfully its current research phase with probability, b, a firm incurs a cost of $c(b)$. b is also interpreted as the firm's research intensity. I assume that the cost structure of R&D is identical across firms and in each research phase, and that $c(0) = 0$, $c'(\cdot) \geq 0$, $c'(0) = 0$ and $c''(\cdot) \geq 0$.

The standings in the race are common knowledge but the technology obtained by each firm is secret. Unintended technology spillovers do not occur. The only means by which technology is transferred is if a firm intentionally discloses the findings of a particular research phase. When disclosure occurs, the technology necessary to advance past the particular step is transferred to any firm that needs it.[16]

Once a firm enters the market its innovation is publicly disclosed and is thus susceptible to imitation. Unless the firm patents, free entry of differentiated products based on the same innovation eliminates all profits. Consequently, each innovative firm patents to protect its intellectual property. Furthermore, although patent protection is perfect, it does not block subsequent entry by competitors; the patent only excludes other firms from practicing the same innovation but it fails to prevent firms from designing around the existing patent by completing their own innovation process and

[15]This is as in Grossman and Shapiro (1987). The initial step can be thought of, for example, as the search for a research tool needed for the second phase.

[16]We implicitly assume that it is costless to adopt new technology. That is, absorptive capacity is not a constraint.

subsequently entering the market. In this sense the R&D race does not end with the first innovation. Firms that are yet to innovate may still profit from further research.

The objective of each firm is then to maximize its expected profit by choosing its optimal R&D intensity and disclosure strategy. Each firm arrives at its optimal strategy by considering the standings in the race, the cost of R&D, and the time until the first patent expires. As well, the firms contend with the actions of their opponents which they take as given.

The game modeled here begins half way through the race, after differences in fortune have allowed some firms to progress further than others. Figure 2.1 illustrates the standings. The Leader is the firm furthest ahead, having successfully completed all research. In contrast, each follower still requires to undertake research. The Challenger must finish the last research phases while the Dawdler still needs to accomplish both phases.

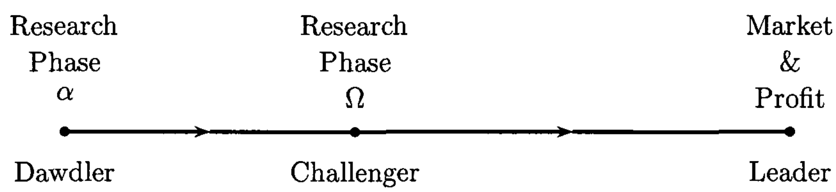

Figure 2.1: Initial race standings.

The sequence of actions is illustrated in Figure 2.2. In Period 1, the Leader decides whether to disclose information that pulls the Dawdler even with the Challenger. That is, the Leader chooses whether to disclose the results of research phase α.[17]

[17]The Leader would never disclose the results of the second research stage. Doing so would not only help the Dawdler come one step closer to enter the market but it would

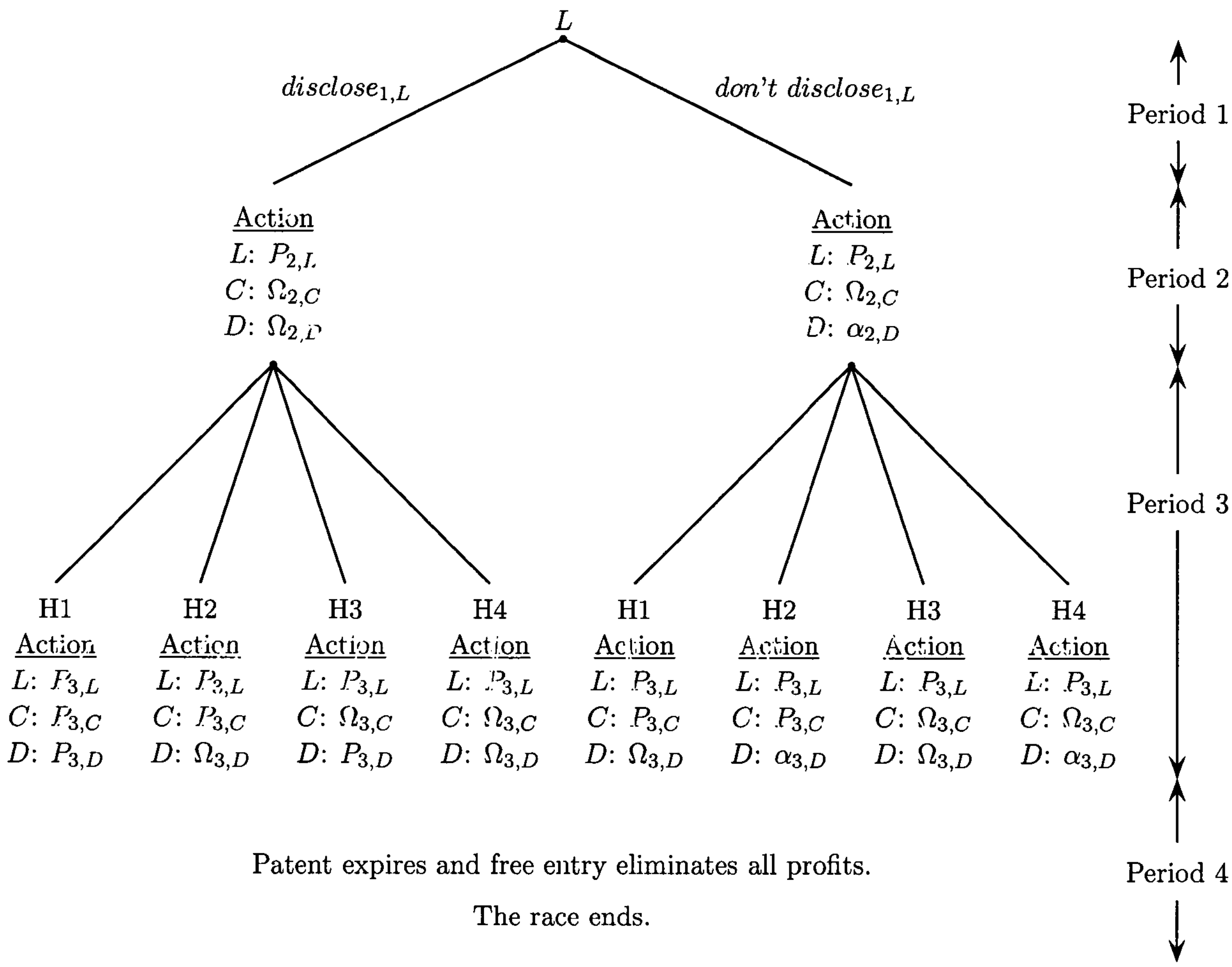

Figure 2.2: Sequence of actions: L - Leader, C - Challenger, D - Dawdler. H1 - Both followers succeed in Period 2, H2 - Only Challenger succeeds in Period 2, H3 - Only Dawdler succeeds in Period 2, H4 - Both followers fail in Period 2.

In Period 2, all firms move simultaneously after observing the Leader's action in Period 1. At this time, the Leader patents its innovation and enters the market. The Leader's only decision is the price, $P_{2,L} \in [0, \infty)$, it charges consumers in Period 2.

In contrast, the Challenger and Dawdler must still research in order to complete their innovation process.[18] In the Challenger's case, it chooses, $\Omega_{2,C} \in [0, 1]$, the probability of completing the second research phase and entering the product market in Period 3. Similarly, the Dawdler chooses the probability of its success. However, the research focus of this firm depends on the Leader's Period 1 action. If the Leader revealed nothing, the Dawdler chooses, $\alpha_{2,D} \in [0, 1]$, its probability of advancing to the last research phase. Otherwise, the Dawdler chooses, $\Omega_{2,D} \in [0, 1]$.

In Period 3, after observing the outcome of play, all firms again move simultaneously. Each firm that has successfully innovated, chooses $P_{3,i} \in [0, \infty)$ for $i \in \{L, C, D\}$, the price it charges consumers. Any firm still needing to innovate successfully chooses its R&D intensity. If the Challenger is unsuccessful in Period 2 and, thus, still needs to finish the last research phase, it chooses $\Omega_{3,C} \in [0, 1]$. Similarly, if the Dawdler is also in the last phase, it chooses $\Omega_{3,D} \in [0, 1]$. If, however, there was no disclosure and the Dawdler was unsuccessful in Period 2, the Dawdler remains in the initial research stage and chooses $\alpha_{3,D} \in [0, 1]$.

In Period 4 the Leader's patent expires and free entry of differentiated products eliminates profits. At this point the game ends.

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also automatically bring the Challenger into the market.

[18]Entering the product market without innovating could be thought to be possible but only with prohibitively costly production.

2.3 Subgame perfect Nash equilibria

The solution concept used to solve this model is subgame perfection. What this entails is that we work backwards to obtain the Nash equilibria of each stage game.

2.3.1 Period 3

Any firm yet to innovate by Period 3, does not conduct research. A lagging firm such as this can only hope to innovate after the first patent expires and free entry eliminates all profit opportunities. Consequently, without compensation for R&D effort, it is never worth while for the firm to incur further research costs in Period 3, $Z^*_{3,D} = 0$ for $Z \in \{\alpha, \Omega\}$ and $\Omega^*_{3,C} = 0$.

A firm in the product market optimally prices its output taking as given its competitors' prices. Given the market is populated by n firms, the price set by each producing firm, i, is the symmetric, n-firm Nash equilibrium price, $P^*_{3,i}(n)$, of Bertrand competition in differentiated products.[19]

2.3.2 Period 2

By Period 2 the Leader is the only firm to innovate and it is thus the only producing firm. Accordingly, the Leader maximizes its profit by charging the monopolist's price, $P^*_{2,L}(1)$.[20] In contrast, the trailing firms, still needing to innovate, decide on their optimal research intensity. The problem faced

[19] Again, to focus on the main insight of this paper, Bertrand competition is not modeled other than to say that firms are symmetric. That is, all innovative firms compete on equal footing in the product market.

[20] The Leader's optimal pricing decision is not modeled. Instead, the Leader is assumed to select correctly the profit maximizing price when there is only one firm in the market.

by each of these two firms depends greatly on whether the Leader disclosed technology in Period 1.

If the Leader does not disclose in Period 1, the Dawdler drops out. This is optimal because without help, the Dawdler can not innovate before the Leader's patent expires. If it continues to incur R&D costs, the Dawdler can only hope to enter the market, after free entry eliminates profits. Without profits to rationalize its R&D costs, the Dawdler does not conduct further research, $\alpha^*_{2,D} = 0$.

Regardless of whether the Leader discloses, the Challenger always has incentive to innovate in Period 2. This is because research has no fixed costs, marginal cost are zero given no research, $c'(0) = 0$, and π_d and π_o are positive. Consequently, the Challenger always expects to earn positive profits if it provides low enough effort. The Challenger's optimal R&D intensity will differ, however, depending on whether the Leader divulged information in Period 1.

If the Leader does not disclose, the Challenger is aware that the Dawdler will drop out of the race. The Challenger's maximization problem is then:

$$\max_{\Omega_{2,C}} \Omega_{2,C}\pi_d - c(\Omega_{2,C})$$

s.t.

$$0 \leq \Omega_{2,C} \leq 1.$$

The Challenger's objective function is simply the expected profit of R&D investment. With probability $\Omega_{2,C}$ the Challenger successfully innovates and joins the Leader in the product market to earn π_d. With the residual probability, $(1 - \Omega_{2,C})$, the Challenger fails to innovate and earns nothing. The firm's research costs are incurred with certainty in Period 2, $c(\Omega_{2,C})$.

By simply equating the marginal cost of research to its expected marginal benefit, the Challenger's optimal action is given by:

$$\Omega^*_{2,C} = \begin{cases} c'(\pi_d)^{-1} & \text{if no disclosure and } c'(1) > \pi_d \\ 1 & \text{if no disclosure and } \pi_d \geq c'(1) \end{cases} .$$

Following disclosure in Period 1, the problem faced by the trailing firms changes dramatically. The help pulls the Dawdler closer to the finish and makes feasible profitable R&D investment. Consequently, the promise of profit spurs the Dawdler to continue the race. The Challenger, on the other hand, remains no closer to the finish; disclosure teaches nothing new to the Challenger. However, because disclosure renders the Challenger's position less exclusive, the Challenger must contemplate that, it may no longer only share the product market with the Leader. The Challenger considers the possibility that, if it innovates, it may not earn π_d. If the Dawdler succeeds, the Challenger can only hope to earn π_o.

Technology disclosure in Period 1 makes both trailing firms indistinguishable. This arises because the Dawdler and Challenger are in the same position, they have the same research costs and once in the market, neither has an advantage giving it higher profits than its competitors.[21]

As in the case where the Leader does not disclose, the Challenger maximizes its expected profits. The probability that this firm earns π_d, in Period

[21] In the analysis to follow I only consider the Challenger's case because the Dawdler's situation is analogous and the results are symmetric.

3 depends on whether it innovates and the Dawdler fails to keep-up. These events are independent and their joint probability is $\Omega_{2,C}(1-\Omega_{2,D})$. Similarly, the probability that the firm earns π_o, is given by the probability that both lagging firms succeed simultaneously, $\Omega_{2,C}\Omega_{2,D}$. Again, the costs of research are incurred with certainty in Period 2. The Challenger's profit maximizing problem is:

$$\max_{\Omega_{2,C}} \Omega_{2,C}\left[1-\Omega_{2,D}\right]\pi_d + \Omega_{2,C}\Omega_{2,D}\pi_o - c(\Omega_{2,C})$$

s.t.

$$0 \leq \Omega_{2,C} \leq 1.$$

The Challenger's solution to this problem is given by the reaction function:

$$\Omega^*_{2,C} = \begin{cases} c'(\pi_d - \left[\pi_d - \pi_o\right]\Omega_{2,D})^{-1} & \text{if } c'(1) > \pi_d - \left[\pi_d - \pi_o\right]\Omega_{2,D} \\ 1 & \text{if } c'(1) \leq \pi_d - \left[\pi_d - \pi_o\right]\Omega_{2,D} \end{cases}. \tag{2.1}$$

By symmetry, the Dawdler's reaction function given disclosure in Period 1 is:

$$\Omega^*_{2,D} = \begin{cases} c'(\pi_d - \left[\pi_d - \pi_o\right]\Omega_{2,C})^{-1} & \text{if } c'(1) > \pi_d - \left[\pi_d - \pi_o\right]\Omega_{2,C} \\ 1 & \text{if } c'(1) \leq \pi_d - \left[\pi_d - \pi_o\right]\Omega_{2,C} \end{cases}. \tag{2.2}$$

Several conclusions can be inferred from the firms' reaction functions, Equation (2.1) and (2.2).

Lemma 1. *Given technology disclosure in Period 1, the reaction function* *of each trailing firm is non-increasing.*

The intuition of Lemma 1 is straight forward. As a competitor raises its research intensity it decreases a firm's expected marginal benefit of innovating. This is because a more aggressive rival makes more likely that a firm earns π_o rather than π_d. In turn, the firm optimally reduces its R&D the more aggressive is its rival.[22]

Lemma 2. *Given technology disclosure in Period 1, a trailing firm always invests in R&D.*

It is always profitable for a firm to invest regardless of its rival's research intensity. Even in the worst case, when the rival innovates with certainty, a firm can still hope to earn positive oligopoly profits if it innovates as well. Since a firm's cost function is continuously differentiable, $c'(0) = 0$, and no fixed costs exist, it will always have some incentive to innovate.

Lemma 3. *Given technology disclosure in Period 1, a symmetric Nash equilibrium always exists.*

Lemma 3 follows from the fact that the reaction function of each trailing firms is non-increasing and continuous. These assumptions are important because they guarantee each function has a fixed point. Furthermore, because disclosure pulls the Dawdler equal to the Challenger, the firms are

[22]This intuition is also clear from the derivative of firm i's reaction function with respect to $\Omega_{2,j}$ $i \neq j$,

$$\frac{\partial \Omega^*_{2,i}}{\partial \Omega_{2,j}} = \begin{cases} -\frac{\pi_d - \pi_o}{c''(\Omega^*_{2,i})} & \forall \Omega_{2,j} \in [0,1] \text{ s.t. } c'(\Omega^*_{2,i}) = \pi_d - [\pi_d - \pi_o]\Omega_{2,j} \\ 0 & \forall \Omega_{2,j} \in [0,1] \text{ s.t. } c'(\Omega^*_{2,i}) < \pi_d - [\pi_d - \pi_o]\Omega_{2,j} \end{cases}.$$

made identical; both firms are in the same position and each firm adopts the same strategy with the same fixed point. Consequently, a symmetric Nash equilibrium exists at the common fixed point.

Proposition 1. *If*

$$\left[\pi_d - \pi_o\right]^2 < c''(\Omega_{2,D})\, c''\left(c'(\pi_d - \left[\pi_d - \pi_o\right]\Omega_{2,D})^{-1}\right), \tag{2.3}$$

then the pure strategy Nash equilibrium is unique and symmetric.

Since a symmetric equilibrium always exists, by Lemma 3, uniqueness follows as long as the reaction functions cross only once. The single crossing of these reaction functions is assured if the slope of the Challenger's reaction function is less steep than that of the Dawdler with respect to $\Omega_{2,C}$. This same condition is given by Condition 2.3.[23,24]

2.3.3 Period 1

Finally, in Period 1, the Leader takes its followers' optimal strategies as given and chooses whether or not to disclose information valuable to the Dawdler. The Leader's optimal action yields it the greatest expected profit, Π_L. That is, the Leader's optimal decision rule, l_1^*, is,

$$l_1^* = \begin{cases} \textit{disclose} & \text{if } \Pi_L(\textit{disclose}) \geq \Pi_L(\textit{don't disclose}) \\ \textit{don't disclose} & \text{if } \Pi_L(\textit{disclose}) < \Pi_L(\textit{don't disclose}) \end{cases}.$$

[23]Given Condition 2.3 is satisfied, no corner equilibria are possible.
[24]For the remainder of the paper I consider only the symmetric equilibrium.

where,

$$\Pi_L(disclose) = \left[1 - \Omega^*_{2,C}(\Omega^*_{2,D})\right]\left[1 - \Omega^*_{2,D}(\Omega^*_{2,C})\right]$$

$$+\left\{\Omega^*_{2,C}(\Omega^*_{2,D})\left[1 - \Omega^*_{2,D}(\Omega^*_{2,C})\right] + \Omega^*_{2,D}(\Omega^*_{2,C})\left[1 - \Omega^*_{2,C}(\Omega^*_{2,D})\right]\right\}\pi_d$$

$$+\Omega^*_{2,C}(\Omega^*_{2,D})\Omega^*_{2,D}(\Omega^*_{2,C})\pi_o$$

and

$$\Pi_L(don't\ disclose) = \left[1 - \Omega^*_{2,C}(0)\right] + \Omega^*_{2,C}(0)\pi_d \quad .$$

2.3.4 Subgame perfect Nash equilibrium

Given the Nash equilibria of each stage game, the subgame perfect equilibria are presented.

Disclosure

Given $\Pi_L(disclose) \geq \Pi_L(don't\ disclose)$, the Leader chooses to disclose in Period 1. In Period 2, the Leader then charges the monopoly price, $P^*(1)$, whether or not it disclosed. Finally, it uses the optimal pricing policy $P^*(n)$ in Period 3 regardless of whether or not it disclosed. In summary, the Leader's strategy is:

$$\left\{\left[disclose\right], \left[P^*(1), P^*(1)\right], \left[P^*(n), P^*(n)\right]\right\}.$$

The Challenger in Period 2 chooses $\Omega^*_{2,C}(\Omega_{2,D})$ if there was disclosure and $\Omega^*_{2,C}(0)$ otherwise. In Period 3, regardless of disclosure but depending on the outcome of Period 2, the Challenger chooses the optimal price $P^*(n)$ if it successfully innovated. Otherwise, it does not expend any research effort, $\Omega^*_{3,C} = 0$. This player's optimal strategy is:

$$\left\{ [\Omega^*_{2,C}(\Omega_{2,D}), \Omega^*_{2,C}(0)], [(P^*(n), 0), (P^*(n), 0)] \right\}.$$

Finally, the Dawdler's strategy provides research effort in Period 2, $\Omega^*_{2,D}(\Omega_{2,C})$, if there is disclosure. Otherwise no research is undertaken, $\alpha^*_{2,D} = 0$. In Period 3, given disclosure, if the Dawdler innovates successfully it sets its price according to $P^*(n)$ otherwise the firm does not research, $\Omega^*_{3,D} = 0$. If however there is no disclosure, the Dawdler does not research in any event, even if it has research success in Period 2. This then gives the Dawdler's strategy as,

$$\left\{ [\Omega^*_{2,D}(\Omega_{2,C}), 0], [(P^*(n), 0), (0, 0)] \right\}.$$

No disclosure

In the alternate subgame perfect equilibrium, the Leader does not disclose. Other than the Leader's first period action, the players' equilibrium strategies are the same as with disclosure. Consequently, if $\Pi_L(\textit{disclose}) < \Pi_L(\textit{don't disclose})$ the Leader's optimal strategy is:

$$\left\{ [\textit{don't disclose}], [P^*(1), P^*(1)], [P^*(n), P^*(n)] \right\},$$

the Challengers strategy is:

$$\left\{ [\Omega^*_{2,C}(\Omega_{2,D}), \Omega^*_{2,C}(0)], [(P^*(n), 0), (P^*(n), 0)] \right\},$$

and the Dawdler's strategy is:

$$\left\{[\Omega^*_{2,D}(\Omega_{2,C}),0],[(P^*(n),0),(0,0)]\right\}.$$

2.4 Profitable disclosure

To obtain explicit conditions under which it is profitable for the Leader to disclose information we assume functional forms for consumer utility and the R&D cost function.

As an example we assume that consumers in the new market have constant elasticity of substitution (CES) preferences. Given these preferences, the joint profits of producing firms decrease as the number of producing firms increase and the market power of each decreases. CES preferences also make analysis tractable; they collapse the parameter space to only two variables.[25]

Each period consumers solve the following problem,

$$\max_{\{q_i\}_{i=1}^n}\left(\sum_{i=1}^n q_i^\phi\right)^{\frac{1}{\phi}}$$

s.t.

$$\sum_{i=n}^n p_i q_i \leq I,$$

where $n \in \{1,2,3\}$ is the number of firms producing in the market, p_i and q_i are respectively the price and quantity of each differentiated product, $I = 1$ is the consumer's total income and ϕ is the degree of substitutability between

[25]The results that follow are more general to the CES specification.

the differentiated goods. With these preferences the Bertrand equilibrium profits are,

$$\pi_m = 1, \quad \pi_d = \frac{1-\phi}{2-\phi} \quad \text{and} \quad \pi_o = \frac{1-\phi}{3-\phi}.$$

These profits are illustrated in Figure 2.3 and they are consistent with intuition. When there is no substitution between goods, $\phi = 0$, producing firms evenly split the consumer's income. But as the degree of substitutability increases, profits decrease to zero as long as there are multiple firms in the market.

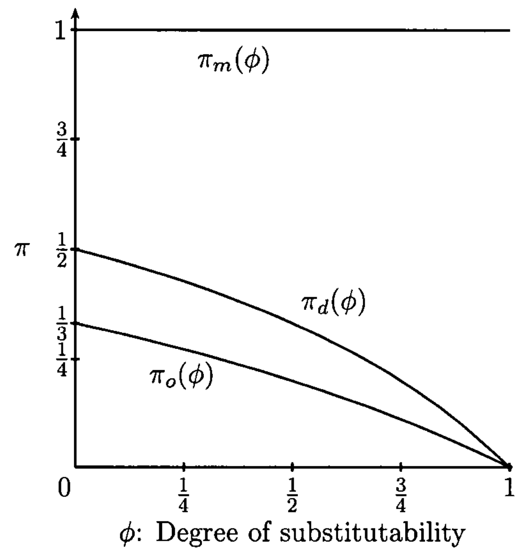

Figure 2.3: Firm profits given CES preferences: Monopoly π_m, duopoly π_d and oligopoly π_o profits.

The functional form of R&D costs is chosen to satisfy the characteristics of the cost function specified above and is the standard form used in the R&D race literature. The cost function for $Z \in \{\alpha, \Omega\}$, $i \in \{C, D\}$, and

$t \in \{2, 3\}$ is,

$$c(Z_{t,i}) = \frac{A}{2} Z_{t,i}^2.$$

With these functional forms, the Challenger's optimal research intensity given no disclosure is,

$$\Omega_{2,C}^* = \begin{cases} \frac{1}{A}\frac{1-\phi}{2-\phi} & \text{if } A > \frac{1-\phi}{2-\phi} \\ 1 & \text{if } A \leq \frac{1-\phi}{2-\phi} \end{cases}.$$

When there is disclosure, the reaction function for trailing firm $i \in \{C, D\}$, $i \neq j$, is,

$$\Omega_{2,i}^* = \begin{cases} \frac{1}{A}\frac{1-\phi}{2-\phi}\left[1 - \frac{\Omega_{2,j}}{3-\phi}\right] & \forall \Omega_{2,j} \in [0,1] \text{ s.t. } \Omega_{2,j} > (3-\phi)\left[1 - \frac{(2-\phi)A}{1-\phi}\right] \\ 1 & \forall \Omega_{2,j} \in [0,1] \text{ s.t. } \Omega_{2,j} \leq (3-\phi)\left[1 - \frac{(2-\phi)A}{1-\phi}\right] \end{cases}.$$

Finally, when there is disclosure, the symmetric Nash equilibrium outcome of research between trailing firms in the second stage game is $\Omega_{2,S}^*$ and is defined by,

$$\Omega_{2,C}^* = \Omega_{2,D}^* = \Omega_{2,S}^* = \begin{cases} \frac{(1-\phi)(3-\phi)}{(1-\phi)+(2-\phi)(3-\phi)A} & \text{if } A > \frac{1-\phi}{3-\phi} \\ 1 & \text{if } A \leq \frac{1-\phi}{3-\phi} \end{cases}.$$

To find the Leader's optimal Period 1 action, we assume that the equilibrium of the second period stage game is symmetric, though not necessarily unique. With this assumption and comparing the Leader's expected profits under disclosure and no disclosure we can identify two sufficient conditions guaranteeing that disclosure is optimal.

First, given that, $A \in \left(\pi_o\,,\,\pi_d\right]$, as long as,

$$A \geq \frac{1-\phi}{3-\phi} + \frac{1-\phi}{2-\phi}\sqrt{\frac{1-\phi}{3-\phi}}, \tag{2.4}$$

disclosure makes the Leader better off. In this case, when $A \leq \pi_d$, the Leader benefits from disclosure by decreasing the Challenger's expected marginal benefit of innovation by enough to no longer make this trailing firm's success a certainty.[26] Yet, as long as A is high enough, Condition 2.4 is satisfied, the Dawdler does not research intensively enough to make the Leader regret its disclosure.

Second, given $A > \pi_d$, if

$$A \leq \frac{1-\phi}{(2-\phi)(3-\phi)}\left[1+\sqrt{2}\right] \tag{2.5}$$

then, disclosure again benefits the Leader. In this case, disclosure does not avert a certain duopoly in the following period. However, it still discourages the Challenger's effort enough to increase the Leader's expected profits.

Conditions 2.4 and 2.5 can be combined to outline all possible (ϕ, A) that allow disclosure to be a profitable strategy for the Leader. The lens shaped region in Figure 2.4 represents this set of (ϕ, A).

It is interesting to note that the Leader only benefits from disclosure when (ϕ, A) belongs to the lens shaped region in Figure 2.4. That is, we do not ignore any other pure or mixed strategy equilibria in Period 2 that

[26] The Challenger's reaction function shows that if $A \leq \pi_d = \frac{1-\phi}{2-\phi}$, then $\Omega^*_{2,C} = 1$.

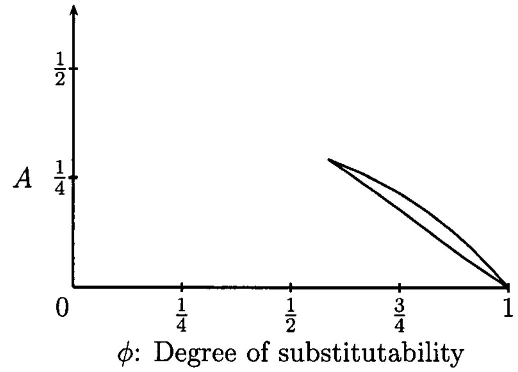

Figure 2.4: The set of (ϕ, A) for which disclosure is profitable.

might also make disclosure profitable for the Leader.

Given our functional form assumptions, in Period 2 there can only exist one unique, symmetric equilibrium, as depicted by the left panel of Figure 2.5, or three multiple equilibria, one symmetric equilibrium and two corner equilibria, depicted in the right panel of Figure 2.5. When there are multiple equilibria after disclosure, the Leader is worse-off if the outcome is at a corner. At such an equilibrium not only does disclosure ensure one rival innovates with certainty, the worst possible outcome without disclosure, but it also makes possible that a second rival can also innovate. Consequently, the only pure strategy equilibrium that is profitable with disclosure is the symmetric equilibrium. However, when a symmetric equilibrium is profitable, it is also unique. That is, the conditions on A necessary to make the symmetric equilibrium profitable are more binding than the condition guaranteeing a unique equilibrium given disclosure. It is easy to show that when (ϕ, A) belongs to the lens shaped region of Figure 2.4, the single crossing

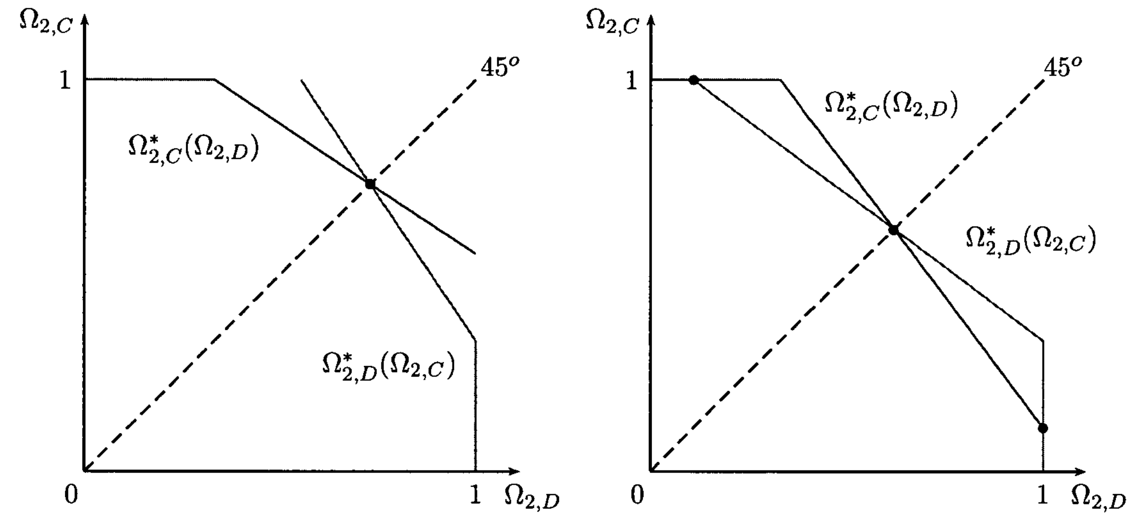

Figure 2.5: Period 2 R&D pure strategy equilibria. The left figure shows only a unique and symmetric equilibrium. The right figure shows two corner equilibria and one symmetric equilibrium.

condition, Condition 2.3, is also satisfied.[27]

2.5 The forces behind profitable disclosure

The Leader profits from disclosure by trading off countervailing forces. A positive force arises because disclosure discourages a very motivated Challenger from innovating and entering the market in Period 3. This is beneficial for the Leader. However, disclosure also induces two negative forces. First, as a result of disclosure, one additional firm has the potential to enter the market in Period 3. Though taken individually, each trailing firm invests less in R&D than the Challenger in the case of no disclosure, the total probability that the Leader will share the market with at least one other firm may still rise. This is simply due to the fact that more firms chase duopoly profits after disclosure. Second, disclosure also opens the possibility that the Leader will have to share the market with two other firms. This is a cost because without disclosure, the Leader can not earn anything less than

[27]In short, given the functional form assumptions, the single crossing condition, Condition 2.3, is,

$$A > \frac{1-\phi}{(2-\phi)(3-\phi)} = \pi_d - \pi_o.$$

Consequently, if $A \in (\pi_o, \pi_d]$ and the symmetric equilibrium is profitable (i.e. $A \geq \frac{1-\phi}{3-\phi} + \frac{1-\phi}{2-\phi}\sqrt{\frac{1-\phi}{3-\phi}}$), then the symmetric equilibrium is unique because, given $\phi \in [0,1]$:

$$A \geq \frac{1-\phi}{3-\phi} + \frac{1-\phi}{2-\phi}\sqrt{\frac{1-\phi}{3-\phi}} > \frac{1-\phi}{(2-\phi)(3-\phi)}.$$

Similarly, if $A > \pi_d$ and the symmetric equilibrium is profitable (i.e. $A \leq \frac{1-\phi}{(2-\phi)(3-\phi)}[1+\sqrt{2}]$), then the symmetric equilibrium is also unique because:

$$A > \pi_d \geq \pi_d - \pi_o.$$

duopoly profits.

By examining the difference in profit between when the leader discloses and when it does not disclose we can highlight the three forces. Given,

$$\Pi_L(\textit{disclosure}) \geq \Pi_L(\textit{no disclosure}),$$

one can manipulate the expression to obtain,

$$\left[\Omega^*_{2,C}(0) - \Omega^*_{2,S}\right](1-\pi_d) \geq \Omega^*_{2,S}(1-\Omega^*_{2,S})(1-\pi_d) + \Omega^{*2}_{2,S}(\pi_d - \pi_o). \quad (2.6)$$

The term on the left hand side of Expression (2.6) gives the expected benefit of disclosure. When the Leader discloses, the probability that the Challenger does not innovate increases by $\Omega^*_{2,C}(0) - \Omega^*_{2,S}$. In turn, this means that the Leader's profits are less likely to fall by $(1-\pi_d)$ when the Leader is made a duopolist by the Challenger's entry.

In contrast, the right hand side of Expression (2.6) represents the costs of disclosure. The first term on right is the expected cost associated with the possibility that the Leader will be a duopolist with the Dawdler, rather than the Challenger. That is, given the Challenger fails and the Dawdler successfully innovates, occurring with probability $\Omega^*_{2,S}(1-\Omega^*_{2,S})$, the Leader stands to lose $(1-\pi_d)$.

The second term on the right hand side of Expression 2.6 gives the cost of creating the possibility that disclosure will lead to oligopoly profits. Compared to when there is no disclosure and given that the Challenger innovates, the Leader experiences a fall in profit equal to $(\pi_d - \pi_o)$ when the

Dawdler also innovates. The conditional probability of this event is $\Omega^{*2}_{2,S}$.

The degree of profit dissipation is a significant determinant of what forces dominate in Expression (2.6). Figure 2.6 best illustrates this. Utilizing the same cost function as in Section 2.4, $\frac{1}{A}c(\cdot)$, and for a given value of A, $A = 0.35$, Figure 2.6 shows all possible combinations of duopoly and oligopoly profits for which disclosure is profitable. This set of duopoly and oligopoly profits is given by the triangular region in Figure 2.6.[28]

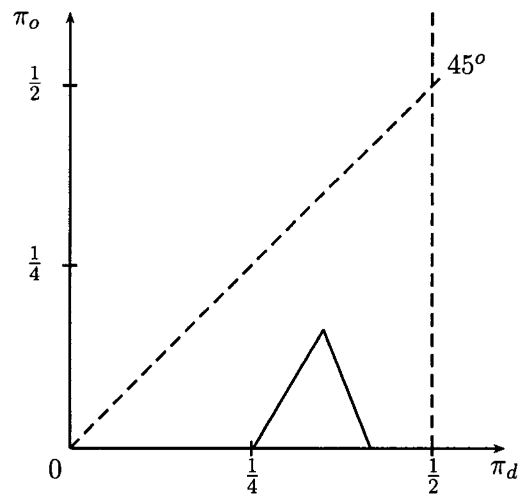

Figure 2.6: The set of (π_d, π_o) for which disclosure is profitable given $A = 0.35$.

For disclosure to be profitable, oligopoly profits must be sufficiently less than duopoly profits; this is why the triangle shaped region is well away from the 45^o line. A sufficient difference in these profits is necessary to depress the Challenger's incentive to innovate and hence raise the benefit of

[28]Figure 2.6 is analogous to Figure 2.4, except that no consumer utility is assumed to generate the relationship between duopoly and oligopoly profits. Instead, I just find all combinations of profits that make disclosure profitable.

disclosure. This difference is what causes the drop-off in Challenger research intensity, given by $\Omega_{2,C}(0)^* - \Omega_{2,S}^*$, and raises the value of the left hand term in Expression (2.6), $[\Omega_{2,C}^* - \Omega_{2,S}^*](1 - \pi_d)$.

The difference in duopoly and oligopoly profits can not be too great, however, for two reasons. First, by increasing the difference between duopoly and oligopoly profits, the Leader stands to lose more given both followers' research intensity. If both followers innovate, the drop-off in profits is more substantial than if the Leader had not disclosed. This cost is captured by the second term on the right hand side of Expression (2.6), $\Omega_{2,S}^{*2}(\pi_d - \pi_o)$.

And, second, the difference between duopoly and oligopoly profits can not be too great because this then implies that the drop-off between monopoly and duopoly profits, $(1 - \pi_d)$, decreases.[29] As a consequence, there is less benefit for the Leader to discourage the Challenger's innovation process. These two reasons are why disclosure is not profitable in the area to the right of the triangle in Figure 2.6.

2.6 Conclusion

In general, innovators are motivated by the incremental benefit they can expect from successful innovation. In this respect, the difference between expected future profits given innovation and expected profits without innovation is important; this difference defines the incremental benefit. The important question then is, how does increased competition amongst innovators affect this benefit?

[29] That is, for example, given π_o, we can only make $\pi_d - \pi_o$ larger by increasing π_d. This then decreases $1 - \pi_d$.

On one hand, competition lowers the desire to innovate by lowering the profits a firm expects to earn if it successfully innovates; with more competition, the expected rewards to invention are diluted. This is a Schumpeterian effect of the type discussed in standard industrial organization theory. This effect is also what the technological Leader in this paper depends on to make disclosure a beneficial action. By revealing information that helps the Dawdler, the Leader wrenches-up the expected competition the Challenger expects if it reaches the product market and thus lowers both the Challenger's expected profits and its incentive to innovate.

On the other hand, greater competition can encourage innovation. In an R&D race, firms may want to innovate because they do not want to fall behind their competitors. For example, a firm will experience a fall in its expected future profit if it fails to innovate and, at the same time, sees its rivals successfully innovate and advance in the race. If this fall in expected profit is greater when more competing firms can advance, competition increases, the incentive to innovate also increases. In this situation, a firm will increase its R&D intensity in order to try to avoid falling behind.[30]

In the model presented here, greater competition in no way mitigates the Schumpeterian effect. That is, for example, the Challenger does not want to innovate more after disclosure because it does not want the Dawdler to move past it. The reason for this is the length of the patent life. Since free entry eliminates profits after Period 3, followers only have one chance to enter the market and earn any profit. Consequently, if a lagging firm fails to

[30]This effect of competition is analogous to the "escape competition" effect described by Aghion et al. (2001) and Aghion et al. (2005) in that competition increases the incremental benefit of innovation by decreasing the profits a firm expects when it fails to innovate.

innovate, its expected profits are zero regardless of its rival's success. This invariance in a firm's expected profit to an increase in competition is what makes disclosure work unambiguously to depress innovativeness and benefit the Leader.

Extending the patent life in this model may make the disclosure equilibrium tenuous. This is because an increase in competition would no longer only invoke the Schumpeterian effect. Consequently, the theory presented here might be best suited for disclosure that occurs during the later stages of an R&D race.

Chapter 3

A Theory of the Proletarianization of Attached Labour in Agrarian Economies

3.1 Introduction

Attached labour has been a common feature on the plantations and estates of developing agrarian economies at various times and in all parts of the world.[1] The *colonato* system in Brazil (1888-1980), the *inquilino* system in Chile (pre-1930) and the *izbah* system in Egypt (1850-1940) are only a few

[1] Attached labour is alternatively referred to as tied, estate, or permanent workers.

examples where attached workers have existed.[2] These workers are primarily identified by the long-term contracts that tie them to their respective employer, the farm owner, for periods spanning an entire agricultural cycle or longer. Consequently, attached labour sharply contrasts other workers in these economies who are hired on a temporary or daily basis during periods of peak labour demand, the harvest season.

Over the past quarter century the institution of attached labour has been the subject of interesting economic analysis. Effort has been expended not only to understand better a widely occurring phenomenon. As with other forms of land tenancy, the knowledge obtained from the study of attached labour are more general and far reaching. Study of the pre-capitalist, semi-feudal qualities of this form of labour promises a better understanding of the role of institutions in economic development. Further still, analysis of attached labour can shed insight into incentive mechanisms of modern day contractual arrangements.

In this vein, the objective of this paper is to explain the proletarianization of attached labour. That is, I explain how and why long-term estate workers transitioned from labourers paid entirely with the usufruct of small pieces of land, subsistence plots, located on estate grounds to pure wage earners. At the heart of this change is the need of farmers to elicit effort that is not immediately observable from their workers while, at the same time, being unable to commit credibly to make effort contingent cash payments.

By focusing on the composition of payment, this paper addresses a

[2]Other instances have occurred in thirteenth century England and Japan, East Elbian Germany (1750-1860), and present day India.

largely underdeveloped topic in the study permanent workers. Despite seminal work by Morner (1970) and Richards (1979) giving prominence to the granting of subsistence plots as a form of payment, much of the literature is instead preoccupied with explaining the existence of permanent workers. Bardhan (1983), for example, argues that risk neutral farmers reduce their labour costs by providing risk averse workers an implicit form of credit. By smoothing the consumption of permanent workers, farmers need not pay as much to retain employees who do not have access to credit and would otherwise experience substantial fluctuations in casual wages between seasons of high and low labour demand.

Eswaran and Kotwal (1985) rationalizes long-term workers by theorizing that these labourers are hired to perform crucial tasks requiring effort that is not immediately observed.[3] Farmers smooth consumption and pay enough each period to elevate their permanent workers' welfare high enough above what casual workers enjoy to make the threat of dismissal a powerful disciplining device. That is, farmers use efficiency wages as described by Shapiro and Stiglitz (1984) to align the interests of tied workers with their own.[4]

Alternatively, Bardhan (1984) suggests permanent labour lowers recruitment costs of peak season workers. Due to the uncertainty in the exact

[3]In agriculture, the fruits of labour required during planting are not seen until the harvest. This could be because these tasks require subtle skills and good judgement to perform or because they are difficult to monitor, workers are spread out over large areas.

[4]Guha (1989) also suggests that nutritional efficiency wages may also be used. In very poor economies, peak season labour may not be very effective due to malnutrition. Consequently, a farmer may want to ensure employment of highly productive workers during the harvest by maintaining a high level of nutrition for the same employees during the planting season.

timing and scale of the harvest, farmers have an incentive to retain an army of permanent and ready labour. The extra costs of keeping surplus labour during seasons of low labour demand are off-set by avoiding costly delays during the harvest. Casual workers are only then employed in the peak season when the harvest is unexpectedly large and more hands are needed.

Finally, Mukherjee and Ray (1995) criticize the literature by highlighting an implicit and flawed assumption that is commonly made. The assumption is that workers disregard their incentives to abrogate their contracts. Rather than defecting to the casual labour market during periods of peak labour demand, permanent workers are assumed to be loyal; they accept a daily tied wage that is less than the peak season, casual rate after benefiting from higher wages than casual workers during the prior season of low labour demand. Mukherjee and Ray (1995) however show that permanent workers can still exist as long as casual wages fluctuate sufficiently between seasons. It is in this environment that self-enforcing contracts, similar to those in Eswaran and Kotwal (1985), tie workers to their employer.

Contrasting the debate discussing the rationales of permanent labour, the literature addressing the usufruct rights granted to workers is less detailed. For example, Thorner and Thorner (1962), Berry (1983), and Anrup (1990) tangentially suggest subsistence plots are used to keep agricultural workers on the farm throughout the year. The allotted plots provide workers a way to maintain themselves during low labour demand seasons and, if workers want to take advantage, their presence on the farm is necessary at all times.

An exception in this field of the literature is Sadoulet (1992) because it directly analyzes, in detail, a potential link between land and labour. Sadoulet (1992) considers that the land granted to workers is part of a rental arrangement between the farmer and permanent workers. Long-term labourers, or tenants, work for the farmer because pure rent contracts exposes the landlord to excessive rates of default. Risky production and limited liability on the part of tenants encourages them to devote too much time to their rental property. As a consequence, there are greater rates of default because tenants do not earn enough secured income in the labour market to ensure full payment of their rent. The merger of land and labour contracts gives the farmer the ability to make tenants work-off part of their rent by tending the farmer's cash crops.[5]

Though the literature partially addresses the links between permanent workers and subsistence plots, no prior article focuses on the transition of tied labour from workers paid only with subsistence plots to pure wage earners. Interpreting subsistence plots as a contracting tool that alleviates moral hazards wherever worker effort is not readily observed but no institution exists to prevent employers from wrongfully withholding contingent payments, yields an environment where the observed pattern of proletarianization of permanent workers can occur. An implicit contract consisting of contingent payments, in the form of subsistence plots, to motivate workers and reputation effects that discipline employers can explain the following common characteristics of proletarianization: 1) The simultaneous use of both cash and subsistence plots to compensate workers; 2) The negative relationship between subsistence plot size and cash crop price; 3) The longevity of

[5] A cash crop is defined as a commercial crop sold in an outside market.

subsistence plots as a form of payment; and, 4) The effective and sudden disappearance of subsistence plots due to improved enforcement of worker rights.

This paper is organized as follows. Section 3.2 provides a brief account of long-term workers in Brazil, a typical example of permanent workers. The intent of this section is to convince the reader that subsistence plots were used as a credible, effort contingent form of payment. This section also provides evidence of the four characteristics of proletarianization. Section 3.3, presents a model of partial contract enforcement. In this environment, only workers are able to abrogate their contracted responsibilities. As a result, the model can not capture all of the features of proletarianization specified above. However, if we relax the assumption of partial contract enforcement by allowing farmers the ability to cheat workers of their wages, we can come closer to capturing the features of proletarianization. This extension done in Section 3.4. Finally, Section 3.5 concludes the paper.

3.2 Attached labour in Brazil: *colonos* and *moradores*

To understand the proletarianization of permanent workers it is enlightening to study the experience of these workers in Brazil. Brazil's experience suggests that subsistence plots are a credible form of contingent payment that in turn allows one to account for the pattern of proletarianization. Also, the experience of attached labour on the coffee plantations in the state of São Paulo, *colonos*, and on the sugar estates in the state of Pernambuco, *moradores*, serve as a typical example of long-term workers elsewhere.[6]

The emancipation of slaves in Brazil was long expected by the country's coffee and sugar farmers. Early indication of the emancipation of slaves came as early as 1850, when the slave trade was ended. However, it was not until 1888 when finally, the feudal-like environment existing in the country ended as suddenly all workers were free to leave their employer whenever their treatment proved too unbearable or unfair.[7]

Yet, in the same setting, capitalist labour contracts could not yet function properly. Theoretically, such contracts require workers to be the legal equals of their employers (Richards (1979)). In the Brazilian countryside, however, this was not the case. Even after emancipation, the status and power of workers remained lower than that of farmers. In Pernambuco, for example, *moradores* were "subjected to the full force of the proprietor's authority and that of the political machine serving the interests of the land owning class."[8] Similarly, in São Paulo, organizations such as the *Patronato Agrícola* were established to arbitrate disputes between farmers and workers but they did so with a bias in favour of farmers (Stolcke (1988)). In short, no institution existed to enforce equally the contracted obligations of each party and that worked to eliminate farmer opportunism.[9] It is then not surprising that early experiences with free labour failed because farmers were

[6]Specifically, the characteristics of Brazilian long-term workers resemble those of permanent workers in Chile, Egypt and Germany.

[7]Permanent workers in Chile, *inquilinos*, were also free people (Bauer (1971)) as were permanent workers in Egypt and Germany (Richards (1979)).

[8]See Furtado (1965) p.131.

[9]Biased institutions that favoured landowners and farmers is a common feature where tied workers have existed. This is what the environment was like for permanent workers in Germany (1780-1860), Egypt (1850-1940) and Chile prior to 1930 (Richards (1979)).

able to cheat workers.[10]

With time, labour systems in Brazil developed and farmers began to pay workers either, wholly or partially, with subsistence plots. In São Paulo, *colonos* were paid with the right to grow staple foods in between the rows of coffee trees.[11] The primary purpose of these rights was to provide workers a means to supplement their subsistence (Stolcke and Hall (1983)).[12] For the same reason, sugar farmers in Pernambuco gave *moradores* the usufruct of small land plots located in the cane fields of their estates (Furtado (1965); Heath (1981)).[13]

The significance of compensating workers with land in lieu of cash is obvious from the literature; this form of payment facilitated transactions between workers and farmers. On one hand, farmers had to elicit effort from their workers that was not immediately observed.[14] The promise of receiving the fruits from their allotted subsistence plots was used to motivate workers. If a worker did not exert the contracted efforts, payment could be withheld by firing the worker and casting her out from the estate; without access to estate grounds, the worker would also be unable to collect the food from her subsistence plots.[15] In the end, subsistence plots, along with cash

[10]Holloway (1977) describes how farmers in São Paulo initially cheated early share croppers from their contracted share of revenues by under-weighing the harvest, exaggerating shipping costs and undervaluing prices.

[11]This practice is known as intercropping

[12]The crops usually planted were usually rice, beans and manioc (Brannstrom (2000)).

[13]For the case of subsistence plots given to *moradores* see Schaffner (1993) and Furtado (1965), and for *colonos* see Stolcke (1988). Kay (1977) makes the same observation about subsistence plots granted to *inquilinos* who worked on Chilean wheat haciendas.

[14]Weeding and poisoning leaf eating plants on São Paulo coffee plantations are examples of such tasks that were difficult to monitor (Brannstrom (2000)). Furthermore, on coffee plantations in São Paulo, the efforts of labour could not be imputed from yields until weeks or months after any effort was applied (Brannstrom (2000)).

[15]This reasoning is in the spirit of Thorner and Thorner (1962), Berry (1983) and Anrup

payments, proved to be crucial to induce high quality effort from workers (Stolcke (1988)).[16]

On the other hand, and more interestingly, the plots insulated workers from farmer opportunism (Stolcke (1988)). It could do so by decreasing the benefits relative to the costs of cheating workers of their payments. Though workers could not legally enforce their contracts, they could still impose costs on farmers. Workers could damage the farmers' revenue stream by striking. For example, within coffee plantations, *colonos* frequently organized and went on strike when farmers attempted unfairly to withhold payments (Stolcke and Hall (1983); Stolcke (1988)). In the same situation, *moradores* working in sugar mills also chose to strike (Furtado (1965)).

In contrast, the benefits of cheating workers from their subsistence crops were low. Farmers could not benefit greatly from the foods they withheld. Because farmers were rich, they did not need the simple, staple foods for survival.[17] More importantly, farmers could not profit as much by selling these crops. Farmers actively lowered the market value of the food grown by their workers; they prohibited permanent workers from planting the cash crop as well as other high value crops (Heath (1981)). Furthermore, the costs of marketing the subsistence plot output would lower the farmer's value of this food below the value given by attached worker who consumed it directly from the land.[18] In the end, perhaps because subsistence plots succeeded

(1990) when they rationalize the use of subsistence plots. Workers needed to remain on the farm to benefit from their subsistence plots.

[16]This is the same general conclusion reached by Richards (1979) regarding the payment of subsistence plots to permanent workers in Chile, Egypt and Germany.

[17]If present on the estate, farm owners consumed mostly products brought in from outside the estate (Furtado (1965)).

[18]Dean (1976) gives evidence that, around the time of emancipation, transportation

in limiting opportunistic behaviour, workers rarely accepted permanent jobs not promising the usufruct of land as compensation and workers vehemently resisted farmers' attempts to reduce the size of their plots or intercropping rights (Stolcke and Hall (1983)).

Historical accounts prove subsistence plots to have been a tenacious institution with great longevity. This institution was utilized for over 75 years, from around the time of emancipation in 1888 until the early 1960's. Over this time, attached labour generally received, simultaneously, the usufruct of land and cash as payment for their services (Font (1987)). Stolcke and Hall (1983), for example, estimates that in 1916, intercropping accounted for approximately one-third of *colonos'* income. Similarly, *moradores* produced part of their food requirement themselves on these plots (Furtado (1965)). It is difficult however to determine in general, the portion of total subsistence derived from usufruct rights. Subsistence plot size and intercropping rights were not constant. Nor did the subsistence plot component of total income follow a predictable path. The reason for this is that self-provisioning rights varied negatively with cash crop prices. The literature gives various examples of this. Subsistence plots in Pernambuco contracted in size when sugar prices rose and land was annexed to produce more sugarcane (Heath (1981); Furtado (1965)). Farmers decreased self-provisioning opportunities whenever the opportunity cost of land rose too high (Heath (1981)). Conversely, self-provisioning rights increased when cash crop prices decreased. For example, with the fall of coffee prices in 1929, Brazilian coffee farmers adjusted by cutting cash wages by 50% and increasing usufruct rights in

costs of taking maize to market was equivalent to 20% of revenues.

turn (Stolcke and Hall (1983)).

Self-provisioning rights finally ended in a meaningful way in the early 1960's. In both the sugar estates in Pernambuco and in the coffee plantations of São Paulo, attached workers abruptly lost their subsistence plots and intercropping rights. Over a short time period *moradores* and *colonos* became pure wage earners (Furtado (1965); Stolcke and Hall (1983)). The cause of this sudden proletarianization can not be entirely explained by movements in cash crop prices, however. The Cuban revolution disrupted the world supply of sugar and caused sugar prices to increase substantially (Furtado (1965)). However, at the same time, coffee prices were low due to the over supply and accumulation of coffee. In fact, during the early 1960's approximately 40% of permanent workers in São Paulo coffee plantations were fired as a consequence of a coffee tree eradication plan meant to lower the oversupply of coffee (Stolcke (1988)).

Arguably the reason for the end in the use of subsistence plots was the Rural Labour Statute (RLS) that was passed in Brazil in 1963. The RLS required farmers to provide a minimum wage, paid vacation, paid weekly days off and a Christmas bonus. Most importantly, because it was the only stipulation to be actually enforced, the RLS entitled permanent workers to severance pay for unjust dismissal (Schaffner (1993)). This would have served to diminish the threat posed by farmers tempted to dismiss workers unfairly, in order to just to save on paying contingent payments; these savings, to some extent, would have been negated by the required severance payments. Consequently, with fairer representation and explicit protection against farmer opportunism, subsistence plots would have been made redundant as a contracting tool.

3.3 A model with partial contract enforcement

Consider a game of asymmetric information between many workers and a farmer that is played over the course of a year. To capture the basic pattern of production, an agricultural year consists of two halves. The first half is called the Slack Season and represents the period over which crops are planted and cultivated. The second half is called the Peak Season and represents the harvest period.

The typical worker and farmer differ by their endowments, preferences and actions. The worker has no physical assets but is endowed with one unit of labour that can be rented to the farmer in the Slack Season. Worker preferences are such that each derives utility from consuming a subsistence crop and disutility when exerting effort on the job. An individual's preferences are represented by the annual utility function $u(c,e) = c - e$, where c is the quantity of the subsistence crop consumed and $e \in \{0, \varepsilon\}$ is the level of effort exerted when exercising care and good judgement on the job. Since each worker is assetless, subsistence crop consumption is possible only when she receives payment for her services. If a worker purchases consumption, she must pay a price of one for each unit of subsistence consumption. Finally, each worker confronts the same two decisions. Each must decide whether to personally accept or reject a farmer's job offer and whether to provide care on the job. If a worker is careless at work, she expends no effort, $e = 0$, otherwise effort is provided, $e = \varepsilon > 0$.

The farmer is a landowner who possesses a homogenous endowment of land, H. The objective of this individual is to maximize the total rent accrued by her endowment. To this end, the farmer must decide what to grow on her land, how many workers to employ and how best to contract them. Unsurprisingly, all three decisions are interrelated.

Two production technologies are available to the farmer. One technology produces a cash crop which is sold on an international market at price P.[19] Production of this crop requires land and effort in the Slack Season to yield positive output in the Peak Season. In effect, all production is conducted in the Slack Season but output is only revealed in the Peak Season.[20]

The cash crop technology is assumed to be constant returns to scale. It is also assumed that this technology is represented by the Cobb-Douglas production function,

$$Y = (eT)^{1-\alpha}\,\overline{H}^{\alpha}.$$

In this production function, Y is the quantity of the cash crop that is realized in the Peak Season, e is the effort provided by the typical worker in the Slack Season, T is the total number of workers the farmer hires, and $\overline{H}$ is the total amount of land devoted to produce the cash crop.

The second technology produces the same subsistence crop consumed by workers. Unlike the cash crop, land is assumed to be the only input.[21] Production occurs in the Slack Season but output does not emerge until the

[19] This characterizes the experience of coffee and sugar farmers in Brazil.

[20] We abstract from Peak Season production to focus on incentive issues involved in Slack Season activity.

[21] No effort may be required if effort exerted in cash crop production can spill over to subsistence crop production. For example, the same judgements made in the process of cash crop production may be used for subsistence crop production (Holloway (1977)).

following season. It is further assumed that each unit of land devoted to subsistence crop production yields one unit of subsistence output. Finally, the subsistence crop is worthless to the farmer in as much as she can not market it profitably nor can the farmer personally consume this crop.[22]

In this model, the asymmetry of information arises because the farmer is unable to observe the level of effort provided by each worker when producing the cash crop in the Slack Season.[23] This asymmetry is however eliminated in the Peak Season. If and only if there is a cash crop to sell in the Peak Season, the farmer knows that the contracted efforts were provided in the Slack Season [24] Nevertheless, despite its temporary nature, the asymmetry still generates a moral hazard problem for workers that threatens the feasibility of cash crop production.

To produce the cash crop, the farmer must find some way to overcome the workers' moral hazard. For this purpose, the farmer offers each worker the same contract that may consist of both a contingent and non-contingent payment. The contract's structure also depends on the form of payment. The farmer may remunerate a worker with any combination of cash wages and the usufruct of a piece of the farmer's land, a subsistence plot.

The structure of the contract is as follows: Upon accepting the contract in the Slack Season, a worker is paid a non-contingent cash wage, w, and is

[22] This is a simplifying assumption. As long as the farmer does not value the subsistence crop as much as the worker, the analysis remains largely unchanged. This wedge in valuations might be created by transactions costs involved in marketing the subsistence crop.

[23] This is the same asymmetry as described in Eswaran and Kotwal (1985).

[24] As suggested by Newbery (1975) and Kotwal (1985), farmers are able to impute the effects of such things as weather on output. This would then allow them to identify the actions of workers during the Slack Season and would thus eliminate the asymmetry of information.

allocated a subsistence plot of size ϕ from the farmer's land endowment H. At the end of the Peak Season, effort-contingent payments are made. The worker receives a cash payment, $\hat{w}$, and permission to collect the subsistence crop output, ϕ, from her subsistence plot. These payments occur however, if the land assigned to a worker bares evidence of Slack Season effort. Assuming the farmer honors the contract, a worker's total compensation is therefore either w, if no effort was provided, or $w + \widehat{w} + \phi$, given effort.

The timing of the game over the agricultural year is illustrated in Figure 3.1. In the Slack Season, the farmer first searches for employees. To each potential employee the farmer offers the same contract $\{w, \widehat{w}, \phi\}$. If offered a contract, a worker accepts or rejects it in favor of remaining unemployed for the rest of the year. Once the farmer hires her desired number of workers, T, she pays w and provides the subsistence plot to each worker. An employee consumes w and then decides whether to provide the required effort. As soon as effort is combined with cash crop land, $\overline{H} = H - \phi T$, and as soon as the subsistence plots are allocated to workers, production of both crops occurs. Once in the Peak Season, output is realized. The farmer then determines which individual worker provided effort and decides whether or not to make the contingent payments. It is at this time when the farmer decides whether to honor her contract or cheat. Finally, the permanent worker collects the crop on her subsistence plot and consumes $\hat{w} + \phi$ if the farmer is honest.

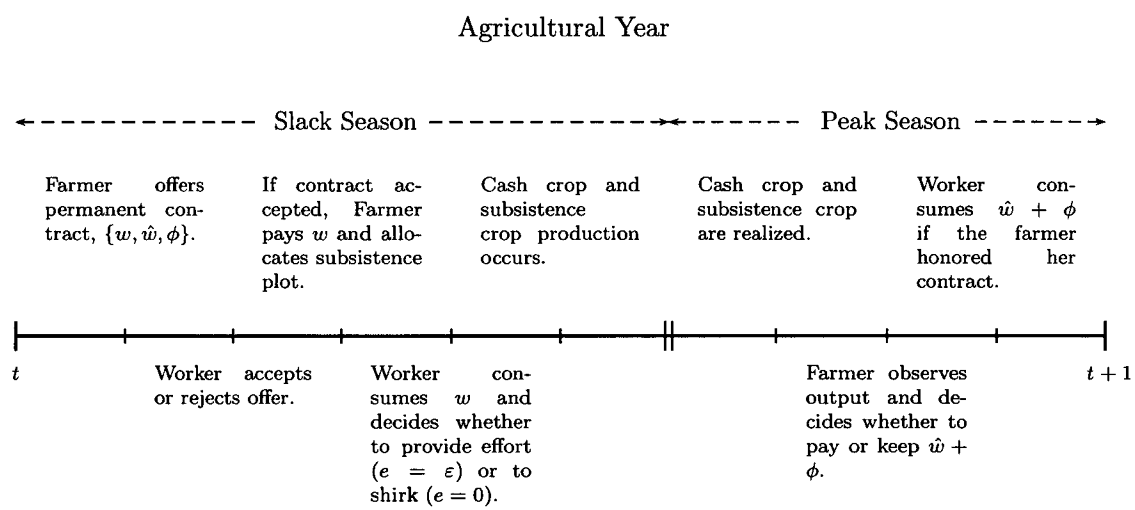

Figure 3.1: Time line.

Given the farmer can commit to make all contingent payments, workers need sufficient motivation to provide the care required to produce the cash crop. The typical worker provides this effort only if the total contingent payment, $\widehat{w} + \phi$, is no less than the disutility incurred when exerting care on the job, $e = \varepsilon$. That is, the contract's structure must satisfy the worker's incentive compatibility constraint,

$$\widehat{w} + \phi \geq \varepsilon. \tag{3.1}$$

Workers must also be given enough incentive to accept the job. A worker accepts any contract that makes her no worse than her best Slack Season alternative. Due to the highly cyclical nature of labour demand in agricultural economies, it is assumed that a worker's best Slack Season alternative is unemployment.[25] Furthermore, to simplify analysis, the utility of unemployment is normalized to zero.[26] Hence, the individual rationality constraint of each worker is given by,

$$w + \widehat{w} + \phi - \varepsilon \geq 0. \tag{3.2}$$

In this environment we assume contracts are partially enforceable. That is, workers have the ability to cheat if they choose but, by assumption, the farmer is unable to renege on any contracted responsibility. Consequently,

[25]This assumption is consistent with labour market descriptions given by Bauer (1971), Richards (1979) and Furtado (1965) and assumptions in other models such as Mukherjee and Ray (1995) and Otsuka et al. (1992).

[26]Zero utility when unemployed does not affect the general results regarding the elimination of subsistence plots in contracts. As it turns out, the desired effects of the model only rely on the total size of the necessary contingent payment. A positive value of unemployment will only increase the size of the non-contingent cash payment, w.

the farmer maximize total rents given available production technologies and the cash crop market price, P, by choosing the optimal number of workers, T, and by offering the optimal incentive compatible and individually rational contract, $\{w, \hat{w}, \phi\}$. Formally, the farmer solves:

$$\max_{T,\, w,\, \widehat{w},\, \phi} AT^{1-\alpha}(H-\phi T)^{\alpha} - wT - \widehat{w}T$$

s.t.

$$\widehat{w} + \phi \geq \varepsilon,$$

$$w + \widehat{w} + \phi - \varepsilon \geq 0,$$

$$T,\ w,\ \widehat{w},\ \phi \geq 0.$$

where in the objective function $A = P\varepsilon^{1-\alpha}$.

Alternatively, the farmer can break her problem down into two, more simple problems. This is done by interpreting her objective function as the product of the average rent per worker and the total number of workers employed. With this approach, for any given number of employees, the farmer first solves for the incentive compatible contract that maximizes the average rent per worker. The average rent per worker is given by,

$$\pi = A(h-\phi)^{\alpha} - w - \hat{w},$$

where, $h = \frac{H}{T}$. Then, second, the farmer takes as given her decision rules dictating the optimal contract and solves for the optimal size of her work force, T, or, more appropriately, the amount of land per worker, h. Breaking the farmer's problem in two not only simplifies the problem but it also helps us better understand the farmer's solution. Consequently, this is the manner in which we solve the problem.

3.3.1 Maximum rent per worker

In this subsection, we develop the decision rules dictating the optimal contract the farmer offers each of her workers. We consequently determine $\pi^*(h)$, the value function expressing the maximum rent per worker for any amount of land per worker, h.

Taking h as given and her ability to commit to make all contingent payments, the farmer's problem is:

$$\max_{w,\ \widehat{w},\ \phi} A\,(h-\phi)^{\alpha} - w - \widehat{w}$$

s.t.

$$\widehat{w} + \phi \geq \varepsilon,$$

$$w + \widehat{w} + \phi \geq \varepsilon,$$

$$w,\ \widehat{w},\ \phi \geq 0.$$

It is easy to see that it is never optimal for the farmer to offer a positive non-contingent wage; that is, $w^* = 0$. This is because a non-contingent payment does not encourage effort. Also, because $w^* = 0$, the optimal contract will be one that makes the incentive compatibility and individual rationality constraints coincide. Finally, the optimal contract will require that the incentive constraints bind with equality. If these constraints were non-binding, $\widehat{w} + \phi > \varepsilon$, the farmer could increase her rents by either decreasing $\widehat{w}$ or by reallocating land from the subsistence plot to cash crop production, decreasing ϕ.

What remains for the farmer is to determine the optimal mix between cash and subsistence plot payments that will make-up the total amount of the contingent payment, ε. This optimal payment mix is determined by allocating each piece of land to its most profitable use. Since land is used in cash crop production or as a subsistence plot, the farmer allocates land to either purpose depending on what has the greatest marginal value.

The marginal value of land in cash crop production decreases as the scale of production rises but it remains positive with finite production. The farmer's marginal valuation of land when used as a subsistence plot also varies. Given the worker's incentive compatibility constraint binds, the farmer values a marginal increase in subsistence plot size by how much it allows $\widehat{w}$ to be lowered. This marginal valuation is either one or zero depending on how much of the total payment, ε, is already made in cash. For example, if $\widehat{w} > 0$, a marginal increment in the size of the subsistence plot lowers cash costs by an equal amount. If however $\widehat{w} = 0$ and $\phi = \varepsilon$, enlarging the subsistence plot does not lower the cash payment.[27]

To summarize the farmer's optimal actions, define $\underline{h}$ as the amount of cash crop land per worker that has a value marginal product equal to one $\left(\text{i.e. } \alpha A\underline{h}^{\alpha-1} = 1 \text{ or } \underline{h} = (\alpha A)^{\frac{1}{1-\alpha}}\right)$. The farmer's optimal contract can then be expressed as a function of the magnitude of h relative to $\underline{h}$.

[27]Implicitly assumed is that workers are destitute and do not have sufficient income to rent land from the farmer. Consequently, $\hat{w} \geq 0$.

If land per worker is less than $\underline{h}$, the marginal value land in cash crop production exceeds one. In this case, the farmer uses her entire endowment to produce the cash crop. This leaves no room for a subsistence plot and forces the farmer to compensate the worker exclusively with cash, $\phi^* = 0$ and $\widehat{w}^* = \varepsilon$. If the land endowment is between $\underline{h}$ and $\underline{h}+ \varepsilon$, the marginal value of land in cash crop production falls below one. To prevent this, the farmer utilizes only an amount of land equal to $\underline{h}$ in cash crop production. The remaining land is used as a subsistence plot to pay the worker and the contingent wage is simply what is necessary to make the contract incentive compatible, $\phi^* = h - \underline{h}$ and $\hat{w}^* = \varepsilon^* - \phi^*$. By utilizing only an amount of land equal to $\underline{h}$ in cash crop production, the farmer maintains the marginal value of land equal to one. Finally, if land per worker is greater than $\underline{h} + \varepsilon$, the farmer pays the worker's entire contingent payment with a subsistence plot, $\phi^* = \varepsilon$ and $\widehat{w}^* = 0$. The rest of the land is used to produce the cash crop. In this case, the marginal value of land is positive but less than one. The optimal decision rules are summarized by:

$$\phi^*(h) = \begin{cases} 0 & \text{if } \leq h \leq \underline{h} \\ h - \underline{h} & \text{if } \underline{h} < h < \underline{h} + \varepsilon \\ \varepsilon & \text{if } \underline{h} + \varepsilon \leq h \end{cases}, \tag{3.3}$$

and

$$\widehat{w}^*(h) = \begin{cases} \varepsilon & \text{if } 0 \leq h \leq \underline{h} \\ \varepsilon + \underline{h} - h & \text{if } \underline{h} < h < \underline{h} + \varepsilon \\ 0 & \text{if } \underline{h} + \varepsilon \leq h \end{cases}. \tag{3.4}$$

Given the decision rules, the maximum rent per worker function is expressed as a function of the land per worker, $\pi^*(h)$. This value function is,

$$\pi^*(h) = \begin{cases} \max\{0, Ah^{\alpha} - \varepsilon\} & \text{if } 0 \leq h \leq \underline{h} \\ \max\left\{0, \left(\frac{1-\alpha}{\alpha}\right)\underline{h} + h - \varepsilon\right\} & \text{if } \underline{h} < h < \underline{h} + \varepsilon \\ A[h-\varepsilon]^{\alpha} & \text{if } \underline{h} + \varepsilon \leq h \end{cases} . \tag{3.5}$$

Equation (3.5) states that when land per worker is small, $h \in \left[0, \underline{h} + \varepsilon\right]$, it maybe the case that rents are negative if cash crop production occurs. If land per worker is too low, the rent per worker may also be too small to recover the cost of effort. This can still be the case despite the use of the optimal contract. In such a case, the farmer elects not to produce and earn zero rents. Otherwise, the farmer produces according to her decision rules (3.3) and (3.4).

An illustration of the maximum rent function is given in Figure 3.2. The shape of the graph is instructive and conveys how the farmer allocates land between corps. For land endowments smaller than $\underline{h}$ but large enough to allow positive profits, the slope of the value function, the marginal value of land, is greater than one. If the land endowment is between $\underline{h}$ and $\underline{h}+\varepsilon$, the slope of the value function is constant and equal to one. Rents increase by holding production constant and increasing the subsistence plot size at the same rate that wages are decreased. Finally, for endowments larger than $\underline{h} + \varepsilon$, the value function's slope gradually decreases from one as cash crop production expands with h.

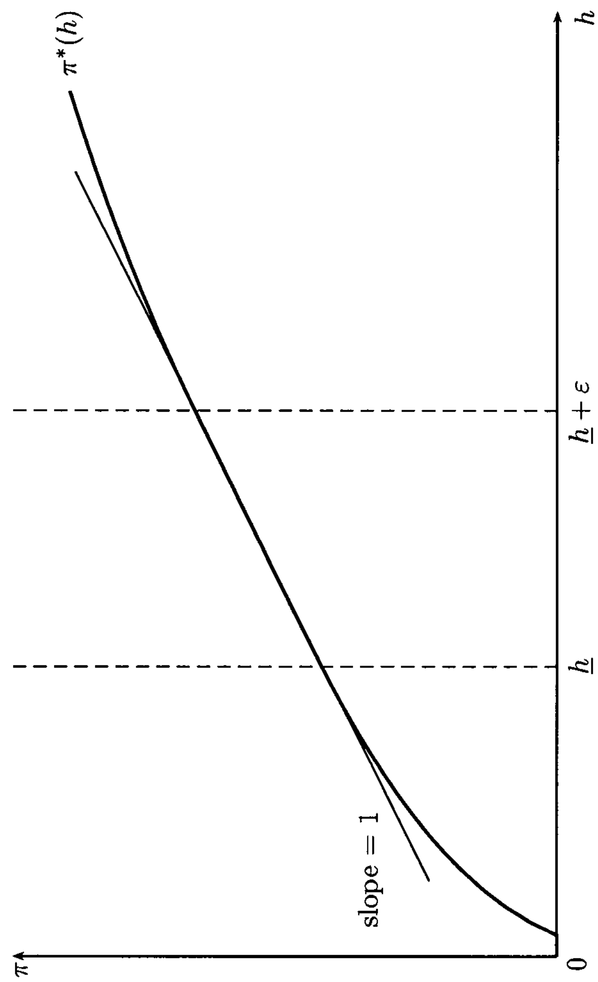

Figure 3.2: Rent value function, $\pi^*(h)$.

3.3.2 Total rents

Given the maximum rent function per worker, $\pi^*(h)$, the farmer can pin-down the optimal number of workers she should hire, T. More appropriately, she can determine the optimal amount of land per worker, h. She consequently solves,

$$\max_h \pi^*(h)\frac{H}{h}$$

s.t.

$$H \geq h \geq 0.$$

The first order condition of this problem reveals that the farmer chooses h to maximize the average rent per unit of land. For an interior solution the optimal amount of land per worker, h^*, is given where the average and marginal rent per worker are equal. This tangency condition is illustrated in Figure 3.3.

Once the optimal number of workers or, alternatively, the optimal amount of land per worker, h^*, is found, the farmer pins-down the optimal contract. Applying h^* to the decision rules given by Equations (3.3) and (3.4), the optimal contract is $\{0, \widehat{w}^*(h^*), \phi^*(h^*)\}$.

Given the farmer's decision rules, the value of exogenous parameters determine the composition of the optimal contract. Of interest is to see how the parameter A affects the equilibrium contract. This is of interest because, given all else, movements in A reflect changes in the cash crop price.

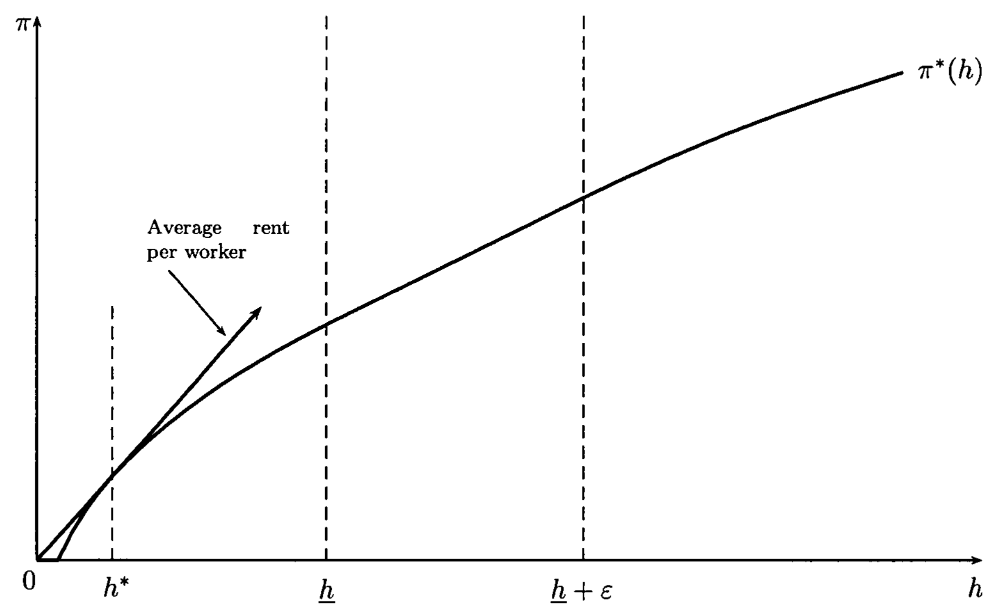

Figure 3.3: Optimal land per worker.

For low values of A, the farmer will be unable to obtain a rent per unit of land greater than one. That is, $\frac{\pi^*(h)}{h} < 1$ for all h. Under these circumstances, the farmer maximizes rents by paying workers exclusively with subsistence plots. The farmer takes advantage of the fact that at low values of A, the opportunity cost of land for the farmer is lower than that of cash.

For high values of A, the farmer can earn an average return greater than one. In this case, the opportunity cost of subsistence plots is too high to allow any contract offering a subsistence plot, $\phi > 0$, to maximize rent. Consequently, the farmer only pays workers in cash.

The only situation in which a rent maximizing contract includes both cash and subsistence plots is if the maximum rent per unit of land is one. In this case, the farmer is indifferent over the composition of her contract. The increase in revenues achieved by a marginal decrease in ϕ is exactly off-set by the increase in $\widehat{w}$ necessary to continue paying a worker ε. This sort of rent neutral change in contract composition is possible only at one threshold value of A, $\widetilde{A}$. Recalling that $\underline{h} = (\alpha A)^{\frac{1}{1-\alpha}}$, $\widetilde{A}$ is defined as A such that:

$$\frac{\partial \pi^*\left(\underline{h}(A)\right)}{\partial h} = \frac{\pi^*\left(\underline{h}(A)\right)}{\underline{h}(A)}.$$

and is equal to $\widetilde{A} = \left(\frac{1}{\alpha}\right)^{\alpha}\left(\frac{\varepsilon}{1-\alpha}\right)^{1-\alpha}$.

The farmer's optimization can then give a decision rule for the optimal contract as a function of A. This is given by:

$$\{0, \widehat{w}^*(A), \phi^*(A)\} = \begin{cases} \{0,0,\varepsilon\} & \text{if } 0 \leq A < \widetilde{A} \\ \gamma\{0,0,\varepsilon\} + (1-\gamma)\{0,\varepsilon,0\}, \ \forall\gamma \in [0,1] & \text{if } A = \widetilde{A} \\ \{0,\varepsilon,0\} & \text{if } \widetilde{A} < A \end{cases} .$$

The optimal amount of land per worker can also be expressed as a function of A. For interior solutions the closed form solution of h^* is given by:

$$h^*(A) = \begin{cases} \frac{\varepsilon}{(1-\alpha)} & \text{if } 0 \leq A < \widetilde{A} \\ \gamma\underline{h} + (1-\gamma)(\underline{h}+\varepsilon), \ \forall\gamma \in [0,1] & \text{if } A = \widetilde{A} \\ \left[\frac{\varepsilon}{A(1-\alpha)}\right]^{\frac{1}{\alpha}} & \text{if } \widetilde{A} < A \end{cases}$$

The significance of a homogeneous land endowment and partial contract enforcement is that the proletarianization of workers is an abrupt event; the switch in contracting regimes has a knife edge quality. For example, as soon as A rises above $\widetilde{A}$, the farmer will jump from paying all employees only with subsistence plots to paying employees only with cash. Though this quality does imply a negative relationship between cash crop prices and subsistence plot size, the model is undesirable. The abruptness of the transition makes unlikely that one would observe payment in both subsistence plots and cash at the same time. Consequently, the model does not capture one of the characteristics of proletarianization.

This model alone is also unsatisfactory because it does not help us think about the impact of stronger worker rights on the size of subsistence plots. By construction, worker rights are perfectly enforced. This leaves no room to think about how improvements in enforcement might suddenly eliminate the use of subsistence plots.

3.4 Unenforceable contracts

To better explain the proletarianization of workers, this section extends the multi-worker model by assuming that contracts are completely non-enforceable; that is, the farmer is no longer able to commit to pay contingent wages. Contract fulfillment is instead established by allowing ongoing interaction between the farmer and workers.

In this game, reputation effects do not only elicit honest behavior from the farmer. Under certain conditions, these effects also captures the four observed characteristics of proletarianization. Movements in A may no longer precipitate a sudden switch between pure subsistence plot and pure wage contracts. Instead, a transition with contracts utilizing both forms of payment can occur over a non-trivial range of A. Furthermore, this model also produces a negative relationship between prices and the size of subsistence plots. Also, relative to the model with partial enforcement, subsistence plots prove to be a more tenacious institution by requiring higher cash crop prices before subsistence plots are eliminated. And lastly, this model also allows for the sudden elimination of subsistence plots once there is a shift in legal regimes from absolutely no contract enforcement to partial enforcement.

The game to be repeated is nearly the same as the static multi-worker game of the previous subsection. Worker preferences and endowments are unchanged; each worker has the same linear annual utility used through out the paper and the same labour endowment in the Slack Season. The farmer also remains largely unchanged. In each period her land endowment is H. Further, to induce effort from her workers, she utilizes the same contract, $\{w, \widehat{w}, \phi\}$ described in preceding section. The farmer's preferences differ however because she now cares about her discounted future rents. The farmer uses the discount factor $\delta \in (0, 1)$.

Considered is a trigger strategy held by each worker that acts to inflict a collective punishment on the farmer if she reneges on any contract. Specifically, the typical worker's strategy is:

- At the beginning of the Slack Season, accept the farmer's job offer if it is individually rational and if the farmer has never cheated *any* employee in the past. If otherwise, the worker rejects the job offer.

- Once employed, the worker provides effort if it is incentive compatible and if the farmer has never cheated any worker in the past. Otherwise, the worker shirks by not providing care when completing her job.

The typical worker's strategy prompts her to reject a farmer's offer even if the worker herself has not been directly affected by the farmer's dishonest action. The rationale for this is that stated in Levin (2002). A worker interprets *all* of the farmer's previous indiscretions as evidence that the farmer may not honor informal commitments in the future and thus refuses to risk working for the farmer.[28] The workers' strategy thus ensures the farmer can not produce once she has cheated any employee.

[28]This is as in Levin (2002) when discussing the drop-off in worker performance once the employer undertakes selective pay cuts or layoffs.

The farmer's strategy on the other hand is:

- At the beginning of the Slack Season, if the farmer has never cheated any worker in the past, she offers workers a contract that satisfies the worker's individual rationality and incentive compatibility. Otherwise, the farmer offers the contract $\{0, \varepsilon, 0\}$ to each worker.

- Once in the Peak Season, if the farmer has always been honest, she honors each contract she made in the previous Slack Season. That is, she pays out the contingent payment, $\widehat{w} + \phi$, to each worker who provided effort in the Slack Season and withholds this payment from any one who shirked. If however, the farmer has cheated any worker in the past, the farmer pays nothing to each worker regardless of whether they shirked or not.

Given the players' strategies we solve for the equilibrium contract and the number of workers maximizing the farmer's discounted rents. If production occurs in equilibrium, the contract must give the farmer enough incentive to honor all contracted obligations. This means that her total discounted future rents, $\frac{\delta}{1-\delta}\left[A\left(h-\phi\right)^{\alpha}-w-\widehat{w}\right]T$, must exceed her one time pay-off from cheating, $\widehat{w}T$.[29] Thus the farmer's incentive compatibility constraint is:

$$D\left[A\left(h-\phi\right)^{\alpha}-w-\widehat{w}\right]T \geq \widehat{w}T \text{ or } A\left(h-\phi\right)^{\alpha}-w-\widehat{w} \geq \frac{\widehat{w}}{D},$$

where $D = \frac{\delta}{1-\delta}$. This leaves the farmer's problem as:[30]

[29] If the farmer reneges, she reneges on all contracts because the farmer's punishment is independent of how many contracts she breaks. Consequently, if the farmer cheats, she will maximize this pay-off and withholds $\widehat{w}T$.

[30] The findings of the previous model still apply. Recall, that $w^{*} = 0$ and the incentive

$$\max_{T,\, w,\, \widehat{w},\, \phi} \left[A\,(h-\phi)^{\alpha} - w - \widehat{w}\right] T$$

s.t.

$$\widehat{w} + \phi \geq \varepsilon,$$

$$w + \widehat{w} + \phi \geq \varepsilon,$$

$$A\,(h-\phi)^{\alpha} - w - \widehat{w} \geq \frac{\widehat{w}}{D},$$

$$T,\ w,\ \widehat{w},\ \phi \geq 0.$$

The contract solving the farmer's problem may be unaffected by the lack of contract enforcement. If $A \leq \widetilde{A}$, the farmer's incentive constraint does not bind because the farmer does not make any monetary payments. Consequently, the farmer does not benefit from cheating. Furthermore, even if $A > \widetilde{A}$, the farmer's constraint may not bind. As long the unconstrained rent per worker, $\pi^*\left(h^*\right) = \frac{\alpha\varepsilon}{1-\alpha}$, exceeds the benefit of cheating, $\frac{\widehat{w}}{D} = \frac{\varepsilon}{D}$, the farmer has no incentive to cheat; she loses too much by cheating. Hence, the farmer's incentive compatibility constraint only binds if $A > \widetilde{A}$ and $\alpha D < 1-\alpha$.[31]

Assuming the farmer's incentive constraint binds and defining

$$\overline{\overline{A}} = \left(\frac{1-\alpha}{\alpha}\right)^{\alpha} \frac{1+D}{D} \varepsilon^{1-\alpha},$$

as the point at which the farmer is able to credibly commit to paying workers

and rationality constraints coincide and bind with equality. Recall, $A = P\varepsilon^{1-\alpha}$.

[31] Note: $\alpha D < 1-\alpha$ is equivalent to $\delta < 1-\alpha$.

exclusively in cash, $\widehat{w}^c = \varepsilon$, the farmer's contingent wage offer, $\widehat{w}^c$, subsistence plot size, ϕ^c, are given by:

$$\widehat{w}^c(A) = \begin{cases} 0 & \text{if } A \leq \widetilde{A} \\ \frac{AD}{1+D}\left[\frac{\alpha\varepsilon}{1-\alpha}\right]^{\alpha} & \text{if } \widetilde{A} < A \leq \overline{\overline{A}} \\ \varepsilon & \text{if } \overline{\overline{A}} < A \end{cases}$$

and

$$\phi^c(A) = \begin{cases} \varepsilon & \text{if } A \leq \widetilde{A} \\ \varepsilon - \frac{AD}{1+D}\left[\frac{\alpha\varepsilon}{1-\alpha}\right]^{\alpha} & \text{if } \widetilde{A} < A \leq \overline{\overline{A}} \\ 0 & \text{if } \overline{\overline{A}} < A \end{cases}.$$

Furthermore, the optimal amount of land per worker, given the farmer's incentive constraint binds, h^c, is given by:

$$h^c(A) = \begin{cases} \frac{\varepsilon}{(1-\alpha)} & \text{if } A \leq \widetilde{A} \\ \frac{\varepsilon}{(1-\alpha)} - \frac{AD}{1+D}\left[\frac{\alpha\varepsilon}{1-\alpha}\right]^{\alpha} & \text{if } \widetilde{A} < A \leq \overline{\overline{A}} \\ \left[\frac{(1+D)\varepsilon}{AD}\right]^{\frac{1}{\alpha}} & \text{if } \overline{\overline{A}} < A \end{cases}.$$

It is now possible two see that over the range $\left(\widetilde{A}, \overline{\overline{A}}\right)$ the optimal contract consists of both cash and subsistence plot payments. The reason for this is that a farmer can not immediately commit to pay workers in cash as soon as $A > \widetilde{A}$. Hence, the farmer must still utilize subsistence plots to lower her incentive to cheat. We also find from $\phi^c(A)$ that when $A \in (\widetilde{A}, \overline{\overline{A}})$ there is a negative relationship between subsistence plot size and cash crop price, A. Also, without partial enforcement of contracts, subsistence plots would prove more difficult to extinguish. While with partial enforcement subsistence plots disappear as soon as $A \geq \widetilde{A}$, without any legal enforcement, these plots disappear when $A \geq \overline{\overline{A}}$. Since, by assumption $\alpha D < 1-\alpha$, this implies that $\widetilde{A} < \overline{\overline{A}}$. That is, with completely unenforceable contracts, subsistence plots are a more tenacious form of payment because prices have to rise higher before the farmer stops paying her workers with land. Finally, when $A \in (\widetilde{A}, \overline{\overline{A}})$ subsistence plots suddenly disappear when contracts become partially enforced. For a given A, better enforcement of the farmer's responsibilities means that subsistence plots would fall in size from $\phi^c(A) > 0$ to $\phi^*(A) = 0$.

3.5 Conclusion

This paper proposes a theory of the proletarianization of attached labour. Essential for this theory is an environment where impartial contract enforcement does not exist but where contingent payments are made to motivate worker effort. In this environment, paying workers partially or wholly with subsistence plots represents a contract technology that facilitates interaction between workers and farmers. The proletarianization of workers is predicted to occur gradually as the price of their cash crop rises and farmers can credibly commit to make more of their contingent payments in cash; much like the experience of attached workers suggests. Also consistent with observation, the model predicts an immediate end of subsistence plots once worker rights are enforced.

Though the simple model present here correctly predicts important aspects of proletarianization, some features of the model can be improved. In particular, incorporating the farmer's moral hazard into the multi-worker model prompts the use of two strong assumptions characterizing the information available to players. These assumptions are necessary to sustain the equilibrium in the multi-worker model.

The first assumption is that a farmer's history is common knowledge. Although there is no reason to discount the possibility of strong information flows among potential workers, such a common knowledge assumption may be too strong. Unlike the case of merchant guilds in Greif et al. (1994), no analogous organization ensuring the dissemination of a farmer's history is obvious from the cases of attached labour I reviewed.

The second assumption is that the farmer can observe the effort or, in this case, the output of each individual employee. This is necessary so that the farmer can discipline individual workers who have shirked. Other than by assigning individual workers to particular sections of land and having some means to monitor the output from each section, would one be able to observe the efforts of each individual worker. Although there is evidence of such sectioning-off of farm land on Brazilian coffee plantations, future research would more closely address how farmers are able to discern the efforts of each individual worker.

Finally, in future work, it would be interesting to identify the relative attractiveness of alternate arrangements that circumvent the farmer's moral hazard. Of particular interest may be efficiency wages. A farmer could promise relatively high non-contingent wages in the Slack Season and low contingent cash wages in the Peak Season. High enough non-contingent wages and some degree of consumption smoothing would make the threat of dismissal a powerful incentive to induce worker effort. Conversely, by lowering the Peak Season wage, the farmer's incentive to cheat would also be lowered. The important question would then be, under what conditions might efficiency wages dominate contingent payments that utilize subsistence plots?

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