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For my mother and father

UTH BANDH KAMAR KIYA DARTA HAI,

PHIR DEKH KHUDA KIYA KARTA HAI...

FAIZ

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Abstract

This thesis is a collection of three principal chapters split into two parts. The first part presents chapter 1 on network design when effort decisions are global substitutes but communication through network links creates local complementarities, and the network is subject to policing. Although it is motivated as a study of criminal networks, the model is general enough to encompass situations of collaborative R&D, employee poaching and peer effects. The second part presents chapters 2 and 3 on R&D collaboration. Chapter 2 empirically assesses the reasons that induce firms to collaborate in R&D projects and finds a strong reason in financial constraints. Chapter 3, firstly studies how firms within collaborative agreements protect their innovations. A comparison with non-collaborators unveils a systematic preference for strategic mechanisms such as secrecy. Chapter 3 then provides a theoretical rationale for this difference and offers additional predictions that are matched by the data.

Resum

Aquesta tesi és una recopilació de tres capítols principals, separada en dues parts. La primera part presenta el capítol 1 relatiu al disseny en xarxa quan les decisions sota esforç són substitutius globals. Però, en aquest context, la comunicació a través de les connexions de la xarxa crea complementarietats locals i la xarxa està subjecte a vigilància. Encara que aquest capítol està motivat com un estudi sobre les xarxes criminals, el model és bastant general i abasta situacions de R&D col·laboratiu, fuga de talents i efectes paritaris. La segona part presenta els capítols 2 i 3 relatius a la col·laboració en matèria de R&D. El capítol 2 avalua empíricament les raons que indueixen a les empreses a col·laborar entre elles en projectes de R&D, destacant sobre les altres raons les restriccions financeres. El capítol 3 estudia, en primer lloc, de quina manera les empreses que operen sota acords de col·laboració protegeixen les seves innovacions. Una comparació amb empreses no col·laboradores desvetlla una preferència sistemàtica per mecanismes estratègics com el secretisme. Seguidament, el capítol 3 proporciona una base teòrica que explica aquesta diferència i ofereix prediccions addicionals que s'ajusten a les dades.

Preface

A network is best described as an organizational map in which nodes represent individual entities and links represent relation specific interactions. Network Theory in Economics seeks to identify (a) how and which organizational structures arise as a consequence of individually rational behavior and (b) the impact of known organizational structures on economic behavior. The former set of problems can be broadly grouped under the banner of Network Formation and Design, while the latter belongs to Network Games.

Network or Graph Theory, as it is otherwise known, dates back to the times of Euler and was first developed by mathematicians to aid in the study of pairwise relations. It was adopted by sociologists, specializing as Social Network Theorists, to study the socioeconomic consequences of social interactions between individuals. Prime examples include a series of studies on the Florentine network of family and business ties conducted by Padgett (1975, 1971).

Economic interest in Network Theory is relatively new but rigorously developed. The earliest mention, by an economist, of the notion of a network probably belongs to Myerson (1972) who brought it up in the context of group behavior and bargaining. Yet it was not until the early 90s that economics witnessed a true interest in applications of this field.

The economics literature like the social networks literature has concentrated on measuring social interactions and the impact of peer-effects on final outcomes such as crime and unemployment (Calvó-Armengol, Verdier and Zenou (2006), Glaeser, Sacerdote and Scheinkman (1995)). The study of peer-effects still dominates the economic literature on network theory, but other applications have also begun to appear. As economics becomes increasingly quantitative in nature, following the natural sciences paradigm, it is no surprise that one of the earliest theoretical economic formalizations of network theory involves the study of co-authorship networks (Jackson and Wolinsky (1996)). Yet, this is a perfect example that highlights the tensions present in any group behavior, namely, the co-existence of complementarities and congestion in actions.

Applications of Network Theory are now, utilized by a varied range of specializations in economics. Buyer-Seller networks have been used to study the problem of market clearing and goods allocation (Corominas-Bosch (2004), Kranton and Minehart (2001)). Network Theory has been used to study the process of correlated trading in financial markets (Mele (2008)), social upheaval and political activism (Chwe (2000)), and general contagion (Morris (2000)). Network theory has been used to study issues relating to bargaining (Polanski (2007)), conflict (Franke and Öztürk (2009)), and informal risk sharing (Abecasis, 2010, Bloch, Genicot and Ray (2008), Bramoullé and Kranton (2007b)) and the provision of public goods (Bramoulle and Kranton (2007a)). Increasingly international trade theorists are also applying the concepts of networks to explain trade patterns (Carvalho (2009)). And even experimental economics is beginning to utilize insights from network theory (Gunes and Gurguc, 2009, Ballester, Brañas-Garza and Espinosa (2008), Charness, Corominas-Bosch and Frechette (2005)).

Economists apply the theory of networks to better understand issues related to scarcity and allocation of resources, production and information dispersion and aggregation. On the other hand social network theorists have dedicated a large amount of time to understanding the concepts of power and centrality. The seminal work of Ballester, Calvó-Armengol and Zenou (2006) shows that these issues are not that far removed from each other. The authors show how complicated network dynamics can be condensed in a simple quadratic utility structure that captures the main elements of congestion and complementarities and show how a rational utility maximizer optimally chooses economic actions according to her centrality within the network.

More importantly, they show how to identify the key player in a network i.e. the network participant whose removal causes most economic harm to the network. This question is becoming increasingly relevant in todays world because more and more complex phenomena rely on network structures e.g. the world wide web, transport networks. Which nodes should be protected and which structures are most vulnerable to attack are questions that even physicists working on complex networks have busied themselves with (Newman (2003), Barabasi, 1999).

Although Ballester et al. (2006) identify the most central player to target in a network, like all centrality based targeting schemes, this mechanism requires perfect knowledge of the network architecture, which is not available in most real world situations. It is also only really beneficial when the network, to be targeted, is highly asymmetric. Otherwise random targeting may provide a more cost effective and equally damaging alternative.

In the first chapter of this thesis I use the Ballester et al. (2006) framework to study the question network design. A network designer has access to limited links which he uses to connect network participants in either a decentralized symmetric or centralized asymmetric way. I find conditions under which centralized networks prevail i.e. situations in which centrality based targeting is preferred to random targeting. I show that if the network structure is not known, a potential targeting or policing authority requires substantial information to predict the optimal structure that will be chosen by the network designer. In addition discrepancies in intelligence gathering by the policing authority can strategically influence the optimal design chosen by the network planner and lead to equilibrium structures that are different from the ones that would prevail if there was no policing.

In addition I study the case in which there are multiple locations and independent policing authorities against one network planner, who designs networks in each location. If the only benefit from coordination is to enable a shift from random to centrality based targeting then the network planner can always induce a breakdown in coordination by designing one decentralized symmetric network in the location where network participants have the highest outside option. Although the analysis is motivated as a study in organizational design of criminal activity I believe the model to be general enough to encompass issues relating to R&D organization and employee poaching.

While the theoretical understandings of network economics and its applications are quite developed and widespread empirical work in this field is still very limited. This mainly has to do with data limitations as any in depth empirical work on network structures and their implications requires detailed data which is not always readily available and difficult and time consuming to collect. Most of the empirical work in network economics has centered around social networks and has either studied neighborhood and peer effects (Darlauf (2003)) or informal risk sharing (Margherita (2007), Fafchamps and Gubert (2005), Krishnan and Sciubba (2004), Weerdt (2002)).

The second part of my thesis looks at R&D collaboration networks and tests empirical reasons for their existence and the appropriability decisions that firms within collaboration networks take. I am also limited by data availability and I am unable to map entire collaboration networks, however, I am able to identify firms that are part of some collaboration network and the type of institutions they collaborate with. These institutions include vertical collaboration partners such as suppliers and customers, horizontal competitors and research institutes including both private and public funded research laboratories and consultancies.

Even with this limited view of the collaboration network interesting results come out. The true source of complementarities in research collaborations vary by type of partner. Complementarities with research institutes, such as universities, stem from a good science base within the firm, whereas collaboration agreements between industry partners such as suppliers or competitors generally exist to reap complementarities from cost sharing and mitigating financial constraints.

Specifically, in the second chapter I use a panel of firms from the UK Community Innovation Survey to study the role of information spillovers, absorptive capacity and financial constraints on the decision to collaborate in R&D. I follow the methodology laid out in Cassiman and Veugelers (2002) and distinguish between incoming and outgoing spillovers. However, I argue that while their original idea is conceptually compelling, their definition of incoming spillovers and choice of instruments can potentially be improved. I use a broader definition of incoming spillovers that takes into account all the information sources available to the firm, the behavior of other firms in limiting their own outgoing spillovers, and the stock of publicly available knowledge capital. I instrument spillovers with the (economy wide) stock of product specific basic research, industry exposure to broadband coverage and industry specific contracting intensity. Using this new set of instruments I find that cost sharing concerns and financial constraints drive vertical collaboration decisions, absorptive capacity improves chances of collaboration with research institutes and strategic appropriability plays a prominent role in horizontal collaborations. I also find evidence that collaborative agreements induce increased spillovers not just within the collaborative agreements but also to non-collaboration partners within the industry.

Information spillovers are closely related to the concept of appropriability i.e. how firms protect their innovations. If collaboration agreements increase informational spillovers not only within the collaboration network but also to non-collaborating partners, then a natural question to ask is how do collaborating firms use appropriability mixes and whether these mixes systematically vary between collaborating and non-collaborating firms. A burgeoning empirical literature shows that there are shortcomings to patenting innovations and that a majority of firms prefer strategic appropriation mechanisms such as secrecy. I evaluate this claim with the Community Innovation Survey and additionally pay special attention to collaborating firms. The analysis unveils a high degree of reliance on strategic mechanisms by collaborating firms, even more than can be explained by other well studied factors. I study a very stylized and simple network model in which firms build links with one another i.e. collaborate, to overcome financial constraints and competition, that may result from simultaneously development of the same innovation. I use the model to rationalize some of the empirical findings and also obtain corroborating empirical evidence for additional theoretical predictions of the model.

Specifically, I use a panel of firms from UK Community Innovation Survey (1998-2006) to study why firms rely on legal property rights, such as patents and trademarks, to protect their innovations and whether they prefer to do so by employing non-exclusive strategic methods such as secrecy and confidentiality agreements. The first set of results are broadly in line with those found in the US. I find suggestive evidence that firms use legal instruments to block markets, improve bargaining power and goodwill reputation in financial markets. Controlling for a host of factors I find strong evidence that multinationals prefer recourse to legal property rights over strategic methods, while firms within collaborative agreements prefer the opposite. I explain this over-reliance, by collaborative agreements, on strategic protection mechanisms, through the existence of financial constraints and information disclosure concerns. A stylized theoretical model in which firms enter collaboration agreements to jointly develop an idea and choose between patenting and secrecy to improve individual post development payoffs shows that financially constrained firms that enter collaboration agreements are more likely to prefer secrecy instead of patenting compared to non-financially constrained firms. Using the UK-CIS panel we find empirical support for the theoretical predictions of the stylized model.

Contents

Part I

Criminal Networks

1 Organizing Teams: Can Coordinated Policing Efforts Influence Network Design?

1.1 Introduction

Consider two organizations in direct competition with each other. Organization A's objective is to maximize its productivity while the primary objective of organization B is to limit the productivity of A. A real world phenomena that readily exhibits this kind of tension is the interaction of a criminal outfit with a policing authority. Like most organizations, a criminal organization needs to balance the rivalry in actions, of participants within the organization, with gains from communication complementarities. However, it has to do this while maintaining secrecy and concealment of its activity.

How does one design an organization when the actions of individuals exhibit substitutability but communication creates complementarities? Are the optimal choices of the designer a function of whether or not the organization is being monitored for targeting? How should policing authorities organize to combat the actions of the network designer? In this chapter I explore the answers to these questions.

In their seminal article Ballester et al. (2006) show two important results. Firstly, they build a bridge between social network theory and economics and show that the measure of centrality first proposed by Bonacich (1987) can be rationalized through a utility maximization problem. Secondly, they show how to quantify the key or Intercentral player in any given network. Removing the Intercentral player from the network optimally disrupts the network by maximizing the loss in total effort level that the removal facilitates.

This is a powerful result, however locating the Intercentral player in a network requires perfect knowledge of the network structure which is a strong requirement. As Ballester, Calvo-Armengol and Zenou (2008) argue targeting the Intercentral player is costly and is preferred to random targeting only when the network is highly asymmetric.

Using the Ballester et al. (2006) framework, I ask the question of network design and show under which conditions asymmetric networks arise. I consider organizations made up of team structures. A network designer has access to limited resources captured by an upper bound on the number of links he can forge between his employees. He can choose to form connected teams in which all players are part of one component, or he can design disconnected and asymmetric teams. Using the same number of links, an asymmetric and centralized component connects more players than a symmetric and decentralized component. However in the limit a binary team structure that only connects two players per component, not only maximizes the total number of players employed but also exhibits decentralization and symmetry.

Only in limited conditions is the centralized and asymmetric star network chosen by the network designer, suggesting a wider role for random targeting. Nonetheless, Intercentral targeting remains a very powerful way to target centralized structures.

Much of the emerging economics literature on strategic network design and policing assumes the policing authority has complete information about network structure. In reality networks that are being policed, and policing strategies, simultaneously evolve over time and policing authorities have to commit to certain strategies at the outset, as in Bar-Isaac and Baccara (2006). An intelligent policing authority needs to evaluate and predict whether in equilibrium it will face a centralized structure before it can commit to random or Intercentral targeting. At the same time this commitment influences the equilibrium.

In this paper I analyze the information structure that an intelligent policing authority requires to evaluate the strategic concerns that predict equilibrium networks and argue that the policing authorities objective function should be centered around these concerns.

Finally the main purpose of this paper is to build a framework with which it is possible to analyze the endogenous and strategic design of organizations that are directly competing against one another. I explore some avenues to conduct this analysis.

I set up a simple model of coordinated policing. Independent policing authorities coordinate against the same network designer who sets up different networks in different locations. I assume that coordination facilitates Intercentral targeting, while policing authorities can only resort to random targeting if acting alone. This is a reasonable but strong assumption in the sense that benefits from coordination only accrue to those locations with centralized structures while the costs are incurred by all. In such a scenario the network designer can always induce a breakdown in coordination by designing a decentralized structure in at least one location. I therefore talk about how to enrich the environment by considering different alternatives including the role of incomplete information.

Although primarily motivated as a study in criminal organization and policing, the problem of strategic organizational design posed here is quite general and applicable to many real life situations. For example, this problem can equally be applied to studying R&D organizations, internal organization and employee poaching, and peer effects. A lot of firms independently engage in correlated R&D projects and joint efforts may combine complementary skill sets and knowledge. A research consortium may be better off organizing its partners in small independent teams if the research agenda is very narrow with high substitutability in skill sets and low complementarities. And in many high profile jobs head hunted individuals tend to migrate with their existing teams.

Papers concerned with internal efficiency and organisational form include Maskin, Qian and Xu (2000) that studies the impact of organizational form on incentives and Garicano and Rossi-Hansberg (2006), Garicano (2000), Van Zandt (2003), Radner (1993) and Radner (1990) that study the role of hierarchical organizations in improving information processing.

A number of recent papers analyze coordination in organisations. Dessein and Matouschek (2008) looks at the trade-off between coordination and the private benefits of independent actions. In decentralized structures managers do not fully internalize the benefits of coordination, whereas under centralized activity the decision maker fails to take into account private benefits. The authors find that higher coordination improves horizontal communication at the expense of vertical communication, when managers are privately informed and communicate strategically. This causes decentralization to dominate centralization. Rantakari (2008) analyses coordination in organisations in which information is dispersed by focusing on cases in which divisions differ in their need for coordination. He argues that it is optimal to design asymmetric organisational structures in which all decision rights are concentrated in one division. Hart and Moore (2004) looks at the optimal hierarchical structure that arises when some agents specialise thoughts about the coordinated use of some assets, while others develop ways to independently use a particular asset.

Lessons from the organizational literature may not be directly applicable to the study of illegal actiivity. This point is forcefully made by Klerks (2001) who argues that we should not directly assume that criminal networks are organized hierarchically just because the organization literature suggests so. Criminal networks balance the need for coordinated activity with the requirement to conceal and Baker and Faulkner (1993) postulate that network based activities requiring high information exchange, that is not easy to conceal, should group in a decentralized way. Garoupa (2007) studies the trade-off between enhancing internal productivity of an illegal activity while and increasing the vulnerability of detection of organisation members. He focuses on the optimal size of the criminal organization taking the internal structure as given.

Bar-Isaac and Baccara (2006) shows that the exchange of potentially incriminating information between criminals helps sorting into criminal networks and also acts as a coordination device. Incriminating information exchanged between direct neighbors can be used for internal punishment and therefore helps to enforce trust and coordination, however, also leaves the organization vulnerable to external threat. They show that depending on the nature of law enforcement both binary team structures and hierarchical structures can be rationalized. It is also the only study on strategic criminal network design that requires the policing authority to commit to a policing strategy prior to network formation.

In general the literature assumes that the network structure is known by the policing authority. Given a particular network structure how does one optimally disrupt the network? As Borgatti (2003) argues this is a problem of identifying the key player in the network. Alternative strategies considered include random and ordered targeting. Ballester et al.

(2006) study the problem of optimal targeting when effort levels are linked through strategic complementarities embedded in the network structure. The key player problem amounts to finding the individual that has the highest influence on the production decisions of all other network participants. Farley (2006, 2003) studies the robustness of terrorist networks to ordered targeting and finds that a hierarchical organisation is least vulnerable.[1]

Goyal and Vigier (2009) look at the strategic interaction between a network designer and an intelligent adversary. The intelligent adversary sees the network and optimal attack involves targeting only a few nodes and ignoring the rest. In response, robust networks consist of equal size groups. When the network designer can utilize a limited budget to defend a subset of nodes the robust network turns out to be a star, as it is best to minimize the number central nodes that can be a target.

In the game I consider, the network planner faces the participation constraint of an individual player and has to take into account that the player may not be willing to join the network. To define the utility function of the individual criminal I adopt the prescription forwarded by Becker (1968). This is becoming an increasingly standard procedure when studying the cost and benefit associated with crime at the individual level (see for example Polinsky and Shavell (1999) and Garoupa (1997)). Ballester, Calvo-Armengol and Zenou (2008) study a model of delinquent networks in which criminals have the option of entering the labour market. This is an individual choice decision and individuals self-organise into stable criminal networks if labour market opportunities are prohibitive. Individuals factor into their decision that the network will be targeted and that their individual probability of detection will depend on their network position. This can reduce the size of the network and also influence structure.[2] My work follows Ballester, Calvo-Armengol and Zenou (2008) closely, however, I

[1]There is a large literature on network security that uses a single agent optimization analysis. Grotschel, Monma and Stoer (1995) looks the design of survivable networks and Borgatti, Carley and Krackhardt (2006) looks at the resilience of various network structures to different concepts of centrality under imperfect information on network structure while Smith (2008) focuses on the adversarys optimal network attack strategy.

[2]See also Bala and Goyal (2000) that studies a game of network formation among nodes faced with an exogenously given uniform probability of link deletion.

consider the problem of network design and not network formation.

I explore the idea of incomplete information in this framework. So far work on network design with incomplete information has been relatively scarce and of closest relevance is the work of McBride (2006), which studies the impact of imperfect monitoring between network participants. Imperfect monitoring in communication networks, where a given network participant is unable to completely visualize other individuals network relationships, leads to too many inefficient equilibria, however star networks are shown to have desirable monitoring characteristics that are robust to refinements that eliminate inefficient equilibria.

Whereas in the first part of the model I study one policing authority against one criminal organization, in the second part I look at many policing authorities and allow them to coordinate efforts. Coordination induces superior policing and one interpretation of this could be that coordination facilitates a move to military methods. Poveda and Tauman (2009) analyse a two stage repeated game in which countries coordinate military effort in the first stage, thereby reducing aggregate terrorist resources, and then decide on defensive policing measures in the second stage. They show the existence of a set of countries that coordinate militarily in the first stage. The size of the set is shown to depend not only on military capabilities but also on political and economic power.[3]

Finally, this paper is also related to the burgeoning literature on peer effects, criminal behaviour and unemployment. Verdier and Zenou (2001), for example, look at the link between racial beliefs and crime and Burdett, Lagos and Wright (2003) study the interaction between crime and unemployment.[4]

The rest of the paper is organized as follows. Section 1.2 covers issues of network theory and centrality and Section 1.3 presents a model of utility and network formation. Section 1.4 looks at the the problem of optimal network design and Section 1.5 introduces and analyzes the strategic in-

[3]More generally there is newly emerging game theoretic literature on counterterrorism, see for example Atkinson, Sandler and Tschirhart (1987), Lapan and Sandler (1988), Sandler and Siqueira (2006) and Sandler and Arce (2007).

[4]See also Huang, Laing and Wang (2004). For an empirical study of social interactions and crime see Glaeser et al. (1995)

teraction between network designer and policing authority and also looks at coordinated policing. Section 1.6 concludes. Proofs of propositions if not explicitly stated in the text can be found in Appendix A.

1.2 Networks and Centrality

In what is to follow I repeatedly talk about Bonacich Centrality, Inter-centrality and the centralization of a network. For this reason this section first introduces the concept of a network and centrality and then proceeds to introduce the model.

1.2.A The Network

A network or graph g consists of a set of n agents (players) linked by a set of weighted edges, where $g_{ij} \in [0,1]$ is the weight assigned to the link $(i \rightarrow j)$ when i is directly connected to j. We consider unweighted networks with at most one link between i, j for any $i, j \in g$, where $g_{ij} \in \{0,1\}$, such that $g_{ij} = 0$ when $(i \nrightarrow j)$ and $g_{ij} = 1$ when $(i \rightarrow j)$.

We restrict attention to undirected networks where $g_{ij} = g_{ji}$ for all $i, j \in g$. We also assume that the network has no self-loops i.e. $g_{ii} = 0$ for all $i \in g$. A player $i \in g$ is isolated if $g_{ij} = 0$ for all $j \in g$. An isolated player is not considered part of the criminal network and his output is normalised to 0.

A path in g of length k from i to j is a sequence $p = \{i_0 \rightarrow i_1 \rightarrow ... \rightarrow i_k\}$ connecting players in k-steps such that $i_0 = i$, $i_k = j$, $i_p \neq i_{p+1}$, and i_p and i_{p+1} are directly linked. Let $g_{ij}^k = 1$ denote the fact that $i \rightarrow j$ indirectly through a path of length k. A connected graph is a network structure in which $g_{ij}^k = 1$ for all pairs of players $i, j \in g$ and some finite length k. In particular we are interested in two specific network structures in g. Before defining these structures we will spend a couple of lines discussing the concept of network centralisation.

1.2.B Network Centrality

The social networks literature offers a plethora of criteria, not always micro-founded, for assessing the centrality of a node. Our preferred measures of centrality are Bonacich and Intercentrality because as shown by Ballester et al. (2006) these are natural outcomes of a network game in which agents maximize their utilities. Here I offer a brief explanation of their workings.

1.2.B.a Bonacich Centrality

The nature of direct links in g can be be succinctly summarised in the n-square adjacency matrix G, so that entry $g_{ij} = \{0, 1\}$ in G captures the direct link between (i, j). Because we are dealing with undirected graphs, G is symmetric. Let G^k be the $k - th$ power of G with coefficients g_{ij}^k for some integer k. The number of indirect paths between (i, j) of length k are counted by $g_{ij}^k \geq 0$ and stored in G^k.

Let $\theta \geq 0$, to be defined more precisely in later sections, be a decay factor such that $m_{ij}(g, a\theta) = \Sigma_{k=0}^{+\infty} \theta^k g_{ij}^k$ counts the total number of paths in g starting at i and ending at j, where paths of length k are weighted by some factor θ^k. The Bonacich Centrality of player i, $b_i(g, \theta) = \Sigma_{j=1}^n m_{ij}(g, \theta)$, counts the total number of paths in g starting from i.

Equivalently we can capture this information in the form of a matrix where $m_{ij}(g, \theta)$ are the coefficients of the following matrix:

$$\mathbf{M}(g, \theta) = [\mathbf{I} - \theta \mathbf{G}]^{-1} = \sum_{k=0}^{+\infty} \theta^k \mathbf{G}^k$$

So that the vector of Bonacich Centralities can be written in the following form:

$$\mathbf{b}(g, \theta) = \mathbf{M} \cdot \mathbf{1} = [\mathbf{I} - \theta \mathbf{G}]^{-1} \cdot \mathbf{1}$$

However, in order for $\mathbf{M}$ to be well defined we require the decay factor θ, that scales down the relative weight of longer paths, to be small enough. In particular we require that θ is less than the inverse of the largest eigenvalue of G, denoted $\rho(g)$.[5] This is required to ensure that the coefficients $m_{ij}(g, \theta)$ are bounded and do not explode.

We can re-write b_i in the following manner:

$$b_i(g, \theta) = m_{ii}(g, \theta) + \sum_{j \neq i} m_{ij}(g, \theta)$$

A node's Bonacich Centrality is increasing not only in his direct links, i.e. his degree centrality, that in turn allow him to access a higher number of indirect links but also in θ which allows the information generated at node i to travel farther distances thus compounding the effect of higher direct links.

One last thing to note is that b_i includes the number of self-loops, $m_{ii}(g, a)$. This is information that originates at i but flows back to i after mixing with information from other nodes $j \neq i$ in path k. By definition $m_{ii}(g, \theta) \geq 1$ therefore $b_i(g, \theta) \geq 1$. Equality is attained when $\theta = 0$[6].

1.2.B.b Intercentrality

Knowing the Bonacich Centrality and number of self loops of player i, we can define the Intercentrality of player i as:

$$d_i(g, \theta) = \frac{b_i(g, \theta)^2}{m_{ii}(g, \theta)}$$

Intercentrality counts the total number of paths in g ending at i and therefore measures the amount of new information flowing to i from elsewhere in the network.[7]

In a quadratic utility setup where the utility of agent i depends, through strategic complementarities, on the effort levels of all other agents in the

[5] Because we are dealing with a square and symmetric matrix G, the Perron-Frobenius theorem guarantees that the largest eigenvalue of G is real and positive.

[6] We are using a normalised Bonacich Centrality. In the original Katz-Bonacich measure $\mathbf{b} = [\mathbf{I} - \theta\mathbf{G}]^{-1} \cdot \mathbf{G}.\mathbf{1}$, and in this case Bonacich Centrality is exactly the same as degree centrality when $\theta = 0$.

[7] A node that exhibits high Betweenness centrality should also, on average, exhibit high Intercentrality depending on the magnitude of θ.

network Ballester et al. (2006) show that removing the agent with the highest Intercentrality from the network maximally reduces the output of the resulting network i.e. Intercentrality is the solution to the following optimization problem, where χ_g denotes total effort level in network g and g_{-i} denotes a network with player i removed

$$\max_{i \in g} \chi_g - \chi_{g_{-i}}$$

1.2.C Network Centralisation

Network centralisation is a concept of group centrality and the heterogeneity within it. In the social networks literature, the standard procedures used to evaluate centralisation either rely on assessing by how much the highest individual centrality differs from the rest, or by looking at how individual centrality is dispersed.

In order to study whether the strategic interdependence between the organizational structure of a criminal outfit and a policing authority leads to centralization of criminal activity I identify clear examples of decentralized and centralized networks that meet both the centralization criteria discussed above.

1.2.C.a Decentralised Networks

Let r denote a fully connected regular graph in which all n players are directly connected to all other $n-1$ players i.e. $g^1_{ij} = 1$ for all $j \neq i \in g$. In this particular network structure each player has exactly the same of connections, $n-1$ and is connected to every other player in the network. Any information originating from player i flows directly to all other players. Both Bonacich and Intercentrality assign the same value to each node in this structure.

Let c denote a network in which each player is only connected to one other player and each team of two players is independent of each other, taking on the form of binary cells. Both r and c are symmetric networks therefore

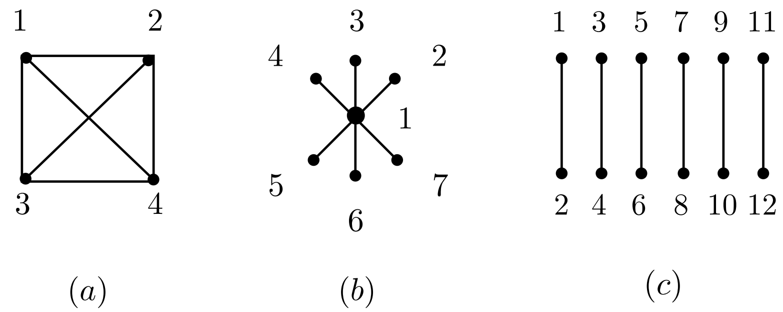

Figure 1.1: Three networks utilizing $\bar{l} = 6$, (a) decentralized regular, (b) centralized star, (c) decentralized binary team.

there is no disparity in node centrality between players. Bonacich Centrality assigns a different value to each node than Intercentrality but this value does not differ across nodes. These structures are ideal candidates for modeling decentralized activity. r represents one big decentralized team, whereas c represents a collection of small independent and decentralized teams.

1.2.C.b A Centralised Network

Let s denote a star graph consisting of one hub h directly connected to all other $n-1$ players i.e. $g^1_{hj} = 1$ for all $j \neq h \in g$ and $n-1$ peripheries such that $g^2_{ij} = 1$ for all $i, j \neq h \in g$. In this structure any player that is not the hub can only share information directly with the hub. Whereas the activities of the hub are directly visible to the periphery, only the hub can see the activities of individual periphery players through his direct links. The social networks literature considers the star graph the most centralized structure in the set of all graphs. We follow this prescription and use the star for modeling centralized activity.

Figure 1 depicts an example of r with $n = 4$, s with $n = 7$ and c with $n = 12$. It is evident that all three structures use the same number of direct links.

1.3 Individual Utility

Consider the simplest formulation of a network game in which each player $i = 1, ..., n$ selects an effort level $x_i \in \mathbb{R}^+$ to obtain a linear-quadratic payoff

$$u_i(x_1, ..., x_n) = \alpha_i x_i - \hat{\delta} x_i^2 - \hat{\delta} \sum_{j \neq i} x_i x_j + \hat{\lambda} \sum_{j \neq i} g_{ij} x_i x_j \tag{1.1}$$

where $\alpha_i = \alpha[i]$ and $[i]$ is an indicator function that takes value 1 if $n = 1$ or if $g_{ij} = 1$ for at least one $j \neq i$, and 0 otherwise.[8] Utility is strictly concave in own effort, $\partial^2 u_i / \partial x_i^2 = -\hat{\delta} < 0$. The influence of other players efforts $j \neq i$ are captured through the cross-partial: $\partial^2 u_i / \partial x_i \partial x_j = -\hat{\delta} + \hat{\lambda} g_{ij}$. The network game exhibits global strategic substitutability in effort levels through $\hat{\delta}$. Recall that $g_{ij} = 1$ if player i and j are directly connected in the network. For this reason the above network also exhibits local strategic complementarity in effort levels through $\hat{\lambda} g_{ij}$. The negative impact of global rivalry is countered through the positive impact of local complementarities. A necessary condition for a unique and stable equilibrium to exist is that $\hat{\lambda} \leq \hat{\delta}$. When the magnitude local complementarities exceed global substitutability the network game exhibits supermodularity and is subject to multiple equilibria.

In this paper I am only interested in the unique and stable Nash equilibrium of the above network game. Before characterizing this for any network g, I characterize the optimal effort level for an isolated player, $n = 1$, and his equilibrium utility.

Remark 1.1. *In the benchmark case, when $n = 1$, the isolated player exerts an effort level of $\bar{x} = \frac{\alpha}{2\hat{\delta}}$ and attains an equilibrium utility of $\bar{u} = \frac{\alpha^2}{4\hat{\delta}} > 0$.*

Anticipating what is to come, I intentionally label $x_1 = \bar{x}$ and $u_1 = \bar{u}$. I borrow two well-known results from Ballester et. al (2006) to first provide

[8] This is actually an innocuous assumption and does not change the nature of results. The assumption has two consequences. On the one hand a player operating in isolation attains a non-negative utility. Additionally players will be indifferent to joining the network absent links because in this case effort levels and utility normalize to 0. The appendix discusses the qualitative impact of this assumption versus the standard model in which $\alpha_i = \alpha$.

a necessary and sufficient condition for the existence of uniqueness and the characterization of the unique equilibrium for any arbitrary network g. Denote $\theta = \frac{\hat{\lambda}}{\hat{\delta}}$ and let $\rho(g)$ be the spectral radius of g, then the following result holds.

Proposition 1.1. *If $\theta\rho(g) < 1$ then there exists a Nash equilibrium in which the effort level of player i is uniquely determined. In this equilibrium player i exerts effort in proportion to his Bonacich Centrality in the network g.*

$$x_i^*(g,\theta) = \frac{\alpha[i]}{\hat{\delta}} \frac{b_i(g,\theta)}{1 + b(g,\theta)}$$

where $b = b_1 + ... + b_i + ... + b_n$ denotes the sum of all individual Bonacich centralities.

The proof of the above proposition relies on θ and g_{ij} being common knowledge for all n players. Knowledge of these parameters allows players to best respond to each others effort choices and attain the unique effort-choice equilibrium.[9]

It is clear that $[i] = 0$ when $n > 1$ and no links exist between any pair $\{i, j\} \in n$. If this case arises the optimal effort level chosen by player i is $x_i = \underline{x} = 0$, and in equilibrium player i obtains utility $u_i = \underline{u} = 0$. I state the following Corollary to be sure that this game permits a non-negative equilibrium utility for individual players in any given network structure g.

Corollary 1.1. *In the unique equilibrium for any given network g each player i attains a non-negative utility in proportion to the square of his Bonacich centrality in g. More precisely*

$$u_i^* = \frac{\alpha^2}{\hat{\delta}} \Big(\frac{b_i(g,\theta)}{1 + b(g,\theta)} \Big)^2 > 0$$

Proof. Follows directly by substituting in x_i^*, from Proposition 1, into (1) and noting that $b_i = 1 - \theta \sum_{j \neq i} g_{ij}$ from the definition of Bonacich centrality. □

[9] Interested readers are referred to a detailed proof in the original article by Ballester et al. (2006).

Global substitutability has an overpowering effect in this model. The following remark describes the strength of global substitutability in the present framework. The condition stated in remark 1.2 is very restrictive and in fact, is easy to see, is never satisfied for any (n, g). Remark 2 says that effort levels in the network game, for any value of θ such that a unique equilibrium exists, are always lower than in a game without global substitutability.

Remark 1.2. *It is always true that* $b_i(g, \theta) \leq 1 + b_{-i}(g, \theta)$*, where* $b_{-i} = b_1 + ... + b_{i-1} + b_{i+1} + ... + b_n$*. Hence for any given network structure* g *player* i *always exerts effort level* $x_i \leq \bar{x}$ *and obtains* $u_i \leq \bar{u}$ *in equilibrium.*

Consider the benchmark case in which $n = 1$. In this case remark 1, tells us, $\bar{u} = \alpha^2/4\hat{\delta}$. Now imagine $n' > 0$ more players would like to enter the network game, but absent any links each player would have to exert effort in isolation. Since individual utility in this scenario is $\underline{u}$, all n' players are indifferent between entering the network game or not. Each potential entrant can be made weakly better off if an arbitrary network structure $g \in \{g_{ij} = 1$ for at least one pair $ij\}$ is imposed. However, player 1 is clearly worse off, although he still attains a positive utility.

Remark 1 and 2 are presented to ground the idea that, in the present framework, imposing any network structure $g \in \{g_{ij} = 1$ for at least one pair $ij\}$ when $n > 1$ is weakly beneficial for all n compared to the benchmark case, where n players simultaneously enter the network game without any links. However the network game displays a first mover advantage in which an isolated player, who cares about maximizing his own utility, can do strictly better by restricting access to potential entrants even if he has at his disposal the technology to build links between himself and potential entrants.

An objective function that does not require some form of utility maximization may render equilibrium network structures that utilize $n > 1$. I develop the idea of network design in the following section.

1.4 Optimal Network Design

Consider the network game determined by equation 1.1 for a given $\hat{\lambda}$ and $\hat{\delta}$. Denote by $\chi(g,\theta) = x_1(g,\theta) + ... + x_n(g,\theta)$ the total effort level of the n players in the network g operating with θ. The n players act alone and do not have the technology to build links with others. Now consider the problem of a Central Network Planner who has access to $\bar{l} \in \mathbb{R}^+$ links, which he can distribute costlessly across the n players. His objective, in doing so, is to choose a link distribution $g : \bar{l} \in \mathbb{N} \rightarrow \mathcal{G}$ such that he maximizes $\chi(g,\theta)$. Isolated players, without a link provided by the central planner, act independently and do not contribute to the planners utility.[10]

For tractability I restrict the strategy-action space of the central planner to three choices $g \in \{r, s, t\}$. Using his links the planner can connect any $k \leq n$ players to each other in a fully connected network denoted r. Instead he can choose to assign player i the role of hub and utilize his links to connect all other $k \leq n-1$ players to the hub in the shape of a star, denoted s. As a third option he can choose a team structure denoted t. The team structure is a network made up of disjoint sub-networks (components) g_k, in which at least two players are connected. I impose some restrictions on the topology of the sub-components and require that $g_k \in \{r, s\}$ i.e. sub-components have to be either regular or star. Thus the binary team structure c presented above is a special case within the set of team structures t.

In addition I also impose the following restriction. This assumption allows us to focus on the important cases in a simplified manner without taking away or changing any of the qualitative results of the paper.

Assumption 1.1. *Let $\bar{l}$ be such that the largest regular network $\bar{r}$ connects an integer number of players and utilizes all $\bar{l}$ links.*

[10] This is consistent with the notion that players have to announce their availability to the organization, which then decides whether to hire them or not i.e. give them a link. Players without organizational links can act independently but their optimal effort choice is 0 and therefore can be ignored.

1.4.A An Example

To ground ideas consider the following example. Let $\bar{g} : g \in \{r, s, c\}$ denote the largest network in its class and let g_n denote a network $g \in \{r, s, c\}$ that connects n players.

The central planner faces $\bar{l} = 6$ and has access to $n \geq 12$ players. He has the following options: (a) he can utilize all his links and connect the 7 players in a star $\{\bar{s}\}$, (b) he can use all of his links to connect only 4 players in a regular network $\{\bar{r}\}$, or (c) he can use the 6 links to create team structures of (i) 2 regular networks of 3 players each $\{2r_3\}$, (ii) a regular network with 3 players and a star network with 4 players $\{r_3, s_4\}$, (iii) two star networks with 5 and 3 players respectively $\{s_5, s_3\}$, (iv) a star network with 5 players and 2 binary cells with two players each $\{s_5, 2c\}$ and (v) 6 binary structures utilizing all 12 players $\{\bar{c}\}$.[11]

$\{\bar{c}\}$ utilizes the most players in this setting. The regular network in (a) concentrates all links on 4 players, while the star in (b) allows the central planner to utilize 3 more players, but still concentrates all links on $7 < 12$ players. The other hybrid structures vary between $k \in [6, 9]$ players.

Anticipating the general characterization provided below, I rank the total effort levels for two values of $\theta \in \{0.1, 0.3\}$. This is easily achieved by writing out the adjacency matrix for each graph and computing the Bonacich centralities as described above.

Remark 1.3. *Based on the different values of θ we obtain a different ranking of total effort levels. In particular for (a) $\theta = 0.1$ and (b) $\theta = 0.3$ we have:*
(a) $\chi(\bar{c}) > \chi(\{s_5, 2c\}) > \chi(\{s_5, s_3\}) > \chi(\bar{s}) > \chi(\{r_3, s_4\}) > \chi(\{2r_3\}) > \chi(\bar{r})$
(b) $\chi(\bar{r}) > \chi(\bar{s}) > \chi(\{s_5, s_3\}) > \chi(\{s_5, 2c\}) > \chi(\bar{c}) > \chi(\{r_3, s_4\}) > \chi(\{2r_3\})$

For a low value of θ network structures that utilize more players generate higher aggregates. Recall that equilibrium effort levels are a function of

[11] Other combinations of hybrid structures also exist for this example, but the five noted are sufficient for the purposes of this example.

Bonacich centrality, which itself counts the total number of paths of length $k = 1, ..., \infty$ and weights them by θ^k. When θ is low only paths of small finite length matter. A network structure that connects as many players as possible maximizes path counts of finite length and for this reason the binary-cell structure maximizes aggregate effort. Intuitively the local complementarities are not strong enough to flow through big networks and are best internalized through a collection of small independent subcomponents. A second order effect is revealed when comparing $\{r_3, s_4\}$ with s_7. Both networks utilize the same number of players yet the star induces a higher aggregate effort level. Intuitively the disjoint hybrid structure can never generate more paths of any given length than a connected network with the same number of players. Hence total Bonacich centrality will always be higher in the connected network.

For high θ the intuition remains broadly the same but with an added component. Local complementarities are large enough, relative to substitutability, for the strategic interaction to traverse through longer paths. Arranging players in sub-components naturally limits the total number of long paths. But we also see that denser networks i.e. networks that concentrate more links on less players, best internalize the strength of relative complementarities.

This intuition forms the basis when characterizing optimal network design, which I now proceed to do.

1.4.B Optimal Design with no Outside Option

I assume that players have recourse to an outside option of $\omega \in \mathbb{R}^+$, if they choose not to be a part of the network game. In this section I analyze optimal network design when $\omega = 0$ i.e. all players find it beneficial to join a network that gives them positive utility.

The main result of this section is summarized in Proposition 2, which shows that the optimal network structure crucially hinges on the θ with which the network can operate, when the resource endowment of the central planner is limited relative to the number of players who want to take part. Before

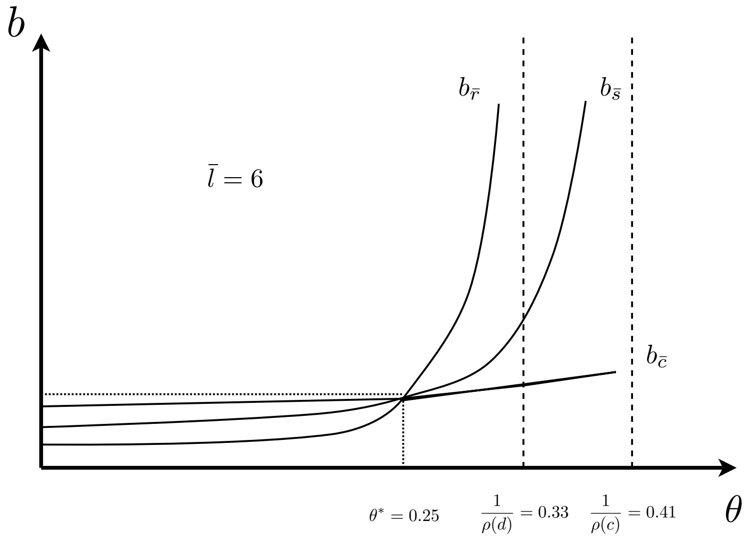

Figure 1.2: Graphical representation of total Bonacich centralities when $\bar{l} = 6$

stating the proposition I state the following definition which will be used frequently in the text.

Definition 1.1. *Let $\bar{g}$ denote the densest network that can be designed using l links and n players i.e. $\rho(\bar{g}) \geq \rho(g')$ for any other g' that can also be designed using the l links and n players. The permissible θ-space, denoted Θ, for the network design game is defined as $\theta \in [0, \rho(\bar{g})^{-1}]$.*

The definition is technical but is necessary to maintain comparability between the the different network structures considered here. For any $\theta \notin \Theta$ the densest network will obtain multiple equilibria while other networks will exhibit a unique equilibrium. In order to avoid this from now on I will restrict attention within Θ when analyzing network design.

Proposition 1.2. *In the network game 1.1 with no outside option, total effort level is maximized by a binary cell structure if $n \geq 2\bar{l}$ and $\theta < \theta^*$. Otherwise a regular network maximizes total effort level. In addition $\theta^* \in \Theta$.*

Proposition 2 shows that it is better to design independent binary teams when θ is low and one decentralized team when θ is large. Either way a decentralized structure is chosen. The proof considers all structures within g before reaching this conclusion, but the intuition is identical to that presented in Section 3.1. It is clear that $b_i(g, \theta)$ is increasing in θ. However, the number of paths a nodes influence can traverse in the network depends not only on θ but also on $|\theta - \frac{1}{\rho(\bar{r})}|$, because $\bar{r}$ is the densest network.

Figure 2 makes clear that the gradient of $b(g, \theta)$ is increasing in θ but only really starts to asymptote as θ approaches its bound. For the three structures depicted in Figure 2 we also see that the aggregate Bonacich curves cross only once. For low θ, $\bar{c}$ produces the highest total Bonacich count but as $|\theta - \frac{1}{\rho(\bar{r})}|$ becomes small, total Bonacich counts more paths in r compared to s which in turn is more than c. s generates more path counts than c for large θ because s is more dense i.e. $\rho(\bar{s}) > \rho(\bar{c})$. This provides graphical intuition of the proof, which requires an assessment of all crossing points between the different graph structures.

1.4.C Optimal Design with a positive Outside Option

Proposition 1.2 characterizes the relationship between aggregate effort level, the size and density of a graph and the θ with which it operates. Below the cutoff θ^* binary cell structures dominate any network design that aims to maximize aggregate effort levels, while above the cutoff network structures with one large regular component dominate. Thus the trade-off always seems to be between small independent decentralized structures or one large decentralized structure. Ultimately the choice of network design hinges on the link constraint $\bar{l}$ that the central planner faces and θ.

The network design proposed by the planner is always accepted by the players because they are guaranteed a non-negative equilibrium utility. In this section I study whether this trade-off changes when the network players have access to a positive outside option if they choose not to join the network.

More precisely imagine an extended network game in which each player either selects an effort level $x_i = 0$ and obtains an outside option of $\omega \in \mathbb{R}^+$ or selects an effort level $x_i > 0$ to obtain the continuation linear-quadratic payoff given by 1.1.

We know from Remark 1.2 that $\omega > \bar{u} = \frac{\alpha}{4\hat{\delta}}$ does not support any network structure in equilibrium. However certain equilibrium structures may be supported in equilibrium when $\omega \in [0, \bar{u}]$. In order to determine precisely the networks supported in the equilibrium of the extended game I first lay down a notion of network stability.

Definition 1.2. *A network g is stable and supported in equilibrium if and only if, given the outside option ω, the lowest utility attained in the existing network is at least as high as ω. Formally,*

$$\min_{i \in g} u_i(g, \theta) \geq \omega$$

The notion of stability that I employ is a weaker version of that present in Ballester et. al (2009). Individual players do not have the ability to form links, therefore all that matters is that no network participant wants to sever an existing link. This is guaranteed as long as the player with the lowest utility in the network obtains at least his outside option.

Denote $\bar{\omega} = \frac{\sqrt{\omega\hat{\delta}}}{\alpha}$. With the above notion of stability, we have the following result.

Lemma 1.1. *The network g is stable if and only if:*

$$\min_{i \in g} \frac{b_i(g, \theta)}{1 + b(g, \theta)} \geq \bar{\omega}$$

Proof. This follows directly from using Corollary 1 in conjunction with the definition of stability. □

From now on let $\underline{b}_g$ denote the player that satisfies $\min_{i \in g} b_i(g, \theta)$, and let $\underline{u}$ denote the utility of this player. With $\omega > 0$ the central planner has an additional participation constraint to consider in the optimization problem. He has to make sure that the network structure that maximizes aggregate effort level also provides $\underline{u} \geq \omega$ to $\underline{b}_g$. This gives rise to an trade-off for the network designer that is characterized by the following proposition.

Proposition 1.3. $\underline{u}_{\bar{c}} < \underline{u}_{\bar{s}} < \underline{u}_{\bar{r}}$ *for any given* θ *and* $\bar{l}$.

Proposition 3 limits the ability of a network designer to use a binary team structure for intermediate ω. Designing just one decentralized team $\bar{r}$ gives the highest utility to players and is also the most productive if $\theta > \theta^*$. However this design loses a lot of effort if $\theta < \theta^*$. In this scenario the network designer would ideally wish to design a binary team structure but may have to limit himself to an intermediate productivity with a centralized star if the outside option makes the binary team structure unstable.

Apart from the binary team network, Proposition 3 does not consider any other team structures in its proof. I therefore deal with characterizing team structures in the next section.

1.4.D Characterizing team structures

We have seen that when there is no outside option the binary team dominates all other team structures for $\theta < \theta^*$ and the decentralized regular network dominates otherwise i.e. apart from the binary team structure the network designer never chooses from the set of team structures. This is true because of the single crossing property of any b_g and $b_{g'}$ and the fact that team structures can never produce more total effort than the binary team for any $\theta < \theta^*$, after which point the regular network clearly dominates.

With a positive outside option ω the analysis is not so clear cut and this section provides a partial mapping of utilities obtained from team structures but is unable to provide a generalization. As a first step I ascertain how to find $\underline{b}$ in any given network g with the help of the following lemma.

Lemma 1.2. *If a team structure contains a binary team then* $\underline{u}$ *resides in the binary team component. If there are no binary components in the team structure then the location of* $\underline{u}$ *depends on the size of the components. If*

$$\frac{n_{\underline{s}} - n_{\underline{r}}}{n_{\underline{r}}} \geq n_{\bar{r}}$$

then $\underline{u}$ resides in the smallest regular component $\underline{r}$, otherwise $\underline{u}$ resides in the smallest star component $\underline{s}$.

Lemma 2 characterizes the location of $\underline{u}$ in a given team structure t. However the exact value of this utility requires knowledge about b_t. It is important to show whether two team structures t, t' can cross each other in Θ as this may affect the ranking of $\underline{u}_t$, however, for now I focus on the bounds within which $\underline{u}_t$ lies.

I state the next result as a conjecture because the identity of the upper bound is not rigorously certified.

Conjecture 1.1. *For any team structure $t \in g$ it must be the case that $\underline{u}_t \in [\underline{u}_{\bar{c}}, \underline{u}_{\bar{r}}]$.*

Assuming that $\underline{u}_t \in [\underline{u}_{\bar{c}}, \underline{u}_{\bar{r}}]$ for any $t \in g$ I still need to ascertain how $\underline{u}_t$ compares with $\underline{u}_{\bar{s}}$ or more precisely which team structures provide higher utility than the star network and which less. This is because there exist team structures that connect less players than the star whose b_t never crosses with $b_{\bar{s}}$ in Θ. At the same there exist team structures connecting more players than the star whose b_t crosses with $b_{\bar{s}}$ at some $\theta^s < \theta^*$. This is not straightforward and remains to be done in future work.

This section touches upon some partial results characterizing team structure topology and shows how to find the lowest utility player in a given team and conjectures a range within which $\underline{u}_t$ should lie. Given these partial results, from now on I will only consider binary team structures along with the star and regular network.

On the basis of Conjecture 1 and Proposition 3 I state the following remark as recapitulation of this section and as a reference point for what is to follow.

Remark 1.4. *If $\omega > \underline{u}_{\bar{r}}$ then no network structure is supported as optimal for the planner. For $\omega \leq \underline{u}_{\bar{r}}$ and $\theta \geq \theta^*$, total effort level is maximized by a regular network. If $\theta < \theta^*$ then total effort level is maximized by*
(a) A binary cell structure if $\omega < \underline{u}_{\bar{c}}$.
(b) A star structure if $\omega \in [\underline{u}_{\bar{c}}, \underline{u}_{\bar{s}}]$.
(c) Either a hybrid structure or regular network if $\omega > \underline{u}_{\bar{s}}$.

1.5 The Role of a Policing Authority

So far I have only considered the optimization problem of the network designer. In this section I introduce a policing authority and study the strategic interaction with the network designer.

1.5.A Beckerian Crime and Punishment

I give the problem a more general structure in this section by considering a Beckerian world of crime and punishment. By being part of a network organization each individual criminal receives a gross benefit, that depends on the network topology, of

$$y_i(x_1, ..., x_n) = \alpha_i x_i - \delta \sum_{j=1}^{n} x_i x_j + \lambda \sum_{j \neq i} g_{ij} x_i x_j$$

where λ and δ respectively represent the true level of local complementarity and global substitutability.

If caught with probability π the criminal pays a fine f in proportion to his utility a_i, that is perceived by the policing authority, from being a part of the network i.e. his expected punishment is $\pi f a_i$ where

$$a_i(x_1, ..., x_n) = \alpha_i x_i - \tilde{\delta} \sum_{j=1}^{n} x_i x_j + \tilde{\lambda} \sum_{j \neq i} g_{ij} x_i x_j$$

i.e. perceived utility is a function not only of network structure g_{ij} but also on the policing authorities perception of local complementarities $\tilde{\lambda}$ and global substitutability $\tilde{\delta}$.[12]

1.5.A.a Perceived Utility and Optimal Policing

Under the assumption that an individual criminal is only liable for his perceived utility I can write the expected utility he obtains from the network

[12] See Becker (1968) from where this representation is inspired. The present framework differs from Ballester, Calvo-Armengol and Zenou (2008) in the sense that higher perceived complementarities reduce individual utility.

as

$$Eu_i(x_1, ..., x_n) = \alpha_i x_i - \hat{\delta} \sum_{j=1}^{n} x_i x_j + \hat{\lambda} \sum_{j \neq i} g_{ij} x_i x_j$$

where $\alpha = 1 - \pi$, $\hat{\delta} = \delta - \pi\tilde{\delta}$ and $\hat{\lambda} = \lambda - \pi\tilde{\lambda}$. This leads us to the next proposition that quantifies how a policing authority assigns utilities to each individual criminal.

Proposition 1.4. *If $\theta\rho(g) < 1$ for any $g \in \mathcal{G}$, in equilibrium a criminal player i, that participates in the criminal network and is caught with probability π, is charged in proportion to his perceived utility that is a weighted average between his Bonacich and Intercentrality*

$$a_i = \frac{\pi(1-\pi)}{(\lambda - \pi\tilde{\lambda})(\delta - \pi\tilde{\delta})} \frac{(\lambda - \tilde{\lambda})b_i + (1-\pi)\tilde{\lambda}(d_i m_{ii})}{(1+b)^2} \tag{1.2}$$

where d_i denotes an individuals Intercentrality and m_{ii} counts the number of self loops. Depending on the policing authorities estimate $\tilde{\lambda}$, of the true local complementary parameter λ, criminal i's perceived utility falls in the following range

$$a_i \in \left[\frac{\pi(1-\pi)}{\delta} \frac{b_i}{(1+b)^2}, \frac{\pi}{\delta} \frac{d_i m_{ii}}{(1+b)^2} \right]$$

Proposition 4 characterizes the ability of a policing authority to assign detection probabilities based on how well informed it is about the network primitives, in particular λ. Ballester et al. (2006) suggest an optimal policy for targeting the Intercentral player from a network. In an ideal world where the policing authority can perfectly visualise the network it should do so. However in a world where policing is subject to the imperfections of monitoring technologies and policing skills, probabilities of detection will be a function both of Intercentrality and Bonacich Centrality. Better informed policing authorities will place more weight on the Intercentrality of a criminal relative to his Bonancich Centrality, whereas poorly informed policing authorities will put more weight on how much a criminal produces relative to others in the network when assigning a perceived utility profile.

For the particular network structures I consider, the ranking of nodes induced by the two measures of centrality coincide.[13] Therefore a policing

[13] Ballester et al. (2006) present an example in which the rankings induced by Intercentrality do not always coincide with those induced by Bonacich centrality.

authority will assign the largest perceived utility to the hub when facing a centralized network and equal probabilities on criminals when facing decentralized activity, regardless of the signal it receives. By definition, however, the Intercentrality of a node is always larger than the Bonacich Centrality hence when facing the same network with the same aggregate Bonacich, the better informed policing authority will assign a higher perceived utility to each criminal in the network.

Let $\mathbf{a} = (a_1, ..., a_i, ...a_n)$ be the vector of perceived utilities induced by the network structure g. I will assume here that the policing authority only benefits from $a_m = \max\{\mathbf{a}\}$. The policing authority chooses π to maximize this value but faces a convex cost function in π. The net payoff of the policing authority is given by the following expression

$$a_m(g, \pi) - c(\pi) \tag{1.3}$$

where $c'(\pi), c''(\pi) \geq 0$.

Proposition 4 allows us to characterise p_m which depends not only on policing skill but also on the expected punishment π. Using this fact, and assuming $c(\pi) = c\pi^2$, we state the following result that determines the optimal π.

Proposition 1.5. *The optimal π is the solution to fourth-order polynomial:*

$$\alpha\pi^4 + \beta\pi^3 + \eta\pi^2 + \kappa\pi + \tau = 0$$

Where $\alpha, \beta, \eta, \kappa$ are all functions of $(b_m, d_m, \lambda, \tilde{\lambda}, \delta, \tilde{\delta})$ and τ is a function of (b_m, λ, δ).

Proof. Taking the first order condition w.r.t π of

$$\frac{\pi(1-\pi)}{(\lambda - \pi\tilde{\lambda})(\delta - \pi\tilde{\delta})} \frac{(\lambda - \tilde{\lambda})b_m + (1-\pi)\tilde{\lambda}(d_m m_{ii})}{(1+b)^2} - c\pi^2$$

and rearranging gives the desired result. □

The characteristic equation in Proposition 5 takes a polynomial form indicating the possibility for multiple equilibria in π. In any of these equilibria π^* will be a function of the information signal, network primitives and more specifically of the network structure. Considering more general objective functions for the policing authority, that do not explicitly rely on network structure can potentially alleviate problems of multiplicity of equilibria.[14]

1.5.A.b Policing Global and Local Network Effects and Network Design

Assume that ω and $\bar{l}$ are common knowledge i.e. the policing authority knows the outside option of the individual player and also knows the resource endowment of the network designer. Knowing $\bar{l}$ means the policing authority knows θ^* and chooses $\pi \in [0, 1]$.

To exhibit local complementarities and global substitutability this model simultaneously requires that $\tilde{\lambda} \leq \lambda$ and $\tilde{\delta} \leq \delta$. In this section I talk about how this set of assumptions impacts the network design choice.

I do not provide a formal micro-founding here, however, assume that information on λ and δ is privately held by the network designer and individual criminals. The policing authority receives a signal on these primitives, which is common knowledge and respectively denoted $\tilde{\lambda} \in [0, \lambda]$ and $\tilde{\delta} \in [0, \delta]$. The closer the signal is to the real value the more informative it is.

A network designer has to take this into account. The designer wants to operate the network at $\theta = \frac{\lambda}{\delta}$, however, due to policing he faces an effective

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[14]We note that $\lambda - \pi\tilde{\lambda}$ can be considered an efficiency loss in policing local criminal interactions. Given its policing skill s a policing authority can reduce this efficiency loss by increasing π. Imagine a situation where a policing authority cares about minimising the product of efficiency losses both at the local and global level. Its objective function takes the form:

$$-(\lambda - \pi\tilde{\lambda})(\delta - \pi\tilde{\delta}) - c\pi^2$$

The F.O.C of this maximisation problem is linear in π and yields the following interior solution for $c > 0$

$$\pi = \frac{\tilde{\lambda}\delta + \lambda\tilde{\delta}}{2(c + \tilde{\lambda}\tilde{\delta})}$$

network design parameter given by

$$\theta' = \frac{\lambda - \pi\tilde{\lambda}}{\delta - \pi\tilde{\delta}}$$

When the signal is perfect i.e. $\tilde{\lambda} = \lambda$ and $\tilde{\delta} = \delta$ or when the signal reveals no information i.e. $\tilde{\lambda}, \tilde{\delta} = 0$ the network designer faces the same effective θ as would prevail without policing. In both these cases the policing authority is unable to influence the network design, but given Proposition 4 the perfect signal enables the policing authority to assign the highest perceived utility a_m to the most Intercentral player within the network, whereas a non-informative signal only enables the policing authority to assign a_m to the most Bonacich central player.

The relative strength of the two signals influences the θ' with which the network can operate. We obtain $\theta' \geq \theta$ if

$$\frac{\tilde{\lambda}}{\lambda} \leq \frac{\tilde{\delta}}{\delta}$$

i.e. the signal on local complementarities is relatively less informative than the signal on global substitutability. When this happens the network designer is able to exploit complementarities more than substitutability.

If θ exists in an open neighborhood of θ^* a policing authority that receives a relatively weak signal on complementarities compared to substitutability can induce $\theta' > \theta^*$. This will make a decentralized regular structure more productive for the network designer. Alternatively a weak signal on substitutability compared to complementarities can induce $\theta' < \theta^*$. Depending on the outside option the network planner will either choose a decentralized binary team structure, if the outside option is negligible, or design a centralized star network if the binary structure is not stable.

1.5.B Multiple Locations and Coordinated Policing

Consider a situation in which there is more than one location where the network designer can set up a network. Each location has its own policing authority that can act independently or coordinate with other policing authorities. By acting alone it is limited to randomly targeting individuals in the network. By coordinating, it can target the Intercentral player.

For simplicity assume that the network designer is endowed with an equal $\bar{l}$ for each location which is common knowledge. ω can differ across locations but is common knowledge. The different outside options can be summarized in the ordered vector $\vec{\omega} = (\omega_1, ..., \omega_i, \omega_{i+1}, ...\omega_k)$ such that $\omega_{i+1} \geq \omega_i$ for any consecutive pairing. The following definition will be useful in the analysis.

Definition 1.3. *Let $\Omega \subseteq \mathbf{R}$ be a subset of the real line and partition Ω into independent sets such that $\Omega_1 = \{w \in \mathbf{R} | w \leq \underline{u_{\bar{c}}}\}$, $\Omega_2 = \{w \in \mathbf{R} | \underline{u_{\bar{s}}} \leq w \leq \underline{u_{\bar{r}}}\}$, and $\Omega_1 = \{w \in \mathbf{R} | w \leq \underline{u_{\bar{r}}}\}$. The vector $\vec{\omega} = (\omega_1, \ldots, \omega_n)$ is Ω-complete if $\vec{\omega} \in \Omega^n$*

1.5.B.a Coordinated Policing

Assume that each location receives a perfect signal on λ and δ. Each policing authority knows θ^* and the vector of outside options. Coordination incurs a cost that is proportional to the resources $\tau \in [0, 1]$ spent coordinating. The benefits of coordination are governed by a minimum effort game such that the payoff location k obtains is given by

$$\gamma_k = (1 - \tau_k) v_k^g + z_k^g \min(\tau_k, \tau_{-k}) - c_k \tau_k$$

where τ_{-k} measures the effort profile of all other policing authorities, v_k^g measures the disruption caused to the network by the policing authority when acting alone and z_k^g is the disruption caused by coordinated policing. Exerting effort to coordinate actions and target the Intercentral player only makes sense when the policing authority faces a star network and the costs of coordination do not outweigh the benefits. In the other two networks all players are equally Intercentral so random targeting is the preferred option for the policing authority. This is summarized in the following lemma. Let $\underline{\tau} = \min\{\tau_{-k}\}$.

Lemma 1.3. *The best response depends jointly on c_k and g_k.*
(a) If location k faces either a regular or binary team network and $c_k \geq 0$

then the best response for k is to set $\tau_k = 0$.
(b) If $c_k > b_k^s(\theta)$ then the best response for local policing authority k is to set $\tau_k = 0$.
(c) If $c_k \leq b_k^s(\theta)$ then the best response requires that k set $\tau_k = \underline{\tau}$.
(d) If there exists k such that $\tau_k = 0$ then all other policing authorities set $\tau_{k'} = 0$.

1.5.B.b Network Design

In this section I will assume that the network designer maximizes post disruption effort levels. If the policing authority does not coordinate it spends resources targeting individuals at random and with probability $p = 1$ the network designer looses one criminal from the network. If he designs a n - regular network he obtains the total effort level of a $(n-1)$ - regular network. If he designs a n - binary team network he obtains the total effort level of a $(n-2)$ - binary team network. Finally if he designs a n - star he obtains the total effort level of a $(n-1)$ - star with probability $(n-1)/n$ and with the remaining probability the hub is targeted and the network designer obtains an effort level of 0.

Let b_{g-} denote expected post disruption total effort level from network g. The expected total effort level from a disrupted star is given by

$$b_{\bar{s}-} = \frac{(n-1)(n-1+2(n-2)\theta)}{n(1-(n-2)\theta^2)}$$

We have the following lemma.

Lemma 1.4. *Random targeting obtains $b_{\bar{c}-} > b_{\bar{s}-} > b_{\bar{r}-}$ if $\theta < \theta^{**}$ and $b_{\bar{s}-} > b_{\bar{c}-} > b_{\bar{r}-}$ if $\theta > \theta^{**}$, where $\theta^{**} > \theta^*$ and $\theta^{**} \in \Theta$.*

Proof. Follows the proof of Proposition 2. □

Lemma 3 shows that the decentralized regular network is not very resilient to random player removal. As we have seen it provides the highest utility to each individual player but removal of one player has a big impact on the effort levels of the other players.[15]

At the same time, random and Intercentrality targeting have exactly the same effect in the regular and binary team networks because everyone has the same Intercentrality. In light of Lemma 2, the network designer has to design a decentralized network in at least one location to induce a breakdown in coordination. If possible, he will prefer to design a binary team structure as this will yield higher post disruption effort level than the regular network.

Imagine a situation in which Ω_3 is complete. In this trivial case the network designer will design regular networks in each location for any $\theta \in \Theta$ and there will be no coordination.

Imagine the network designer can only commit to choosing $\theta \leq \theta^{**}$ and the set Ω_1 is complete. The trivial outcome of this game is no coordination between the policing authorities and decentralized binary team networks in every location.

Consider the situation in which the network designer can commit to $\theta > \theta^{**}$. It is in his interest to design as many centralized star networks as possible. However designing star networks in each location induces coordination, conditional on the costs of coordination being not too high, and with a certain probability τ^* all networks are disrupted. Alternatively the network designer can design a decentralized network in one location and induce no coordination.

The equilibrium of the game crucially depends on the set of coordination costs $\mathcal{C}$. If there exists $c_k \in \mathcal{C} : c_k > b_k^s$ then k has no incentive to coordinate even when he faces a centralized network. If the set Ω_3 is empty the outcome of this game is centralized networks in every location and no coordination between policing authorities. If the set Ω_3 is non-empty the network planner needs to design regular networks in the locations that reside in Ω_3.

Instead, if $\max c_k \leq b_k^s, c_k \in \mathcal{C}$ then coordination is always feasible. How-

[15]This is in line with Albert, Jeong and Barabási (2000) who argue that scale-free networks are robust to random attacks but very vulnerable to targeted attacks.

ever, the coordination game is subject to multiple equilibria. In one set of equilibria the network planner can induce a breakdown in coordination. How this is achieved is stated in the following proposition, which relies on the following definition.

Proposition 1.6. *If $\theta > \theta^{**}$ in every location and*
(a) Ω_3 is empty, the network planner can induce a break down in coordination by designing a binary team in one location that resides in Ω_1 and star networks everywhere else.
(b) Ω is complete, the network planner has to design a regular network in every $k \in \Omega_3$ and star networks everywhere else. This naturally induces a break down in coordination.

Proof. Follows naturally from the arguments presented above. □

Proposition 6 suggests the existence of binary team networks in locations where the outside option for individual players is very low. Whereas in locations with a high outside option only decentralized regular networks can entice individuals to take part in the network. Designing a decentralized structure induces a break down in coordination between policing authorities but does not maximize the total effort level of the organization.

Here I formally introduce the pay off function for the network designer to make this point and characterize the remaining set of equilibria. Let $\mathcal{R}$, $\mathcal{S}$ and $\mathcal{T}$ respectively denote the set of locations in which the network designer implements regular, star and binary team structures. His expected payoff is given by

$$\sum_{k \in \mathcal{R}} b_{\bar{r}-} + \sum_{k \in \mathcal{T}} b_{\bar{c}-} + (1-\tau) \sum_{k \in \mathcal{S}} b_{\bar{s}-} \tag{1.4}$$

Any $\tau \in [0, 1]$ constitutes a Nash Equilibrium of the minimum effort coordination game. For low equilibrium realizations of τ the network designer may prefer to design star networks in every location because the coordination effort is not very high. For high equilibrium realizations of τ the network planner will prefer to design a decentralized network in one location to induce a situation of no coordination. The composition of Ω along with equation 4 determines a threshold τ^*. A coordination equilibrium in which $\tau \leq \tau^*$ will require star networks in each location. Otherwise the network planner will induce a breakdown in coordination in equilibrium.

1.5.C The Role of Incomplete Information

The coordination game of Section 3.2 gives a strong result. A network designer can induce a break down in coordination by designing decentralized networks. This result is purely a function of the benefit structure assumed so far. Benefits from coordination only accrue to those locations that face centralized structures and policing authorities are not influenced by network activity in other locations. Relaxing these assumptions is likely to introduce some variation in the analysis. Alternatively we can think of how incomplete information should be modeled in this setting and its implications.

This section discusses an avenue to link the coordination game of Section 3.2 with the analysis of Section 3.1 and also other ways to view the problem.

1.5.C.a Unknown θ

Consider the situation in which the vector $\vec{\omega}$, $\bar{l}$ and Θ are common knowledge. Each local policing authority draws a signal $\tilde{\lambda}$ and $\tilde{\delta}$ but is unaware of the true primitives λ and δ. Given its signal the policing authority figures out the probability with which effective $\theta < \theta^*$. This probability determines the policing authority's incentive to coordinate conditional on facing an intermdediate ω. The network designer would know the distribution of these probabilities because he operates in each location. The distribution of probabilities may or may not be common knowledge amongst the independent policing authorities raising the need for communication and cooperation if there exist externalities in the policing authorities objective functions. For example, location k may derive direct benefit from successfully disrupting criminal activity in location k', which may be the same or less than the benefit k receives from direct disruption in its own location.

1.5.C.b A General Blotto Framework

Alternatively we could think of a General Blotto framework in which the network designer has a limited number of resources $\bar{l}$, which have to distributed across the different locations. Locations with low ω should witness a larger resource allocation, however $\bar{l}$ and its distribution is private knowledge. Local policing authorities receive a noisy signal about the distribution of $\bar{l}$ and only care about policing their own locality. The vector of outside options $\vec{\omega}$ is known by the network designer however each policing authority only knows its own ω. Communication between policing authorities, modeled through cheap talk, would potentially allow for a more precise distribution of $\bar{l}$. For simplicity assume that θ is common across all locations and common knowledge. A more precise distribution of $\bar{l}$ determines a more precise distribution of θ^* which in turn determines which locations are centralized. If total policing resources are allocated to centralized locations, cheap talk, under certain conditions, may not be informative and induce lying which the network designer may or may not be able to exploit.

Both extensions introduce a problem of endogenous organizational structure between competing entities and within this problem the need to study the mechanism design of truthful coordination. Within either framework it may be fruitful to give more structure to the tension between random and Intercentral targeting. Imagine the cost of random targeting is a fixed amount γ and the cost of Intercentral targeting is convex function of the number of players in the network, but a concave function of the resources available to the policing authority. Coordination allows the shifting of policing resources from location k to k' such that the location with more resources enjoys less convex targeting costs in n, but the location with less resources faces highly convex costs of Intercentral targeting. Such a shift in resources would only be justified from a decentralized to a centralized location. However policing authorities may have an incentive to lie about the degree of centralization they face leading to a breakdown in coordination.

It could be of interest to formalize these concerns in a rigorous theoretical framework and characterize the equilibrium actions of the various players.

1.6 Conclusion

I use the model of Ballester et al. (2006) to study the issue of network design. The network designer is endowed with a limited number of links. The effort decisions of individual players are global substitutes, however, linking any two players together with a network link induces local complementarities. The network designer chooses between team structures that either take the form of one connected centralized team i.e. the star network, one connected decentralized team i.e. the regular network, or a collection of small independent teams that can either be centralized or decentralized, in which a special case of a collection of binary teams.

Given a link endowment the choices of a network planner are shaped by the magnitude of complementarities relative to global substitutability, captured by the parameter θ. When this is very low the binary team structure maximizes total effort level, however, it also provides the lowest level of utility to individual players, compared to all other network structures. If the outside option available to individual players renders the the binary team structure unstable the network planner resorts to the centralized structure of the star. For high values of θ the decentralized regular network not only provides the highest total effort level but also the highest utility for each individual player.

If a policing authority does not know the true magnitude of local complementarities and global substitutability in effort decisions, the relative precision of the signals that it receives about these primitives will influence the effective θ with which the network designer can operate the network. In a situation where an equally precise signal on complementarities and substitutability would induce a centralized star network, a more precise signal on global substitutability relative to local complementarities can lead to a decentralized regular network.

I also study the incentives of independent policing authorities to coordinate, with one another, against a network designer who sets up a network in each location that is policed. I assume that coordination allows for targeting of the Intercentral player while acting alone only allows for random targeting. Coordination is only beneficial for a policing authority if it faces a centralized star network.

In a location with a high outside option for individual players, the only stable network available to the network designer is that of a decentralized regular network. This naturally rules out any coordination between policing authorities. If outside options are very low in every location and the network designer is bound to operate at a low θ then decentralized binary teams in each location not only induce a breakdown in coordination but also provide the highest level of total effort. It is only when binary teams are unstable, in every location, that the network designer may have to forgo, in one location, the higher effort level from a centralized star to guarantee a breakdown in coordination amongst the policing authorities.

Clearly a more realistic model would incorporate the strategic role of incomplete information. However even this simple reduced form model shows that the analysis is not as straightforward as it seems. All the model primitives interact with each other in a non-trivial way to influence network design and equilibrium strategies. A policing authority that does not have perfect information on network design requires information on all network primitives to predict the network structure in equilibrium. Which of these primitives should the policing authority be informed about and how should its objective function be defined is a matter of debate which I touch upon in this paper and hope to formalize with rigor in future work.

Part II

R&D Collaboration

Economists and policy makers alike have long recognized the integral part innovative activities play in fostering economic growth and development. Technological progress and the specific use of it in production processes allows firms to expand their technological possibility frontiers, operate with more efficient mixes on existing possibility frontiers and increase the range or quality of goods available to the consumer.[1]

Private benefits are likely to accrue to firms that successfully innovate. The introduction of a new differentiated product will confer temporal monopoly rights to the firm responsible for the production of the new good. On the other hand, successful process innovation may increase profitability of the firm by reducing its marginal costs of production relative to competitors, allowing it to escape competition (Aghion et al., (2005, 2001)), gaining market share in the process, regardless of whether it faces Cournot or Bertrand competition in the market. This will in turn provide an impetus to the disadvantaged firms to compete in R&D investments, in order to make up lost ground, leading to further technological progress.[2]

Underlying every successful innovation, be it incremental or drastic in nature, is a costly and risky research and development phase. The incentives to innovate rest on the temporal increase of economic rents that accrue to the firm as a result of its R&D investment and its ability to protect them from its competitors i.e. private incentives are shaped through the anticipated and current possession of market power (Kamien and Schwartz (1982)).

While much debate surrounds how the prevailing competitive environment

[1]This work presented in this part of the thesis contains statistical data from the Office of National Statistics (ONS), which is Crown copyright and reproduced with the permission of the controller of HMSO and Queens Printer for Scotland. The use of the ONS statistical data in this work does not imply the endorsement of the ONS in relation to the interpretation or analysis of the statistical data.

[2]This impetus may only exist however, either when disadvantaged firms can steal monopoly status through drastic innovations (Gilbert and Newberry (1982) and Reinganum (1983)), or when they are able to leapfrog the R&D experience of the leading monopolist (Fudenberg et al. (1983), Harris and Vickers (1985, 1987), Judd (1985), Grossman and Shapiro (1987)).

influences a firms incentives to conduct R&D the classic Schumpeterian view is widely accepted: the creation of ex-post monopoly, as a mechanism for protecting innovation rents, is a necessary prerequisite to induce firms to undertake R&D investment, and has played a central role in shaping antitrust and intellectual property policies in advanced economies, evident in a growing willingness of policy makers to provide better legal infrastructure for patent protection.

Underlying this is the notion that innovation is a public good or more accurately the informational content of the innovation is almost completely non-appropriable and costless to acquire (Arrow (1962), Nelson (1959)). Absent an appropriate protection mechanism this information spillover creates free-rider problems. In the extreme case where innovations are readily implementable firms will wait to copy profitable innovations and disengage from R&D activity of their own leading to an insufficient dissemination of knowledge.[3]

By conferring temporal monopoly rights to those awarded, patents create social inefficiencies through deadweight losses.[4] Proponents of a patent system have concentrated efforts on quantifying the optimal length and breadth of patents such that incentives to innovate are maximized while minimizing the associated deadweight losses (Takalo (1998), Gallini (1992)).[5]

Deadweight loss aside, patent policy has also been attacked on the grounds that it might induce inefficient rent seeking and wasteful duplication of R&D efforts by firms entering patent races in an attempt to secure poten-

[3]Even in the absence of informational spillovers, the inability of a firm to perfectly price discriminate its R&D output can lead it to sell (license) its R&D results at prices that lead to inefficiently low levels of utilization by other firms. Moreover, the failure to license may lead competing firms to respond by duplicating research. Given the low costs of distributing the knowledge generated by R&D (relative to the costs of discovery), it is inefficient for firms to duplicate each other's R&D activities Katz (1986).

[4]In principle deadweight losses are eliminated if the resulting monopoly can perfectly price discriminate, but this will be at the expense of a total transfer of consumer surplus to the monopolist i.e. IP protection may still raise distributional concerns absent in other mechanisms.

[5]The efficiency of the policy is measured by the ratio of per-period profit to per-period deadweight loss in the presence and absence of monopoly rights (Gilbert and Shapiro (1990), Klemperer (1990), Denicolo (1996), Ayres and Klemperer (1999), Maurer and Scotchmer (2002)).

tial monopoly rents. Yet it seems that this kind of opportunistic behavior is unavoidable even in the presence of alternative schemes that avoid the creation of ex-post deadweight losses (Scotchmer (2004), Che and Gayle (2003)).

Critics argue that patents are unnecessary and more socially efficient incentive mechanisms exist.[6] An alternative mechanism, that has received much attention in the theoretical literature, which avoids the creation of monopoly inefficiencies without stifling the incentives to innovate, is an awards based or contractual system. However, an awards based system is subject to issues of information aggregation. While awards for innovation ideas originating from the sponsor can be made contingent on formal performance standards set up ex-ante, private initiatives not stipulated in advance can become subject to ex-post hold up problems. In addition parties are likely to have asymmetric information on the innovation value, which may not be observable or verifiable.

Thus proponents of a patent system argue in favor from an ex-ante perspective: the patent incentive mechanism decentralizes decision making and encourages potential innovators to first screen their ideas against expected social valuations, which is specially beneficial when the information asymmetry pertains to the private and social benefit of the innovation (Wright (1983)). It also limits risk transfers to tax payers and it imposes the costs of invention on its end users (Gallini and Scotchmer (2001)).

The design of appropriate award schemes can overcome these problems: mechanisms considered in the literature include contractual schemes, auction design, commitment prizes and hybrids (Kremer (1998), Green and Scotchmer (1995), Sappington (1982)). And in fact it has been shown that even under various asymmetric information and market structures awards systems are more social welfare enhancing than the patent system.

Despite limited theoretical evidence in favor of a patent system, over contractual and award-based systems, it is still the most widespread incentive

[6]In a recent paper Boldrin and Levine (2005) argue that intellectual property is not necessary for innovation and growth, in fact they suggest that IP should not be the norm but rather an exception, because competitive rents are enough for innovators to appropriate a large enough share of the social surplus to compensate them for their opportunity costs.

mechanism in use by policy makers. This might have to do with the fact that in practice identifying all possible innovations and assessing the private and social benefits of each individual innovation would be too costly an enterprise for a centralized institution that would not be able to credibly commit to avoiding ex-post holdup problems.[7]

Spillovers reduce the incentives of firms to conduct R&D. The ability of rivals to use the R&D knowledge of an innovator without its permission can lead to an increase in market competition for the innovator and reduce the expected payoff for the winner of a patent race. Yet there is a socially beneficial element to spillovers: firms are forced to share their R&D knowledge, and while tight patent and copyright laws will help to maintain firm incentives to conduct R&D, by pragmatically eliminating spillovers they do not alleviate the problem of insufficient knowledge dissemination and may actually reduce the efficient sharing of R&D (Katz (1986), Spence (1984)).

An institutional mechanism that allows efficient sharing of information and internalization of the positive externality of informational spillovers is through cooperative R&D arrangements between rivals.[8] These agreements may vary from highly structured Research Joint Ventures (RJVs) to less explicitly structured research consortia and cross-participation agreements (Veugelers (1998), Vonortas (1994), Hagedoorn and Schakenraad (1990), Cainarca et al. (1989)).[9] Inevitably the precise function of the collaboration agreement will also vary ranging from fundamental research

[7]Award schemes are still employed in some industries e.g. in 1992 a $30m prize was announced to develop a new super efficient refrigerator (Penn (1993), Zuckerman (2003)) and in 1996 the X Prize Foundation was set up for the airplane industry (Hoffman (2003)).

[8]Other mechanisms have also been analyzed in the literature. Spence (1984) argues that government subsidies can be an effective policy tool in markets where spillovers are high. But in the world of Dasgupta and Stiglitz (1980) where firms have socially excessive incentives to conduct R&D, subsidies may only serve to confound market distortions. As argued later in the text cooperation agreements can help alleviate the problem here and for the purposes of this thesis I choose to focus on the study of this mechanism.

[9]See also Fusfeld (1986), Contractor and Lorange (1988), Ouchi (1989) and Lewis (1990). For a by no means exhaustive list on the literature studying advantages of different organizational forms for the promotion of R&D and innovation see Link and Tassey (1987), Dertouzos et al. (1989), Teece (1989), Kline (1990) and Kash and Rycroft (1993).

to exchange of existing know-how in cross-licensing agreements to joint development and possible joint production.[10]

Such collaboration agreements may induce new problems of their own, however the benefits may not just be limited to internalizing informational spillovers. Focusing on fundamental and applied development research, what exactly are the costs and benefits of collaborative agreements identified in the literature?

Cooperative R&D, through the sharing of research output, eliminates wasteful duplication of R&D making research effort more efficient. It can also facilitate properly designed cost and risk sharing provisions that restore incentives to share information between partners. Increased access to partners complementary knowledge base, markets and products can create efficiency enhancements through synergies and economies of scale in joint R&D efforts.

Firms may also wish to enter into a collaboration agreement if they are financially constrained, in the hope of receiving direct financing from a cash rich partner. In addition, extending the Holmstrom and Tirole (1997) argument, firms in collaboration agreements may also find it easier to obtain external financing at more favorable rates because they can use the collaboration agreement as a signal of project viability and success e.g. government subsidies supporting cooperation can be considered a special case of external financing, supporting financially constrained firms.

Collaborative ventures open themselves up to the well-known issues of coordination and agency costs. Asymmetric information between collab-

[10] Scotchmer (2004) talks in detail about collaboration agreements set up in order to facilitate cross-licensing between members, specially in industries that require the use of complementary proprietary technologies. Cainarca et al (1989) find evidence that suggests that while firms entering marketing agreements tend to favor the joint venture format, research consortia are initiated primarily to exploit technology agreements, with production and marketing agreements only playing a minor role. Veugelers (1993) finds that only 18% of alliances involve R&D and these concentrate on core technologies like IT. Comparing R&D and non-R&D alliances she also finds that R&D alliances are comparatively less prone to adopt a joint venture format. Mytelka (1991) finds that only 29% of alliances involve knowledge. In contrast Hergert and Morris (1988) find that 64% of alliances involve some research activity, although their dataset is constructed to favor technological cooperation.

orators and limited monitoring ability makes it difficult to assess a partners effort both a-priori and ex-post. Differing objectives may hamper decision-making and partners may free ride on others R&D investments e.g. contributing less able personnel to the project (Shapiro and Willig (1990)).

This makes it difficult to write down an exact contract stipulating the nature of information flows and the contingent cost and effort sharing levels. It is also likely to influence how partners protect themselves from information leakage to external rivals. These negative externalities will impose relation specific infrastructural needs e.g. monitoring technologies, and impact start-up negotiation costs which rational actors will discount prior to the cooperation decision. The tension behind these forces is likely to lead to variation in the observed organizational structures of collaborative agreements. In the extreme case the costs may be high enough for cooperation not to be beneficial.

In an effort to control the revenues from the R&D output, collaborators may also be able to extend their cooperation agreement to decisions that influence the existing competitive environment e.g. pre-emptive R&D, product market collusion etc. Indeed this is a real concern for policy makers that face the difficult challenge of designing antitrust regulation in such a way that encourages greater R&D activity through collaboration while limiting the anticompetitive impact.

Ensuring that cooperative R&D agreements do not extend to collusive behavior is especially relevant in situations where product-market competition is intense and joint cooperative R&D leads to a reduction in production costs for all involved. High competition will lead to a direct transfer of lower production costs to lower prices and dissipated profits. In this scenario firms will either reduce their joint R&D initiative, or will think of ways to cushion the competitive pressure through, for example, collusive measures.

Collaborative agreements may allow partner firms to internalize informational spillovers in competitive way, however defining ownership over R&D outputs may still be necessary to prevent the leakage to and use of innovation enabling knowledge by non-partners.[11] In addition to the traditional instruments of patents, copyrights and design registration that confer exclusive property rights, firms also utilize other mechanisms to protect their innovations.

Recent work by Levin et al. (1987) and Cohen et al. (2000) suggests that firms are more likely to employ non-exclusive strategies such as confidentiality agreements and secrecy in protecting their R&D and subsequent returns. Firms that do avail exclusive property rights such as patents predominantly tend to do so more to improve their subsequent bargaining status in the market, to block rivals from patenting related inventions and for the prevention of legal suits rather than for protecting economic rents from commercialization and licensing.

In order to understand why this might be the case it is instructive to think about what is at the core of the firms appropriability problem, loosely defined here as the firms ability to protect ex-post R&D investment. As long as a rival cannot copy the firms research and produce a similar invention the firm will be able to reap the benefits of its invention.[12] When this is the case, the main decision variable for the firm is how to control information leakage. From the perspective of the firm a cost effective first best solution to this problem is a mechanism that completely eliminates involuntary information outflow, allowing the firm to retain its competitive edge e.g. secrecy.

In the absence of such a mechanism a second best solution is a device that requires some information sharing but limits the ability of rival firms to use the leaked information to reproduce the innovation that gives the innovative firm its competitive advantage e.g. patents (Teece (2000)). Monitoring patent infringement can be an extremely costly procedure, yet it can be relatively cost effective as a way of protecting oneself against infringement suits. This will clearly depend on how correlated the research strategies are between rivals. In industries characterized by small incremental and cumulative innovations it may prove profitable to disclose existing ideas

[11] This has become a central focus of EU innovation policy, which simultaneously advocates collaborative R&D. Further details of various complementary initiatives can be found on www.europa.eu.

[12] This is especially true when firms innovate to primarily use the technology themselves and licensing is not a major concern.

protected by patent to improve chances of inclusion and bargaining power in future R&D decisions.[13]

R&D activity and innovation are good from a social welfare point of view. However, externalities exist that create a wedge between private and social incentives to undertake R&D expenditures. As policy makers work hard to stimulate innovative activity it becomes increasingly important to analyze how firms exploit and rectify market limitations to realize and protect private benefits from an a-priori profitable, albeit risky, enterprise. In particular the following questions are of relevance:

Question 1. *How do competitive forces and spillovers influence firm level R&D decisions? Do firms in active collaboration agreements systematically spend more on R&D?*
Question 2. *What factors help shape the decision of a firm to collaborate?*
Question 3. *How do competitive forces interact with other factors in shaping a firms effective appropriability mix between exclusive and non-exclusive property rights? Do collaborating firms systematically report different mixes from non-collaborating ones?*

I tackle these questions empirically by exploiting a data source particularly suited for their study. My analysis is guided by existing theoretical insights but at the same time I use real world business data to uncover results that in turn may help to shape new theoretical concerns and provide implications for policy makers actively thinking on the interrelated issues of appropriability, spillovers, competition and R&D cooperation.

I first provide a brief description of the Community Innovation Survey in order to acquaint the reader with the principal data source used for this study. Question 1 is dealt with here, while separate chapters are dedicated to Questions 2 and 3.

The principal data source used to answer the above questions is the Com-

[13]While we are primarily interested in ex-ante R&D collaboration, it is possible that firms engage in ex-post collaboration through patent pooling. When the innovative process in the industry requires the use of multiple proprietary components firms may have an incentive to patent their own innovations as a blocking device and as a way of inclusion in patent pools which will allow them to take part in the joint pricing of complementary pieces of intellectual property (Shapiro, 2001) and licensing decisions (Gilbert (2002), Lerner and Tirole (2002), Merges (1999,1996)).

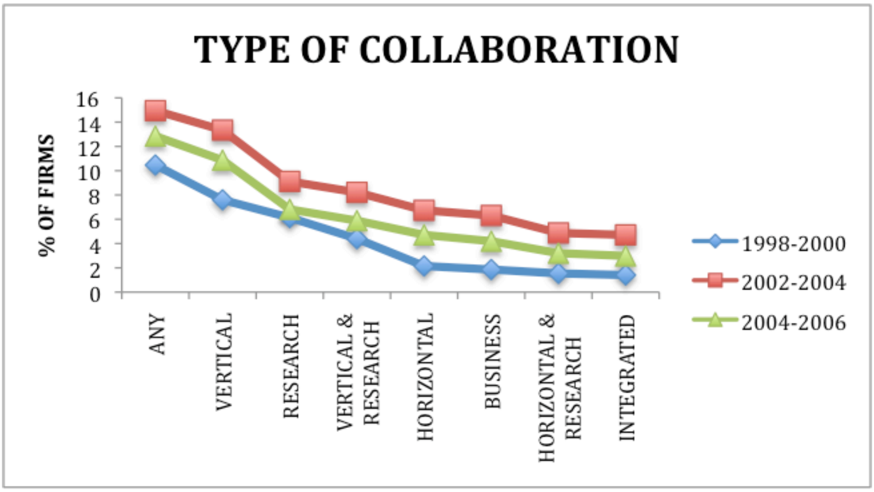
munity Innovation Survey (CIS), 1998-2006, for the UK.[14] The CIS represents a Europe wide initiative launched in 1990 by the European Commission and its statistical arm EUROSTAT. It is based on a harmonized methodology and questionnaire, agreed upon by the EU member states, although some national idiosyncracies in wording and survey structure exist. Initially the survey was circulated once every 4-6 years, to a representative sample of the business population, to retrospectively enquire about innovation behavior during the most recent 3 years. Its informative and policy oriented content has meant that increasingly member nations are conducting it on a more frequent basis. The UK government, through its statistical department, now circulates this survey once every 3 years, while the Spanish government has made its survey annual.

The most recent waves are largely modeled on the Oslo Manual (OECD, 1997). Firms are asked to report, amongst other things, if they process or product innovated, whether this innovation was new to market or just new to firm, how they protect their innovative activity, whether they faced obstacles to innovation, whether they collaborate in their R&D with external partners and whether they use external information sources to inform their innovative activity. Thus the survey provides a wealth of information ideally suited to studying the issues we are interested in.[15]

In the UK survey, each wave sends out 12000 survey forms to independent businesses from a stratified population consisting of both manufacturing and service sector firms. Almost all the largest firms, i.e. with more than 400 employees, are sampled in every wave, whilst smaller firms are randomly chosen. Survey response is voluntary and usually attains a 60% response rate. This means combining cross-sections leads to an unbalanced panel, of which only the largest firms provide the balancing component. I combine the 1998, 2004 and 2006 waves and obtain a panel of almost 28,000 observations. Most of the observations in the panel only appear once, but there is a large enough component of firms that appears twice, and a small

[14] This data source is augmented with information from other business survey data in order to build a more complete dataset that reflects the market environment faced by firms in our CIS sample. Details of the various other data sources will be made available along the course of the presentation.

[15] For a more detailed description of the survey see European Commission (2004). Also Abramovsky et al. (2004) provide a good description of the surveys and sampling methodology in France, Germany, Spain and the UK.



component that appears in all three waves to make a longitudinal analysis meaningful.

The data allows us to look at collaboration tendencies amongst UK firms, across all manufacturing and service sectors for the eight-year period between 1998-2006. It is clear that increasingly more firms entered collaboration agreements over time: an insight that may partially reflect increased policy support for such agreements.[16] What is also evident is the ranking

[16]During 1998-2000 the LINK and Faraday Partnerships schemes were set up to provide funding for establishing research consortia to induce technology transfers. Since the mid 90s specific sectors have been able to access public money to support collaborative agreements through the INTERREG II and III schemes. EUREKA, set up in 1985, is another example of an EU led initiative specifically set up to promote collaborative market-oriented R&D. More recently UK SMEs taking part in collaborative R&D have been given access to research grants and R&D tax credits through the Department for Business Innovation and Skills (BIS). The new EU-FP7 research programme has promised to allocate EUR 32m to the Cooperation programme and ERA-NET scheme to promote research collaboration. Pro-collaboration policies in the UK and EU are not just confined to funding decisions. The BIS in the UK has been working actively towards facilitating collaborative agreements by making them easier to negotiate and secure, see for example the Lambert Research Collaboration Agreement Toolkit. EU policy has also been directed towards increasing awareness about the costs and benefits of collaborative agreements, in particular on issues related to IPRs. A good example of this is the CREST cross border collaboration decision guide. Increasingly we are seeing a trend in EU and UK policy directed towards promoting collaboration between the business and academic community but also between private businesses both within national borders and internationally. See also Abramovsky et al. (2004) for a summary of recent pro-collaboration policies adopted by the UK.

TABLE 1 – COLLABORATION LINKS INTENSITY BY INDUSTRY

Industry Digit		Vertical Links	Horizontal Links	Research Links
73	**Research & Development**	36	19	41
33	**Manufacture of Medical, Precision and Optical Instruments, Watches and Clocks**	29	11	26
32	**Manufacture of Radio, Television and Communication Equipment and Apparatus**	23	10	20
55	**Hotels and Restaurants**	6	4	4
60	**Land Transport**	6	3	3
18	**Manufacture of Wearing Apparel**	6	3	2

* Numbers in %, calculated as the un-weighted SIC 2-industry averages from the 1998-2006 pooled-sample of firms.

between different collaboration agreements with systematically more vertical than research collaboration, which in turn dominates the number of horizontal collaboration agreements.

Table 1 provides an industrial breakdown for the prevalent collaboration agreements for this eight-year period. The sample exhibits a high degree of collaboration within high technology sectors.[17] Listed within this table are, the top and bottom three industries common to all types of collaboration.

In addition to these, vertical and research links were predominant i.e. exceeding 20% of the sample, in industries (72) Computer and Related activities and (24) Manufacture of Chemicals and Chemical Products. While for horizontal links the top five also included (40) Electricity, Gas and Steam and (41) Distribution of Water.

A valuable source of information that I will exploit in the econometric analyses and that forms the basis of the spillover variable is presented in raw form in Table 2. Firms, in relation to their innovation activity, are asked to rank the importance of various informational sources. Table 2 states the top five informational sources for each type of collaboration link. Concentrating on external information sources[18] we find a high importance

[17]We use the definition provided by Eurostat (2005) on high-tech trade to classify SIC2 industries as either belonging to high technology or not.

[18]Firms generally report a high level of information sharing within the enterprise group, and this information source always features in the top 2 regardless of the collaborative inclinations.

TABLE 2 – INTENSITY OF EXTERNAL INFORMATION SOURCING BY COLLABORATION TYPE

	Clients	**Suppliers**	**Competitors**	**TIS**	**PIA**
None	1.2	1.1	0.9	0.7	0.7
	(1.2)	(1.1)	(1.0)	(1.0)	(0.9)
	Clients	**Suppliers**	**Competitors**	**TIS**	**PIA**
Vertical	2.2	1.9	1.4	1.3	1.0
	(1.0)	(0.9)	(1.0)	(1.0)	(0.9)
	Clients	**Competitors**	**Suppliers**	**TIS**	**CTE**
Horizontal	2.1	1.8	1.7	1.2	1.2
	(1.0)	(1.0)	(0.9)	(1.0)	(0.9)
	Clients	**Suppliers**	**Competitors**	**TIS**	**PIA**
Industrial	2.3	2.0	1.9	1.4	1.3
	(0.9)	(0.9)	(0.9)	(1.0)	(0.9)
	Clients	**Suppliers**	**TIS**	**CCPRD**	**Univ**
Research	1.8	1.6	1.4	1.3	1.3
	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
	Clients	**Suppliers**	**TIS**	**Competitors**	**CCPRD**
Vertical Research	2.3	2.0	1.7	1.5	1.5
	(0.9)	(0.9)	(1.0)	(0.9)	(0.9)
	Clients	**Suppliers**	**TIS**	**PIA**	**Competitors**
Horizontal Research	1.9	1.6	1.6	1.5	1.5
	(1.2)	(1.1)	(1.2)	(1.0)	(1.1)
	Clients	**Suppliers**	**Competitors**	**TIS**	**PIA**
Integrated	2.3	2.0	1.9	1.8	1.6
	(0.9)	(0.9)	(0.9)	(1.0)	(0.9)

* Firm responses are graded on a likert scale ranging from 0 – not used to 3 – high use. Numbers reported are the un-weighted averages for each collaboration type pooling together information from the entire 1998-2006 sample of manufacturing and service sector firms. Numbers close to 2 suggest medium use of information source on average. Standard errors reported in parenthesis.

TABLE 3 – INNOVATION & STRATEGIC CONCERNS BY COLLABORATION TYPE

	None	Vertical	Horizontal	Research
Success Rate	25.8	73.1	64.9	68.5
Process vs. Product	0.7	0.7	0.6	0.7
Relative Strategic	3.2	4.0	4.2	4.6
Relative Legal	3.1	3.3	3.6	4.2
Strategic vs. Legal	1.0	1.2	1.2	1.1
Relative Financial Constraints	1.8	1.9	1.6	2.0
Relative Perceived Risk	2.0	2.3	2.3	2.3
Relative Costs	2.1	2.3	2.4	2.5

* All figures calculated are based on the un-weighted averages for each collaboration type pooling together information from the entire 1998-2006 sample of manufacturing and service sector firms. Process and Product innovation are binary variables at firm-level where 1 indicates successful innovation as reported by the firm. Strategic is a measure of the intensity of use of non-exclusive property rights for protecting innovative activity. It combines firm level responses to the use of secrecy, confidentiality agreements, complexity of design and lead-time advantage, all measured on the likert scale from 0 – no use to 3 – high use. Legal is measure of intensity of use of exclusive property rights constructed by combining firm-level responses to use of patents, trademarks, design registration and copyright. All these variables along with financial constraints, perceived economic risk and relative costs (as an obstacle to innovation) are measure on the 0-3likert scale. The reference category for all "Relative" measures is the pooled group of firms that have no collaboration links and did not innovate.

attached to vertical information sourcing i.e. from clients and suppliers. Other information sources that appear here are competitors, technical, industry and service standards (TIS), Professional and industry associations (PIA) and conferences, trade fairs and exhibitions (CTE). There is weak evidence (I abstract from presenting formal tests of significant differences) that collaboration is associated with more intense information sourcing. Different types of collaboration links are associated with different rankings of information sources, with a weak preference for sourcing information from the same industry as the collaboration partner e.g. firms collaborating with research institutes place more importance on information from universities, while firms that do not have collaboration links do not consider universities as a top five information source.[19]

Table 3 digs deeper into the ranking of collaboration links identified in previous table. We see that firms with collaboration links have a substantially higher innovation success rate, defined as a combination of product and process innovation. In our sample we are more likely to find firms product innovating, however, the split of process to product innovation is pretty

[19]Firms without collaboration links give an average score of 0.2 to universities as a source of information, while firms with vertical or horizontal links assign a score of 0.3. In both cases this information source is ranked the least important. Thus the 1.3 score assigned by research collaborators marks a significant economic and statistical difference.

stable across collaboration structures. For every 10 instances of product innovation within vertical collaboration we also find 7 instances of process innovation. Horizontal collaboration agreements seem to slightly skewed towards product innovations, but again we cannot say anything conclusive without formal testing.

Relative to an average non-innovating firm with no collaboration links, successful innovators report financial constraints, perceived risk and costs of almost twice the magnitude. In turn collaborating innovators report even higher magnitudes. Although marginal there exist differences in the constraints faced by different types of collaborators. Collaborators generally report a higher perceived economic risk that seems to independent of the type of collaboration link. On the other hand research collaborators report the highest relative costs while horizontal collaborators report the lowest financial constraints.

Table 3 also shows us how collaborative innovators protect their R&D investment. Relative to non-innovators without collaboration links, collaborators are almost three times as likely to use legal instruments as a protection mechanism. At the same time they are four times more likely to employ strategic protection mechanisms. Thus while non-innovating firms without collaboration links are likely to put an equal weight on legal and strategic means of protection, collaboration links more actively rely on strategic mechanisms.[20] The degree to which they do this seems to depend on the type of collaboration link they have, with business links utilizing strategic protection methods relative to legal, more than research links. Yet research links report using both strategic and legal methods more intensively in comparison to business links.

Are there other reasons that influence choice of collaborating partner? I focus on process and product innovation separately and distinguish between innovation that is new to market (NTM) and imitation i.e. innovation that is only new to firm (NTF). Table 4 shows this breakdown.

Again we see that firms with collaboration links are the more successful

[20] (Surprisingly) the average non-innovating firm without collaboration links reports a positive use of both legal and strategic instruments despite not successfully innovating in the period under consideration.

innovators, however interesting differences arise. While imitations dominate process innovations, pure innovations dominate product imitations. Here there is a clear indication that horizontal and research collaboration are associated with more pure innovations, be it process or product, while vertical collaboration concentrates on imitation.

We also note clear differences in the appropriability mixes. Firms that successfully process innovate without collaboration links protect their innovation 40% more, through legal means, and 30% more, through strategic means, than firms that are successfully able to imitate without collaboration links.

An almost similar difference is seen between innovators and imitators with vertical links. However we see that horizontal collaborators that successfully innovate protect their innovation 60% more, through strategic means, while only placing 10% more weight on legal protection compared with horizontally collaborating imitators.

Thus we see that innovators with no or vertical collaboration put more emphasis on legal protection relative to their imitating counterparts, while horizontal and research collaborators with innovations place a lot more weight on strategic protection relative to their imitating counterparts. A similar story though not as pronounced is also observed for product innovations.

A more detailed look at the data reveals that within each collaboration type, firms that innovate systematically report higher use of each component part of legal and strategic protection in comparison to imitators. Focusing on strategic protection and a within group breakdown, both imitators and innovators place highest emphasis on confidentiality agreements and lead-time advantage as a source of strategic protection. However a between groups breakdown shows that innovators choose to exploit, from all the strategic options, complexity of design to a larger degree than imitators.

A within group breakdown on the legal front shows that both imitators and innovators with vertical collaboration partners attach a greater weight to trademarks, those with horizontal partners report greater use of copy-

TABLE 4 – IMITATION, INNOVATION AND APPROPRIABILITY

		None	Vertical	Horizontal	Research
Process	**Success Rate**	13.37	43.26	35.11	38.74
	Relative Freq	0.33	0.41	0.65	0.68
NTM vs NTF	**Strategic**	1.32	1.29	1.63	1.13
	Legal	1.38	1.36	1.13	1.00
	Protection mix	0.95	0.96	1.44	1.13
Product	**Success Rate**	20.39	62.38	58.51	56.46
	Relative Freq	0.71	1.18	1.39	1.35
NTM vs NTF	**Strategic**	1.47	1.43	1.77	1.14
	Legal	1.64	1.73	1.64	1.08
	Protection mix	0.90	0.83	1.08	1.05

* All figures calculated are based on the un-weighted averages for each collaboration type pooling together information from the entire 1998-2006 sample of manufacturing and service sector firms. Process and Product innovation are binary variables at firm-level where 1 indicates successful innovation as reported by the firm. These two categories are further broken down into whether the innovation was new to market (NTM) or new to firm (NTF). Apart from the success rate, all numbers presented are ratios and the reference category is NTF i.e. 13% of firms with no collaboration links introduced a process innovation. For every 10 occurrences of NTF we also have 3 NTM's. Strategic and Legal is defined in Table 3. Thus firms without collaboration links that introduce NTM process innovation use 1.3 times as much strategic protection as firms without collaboration links that introduced a NTF.

right, while research collaborators employ more patents. Yet the between group breakdown reveals that innovators, independently of the type of collaboration link they have, exploit patents relatively more than imitators, in comparison to other legal protection methods. These findings are qualitatively similar and relatively stable across collaboration links for both product and process innovation and therefore not presented in tabular form.

Firms report on the importance of various reasons as drivers for innovative activity. Firms may choose to innovate due to market driven forces to 1) increase range of goods or services, 2) enter new markets or increase market share, 3) Improve quality of goods or services, 4) increase value added, 5) Improve production flexibility, 6) Increase capacity, 7) Reduce unit costs or due exogenous factors to 8) Improve health and safety and meet environmental standards and 9) meet regulatory requirements. Firms in the sample generally report more than one factor as a driver for innovation that obscures the detection of any distinguishing features, in tabular form, for the various factors. In Table 5 I present a snapshot for entering new markets or increasing market share.[21]

[21]The purpose here is to notify the reader that this dimension to the data also exists. It is not that these data lack identification potential. In the analysis to

TABLE 5 – STRATEGIC CONSTRAINTS AND COOPERATION WHEN INNOVATING TO ENTER NEW MARKETS

	None	Vertical	Horizontal	Research
Frequency	75.9	6.3	0.5	1.6
Relative Cost	2.4	2.6	2.7	2.8
Relative FinCon	2.1	2.2	1.9	2.3
Relative Risk	2.4	2.6	2.8	2.8
Relative Strategic	3.1	4.4	4.3	4.9
Relative Legal	3.0	3.6	3.6	4.6
Protective mix	1.0	1.2	1.2	1.1

* All figures calculated are based on the un-weighted averages for each collaboration type pooling together information from the entire 1998-2006 sample of manufacturing and service sector firms. Strategic is a measure of non-exclusive property rights and Legal is measure of exclusive property rights defined in Table 3 along with financial constraints, perceived economic risk and relative costs. The reference category for all "Relative" measures is the pooled group of firms that have no collaboration links and did not report "entering new markets" as a reason to innovate. Firms that reported either 1,2 or 3, on the likert scale, to innovating in order to "enter new markets and increase market share" are all grouped together according collaboration type. Frequency statistics refer to firms in this grouping i.e. 76% of firms that wanted to enter new markets did not have collaboration links and faced costs 2.5 times higher than firms that did not want to innovate to enter new markets and also used strategic protection 3 times as intensively as the reference category.

Before concluding I highlight with Table 6, how appropriability tendencies vary with reported financial constraints, exposure to risk and the real costs associated with innovative activity. Real costs are defined as a combination of excessive perceived economic risk and direct costs of innovation too high as an obstacle to innovation. Risk is defined as a combination of uncertain demand for innovation and lack of information on markets as an obstacle to innovation.[22] A very similar pattern emerges for all three variables. We see that relative to a non-innovating firm, without collaboration links, that does not report excessive exposure to the constraints, collaborating firms report more intensive use of both legal and strategic protection methods. Again there is weak evidence that firms collaborating horizontally favor strategic methods relatively more than legal protection.

It is argued that the absorptive capacity of a firm enhances its ability to assimilate and utilize incoming spillovers (Cohen and Levinthal (1988)). Many studies that focus on incoming spillovers and the incentives to collaborate use firm level R&D spending as a proxy for absorptive capacity (Abramovsky et al. (2009), Belderbos et al. (2004), Cassiman and Veugelers (2002)). Theoretically, however, R&D spending decisions arise as a consequence of incoming spillovers and collaborative decisions, raising po-

follow we will subject the above factors to a principal component analysis when looking at their influence on appropriability mixes.

[22]Unless specified all variables constructed as a combination of firm responses to more than one question are done so as un-weighted averages.

TABLE 6 – STRATEGIC CONSTRAINTS AND APPROPRIABILITY IN COLLABORATIVE AGREEMENTS

		None	Vertical	Horizontal	Research
	Legal	1.7	2.9	2.8	3.8
FinCon	**Strategic**	1.6	3.4	3.3	3.8
	Protective Mix	1.0	1.2	1.2	1.0
	Legal	1.6	2.8	2.6	3.6
Risk	**Strategic**	1.6	3.3	3.3	3.9
	Protective Mix	1.0	1.2	1.3	1.1
	Legal	1.8	3.0	2.8	3.9
Real Cost	**Strategic**	1.8	3.7	3.6	4.1
	Protective Mix	1.0	1.2	1.3	1.1

* All figures calculated are based on the un-weighted averages for each collaboration type pooling together information from the entire 1998-2006 sample of manufacturing and service sector firms. Firms that report being affected by the three obstacles to innovation (1,2, or 3 on the likert scale) are grouped together by collaboration type for each obstacle, respectively. For each type of obstacle the reference category are the group of firms that did not face the obstacle and did not have any collaboration links. Strategic is a measure of non-exclusive property rights and Legal is measure of exclusive property rights defined in Table 3. Thus, Firms with no collaboration links that faced financial constraints chose to protect their innovations with legal instruments 1.7 times more intensively than firms with no collaboration links and no financial constraints.

tential endogeneity concerns.

In the widely used dAspremont and Jacquemin (1988) type of models on incoming spillovers, the standard result reveals how R&D expenditures in collaborative agreements are higher when incoming spillovers are high and competition is low (Vonortas (1994), Beath et al. (1992), Kamien et al. (1992), Spence (1984), and DeBondt (1997) for a survey).

An empirical argument mitigating the endogeneity of R&D expenditures entails the idea that in general firms carry out many independent and mutually exclusive strands of research. Recent theoretical work by Moraga et al. (2008) suggests that it might be fallacious to think in this way. They show that even in the absence of technological spillovers between independent research projects, market forces create complementarities and collaboration networks induce R&D investments in both joint and independent in-house projects.

As a starting point it is worthwhile assessing the reliability of the CIS data and whether it supports the standard theoretical views on incoming spillovers and R&D. The CIS survey allows me to separately identify spending on internal and external R&D and external knowledge acquisition. In light of the discussion above, I choose to focus on internal R&D

Table 7 - Regressions: Internal R&D Expenditure

	(1)	(2)	(3)
Collaboration	0.109	0.109	-0.063
	(0.079)	(0.079)	(0.092)
Incoming Spillovers	0.363	0.374	0.045
	(0.107)***	(0.107)***	(0.140)
Incoming Spillovers in Collaboration Agreements			0.463
			(0.126)***
Inverse Industry Mark-up		0.299	0.236
		(0.356)	(0.355)
High Technology Firms	1.012	1.032	1.175
	(0.350)***	(0.351)***	(0.351)***
Fixed Effects		Yes	
Firm Level Controls		No	
Observations	7328	7328	7328
Adjusted R-squared	0.74	0.74	0.74

Standard errors in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%

spending as the most relevant and least endogenous choice variable in the present context.

Table 7 runs a regression of internal R&D spending as a function of incoming spillovers and collaboration agreements. I restrict attention to those firms that report a positive expenditure.[23] Firms in high-tech industries spend significantly more on internal R&D. Controlling for this, and firm level fixed effects I find strong evidence in support of the theory that higher incoming spillovers encourage spending on internal R&D. Internal R&D spending is higher in collaboration agreements but is insignificant.

How innovative activity is influenced by competitive pressure is the subject of a living theoretical and empirical debate.[24] While competitive pressures can influence R&D spending, the industry composition of R&D spending can just as well influence competitive pressure. To avoid any potential endogeneity I use an indicator of competitive pressure measured at the beginning of each sample period. Surprisingly R&D expenditures, in the

[23]This does not introduce sample selection issues. Running the same regression on all non-missing observations on internal R&D gives qualitatively similar results.

[24]See for example Gilbert (2006), Aghion et al. (2005) and Vives (2005), and references cited therein, for theoretical and empirical considerations.

present sample, do not seem to be influenced by competitive pressures and inclusion of this variable in Column 2 does not alter the results.

When I introduce an interaction between collaboration agreements and incoming spillovers it becomes apparent that internal R&D spending is extremely sensitive to incoming spillovers within collaborative agreements. In isolation collaborative agreements or incoming spillovers do not hold any significant explanatory power. Thus, I find empirical support for the theoretical view that, controlling for competitive forces, collaborative agreements induce higher R&D expenditure when spillovers are high. Kaiser (2001) finds similar evidence using German CIS data.[25]

However, because I am unable to measure total R&D expenditure in the collaborative agreement this result might reflect concerns within the endogenous spillover literature that firms with access to larger incoming spillovers or superior knowledge also undertake most of the R&D expenditures in the collaborative agreement (Amir et al. (2003), Bhattacharya et al. (1990), Katz (1986)).

From an empirical standpoint however, it highlights the problems associated with using any form of R&D expenditure as a determinant of collaborative agreements.

There is evidence that vertical collaboration is more ubiquitous than horizontal, but that horizontal collaboration (weakly) favors innovation over imitation. Firms use a fair amount of information from external sources in their innovation activity yet they also employ procedures to limit the outgoing spillovers. The right mix of protection measures seems to depend on various factors including the constraints a firm faces but also its innovative activity and remains to be formally tested.

[25]Empirical evidence on this issue remains mixed. Irwin and Klenow (1996) find a reduction in R&D investment by members of SEMATECH. Inkmann (2000) uses German CIS data and finds an insignificant impact of vertical and horizontal cooperations on R&D intensity of German firms. He also finds a negative impact of intra-industry spillovers on R&D intensity but the opposite result for inter-industry spillovers. In contrast, Konig et al (1994) also using German data find a positive effect of cooperation on R&D intensity. Differences in empirical results may simply be by-product of the use of different cross-section samples and estimation procedures.

In addition there is support for the theoretical prediction that, controlling for competitive pressures, higher spillovers are associated with more R&D spending. Collaborative R&D agreements are also associated with higher internal R&D spending, especially when the collaborative agreement involves higher incoming spillovers. This result suggests that using R&D spending, even if limited to in-house spending, as a proxy for factors that influence collaborative decisions, may lead to biases.

2 R&D Collaboration with Spillovers, Absorptive Capacity and Financial Constraints

2.1 Introduction

In an influential study Cassiman and Veugelers (2002) propose a novel use of data contained within the Belgian Community Innovation Survey (CIS) to quantify the impact of informational spillovers on a firms decision to build R&D collaboration links with external institutions. The study is novel in two important ways. Firstly, it departs from the prevalent theoretical and empirical literature and distinguishes between the individual roles of incoming and outgoing spillovers in shaping incentives to collaborate. Secondly, it provides a simple methodology to measure these two distinct phenomena and identify their impact on collaboration decisions.

The European coverage of the CIS survey coupled with the ease with which the analysis can be conducted has spurred a wave of replications and similar studies across the EU employing identical or very close variants of the Cassiman and Veugelers estimation methodology (Abramovsky, Kremp, Lopez, Schmidt and Simpson (2009), Veugelers and Cassiman (2005), Belderbos, Carree, Diederen, Lokshin and Veugelers (2003)). The results from Belgium gain good support. However, most of these studies, like the original, are conducted on cross-section specific data using an identical or very similar instrument set and may have two possible shortcomings.

Firstly, the viability of the instrument set is always taken for granted, without any formal testing on its strength, even though it is well known that the use of a sizeable but weak instrument set potentially leads to other biases, not necessarily to be preferred over standard OLS methods (Hahn and Hausman (2002)). With a panel data structure the instrument set proposed by Cassiman and Veugelers only serves as a control for unobserved industry level heterogeneity.

Secondly, by restricting attention to the sample of innovators, these studies ignore the behavior of collaboration agreements that fail to realize immediate innovation benefits, introducing potential selection bias in the estimates. Even within the sample of innovators, it may be of interest to gauge differences in the incentive structures between the subset of imitators, firms that introduce innovations that are only new to the firm, and pure innovators, firms that introduce innovations new to the market.

This paper subjects the basic framework in Cassiman and Veugelers (2002) to these issues. Using a collection of consecutive CIS surveys for the UK, to construct a (representative) panel of firms, I first assess whether the original findings are robust to the control of unobserved heterogeneity. I then proceed to estimate fully interacted structural models to highlight differences between non-innovators, imitators and pure innovators. In addition I argue that the identification strategy is not well specified, discuss why this is so and offer suggestions for improvements. I follow through by implementing these suggestions to find improved results, which depart from the empirical findings on spillovers and absorptive capacity of Abramovsky et al. (2009) and Cassiman and Veugelers (2002).

2.1.A Reasons to Collaborate and Related Literature

Economists have long recognized the inability of free markets to fully price in the private benefits of R&D investment. Since the days of Nelson (1959) and Arrow and Nerlove (1962) it is widely accepted that the knowledge created through R&D investment is imperfectly appropriable and subject to informational spillovers. This market failure reduces private incentives to conduct R&D at the socially optimal level.

One institutional mechanism that overcomes this imperfection is the creation of research joint ventures or collaborative research agreements (Katz and Ordover (1990)). Combining research decisions under one umbrella allows participating partners to make efficient choices on R&D investments after internalizing the externality caused by the otherwise inevitable informational spillovers. In principle this seems like a winning strategy, but in theory whether the collaborative research agreement actually induces more R&D investments by the participants depends on a host of factors.

Theoretical models originating with the work of d'Aspremont and Jacquemin

(1988) show that under most circumstances whether collaborative agreements raise R&D expenditures crucially depends on the magnitude of spillovers to be internalized and the competitive structure of the market (De Bondt, Slaets and Cassiman (1992), Kamien, Muller and Zang (1992), Suzumura (1992)). For each competitive structure there exists a critical level of spillover, increasing in competitive pressure, above which collaborative agreements increase the industry level of R&D (De Bondt (1997) for an interesting literature review).

This is not the only reason in favor of research joint ventures. Theoretical models that allow for informational spillovers to be endogenously determined within the collaborative agreement show that this decision can be implicitly linked to the distribution of R&D costs, efforts, risks and proprietary rights, between participating partners to reach greater overall efficiency (Amir, Evstigneev and Wooders (2003), Bhattacharya, Glazer and Sappington (1992), Katz (1986)).

The trouble arises when the collaboration agreement extends to noncompetitive behavior in the product market e.g. price or product collusion, or if the R&D decisions within the collaborative agreement are made to exclude potential market entrants and maintain monopoly power. While EU and Japan have long been lenient towards collaborative R&D agreements, only recently have antitrust authorities in the US started to look upon this arrangements in a favorable light, as a means to increase the quantity and quality of R&D investments.

What are the trade-offs that firms face when deciding whether to collaborate? In order to answer this question, as Cassiman and Veugelers argue, it is necessary to distinguish between a firms incoming and outgoing spillovers. Imperfect appropriability, manifesting in information leakages to competitors, can lead to theoretically opposing effects, obscuring a clear empirical prediction on its expected sign.

Exogenously determined spillovers can induce free-riding and threaten the stability of the cooperative agreement (Shapiro and Willig (1990)). However, technology sharing and appropriately determined endogenous spillovers within the cooperative agreement enable greater stability (Eaton and Eswaran (1997), Kesteloot and Veugelers (1995)).

Cooperative R&D agreements allow partners to internalize the information leakages,[1] providing strong incentives to collaborate when information leakages are high. In addition, high incoming spillovers, within collaborative R&D agreements, increase the scope for learning and should be associated with a higher probability of collaboration.

For these reasons Cassiman and Veugelers (2002) take the view that firms manage external information flows to maximize incoming spillovers from partners and non-partners while at the same time minimize information outflows to non-partners (Martin (2002)).

While cooperation agreements allow an effective internalization of spillovers there exist many other reasons, identified in the management literature, why firms may choose to collaborate in R&D. Some of which are taken up in the Cassiman and Veugelers (2002) analysis.

Firms in collaboration agreements are likely to avoid wasteful duplication of R&D and efficiently share the associated costs (Douglas, 1990, Jacquemin (1988)). Collaboration may also allow the spreading of risk, associated with the innovation project, across the partner firms (Sakakibara (1997)). Collaboration agreements can also induce the asymmetric sharing of superior knowledge (Bhattacharya et al. (1992), 1990, Hamel *et al.*, 1989), and combining existing firm specific technological know-how and infrastructure may induce synergies through complementarities (Hagedoorn and Schakenraad (1992)).

The degree to which a firm is able to benefit from these complementarities will crucially hinge on its absorptive capacity i.e. the effectiveness with which a firm can use its internal resources to profitably convert externally generated knowledge (Cohen and Levinthal (1989)). Absorptive capacity can increase likelihood of innovative success making it a good trait for

[1] This is a central premise formally originating from the works of Spence (1984), Katz (1986), d'Aspremont and Jacquemin (1988) and De Bondt and Veugelers (1991). Kamien et al. (1992) provide general extensions to oligopolies, shared by Suzumura (1992), heterogenous products, and price competition, shared by Ziss (1994) and Hinloopen (2000). Motta (1992), Beath, Poyago-Theotoky and Ulph (1998) and Bonanno and Haworth (1998), to name a few authors, consider product innovation. The ramifications of public policy are explicitly considered in Leahy and Neary (1997). De Bondt (1997) and Veugelers (1998) provide good literature reviews.

partners to have (Abramovsky et al. (2009)).

However, going back to the free-riding argument, firms that enjoy a high degree of incoming spillovers in the absence of a collaborative agreement, will not have the right incentives to incur the costs of the collaborative agreement. This may be especially true for firms with large absorptive capacity.

Finally, although largely ignored in this literature until very recently, corporate finance related issues might also play a role. Due to its non-contractible nature, obtaining financing to develop a potential innovation can be a difficult proposition for a cash constrained firm. Holmstrom and Tirole (1997) argue that in world fraught with unobservable effort and moral hazard, a cash constrained firm can induce non-specialist investors to back its project by first asking a specialist financier to take a partial financial stake in the project. The specialist financier is able to monitor the effort of the entrepreneur and this sends out a signal to non-specialist investors that the project is viable.

The rest of the paper is organized as follows. Section 2.2 replicates the work of Cassiman and Veugelers in a panel setting and offers reasons why the estimation can be improved. Section 2.3 introduces the data and the estimation strategy. In section 2.4 I present the results from the new methodology and section 2.5 concludes.

2.2 Replicating Cassiman and Veugelers (2002)

In their original article Cassiman and Veugelers focus on five separately identifiable reasons and study how these influence the decision to collaborate in R&D. Three of these reasons - cost and risk sharing and exploiting complementarities in technology - have been shown, in the management literature, to play significant roles in shaping collaboration decisions. On the other hand, the study of collaborations in R&D as a mechanism for internalizing information spillovers has largely been the remit of the IO literature on R&D and innovation.

The authors distinguish between incoming and outgoing spillovers and argue that while firms use collaboration agreements to maximize incoming information, at the same time they try to limit outgoing spillovers. They argue, rightfully, that any measure of incoming and outgoing spillovers is bound to be endogenously determined with the decision to collaborate and suggest an identification mechanism to rectify this issue.

Their instrumental variables approach supports the theory that firms benefit from incoming knowledge flows but prefer to limit free-riding, both within and outside the cooperative agreement, and are more likely to cooperate when they are able to do so.

I replicate their exact specification using identically constructed variables and instruments. Additionally, in the specification, I control for unobserved time varying and invariant industry effects. The inclusion of the industry fixed effects reduces the effectiveness of the industry level instruments. As the first column of Table 2.1 shows, only one instrument, basicness of R&D, actually serves as a potential instrument, and gives rise to the large Hausman test statistic. The other instruments play no role in alleviating the endogeneity. This is evident from the test statistics that emerge when I remove basicness of R&D from the instrument set.

Based on my readings of other studies using CIS data from across Europe and the strong similarities therein (see for example Abramovsky et al. (2009), for another review), I strongly suspect that it is only the basicness of R&D variable that plays the role of a valid instrument in the Cassiman and Veugelers specification.

However, as I will argue in the next section, the original regression results presented by the authors are biased, in a panel setting, not only because of the use of redundant excluded instruments but primarily because the only potential instrument of interest, basic R&D, as it is defined is endogenous itself.

2.2.A A Critique

Cassiman and Veugelers (2002) distinguish between collaboration links with vertical business partners and research institutes. They find that while firms benefiting from high incoming spillovers are more likely to collaborate with research institutes, only firms that can maintain high level of appropriability will collaborate with vertical partners.

I argue that this interesting finding is purely driven by the definition of spillovers and basic R&D employed by the authors and by the incorrect presumption that, their measure, of basic R&D is exogenously determined.

The CIS survey asks firms to report on the importance of various different external information sources as inputs to their innovation process. Cassiman and Veugelers group together responses on the importance of conferences, trade fairs, exhibitions, scientific journals and trade/technical publications, professional and industry associations and technical, industry and service standards to capture spillovers from publicly available information sources. This measure defines the firm-specific magnitude of incoming spillovers.

The authors consider information as applied in nature if a firm reports information sourcing from suppliers, customers and competitors. Basic (generic) information sources include combined responses from universities, consultants and private R&D labs and government and public research institutes. The authors argue that firms conducting basic R&D will rely more on basic information sources relative to applied and use this ratio as a measure of basic R&D. Basic R&D is, also, more amenable to acquisition so firms conducting basic R&D will naturally enjoy larger incoming spillovers.

There are two immediate issues with this chain of thought. The idea that the ratio of basic to applied information intensity is a proxy for basic R&D is not immediate. It is possible that firms that source more basic information relative to applied information actually conduct more basic R&D. However, it is also conceivable that a firm with no exploitable basic

R&D stock of its own exploits other basic information sources to a larger degree than applied information, which it can generate in-house, when experimenting with a new idea.

More importantly, to be a viable instrument, the measure of basicness of R&D needs to be exogenously and independently determined from the decision to collaborate. However, there is no reason to believe, a priori, that spillover intensity is more responsive to collaboration agreements than basicness of R&D. In fact, firms collaborating with research institutes (vertical partners) should find it more cost effective to source basic (applied) information relative to other sources, leading to a reported bias towards basic (applied) information relative to applied (basic) and incoming spillovers. If this is indeed the case then basic R&D will be just as endogenous with the decision to collaborate as spillovers.

Concentrating on the sub-sample of firms that are surveyed in more than one year, Tables 2.2 reports a first difference estimation of the different measures of information spillovers on changes in collaboration status. I estimate

$$\Delta y_{ij} = \beta_h \Delta h_{ij} + \beta_v \Delta v_{ij} + \beta_r \Delta r_{ij} + \mu_{ij}$$

where $\{h, v, r\}$ respectively denote the collaborative links, of firm i in industry j, with horizontal i.e. competitors, vertical i.e. suppliers and customers, and private and government research institutes. Δ denotes the change between time period t and $t-1$ i.e. $\Delta h = 1$ indicates a new horizontal collaboration, $\Delta h = 0$ indicates no change, and $\Delta h = -1$ indicates the end of a horizontal collaborative agreement. In order to measure endogeneity and the responsiveness of the different types of information sources to collaboration links y measures spillover, basic information intensity, applied information intensity and basic R&D, all estimated separately in Table 2.2.

It is clear from the results and significance tests that, while spillovers are generally more responsive to collaboration agreements, they do not exhibit response differentials across collaboration types. In contrast, as predicted, applied and basic information intensities are subject to significantly different responses across collaboration types, rendering basic R&D endogenous. Specifically, whereas decisions to collaborate with vertical and horizontal links do not significantly influence changes in the intensity of basic R&D, establishing a collaboration link with a research institute does.

The construction of the basic R&D proxy as the ratio of basic to applied information intensity exacerbates the endogeneity problem portending results that will be misleading. The endogeneity biases the estimates in a predictable manner. Firms that report collaboration links with research institutes will also report a high basic R&D relative to firms with no collaboration links. On the other hand, firms with vertical collaboration links will report a low basic R&D relative to firms with no collaboration links. When estimating a reduced form equation of the decision to cooperate on basic R&D we would expect to find a large positive coefficient on basic R&D in the sample of research collaboration links, and a coefficient biased towards negative signs in the sample of vertical collaboration links.

This bias will filter through into the second stage of the instrumental variable estimation because in the first stage we would estimate incoming spillovers as a linear combination of basic R&D, and other exogenous determinants, which would lead us to a similar conclusion, as the preceeding paragraph, on the coefficient of incoming spillovers in the structural regression of collaboration agreements.[2]

The results of Cassiman and Veugelers (2002) are less surprising when taking into consideration the above argument. Column 2 of Table 2.1 shows that if we were to follow the authors and instrument basic R&D with its industry average then the instrumental variable approach becomes completely useless and we fail to reject the hypothesis in favor of a standard OLS regression. This suggests that the set of instruments under consideration are weak and are not, in the present context, properly correcting for the endogeneity.[3]

[2]In their replication of Cassiman and Veugelers across a set of European countries Abramovsky et al. (2009) also instrument incoming spillovers with a proxy for basic R&D. However their proxy differs in that they only consider basic information and not the ratio of basic to applied information. Although they do not state why they use this strategy, the results are clear. Incoming spillovers play a significant role in the decision to vertically collaborate in all European countries considered. Yet this study may also be flawed because as we can see in Table 2.2 Column 2 the intensity with which firms use basic information sources is also endogenous with the decision to collaborate.

[3]This is evident from the Redundancy statistic presented at the bottom of the

In this scenario, the OLS estimates, presented in Column 3 of Table 2.1, are likely to be more informative (Hahn and Hausman (2002), Hahn and Hausman (2003)). The OLS results show that firms that are better able to appropriate outgoing informational spillovers through strategic means, while maintaining a higher level of incoming spillovers are more likely to enter collaboration agreements. At the same time larger absorptive capacity, captured by the permanent R&D identifier, and complementarities in technological know-how also increase chances of collaboration. However, cost and risk sharing concerns do not seem to play a significant role here.

2.2.B Industry Legal Protection

A finding that is very stable across studies,[4] but has not received due attention is the negative coefficient on industry use of legal protection. This indicates that firms in industries reporting high importance of patents, trademarks etc tend to collaborate less. The question is why? If a higher reliance on legal instruments indicates a higher level of informational spillovers into the public domain (Schmidt, 2006, Teece, 2000) then it is clear that firms face low incentives to collaborate because a large portion of knowledge capital is made public within the industry.

In cumulative innovation industries, however, greater reliance on legal instruments should spur collaboration agreements to facilitate patent pooling and cross-licensing agreements (Scotchmer, 2004). I capture cumulative industries by identifying, using EUROSTAT classifications, all high technology sectors and Column 4, of Tables 2.1, shows that high legal reliance within the industry generally lowers incentives to collaborate ($\beta_L = -1.03$)

Table 2.1 in column 2. Alternatively Table 2.1 also presents Hausman tests on different specifications. The Hausman test in column 1 is very strong because the instrument set contains basicness of R&D. In column 2 the I replace basicness of R&D with its industry average and the Hausman test loses its significance. Finally in column 3 I remove both basicness of R&D and its industry average from the instrument set. This allows me to check the validity of the remaining instrument set. The regression results presented in column 3 are of the OLS. I suppressed the regression output of the reduced instrument set and only report its Hausman test at the bottom of column 3. This also shows that the instrument set is redundant.

[4]See for example Abramovsky et al. (2009) for cross country comparisons of this finding.

but firms within high technology and high legal protection industries do collaborate, relatively and significantly, more than the rest ($\beta_H + \beta_{LH} = -1.03 + 0.31 = 0.72$).

2.2.C Financial Constraints

A potential driver of collaboration seldom considered in the literature yet closely related to costs of innovation and risk is financial constraints. I introduce a measure of how financially constrained a firm is in Column 2 of Table 2.3. First however, Column 1 of Table 2.3 presents the results of a SIC 4-digit fixed effects analysis carried out on the original specification i.e. without financial constraints. The introduction of more narrowly defined fixed effects allows us to mitigate the simultaneity bias in the absence of appropriate instruments. This inclusion does not seem to alter the qualitative results obtained from the OLS analysis obtained in Table 2.1.

At first it seems that the exclusion of financial constraints from previous analysis may be justified i.e. it is insignificant in Column 2. However, like the original study, by Cassiman and Veugelers, the first two columns of Tables 2.3 restrict attention to the sub-sample of successful innovators, although the sample is drawn from both the manufacturing and services sector.

As Column 3-5 make clear, there is evidence of sample selection. Financial constraints and risk seem to play a more prominent role for imitators in the decision to collaborate, while complementarities are more important for innovators. On the other hand higher incoming spillovers, strategic appropriability and absorptive capacity seem to influence the decision to collaborate across all samples.

The industry level fixed effects drown out the effect of industry level legal protection in high technology industries. Yet, I still find a significantly negative effect of this variable on the decision to collaborate for non-innovators ($\beta^{ni}_{LH} = -0.32$), while the effect is positive ($\beta^{i}_{LH} = 0.63$) but insignificant, for pure innovators. This weakly supports the idea that some collaboration agreements transpire purely to pool existing proprietary technologies.

An F-test confirms that there may be systematic differences between the 3 samples. However the coefficients on incoming spillovers, strategic appropriability and absorptive capacity do not seem to be crucially different. Therefore, in the analysis to follow, I pool all three samples together. Aside from allowing us to gauge the average influence of each factor on collaboration, this strategy will also give me greater degrees of freedom to subject the model to fixed effects estimation, which is ultimately where the analysis should be directed.[5]

2.3 Data and Estimation

This section explains i) the way I construct the variables of interest, and ii) the identification strategies, including in both cases a comparison with the original study of Cassiman and Veugelers when possible.

2.3.A Variable Description

Here I describe how I construct the variables of interest and, when applicable, how they differ from Cassiman and Veugelers definitions.

[5] Estimating the Cassiman and Veugelers specification on the pooled sample with SIC 4 industry fixed effects, I find positive and significant coefficients on spillovers, appropriability, absorptive capacity, complementarities, risk and industry level of cooperation. As before I find a negative coefficient on industry legal protection. Estimating the same Cassiman and Veugelers specification with firm level fixed effects I find only incoming spillovers, strategic appropriability and absorptive capacity remain significant, each with a positive impact on collaboration.

2.3.A.a Costs

I construct costs as the combined response to direct innovation costs and excessive perceived economic risk, rescaled between $[0, 1]$.[6] The phrasing of this option suggests a very subjective response that is most likely capturing information about the firms risk aversion and subjective discount factor. If this were to be true, we are likely to find a strong positive correlation between the firms responses to direct innovation costs and excessive perceived economic risk, which indeed seems to be the case. For this reason the grouping is justified.[7]

2.3.A.b Risk

I am interested in capturing the demand risk associated with innovative activity and I define this as the combined response to lack of information on markets and uncertain demand, rescaled between $[0, 1]$.[8] As Shapiro and Willig (1990) point out collaborative activities can generate significant private and social benefit including the sharing of risks associated with investments that serve uncertain demand.

2.3.A.c Financial Constraints

I construct a measure of financial constraints that takes into account whether the firm was credit constrained, credit rationed or both. I consider firms that give a high importance to lack of availability of finance as an obstacle as credit rationed. While, firms that give high importance to cost of financing as an obstacle to innovation are labeled credit constrained. I combine these measures such that all firms that are credit rationed and

[6]For the comparison in Tables 1 and 3 I stick to the Cassiman and Veugelers definition of cost. This is the combined response to direct innovation costs to high, availability of finance and cost of finance.

[7]A principal component analysis on the various responses to obstacles to innovation shows a very strong correlation between direct innovation costs and excessive economic risk, in relation to other options. Results are available upon request.

[8]For the comparisons in Tables 2.1 and 3, I use the Cassiman and Veugelers definition of risk i.e. the firms perceived economic risk.

those firms that are both credit rationed and constrained obtain a score of 1. Firms that are credit constrained but not rationed get 0.5, and all others get 0.[9]

2.3.A.d Complementarities

It is argued that technological know-how within the firm increases the scope of complementarities between partners. The unimportance of lack of technological information as an obstacle to innovation is used to construct a proxy for complementarities.

2.3.A.e Absorptive Capacity

Cohen and Levinthal (1989, p.569) define absorptive capacity as a firms ability to identify, assimilate, and exploit knowledge from the environment. Underlying this is the notion that the benefit of incoming spillovers cannot be assumed exogenous and depends on the efforts of the recipient firm in making the information usable.[10] While Cohen and Levinthal operationalize absorptive capacity using firm-level R&D spending, the definition is in fact quite broad and is open to many significant measurement strategies (Girma (2005), Griffith, Redding and Reenen (2003), Cockburn and Henderson (1998), Blomstrom and Kokko (1998), Wakelin, 1998, Henderson, 1994). I use the science base i.e. the percentage of full-time employees hired by the firm with science degrees, as a measure of absorptive capacity.

[9] The use of this variable precludes any non-linear effects, however I did not find strong evidence of non-linear effects and therefore I retain this semi-continuous measure.

[10] Although the coining of the term absorptive capacity and the first formal study of it is attributed to Cohen and Levinthal (1989), the idea itself has been observed in the technological change literature in early works of Tilton (1971), Evenson and Kislev (1973), Allen (1977), Mowrey (1983).

2.3.A.f Appropriability

The ability of a firm to limit its outgoing spillovers is termed appropriability. As in the original study, on which I build this comment, I distinguish between strategic and legal protection of information. Appropriability, rescaled between [0,1] is the combined score of a firms use intensity of strategic non-exclusive protection methods including confidentiality agreements, secrecy, complexity of design and lead-time advantage. Legal protection represents the combined score of a firms use intensity of exclusive property rights including trademarks, patents, copyright and design registration.[11]

2.3.A.g Incoming Spillovers

I employ the simplest notion of incoming spillovers i.e. the voluntary or involuntary flow of innovative information from one firm to another (Veugelers, 1998). In a spirit similar to Jaffe (1986), I define spillovers as a function of the potentially accessible spillover pool and the intensity with which firms access this pool.

Using the annual UK Business Expenditure on Research and Development Survey I first construct a knowledge capital pool R_{jt} by aggregating all civilian R&D spending, on basic, applied and development research, within each industry j for the three consecutive years prior to the start of each reporting period in the CIS.

$$R_{jT} = \sum_{t=1}^{3} \sum_{i \in j} r_{ijT-t}$$

How much of this knowledge capital pool flows into firm i depends on how well the knowledge capital pool is protected, and the intensity with which firm i accesses the unprotected portion of the pool. Above I interpreted the coefficient on the industry level of legal protection as evidence that patents, trademarks and other legal devices are source of information spillovers. It is true that these instruments assign property rights to the

[11] The time variant industry average of legal protection was used to capture the property rights regime of the industry in the regressions in Tables 2.1 and 2.2.

innovating firm, but they do so at the expense of disclosure of knowledge into the public domain to facilitate imitation and further innovation when the patent expires (Teece, 2000). On the other hand, like others, I interpret strategic protection as a purely information concealment mechanism that forgoes legal recourse should the concealment fail (Bhattacharya and Guriev (2006), Anton and Yao (2004)).

With $\bar{l}_{jt} = \frac{1}{n_j}\sum_{i\in j} l_{ijt}$ and $\bar{a}_{jt} = \frac{1}{n_j}\sum_{i\in j} a_{ijt}$ I denote industry reliance on legal and strategic protection, respectively, for reporting period t. The proportion of information on R&D activity the industry collectively decides to share with each other is $\frac{\bar{l}_{jt}+(1-\bar{a}_{jt})}{2}$, reflecting the fact that legal instruments reveal information.[12]

For the concept of incoming spillovers I assume that all sources of information are equally relevant. It does not matter whether firm A learns about the innovative activity of firm B, through direct contact, or indirect, be it a mutual competitor C, supplier S, private consultant D or trade publication E. All that matters, is that firm A has learnt something about B. For this reason I group all three information sources i.e. public, basic and applied into one linear combination, giving an equal weight to each category.[13]

The θ in Spences (1984) canonical model on R&D spillovers can then be thought of as firm specific, and a product of the firms individual intensity with which it sources information, and the industry specific decision to share information:

$$\theta_{ijt} = \frac{\bar{l}_{jt} + (1 - \bar{a}_{jt})}{2}\gamma_{ijt}$$

Finally firm specific incoming spillovers, that will influence the decision to collaborate, can be written as:

$$s_{ijt} = \theta_{ijt} R_{jt}$$

[12] The normalization is there to ensure the fraction is bounded between $[0, 1]$ and does not affect the sign of the regression estimates.

[13] Clearly a model in which the quality of information decays as it flows from one source to another would not support such a grouping, thus the implicit assumption here is that there is no decay. By aggregating all information sources used by a firm I am also able to minimize any noise present in any one individual category.

2.3.A.h Cooperation

Using a binary indicator I identify firms with and without collaboration partners. The structure of the questionnaire is such that I can classify collaboration agreements by type of institution, but the identity of the collaboration link is not disclosed. Collaboration links can be across the vertical chain i.e. with suppliers and customers vertical collaboration, with competitors horizontal collaboration, or with research institutes such as consultants, commercial labs, private R&D institutes, universities and other higher education bodies and government and public research institutes research collaboration.[14] Responses to these questions are not just restricted to the set of innovating firms and I am able to exploit variation on characteristics within collaborative agreements that did not witness a contemporaneous innovation.

2.3.A.i Competition

I use industry mark-ups for the year prior to the CIS reporting periods. These are constructed using a representative sample of firms from the UK Annual Respondents Database and the methodology of Martin (2005).[15]

[14] As in the Cassiman and Veugelers analysis, the binary indicator that we employ tells us that at least one collaboration partnership exists. We are unable to ascertain the exact number of collaboration agreements that a firm has with any given type of partner, and we are also unable to pin down the exact resource distribution across links.

[15] I also experimented with industry level import intensity, constructed from UK input-output tables. The results were qualitatively similar. I prefer using industry mark-ups because they capture the degree of domestic competition between locally differentiated firms. Cassiman and Veugelers use firm export intensity, reported in the CIS as their measure of competition. I depart from this measure, as it is likely to be highly endogenous with other responses from the survey. For the instrumental variable replications in Tables 2.1 I use a dummy marker that identifies exporting firms. Due to inconsistencies in the survey design, I do not have information on export intensity for one of the cross-sections. For the cross-sections for which we have information on export intensity, I compared the results on the baseline regression, using this variable and the export dummy. I found qualitatively similar results, justifying the use of the export dummy as a proxy for export intensity.

2.3.A.j Contracting Intensity

Following Nunn (2007), I construct a measure of contracting intensity to measure the degree of common suppliers an industry faces. Using UK input-output tables I first identify all the intermediate inputs of industry j and the proportion of js total procurement from each intermediate input industry. I then classify each proportion as being relationship specific if products from the particular input industry cannot be bought through organized exchanges or are not reference priced. I obtain this information from Rauch (1999). I obtain each industrys contracting intensity by aggregating all input proportions of a relationship specific nature.

2.3.B Identification

To begin with, like Cassiman and Veugelers (2002), I assume from the outset that costs, risk and complementarities are exogenously determined.[16] I also assume the exogeneity of financial constraints.

Cassiman and Veugelers argue for the endogeneity of incoming spillovers, appropriability and absorptive capacity (permanent R&D). They use the industry averages of each of these variables along with firm specific basicness of R&D and export intensity as instruments. As shown above basicness of R&D is just as endogenous as incoming spillovers, if not more. I do not follow Cassiman and Veugelers in their choice of instrument set and construct my own from scratch. This section outlines which instruments I choose and why.

The structural equation 1, is likely to suffer from identification problems due to two main reasons. On the one hand all the responses we use are approximated subjective beliefs of the firm. This gives rise to issues of measurement error. However, Wooldridge (2000) points out the attenuation bias in our setting, where all variables of interest are measured on a

[16] This assumption is consistent with the argument that firms first weigh different innovation paths based on expected costs and risks, and then decide whether collaboration will allow them to share the costs and risks while improving their own chances of successfully realizing the innovation.

Likert scale, should not be too large.[17]

More importantly, it is highly likely that through certain unobserved factors some of the presumed exogenous variables are jointly determined with the decision to collaborate. The issue of simultaneity is more pressing in this setting and so I will spend some time talking about the identification strategies I employ, and how they vary from the methodology set out in Cassiman et. al.

It is very likely that more than one variable is jointly determined. However, I adhere to the view that it is better to be parsimonious in the choice of instruments, especially if the instruments are weak (Hahn and Hausman (2003), Staiger and Stock (1997)). For this reason, I will assume that only spillovers and appropriability are simultaneously determined with the decision to collaborate.

A priori, we would expect absorptive capacity to play an important role in the decision to collaborate. While most empirical studies, e.g. Abramovsky et al. (2009), proxy absorptive capacity with some form of R&D intensity it is clear that such a measure would be extremely endogenous. This simultaneity is not just limited to firm and project specific choices of R&D (Goyal, Moraga-González and Konovalov (2008)). The theory tells us that even an industry aggregated R&D intensity measure would suffer from simultaneity.[18] In order to minimize simultaneity, I prefer to proxy absorp-

[17]The intuition here is the following. Whether measurement error in the independent variables leads to biased estimates crucially depends on whether the measurement error is correlated with the observed variable (classical errors in variables) or the true unobserved variable. In the case of variables measured on a Likert scale it is more likely that the measurement error is correlated with the unobserved variable, in which case measurement error does not lead to attenuation bias. For example, firms that do not face high innovation costs will always report the correct value. While firms that face positive innovation costs will always round off their answers to one of the available options. Hence firms with positive unobserved innovation costs are also likely to be the observations most prone to measurement error. The rounding off carried out by firms when responding on the Likert scale also means that in expectation the population variance of the observed variable is less than the population variance of the actual unobserved variable. This violates the classical errors in variables assumption.

[18]We could follow the literature and use (internal) R&D intensity as a measure of absorptive capacity. However it is clear that industry level of R&D intensity would not suffice as an appropriate instrument here as this is also endogenous to the cooperation decisions within the industry.

tive capacity with the firms science base. I believe this to be compatible with the original definition of absorptive capacity put forward by Cohen and Levinthal (1989), and due to labor market rigidities, especially for skilled labor (A. Gautier, J. van den Berg, C. van Ours and Ridder (2002), Farber (n.d.), Royalty (1998)), I believe this to be a suitably exogenous measure.[19]

As I will show in the next chapter, collaborative agreements make firms more reliant on strategic appropriability mechanisms. This may be because firms within collaborative agreements are more likely to introduce drastic innovations (Anton and Yao (2004)) or because financially constrained firms entering collaborative agreements to alleviate the constraint can better maintain bargaining power with financing partners through strategic protection.[20] Other explanations based on transaction costs and legal institutions may also exist to support the simultaneity argument.

2.3.B.a Identifying Appropriability

In order to identify the impact of higher appropriability on a firms decision to collaborate, I use the industrys potential exposure to broadband technology as an instrument for appropriability. Case studies and anecdotal evidence suggest that adoption of this technology has had a major impact on how firms communicate and share information. Because broadband technology has significantly improved, the efficiency and ease with information can be gathered and communicated to others has become all the more important for firms to define their strategic information disclosure policies.

Improving community access to broadband technology has been a priori-

[19] Cassiman and Veugelers use a question asking firms whether they permanently conduct R&D which is not available to us for all three cross-sections. Instead we construct this variable for each firm using a combination of questions that enquire about innovation tendencies of firms. Our variable behaves relatively well but may be subject to imposed measurement error. Details are available upon request.

[20] Aghion and Tirole (1994) introduce a setup of incomplete contracts and study the role of property rights in facilitating investment agreements between a financially constrained research unit and cash rich development unit. The extension to collaborative agreements is my own interpretation and extension of their results.

tized UK policy initiative since early 1999, following the privatization of telecoms exchanges. By 2003 nearly 85% of the UK had broadband coverage. Providing broadband access was primarily a regionally led affair.[21] Using detailed time varying post-sector data on broadband coverage, provided by Analysis Consulting, I calculate the percentage of firms within an SIC 2 industry based in locations with broadband coverage at the start of each reporting period.

I use the exogenous variation in broadband coverage, and hence the proportion of firms within an industry that can potentially adopt broadband technology as the instrument for appropriability. I posit a positive relationship between the two: firms anticipating greater information leakages will strengthen their strategic protection mechanisms.

2.3.B.b Identifying Incoming Spillovers

The theoretical IO literature on R&D presumes that knowledge created by basic (generic) R&D is more amenable to spillovers than applied and development research that tends to be firm-environment specific and costly to adapt (Vonortas (1994), Mowery and Rosenberg, 1992). For this reason, firms that rely more on basic information sources relative to applied are more likely to benefit from incoming spillovers (Kamien and Zang (2000)).

I follow Cassiman and Veugelers and use basic R&D as an instrument for spillovers. However I employ a very different and more direct measure of basic R&D.[22]

In the spirit of Jaffe (1986) and Jaffe, Trajtenberg and Henderson (1993),

[21] In some regions the effort to provide broadband access to business was demand triggered, with local firms invited to submit requests for broadband. Once a certain threshold was reached an exchange in the area was activated. However there is no clear evidence that the demand trigger was systematically activated by certain industries. In most regions broadband was diffused through exogenous government policy. More details can be found in Farooqui and Sadun (2006).

[22] I depart slightly from the Cassiman and Veugelers specification of basicness of R&D in that I include competitors as a potential source of information on applied research.

using the BERD survey I first identify all the different civilian products on which the industry reported R&D expenditures for each three-year reporting period of the CIS. Then in order to avoid any contemporaneous feedback I calculate total basic R&D expenditure on these products, throughout the economy for the three-year period prior to the start of each CIS reporting period.

This can be written down more succinctly in the following form. Let

$$P_t^j = \{p_{1_t}^j, p_{1_{t+1}}^j, p_{1_{t+2}}^j, ..., p_{K_t}^j, p_{K_{t+1}}^j, p_{K_{t+2}}^j\}$$

denote the set of all products that industry j conducted basic R&D on during the period t to $t+2$, with elements $p_{k_t}^j$. Then the measure of basic R&D that we are interested in is given by

$$b_{ijT} = \sum_{k \in P_T^j} \sum_{j=1}^{N} \sum_{t=1}^{3} p_{k_{T-t}}^j$$

The important ingredient in the identification strategy is that I am not restricting attention to basic R&D expenditures within the sector, but considering all related expenditures throughout the economy i.e. I am factoring in potential intra-industry product related spillovers in basic R&D.

Finally, to ensure the rank condition is satisfied and the over-identification test is calculable I introduce one last instrument. The instrument I opt for the degree of contracting intensity within the industry as described above. I choose this instrument because one of the main findings in Cassiman and Veugelers, which has found support in the replications, stresses the effectiveness of strategic protection in inducing vertical collaboration. According to the authors, This is reminiscent of the idea that competitors learn about their rivals through common suppliers or customers. Furthermore, firms want to avoid backward integration by customers or forward integration by suppliers because of what they learn through cooperative agreements.

I control for this hypothesis explicitly and use the degree of contracting intensity within an industry as an instrument for incoming spillovers. Firms within differentiated industries with a high degree of relationship specificity are unlikely to buy inputs from the same set of suppliers. Firms that do not buy exclusively from a small set of common suppliers can easily, either implicitly or explicitly, work in clauses into long-term procurement contracts specifying secrecy. In addition leakage of valuable information through suppliers will be easily detectable in this environment. For this reason, industries with high contracting intensity should not evidence a large degree of informational spillovers.[23]

I could follow Cassiman and Veugelers who argue that the appropriability decision of a firm is likely to be influenced by the degree of competition a firm faces. However because Goyal and Moraga-Gonzalez (2001) make the point that competitive pressures directly influence the decision to collaborate in R&D and that competing firms may have excessive incentives to collaborate, I directly consider industry mark-up as a covariate in the collaboration specification, instead of as an instrument for appropriability.[24]

2.3.C Estimation Specification

Focusing on the above discussion on factors that drive collaboration decisions, I am interested in estimating the following structural equation

$$\begin{aligned} g_{ijt} = \alpha_0 + \beta_1 s_{ijt} + \beta_2 a_{ijt} + \beta_3 (ac)_{ijt} + \beta_4 c_{ijt} + \beta_5 r_{ijt} + \beta_6 d_{ijt} \\ + \beta_7 f_{ijt} + \alpha_1 g_{jt} + \gamma' X_{ijt} + \delta_t + \mu_j + \epsilon_{ijt} \qquad (2.1) \end{aligned}$$

Where g_{ijt} is the firms decision to collaborate, s_{ijt} captures incoming spillovers for firm i in industry j at time t, a_{ijt} refers to appropriability as defined above, $(ac)_{ijt}$ captures absorptive capacity and c_{ijt}, r_{ijt}, d_{ijt} and f_{jt} refer to cost, risk, complementarities and financial constraints respectively. I also include the frequency of collaboration links, g_{jt}, within industry j at time t to capture unobserved industrial factors that lead to

[23] It is very likely that firms enter vertical collaboration agreements with suppliers with whom they have existing contractual ties. This is why I do not attempt to measure contracting intensity at the firm level, and opt for an industry measure of contracting intensity, which avoids this potential endogeneity.

[24] There is a vast literature that considers the endogeneity of competitive market structure and innovation, see for example Gilbert (2006) for a comprehensive survey. In order to avoid the simultaneity of collaboration and competition I use a lagged industry mark up.

more (or less) cooperation. The β coefficients capture the effects of firm specific variables, while the α coefficients capture industry level effects. X_{ijt} is a matrix of firm level characteristics,[25] and finally the error term has three components: δ_t captures year specific effects while μ_i is added to capture any remaining time invariant unobserved heterogeneity at the firm level. I assume that the remaining firm specific error is conditionally uncorrelated with our variables of interest e.g. in the case of incoming spillovers, $Cov(\epsilon_{ijt}, s_{ijt}|X_{ijt}, z_{ijt}, \mu_j, \delta_t) = 0$, where X_{ijt} includes all covariates and z_{ijt} represents the set of industry level instruments.

The instruments and industry aggregated collaboration are measured at the SIC2 level to keep them as representative as possible. However, because interdependent unobserved strategies between firms within the same industry might result in an error correlation structure that violates independency, I cluster standard errors at the narrower SIC4 level.

2.4 Results

Column 1 of Tables 2.4 presents the results from the firm-level fixed effects analysis of the original specification using the newly constructed variables. The sample pools together all sectors and focuses on those firms that were selected in more than one year of the survey sample. In addition, I control for firm-specific characteristics including size, age and ownership status.[26]

[25] These include size and age of firm, whether the firm was multi-plant and part of a larger operating group, multinational status, ownership status i.e. whether it was sole proprietorship, private partnership or publicly owned and whether it was subject to a takeover or merger at the start of the survey period.

[26] Size is based on the number of full time employees reported by the firm. Firm age is a continuous variable, and I also include a binary variable indicating if the firm was just established at the start of the reporting period. Ownership status includes whether the firm is part of a larger enterprise group that is a corporation, government owned, private partnership or sole proprietorship and multinational status. I also include indicators of whether the firm was subject to a takeover or merger at the start of the reporting period. All of the results are based on a Generalized Method of Moments Fixed Effects estimation of a linear probability model with collaboration (or a specific type of collaboration) as the dependent variable.

Higher incoming spillovers still have a positive influence on the decision to collaborate, and firms that can limit their outgoing spillovers also are more likely to collaborate, although the magnitudes of these effects are not as high as those reported in Cassiman and Veugelers (2002) and Abramovsky et al. (2009). Absorptive capacity has a positive influence on the decision to collaborate however this impact is not significant at traditional levels of confidence.

Of interest is the significance of financial constraints that positively influences the decision to collaborate. This influence is independent of the widely talked about cost sharing motive which is significant in its own right. The fact that firms are more likely to enter collaboration agreements not only to share costs but also to alleviate their financial constraints suggests there might be a Holmstrom and Tirole (1997) type of collaborative screening story at play here. Sharing market uncertainty and risk does not seem to be a major motive in shaping collaboration decisions, at least in the present sample of firms. However there is evidence that competitive environments stimulate collaboration.

In Columns 2-4, I present the results of instrumental variable estimation. The Hansen statistic supports the view that the instruments are truly exogenous, while the large weak identification test suggests that the instrument set is of decent strength. Interestingly, the instrumental variable approach reverses the sign on incoming spillovers, although the magnitude is insignificant. All other variables retain their sign but also lose their significance. Only cost sharing and financial constraints remain significant motives for collaboration.

The first stage regressions are as suspected. The anticipation of greater knowledge leakages through the use of broadband technologies forced firms to rely more on strategic appropriability as industry exposure to broadband coverage increased, simultaneously causing a significant decrease in incoming spillovers. At the same time industries with a high degree of contracting intensity do show a lower degree of incoming spillovers through their relationship specificity.

A high total stock of intra-industry product specific basic research translates into a significant increase in incoming spillovers. Incoming spillovers are significantly lower in more competitive markets and in firms that do not lack information on technology.

Absorptive capacity makes incoming spillovers more useful and firms with a larger science base enjoy higher incoming spillovers, but this ability can be a double-edged sword, and firms mitigate information leakages through the science base by choosing higher levels of strategic protection. The size of the coefficients on science base in the two first stage regressions suggest the benefits of higher incoming spillovers outweigh the potential losses of information leakage through a larger science base.

While market uncertainty does not directly influence the decision to collaborate it does cause firms to significantly increase their strategic appropriability. Firms with high complementarities enjoy lower incoming spillovers but also limit their outgoing spillovers to a lesser degree. Cost considerations induce higher incoming spillovers but also induce firms to limit their outgoing spillovers to a greater degree.

In contrast to other studies I also find that collaboration within the industry significantly facilitates incoming spillovers ($\beta = 0.65$), without significantly influencing firm specific strategic appropriability.

2.4.A Different Types of Collaboration Links

In this final results section I concentrate on differences between the types of collaboration links. Using the same sample as before in each column of Tables 2.5, I replace collaboration as the dependent variable with collaboration of a particular type. The results presented are IV treated and again we see that all the specifications pass the main endogeneity tests of under- and over-identification.[27]

It is of interest to note the differences in influences across the three specifications. Although never significant, the influence of incoming spillovers is always negative for each collaboration decision. On the other hand,

[27] I have suppressed the individual first stage results for brevity, but these are available upon request.

the degree of collaboration within the industry positively and significantly influences each type of decision to collaborate to an almost similar degree.

There are also some type specific influences. Cost sharing concerns and financial constraints significantly increase the probability of vertical collaboration. As in Cassiman and Veugelers, I also find that firms that can better control outgoing spillovers are more likely to enter vertical collaboration agreements, however this effect is not significant at traditional confidence levels. Meanwhile, this is the only factor that significantly drives the decision to collaborate with horizontal competitors.

Two factors influence the decision to collaborate with research institutes in this sample of firms. A larger science base, and therefore a higher absorptive capacity, increases the chances of research collaboration, while financial constraints also induce a greater probability of collaboration with research institutes. The latter result may seem surprising at first but it is likely to reflect that such agreements allow the financially constrained firm to benefit from public funding made contingent on the collaboration agreement.

2.5 Concluding Remarks

My main contribution to the recently emerging literature on structural IO and innovation economics is the use of a panel dataset to study the incentives that drive a firms decision to collaborate in R&D. Cassiman and Veugelers (2002) provide a great starting point to address the topic and I hope to provide an improved methodology here.

I also consider whether financial constraints play a role in shaping the decision to collaborate in R&D a feature that has been largely ignored in the existing literature.

I use the spread of broadband coverage across the UK as an instrument for firm level strategic appropriability. I also use economy wide product specific basic R&D spending and industry contracting intensity as instruments for incoming spillovers. With these new instruments I find results that depart from existing findings.

Instrumenting strategic appropriability in this way, I find that firms that can limit outgoing spillovers are more likely to collaborate with business partners. This is similar to the results in Cassiman and Veugelers, but I find that this effect is strongest for collaborations with competitors. Vertical agreements seem to be built in order to exploit cost sharing concerns and overcome financial constraints.

What is interesting is that firms that form collaboration links with research institutes, are not firms that enjoy large incoming spillovers, as in Cassiman and Veugelers (2002), but firms that have a large absorptive capacity through their science base. While absorptive capacity is not significant across all specifications it does retain a positive sign, which is in contrast to the negative sign of Cassiman and Veugelers (2002) and Abramovsky et al. (2009) definition of absorptive capacity.

Instrumenting incoming spillovers, as above, I find a negative coefficient, again in contrast to the positive coefficient generally found in the literature. Although insignificant, this may contain economic meaning i.e. firms that enjoy high incoming spillovers do not base their collaboration decisions on potential spillover gains and may even be discouraged to collaborate.

I also find that industry collaboration intensity improves the spillovers to all firms, whether they are part of their own collaborative agreement or not. This is in contrast to existing work where either this effect is found to be insignificant or negative. Generally the theoretical literature on R&D spillovers remains silent on information spillovers to non-collaboration partners. The little that has been written assumes constant spillovers outside the collaboration agreement that remains unaffected by decisions within (Goyal et al. (2008), Goyal and Moraga-Gonzalez (2001), Katz (1986)).

My methodology leads to findings that are not startling, but differ from previous works that have conducted a similar exercise. Clearly, the results depend on the choice of the instrument set and the choice of endogenous variables. In a setting like this, it is difficult to be sure about what each covariate represents and the direction of causality associated with it.

For example, it is likely that firms exploit their good science base as a monitoring technology to limit adverse selection and moral hazard within a cooperation agreement. Yet, any effort by a firm to limit the impact of these two market imperfections is likely to directly improve the firms absorptive capacity. Either way we would predict a larger science base in improving the chances of collaboration even thought we cannot be sure whether we are identifying the impact of absorptive capacity or the ability of the firm to avoid moral hazard.

Cassiman and Veugelers (2002) find a strongly significant and positive coefficient on complementarities and confer it a causal interpretation. This is a strong finding that is present in all replications, yet I use a different set of instruments and the effect completely vanishes. In fact, I only find evidence of a positive complementarities effect in the OLS regression of innovators.

In the absence of properly specified instruments, OLS estimates are likely to be the most informative. The OLS estimates suggest that only within the sample of innovating firms there is enough variation to explain a positive correlation between complementarities and collaboration. Is this variable really capturing complementarities? Could this variable reflect expost technology choices by collaborating firms that help shape successful innovation policy?

A class of theoretical models on R&D patent races suggests that firms competing in R&D may have incentives to overinvest, compared to the social optimal, in highly risky projects in an attempt to preempt rivals. Firms find themselves in a situation where simultaneously reducing the risk of the technology is beneficial for both but not credible. In this scenario cooperative agreements can lead to less risky technological choices (Dasgupta and Maskin (1987), Klette and de Meza (1986), Judd (1985)).

It could be that firms employing very risky projects are also the firms that lack information on the technology. This interpretation provides another perspective for the positive and significant coefficient on the complementarity variable within the innovating sample. If this is the case then our complementarities variable is likely to be endogenous. Future research should take these considerations into account.

3 Choosing the Right Appropriability Mix: Strategic vs. Legal Instruments

"No rational person with a patentable invention would fail to seek a patent"

Friedman et al. (1991) on the workings of the trade secrecy law in the US

3.1 Introduction

In todays global economy fraught with informational spillovers, how do firms prevent their innovations from infringement and duplication? Do firms within collaboration agreements protect their interests differently? The purpose of this study is twofold. First, we[1] empirically determine whether firms in UK predominantly prefer legal appropriation, such as patents, to strategic appropriation, such as secrecy. The answer to this question is a big No. Knowing this we also ask the closely related question, why do firms patent at all? Secondly, we specifically study, for the first time, how firms in collaboration agreements choose to appropriate their innovations. We find that firms within collaboration agreements report a strong preference for strategic appropriation over legal as a means of protecting their interests.

The classic Schumpeterian view advocates the granting of monopoly rights to successful innovators and traditionally many economists and policy makers have favored the patent system, even though more efficient alternatives have been devised.[2]

Entering the patent system can be a costly procedure, especially for small

[1] This chapter was written with the partial help of Federico Todeschini, who assisted in the project development phase and contributed in data methodology. For this reason the chapter is presented in first person plural.

[2] There exists a large literature on awards systems discussing the efficient design of mechanisms inducing the right incentives to innovate without the granting of monopoly power. See for example Sappington (1982), Kremer (1998), Green and Scotchmer (1995). Scotchmer (2004) discusses issues of practical implementation and general success of such ventures.

firms, both from an ex-ante filing and ex-post monitoring perspective (Lerner (1995)). Despite the large costs patents seem to offer limited protection to the innovator. As Teece (2000) points out patenting awards excludability but involves information sharing with the public that can facilitate inventing around and second stage innovations. Infringement may be hard to detect and prove, especially for process innovations or if the patent can be easily circumvented, the patent may be invalidated if challenged and successful infringement litigation may only award minimal legal damages.

In this paper we use a panel of firms taken from three waves of the UK CIS survey, 1998-2006, to look at empirical reasons for why firms use patents and other legal protection instruments i.e. trademarks, copyright and design registration. Controlling for a host of factors we find that multinationals and financially constrained firms both report significant reliance on legal instruments. In contrast firms in collaboration agreements report an insignificant reliance on legal appropriation, but a strong significant reliance on strategic appropriation.

Collaboration agreements in R&D have the benefit of internalizing informational spillovers, creating synergies and complementarities between partners and allowing the efficient sharing of costs and risks and alleviating financial constraints. Such alliances must be built on some form of knowledge sharing (Amir et al. (2003), Bhattacharya et al. (1992), Katz (1986)). The issue of how to manage intellectual property becomes more acute when firms undertake joint research projects especially under loosely defined collaboration agreements. As Anton and Yao (2004) point out:

"Exploitation of an innovation commonly requires some disclosure of enabling knowledge to selected firms or to the public (e.g., to obtain a patent, obtain an alliance partner, or to induce investment in complementary assets). When property rights offer only limited protection, however, the value of the disclosure is offset by the increased threat of imitation."

Defining ownership structures and property rights within multiple partner groups may prove a difficult task. Although existing theoretical models on strategic information disclosure do not directly analyze collaborative agreements they do suggest that firms in collaboration agreements would prefer to use strategic means of appropriation such as secrecy.

An exception is the work of Baccara and Razin (2004) who argue that under imperfect property rights, collaborators could potentially leak innovative knowledge to non-partners. Under the threat of information leakage the lead innovator can find it beneficial to withhold information from collaborating partners, i.e. rely on secrecy, in an attempt to threaten the collaborators with the loss of ex-post monopoly rents through further information disclosures.

Models of strategic information disclosure build on the premise of weak property rights, and may be, strengthening the effectiveness of intellectual property is the right way for policy to proceed.

EU and Japanese policy have long advocated the benefits of collaborative R&D, with the US recently following suit. At the same time, in recent decades, EU policy has been strongly geared towards improving the legal infrastructure surrounding EU patenting and making it user-friendly. The fact that EU policy makers understand the difficulties and detailed intricacies involved in properly defining property rights within collaborative agreements, and that this is a central concern, is evident from all guidance notes and research reports published by the EU patent office.[3]

These concerns lead us to study the incentives to patent or maintain secrecy in a theoretical framework that bears some resemblance to Kultti, Takalo and Toikka (2006), in which we explicitly model financial constraints and collaboration agreements between firms.

Firms are allowed to simultaneously develop an idea that is in the public domain, however they can also enter collaboration agreements that are finalized before the development stage. Firms maintain secrecy or patent prior to entering collaborative agreements in order to maximize

[3]Recent examples of pro-patent EU policy include the London Agreement and EPC2000 (www.epo.org). Guidance, aimed towards collaborating businesses, on properly defining property rights within the agreement can be found at www.europa.eu.

ex-post payoffs from collaboration and development. We model patents as uncertain property rights (Lemley and Shapiro (2005)) that put information into the public domain for everyone to use (Scotchmer and Green (1990)).

In line with the emerging theoretical literature on strategic information disclosure, e.g. Anton and Yao (2004), we find that firms prefer secrecy to patenting when the value of the innovation is large, when the probability of information revelation is low and when the patenting technology is weak. Moreover, the model also predicts that collaborating firms generally prefer secrecy and within the set of collaborators financially constrained firms prefer more secrecy than non-financially constrained firms.

We empirically test the model predictions and find broad support. Collaborating firms in the UK CIS sample rely significantly more on strategic protection i.e. secrecy, confidentiality agreements and lead-time advantage, than legal protection. Within the sample of collaborating firms we find that financially constrained collaborators rely more on secrecy, as do firms with high complexity of innovation design, which we interpret to mean a low probability of information disclosure.

3.1.A Existing Empirical Studies

Survey based studies in the US have shown that in reality patents only foster innovation incentives in a few high technology industries, most notably pharmaceuticals (Mansfield (1986), Mansfield, Schwartz and Wagner (1981), Scherer et al. (1959)). A similar conclusion for the UK is reported in the findings of Taylor and Silberston (1973).

Levin, Klevorick, Nelson and Winter (1988) use a survey targeted at high level R&D executives and find that despite a few notable exceptions, mainly pharmaceuticals, most R&D intensive industries prefer recourse to alternative forms of intellectual appropriation, in particular strategic mechanisms including lead-time learning advantages and secrecy. The ease with which process innovations can be kept secret and the desire to market product innovations gives rise to an innovation specific preference

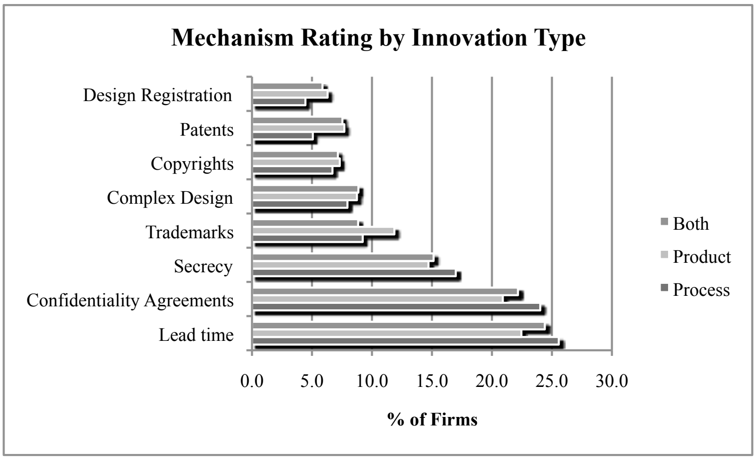


Figure 3.1: Authors own calculations using UK-CIS panel (1998-2006).

between the use of secrecy and patents but in general they find that strategic appropriation measures are still generally preferred even for product innovations.

These early finds have been corroborated by empirical studies from around the world. The use of data sources from The Netherlands, Germany, Japan has found broad support for the initial findings of the US, these include Arundel (2001), Cohen, Goto, Nagata, Nelson and Walsh (2002), Pitkethly (2001) Schalk et al. (1999) and Arundel and Kabla (1998). An informative summary of the results is available in Blind et al. (2006).

In support of these general findings, Figure 1, constructed from our UK-CIS panel, shows how firms rank the effectiveness of various protection mechanisms according to the type of innovation undertaken. It shows the percentage of firms, by type of innovation, that assign the highest importance to each type of protection mechanism.[4]

In this paper we analyze the role of financial constraints in R&D collaboration agreements and the appropriability choices made within. Our theoretical model is built on the premise that financially constrained firms

[4]We follow the methodology of Arundel (2001), who finds a similar result using a cross-section of the Dutch CIS, and look for the most preferred option. See Pajak (2008) for more recent results from France.

collaborate to acquire enough capital to develop their innovative ideas. In related work, Bond, Harhoff and Reenen (2003) study the role of financial constraints in Germany and the UK and find that financial constraints are more significant in Britain, that they affect the decision to engage in R&D rather than the level of R&D spending by participants, and that consequently the British firms that do engage in R&D are a self-selected group where financing constraints tend to be less binding.

3.1.B Existing Theoretical Studies

The emergence of such strong empirical findings both in the US and Europe have inspired a renewed interest in the theoretical considerations behind innovation protection and strategic information disclosure . The main underlying assumption in these studies is that patents are a source of information disclosure. The earliest works can be traced back to Bhattacharya and Ritter (1983) and Horstmann, MacDonald and Slivinski (1985). The latter model an information-signaling problem, in a leader-follower framework, where the innovator chooses whether to patent to signal his private information to the imitator.

Anton and Yao (2004) extend this to the strategic choice of knowledge disclosure and show that a world of weak property rights induces information disclosure incentives inversely proportional to the size of the innovation. Limited patent protection allows imitation and firms use secrecy to contain imitation enhancing information disclosure and protect large innovations. In this environment patents signal the size of the innovation to potential imitators and are only used when the innovation is small.

In a complementary study Denicolo and Franzoni (2004) look at the patenting incentives of both the innovator and imitator. Innovators can choose to protect their innovation either through patents or secrecy. Secrecy opens the possibility of imitation, through information leakage, and a successful imitator can choose to patent the secret innovation. The authors show that prior user rights limit the incentives of patenting imitations but at the same time also limit the incentives to patent innovations.

Aghion and Tirole (1994) study the case of a cash constrained research unit whose innovation is financed by end-customers. They show that in a world of incomplete contracts, because the precise details of the innovation cannot be specified ex-ante, the allocation of property rights between research unit and customer is always efficient and better for the research unit when it has ex-ante bargaining power. They argue that the financial constraints shift ex-ante bargaining power to the customer, especially if the research unit resides in a highly competitive environment.

In a slightly different setting, however, Anton and Yao (1994) show how a research unit can maintain ex-ante bargaining power. They model a research unit with access to non-verifiable knowledge that it cannot develop. The research unit proposes a closed sale to a development unit and extracts a payment through the threat of revealing the secret information to another competing development unit if payment is not made.

The extension of Bhattacharya and Guriev (2006) explicitly analyzes a bargaining game between a research unit, with access to non-verifiable knowledge, and two potential buyers development units. A patent facilitated open sale provides the legal support for exclusive disclosure, but also leads to public information leakage. On the other hand a closed sale, through secrecy agreements, can limit indirect information leakage but may allow the research unit to sell the non-rivalrous information to the other development unit. This issue can be circumvented if the development unit agrees to share its post-innovation revenues with the research unit but this reduces incentives to invest in the development. However both research and development units are more likely to choose a closed sale if the interim knowledge is very valuable and intellectual property is not very well protected.

While these studies are evaluated within an ex-post licensing framework, in which the cash constrained research unit sells its knowledge, Holmstrom and Tirole (1997) consider the ex-ante financing problem of a research unit that wishes to implement the innovation in-house. They argue that when the innovation idea is characterized by unobservable effort and moral hazard, a cash constrained firm can induce non-specialist investors to back its project by first collaborating with a specialist financier in return for a partial financial stake in the project. The collaboration allows the specialist financier to monitor the effort of the entrepreneur and this sends out a signal to non-specialist investors that the project is viable. However, Bhattacharya and Ritter (1983), were the first to acknowledge that securing financing requires information disclosure to investors that potentially spills over to competing research units enhancing their research capabilities.

Our work is also closely related to the literature on endogenous spillovers and R&D cooperation agreements. We assume that a firm cannot enter more than one collaboration agreement, which is equivalent to the two firms entering a perfectly enforceable state contingent confidentiality agreement that discloses all relevant information between the collaborators but perfectly limits information sharing with non-partners. A generalization would potentially relax this extreme assumption .

Traditionally the literature on information spillovers has focused on the case of exogenously determined symmetric spillovers between firms and has unequivocally come to the conclusion that R&D cooperation agreements better internalize the associated externalities when the spillovers are above some critical bound (De Bondt (1997)). More recently studies have focused on the idea that the degree of spillovers, equivalently appropriability, may arise endogenously within the cooperative agreement as a result of a firms absorptive capacity and how other decisions on cost and production sharing take shape (Leahy and Neary (2007), Amir et al. (2003), Grunfeld (2003), Martin (2002), Kamien and Zang (2000)).

In some sense our work also provides insights for the strand of literature focusing on the optimal length and breadth of patents (Takalo (1998), Gallini (1992)). Our theoretical analysis suggests that firms prefer recourse to strategic appropriation when patents fail to appropriately compensate the originator of the idea. However competitive forces also have to be taken into consideration. In a similar vein this work also helps provide insight into estimating the Schumpeterian Hypothesis, by providing further evidence for why patent data may not be the best indicator of innovative activity (Trajtenberg (1990)).[5]

[5]For examples of how patent data is used to proxy innovative activity in empirical work, see Bloom and Reenen (2002), and references cited therein.

The rest of the paper is organized as follows. Section 3.2 describes the data. Section 3.3 discusses the empirical strategy and provides empirical evidence of why firms use patents to protect their innovations. Section 3.4 motivates a stylized game-theoretic model of financial constraints, R&D collaboration and appropriability. Section 3.5 revisits empirics with a special focus on collaboration agreements and finds evidence in support of the theory. Section 3.6 concludes. All relevant empirical Tables can be found in the Tables appendix, and all proofs are contained within the Proofs appendix.

3.2 Data

We use three waves of the CIS survey, CIS3 1998-2000, CIS4 2002-2004 and CIS5 2004-2006, to construct an unbalanced panel of almost 30000 observations. We restrict our attention to the sub-sample of firms, 15539 observations, for which we have information on the science base, the percentage of full-time employees with a science degree, and that report positive contemporaneous R&D expenditure. This allows us to avoid the diluting effect of those firms reporting protective mixes for innovations and R&D conducted in the distant past and in the absence of internal R&D capabilities.

Most variables of interest are sourced from the CIS survey. Information on multinational status, ownership structure, mergers, takeovers, age and geographic location are sourced from the UK Business Register. Import intensity data is collected from the UK input-output tables, which are also used to construct the measure of relationship specificity. Patent distributions are calculated using NBER data on US patent applications.

3.2.A Appropriability

The CIS survey asks respondents to list the use and importance of various methods available for protecting innovation. Firms rank these variables on a Likert scale between 0-3, where 0 signifies no use and 3 signifies high use. In raw form these variables are likely to suffer from subjective reporting bias. Therefore, following Bloom and Reenen (2006), we first standardize all the responses to a $N\ (0,1)$ distribution.

We group together the importance of patents, trademarks, copyright, and design registration. In order to further eliminate and subjective bias or the influence of outlier responses we take the average of all four responses as our measure of legal protection.

Similarly we take the average normalized response from secrecy, lead-time and confidentiality agreements as our measure of strategic protection. Similar groupings can be found in the literature, e.g. Rammer (2003) and Cohen et al. (2002).

Firms also report on the importance of complexity of design in protecting innovation. This interpretation gives credence to our interpretation that complexity of design measures the firms belief on how likely it is its idea will become publicly available. We also standardize this variable as described above.

3.2.B Financial Constraints

Firms report, on a Likert scale between 0-3, how important availability of finance was in hampering innovation activity. We interpret this as credit rationing. In addition firms also report on the importance of high costs of finance as an obstacle to innovation. This we interpret as credit constrained. We construct a categorical variable that captures financial constraints in the following way: 2 if a firm reports 3 for credit rationing, 1 if the firm reports 3 for credit constraints and 0 for everyone else.

3.2.C Demand Risk

Firms report the importance of uncertain demand for innovative goods and services and lack of information on markets as obstacles to innovation. We group these two responses together and take the average, of the standardized variables, as our measure of demand risk.

3.2.D Contracting Intensity

We follow the methodology and assumptions laid out in Nunn (2007). Using the product market classification of Rauch (1999) we first identify whether the primary set of products within a given UK Input-Output grouping are sold over an organized exchange or reference priced in trade publications. If so, the goods market is assumed to be sufficiently thick. When the primary set of goods are neither reference priced or sold over an organized exchange, they are assumed to bought and sold via relationship specific contracts. Using equal weighting for all primary products we define $R_j^{niether}$ as the fraction of industry j goods that require relationship specificity.

Using information on intermediate demand from the UK I-O tables we construct a matrix that identifies the fraction of intermediate inputs $\theta_{kj} = \frac{u_{kj}}{u_k}$ that industry k procures from industry j, where u_k is the total intermediate demand of industry k and u_{kj} is the amount procured from industry j. This gives an industry level of relationship specificity captured by $r_k = \sum_j \theta_{kj} R_j^{neither}$.

In order to introduce some time-variation in r_k, we construct 3 different matrices for years 1998, 2001 and 2003. Rauchs data is organized according to the SITC trade classification. In order to map to UK I-O data we use concordance tables published on the UN statistics website.

The CIS survey does not obtain firm level information on intermediate purchases. In order to operationalize a firm level measure of relationship specificity we assume a Leontief relationship between labor and intermediate purchases, $\min\{l_i, \gamma m_i\}$, such that $l_i \leq \gamma m_i$ for any $\gamma \geq 0$. This allows us to construct a firm level measure of relationship specificity, which we use in the regression analysis, given by

$$z_{it} = r_{kt} l_{it}$$

Where l_{it} is total full time employment for firm i in the first year t of the survey time frame.

3.2.E Patent Distribution

We use the NBER database on patents to construct a measure of patent concentration within a given industry. The database runs from 1975 to 2005 and has over 3 million patents from all over the world, particularly the US. Unfortunately patents are coded using the International Patent Classification system, which is different than the UK Industry Standard Classification. In order to solve this problem a concordance was constructed using the Canadian SIC and the US NAICS in order to have a complete match at a SIC 3-digit aggregation.

Patent concentration is measured with industry specific Gini coefficients constructed from the accumulated patent stock. One potential problem with this measure is that if for a given industry very few patents are recorded, and some of them are not, the Gini coefficient could be biased. Following Verbeek (1992) we assume a negligible bias in industries where more than 100 patents were available. There are not many instances where we find an industry with less than 100 patents and therefore conclude that the bias should be small.

In order to have inter-temporal variability, we construct the measure using three different time thresholds: 1998, 2001 and 2003 i.e. we construct the Gini coefficient for patents accumulated up to 1999, another for those patents accumulated up to 2001 and so on.

3.2.F Internal Research Capability

CIS firms report their spending on in-house R&D. At the same time they also report the percentage of active employees with a science degree, which we call the science base. We believe the science base to be a good proxy for the firm's absorptive capacity. A higher absorptive capacity means better research capabilities for a given amount of spent money. At the same time internal research capabilities should exhibit diminishing returns to scale. For this reason we take the natural log of in-house R&D spending and multiply this by the science base. The resulting variable is our measure of internal research capability.

3.3 Estimation Strategy

The estimation strategy is to implement fixed effects estimation on the following specification:

$$y_{ijt} = \beta_0 + \beta_1 c_{ijt} + \beta_2 q_{ijt} + \delta_1 b_{ijt} + \delta_1 b_{jt} + \gamma_1 f_{ijt} + \gamma_1 o_{ijt} + \mu_t + \phi_r + \epsilon_{ijt}$$

Where c_{ijt} captures either process imitators or innovators, q_{ijt} captures either product imitators or innovators, b_{ijt} is a vector of firm-specific behavioral variables i.e. financial constraints, demand risk and contracting intensity, b_{jt} is a vector of industry specific behavioral variables i.e. import intensity and patent distribution, f_{ijt} is a vector of firm level controls and o_{ijt} is a vector of additional characteristics that may lead to omitted variable bias if not included. Time variant unobserved heterogeneity is captured through μ_t and ϕ_r captures time-invariant unobserved heterogeneity at the local geographic level. The working assumption is that the remaining error captured by ϵ_{ijt} is uncorrelated with any of the explanatory variables.

Why do firms patent at all if they always have recourse to more effective appropriation mechanisms? Firms responding to the Levin et al. (1988) survey say patents are primarily more effective in preventing duplication, rather than securing royalties, and prove ineffective when innovations are easy to innovate around and infringement is difficult to prove.[6] Cohen, Nelson and Walsh (2000) explore this question in their own survey and find that firms primarily use patents for non-commercial benefits. Aside from preventing copying, other motives for patent use mainly include patent blocking, prevention of infringement suits, for use as negotiation tools and as reputation enhancers.

Drawing inspiration from these works we first concentrate on why firms choose to patent. More generally we define legal protection, l_{ijt}, as the

[6] Interestingly, detailed interviews from their survey sample indicate that many firms use patents as a mechanism to gauge the performance of science personnel, a result also found by Blind et al. (2006), while others use it as an entry mechanism into foreign markets, where licensing agreements between the multinational and foreign country are necessary pre-requisites to entry. This is internally consistent with reports, from their survey, that licensing agreements are extremely effective sources of knowledge spillovers.

mean importance of patents, copyrights, trademarks and design registration as innovation protection methods reported by the firm.[7] Our variable of interest, in the first part of the empirical analysis, Section 2, is defined as

$$y_{ijt} = l_{ijt}$$

We next define strategic protection, s_{ijt}, as the mean importance of confidentiality agreements, lead-time advantage and secrecy as innovation protection methods reported by the firm. Our variable of interest, in the second part of the analysis, Section 3.5, is defined as the difference[8]

$$y_{ijt} = s_{ijt} - l_{ijt}$$

In the second empirical part, Section 3.5, we will see (a) whether the reasons to patent, identified in this section, dominate the preference structure and (b) whether collaborating firms systematically report a different preference structure and why.

3.3.A Empirical Support for the Importance of Legal Instruments

Process innovations tend to be firm specific and easier to conceal, which means patent infringement is difficult to detect and potentially costly to verify. Product innovations, however, need to be publicized for success and direct infringement is easier to detect. This suggests that product innovators, in comparison to process innovators, are more likely to find patents, and other legal instruments, beneficial (Cohen et al. (2000), Arundel and Kabla (1998)). In the baseline specification we introduce indicator variables for process and product innovators and imitators.

[7] We could just concentrate on patents and secrecy as the dependent variables of interest, which would be the closest empirical counterpart to theory. Specification testing revealed similar results. However, individual measures are likely to be more sensitive to extreme values, and responses within each type were correlated enough to justify the averaging.

[8] There are many ways in which we could have chosen to measure this relation e.g. we could have used the ratio of the two. Taking the difference has the advantage, as advocated by Arundel (2001), of minimizing disparities in scoring and inter-rate differences making the derived rating scale more amenable to interpretation.

Table 3.1 finds a statistically significant hierarchy in responses, confirming the above view and other empirical results. Innovators, be it product or process, report a statistically higher reliance on patents than an imitator from the same category of innovation. More importantly, product innovators report an even higher reliance on patents compared to process innovators. It is also interesting to note that while process imitators do not significantly rely on patents, product imitators do, in fact to a similar extent to process innovators.[9] This might be attributed to a lenient Intellectual Property Rights (IPR) policy in the UK that allows firms to invent around existing innovations, or it may simply reflect the import of ideas i.e. firms adopting internationally patented ideas and patenting them at home.

Also in line with existing empirical findings we see that firms belonging to high (cumulative) technology industries rely significantly more on patents.[10] The firm controls we introduce are all broadly significant, and deserve some mention. We interact the size, firms with more than 250 employees, and age of the firm to capture the idea of large well established business, with a potentially sound asset holding.[11] We also control for

[9] Restriction tests reveal that the differences are significant across all specifications in Table 3.1, where we progressively add more and more controls to the baseline. Even the baseline regressions starts by controlling for firm level fixed effects, and therefore is a powerful result in its own right. It is very well known that fixed effects analysis can lead to attenuation bias, especially in the face of measurement error i.e. the results were are presenting provide a lower bound. The fixed effects are actually calculated at 7 digit postcode level. UK postcodes are extremely detailed and change with almost every street. This means most firms in our sample residing in different streets are treated as separate entities, but firms on the same street, building or retail parks are treated as one.

[10] It is widely accepted in the empirical literature that patents are mainly used in complex cumulative industries to enhance negotiation power with rivals, see for example Cohen et al. (2002) and Reitzig (2004). In our specification we also control for product innovators within high-tech industries to differentiate between the industry effect and the within industry firm effect. This effect is not significant suggesting only the presence of a between industry effect within the present sample. In the entire sample, i.e. including firms that do not provide information on their science base, we find both a between and within industry effect with respect to product innovations. Likewise, in our general analysis we also experimented with modeling the differential behavior of product imitators, process innovators and imitators in high technology industries. We found no evidence that these categories of innovators relied more on patents than their counterparts in other industries.

[11] We chose to interact the size and age variable because an analysis of the UK Business register reveals the two to be highly correlated and in effect they capture the same factor. Survey respondents on the other hand, might be part of a larger

whether the firm is part of a larger enterprise group. We find strongly significant and positive coefficients on both these variables that remain stable across all specifications.[12] Additionally, we find that sole proprietorships and private partnerships are less likely to rely on patents than public corporations, which in turn rely on patents less than government institutions. Distinguishing between new reporting units in old enterprises and completely new enterprises, we find that only the former report significantly higher reliance on patents. Taking all of this in conjunction, we interpret this as support for the hypothesis that the effectiveness of patents depend on the ex-post costs incurred by firms, for which larger firms are institutionally better placed.[13]

In their survey based study, Cohen et al. (2000) ask their respondents to the list the main reasons behind patenting inventions. They find that their respondents do so primarily to block competitors, to improve goodwill reputation and improve bargaining power in the market. We do not have access to such direct responses but in what follows we use constructed data, to argue that similar influences arise in the UK-CIS sample.

In columns 2-7 of Table 3.1, we include as extra explanatory variables competition pressure, market risk, financial constraints, contracting intensity and a measure of patent distribution within industries.

3.3.A.a Escaping Competition

In column 2 of Table 3.1 firms facing greater competitive pressure, captured through a measure of import intensity within the industry, report a greater reliance on patents.[14] This is reminiscent of the escaping compe-

group enterprise, with many other subsidiaries, but still be small in size or young. We therefore retain the group variable separately.

[12] In the legal regressions the coefficient on size and age is always significant and remains in the range of 0.005-0.007. The enterprise group coefficient varies between 0.08-0.11, but again always remains significant.

[13] For similar interpretations and findings see Bussy et al. (1994), Kortum and Lerner (1999), Janz et al. (2001) and Hussinger (2006).

[14] This result is robust to the use of alternative measures of competition, such as the industry mark-up used in the previous chapter. We prefer using import intensity here as it reflects global competition, rather than local, and is likely to induce a higher reliance on patenting.

tition postulate put forward by Aghion (2001) i.e. firms innovate to earn monopoly rents and escape ex-ante competitive structures. However, in competitive markets categorized by weakly differentiated goods and technologies, firms may also report a greater reliance on patents as a way of protection against infringement suits, and as a blocking mechanism.

3.3.A.b Blocking Patents

In column 3 of Table 3.1 we introduce a measure of market risk, constructed as the amalgam of two firm-level responses. Firms report the importance of lack of information on markets and uncertain demand for innovations as potential obstacles to innovation. We see that firms facing these barriers also rely significantly on patents as a source of protection. The fact that patents are used to secure rights to uncertain markets is taken by us to mean that firms use patents to secure the option to operate in future markets and block rivals from entering, should the innovation become profitable. Introducing this variable in the regression does not take significance away from competitive pressure, suggesting the presence of an independent escaping competition or legal protection motive.

3.3.A.c Goodwill Reputation

In column 4 of Table 3.1 financially constrained firms also report a positively significant reliance on patents, above and beyond, what is explained by their innovative stance, firm characteristics and competitive environment. In line with Blind et al. (2006), we interpret this reliance as an attempt by financially constrained firms to build a patent portfolio as a way of defining their goodwill and reputation for future transactions with financial markets and industrial competitors.

3.3.A.d Bargaining Power

Cohen et al. (2000) identify the need to improve market bargaining power as a major motive for patenting in the US. In order to infer whether similar concerns exist for firms operating in the UK, columns 5 and 6 of Table 3.1, employ two independent and externally constructed measures. Following Nunn (2007) in Column 5 we construct a measure of contracting intensity with the vertical supply chain. In column 6 we introduce a measure of the degree of inequality in the patent distribution in a particular industry.

We argue that contracting intensity measures the degree of specific relationships a firm has in its inputs procurement. It therefore proxies the desire to maintain bargaining power within vertical supply chains, while industry patent distributions reflect differences in horizontal bargaining power amongst rivals.

Vertical Bargaining Power A commonly held belief in the theoretical IO and International trade literature on vertical relationships is that relationship specificity exposes downstream firms (buyers) to hold up problems. Firms that rely heavily on complex differentiated inputs sourced through contractual agreements will suffer more acutely from supplier-induced hold up (Nunn (2007), Reitzig (2004)). If the particular input mix could be protected by patent, suppliers would not be able to credibly commit to hold up and the buyer would gain substantial bargaining power. As argued above, our contracting intensity variable captures the degree of relationship specific inputs the firm has. The fact that we see firms with a high level of contracting intensity rely significantly on patents, column 5, suggests that maintaining bargaining power in vertical relationships can drive the decision to patent.[15]

Horizontal Bargaining Power The results in column 6 of Table 3.1 show the relationship of patent distribution within an industry and indi-

[15]Given that the size effect is captured through the size dummy and age interaction, and does not diminish after inclusion of contracting intensity, is evidence that contracting intensity is not just picking up a size effect that is not fully explained by our size dummy. Much of the empirical literature that tries to understand reasons for patenting show, like us, that size of firm increases reliance on patents. Many of these studies use continuous measures of size e.g. employee counts (Hall and Ziedonis (2001)). Our formulation of contracting intensity gives an alternative rationale for the result when continuous measures of size are used.

vidual reliance on patents is not so clear-cut. We use a dummy variable that identifies industries where the Gini-coefficient of patent distributions is less than 0.2 and we find that firms in these industries rely on patents more. In many industries technology patents are held by, relatively few firms, which leads to a highly uneven distribution of patent portfolios. If the magnitude of patents over which this distribution is defined is also high, an infra-marginal firm will not gain much bargaining power with the use of a patent. However firms in industries where the distribution disparity is not very high are still likely to find use in patents, as potential bargaining tools. Also in high technology industries where most innovations are of a cumulative nature securing property rights on even the slightest of innovations may confer some bargaining power.[16]

We conclude the positive and significant coefficient on both contracting intensity and unequal patent distributions suggests that maintaining bargaining power is a significant reason for relying on patents.

Finally, column 7 of Table 3.1 shows that all the influences discussed above are significant in their own right.

3.3.B Multinationals

Table 3.1 also shows that foreign multinationals report a strong reliance on patents. This finding is very robust to our inclusion of the various competitive and behavioral variables, and firm characteristics. The coefficient hardly changes and retains its significance in every column of Table 3.1. Levin et al. (1988) explain the reliance of many multinationals on

[16] Although not presented here, we find a positive reliance on patents by product innovators in high technology industries. We obtain this result by interacting the raw Gini-coefficient of patent distributions, and not the derived dummy, with product innovators. We experimented with many cut-off points for the dummy variable. The maximum Gini-coefficient in our sample is around 0.85 and the mean and median, over the 8 years are both 0.48. Increasing the cut-off reduces the magnitude and significance of the coefficient on the dummy and in the extreme when we simply use the Gini-coefficient we find a negative relationship between size of distribution disparity and reliance on patents. This confirms our belief that there are non-linear considerations at play when considering horizontal bargaining power.

patents because of the need to license their technologies as a prerequisite to entry in foreign markets. This argument seems more relevant for multinationals operating in developing economies but may have some strength in economies such as the UK. Alternatively, multinationals may prefer patenting because they can achieve economies of scale by utilizing their globally spread out legal infrastructure.

Table 3.2 specifically focuses on multinationals and why they patent. In each column of Table 3.2 we interact the behavioral variables with the multinational identifier to individually distinguish the differential effects across the subsample of multinationals.[17] In column 2 of Table 3.2 we see the subsample of multinationals in highly competitive industries does not seem to rely on patents any differently from the average multinational i.e. the coefficient on this interaction is insignificant. Similar conclusions arise in column 5 for multinationals in evenly distributed patent industries, and in column 6 for those multinationals that face a high degree of relationship specificity. However, in column 3 and 4 we see that the entire multinational premium, now insignificant, is captured by the subsample of multinationals that are either subject to uncertain demand or financial constraints.

Multinationals seem to use patents mainly as blocking devices and as financial reputation enhancers. They do not seem to suffer bargaining concerns and do not necessarily use patents to escape competition, column 7.

Arundel and Kabla (1998) finds that firms conducting R&D on a permanent basis prefer patenting their innovation investments. It may be that multinationals are more prone to conduct permanent R&D in a constant effort to expand market reach. In addition, it may be the case that multinationals are also more prone to collaborate in R&D with domestic partners e.g. Brouwer and Kleinknecht (1999) find a positive relationship between collaboration and patenting. Not controlling for these aspects of multinational behavior may inflate the coefficient with a positive bias.

Column 8 introduces an identifier for those firms that report conducting permanent R&D, and those firms that report collaborative agreements

[17] All regression variables from Table 3.1, i.e. product and process imitation and innovation, were also included in these regressions, however we suppressed the output to focus on multinationals.

in R&D. Firms conducting permanent R&D report a higher reliance on patents. In contrast to Brouwer and Kleinknecht (1999), we do not find a significant reliance on patents by firms in collaborative agreements.

In addition, controlling for these two factors does not diminish the significance of the patent-premium for those multinationals that face uncertain demand or financial constraints.

3.3.C Just Established Firms

Column 7 of Table 3.1 shows how newly established firms rely on patents. Just established reporting units operating within existing enterprises report higher reliance on patents, than the average, while just established enterprise reporting units do not report significant differences in patent reliance. Yet it is precisely these firms that are likely to suffer from the fiercest market conditions and have the highest valuation for mechanisms that help them maintain a footing within the market i.e. we would expect them to value patents differently from the average, however, it seems they do not.

We explore this issue further in Table 3.3. Controlling for all the other factors already identified, we only find one significant effect in column 2. Newly established enterprises in industries with highly uneven patent distributions significantly underreport the importance of patents as useful protection mechanisms.

The remaining behavioral factors are all insignificant. However, we believe, the signs they take may contain some economic significance.[18] Newly established firms that face competition pressure report a positive reliance on patents, as do newly established firms with relationship specific vertical relations. Moreover, the fact that these firms undervalue patents in the face of financial constraints and as a blocking mechanism may indeed suggest that initial costs of patenting outweigh the potential benefits awarded to new firms, especially in the face of market uncertainty.

[18]The sample of newly established firms is extremely small, and therefore it is no surprise that fail to find significant results.

We check, in columns 4 and 5, whether the over-reliance of permanent R&D conductors on patents can be explained by any of the behavioral factors. This does not seem to be the case, suggesting other reasons for this preference, worthy of a separate study.

3.3.D Evidence of Financial Constraints and Type of Innovation

In this section we check whether collaborating firms are more likely to be financially constrained than multinationals and whether we can find systematic differences in innovative activity.

Figure 1 shows that firms in the UK-CIS sample are more likely to assign priority to strategic mechanisms rather than legal protection, yet the regression analysis presented shows evidence of a significant positive reliance, by firms, on legal protection methods.

Even though we control for whether the firm innovated or imitated, the type of innovation it carried out and additional firm level controls, we find strong evidence of firms relying on patents when they are financially constrained, when they face intense competition, where there is market uncertainty and when there is a need to improve bargaining power.

A priori we would expect newly established firms to face all of these problems. However newly established firms do not report a patent premium beyond what is already explained by our behavioral factors. We find a similar result for firms in collaboration agreements.

Multinationals, on the other hand, value legal protection as way of securing potential future gains and report a patent premium. This could be an indication of the workings of an IPR system that favors large firms, either because it is easier for large firms to incur the initial costs or because they have access to the right resources, e.g. in-house legal teams, to utilize the patent ex-post through infringement detection and valuation.

Or it could be that the multinational coefficient is picking up idiosyncracies not accounted for by our covariates. For example if multinationals are more likely to innovate rather than imitate compared to other firms, they may report a patent premium. On the other hand the reliance of collaborating firms on patents may completely be explained by financial factors if they are more likely to be financially constrained than multinationals.

The new theories on strategic information disclosure do not explicitly differentiate between these types of firms and so we look for empirical evidence.

3.3.D.a Financial Constraints

A difference in means test in Table 3.E, across samples, reveals that multinationals are less likely to be financially constrained than domestic firms. In contrast firms in collaborative agreements are more likely to be financially constrained than non-collaborating firms. We explore this result further with a simple regression that controls for other factors that might influence the financial constraints a firm faces. Firms that conduct permanent R&D, report a high complexity of design or are forced to innovate due to regulatory needs report higher financial constraints. Controlling for these and other firm characteristics, such as size and age, we find that indeed collaborating firms report high financial constraints while multinationals generally do not suffer from financial considerations. As Table 3.F shows this contrast is more profound in the entire sample, but also exists in the sample of firms that report positive R&D expenditures.

Blind et al. (2006) suggest that firms aiming to cooperate with competitors on R&D matters can improve their exchange prospects by patenting existing ideas. However, our results do not seem to reflect this hypothesis.

Alternatively if multinationals are more likely to product innovate while collaboration agreements process innovate, or one leads to more innovation while the other leads to more imitation, then the respective coefficients would reflect these idiosyncracies.

3.3.D.b Innovation vs. Imitation

To see whether collaborative agreements lead to more innovation than imitation we estimated a multinomial logit.[19] The multinomial logit assumes the Independence of Irrelevant Alternatives. While this may not seem a natural assumption in the present setting, we could not reject IIA through formal testing.[20] The presence of IIA allows us to recast the estimation slightly, without biasing the results (Wooldridge (2001)), and focus on the logit estimation of the combined sub-sample of imitators and innovators. Table 3.I shows that collaborators are more likely to innovate than imitate in both product and process innovations.

In Table 3.I, multinationals are just as likely to process innovate as they are to imitate, however, they are more likely to product innovate rather than imitate. These results are robust to the inclusion of various other explanatory factors such as public spillovers, defined in the previous chapter, research spending, personnel training, reasons to innovate and other firm characteristics. These differences in innovative capabilities between multinationals and collaborating firms do not seem large enough to justify the multinational premium. At the same time we find evidence that firms in collaborative agreements are more likely to be financially constrained than multinationals. For this reason we present a model in the next section that considers the role of strategic information disclosure but centers on financial constraints and collaboration agreements.

[19] The multinomial logit does not assign any ordinal value to the different alternatives. In keeping with the idea that innovation is better than imitation we also considered an ordered logit estimation. While the results were qualitatively similar, the multinomial logit returns a continuum of predicted probabilities, which we prefer to the abrupt cut-off points of the ordered logit. Results are available upon request.

[20] We subjected this assumption to two well-known tests, Small-Hsiao and Hausmann. Although it is extensively documented that these tests do not always agree (Long and Freese, 2006), in our case they both unequivocally failed to reject the assumption of IIA.

3.4 A Theoretical Model of Appropriability

In this section we construct, within a world of strategic information disclosure, a stylized model of financial constraints, R&D collaboration agreements and simultaneous innovation. We compute the equilibria of the game and present a set of comparative statics relevant for empirical testing.

We incorporate financial constraints by introducing a cost of idea development and by restricting the cash endowment of a subsample of firms such that they are unable to develop the idea independently. Firms to enter collaboration agreements to jointly develop ideas. Collaboration agreements are agreed upon through a process of bargaining. Bargaining power initially resides with the idea holder who initiates bargaining, but subsequently other firms are allowed to bargain as well. We introduce the dimension of strategic information disclosure by allowing firms to choose between patenting their idea and keeping it a secret.

Consider a firm within the plasma screen industry. It has private access to an idea on how to develop a technology that enhances screen resolution by 50%. It is commonly known by other firms in the industry, that the idea, in its developed form, is worth V. With a certain probability the blueprint of how to develop the idea reveals itself to everyone in the industry and this happens before the firm, originally holding the idea privately, can commit to development. The probability of information revelation is exogenous and commonly known by all industry participants.

The firm requires access to a certain amount of capital to develop the idea. It may or may not have access to the necessary capital, but if it does, it develops the idea with certainty. Without the necessary capital the firm is unable to develop the idea at all. Inspired by Holmstrom and Tirole (1997), we assume that the firm is unable to approach investors outside the industry for the necessary financing. Its only option to obtain the required financing is to form a collaboration agreement with an industry rival. Any such collaboration agreement has to be agreed before the information revelation stage.

Anticipating collaboration needs and information revelation, prior to agreeing on a collaboration agreement, the firm chooses whether to patent its idea or keep it a secret. The patenting technology is not perfect. A patent is costless to obtain but it immediately deposits the blueprint into the public domain, allowing competitors to develop an idea they did not devise. Any ensuing collaboration agreement is signed in the backdrop of full information revelation. The patent allows the firm to extract a certain ex-post license fee from an an infringing party that develops the idea without the patent holders direct involvement. However the license fee is always assumed to be less than the net value of the developed idea. This may be because the net private benefit of the developed idea is not verifiable by courts, or it could be that infringing parties are never perfectly detected because the idea can be innovated around.[21]

Alternatively the idea holder can maintain secrecy and enter collaboration agreement negotiations with an informational advantage. Nonetheless this option is also assumed to be imperfect, in the sense that prior to development the idea reveals itself to the public with a certain exogenous probability. If the idea reveals itself then any firm or collaboration agreement with the necessary amount of capital can develop the idea and directly compete in the product market. Secrecy rules out the possibility of extracting surplus, post development, as in the case of patenting. I assume that patenting the blueprint once it has become common knowledge is no longer feasible.

3.4.A The Model

More formally, at the beginning of play and without loss of generality firm 1 obtains an innovation idea. The identity of the firm is common knowledge. The firm chooses whether to patent its idea or keep it secret, and subsequently negotiates a collaboration agreement.

[21] Areeda and Kaplow (1998) argue that it often happens that a granted patent is considered unlikely to stand in court if ever litigated. Besen and Raskind (1991) and Fisk (2001) discuss limitations in enforcement of trade secrets law and no-compete agreements.

3.4.A.a Bargaining

The negotiations follow a specific protocol. The idea/patent holding firm 1 makes a take it or leave it offer to one other firm $i \neq 1$ from the industry. The offer specifies financial contributions of each party and how the post development profits are to be split. If firm 1 refuses to make an offer or makes an offer and is rejected by firm $i \neq 1$, then any remaining $i, j \neq 1$ pair of firms, in the industry, can enter collaboration negotiations amongst themselves al a Nash Bargaining. Collaboration agreements are always negotiated in pairs of two and no firm can enter more than one collaboration agreement.

3.4.A.b Timing

Subsequently and conditional on secrecy in the first stage, the idea is revealed by nature with probability $\beta \in [0, 1]$, i.e. it becomes common knowledge. At this stage it is no longer possible for any of the firms to apply for a patent.[22] Finally development occurs. The idea requires $2b$ units of cash to develop. The idea is worth V to the developing entity if developed by itself and αV if developed by itself and a competing entity, where $\alpha \in [0, \frac{1}{2}]$ captures the degree of competition.

Stage 1. *Firm 1, receives an idea and how to implement it.*
Stage 2. *Firm 1 decides on whether to patent the idea or keep it secret.*
Stage 3. *Collaboration negotiations, as explained in Section 3.1.1, ensue.*
Stage 4. *With probability $\beta \in [0, 1]$, known to all three firms, the idea enters the public domain and becomes common knowledge.*
Stage 5. *Firms or their groupings develop product(s). Each product earns revenue αV. Where $\alpha \in [0, \frac{1}{2}]$ measures the severity of market competition, and $\alpha = 1$ if only one entity develops the idea.*

[22] We impose this in order to keep the model simple and abstract away from considering patenting rules such as first to file or first to develop. See Scotchmer and Green (1990) for a discussion of how these rules affect ex-ante profitability of research.

3.4.A.c Assumptions

We state 3 important assumptions.

Assumption 3.1. $\alpha \geq \frac{2b}{V}$

Assumption 1 ensures that, in the absence of patents, more than one developed idea can be introduced in the market. One interpretation of α is the degree of market competition i.e. an increase in α is analogous to a decrease in market competition. Alternatively it can be thought of as the degree of differentiation between the developed ideas. Thus in the limit as $\alpha \to 0$ we approach Bertrand competition on homogenous goods.

Assumption 3.2. $L \leq V - 2b$

Assumption 2 captures the notion that the patenting technology is not perfect and almost never guarantees a license fee as high as the maximum net private benefit from developing the idea.

Assumption 3.3. *There is no collaboration between two firms if both are indifferent between collaborating or not. A firm is said to be indifferent when acting outside the collaboration agreement gives it exactly the same pay off as it would obtain within a collaboration agreement.*

Assumption 3 helps to narrow down the set of equilibria by precluding uninteresting situations. It can easily be rationalized by a small $\epsilon > 0$ cost of entering into a collaboration agreement that is incurred by each party. As long as one party gains from the collaboration agreement it will gladly incur the cost of $2\epsilon > 0$ which can be adjusted in the net transfers made through the collaboration agreement. However if both parties are completely indifferent neither of them is willing to incur the cost of $\epsilon > 0$.

3.4.B Industry Structure and Equilibria

In this section we consider four different types of industry structure. A firm is considered financially constrained if it is endowed with only b units of cash i.e. in order to develop the idea it has to enter a collaboration agreement to secure the remaining b units. A firm is not financially constrained when it is endowed with $2b$ units of cash.

To fix ideas we first consider an industry with only two financially constrained firms, and then an industry with only two non-financially constrained firms. These two symmetric benchmarks provide us with the intuition to analyze the more interesting industry structures with three firms in which either two firms are financially constrained, or non-financially constrained.

3.4.B.a Two Financially Constrained Firms

First consider an industry structure made up of two firms in which both firms have access to b units of cash. Neither firm can develop independently therefore information disclosure plays no role and patents are never enforced either. Hence firm 1 is indifferent between patenting and secrecy. Collaboration is a trivial outcome of the game. Any take it or leave it offer, made by firm 1, is accepted. Hence firm 1 collaborates and obtains $V - 2b$ while firm 2 collaborates and obtains 0.

3.4.B.b Two Non-Financially Constrained Firms

Consider an industry structure made up of two firms in which both firms have access to $2b$ units of cash. Conditional on information revelation both firms can develop the idea independently. Under secrecy and no collaboration firm 1 gets an expected payoff of $\beta(\alpha V - 2b) + (1-\beta)(V - 2b)$ and the other firm gets $\beta(\alpha V - 2b)$. Therefore if firm 1 wishes to collaborate it has to offer the other firm at least $\beta(\alpha V - 2b)$ for it to accept and earns $V - 2b - \beta(\alpha V - 2b)$. Under secrecy firm 1 always prefers to collaborate.

Under patenting and no collaboration firm 1 gets $\alpha V - 2b + L$ and the other firm obtains $\alpha V - 2b - L$, if this payoff is positive. To induce collaboration firm 1 has to offer $\alpha V - 2b - L$, to the other firm, which is accepted, and earns $(1-\alpha)V + L$. Thus collaboration under patenting is always preferred to non-collaboration, when $\alpha V - 2b - L > 0$. Finally secrecy and collaboration is always preferred to patenting and collaboration, by firm 1, when

$$\beta < 1 - \frac{L}{\alpha V - 2b} \equiv \beta_h^*$$

If however, $\alpha V - 2b - L < 0$, firm 2 prefers not to develop the idea and firm 1 earns $V - 2b$, regardless of whether it collaborates or not. In this scenario Assumption 3 rules out collaboration and it clear that firm 1 can do strictly better by patenting the idea and blocking development by firm 2 in comparison to maintaining secrecy and collaborating.

Remark 3.1. *The collaboration agreement between the two firms closely resembles collusive behavior. The idea holder pays its partner as much as it would earn under direct competition and secures monopoly rents. Under secrecy it allows the two firms to escape direct competition with each other should the idea reveal itself. Patenting and collaboration allows the idea holder to shift the entire cost of production to its partner, extract the license fee, and the entire private surplus generated by moving from a competitive environment to a monopoly.*

It is not clear whether such collaboration agreements would pass an antitrust stringency test. Therefore the following assumption rules out such collaboration.

Assumption 3.4. *Firms are not allowed to collaborate:*
(a) Neither under secrecy nor under patenting, if they are both non-financially constrained.
(b) Under patenting, if the patent holder is non-financially constrained.

Under assumption 4 firm 1 simply has to choose between secrecy and patenting. It chooses secrecy if and only if $\beta(\alpha V - 2b) + (1-\beta)(V - 2b) > \alpha V - 2b + L$ which is equivalent to

$$\beta < \frac{(1-\alpha)V - L)}{(1-\alpha)V} \equiv \beta_{3A}^*$$

this is always satisfied for any $L, V \geq 0$ and $\beta \in [0,1]$ hence firm 1 always chooses secrecy.

Assumption 4 at first seems rather restrictive. However, it does not take away any of the qualitative aspects of the results that follow.[23]

In what follows consider two industry structures A and B. Industry A consists of two non-financially constrained firms and one financially constrained firm. Industry B consists of two financially constrained firms and one non-financially constrained firm.

Let v_i^d denote the value firm i gets from acting alone, v_{ic}^d denote the value firm i gets from collaborating when it is indifferent between collaboration partner i.e. all collaboration agreements lead to the same pay off and are not identity dependent, and let v_{ij}^d denote the value of the specific collaboration agreement between firm i and j when firm 1 decides between patent and secrecy $d \in \{p, s\}$.

3.4.B.c A Non-Financially Constrained Idea holder

Proposition 1 relates the appropriability choices a non-financially constrained idea holder makes in either industry.

Proposition 3.1. *If $\alpha V - 2b - L > 0$, the non-financially constrained idea holder prefers secrecy and collaboration when $\beta < \beta^*_{nI}$, where n denotes the non-financially constrained firm, $I \in \{A, B\}$ denotes the industry and*

$$\beta^*_{nA} = \frac{(1-\alpha)V - L}{(1-\alpha)V}; \beta^*_{nB} = \frac{2((1-\alpha)V - L)}{\alpha V - 2b}$$

Otherwise it patents the idea and develops it alone.

Proposition 1 tells us the non-financially constrained firm can always keep its idea secret and develop alone. However this allows its rivals to develop the idea, if it is revealed, free of charge. Patenting brings the idea into the public domain, which induces competition in both industries with certainty, but developing the idea is no longer free of charge. When the firm

[23] In addition we restrict attention to pure strategy Nash Equilibria. A web appendix shows that relaxing Assumptions 3 and 4 and considering mixed strategy equilibria only serves to expand the analysis without adding new insight.

is almost sure that it cannot safeguard its idea through secrecy it opts for patenting.

In industry B the non-financially constrained firm can choose to internalize this information spillover by collaborating with one of the financially constrained firms, so that there is no competition in the development stage. This form of blocking collaboration comes at a price. The non-financially constrained firm has to guarantee the financially constrained firm as much revenue as it would earn in expectation by forming a collaborative agreement with the other financially constrained firm. For large probabilities of information revelation these expected profits are too high and the non-financially constrained firm finds it more profitable to induce competition and collect the license fee.

Proposition 3.2. *If $\alpha V - 2b - L < 0$, a non-financially constrained firm always prefers to patent its idea, independently of industry structure, and develop alone.*

The intuition that underlies Proposition 2 is immediate. When the rewards from the license fee L, are larger than competitive profits under secrecy $\alpha V - 2b$ firms prefer to escape competition and use the patent to block rivals from the developing the idea. Secrecy does not ensure monopoly rents, as there is chance of information disclosure. Maintaining monopoly rents under secrecy requires collaboration agreements, which is not allowed in industry A and requires non-negative transfers, that eat into the firms profits, in industry B. Patenting discourages development by others and guarantees monopoly rents and therefore is a strictly dominant strategy.

3.4.B.d A Financially Constrained Idea holder

Here we state the appropriability choices made by a financially constrained idea holder in the two different industries.

Proposition 3.3. *If $\alpha V - 2b - L > 0$, in industry A the financially constrained idea holder collaborates only under secrecy but is indifferent between collaboration partner. In industry B the financially constrained* *idea holder always collaborates with the other financially constrained firm. The financially constrained idea holder prefers secrecy and collaboration when $\beta < \beta^*_{fI}$, where f denotes the financially constrained firm, $I \in \{A, B\}$ denotes the industry and*

$$\beta^*_{fA} = \frac{V - 2b - 2L}{V - 2b}; \beta^*_{fB} = \frac{(1-\alpha)V - L}{(1-\alpha)V}$$

Conditional on information revelation the non-collaborating, non-financially constrained firm simultaneously develops the idea.
Otherwise, in industry A the financially constrained firm patents the idea, does not collaborate and collects the license fee from any development. Both the non-financially constrained firms simultaneously and independently develop the idea. In industry B the financially constrained firm patents the idea and collaborates with the other financially constrained firm. The remaining non-financially constrained firm simultaneously develops the idea.

In industry A the financially constrained firm, conditional on patenting its idea, can never extract more than the license fee from a collaboration agreement because a non-financially constrained firm can always develop the idea independently. The financially constrained firm can only develop the idea if it maintains secrecy and collaborates. However this strategy does not limit the non-collaborating, non-financially constrained firm from developing the idea if the idea is revealed. Under this strategy the financially constrained firm earns monopoly profits if the idea stays secret, but forgoes all competitive profits to its collaboration partner conditional on information revelation. Therefore for high information revelation patenting becomes the preferred option. When the market is not too competitive and simultaneously developed ideas can co-exist, the financially constrained firm can exploit the inability of the two non-financially constrained firms to enter into a collaboration agreement and prefers patenting even more.

In industry B the non-financially constrained can develop the idea alone therefore it has a strictly positive participation constraint for a collaborative agreement. Instead the other financially constrained firm does not have any bargaining power. So it is always better for the financially constrained idea holder to collaborate with the other financially constrained firm because collaboration yields greater payoffs compared to not collaborating. The choice of patenting or secrecy is made to secure the highest expected payoff. If the firm is certain that its collaboration agreement will have to compete with developed idea of the non-financially constrained firm, it prefers to collect the license fee as compensation for the competition.

Proposition 3.4. *If $\alpha V - 2b - L < 0$, the financially constrained idea holder always patents its idea and collaborates. In industry A the financially constrained firm collaborates with the non-financially constrained firm that would not have developed the idea if it was not collaborating. In industry B the financially constrained collaborates with the other financially constrained firm. In both industries the non-collaborating, non-financially constrained firm does not develop the idea.*

The intuition here is very similar to that of Proposition 2. When the license is large enough to exclude the rival i.e. when the rewards from the license fee L, are larger than competitive profits $\alpha V - 2b$, the escaping competition effect dominates and firm uses the patent to block competition. In both industries the financially constrained does better by entering into a collaboration agreement with the disadvantaged firm. In industry A this is the non-financially constrained that cannot commit to developing the idea, while in industry B it is the other financially constrained firm.

3.4.C Comparative Statics

The simple and stylized theoretical model goes some way in providing a rationale for why firms may choose to patent their ideas, in support of the empirical results found in section 2. At the same time it provides theoretical reasons for the cases in which secrecy is preferred to patenting and collaborative agreements arise. Here we provide a number of comparative statics results amenable to empirical testing.

The model focuses on a financially constrained firms inability to develop an idea itself. This force drives it to enter collaboration agreements. The choice of patenting or secrecy is taken to improve its returns from the collaboration agreement and crucially hinges on industry structure and market forces. While the patenting technology is assumed to be not perfect, the ability of the firm to guard its idea through secrecy is also subject to imperfections.

Proposition 3.5. *(a) Any configuration of V, L and b gives $\beta^*_{nA} > \beta^*_{fA}$, $\beta^*_{fB} > \beta^*_{nB}$ and $\beta^*_{fB} > \beta^*_{fA}$. (b) An increase in size of innovation V, is accompanied by an increase in β^*_{fA}, β^*_{fB} and β^*_{nB}. (c) An increase in patent effectiveness L, is accompanied by a decrease in β^*_{fA}, β^*_{fB} and β^*_{nB}. (d) In industry A, a change in competition pressure α, does not influence β^*_{fA}. In contrast, in industry B, a decrease in α, is accompanied by an increase in both β^*_{fB} and β^*_{nB}.*

Part (a) of Proposition 5 tells us that within collaborative agreements financially constrained firms have a larger threshold for preferring secrecy if they are not disadvantaged. For low probabilities of information revelation, in industry B, both types of firms prefer secrecy. For large probabilities of information revelation both types prefer patenting. However for intermediate levels a non-financially constrained firm switches to patenting while the financially constrained is still able to extract more gains from secrecy. Hence all things equal, financially constrained firms within collaboration agreements are more likely to rely on secrecy.[24]

Part (b) of Proposition 5 relates how both types of firm, in any industry, are more likely to opt for secrecy over patenting if the value of the innovation is large.[25] An increase in the value of the innovation causes the bounds for which secrecy is preferred to also increase. Empirically this should translate into a higher tendency to maintain secrecy.

Part (c) of Proposition 5 suggests that firms lean towards patenting over secrecy when the licensing fees they can extract are large enough, or more likely to secure a given license fee. Large firms, such as multinationals, may be more likely to detect infringement, extract license fees, or prove the worth of their ideas by having access to the necessary resources, such as highly qualified legal and monitoring staff, which allow them to fully

[24] As we have seen this is not quite true in Industry A where under certain conditions the non-financially constrained firm always prefers secrecy while the financially constrained firm has a threshold. In the appendix we relax assumptions about which firms collaborate and see that similar results arise in industry A.

[25] The choice for the non-financially constrained firm in Industry B is not so clear-cut. Depending on competitive pressures and the other parameters of the model, it may prefer patenting in certain cases. And in others it may prefer more secrecy with larger innovation values.

extract the benefits of IPR protection. If these firms can extract a higher L than small or financially constrained firms, they will prefer patenting. Thus we find theoretical support for the empirical finding that large firms and multinationals prefer patenting.

Part (d) of Proposition 5 highlights that the relationship between the choice of patenting and secrecy and competition is not straightforward and depends on the industry structure. Within industry A, competitive pressure plays no strategic role.

In industry B maintaining secrecy has two benefits. It first allows firms to imperfectly guard monopoly rights and it also allows for potentially collusive collaboration agreements. Hence when competitive pressures are extremely high both types of firms prefer more secrecy.

In the extreme case where high competitive pressure is accompanied by large enough license fees, patenting can dissuade rivals from developing an idea even though it is in the public domain. Non-financially constrained firms always prefer patenting regardless of industry structure, because it is the least costly way of securing monopoly rights. The patent is used as a blocking mechanism that allows the firm to be the sole developer of the idea.

Financially constrained firms may also use the patent as blocking device conditional on being in an industry where they can collaborate. When this is not possible the patent serves its main purpose of a commercial means to transfer property rights. Either way we find theoretical evidence of why financially constrained firms may rely on patents.

A general prediction of the model is that if a firm resorts to patenting it seldom collaborates. The only exception is a financially constrained firm that has the possibility of collaborating with another financially constrained firm. In this case a financially constrained firm will patent its idea to dissuade the non-financially constrained from developing the idea independently and will collaborate with the other financially constrained firm.

More generally the model is set up in such a way that secrecy enables collaboration. This assertion would be supported empirically if we find that on average, firms that report collaboration also report a greater reliance on secrecy versus patenting.

3.4.D Extensions

In preceding empirics we related patent blocking to demand risk, which we do not explicitly consider in the model. The following extension rationalizes why firms facing demand uncertainty strongly report the importance of patents as a protection mechanism.

Consider the case where V is uncertain. V exists in a finite support bounded between $[\underline{V}, \bar{V}]$ with a positive density that is common knowledge. However the exact of value of V is realized post-development. Lets say the probability distribution is skewed towards low realizations of V, such that $\alpha E(V) - 2b \geq 0$ and $\underline{V} - 2b > 0$. A firm that keeps secrecy may induce competition that offers weakly positive gains in expectation, but results in negative profits for both firms once the true value of V is realized. If the licensing fee it can extract is a sure outcome then it may prefer to issue a patent at the outset and dissuade its competition from developing the idea.

3.5 Empirical Support for the Importance of Strategic Instruments in R&D Collaboration

The previous section presented a theoretical model of financial constraints, collaboration and strategic information disclosure. Here we empirically test the model predictions. We find evidence in support of the theoretical prediction that collaboration agreements are more likely to adopt secrecy, in addition within the sample of collaboration agreements we find that financially constrained firms prefer strategic appropriation more than non-financially constrained firms. We also find that the multinational patent premium disappears in the subsample of collaborating firms.

We could have skipped the theoretical exercise and directly used the CIS data to test the existing theories of Anton and Yao (2004), Kultti et al. (2006) and Bhattacharya and Guriev (2006). However these theories do not explicitly account for collaboration agreements and this is the focus of our paper. Moreover, we believe our model is slightly more general because no explicit assumption is made on the type of innovation. The developed idea can be either process or product, all we require is that it is worth a certain amount.

Because our theory of financial constraints, collaboration and information disclosure is new we also look for support for the well-known theory of Anton and Yao (2004). Their model is based on the size of a process innovation. Firms choose whether to patent or maintain secrecy and strategically signal the size of their innovation to competitors. Patenting opens up the possibility of infringement. Firms only patent low valued innovations for which competitors do not find it profitable to infringe. Therefore their model predicts a tendency towards secrecy as the value of the innovation increases.

Our model draws similar implications from the size of the innovation captured by V i.e. an increase in the size of the innovation leads to a higher threshold of information disclosure and a preference for secrecy.

3.5.A Innovation Size

Finding a way to measure the size of an innovation is not a straightforward task and necessarily depends on whether the innovation is process or product oriented. We measure whether a firm imitates or innovates. It has been suggested that this may be a measure of the size of an innovation. In this section we relate imitation and innovation to the tendency for strategic over legal appropriation and argue that other measures such as percentage of innovation sales are likely to be a better proxy for innovation size.

While the theoretical literature measures the size of a process innovation through the magnitude of marginal cost reductions it facilitates, the size of a product innovation is determined by the magnitude of existing substitute products displaced. In the absence of detailed data on ex-ante and ex-post marginal costs and substitute products, inferences about size of innovation are difficult to make.[26]

In independent work using French CIS data,[27] Serge Pajak (2008) assumes that the size of the innovation is larger when the innovation is new to the market rather than when it is new to the firm. He also studies the percentage of total firm sales that can be attributed to the innovation, implicitly assuming that a higher percentage of innovative sales reflect a larger innovation. The percentage of innovative sales is likely to be a marginally better indicator of the size of innovation, at least from a theoretical perspective.

In Table 3.4 we present a measure of a firm's tendency for strategic over legal protection, described in Section 2, as a function of various factors. Three results stand out. First we find a significant preference for strategic protection by collaborating firms. Secondly the strong negative coefficient on multinationals suggests a very strong tendency for legal protection within this group of firms. Finally firms in highly competitive industries or in industries where patenting can award horizontal bargaining power prefer legal protection over strategic.

Process imitators and product innovators report a strong preference for strategic protection. As a robustness check we substitute these markers with the percentage of innovative sales, which is also strongly correlated with greater strategic protection.[28]

Imitations suggest that the innovation in question already exists. Imitations based on licensed patents will not leave much room for further

[26] From the reasons to innovate, we thought about using the firms response to the importance of reducing costs as a reason to innovate. However, firms with high marginal costs are likely to give high importance to this reason even if the end result is not a sizeable reduction in costs.

[27] Pajak does not distinguish between imitators and innovators in the way that we do i.e. he does not consider new to the firm innovations as imitations. Pajak uses a different methodology and concentrates on empirically unveiling the Anton and Yao (2004) hypothesis.

[28] We do not find any evidence that large firms that are part of enterprise groups, or government owned etc systematically prefer one type of protection instead of the other.

patenting by the imitator, and imitations that require firm-specific auxiliary operational innovations will be best protected through secrecy. On the other hand, imitations carried out through reverse engineering without licensing rights will be better protected through secrecy, to limit leakage of the infringement. Denicolo and Franzoni (2004) suggest that the presence of prior user rights may limit the incentives of both innovator and imitator to patent. The significant reliance of process imitators and, to a lesser extent, product imitators, on secrecy, given the results presented in Table 3.1, seem to endorse these views.

3.5.B Robustness Checks

In the preceding analysis, we have used firm-level fixed effects to control for any unobserved heterogeneity that might have influenced both the decision on appropiability mix and the decision to innovate. However, there may exist other factors that drive commonalities in both the dependent and supposedly independent variables. Omitting these factors would cause us to report biased estimates. In this section we consider some of these factors and analyze the robustness of the collaboration and multinational coefficients to their inclusion.

3.5.B.a Research Capabilities

As a first step we include in Table 3.5, whether the firm conducts permanent R&D and its internal research capabilities. Internal research capability is defined as an amalgam of internal R&D spending and the science base and is described in detail in Section 7. Permanent R&D is not significant, suggesting that firms conducting R&D on a permanent basis favor both strategic and legal appropriation methods to an equal extent. In column 7 of Table 3.5 we find weak evidence that a higher internal research capability leads to more legal appropriation. However, the inclusion of these variables does not diminish the strength of the collaboration and multinational variables.

3.5.B.b Complexity of Design

The decision to maintain secrecy or patent depends on many factors but is crucially driven by chances of information revelation prior to development. The model assumes an exogenous β. However it is very likely that β is determined by a host of factors both endogenous, e.g. informational spillovers through worker poaching between firms, and exogenous e.g. the ability of an external research community, such as academia, to come up the same blueprint. It seems reasonable to assume that the more complex the blueprint, the less likely it is that it gets revealed to the public i.e. β is a decreasing function of complexity. Therefore we should expect complexity of design to be positively correlated with a preference for secrecy over patenting.

At the same time it is reasonable to assume that the size of the innovation is directly proportional to its complexity of design. It is true that sometimes the simplest ideas have the largest consequences, but innovative processes tend to be cumulative in many industries (Scotchmer (2003), Scotchmer (1991)) and with technological development comes greater complexity. As Boldrin and Levine (2002) argue firms adopt certain cut-off criteria for design complexity that determine the extent of innovation, and this seems to be a standard assumption in the quality ladder literature (Aghion and Howitt (1992), Grossman and Helpman (1991), Romer (1990)).

Ceteris paribus, it seems plausible that conditional on history, greater technological complexity should be associated with larger innovation and the more complex the design the less likely it is to reveal itself to the public easily i.e. it is better protected through secrecy. The results in column 2 of Table 3.5 corroborate this idea.

3.5.B.c Management Practices

It is well documented that differences in management practices induce productivity differentials (Bloom and Reenen (2006)), either through the choice of different organizational structures and input mixes (Black and Lynch (2001), Lazear (2000)) or through more efficient use of the input mix (Bloom, Sadun and Reenen (2007), Ichniowski, Shaw and Prennushi (1997)). So far we have controlled for differences in organizational structures and practices through our company ownership variable, but it is likely that this variable does not capture all influential dimensions. Changes in management practices may influence the innovative outlook of the firm and at the same time influence its protection outlook as well. In column 3 of Table 3.5 we account for this potential endogeneity by directly controlling for changes in management practices within the firm. Firms that introduce new corporate strategies are found to significantly favor strategic over legal protection, yet controlling for this aspect does not reduce the significance of our original findings on collaborative agreements.

3.5.B.d Personnel Training

In column 4 of Table 3.5 we use a binary marker to control for whether a firm undertook personnel training in innovative procedures. It is argued that a firms workforce can be a major source of informational spillovers either through worker mobility or worker-contact with rival firms (Baccara and Razin (2004), Zabojnik (2002)). Firms that undertake innovation enhancing personnel training will also be more vulnerable to information leakages and will have to trade-off the improved chances of success with potentially reduced appropriability. Thus, the decision to train personnel will influence both the nature of the innovation and the appropriation mix. Personnel training is insignificantly correlated with a preference for strategic protection, and the original findings remain robust to its inclusion.

3.5.B.e Regulation

While complexity of design captures a specific part of the innovation process, there are likely to be global factors that influence the overall outlook of a firm and omitting these may strongly bias the results. For example, a firm whose objective function is only to increase its market share may jointly decide to design a new product and patent it. On the other hand a firm that is forced to process innovate for regulatory needs may patent its invention, for potential licensing, if its only objective is to stay in business. However, if the complexity of design of the regulatory requirement is so high that it can drive technologically inefficient firms out of the market, an innovative firm might be able to shape market structure for its benefit by choosing secrecy.

The survey allows us to identify the reasons why firms chose to innovate in the first place. The reasons can be grouped together into a) process oriented i.e. increasing production capacity, production flexibility, value added and reducing costs, b) product oriented i.e. increasing market share and entering new markets, increasing range of goods and services and improving quality of goods and services and c) regulation oriented i.e. meeting regulatory requirements and reducing environmental impacts.

In column 5 of Table 3.5 we focus on innovation carried out to meet regulatory standards.[29] Firms that face regulatory pressures to innovate significantly prefer legal protection methods over strategic. Regulatory requirements potentially reflect industry trends of marginal innovations that first movers can exploit through licensing. However the inclusion of this variable does not influence the significance of our original results.

Column 6 of Table 3.5 pools all the different explanatory variables into one regression and shows that even though each is significant in its own right, the collaboration premium for strategic protection and the multinational premium for legal protection remain robust to these inclusions. Column 7 interacts the multinational marker with the collaboration marker to see whether collaborating multinationals prefer secrecy. Although we pick up a positive coefficient on this new variable it remains insignificant.[30]

[29]We focus on this reason because innovation carried out to meet regulatory requirements is more likely to be exogenously determined for the firm, than process and product oriented innovation. In addition firms do not report mutually exclusive product and process oriented reasons to innovate e.g. firms reporting a high importance on increasing production capacity also report a high importance of increasing production flexibility and reducing costs, or as another example, firms that report increasing market share and entering new product markets also report the importance of increasing capacity and flexibility of the production process. Because of this our innovation and imitation identifiers are likely to already reflect the various product and process oriented reasons to innovate.

[30]Finally, alongside our firm-level fixed effects, we also introduced industry dummies to control for any unobserved time-invariant heterogeneity within SIC 4-digit industries that could potentially influence both sides of our regression specification.

3.5.C Financial Constraints and Design Complexity within Collaboration Agreements

The predictions of the theoretical model presented in Section 3 are primarily suited for collaborative agreements. For this reason, here we limit attention to the subsample of collaborating firms. The model suggests that appropriability choices not only hinge on explicit parameters, which we measure through our survey data, but also on implicit unobservables such as the financial structure and regulatory stance within the industry. Therefore, in order to control for this unobserved industry level heterogeneity we estimate all the relevant regressions using SIC 4-digit industry fixed effects.

Table 3.6 concentrates on the subsample of collaborating firms, with positive R&D expenditures, and shows that only process imitators report a significant preference for strategic protection over legal. Higher innovative sales are associated with a positive preference for strategic protection, however, this effect is not significant.

More importantly, we find evidence in support of financially constrained firms preferring more strategic protection to legal. Within this sample, complexity of design is strongly correlated with strategic reliance, confirming the idea that complexity of design may be a good proxy for a firms belief about the probability with which its idea can potentially reveal itself.

Interestingly, within the sample of collaborating firms we find no evidence of the multinational premium for patents.[31] We find multinationals are indifferent in their choice of legal and strategic protection. These results

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We could not reject joint significance of the industry dummies, but closer inspection showed they were capturing effects similar to the high-tech dummy. Adding SIC 4-digit dummies alongside firm-level firxed effects only serves to deepen the attenuation bias and it is true that some variables lose their significance. Nonetheless, the signs of individual coefficients remain robust.

[31] Another interesting finding, suppressed in the current output is that collaborative firms, over time, exhibit a significantly increasing tendency towards preferring legal protection, which seems to mirror the case studies of Thurrow (1997) and Granstrand (1999) that argue firms are beginning to use patents more intensively. Also within this sample larger firms that are part of enterprise groups also report significant preference for legal over strategic protection.

remain robust to the inclusion of other firm characteristics and SIC 4-digit industry fixed effects.

It is a somewhat striking result that multinationals that collaborate do not report a patent premium as do their non-collaborating counterparts. In light of the theory presented this result makes sense if multinationals are more likely to be non-financially constrained, which we have seen to be the case.

3.6 Conclusion

This paper uses a panel of UK firms, constructed from the CIS survey, to analyze the factors that drive firms to protect their innovations through legal and strategic means. In support of the US findings of Cohen et al. (2000), we show that firms in the UK may indeed be using legal protection as a way to block competitors, improve bargaining power in the market and goodwill reputation in financial markets.

However as in Cohen et al. (2000) and Levin et al. (1988), the majority of firms in our sample report a preference for strategic over legal means of protecting their innovations. A theoretical rationalization of this empirical finding, based on strategic information disclosures and innovation size, has recently been offered by Anton and Yao (2004), who suggest that the incentives for secrecy strengthen with the size of the innovation. Measuring the size of an innovation is empirically difficult and we find weak support for this hypothesis.

We offer a similar yet alternative rationalization based on a game theoretic framework in which firms with financial constraints bargain over collaboration agreements and choose between patenting and secrecy to improve their bargaining outcome. We argue that financially constrained firms prefer using strategic mechanisms instead of legal protection to constrain information leakage and maintain a competitive edge. We find empirical support for this rationalization in the subsample of collaborating firms, some of which might have been induced to collaborate due to financial constraints.

In reality both strategic information disclosure and financial constraints are likely to play a role in defining appropriability decisions, and theoretical models should take a closer look not only at the role of financial constraints but also their interaction with information disclosure especially in the context of collaborative R&D. However, in order to fully improve our understanding of the underlying fundamentals efforts will have to be made to obtain better estimates of innovation size and financial constraints empirically.

This paper also holds ramifications for EU policy, currently focused on promoting cross-regional and institutional collaboration in R&D. The definition and sharing of property rights becomes increasingly difficult when there is more than one independent party associated with an innovation. It seems that firms circumvent these issues by attaching greater importance to non-exclusive strategic protection. Thus policy makers should not only focus on the best and most equitable way to define property rights between collaborating partners but also consider the availability of strategic mechanisms and the influence they hold in shaping decisions on legal protection means and the overall appropriability mix.

We also hope that our empirical findings contribute towards focusing attention on the gulf between the Corporate Finance and Industrial Organization literature. Financial constraints play a central role in shaping innovation decisions and appropriation mixes in general and specifically within cooperative agreements. Bhattacharya and Ritter (1983), Aghion and Tirole (1994), Holmstrom and Tirole (1997) have helped to change attitudes and recent years have witnessed a gradual emergence of IO literature dealing with these issues.

The theoretical IO literature has largely distanced itself from the role of financing constraints. Traditionally either it has assumed self financed innovations or the licensing of non-implementable knowledge. However, as our simple framework shows under certain conditions a financially constrained firm may choose to license its technology to a third party and yet try to secure financing to also develop the idea itself.

While this is definitely a welcome development there still remains room for further improvements in the theoretical underpinnings, especially in light of recently developing policy interest. The theoretical literature remains largely reticent on why firms use different appropriation mechanisms and the potential trade-offs between these choices. Research in this direction can be beneficial in two ways. It can help elucidate why patent data might not be the best indicator of innovation and it can better inform the theoretical literature on endogenous spillovers both within and outside of collaborative agreements, of which the latter has been largely ignored.[32] Clearly the decisions cooperating partners take within the agreement will also define the spillovers to rivals outside the agreement and the choice of appropriation mechanism may be instrumental in this context.

[32] A notable exception is the works of Goyal et al. (2008), Goyal and Joshi (2003), Goyal and Moraga-Gonzalez (2001) that study the formation of R&D networks. The modeling approach allows for differences in spillover rates between collaborating and non-collaborating partners, however, these are assumed to e exogenously determined.

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A Proofs

Chapter 1

Proof of Proposition 1.2

Proof. I proceed to prove the proposition with a series of lemma's. Let $n > 1$. Conditional on being connected to at least one other player, the first order condition of an individual player's utility maximization is given by

$$\alpha - 2\hat{\delta}x_i - \hat{\delta}\sum_{j\neq i} x_j + \hat{\lambda}\sum_{j\neq i} g_{ij}x_j = 0 \tag{A.1}$$

Using Proposition 1, and summing across all non-isolated nodes, total output for any $g \in \{r, s, c\}$ is given by:

$$\chi_g(n, \theta) = \frac{\alpha b_g}{\hat{\delta}(1 + b_g)} \tag{A.2}$$

Identity A.2 establishes that $\chi_g(n, \theta)$ is monotone concave in $b_g(n, \theta)$. Therefore for a common triplet $(\alpha, \hat{\lambda}, \hat{\delta})$ for all $g \in \{r, s, c, h\}$, it suffices to focus attention on $b_g(n, \theta)$.

For a given number of links l let $\{\bar{r}, \bar{s}, \bar{c}\}$ respectively denote the largest regular, star and binary-cell structure permissible.

Lemma A.1. *Let n be the number of individual players connected in a regular network. Then total Bonacich Centrality is given by* $b_r(n, \theta) = \frac{n}{1-(n-1)\theta}$.

Proof. First consider the case of a regular network. Given the network structure r and a pre-determined choice of $(\alpha, \hat{\delta}, \hat{\lambda})$ an individual player chooses an optimal effort level x_i that satisfies identity A.1 given x_j. Because of the symmetry in the structure of the regular graph, in equilibrium we must have $x_i^* = x_j^* = x^*$ for all $j \neq i \in r$. Noting that $g_{ij} = 1$ for all $j \neq i$ and rearranging identity A.1, after direct substitution of x^*, gives us

$$x^* = \frac{\alpha}{\hat{\delta}\left(n + 1 - \theta(n-1)\right)}$$

Where $\theta = \frac{\hat{\lambda}}{\hat{\delta}}$. The total effort level in the regular network with n players and given θ is

$$\chi_r(n, \theta) = nx^* = \frac{n\alpha}{\hat{\delta}\,(n + 1 - \theta(n-1))} \tag{A.3}$$

Finally equating identities A.2 and A.3 and rearranging in terms of b_r gives us the desired result. □

Lemma A.2. *Let n be the number of individual players connected in a binary network. Then total Bonacich Centrality is given by $b_c(n, \theta) = \frac{n}{1-\theta}$.*

Proof. The proof is very similar to that of the regular network. Here we have to remember that $g_{ij} = 1$ for only one $j \neq i$. However there is still a symmetry in structure in the binary-cell, so in equilibrium we must have $x_i^* = x_j^* = x^*$ for all $j \neq i \in c$. Following the computational steps of part (a) leads to the desired result. □

Lemma A.3. *Let n be the number of individual players connected in a star network. Then total Bonacich Centrality is given by $b_s(n, \theta) = \frac{n+2\theta(n-1)}{1-(n-1)\theta^2}$.*

Proof. Network position plays a role in the star network. We have two positions (i) the periphery and (ii) the hub. Denote each periphery player with x_p and the hub player with x_I.

(i) Given the network structure s, the number of players n and a pre-determined choice of $(\hat{\delta}, \hat{\lambda}, \alpha)$ an individual periphery chooses an optimal effort level x_p that satisfies A.1, given the effort levels $\{x_p, x_I\}$ of all other players. Each periphery player has only one link to the hub i.e. $g_{pI} = 1$ and $g_{pp} = 0$, which makes all periphery players symmetric, inducing all periphery players to exert the same effort level in equilibrium. Therefore the F.O.C for a periphery can be written as

$$\alpha - n\hat{\delta}x_p - (\hat{\lambda} - \hat{\delta})x_h = 0$$

Rearranging we have

$$x_p = \frac{\alpha - (\hat{\delta} - \hat{\lambda})x_I}{n\hat{\delta}} \tag{A.4}$$

Exploiting the same symmetry the F.O.C for the hub can be written as

$$\alpha - (n-1)(\hat{\delta} - \hat{\lambda})x_p - 2\hat{\delta}x_I = 0$$

Rearranging we have

$$x_I = \frac{\alpha - (n-1)(\hat{\delta} - \hat{\lambda})x_p}{2\hat{\delta}} \tag{A.5}$$

Direct substitution of equation A.5 into equation A.4 eliminates x_I and rearranging in terms of x_p gives

$$x_p = \frac{\alpha(1+\theta)}{\hat{\delta}((n+1) + 2(n-1)\theta - (n-1)\theta^2)} \tag{A.6}$$

Similarly substituting equation A.4 into equation A.5 gives after some algebraic manipulation

$$x_I = \frac{\alpha(1+(n-1)\theta)}{\hat{\delta}((n+1) + 2(n-1)\theta - (n-1)\theta^2)} \tag{A.7}$$

Summing together $(n-1)x_p + x_I$ we obtain the total effort level of the star

$$\chi_s(n,\theta) = \frac{\alpha(n+2(n-1)\theta)}{\hat{\delta}((n+1) + 2(n-1)\theta - (n-1)\theta^2)} \tag{A.8}$$

Finally using identities A.8 and A.2 and rearranging in terms of b_s gives the desired result. □

Lemma A.4. *Let l_n denote the number of links used by an n-regular network. For every n-regular network there exists a unique $\theta^* = \frac{1}{n}$ such that $b_r(l_n,\theta^*) = b_s(l_n,\theta^*) = b_c(l_n,\theta^*)$ i.e. all three structures, regular, star and binary-cell, using the same number of links, induce the same aggregate Bonacich.*

Proof. A regular network that connects $n_r = n$ players utilizes $l = \frac{n(n-1)}{2}$ links. The same number of links connect $n_c = n(n-1)$ in binary network and $n_s = \frac{n(n-1)}{2} + 1$ in a star network. Plugging in n_r, n_c and n_s into b_r, b_c and b_s respectively, and directly comparing the resulting expressions gives the desired result. The comparison also shows that the solution is unique in $\mathbb{R}^+$.[1] □

Lemma A.5. *θ^* lies in the permissible set of Θ.*

Proof. Using a well known result from Graph Theory (see Bollobas (2002)) we know that $\rho(r) = n_r - 1$ and $\rho(s) = \sqrt{n_s - 1}$. It is straightforward to

[1] A longer proof based on induction is available on request.

see that $n-1 \geq \sqrt{\frac{n(n-1)}{2}}$ for $n \geq 2$. Therefore a regular network connecting more than 2 players is more dense than a star network, if both use the same number of links. The adjacency matrix of any hybrid structure takes a block diagonal structure because the hybrid consists of a set of disconnected sub-components. Consider each sub-component k individually as a separate graph and denote its maximum eigenvalue $\rho(h_k)$. Then the maximum eigenvalue of the hybrid $\rho(h)$ is the maximum $\rho(h_k)$ such that $k \in h$. This follows directly by noting that any block diagonal matrix can be recast as a Jordan Block that can be diagonalized to give the desired result. A large regular component within a hybrid structure, by definition, cannot connect more than n players, whereas a large star component within a hybrid structure cannot connect more than n_s players. It is clear that $\rho(r)$ and $\rho(s)$ are increasing in n_r and n_s respectively. Hence the regular network that utilizes all available links to connect n players has the largest eigenvalue, making it the densest, i.e. $\frac{1}{\rho(r)}$ defines the permissible Θ-space and since $\frac{1}{n} < \frac{1}{n-1}$, θ^* always resides in this space. $\square$

Lemma A.6. *When $\theta < \theta^*$ the ranking $b_c(l_n,\theta) > b_s(l_n,\theta) > b_r(l_n,\theta)$ obtains. Conversely if $\theta > \theta^*$ then the ranking $b_c(l_n,\theta) < b_s(l_n,\theta) < b_r(l_n,\theta)$ obtains.*

Proof. To show how b_r, b_c and b_s compare when $\theta \neq \theta^*$, I first show that $b_g(n,\theta)$ for $g \in \{r,c,s\}$ is continuous and strictly monotone in θ because it can be represented as an infinite polynomial, in θ, with real and positive coefficients when written as a sum of its component parts

$$b(g,\theta) = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{+\infty}\theta^k g_{ij}^k$$

I now look at the limiting case of $\theta = 0$. Using Lemma A.1-A.3 it is straightforward to see $\lim_{\theta\to 0} b_g = n_g$ for $g \in \{r,s,c\}$. So that in the limit as $\theta \to 0$, $n_{\bar{c}} > n_{\bar{s}} > n_{\bar{r}}$ implies that $b_{\bar{c}} > b_{\bar{s}} > b_{\bar{r}}$[2]. We know the existence of a unique crossing point between b_r, b_c and b_s. The continuity and strict monotonicity of b in θ allows us to conclude the first part of the proof.

From Lemma A.5 we know that θ^* exists in the permissible set Θ and also

[2]The limiting case also follows directly from the fact that $b_i(g,\theta) = m_{ii}(g,\theta) + \sum_{j\neq i}^{n} m_{ij}(g,\theta)$. By definition $\lim_{\theta\to 0} m_{ii}(g,\theta) = 1$ and $\lim_{\theta\to 0} m_{ij}(g,\theta) = 0$. Hence $\lim_{\theta\to 0} b_i(g,\theta) = 1$ and $\lim_{\theta\to 0} b_g(n,\theta) = n$.

that for $n > 2$, $\theta^* < \frac{1}{\rho_{\bar{r}}} < \frac{1}{\rho_{\bar{s}}} < \frac{1}{\rho_{\bar{c}}}$. Therefore when $\theta > \theta^*$, $\frac{1}{\rho_{\bar{r}}} < \frac{1}{\rho_{\bar{s}}} < \frac{1}{\rho_{\bar{c}}}$ implies total Bonacich Centrality $b_{\bar{r}} \rightarrow \infty$ faster than $b_{\bar{s}} \rightarrow \infty$, which in turn is faster than $b_{\bar{c}} \rightarrow \infty$ which concludes the second part of the proof. □

Lemma A.7. *$b_c = \max_{g \in \mathcal{G}} b_g$ if $\theta < \theta^*$ and $b_r = \max_{g \in \mathcal{G}} b_g$ if $\theta > \theta^*$.*

Proof. It is clear from the previous lemma that the regular network is the densest network in the set $\mathcal{G}$ therefore $b_r = \max_{g \in \mathcal{G}} b_g$ when $\theta > \theta^*$. Therefore, all that remains to be shown is that there does not exist a hybrid structure h such that $b_h = b_c$ for some $\theta^c \leq \theta^*$.

Let H denote the adjacency matrix for a given hybrid network $h \in \mathcal{H}$, and H_k denote the adjacency sub-matrix for the *k-th* independent component of h. The disconnected structure of h gives rise to a block-diagonal adjacency matrix $H = diag(H_1, H_2, ..., H_k)$.

By definition the Identity matrix is block-diagonal and I rewrite the matrix M as $M = [diag(I_1, ..., I_k) - \theta diag(H_1, ..., H_k)]^{-1}$, such that $size(I_k) = size(H_k)$. Denoting $M_k = I_k - \theta H_k$ allows me to write

$$M = [diag(M_1, ..., M_k)]^{-1} = diag([M_1]^{-1}, ..., [M_k]^{-1})$$

Letting $\mathbf{b}$ denote the entire vector of Bonacich Centralities in h and $\mathbf{b_k}$ denote the vector of Bonacich Centralities of sub-component k, we obtain a stacked collection of Bonacich Centralities from each individual sub-component

$$\mathbf{b}' = (M.\mathbf{1})' = (diag([M_1]^{-1}, ..., [M_k]^{-1}) \cdot \mathbf{1})' = (\mathbf{b_1'}, ..., \mathbf{b_k'})$$

The total number of players, $n_h = n_1^h + ... + n_k^h$, connected by a given h, is bounded between $[n_{\bar{r}}, n_{\bar{c}}]$. A hybrid structure that uses all links in one component has to utilize at least as many players as $\bar{r}$. The upper bound is set by $\bar{c}$ because in this structure each link represents a independent component i.e. no two links originate or end at the same player. Therefore in the limit as $\theta \rightarrow 0$ the binary cell maximizes total Bonacich centrality.

Now consider each *k-th* sub-component of h and define a fictional binary-cell structure, denoted c_k that utilizes as many links as h_k. For each pairing of (h_k, c_k) there exists a unique θ'_k, determined by Lemma A.4, such that $b_{h_k}(\theta'_k) = b_{c_k}(\theta'_k)$. By definition $n_{\bar{c}} = \sum_{k=1}^{K} n_{c_k}$.

Let $\underline{\theta}'_k$ and $\bar{\theta}'_k$ respectively denote the lowest and highest crossing point for all (h_k, c_k) pairings. The independence and additivity of Bonacich Centralities in h implies that $\theta^c \in [\underline{\theta}'_k, \bar{\theta}'_k]$. Therefore, in order to prove the lemma I have to show that $\underline{\theta}'_k > \theta^*$ for any $h \in \mathcal{H}$.

Let $\{r_1, r_2, ...\}$ denote a series of regular networks that respectively connect $j = \{1, 2, ...\}$ less players than $\bar{r}$. And define $\{s_1, s_2, ...\}$ as an equivalent series for star networks.

By definition the largest regular network contained in a hybrid structure, h, with more than one component, will at most be r_1. Analogously, if a hybrid structure, contains a star network then the largest star has to be s_1 or smaller.

Consider the fictional binary-cell structure that utilizes the same number of links as r_j and label this c_j. Given Lemma A.4 we have that $b_{r_j} = b_{c_j}$ at $\theta^r_j = \frac{1}{n_{\bar{r}} - j}$. Now consider the star network s_j. From Lemma A.4 we have that $b_{s_j} = c_{s_j}$ at $\theta^s_j = \frac{2}{1+\sqrt{8(n_{\bar{s}} - j) - 7}}$.

Both θ^r_j and θ^s_j are increasing functions of j and are minimized at $j = 0$ hence it cannot be the case that $b_h = b_c$ for some $\theta^c \leq \theta^*$. □

Applying all the above lemmata proves the proposition. □

Proof of Proposition 1.3

Proof. I focus attention on

$$\min_{i \in g} \frac{b_i(g, \theta)}{1 + b(g, \theta)}$$

Abusing notation slightly, from now on, I will refer to this as $\underline{u}_g$ i.e. the minimum utility obtained from network $g \in \{\bar{r}, \bar{c}, \bar{s}\}$. From Lemma 1 and the symmetry of the regular network we have that

$$\underline{u}_r = \frac{1}{n_r + 1 - (n_r - 1)\theta}$$

Similarly from Lemma 2 and the symmetry of the binary network we have that

$$\underline{u}_c = \frac{1}{n_c + 1 - \theta}$$

The definition of Bonacich Centrality suffices to argue that the periphery player within the star network has the lowest Bonacich Centrality and therefore from Lemma 3 we have that

$$\underline{u}_s = \frac{1}{n_s + 1 - (n_s - 1)(\theta^2 - 2\theta)}$$

Simple algebraic manipulation shows that $\underline{u}_s \geq \underline{u}_c$ if and only if $n_c - n_s \geq (2n_s - 1)\theta - (n_s - 1)\theta^2$. In the case of $\bar{s}$ and $\bar{c}$ we know that $n_s = l + 1$ and $n_c = 2l$. Therefore the necessary condition simplifies to

$$l \geq \frac{1 - \theta^2}{2\theta^2 - \theta + 1}$$

It is easy to verify that for $\theta \in \mathbb{R}^+$ the RHS of the above expression attains a maximum of 1 at $\theta = 0$. Hence as long as $l > 1$ we obtain $\underline{u}_{\bar{s}} > \underline{u}_{\bar{c}}$.

In addition we have that $\underline{u}_s \leq \underline{u}_r$ if and only if

$$n_r - n_s \leq \frac{2(n_s - 2)\theta}{1 - \theta^2}$$

When r and s utilize the same number of links l, the LHS of the above equation is always negative. On the other hand for any $\theta \in [0, \frac{1}{\rho_{\bar{r}}}]$ the RHS is always positive hence $\underline{u}_{\bar{s}} \leq \underline{u}_{\bar{r}}$ always obtains.

Hence we obtain a ranking of utilities that satisfies $\underline{u}_{\bar{c}} < \underline{u}_{\bar{s}} < \underline{u}_{\bar{r}}$. □

Proof of Lemma 1.2

Proof. Consider a hybrid structure t with at least two components $\{r, s\}$ such that $n_s \geq n_r \geq 2$. Let k denote a sub-component of t. Because $b_t = \sum_k b_t^k$ each player in t faces the same total Bonacich Centrality for any value of θ and the player with lowest Bonacich $\underline{b}_t$ will also attain the lowest level of utility.

Given that total Bonacich Centrality b_t^k is independent across sub-components, all we need to do is find $\min \underline{b}_t^h$ for all k in t.

Consider the explicit form of $\underline{b}_g$ for $g \in \{r, s, c\}$. We have

$$\underline{b}_r = \frac{1}{1-(n_r-1)\theta}, \underline{b}_s = \frac{1+\theta}{1-(n_s-1)\theta^2}, \underline{b}_c = \frac{1}{1-\theta}$$

Quick inspection shows that $\underline{b}_r \geq \underline{b}_c$ and $\underline{b}_s \geq \underline{b}_c$ always obtain for any (n_r, n_s) and $\theta \geq 0$. Comparing $\underline{b}_r$ with $\underline{b}_s$ we have that $\underline{b}_s \geq \underline{b}_r$ if and only if

$$\theta \geq \frac{n_r}{n_s - n_r}$$

At the same time we require $\theta \leq \frac{1}{n_{\bar{r}}}$. Combining the two inequalities we obtain $\underline{b}_s \geq \underline{b}_r \Leftrightarrow \frac{n_s - n_r}{n_r} \geq n_{\bar{r}}$. □

Proof of Conjecture 1.1

Proof. It is clear that $\underline{u}_{\bar{c}} = \min\{\underline{u}_g\}$ from the set of all networks g considered here i.e. it provides the minimum of all minimum utilities, for $\theta < \theta^*$. This follows directly from Lemma 10 which states that the binary team provides the highest total effort level in g for $\theta < \theta^*$. At the same time it connects the most people and minimizes individual Bonacich centrality in g.

Because $b_{\bar{r}} = b_{\bar{c}}$ at θ^* it must be the case that $b_{\bar{r}} = b_t$ for some $\theta^t \leq \theta^*$. For any $\theta < \theta^t$ the regular network has lower b and at the same time connects less players than any team structure it is being compared to, hence it must be the case that for $\theta < \theta^t$ we have $\underline{u}_t \leq \underline{u}_{\bar{r}}$. When $\theta > \theta^t$ the comparison requires inspection of

$$\min_{i \in g} \frac{b_i}{1 + b_g}$$

where $g \in \{\bar{r}, t\}$. The analysis is not so clear cut any more as the analysis is equivalent to comparing

$$\frac{1 + b_{\bar{r}}}{1 + b_t} \lesseqgtr \frac{\underline{b}_{\bar{r}}}{\underline{b}_t}$$

where $\underline{b}_g$ denotes the player with the lowest Bonacich centrality in g. For large θ it is possible that $\underline{u}_t > \underline{u}_{\bar{r}}$ if the left hand side of the above expression is greater than the right. This seems highly unlikely because

$$\frac{\underline{b}_{\bar{r}}}{1 + b_{\bar{r}}} \approx \frac{1}{n_{\bar{r}}}$$

Within the team structure there or may not exist a highly uneven distribution of b_i, but this unevenness is bounded by the structure of the team networks I am considering. Remembering that $n_{\bar{r}}$ sets the lower bound on the number of players connected by any g it seems plausible that $\underline{u}_{\bar{r}} = \max\{\underline{u}_g\}$ i.e. no team structure can provide a higher utility than the decentralized regular network. □

Proof of Proposition 1.4

Proof. Using Proposition 1 we have that in equilibrium

$$x_i^*(g, \theta) = \frac{\alpha[i]}{\hat{\delta}} \frac{b_i(g, \theta)}{1 + b(g, \theta)}$$

where $\alpha = 1 - \pi$, $\hat{\delta} = \delta - \pi\tilde{\delta}$ and $\theta = \frac{\lambda - \pi\tilde{\lambda}}{\delta - \pi\tilde{\delta}}$. Substituting x_i^* into the expression for a_i, noting that $b_i = 1 - \theta \sum_{j \neq i} g_{ij}$ and manipulating the expression gives

$$a_i = \frac{\pi(1 - \pi)}{(\lambda - \pi\tilde{\lambda})(\delta - \pi\tilde{\delta})} \frac{(\lambda - \tilde{\lambda})b_i + (1 - \pi)\tilde{\lambda}(d_i m_{ii})}{(1 + b)^2}$$

where I also make use of the definition of Intercentrality

$$d_i = \frac{b_i^2}{m_{ii}}$$

and where d_i and m_{ii} respectively capture the Intercentrality and number of self loops of node i. This gives us the first half of the proof.

In equilibrium a_i is a weighted average between Bonacich and Intercentrality, where the weights are determined by the precision of the policing authority signal. In the case where the signal is fully informative we have that $\tilde{\delta} = \delta$ and $\tilde{\lambda} = \lambda$ and

$$a_i = \frac{\pi}{\delta} \frac{d_i m_{ii}}{(1 + b)^2}$$

the perceived utility is purely a function of a player's Intercentrality.

In fact for a given graph structure and therefore a fixed b, the above result does not require $\tilde{\delta} = \delta$ to hold. $\tilde{\lambda} = \lambda$ is a sufficient and necessary condition for this result. For any $\tilde{\delta} < \delta$ we have that

$$a_i = \frac{\pi(1-\pi)}{\delta - \pi\tilde{\delta}} \frac{d_i m_i}{(1+b)^2} < \frac{\pi}{\delta} \frac{d_i m_i}{(1+b)^2}$$

A sufficient and necessary condition for a_i to be a function only of Bonacich centrality is $\tilde{\lambda} = 0$. For any $\tilde{\delta} < \delta$ we have that

$$a_i = \frac{\pi(1-\pi)}{\delta - \pi\tilde{\delta}} \frac{b_i}{(1+b)^2}$$

For $\tilde{\delta} = 0$ we have that

$$p_i = \frac{\pi(1-\pi)}{\delta} \frac{b_i}{(1+b)^2} < \frac{\pi(1-\pi)}{\delta - \pi\tilde{\delta}} \frac{b_i}{(1+b)^2}$$

Hence we obtain the second half of the proof. □

Proof of Lemma 1.3

Proof. The payoff from coordinating is

$$(1-\tau_k)(v_k^g + c_k) + \underline{\tau} z_k^g$$

a) For any decentralized symmetric network structure $v_k^g = z_k^g$. Therefore it is weakly dominant to set $\tau_k = 0$ for $c_k \geq 0$ and strictly dominant with strict inequality.

b) For a centralized star network we know that $v_k^g < z_k^g$ and $z_k^g = b_k^s$. Consider a given $\underline{\tau}$. If $\tau_k \neq \underline{\tau}$ then it must be the case that $\tau_k > \underline{\tau}$. For any $\tau_k \geq \underline{\tau}$ we have $\underline{\tau} z_k^g - \tau_k c_k < 0$ and $(1-\tau_k)v_k^g >$ is maximized at $\tau_k = 0$.

c) Start with a given $\underline{\tau}$ and set $\tau_k > \underline{\tau} > 0$. Rearrange payoffs to obtain

$$(1-\tau_k)v_k^g + \underline{\tau}(z_k^g - c_k) - (\tau_k - \underline{\tau})c_k$$

The policing authority's payoff is decreasing in $(\underline{\tau} - \tau_k)$ hence k has an incentive to decrease τ_k until $\tau_k = \underline{\tau}$. However, the policing authority's payoff is increasing in $\underline{\tau}$ since $b_k^s > c_k$. k does not have an incentive to undercut $\underline{\tau}$ because setting $\tau_k < \underline{\tau}$ leads to payoffs

$$(1 - \tau_k)v_k^g + (z_k^g - c_k)\tau_k$$

Now payoff is increasing in τ_k since $z_k^g > v_k^g$ and $z_k^g > c_k$. It reaches its maximum at $\tau_k = \underline{\tau}$.

d) This follows straight from the fact that if $\tau_k = 0$ for some k then $\min(\tau_k, \underline{\tau}) = 0$ for all $k' \neq k$. □

Chapter 3

Proof of Proposition 3.1

Proof. The non-financially constrained firm is endowed with the idea and $\alpha V - 2b - L >$. I consider the two different industries in turn.

Adding a financially constrained firm in Industry A plays no strategic role if it does not hold the idea. This leads to the same conclusion as the case with two non-financially constrained firms presented in the main text.

Consider industry B and assume the non-financially constrained firm chooses secrecy. The two financially constrained firms, labeled f, always prefer to form a collaboration agreement amongst themselves if either of them rejects the offer made by the non-financially constrained firm, labeled n, or the non-financially constrained makes no offer.

To see this note that if the two financially constrained firms are not part of any collaboration agreement their expected payoff is 0 each and this constitutes their outside option in any ensuing Nash Bargaining game.

When the two financially constrained firms collaborate with each other, denoted ff, with probability β information is revealed ands they develop the idea jointly, while the non-financially constrained firm n develops it simultaneously and independently i.e. ff earns a joint expected payoff of $\beta(\alpha V - 2b)$ as does n because they are in direct competition with each other. With probability $1-\beta$ the information remains a secret. In this scenario n earns expected monopoly profits of $(1-\beta)(V-2b)$ and ff earn joint expected payoff of 0. The financially constrained firms have the same outside option hence the Nash Bargaining solution splits the pie in two. Respective payoffs are given by

$$v_{ff}^{s} = \frac{\beta(\alpha V - 2b)}{2}; v^{n} = V(1-\beta(1-\alpha)) - 2b$$

n is indifferent in its choice of collaboration partner. If it offers v_{ff}^{s} to either f the offer is accepted and the idea is developed by the collaboration agreement of nf giving joint expected payoff of $V-2b$. Therefore n gets an expected payoff from the collaboration agreement of

$$v_{nf}^{s} = V(1-\frac{\alpha\beta}{2}) - b(2-\beta)$$

By not making an offer, or equivalently by making an offer that is rejected, n receives an expected payoff of v_{n}^{s}. Instead it can make an offer of collaboration that is accepted and obtain expected payoff v_{nf}^{s}. n prefers collaborating when

$$\alpha \leq \frac{2}{3}(\frac{b}{V}+1)$$

We note that $\frac{2}{3}(\frac{b}{V}+1) \geq \frac{1}{2}$ for any positive configuration of b and V. Therefore n always prefers collaborating for a non-zero probability of information disclosure. n is indifferent between collaborating or not if there is no information revelation i.e. $\beta = 0$, and we rule out collaboration by Assumption 3.

Now assume that n patents its idea. The patent rules out any possibility of collaboration between n and f. The two financially constrained firms decide whether to collaborate and form ff or not. If they do not collaborate they both receive a payoff of 0. If they form a collaboration agreement they obtain a joint payoff of $\alpha V - 2b - L$ and each receives through Nash Bargaining

$$v_{ff}^{p} = \frac{\alpha V - 2b - L}{2}$$

Therefore the two financially constrained firms prefer to form ff and n develops the idea simultaneously and independently and receives a payoff, greater than just the license fee, of

$$v_{n}^{p} = \alpha V - 2b + L$$

n prefers secrecy and collaboration when $v^s_{nf} > v^p_n$. This is the case if and only if

$$\beta < \frac{2((1-\alpha)V - L)}{\alpha V - 2b}$$

This concludes the proof. □

Proof of Proposition 3.2

Proof. When $\alpha V - 2b - L < 0$ n can credibly commit to developing the idea independently and in light of Assumption 1 earns positive profits under competition. By patenting its idea it blocks competition as potential rivals no longer find it profitable to pay a license fee and compete in the market for the developed idea. In industry A the patent blocks the other non-financially constrained firm from developing the idea. In industry B it blocks the collaboration agreement ff. n is indifferent between collaborating or not in industry B, so we use Assumption 3 to rule this out. By patenting and developing the idea, n secures monopoly profit, $V-2b$, which is greater than just the license fee given Assumption 2. Hence developing the idea is credible in every possible scenario. Secrecy does not ensure monopoly rents, as there is chance of information disclosure. Maintaining monopoly rents under secrecy requires collaboration agreements and non-negative transfers that eat into the firms profits. Hence patenting is always preferred to secrecy. This reasoning applies to both industry structures therefore patenting is a strictly dominant strategy. This concludes the proof. □

Proof of Proposition 3.3

Proof. The financially constrained firm f is endowed with the idea and $\alpha V - 2b - L >$. I consider the two different industries in turn.

Consider industry A and imagine that f keeps the idea secret, and does not make an offer to either n. Or equivalently f makes an offer and is rejected. The two non-financially constrained firms cannot enter a collaboration agreement. The idea is revealed with probability β and each firm earns an expected payoff of

$$v_f^s = 0; v_n^s = \beta(\alpha V - 2b)$$

If f wishes to enter a collaboration agreement with either n it has to offer at least v_n^s. Nonetheless, the remaining n can still develop the idea simultaneously and independently and still receive an expected payoff of v_n^s. Therefore f makes it a take or leave it offer to n and obtains

$$v_{fn}^s = (1 - \beta)(V - 2b)$$

If f patents the idea and does not enter a collaboration agreement then the two n cannot collaborate with each other and each firm receives payoff

$$v_f^p = 2L; v_n^p = \alpha V - 2b - L$$

For f to enter a collaboration agreement with either n it has to offer at least v_n^p. Nonetheless, the remaining n still prefers to develop the idea and pay the license fee to f. Therefore f collects the license fee n and offers the other non-financially constrained firm enough to leave it indifferent and enter fn. f obtains $v_{fn}^p = \alpha V - 2b - (\alpha V - 2b - L) + L = 2L$ and is indifferent between patenting the idea and collaborating and allowing the two non-financially constrained to compete in the market and collect the license fee. Thus, collaboration fn is ruled out by Assumption 3. However, f can choose to maintain secrecy and collaborate. It will choose to do so when $v_{fn}^s > 2L$ i.e. if and only if

$$\beta < \frac{V - 2b - 2L}{V - 2b}$$

Now consider industry B and imagine that f makes an offer to the other financially constrained firm, labeled f' which is rejected and that f' and n also do not enter a collaboration agreement. Both f, f' earn an expected payoff of 0. Conditional on information revelation n develops the idea and earns expected payoff of $\beta(V - 2b)$.

If f' collaborates with n and there is information revelation, with probability β, the idea is developed by nf' and is worth $V - 2b$. n earns the same from nf' as it gets from its outside option of not collaborating. f' stands to gain but has an outside option of 0. Hence the Nash Bargaining solution yields

$$v_{f'}^s = 0; v_n^s = \beta(V - 2b)$$

Both f' and n are indifferent in their collaboration decision and Assumption 3 rules out this possibility.

Assume f' accepts the offer made by f and the idea is revealed with probability β and ff' and n develop the idea simultaneously and compete in the product market. With probability $1-\beta$ the idea remains private knowledge and collaboration ff' results in a joint payoff of $V-2b$. f can always offer f' 0 which is accepted and obtains expected payoff

$$v^s_{ff'} = V(1-\beta(1-\alpha)) - 2b \geq 0$$

If f makes an offer to n that is accepted then expected joint payoff is $V-2b$. n can always obtain the outside option given by v^s_n so f will have to offer at least this for n to accept. f has expected payoff

$$v^s_{fn} = (1-\beta)(V-2b)$$

Comparing $v^s_{ff'}$ with v^s_{fn} shows that under secrecy f prefers collaborating with f' whenever Assumption 1 holds. In the limit, when there is no information revelation i.e. $\beta = 0$, f is indifferent between collaboration partners. However for a positive probability of information revelation f prefers to collaborate with f' because it has relatively more bargaining power than with n.

Now consider that f has patented its idea. If f makes no offer to f' or f' rejects the offer, f' can still Nash Bargain with n. n gets $V-2b-L$ and f' gets 0 if it refuses to collaborate with f'. The collaboration of nf' yields joint profits of $V-2b-L$. It is clear that in the Nash Bargaining solution of the collaboration agreement nf', n appropriates the entire value of the developed idea.

$$v^p_f = L; v^p_{f'} = 0; v^p_n = V - 2b - L$$

f' and n are indifferent between collaborating and this possibility is ruled out by Assumption 3.

In order to induce n to collaborate, f has to offer $V-2b-L$ from the developed idea, which is worth $V-2b$. Hence f only retains the license fee L in the collaborative agreement fn. Both f and n are indifferent and Assumption 3 rules out collaboration between the two.

f' has no bargaining power and f can induce its collaboration by offering it 0. ff' and n develop the idea simultaneously and independently. Patenting and collaboration ff' yields f a gross payoff of

$$v^p_{ff'} = \alpha V - 2b + L \geq L$$

f always prefers collaborating with f'. Therefore, given competitive pressure, secrecy earns f a higher payoff than patenting if and only if

$$\beta < \frac{(1-\alpha)V - L}{(1-\alpha)V}$$

This concludes the proof. □

Proof of Proposition 3.4

Proof. Consider in industry A the subgame that arises when f patents its idea and none of the three firms are in a collaboration agreement. If neither n develop the idea, everyone is left with a payoff of 0. In dependent and simultaneous development leads to negative profits for both n. However if one n develops and the other does not, the developing firm obtains monopoly profits less the license fee while the other gets 0. This is the classic chicken game with two pure strategy Nash equilibria in which one firm develops and the other does not, and one mixed equilibrium in which both firms randomize.

Lets focus on the two pure strategy Nash equilibria of the chicken game and the Sub-game Perfect Nash Equilibria that arise through them. The collaboration agreement nn is ruled out by Assumption 4. f is indifferent between offering the developing firm $V - 2b - L$ and collecting the license fee. In either case it receives a net payoff of L. However it can always offer the loser of the chicken game 0, which is accepted, develop the idea through the collaboration agreement fn and earn $V - 2b$ because the remaining n that would have developed if fn did not exist, no longer develops the product. Thus f always prefers patenting in industry A.

In industry B f can exploit the other financially constrained firm and enter the collaboration agreement ff'. By patenting the idea f earns $V - 2b$ and cannot do better through secrecy. Hence f alwasys prefers to patent. This concludes the proof. □

Proof of Proposition 3.5

Proof. (a) $\beta^{**}_{fA} > \beta^{*}_{fA}$ follows directly by comparing the relevant expressions. For $\beta^{**}_{fA} > \beta^{*}_{nA}$ we require assumption 1 to be satisfied which is always the case. Assume that $\beta^{*}_{fA} > \beta^{*}_{nA}$. This can be if and only if $(1-\alpha)V < \alpha V - 2b$, but this is a contradiction as long as Assumption 1 is satisfied and $\alpha \in [0, \frac{1}{2}]$. Hence we have the first ranking.
For $\beta^{*}_{fB} > \beta^{*}_{nB}$ we require that $(2b-(2-\alpha)V)(L-(1-\alpha)V) > 0$ which is always satisfied. The last ranking follows directly by noting that $\beta^{*}_{fB} = \beta^{*}_{nA}$.
(b), (c) and (d) follow directly by taking the relevant derivatives. $\square$

B Tables

This appendix presents regression and other empirical output for Chapters 2 and 3. Each set of tables is preceded by accompanying notes.

Notes for Chapter 2

* significant at 10%; ** significant at 5%; *** significant at 1%. Reported standard errors are robust and clustered by SIC 4-digits. If specified regressions control for SIC 2-digit industry fixed effects.

Table 2.1 replicates Cassiman and Veugelers. The suffix - CV indicates that the Cassiman and Veugelers definition of the variable is used. Table 2.1 presents Hausman specification tests for validity of instruments. The OLS estimate is always compared to the instrumental variable estimation. All three IV estimations use the instrument set proposed by Cassiman and Veugelers, with the following variation. Column 1 is exactly the same. Column 2 replaces basicness of R&D with the SIC 2-digit industry average of basicness of R&D and column 3 completely removes basicness of R&D from the set of instruments.

Table 2.2. presents a first difference regression on the balanced sub sample of CIS firms. The tests presented are for the equality of coefficients. D. represents Δ_t.

Tables 2.4-2.5 use the same instrument set, enumerated in Table 2.4. Both tables present an IV estimation that controls for firm level fixed effects. Both tables use firm level controls and control for High Technology industries. High Technology industries are identified using EUROSTAT High Technology trade classification.

Notes for Chapter 3

* significant at 10%; ** significant at 5%; *** significant at 1%. Reported standard errors are robust and clustered by SIC 4-digits. All regressions control for 7-digit UK postcode fixed effects. UK postcodes are extremely detailed and almost every street is assigned a different code. This means that we implicitly assume multiple reporting units on the same street or in the same retail park are subjected to the same unobserved time-invariant heterogeneity.

High Technology industries are identified using EUROSTAT High Technology trade classification. Patent distributions are calculated for SIC 4-digit, where this information is unavailable we have used SIC 3 and 2-digit distributions. Import intensities are taken from published UK I-O tables. Information on firm ownership and multinational status, takeovers and mergers is taken from the UK Businees Register Database.

If mentioned the fixed effects estimation uses SIC 4-digit controls rather than postcode.

In Tables 3.1-3.3 the dependent variable legal is calculated as average use of (1) patents, (2) trademarks, (3) Copyrights and (4) Design registration in protecting innovations. Each variable is first standardized to N (0,1) to eliminate subjectivity in responses, and then the aggregate is calculated.

In Tables 3.4-3.6 the dependent variable protect is calculated as the difference between strategic and legal.

The variable strategic is the average use of (1) Secrecy, (2) Cofidentiality agreements and (3) Lead-time advantage in protecting innovations. Each variable is first standardized to N (0,1) to eliminate subjectivity in responses, and then the aggregate is calculated.

In Table 3.I all reported coefficients are the odds-ratio between the two alternatives imitate and innovate. Reported standard errors are robust and clustered by SIC 4-digits. If specified regressions control for SIC 4-digit industry fixed effects. Each reason to innovate variable is first standardized to N (0,1) to eliminate subjectivity in responses, and then the aggregate is calculated.

Table 2.1 - Replication

	(1)	(2)	(3)	(4)
Spillovers - CV	0.84	0.49	0.23	0.23
	(0.16)***	-0.35	(0.02)***	(0.02)***
Strategic Appropriability	0.61	0.67	0.11	0.11
	(0.18)***	(0.17)***	(0.03)***	(0.03)***
Permanent R&D	-0.15	-0.08	0.2	0.2
	(0.16)	(0.16)	(0.01)***	(0.01)***
Complementarities	0.16	0.14	0.06	0.06
	(0.03)***	(0.04)***	(0.03)**	(0.03)**
Risk - CV	-0.03	-0.02	0.01	0.01
	(0.03)	(0.03)	(0.02)	(0.02)
Cost - CV	-0.06	-0.03	0.03	0.03
	(0.03)*	(0.04)	(0.03)	(0.03)
Industry use of Legal Protection	-0.86	-0.81	-0.93	-1.05
	(0.54)	(0.50)	(0.42)**	(0.43)**
High Tech Industry Legal Protection				0.31
				(0.08)***
Industry collaboration	1.52	1.49	1.41	1.38
	(0.28)***	(0.26)***	(0.25)***	(0.26)***
Instruments	Industry level (Spill, Appropriability, Perm R&D), Basic R&D (CV), Export Intensity	Industry level (Spill, Appropriability, Perm R&D), Basic R&D (CV), Export Intensity	OLS	OLS
Industry Dummies	SIC 2	SIC 2	SIC 2	SIC 2
Firm Controls	NO	NO	NO	NO
High Tech Dummy	NO	NO	NO	NO

Table 2.2 - Endogeneity of Basic R&D

		D.Spill	D.Binfo	D.Vinfo	D.Basic
D.Horizontal Collaboration		0.07	0.01	0.04	-0.01
		(0.01)***	(0.01)	(0.01)***	(0.03)
D.Vertical Collaboration		0.08	0.02	0.1	0.01
		(0.01)***	(0.01)**	(0.01)***	(0.02)
D.Research Collaboration		0.04	0.12	0.01	0.3
		(0.01)***	(0.01)***	(0.01)	(0.03)***
Observations		7937	7937	7937	7937
Adjusted R2		0.04	0.05	0.03	0.03
F		99.82	136.57	88.74	72.67
Tests					
D.H == D.V == D.R	chi2(2)	3.53	63.25	21.2	64.98
	Prob > chi2	0.17	0.00	0.00	0.00
D.H == D.V	chi2(1)	0.18	0.13	8.73	0.42
	Prob > chi2	0.67	0.71	0.00	0.51

Table 2.3 - Innovation and Imitation

	(1)	(2)	(3)	(4)	(5)
	All Innovators	All Innovators	Innovators	Imitators	Non-Innovators
Spillovers - CV	0.19	0.19	0.23	0.17	0.12
	(0.02)***	(0.02)***	(0.04)***	(0.02)***	(0.01)***
Strategic Appropriability	0.11	0.11	0.11	0.09	0.06
	(0.02)***	(0.02)***	(0.04)***	(0.02)***	(0.01)***
Permanent R&D	0.18	0.18	0.17	0.17	0.13
	(0.01)***	(0.01)***	(0.02)***	(0.01)***	(0.01)***
Complementarities	0.05	0.04	0.06	0.03	0.01
	(0.02)**	(0.02)**	(0.04)*	(0.02)	(0.01)
Financial Constraints		0.03	0.02	0.04	0.01
		(0.02)*	(0.03)	(0.02)*	(0.01)
Cost - CV	0.01	-0.03	-0.06	-0.01	0.02
	(0.02)	(0.02)	(0.04)	(0.03)	(0.01)
Risk - CV	0.02	0.03	0.01	0.04	0
	(0.02)	(0.02)*	(0.03)	(0.02)*	(0.01)
Industry use of Legal Protection	-0.59	-0.58	-1.5	-0.12	-0.03
	(0.35)*	(0.35)	(0.65)**	(0.45)	(0.13)
High Tech Industry Legal Protection	0.05	0.04	0.63	-0.27	-0.32
	(0.33)	(0.33)	(0.49)	(0.41)	(0.14)**
Industry collaboration	1.21	1.22	1.78	0.91	0.45
	(0.23)***	(0.23)***	(0.43)***	(0.26)***	(0.11)***
Inverse Industry Mark-up	-0.02	-0.02	-0.23	0.05	0.05
	(0.09)	(0.09)	(0.15)	(0.11)	(0.04)
Firm Controls			NO		
Year Dummies			YES		
Observations	11750	11750	3721	8040	24818
Adjusted R2	0.14	0.15	0.2	0.15	0.08
F	55.36	51.67	23.96	38.92	38.61

Table 2.4 - Instrumental Variable Estimation

	(1) Collaboration	(2) Collaboration	(3) Spillovers	(4) Appropriability
Public Spillovers	0.07	-0.02		
	(0.03)**	(0.10)		
Strategic Appropriability	0.13	0.2		
	(0.03)***	(0.19)		
Science base	0.05	0.07	0.26	0.09
	(0.04)	(0.06)	(0.06)***	(0.03)***
Complementarities	0.01	0.01	-0.09	-0.09
	(0.03)	(0.03)	(0.02)***	(0.01)***
Risk	0.01	0.01	0.03	0.07
	(0.02)	(0.03)	(0.02)	(0.01)***
Real Cost	0.08	0.08	0.09	0.1
	(0.02)***	(0.03)**	(0.01)***	(0.01)***
Financial Constraints	0.03	0.04	0.02	< 0.01
	(0.02)*	(0.02)*	(0.02)	(0.01)
Industry collaboration	0.46	0.55	1.23	0.09
	(0.13)***	(0.18)***	(0.20)***	(0.07)
Inverse Industry Mark-up	0.07	0.05	-0.19	0.02
	(0.04)*	(0.06)	(0.04)***	(0.03)
Excluded Instruments				
Industry Broadband Exposure			-0.04	0.11
			(0.02)***	(0.01)***
Industry contracting intensity			-0.27	-0.02
			(0.07)***	(0.03)
Basic Research Knowledge Capital			1.37	0.03
			(0.22)***	(0.08)
IV	OLS	2nd Stage	1st Stage	1st Stage
Year Dummy		YES		
High Technology Dummy		YES		
Firm Level Controls		YES		
Fixed Effects		Firm		
N	12694	12694	12694	12694
R2 (Uncentered R2)	0.64	0.03	0.09	0.15
Adjusted R2 (Shea Partial R2)	6.25	-0.91	0.04	0.02
F (Shea Partial F)		10.41	16.07	30.2
Hansen's J			0.99	
jdf			1	
p-value (Hansen's J)			0.32	
Weak ID Statistic			28.51	
Anderson-Rubin Chi2			2.05	
p-value (Anderson-Rubin Chi2)			0.56	

Table 2.5 - Type of Collaboration Link

	(1) Vertical	(2) Research	(3) Horizontal
Public Spillovers	0.02	-0.02	-0.02
	(0.11)	(0.09)	(0.07)
Strategic Appropriability	0.27	0.05	0.28
	(0.18)	(0.15)	(0.14)**
Science base	0.05	0.09	0.04
	(0.06)	(0.05)*	(0.05)
Complementarities	< 0.01	-0.01	-0.01
	(0.03)	(0.03)	(0.02)
Risk	-0.02	0.02	< 0.01
	(0.02)	(0.02)	(0.02)
Real Cost	0.06	0.04	< 0.01
	(0.03)*	(0.03)	(0.02)
Financial Constraints	0.04	0.04	0.02
	(0.02)**	(0.02)**	(0.01)
Industry collaboration	0.48	0.44	0.34
	(0.18)***	(0.15)***	(0.13)**
Inverse Industry Mark-up	0.03	-0.02	0.04
	(0.05)	(0.05)	(0.04)
Observations	12694	12694	12694
R2	0.02	0.02	-0.02
Adjusted R2	-0.91	-0.93	-1
F	10.09	7.24	6.76
Hansen's J	2.04	0.05	0.42
jdf	1	1	1
p-value (Hansen's J)	0.15	0.82	0.52
Weak ID Statistic	28.51	28.51	28.51

Table 3.1 - Reasons to Patent

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Process Imitators	0.013	0.015	0.015	0.013	0.016	0.015	0.012
	(0.035)	(0.035)	(0.035)	(0.035)	(0.035)	(0.035)	(0.035)
Process Innovators	0.163	0.164	0.156	0.152	0.155	0.159	0.155
	(0.056)***	(0.056)***	(0.054)***	(0.054)***	(0.054)***	(0.054)***	(0.053)***
Product Imitators	0.190	0.186	0.133	0.132	0.132	0.132	0.126
	(0.041)***	(0.041)***	(0.040)***	(0.040)***	(0.040)***	(0.040)***	(0.039)***
Product Innovators	0.336	0.335	0.283	0.278	0.283	0.283	0.267
	(0.047)***	(0.047)***	(0.046)***	(0.046)***	(0.045)***	(0.046)***	(0.045)***
High-Tech firm	0.151	0.130	0.137	0.133	0.134	0.135	0.124
	(0.078)*	(0.074)*	(0.069)**	(0.069)*	(0.069)*	(0.068)**	(0.069)*
Multinational	0.081	0.078	0.079	0.083	0.080	0.081	0.084
	(0.041)**	(0.041)*	(0.039)**	(0.039)**	(0.039)**	(0.039)**	(0.039)**
Competition - Import Intensity		0.304	0.283	0.285	0.285	0.287	0.295
		(0.082)***	(0.078)***	(0.078)***	(0.079)***	(0.078)***	(0.079)***
Market Demand risk			0.385	0.376	0.385	0.384	0.373
			(0.033)***	(0.033)***	(0.033)***	(0.033)***	(0.033)***
Financially Constrained				0.133			0.128
				(0.047)***			(0.048)***
Specificity of Vertical Relations					0.024		0.023
					(0.013)*		(0.013)*
Even Industry Patent Distribution						0.207	0.212
						(0.090)**	(0.087)**
New Firm							0.227
							(0.064)***
New Enterprise							-0.343
							(0.078)***
Firm Level Controls				Yes			
Fixed Effects				Postcode			
Observations	15539	15539	15539	15539	15539	15539	15539
Adjusted R-squared	0.87	0.87	0.87	0.87	0.87	0.87	0.87

Table 3.2 - Multinationals

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Competition - Import Intensity	0.291	0.358	0.291	0.293	0.290	0.290	0.369	0.330
	(0.078)***	(0.091)***	(0.079)***	(0.078)***	(0.078)***	(0.078)***	(0.092)***	(0.097)***
Market Demand risk	0.376	0.376	0.321	0.376	0.376	0.376	0.326	0.320
	(0.033)***	(0.033)***	(0.032)***	(0.033)***	(0.033)***	(0.033)***	(0.033)***	(0.037)***
Financially Constrained	0.130	0.129	0.133	0.065	0.130	0.130	0.075	0.125
	(0.047)***	(0.047)***	(0.047)***	(0.052)	(0.047)***	(0.047)***	(0.053)	(0.072)*
Specificity of Vertical Relations	0.024	0.024	0.024	0.024	0.025	0.024	0.027	0.085
	(0.013)*	(0.013)*	(0.013)*	(0.013)*	(0.013)*	(0.013)*	(0.013)**	(0.043)**
Even Industry Patent Distribution	0.211	0.209	0.212	0.213	0.211	0.243	0.243	0.238
	(0.090)**	(0.090)**	(0.091)**	(0.090)**	(0.090)**	(0.103)**	(0.104)**	(0.104)**
Multinational	0.085	0.113	-0.026	0.053	0.088	0.090	-0.004	-0.007
	(0.039)**	(0.042)***	(0.055)	(0.039)	(0.040)**	(0.039)**	(0.055)	(0.056)
MNE with competition		-0.135					-0.155	-0.132
		(0.103)					(0.105)	(0.105)
MNE with demand risk			0.182				0.167	0.177
			(0.060)***				(0.062)***	(0.061)***
MNE with financial constraints				0.268			0.235	0.210
				(0.107)**			(0.109)**	(0.110)*
MNE with specificity of vertical relations					-0.012		-0.018	-0.024
					(0.033)		(0.033)	(0.028)
MNE and patent distribution						-0.143	-0.132	-0.158
						(0.131)	(0.129)	(0.136)
Permanent R&D								0.090
								(0.076)
Collaboration								0.056
								(0.057)
Baseline Variables				Yes				
Firm Controls				Yes				
Time Dummies				Yes				
Fixed Effects				Postcode				
Observations	15539	15539	15539	15539	15539	15539	15539	15539
Adjusted R-squared	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87

Table 3.3 - Newly Established Firms, Permanent R&D and Collaboration

	(1)	(2)	(3)	(4)	(5)
Competition - Import Intensity	0.290	0.287	0.330	0.286	0.272
	(0.078)***	(0.079)***	(0.097)***	(0.077)***	(0.084)***
Market Demand risk	0.375	0.377	0.320	0.364	0.347
	(0.033)***	(0.034)***	(0.037)***	(0.034)***	(0.033)***
Financially Constrained	0.131	0.139	0.125	0.125	0.118
	(0.048)***	(0.050)***	(0.072)*	(0.047)***	(0.056)**
Specificity of Vertical Relations	0.024	0.022	0.085	0.024	0.043
	(0.013)*	(0.013)*	(0.043)**	(0.013)*	(0.029)
Even Industry Patent Distribution	0.212	0.227	0.238	0.209	0.185
	(0.090)**	(0.087)***	(0.104)**	(0.091)**	(0.093)**
New Firm enterprise (NFE)	-0.065	-0.088			
	(0.071)	(0.119)			
Permanent R&D			0.090	0.163	0.098
			(0.076)	(0.042)***	(0.073)
Collaboration			0.056		0.056
			(0.057)		(0.057)
x competition		0.412	0.468		0.061
		(0.491)	(0.481)		(0.141)
x demand risk		-0.014	0.013		0.070
		(0.132)	(0.128)		(0.066)
x financial constraints		-0.174	-0.160		0.025
		(0.171)	(0.177)		(0.101)
x specificity of vertical relations		0.410	0.296		-0.024
		(0.320)	(0.308)		(0.031)
x patent distribution		-0.664	-0.682		0.094
		(0.298)**	(0.304)**		(0.155)
Baseline Variables			Yes		
Firm Controls			Yes		
Time Dummies			Yes		
Fixed Effects			Postcode		
Observations	15539	15539	15539	15539	15539
Adjusted R-squared	0.87	0.87	0.87	0.87	0.87

Table 3.4 - Collaboration & Appropriability mix

	(1)	(2)	(3)
% of Innovative Sales			0.114
			(0.047)**
Process Imitators	0.116	0.096	
	(0.032)***	(0.033)***	
Process Innovators	0.026	-0.003	
	(0.055)	(0.056)	
Product Imitators	0.075	0.057	
	(0.034)**	(0.035)	
Product Innovators	0.154	0.127	
	(0.040)***	(0.038)***	
Collaboration		0.131	0.150
		(0.029)***	(0.028)***
Multinational	-0.069	-0.069	-0.068
	(0.036)*	(0.035)*	(0.036)*
New Firm enterprise (NFE)	-0.136	0.042	0.034
	(0.100)	(0.066)	(0.066)
Competition - Import Intensity	-0.182	-0.180	-0.183
	(0.068)***	(0.069)***	(0.070)***
Market Demand risk	0.007	0.010	0.013
	(0.031)	(0.032)	(0.032)
Financially Constrained	0.041	0.039	0.042
	(0.044)	(0.043)	(0.043)
Specificity of Vertical Relations	-0.006	-0.007	-0.008
	(0.011)	(0.011)	(0.011)
Even Industry Patent Distribution	-0.128	-0.133	-0.122
	(0.096)	(0.094)	(0.092)
High-Tech firm	0.028	0.027	0.014
	(0.045)	(0.044)	(0.043)
Firm Controls		Yes	
Fixed Effects		Yes	
Time Dummies		Yes	
Observations	15539	15539	15539
Adjusted R-squared	0.83	0.83	0.83

Table 3.5 - Appropriability Mix: Robustness Checks

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Collaboration	0.133	0.128	0.128	0.131	0.136	0.126	0.125
	(0.029)***	(0.029)***	(0.029)***	(0.029)***	(0.029)***	(0.029)***	(0.036)***
Permanent R&D	0.024	0.012	0.014	0.022	0.034	0.015	-0.007
	(0.037)	(0.037)	(0.037)	(0.037)	(0.036)	(0.036)	(0.039)
Internal Research Capability	-0.026	-0.033	-0.027	-0.027	-0.025	-0.033	-0.061
	(0.020)	(0.020)*	(0.021)	(0.020)	(0.020)	(0.020)*	(0.022)***
Multinational	-0.065	-0.067	-0.063	-0.065	-0.064	-0.064	-0.044
	(0.036)*	(0.035)*	(0.036)*	(0.036)*	(0.036)*	(0.036)*	(0.037)
Complexity of design		0.070				0.072	0.077
		(0.015)***				(0.015)***	(0.016)***
New corporate strategy			0.112			0.112	0.108
			(0.028)***			(0.028)***	(0.028)***
Innovation related person. training				0.024		0.020	0.007
				(0.031)		(0.031)	(0.030)
Regulatory needs					-0.035	-0.044	-0.048
					(0.015)**	(0.015)***	(0.016)***
Multinational Collaboration							0.013
							(0.070)
Baseline Variables				Yes			
Firm Controls				Yes			
Time Dummies				Yes			
Fixed Effects				Postcode			
Observations	15539	15539	15539	15539	15539	15539	15539
Adjusted R-squared	0.83	0.84	0.83	0.83	0.83	0.84	0.85

Table 3.6 - Collaborating Firms

	(1)	(2)	(3)	(4)	(5)	(6)
% of Innovative Sales				0.061	0.082	0.021
				(0.054)	(0.054)	(0.055)
Process Imitators	0.101	0.105	0.112			
	(0.038)***	(0.039)***	(0.038)***			
Process Innovators	-0.002	0.004	-0.007			
	(0.047)	(0.047)	(0.047)			
Product Imitators	0.018	0.027	0.009			
	(0.045)	(0.045)	(0.045)			
Product Innovators	0.030	0.037	0.004			
	(0.043)	(0.044)	(0.044)			
Financially Constrained	0.100	0.102	0.059	0.098	0.102	0.063
	(0.044)**	(0.044)**	(0.044)	(0.044)**	(0.044)**	(0.044)
Complexity of design			0.061			0.063
			(0.015)***			(0.015)***
Multinational			-0.037			-0.031
			(0.045)			(0.045)
Innovation related person. training		-0.040	-0.013		-0.028	-0.002
		(0.039)	(0.039)		(0.038)	(0.038)
Internal Research Capability					-0.036	-0.032
					(0.014)**	(0.014)**
Market Demand risk	No	Yes		No	Yes	
Competition - Import Intensity	No	Yes		No	Yes	
Firm Controls		No	Yes		No	Yes
Time Dummies		No	Yes		No	Yes
Fixed Effects		No	SIC 4-dig		No	SIC 4-dig
Observations	3489	3489	3489	3489	3489	3489
Adjusted R-squared	0.04	0.04	0.06	0.04	0.04	0.06

Table 3.E - Difference in Means Test

	Obs	Mean	Std. Err.	|t-statistic|
Non Multinationals	31164	0.1244224	0.0017657	
Multinationals	7404	0.0875203	0.0031104	
Difference	38568	0.0369022	0.0035766	10.3175
Non-Collaborators	33429	0.107676	0.0015994	
Collaborators	5139	0.1801907	0.0050902	
Difference	38568	-0.0725147	0.0053356	13.5907

Table 3.F - Financial Constraints

	(1)	(2)	(3)	(4)
Collaboration	0.023	0.032	0.012	-0.007
	(0.005)***	(0.008)***	(0.007)*	(0.015)
Multinational	-0.042	-0.013	-0.058	-0.022
	(0.004)***	(0.008)*	(0.008)***	(0.018)
Permanent R&D	0.038	0.022	0.028	0.012
	(0.005)***	(0.009)**	(0.007)***	(0.016)
Complexity of design	0.033	0.031	0.026	0.020
	(0.002)***	(0.003)***	(0.003)***	(0.006)***
Regulatory needs	0.026	0.023	0.020	0.007
	(0.002)***	(0.003)***	(0.003)***	(0.007)
Firm Controls	No			
Time Dummies	Yes			
Fixed Effects	SIC 4-dig	Postcode	SIC 4-dig	Postcode
Sample	All		Innovators & Imitators	
Observations	38568	38568	12494	12494
Adjusted R-squared	0.05	0.22	0.03	0.26

Table 3.I - Imitation vs Innovation

	(1)	(2)	(3)	(4)
Collaboration	1.516	1.491	1.697	1.669
	(0.097)***	(0.104)***	(0.103)***	(0.110)***
Multinational	1.034	1.044	1.196	1.146
	(0.100)	(0.116)	(0.080)***	(0.083)*
Total Research Capability	1.137	1.111	1.235	1.194
	(0.035)***	(0.042)***	(0.039)***	(0.037)***
Total Spillovers	1.000	1.000	1.000	1.000
	(0.000)***	(0.000)	(0.000)	(0.000)
Innovation related person. training	1.279	1.328	1.014	1.072
	(0.099)***	(0.116)***	(0.062)	(0.071)
Improving Production Flexbility	1.046	1.047		
	(0.049)	(0.052)		
Increasing Production Capacity	1.013	1.041		
	(0.045)	(0.052)		
Reducing Unit Costs	0.945	0.918		
	(0.044)	(0.048)*		
Increasing Value Added	1.272	1.275		
	(0.066)***	(0.078)***		
Regulatory needs	1.172	1.219		
	(0.052)***	(0.061)***		
Increasing Range of Goods & Services			1.180	1.148
			(0.048)***	(0.049)***
Entering New Markets			1.333	1.321
			(0.052)***	(0.056)***
Increasing Quality of Goods & Services			0.946	0.978
			(0.041)	(0.046)
Competition - Import Intensity	0.638	2.500	1.600	0.512
	(0.120)**	(1.860)	(0.236)***	(0.142)**
Firm Controls	Yes			
Time Dummies	Yes			
Fixed Effects	No	SIC 4	No	SIC 4
Sample	Process Innovators and Imitators		Product Innovators and Imitators	
Observations	4943	4684	6852	6736
Log-likelihood	-2843.00	-2600.10	-4365.18	-4084.13
LR Chi-squared	304.57		742.22	
Psuedo R-squared	0.05	0.09	0.08	0.13