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Three Essays on Competition Policy and Innovation

by

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ABSTRACT

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This thesis looks at the various activities of competition authorities, such as the United Kingdom's Office of Fair Trading or the US Federal Trade Commission, and shows examples of how a tough, competition-promoting stance can boost innovation. Each chapter considers one of the three main branches of competition policy: mergers, agreements between competitors and the conduct of dominant firms.

Chapter 2 shows how a government can foster innovation by tightening merger restrictions. A detailed model of innovation is used to show how merger policy affects market structure over the life-cycle of an industry. We show that mergers are only possible in later periods, once incumbent firms have established a technological lead over potential entrants. This means that the expectation of future rents from a relaxed merger policy encourages entry in the early stages. This can reduce R&D in the early stages and, as latter R&D builds on initial discoveries, limit innovation at the end of the life-cycle. We show that, in large markets, a government that aims to promote innovation should ban mergers when early innovation is sufficiently important for later research. A ban is also the optimal policy when a government aims to maximize welfare.

In Chapter 3 we look at the effects of R&D cooperation among competing firms on technology choice. We demonstrate how firms in a duopoly can ensure that each adopts different technologies by agreeing, prior to conducting R&D, to share the results of their research. This has the effect of reducing product substitutability, thereby softening competition and increasing profits. We show that this can reduce innovation, consumer welfare and total welfare. The model also demonstrates how, once technology choice is taken into account, spillovers can be harmful even when R&D and output decisions are made simultaneously. Thus, unlike the rest of the literature, this result does not depend on the existence of the strategic motive to (over-)invest.

In Chapter 4, we look at a systems market and show how an incumbent monopoly supplier of a primary product can protect its position through the technological tying of complementary goods. The key feature is that the production of complementary goods allows rivals to build up an *absorptive capacity* and thus benefits from spillovers from the incumbent. This in turn helps them challenge the incumbent in an R&D race to produce a superior version of the primary product. Tying reduces the aggregate rate of innovation and a competition authority that seeks to promote innovation should therefore ban it. Unlike other models in the literature, we do not drop the Chicago-School assumption that the complementary market is perfectly competitive.

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Chapter 1

Introduction

This thesis looks at the various activities of competition authorities, such as the United Kingdom's Office of Fair Trading or the US Federal Trade Commission, and shows examples of how a tough, competition-promoting stance can boost innovation. Each chapter considers one of the three central branches of competition policy: the regulation of mergers, agreements between competitors and the conduct of dominant firms. In each case we analyze a specific scenario and show how tighter regulation can promote innovation. The mechanisms by which this happens are diverse and a central theme of this thesis is that specific regulations have subtle and idiosyncratic effects that need to be taken into account by enforcers on the front line. The thesis is motivated by the increased interest that policy-makers have shown in the idea that economy-wide rates of innovation can be increased by strengthening competition. We argue that, despite clear empirical evidence that greater competition promotes innovation, this does not necessarily translate into simple policies at the ground level and that in each case the specific characteristics of the relevant market need to be considered carefully.

There is a large number of empirical studies suggesting that product market competition promotes productivity and innovation. A comprehensive survey is provided by Ahn (2002) in an OECD working paper. The UK's Office of Fair Trading also provides a survey (See OFT 887 published in 2007). Many of these studies show that increased levels of competition in an industry, as measured by variables such as import penetration, market concentration and price-cost margins, are positively associated with the levels and growth rates of Total Factor Productivity (see, for example, Nickell (1996) and Disney et al (2003) for evidence based on UK data, see Januszewski et al (2001) for similar results based on German data). As Total Factor Productivity is often interpreted as reflecting the level of technology in an industry or economy, these studies also suggest that competition is good for innovation. Other studies measure innovation in a more direct way and find similar results. Blundell, Griffith and Van Reenen (1999) use the Science Policy Research Unit database which employed experts to identify 4378 major innovations in the UK between 1945 and 1983. They find that more competitive industries have higher rates of aggregate innovation (although within an industry larger firms are more likely to innovate). Aghion et al (2005) use citation-weighted patent count data and find an inverted-U relationship between competition, as measured by price-cost margins, and the rate of innovation. Competition initially promotes innovation, but beyond a certain point has harmful effects.

Other evidence comes from studies investigating the effects of those government regulations that have a direct impact on competition. For example, Maher and Wise (2005) look at the productivity effects of the liberalization of the UK's gas, water and electricity markets and find high levels of productivity growth in the 1990s. Nicoletti and Scarpetta (2005) look at international variation in levels of product market regulation and find that reduced regulation in the UK, US and Canada boosted productivity growth while a lack of reform in continental Europe restricted growth. Finally, some evidence comes from studies of individual industries. Comanor and Scherer (1995) contrast the poor performance of the concentrated US steel industry to that of the more competitive (because of anti-trust action in 1911) petroleum industry. Zitzewitz (2001) contrasts the lack of innovation in the highly concentrated UK tobacco industry in the inter-war years with that of the more competitive US industry.

In response to the mounting evidence, policymakers around the world have enacted a number of reforms aimed at strengthening competition. There is growing recognition that high technology industries are important to the development of modern economies and that the potential welfare gains from innovation far outweigh the negative effects of monopoly pricing, the traditional focus of competition policy. This is particularly true given that innovation can affect growth rates in productivity. Griliches (1980), for example, finds that a 1% increase in R&D raises Total Factor Productivity growth by 0.07%. While the deadweight loss from monopoly pricing is likely to be fairly static over time, the cumulative nature of innovation means that the benefits over the long run are likely to be much larger. Even if the focus is on consumer welfare alone, the returns to innovation are still large. Nordhaus (2004) estimates that in the US since the war, producers have only received 2% of the social value of innovations with the rest going to consumers.

The United Kingdom has been particularly enthusiastic in the use of competition policy as an instrument to boost productivity performance. The UK has a large productivity gap with other industrialized countries, with an output per hour 13% below Germany, 18% below the US and 20% below France in 2005[1]. Competition is identified as one of five drivers of productivity growth by the UK's Treasury[2] and significant steps have been taken to strengthen competition policy. The Enterprise Act 2002 strengthened the criteria for evaluating mergers from a rather vague "public interest" test to a simpler test of whether the merger would "substantially lessen competition", thus bringing the UK in line with the US. The Act also criminalizes cartels, encourages private actions in competition cases and makes the UK's competition authorities (i.e. the Office of Fair Trading, the Competition Commission and the sectoral regulators such as the Office of Communications) more independent of Ministers. In addition to this, the competition authorities received significant budget increases.

The European Union has also made a number of reforms as part of its Lisbon agenda, which seeks to boost innovation and the competitiveness of the EU economy. The European Commission sets out its strategy in Communication COM(2004) 293, including an adoption of a new test for merger analysis, similar to the new UK test, improved coordination of the activities of Member States and a move towards a more economics-based and pro-active approach to enforcement. The Commission also aims to boost competition by extending the Single Market to services, although progress with the Services Directive has stalled.

The United States is probably the country whose competition authorities have paid the most attention to innovation. Hart (2001) documents how US competition policy has often focused on innovation, particularly in the post-war era, and has recently moved in this direction again after the more laissez-faire attitude in the 1970s and 80s associated with the influential Chicago School. In 1995 the Federal Trade Commission and the Department of Justice published their joint *Guidelines for the Licensing of Intellectual Property,* which introduces the concept of an "innovation market" into anti-trust enforcement. This refers to instances where firms are competing to develop new products, as opposed to a product market where firms compete for sales. Gilbert (2007) notes that this approach has been increasingly influential in merger analysis, with innovation being important in 38% of merger investigations between 2000 and 2003 compared with just 3% of mergers between 1990 and 1994. In addition, several high-profile cases have involved high-tech sectors including the Department of Justice's case against Microsoft in 1998 and the Federal Trade Commission's investigation of Intel in 1999.

Our thesis is motivated by this increased focus on innovation by competition authorities. Our central theme is that, as innovation is a very complex area, and as competition

[1]Source: Centre for Economic Performance (2007) "UK Productivity in the Blair Era"

[2]The other drivers are: basic science research, skills, enterprise and physical investment (see HM Treasury Budget 2006)

policy encompasses a wide range of individual regulations, the use of competition policy to promote innovation needs to take into account case-specific effects. While empirical studies show that competition boosts innovation, which in turn suggests a role for competition policy, this does not necessarily translate into simple recommendations at the ground level of enforcement. For example, no policy has a simple impact on market concentration, something we look at in our first chapter where we consider merger policy. In each of our three chapters we consider one of the main areas of competition policy, namely, the regulation of mergers, of agreements between firms and of the conduct of dominant firms. The models presented all show, in specific examples, how a tough, pro-competitive stance can boost innovation. The models do not derive general conclusions about each of these policy areas, however, by highlighting the specific nature of the mechanisms involved in each scenario they do illustrate the need for competition authorities to proceed in a considered, case-by-case fashion.

Our first paper, presented in Chapter 2, considers merger regulations. We look at a case where product-improving R&D is deterministic, that is, firms can predict the outcomes of additional R&D investment. This approach is widespread in the non-patent race segment of the literature on R&D. In this case there are, *ceteris parabus*, clear benefits from concentration in the market owing to the economies of scale associated with the fixed costs of R&D. This suggests that competition authorities should be favourable towards mergers. However, we show that this is not the case when entry into the market is considered and when innovation is considered in the context of a product life-cycle.

Existing models of mergers with endogenous entry typically rely on unexplained cost-saving synergies in order to show how mergers can be profitable. Without these, symmetry between entrants and incumbents means that a merger would simply induce another firm to enter, eliminating the profitability of the merger. These models are not convincing because the evidence for synergies from mergers is scant. We consider a model in which innovation is studied in the context of a product life-cycle, allowing us to explain the asymmetry between merging firms and potential entrants that allows mergers to be profitable. Specifically, we assume that only those firms that enter in the early stages of the life-cycle are able to keep up with technological developments in the industry. This means that mergers are only possible in the latter stages of the life-cycle once incumbents have built up a technological advantage over potential entrants. We show that a relaxed merger policy creates an expectation of future rents which encourages entry in the early stages. This, in turn, harms early innovation and, as later innovation builds on initial discoveries, can limit overall technological progress by the end of the product's life-cycle, despite the benefits from increased concentration in the latter stages. Our results focus on large markets, which will be able to sustain large levels of R&D and which will be the focus of a competition authority's attention. We show that, in these cases, a government that aims to promote innovation should choose to ban mergers if early innovation is sufficiently important for later R&D. This is represented by a parameter in the model. When a government aims to maximize total welfare within the market, we get the result that a complete ban is always preferable.

In Chapter 3 we look at technology sharing agreements between firms. There is a huge literature, building on the work of d'Aspremont and Jacquemin (1988), that considers the impact of R&D cooperation between firms that are otherwise in competition in a product market. The literature tends to focus on full cooperation where firms agree to coordinate budgets and maybe operate a joint research laboratory. In contrast, we consider simple agreements to share the output of research. Such agreements are likely to be low-key and to appear quite innocuous on the surface. However, we show that such agreements can be used to coordinate technology choices in order to ensure that product substitutability is reduced and competition softened. The existing literature on R&D cooperation tends to focus on decisions over budgets rather than technology choice, and where technology choice is considered it only affects spillovers rather than product characteristics or the effectiveness of R&D. We consider a scenario where, in the absence of an information sharing agreement, firms in a duopoly are both drawn towards adopting a specific superior technology (which we call the "core" technology), leading to high product substitutability and intense competition. Essentially, the firms become trapped in a Prisoner's Dilemma; they would prefer to choose very different technologies but each has an incentive to adopt the superior core technology, leading to lower profits. We show that, in certain cases, firms can sign a technology sharing agreement in order to overcome this and ensure that neither adopts the core technology, instead choosing very different "peripheral" technologies. The key to this effect is that core and peripheral technologies are sufficiently related that the profitability of adopting the core technology is eliminated if a firm is required to share its research with a rival that adopts a peripheral technology. We show that a competition authority that aims to promote innovation, consumer welfare or total welfare should ban such agreements if the core technology is sufficiently superior to the alternatives. The model also shows that, if technology choice is taken into account, spillovers can have harmful effects even when R&D and output decisions are made simultaneously (so that there is no strategic motive to invest). This is in contrast to the existing literature, for example Leahy and Neary (1997).

Our fourth chapter looks at the much studied issue of technological tying of complementary products by the dominant supplier of a primary product. This is something that has received a lot of attention since the famous case against Microsoft brought by the US Department of Justice in 1998. Microsoft was accused of using its position to exclude Netscape from the market for Internet browsers. Documents presented at the trial showed that one of the key motivations behind Microsoft's actions was a fear that Netscape's browser would evolve into a platform that could challenge Microsoft's position in the operating system market. A number of papers, such as Choi and Stefanadis (2001) and Carlton and Waldman (2002), show how the tying of complementary products can be used to preserve an incumbent's dominant position over the supply of a primary component. Our model adds to this literature and suggests a very different mechanism by which this exclusion can occur. We assume that being active in the production of complementary products helps a firm acquire an *absorptive capacity*, that is an ability to receive and exploit knowledge spillovers from the incumbent. This concept was first introduced by Cohen and Levinthall (1989), who argued that a firm needs to conduct its own R&D in order to benefit from spillovers, and is the subject of a huge literature that investigates its various sources. In particular, the literature emphasizes the importance of contacts with customers and suppliers, something that a producer of complementary products is likely to benefit from. This feature of the model returns to a theme in our first chapter, namely that active firms are able to keep up to date with the latest technology in a way that outsiders are not. An absorptive capacity allows the firm to keep up with the latest technology and so challenge the incumbent firm in the primary sector. We show, using a simple patent race model combined with a method of equilibrium selection, how exclusion unambiguously reduces the aggregate rate of innovation in the industry. Unlike existing models of tying and exclusion we do not drop the assumption, made by Chicago-school critics, that the complementary goods market is perfectly competitive. We also consider a number of extensions to the basic model, which show that the central results hold under a wide range of assumptions. A competition authority that aims to promote innovation should therefore prevent a dominant firm from engaging in technological tying, or indeed other similar forms of exclusion.

Chapter 2

Merger policy, market structure and innovation

Abstract

This paper shows how a government can foster innovation by tightening merger restrictions. A detailed model of innovation is used to show how merger policy affects market structure over the life-cycle of an industry. We show that mergers are only possible in later periods, when incumbent firms have established a technological lead over potential entrants. This means that the expectation of future rents from a relaxed merger policy encourages entry in the early stages. This can reduce R&D in the early stages and, as latter R&D builds on initial discoveries, limit innovation at the end of the life-cycle. In such cases, the optimal policy of a government that wishes to foster innovation is to ban mergers altogether. Welfare implications are also discussed.

2.1 Introduction

A number of recent studies have shown that lower levels of concentration in a product market are associated with higher rates of innovation and productivity growth. This raises the possibility that a restrictive policy towards mergers may boost innovation. Indeed, in recent years, particularly in the US, policymakers have strengthened merger policy with the aim of fostering R&D. However, the relationship between merger policy and market structure is poorly understood and not well explained by the existing literature. In this paper we show how using a fairly rich model of innovation can help explain the impact that merger policy has on the structure of a market over the life-cycle of a new product. In turn this allows us to assess the impact of merger policy on innovation. By contrast, existing models of mergers and market structure fail to incorporate a significant role for innovation. We believe this misses an important factor in the evolution of an industry. In our model, only those firms that enter in the early stages of a new product life cycle have the ability to keep up with the latest technological developments. As we demonstrate, this means that mergers are only possible in the later stages of a product life cycle, once incumbents have built up a technological superiority over potential entrants. This creates a mechanism whereby a restrictive merger policy can foster innovation despite the presence of economies of scale to R&D. A permissive merger policy creates an expectation of future rents which encourages early entry. This depresses R&D in the early stages and, as later research builds on early discoveries, can limit overall progress by the end of the industry's life. Much of our analysis relates to "large" markets, which will have the greatest potential for innovation and which will be the focus of anti-trust activities. While some of our stronger results may not hold in small markets, these, in general, will not be able to sustain large levels of R&D and will not be a priority for regulators.

2.2 Existing literature

There are a number of studies suggesting that lower levels of market concentration promote innovation. Using panel data on several major UK industries, Blundell et al (1995) find that lower levels of concentration, as well as other indicators of more intense product market competition, are associated with higher levels and growth rates of Total Factor Productivity. In a later study, the same authors find similar results using a more direct measure that counts the number of innovations over time (Blundell et al (1999)). Similar results are found in Nickell (1996) and elsewhere (see Ahn (2002) for a review of the literature). The implication for a government that wants to promote innovation is that it should aim to prevent markets from becoming too concentrated. There are a number of policies that can have this effect, including the opening of markets to international trade and the removal of entry barriers, for example, by reducing red tape. Although it is relatively uncommon, a government can even force the break-up of a concentrated industry, for example the break-up of AT&T in 1984. In this paper we focus on the role of merger policy. Although it may be intuitive that a strict merger policy can help prevent a market from becoming too concentrated, the exact link between merger policy and market concentration is not straightforward. In the absence of mergers, markets may still become concentrated via exit or the disproportionate expansion of a few firms and, conversely, entry may erode concentration even if mergers are allowed. Unfortunately, as Tichy (2001) notes in his survey, there is little empirical work on the impact of mergers on market structure. Typically, studies on the evolution of industry structure simply treat a merger as the exit of the acquired firm (see for example Klepper and Simons (2005)). Although a "shakeout" phenomenon is frequently observed in this literature, where market concentration increases rapidly as an industry matures, the role played by mergers is not identified. A European Commission report published in 1996 notes that the industries with the fastest growing levels of concentration are those with the highest levels of merger activity[1]. Although this doesn't establish cause and effect, it does suggest an important role for mergers. Case studies also suggest that mergers can have a significant effect on market concentration. Zitzewitz (2003), for example, shows how the UK tobacco industry became highly concentrated after it was allowed to merge to a monopoly in 1902. He argues that the subsequent productivity performance of this industry in the 1920s and 30s was significantly worse than that of the US tobacco industry, which was broken up by anti-trust action in 1911.

The theoretical literature has explored a number of issues relating to merger policy and market structure and provides some useful insights. Much of the early literature focuses on the effects of an arbitrary merger in a market with an exogenously given number of firms. The general message from these studies is that there are quite a few barriers to mergers and, by implication, that they may not play an important role in the evolution of market structure. The influential paper by Salant, Switzer and Reynolds (1983) showed that, in a Cournot setting, a merged firm often does not gain enough market share for the profits of its owners to increase. The reason is that while the merged firm reduces output in order to raise market price, rivals respond by increasing output. With the exception of mergers that vastly increase concentration or that result in large cost efficiencies, the real beneficiaries are firms that remain outside the merger. A large literature has sought resolutions to this "merger paradox" including the addition of price competition (Deneckre and Davidson,

[1] See European Commission "Economic evaluation of the internal market", European Economy 4, 1996

1985), capacity constraints (Perry and Porter, 1985) and dynamic effects (Cheong and Judd, 2000). Subsequent work, for example Kamien and Zang (1990), endogonizes the merger process and shows how, given that other firms merge, an individual firm would prefer to remain an outsider and not join the merged coalition. As a result, all firms will be reluctant to join. This is known as the *insider's dilemma.* The fact that mergers provide a positive externality to outside firms means that even when they are profitable they may be difficult to coordinate. Overall, the implication of the early literature is that there are significant barriers to mergers and, therefore, that government policy may not have much effect on market structure and competition at all.

A more recent strand of the literature looks at how mergers affect entry into the market, either in response to or in anticipation of them. The idea that entry will mitigate the effects of a merger has played a role in a number of decisions by anti-trust authorities, in particular, the rulings of courts in the United States. In an early paper, Werden and Froeb (1998) criticized the assumption made by many US courts that entry is likely to mitigate the effects of a merger. Using a Logit demand system, they show that, when sunk costs are at a level consistent with the prevailing market structure, entry will frequently render otherwise profitable mergers unprofitable. Assuming that only profitable mergers will be proposed, this implies that a competition authority does not need to consider the possible mitigating effects of entry. The fact that the merging firms perceive the merger to be profitable suggests that entry is unlikely. Similarly, Spector (2003) shows that competition authorities do not need to consider whether a merger will induce entry in order to assess a merger, only whether it generates synergies. In a quantity setting game any profitable merger that does not generate synergies will raise prices and harm consumers. These two papers are largely aimed at giving practical advice to competition authorities and they do not say much about the importance of mergers in the evolution of market structure. They simply point out that if a merger is proposed, and hence is presumably profitable, it is unlikely to generate entry.

Other papers have shown how incorporating entry into a model can overturn the merger paradox and the insiders' dilemma. Davidson and Mukherjee (2005) show that when entry is considered, many of the counter-intuitive results of the merger literature disappear. They show that when there are fixed costs of production but no sunk costs of entry *any* merger will be profitable as long as it creates at least some synergies. Entry adjusts to keep the profits of a non-merged firm at zero and a merged firm, having a cost advantage, will therefore receive positive profits. Marino and Zabojnik (2006) investigate the incentive to merge in a dynamic model where entry is blocked in the short run because of time delays. These time delays mean that mergers are profitable in the short run, but an incumbent firm faces the prospect of having to constantly buy up new entrants in the future. They find that reductions in the cost of entry increase the likelihood of mergers because it implies intense future competition in the absence of mergers and new entrants can be purchased more cheaply. Passendorfer (2005) explores similar themes. The implication of these papers is that mergers may be more profitable and easier to achieve than the early literature suggested.

Mason and Weeds (2006) show how a competition authority can encourage entry by committing itself to allow mergers following negative demand shocks. By allowing entrepreneurs an exit route in hard times, they can be encouraged to enter the market with corresponding benefits for consumers. Although they do not consider market structure beyond a single incumbent and a single entrant, the idea that the possibility of future mergers affects entry decisions is a central theme of the model we present in this paper.

One of the few papers to look explicitly at how mergers affect market structure over time is Gowrisankaran (1999). He develops a full infinite-time dynamic model where, in each period, firms invest in capacity, choose whether to enter and exit, and make bids to acquire other firms. Mergers generate random cost-saving synergies, which are observed prior to merger decisions. The author emphasizes that his main purpose is to show the feasibility of the analysis rather than to derive general results, nevertheless, using numerical techniques to solve the model some broad conclusions are derived: allowing mergers does indeed lead to greater levels of concentration but industries do not merge to monopoly; mergers allow a market to adjust to shocks and achieve long-run structures more quickly; and, finally, mergers are only observed when there are sufficiently strong synergies.

The common feature of models of mergers and entry is that there must be some barrier to entry in order for mergers to be profitable. With the exception of Marino and Zabojnik, this takes the form of a cost advantage. When there is free entry a merger cannot influence the market structure if potential entrants have identical costs to the merged firms; a merger will simply induce entry and market structure will remain unchanged. The existing models usually assume that mergers will create synergies, giving the merged firms a cost advantage over entrants. However, the basis for these synergies is unclear. This is particularly so in models that only consist of one time period, such in Davidson and Mukherjee. If firms enter a market and immediately merge, it is doubtful whether this is likely to generate synergies as the firms have not had a chance to develop experience or knowledge in the market which they can share. In any case, the empirical evidence for strong synergies is weak and anti-trust authorities have been very skeptical of cost-saving claims made by merging firms. For example, Cowling (1980) finds efficiency *losses* in two thirds of the cases he studies (see Tichy (2001) for a survey of the empirical literature on mergers and efficiency).

In this paper we argue that merger and entry decisions need to be studied in the context of an industry's "product life cycle". This refers to how an industry evolves from the point at which a new product or product-type is invented. The literature usually takes the initial discovery of the product as exogenous and studies how market structure evolves over time. Product life cycles have been studied in a number of industries, such as automobiles and televisions (see for example Klepper (1997, 2002)). These studies generally show that entry is relatively easy in the early stages of an industry, but once the industry matures and the technology evolves incumbents have a significant advantage and entry is more difficult. In our model, entry is also easy in the initial stages of an industry's life with the corresponding implication that mergers at this point are not profitable. As existing firms have no technological advantage over potential entrants a merger would simply induce entry. Over time, however, incumbents build up expertise over potential entrants, allowing mergers to occur without inducing entry. This means that merger policy affects entry decisions at the beginning of the life-cycle, as entrants look ahead to the possibility of earning rents in the future. The key point is that mergers need to be studied in conjunction with the evolution of technology in an industry. Without this, models of mergers and entry have to incorporate an unrealistic assumption of cost-saving synergies. By using a fairly detailed model of innovation we are not only able to explain the timing of mergers and entry but also show the effects of merger policy on innovation.

Innovation in our model has three central features. Firstly, we study the case of deterministic cost-reducing/process innovation, as in Dasgupta and Stiglitz (1980). One of the key properties of this model of innovation is the importance of economies of scale. As R&D is a fixed cost, greater output makes investment more cost effective. In an industry with a large number of firms, the market share of each firm will be low and, correspondingly, its incentive to invest will be low. Vives (2005) looks at the effects of market concentration in a deterministic R&D model for a large variety of demand systems (e.g. linear, Logit, Hotelling) and finds that an increase in the number of firms almost always reduces R&D per firm and therefore innovation. This feature of our model means that, all else being equal, a government that is seeking to foster innovation would want to encourage market concentration.

Secondly, the model features an intertemporal spillover, whereby current R&D increases the productivity of future R&D for firms in the industry. We assume that patent protection is not strong and that knowledge generated by one firm spills over to others after a time delay. The productivity of research depends on the level of existing knowledge in the industry and a firm's R&D is thus made more effective by this spillover. This is a common feature of models of the product life-cycle and also of models of R&D-based growth. Indeed, the fact that R&D is more productive when existing technological knowledge is more advanced is a crucial feature for generating endogenous growth (see, for example, Barro and Sala-i-Martin (2004), Chapters 6 and 7). Finally, we assume that the intertemporal spillover only benefits firms that are already active in the market, not outsiders. This relates to Cohen and Levinthal's (1989) notion of *absorptive capacity*: only firms that spend money on R&D can benefit from spillovers. Because of this feature, firms that enter in the early stages build up a technological advantage over potential entrants over time, allowing profitable mergers to occur in later stages of the product life cycle.

The combination of these assumptions means that, although a government wants to allow mergers in order to promote economies of scale, it has to take into account the effect on entry in the early stages of the product life-cycle. Mergers create rents in the later stages which encourages early entry. As we will see, this in turn depresses early innovation and, as later research builds on initial discoveries, can limit technological innovation over the life-cycle as a whole. We show how, under certain conditions, a government that aims to promote R&D should choose to ban mergers. Similar results are derived for welfare.

2.3 The Model

The model is divided into two periods, representing the early and mature phases of an industry's life-cycle. In both periods firms invest in product improving R&D before engaging in Cournot competition. Subject to certain conditions that we outline below, all firms that enter in the first period receive an intertemporal spillover that boosts the productivity of R&D in the second period. This reflects the idea that existing knowledge is an input into research. The size of the spillover depends on the level of technological progress in the industry. We assume that patent protection is not strong and that firms do not retain a private stock of knowledge between periods. Outsiders, who do not join the industry in the first period do not have a sufficient absorptive capacity to receive the spillover. Much of our analysis will focus on large markets, which will be able to sustain high levels of R&D and which will also tend to be the focus of competition authorities' activities.

Firms can enter in both periods and are also free to merge in both periods. However, we assume that new firms can always enter in response to a merger. This means that mergers are never profitable in the first period as merged firms will have no cost advantage over entrants. A merger between two firms would simply induce another firm to enter. We can therefore eliminate the first period merger stage. We also show in the Appendix (section A.5) that, in large markets, entry is not profitable in the second stage because of the technological advantage of incumbents, regardless of how concentrated the market becomes. We therefore eliminate the second period entry stage as well. This means that all entry decisions in the model are made at the beginning of the first period. Upon entry, a firm has to choose whether to develop a product and compete for sales or whether to invest directly in an absorptive capacity, without developing a product.

Finally, we assume the government decides its merger policy before the game begins. The government sets an upper bound to market concentration in the second period and will only tolerate mergers as long as concentration is below this level. We abstract away from the merger process itself and simply assume that all permitted mergers will occur and that each merged coalition comprises an equal number of member firms. This outcome maximizes industry profits subject to the condition that each firm receives an equal share, and it is therefore not unreasonable to assume that firms will be able to coordinate on this outcome. We are implicitly assuming that firms have mechanisms to overcome issues such as the Insider's Dilemma, for example, it may be possible to make merger agreements conditional on other mergers occurring. As a result of these assumptions, the government's policy simply decides the degree of concentration in the second period.

Given the above, the stages of the model are as follows:

Period 1:

- Entry (and choice of whether to develop a product)
- R&D
- Cournot competition

Period 2 (following mergers):

- R&D
- Cournot competition

We now set out the nature of demand and innovation in the model before solving the model backwards to obtain a Subgame Perfect Nash Equilibrium.

2.3.1 Demand and R&D

Demand and innovation in the model are based on Tong (2005). There are S identical consumers with the following utility function:

$$U = \sum_{i=1}^{N}(u_i q_i) - \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N} q_i q_j + y \tag{2.1}$$

Where u_i is the quality of firm i's product, q_i is the quantity and y is a numeraire good. Consumers maximize their utility subject to a standard budget constraint, resulting in the following demand function:

$$p_i = u_i - \sum_{j=1}^{N} q_j \tag{2.2}$$

Where p_i is the price of firm i's product and N is the number of firms (time subscripts are suppressed). Firm i faces a constant marginal cost c_i and a product quality of u_i, which is determined in the preceding R&D stage. We solve the output stage now, as it is relevant to the nature of innovation in the model. Firms set q_i to maximize (gross) profits given the demand function, resulting in an equilibrium output for each firm of:

$$q_i = k_i - \frac{1}{N+1}\sum_{j=1}^{N} k_j, \tag{2.3}$$

where k_i is the technological "capability" of firm i and is equal to $u_i - c_i$. Thus, we can think of R&D as either raising product quality or decreasing production costs. Note that when a firm's capability is sufficiently low relative to its rivals, this expression is negative and we restrict its output to zero. This corresponds to the case where a firm's product is of such low quality that it cannot gain any market share at all.

In each period, firms invest in capability in the stage preceding output decisions. In the first period, a capability of k_i costs $F_{i1}(k_i) = k_i^{\beta}$, where $\beta > 2$ is the elasticity of R&D costs. In the second period R&D costs are:

$$F_{i2}(k_i) = \frac{k_i^{\beta}}{K^{\theta}}, \tag{2.4}$$

where K is the spillover from period one and is determined by the amount of technological progress in the industry in the first period. θ measures the impact of this early research on the productivity of second period R&D, and can be thought of as the extent to which future innovation builds on initial work. We make a number of assumptions about the intertemporal spillover in order to keep the model simple and tractable. First, K is set equal to the *median* technological capability of the firms in the first period. As we will focus on outcomes where firms all invest in identical capabilities, this assumption means that no firm needs to consider the effect of its first period R&D on the second period spillover. This simplifies the model while still capturing the idea that the spillover reflects the general level of technological progress in the industry.

Next, we assume that the spillover only benefits firms that acquire a sufficient *absorptive capacity* in the first period. Following Cohen and Levinthal (1989), absorptive capacity is a product of a firm's own investment in R&D. There are two ways of obtaining an absorptive capacity. Firstly, we assume that firms that enter in the first period, develop a product and compete for sales obtain the spillover as long as their R&D expenditure is sufficiently close to that of the firm with the median capability. This means that a firm cannot do a token amount of research, market a significantly inferior product and still obtain the spillover. The Appendix to this chapter sets out and discusses this assumption in more detail (see Appendix, section A.1). In it, we derive a value $g \in [0, 1]$ and impose the assumption that a firm that sells a product can only obtain the spillover if its R&D expenditure is more than g times the R&D expenditure of the firm with the median capability. The purpose of the assumption is to ensure that an equilibrium outcome where firms have symmetric capabilities always exists[2].

Secondly, we also assume that a firm can enter in the first period and gain the spillover by investing directly in an absorptive capacity, without developing and selling a product. Specifically, we assume that a firm can acquire the spillover by investing a proportion, h, of the R&D expenditure of the firm with the median technological capability. Firms that enter in this way are said to be *inactive* while firms that produce and sell a product are said to be *active*. Inactive firms are merely monitoring and learning from others and do not obtain a technological capability in the first period, only the spillover in the second. We further assume that firms that enter in this way are unable to deviate in the R&D stage and develop a product. As we will see, the purpose of this assumption is to help identify the equilibrium when merger policy induces a very large number of firms to enter in the first period. The assumption is, however, intuitively appealing. High-tech industries that experience large scale entry in their early stages, such as biotechnology and internet industries, often have many firms that do not produce a product but seek to obtain a technological capability to exploit in the future. Furthermore, we note that the assumption actually works against the general results of the model since, as we will see, it implies that entry beyond a certain point does not harm the innovation in the first period

[2] As shown in the Appendix, if the spillover only depends of firms making positive sales in the first period, a firm may have an incentive to make a global deviation to a low level of R&D when there are a lot of firms in the industry. As asymmetric outcomes are difficult to analyse in the model we wish to prevent this.

and therefore does not affect the spillover.

2.3.2 Equilibrium

The equilibrium choices of quantities in the product competition stage are given by equation (2.3). We now study firms' investment choices in the preceding R&D stage. Given the above functions (and suppressing time subscripts), net profits for an active firm i are given by:

$$\Pi_i(k_i; k_{-i}) = \frac{S}{(N+1)^2}\left(k_i + \sum_{j=1}^{N}(k_i - k_j)\right)^2 - F_i(k_i) \tag{2.5}$$

We denote by N_1 the number of firms in the first period. As there is free entry in the first period, this is determined by a zero profit condition. N_2, the number of merged coalitions in the second period, is chosen by the government before the game begins, subject to the obvious constraint that it can not exceed N_1.

In each period, prior to the product competition stage, firms set k_i so as to maximize profits. We focus on a solution that is symmetric in capabilities. Obtaining the first order conditions from equation (2.5) and imposing symmetry gives the following expression for equilibrium capability in period 1 (which is also the spillover parameter, K, in the second period):

$$k_1 = K = \left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{1}{\beta-2}}, \tag{2.6}$$

and similarly for period 2:

$$k_2 = K^{\frac{\theta}{(\beta-2)}}\left(\frac{2SN_2}{\beta(N_2+1)^2}\right)^{\frac{1}{(\beta-2)}}. \tag{2.7}$$

Capability in each period is decreasing in the number of firms. This is because, as the number of firms increases, market share falls and the R&D cost per unit of output rises. It is also clear that an increase in spillovers, K, will increase period two capability, all else being equal.

The second order conditions are discussed fully in the Appendix, section A.1. For now, we note the following lemma:

Lemma 2.1 *An equilibrium that is symmetric in capabilities exists only if the number of firms is less than* $\beta - 1$.

If the number of firms is larger than $\beta - 1$, second order conditions do not hold at the outcome with symmetric capabilities given by equations (2.6) and (2.7). Each firm has an incentive to make a deviation to a much higher level of capability. The implications of this are discussed more fully below. Appendix A.1 shows that as long as the number of firms is less than $\beta - 1$ then, given our assumptions regarding the spillover, equation (2.6) defines a global maximum.

We can substitute equations (2.6) and (2.7) into equation (2.5) and simplify to get the following expression for profit per firm in period 1:

$$\Pi_1 = \left(\frac{\beta}{2N_1} - 1\right)\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\beta}{\beta-2}}, \tag{2.8}$$

and profit per merged coalition in period 2:

$$\Pi_2 = \left(\frac{\beta}{2N_2} - 1\right)\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\theta\beta}{(\beta-2)^2}}\left(\frac{2SN_2}{\beta(N_2+1)^2}\right)^{\frac{\beta}{(\beta-2)}}. \tag{2.9}$$

2.3.3 Entry and merger policy

At the beginning of the first period firms choose whether to enter given the government's merger policy, N_2, and if so whether to develop and sell a product or invest directly in obtaining an absorptive capacity. We distinguish between a *symmetric outcome*, where all firms that enter in the first period are active in the product market, and an *asymmetric outcome*, where some firms are inactive in the first period and only invest in acquiring an absorptive capacity. Symmetric outcomes are relevant when first period entry is modest and firms make, at worst, relatively small losses. In this case, no firm would choose to invest directly in an absorptive capacity and forego sales revenue from the product market. When there is large scale entry in the first period, some firms will choose to invest directly in an absorptive capacity and we need to consider asymmetric outcomes.

A firm's net profits over the two periods is equal to its first period profit plus its share of a merged coalition's profits. As there is free entry in the model, this leads to a zero profit condition. In a symmetric outcome this is:

$$\Pi_1 + \left(\frac{N_2}{N_1}\right)\Pi_2 = 0 \tag{2.10}$$

Where Π_1 and Π_2 are given in (2.8) and (2.9). We treat both N_1 and N_2 as continuous variables in order to avoid integer effects. We first study symmetric outcomes and then look at the case with large scale entry, where we need to consider asymmetric outcomes. When there is a symmetric outcome we can substitute equations (2.8) and (2.9) into equation (2.10) and simplify to get:

$$\left(N_1 - \frac{\beta}{2}\right) = \left(\frac{\beta}{2} - N_2\right)\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\beta\theta}{(\beta-2)^2}}\left(\frac{N_2}{N_1}\right)^{\frac{\beta}{(\beta-2)}}\left(\frac{(N_1+1)}{(N_2+1)}\right)^{\frac{2\beta}{(\beta-2)}} \tag{2.11}$$

This implicitly defines first period entry, N_1, as a function of merger policy, N_2. There are two immediate implications. First, when mergers are banned, so that $N_1 = N_2$, the free entry outcome is for N_1 to equal $\frac{\beta}{2}$. Second, allowing mergers induces entry in the first period (when mergers are allowed so that N_2 is less than $\frac{\beta}{2}$, the right hand side is negative and N_1 must exceed $\frac{\beta}{2}$ for the left hand side to be negative). Using implicit function theory on equation (2.11) we can show that $\frac{dN_1}{dN_2}$ is:

$$\frac{dN_1}{dN_2} = \frac{\left(N_2\left(4\left(N_2-\beta\right)-\beta^2+4\right)+\beta^2\right)\left(\beta-2\right)\left(\frac{N_2}{N_1}\right)^{\frac{2}{(\beta-2)}}\left(\frac{(N_1+1)}{(N_2+1)}\right)^{\frac{3\beta-2}{(\beta-2)}}\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\beta\theta}{(\beta-2)^2}}}{8N_1\left(N_1+1\right)+\beta\left(2\beta-12N_1+2\beta N_1-\beta^2-4N_1^2+\beta^2 N_1\right)+\beta\theta\left(N_1-1\right)\left(2N_1-\beta\right)} \tag{2.12}$$

In the Appendix, section A.2, we prove the following lemma:

Lemma 2.2 *In any symmetric outcome,* $\frac{dN_1}{dN_2}$ *is negative.*

Greater concentration in the second period creates rents that are dissipated through first period entry. As firms enter in period one, not only does the loss suffered by each firm in the first period increase, but, as merged coalitions now consist of a larger number of firms, each firm gets a smaller share of post-merger profits in the second period.

This lemma suggests that there may be a value of N_2 below which the number of firms in the first period exceeds $\beta - 1$ and, by Lemma 2.1, an equilibrium in which active firms have symmetric capabilities does not exist[3]. Outcomes involving asymmetric levels of capability among active firms are not analytically tractable. However, with some restrictions on the value of h, these can be eliminated. Remember that firms can always obtain the spillover by investing a proportion, h, of active firms' R&D expenditure. This means losses in the first period are bounded from below by $-hk_1^{\beta}$. Once this point is reached, additional entry will not be by active firms that compete for sales but by firms that merely invest in order to learn from others and obtain the spillover. The maximum number of active firms in the first period, which we denote by $\overline{N}_1$, is determined by the condition that losses per active firm equals $-hk_1^{\beta}$. Using equations (2.6) and (2.8) this is:

$$\overline{N}_1 = \frac{\beta}{2\left(1-h\right)} \tag{2.13}$$

Total entry, N_1, is determined by the zero profit condition. Once the number of firms in the first period reaches $\overline{N}_1$ additional entry will only be by inactive firms and will have no effect on first period innovation or first period profits. As second period concentration increases further, the zero profit condition holds solely through the increasing size of each

[3]In fact, numerical work shows that, as N_2 falls, N_1 very quickly exceeds $\beta - 1$. It is likely that in all cases, allowing a monopoly in the second period will induce more than $\beta - 1$ firms to enter in the first period.

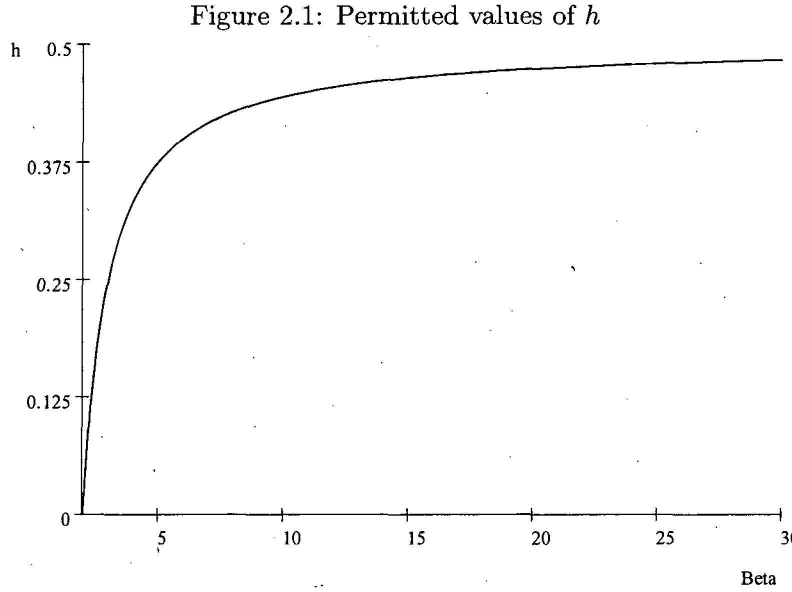
merged coalition, which reduces the share of the profits received by each member. It is clear that $\frac{dN_1}{dN_2}$ remains negative.

It is easy to see that $\overline{N}_1$ is increasing in h. For large values of h it is very costly to invest directly in an absorptive capacity and it is only once large scale entry makes product market competition very intense in the first period that firms will choose to do this. Because of Lemma 2.1, we need to place restrictions on h so that $\overline{N}_1$ is less than $\beta - 1$. Using equation (2.13), the condition for this is:

$$h < \frac{1}{2}\frac{\beta - 2}{(\beta - 1)} \tag{2.14}$$

The right hand side is given by:

Figure 2.1: Permitted values of h



h must lie beneath this line. This is not a particularly restrictive requirement and simply rules out cases where a firm must invest a significant amount of R&D in order to learn from other firms. We combine all these results with Lemma 2.2 to get the following:

Proposition 2.1 *i) In any equilibrium, $\frac{dN_1}{dN_2}$ is negative. ii) The upper limit for the number of active firms in the first period is $\frac{\beta}{2(1-h)}$ (where $h < \frac{1}{2}\frac{\beta-2}{(\beta-1)}$). If N_1 exceeds this, the additional firms merely invest in developing an absorptive capacity and do not compete in the product market.*

We now look at optimal policy of a government that seeks to encourage innovation through its merger policy.

2.3.4 Merger policy and innovation

In this section we assume that the government is interested in maximizing overall innovation by the end of the industry's life (i.e. maximizing k_2). Because of economies of scale in R&D, if there were no linkages between innovation in the first and second periods a government would want to allow mergers. However, the presence of intertemporal spillovers and the effect of merger policy on first period entry means that it is not as straightforward as this.

First of all we consider merger policy when there is a symmetric solution in both periods. This corresponds to a small relaxation in merger policy starting from a complete ban. We then discuss policy that permits highly concentrated markets in the second period and which induces an asymmetric outcome in the first period.

In a symmetric solution, the change in k_2 from a change in merger policy is:

$$\frac{dk_2}{dN_2} = \underbrace{\frac{\partial k_2}{\partial N_2}}_{\text{direct effect}} + \underbrace{\frac{\partial k_2}{\partial N_1}\frac{dN_1}{dN_2}}_{\text{indirect effect}} \tag{2.15}$$

The direct effect is negative, while the indirect effect is positive (see the Appendix, section A.3, for the exact derivatives). This means that a government faces a trade-off. It wants to allow mergers in order to promote R&D effort in the second period but does not want to induce too much entry in the first period which will harm early innovation and therefore the productivity of later research. In general the relevant condition for a tightening of merger policy to be beneficial is quite complex, especially as we do not have an explicit solution for N_1 as a function of N_2. However, in the Appendix we prove the following result:

Proposition 2.2 *When S is sufficiently large and a government seeks to maximize innovation, a ban on mergers is preferred to any other policy that yields a symmetric outcome in the first period.*

When S is large, not only is first period innovation quite sensitive to the number of firms in period one, but a given change in merger policy also induces a large increase in first period entry. This means that the direct effect dominates the benefits of increased concentration in period 2. It should be noted that this result is conditional on there being a symmetric outcome in the first stage. For large S, however, decreases in N_2 very quickly induce more than $\overline{N}_1$ firms to enter in the first period and we have an asymmetric outcome. We now turn to this case.

The first thing to note is that, once we have an asymmetric outcome in the first period then further increases in second period concentration have no impact on first period innovation. The extra firms that are induced to enter are not active in the product market and do not put downward pressure on levels of innovation. The government would therefore choose to allow a monopoly in the second period rather that any other market structure that induces an asymmetric outcome. We now compare this policy stance to a complete ban on mergers, that is compare having $N_2 = 1$ with $\overline{N}_1$ active firms in the first period to $N_1 = N_2 = \frac{\beta}{2}$. Using equations (2.6), (2.7), and equation (2.13) the condition for a ban to be preferred is:

$$\left(\frac{(\beta - 2h + 2)^2}{(\beta + 2)^2 (1 - h)}\right)^{\frac{\theta}{(\beta-2)^2}} > \left(\frac{(\beta + 2)^2}{8\beta}\right)^{\frac{1}{\beta-2}} \tag{2.16}$$

The left hand side is the benefit from increased concentration in the first period, while the right hand side is the benefit from increased second period concentration. The expression within the brackets on the left hand side is greater than 1 and is increasing in h (a higher h implies more active firms in the asymmetric outcome). Thus, the condition implies a critical value for θ, given β and h. Rearranging, we get:

$$\theta > \frac{(\beta - 2)\ln\left(\frac{(\beta+2)^2}{8\beta}\right)}{\ln\left(\frac{(\beta-2h+2)^2}{(\beta+2)^2(1-h)}\right)} \tag{2.17}$$

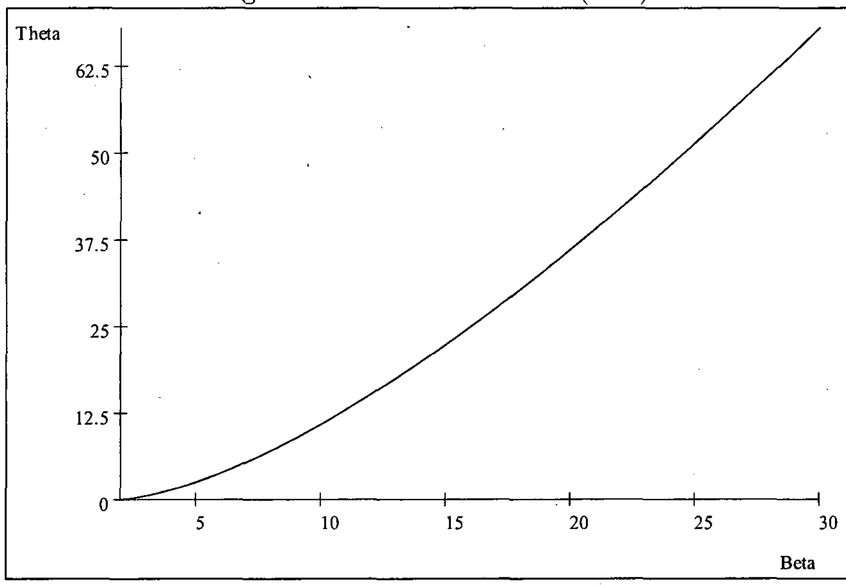
θ represents the extent to which existing knowledge boosts the productivity of future R&D. If this is high enough it becomes relatively more important to protect first period innovation and a government will be reluctant to relax merger restrictions. Essentially, this corresponds to an industry where early pathbreaking discoveries have a large role in shaping future research. The higher h is, the more firms are active in the asymmetric outcome and the lower first period innovation is. The critical threshold for θ is correspondingly lower. The highest value of h that we permit is defined by inequality (2.14). We can set this to an equality and substitute into (2.17) to get the following necessary condition for θ :

$$\theta > \frac{(\beta - 2)\ln\left(\frac{(\beta+2)^2}{8\beta}\right)}{\ln\left(\frac{2\beta^3}{(\beta+2)^2(\beta-1)}\right)} \tag{2.18}$$

which we plot below in Figure 2.2.

For values below the line, there is no permitted value of h for which condition (2.16) holds. Thus a necessary condition is that β and θ lie above this line. Above the line, condition (2.16) can hold for any combination of θ and β by choosing an appropriate value for h (and therefore $\overline{N}_1$). As h approaches 0, θ needs to approach infinity. In this case the number of active firms in the first period is only slightly above that when mergers are banned. Consequently, first period innovation is not much lower and the spillover parameter, θ, needs to be very high for a ban to be preferred. If we consider higher values

Figure 2.2: Plot of condition (2.18)



of h (and correspondingly higher values for $\overline{N}_1$), θ does not need to be especially high for a ban on mergers to be preferred, particularly for high-tech industries, which will have a low β. (Note, however, that high values of h and $\overline{N}_1$ require correspondingly higher values of g, which is not particularly appealing - see Appendix, section A.1.)

We can combine these results with our results for symmetric outcomes to get the following:

Proposition 2.3 *i) When condition (2.16) holds, a ban on mergers is preferred to any policy that induces an asymmetric outcome in the first period. ii) When condition (2.16) holds and S is sufficiently large, a ban on mergers is a global optimum.*

Although it is possible that, in small markets, the optimum may be to allow *some* mergers even though condition (2.16) holds, we are focusing on large markets because these have the most potential for innovation and will be the main focus of anti-trust activity (and also because in these cases we know for certain that entry is blocked in the second period - see the Appendix, section A.5). Given this, our results say that when first period innovation is important enough for subsequent R&D, a ban on mergers is the best way of fostering innovation. This result can be thought of as a rent-seeking story. A relaxed merger policy creates rents which induce firms to enter in the first period. These firms are solely seeking to gain a share of second period rents and, by entering, damage early innovation with corresponding knock-on effects for second period research.

Because we do not have an explicit solution for N_1 as a function of N_2 it is not easy to determine the exact threshold level of S in proposition (2.3). However, we can obtain an expression for the threshold value at the point where mergers are banned (and

$N_1 = N_2 = \frac{\beta}{2}$). We denote this threshold value by $\widetilde{S}$ and show in the Appendix, section A.3, that it is given by:

$$\widetilde{S} = \left(\frac{1}{2}\beta + 1\right)^2 \left(\frac{1}{\theta}(\beta - 2)\right)^{\frac{(\beta-2)^2}{\theta\beta}} \tag{2.19}$$

This implies that, for reasonable values of β and θ, consistent with a high-tech industry, only modest levels of S are required. For example when β equals 6 and θ equals 4, $\widetilde{S}$ is only 16.

We now turn to the case where the government focuses on total welfare.

2.3.5 Merger policy and welfare

Because of the zero profit condition, net welfare in the model only comprises consumer surplus. All gross profits are dissipated by the sunk costs of R&D. Using our utility function (equation (2.1)) and the budget constraint, and imposing symmetry between active firms (and suppressing time subscripts), consumer surplus in any period is:

$$CS = \frac{S}{2}\left(\frac{N}{N+1}\right)^2 k$$

Using equation (2.6) in period 1 this is:

$$CS_1 = \frac{S}{2}\left(\frac{N_1}{N_1+1}\right)^2 \left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{1}{\beta-2}}$$

Where, in an asymmetric solution, N_1 should be replaced by $\overline{N}_1$.

Using equation (2.7) consumer surplus in period 2 is:

$$CS_2 = \frac{S}{2}\left(\frac{N_2}{N_2+1}\right)^2 \left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\theta}{(\beta-2)^2}} \left(\frac{2SN_2}{\beta(N_2+1)^2}\right)^{\frac{1}{(\beta-2)}}$$

In any period, consumer surplus is increasing in the number of firms. Although innovation decreases, the more intense competition means that consumers are better off. Increases in N_1 do, however, have a negative impact on second period consumer surplus via the spillover. An immediate implication is that when there is an asymmetric solution in the first period, so that changes in N_2 do not affect either first period consumer surplus or the spillover, the government will always want to restrict mergers further:

Lemma 2.3 *Conditional on there being an asymmetric outcome in the first period, any increase in N_2 increases total welfare.*

In a symmetric solution, the condition for an increase in N_2 to increase aggregate consumer surplus (that is, the sum of surplus in each period) is:

$$\frac{dTCS}{dN_2} = \frac{\partial CS_2}{\partial N_2} + \left(\frac{dCS_1}{dN_1} + \frac{\partial CS_2}{\partial N_1}\right)\frac{dN_1}{dN_2} \tag{2.20}$$

This is positive if $\left(\frac{dCS_1}{dN_1} + \frac{\partial CS_2}{\partial N_1}\right)$ is negative. This requires that the effect of reduced first period entry on second period consumer surplus (via the spillover) should outweigh the reduced competition in the first period. In the Appendix, section A.4, we prove the following result:

Proposition 2.4 *When S is sufficiently large and a government seeks to maximize total welfare, a ban on mergers is a global optimum. The critical value of S is decreasing in θ, and goes to infinity as θ goes to zero.*

As with the innovation case, we can obtain an explicit solution for the critical value of S starting from a position of a complete ban on mergers. We denote this value by $\overline{S}$ and show in the Appendix, section A.4, that it is given by:

$$\overline{S} = \left(\frac{1}{2}\beta + 1\right)^2 \left(\frac{3}{\theta}(\beta - 2)\right)^{\frac{(\beta-2)^2}{\theta\beta}} \tag{2.21}$$

This is clearly larger than $\widetilde{S}$, though still not big in absolute terms for reasonable values of β and θ. From this we get the result that if a marginal relaxation in mergers harms welfare then it also harms innovation.

2.4 Discussion and Conclusions

Our model uses a detailed account of innovation to show how merger policy can affect market structure and technological progress. The two key features of technology in the model are that early innovation boosts the productivity of later R&D and that this only benefits those who have entered the industry and have attained a sufficient absorptive capacity. Mergers are only possible in the latter stages of an industry's life cycle, once incumbents have a technological lead over potential entrants. This means that a relaxed merger policy creates the expectation of future rents which encourages early entry. This in turn reduces early innovation and, by reducing the productivity of later innovation, can reduce overall technological progress. Similar results apply for net welfare. This can be thought of as an example of the familiar story that regulation and government policy can create rents which encourage wasteful rent-seeking behaviour. Excessive entry in the first period can be regarded as a form of rent seeking as entrants are merely trying to gain a share of later rents. Our analysis focuses on large markets as these will be associated with larger levels of R&D and will be the focus of anti-trust analysis. However, even in small markets we get the result that, as long as first period innovation is sufficiently important, a ban on mergers is preferred to a complete relaxation.

Policy makers and competition authorities have become much more focused on innovation in recent years, as opposed to the more traditional focus on the price effects of mergers. In 1995 the Department of Justice and Federal Trade Commission published their joint *Antitrust Guidelines for the Licensing of Intellectual Property,* setting out the concept of an "innovation market". This refers to a situation where firms are not competing in a product market but are engaged in a competition to develop new products for the future. Since then, the concept has been used in a number of merger investigations, particularly in the pharmaceutical sector. For example the Ciba-Geigy and Sandoz merger in 1996, the FTC was concerned about research into gene therapy, for which no actual products existed (see Morgan (2001) for a discussion of this and other cases). Gilbert (2007) shows how the proportion of merger investigations in which innovation played a major role rose from only 3% in 1990-1994 to 38% in 2000-2003. The EU has to some extent lagged behind the US in this matter. However, the UK has seen a deliberate strengthening of competition policy with the explicit aim of fostering innovation[4]. In 2004, for example, the test for mergers changed from a general "public interest" test to an assessment of whether there is a "substantial lessening of competition". Our model provides support for the shift in focus to the effects of mergers on innovation. Unlike analysis utilizing the concept of an innovation market, however, it shows that restricting mergers in *product* markets as well as innovation markets can foster innovation.

Our results add to the growing literature suggesting that competition is good for innovation and productivity growth (for a discussion see Aghion and Griffith (2005)). Unlike much of this literature, our model has the benefit of suggesting specific policy recommendations rather than making the vague suggestion that policy should encourage competition. As our model demonstrates, specific competition policies have idiosyncratic effects which need to be taken into account. In this case, a competition authority needs to consider the effect that allowing mergers has on early entry into a market.

The model also adds to the literature on mergers and entry by showing the importance of setting out explicitly the source of asymmetries between merging firms and potential entrants. In our model we do this by looking at entry and mergers over the product life-cycle. The model argues that mergers may only be possible in the later stages of an industry, once incumbents have built up an advantage over outsiders, and this leads

[4]The Treasury's strategy for boosting innovation is outlined in the Pre-Budget report 2000, see http://www.archive.official-documents.co.uk/document/hmt/pbr2000/chap03.htm

to particular implications for policy. The issue of the timing of mergers and entry is one that is beginning to be explored by economists. Mason and Weeds (2003) show how a competition authority can encourage entry by committing to allow mergers following negative demand shocks. By allowing entrepreneurs an exit route in hard times, they can be encouraged to enter the market with corresponding benefits for consumers. However, the authors do not consider innovation or market structures other than an incumbent and a single entrant. In Gowrisankaran (1999), entry decisions take into account the possibility of future mergers, however, he does not consider the role of technology and innovation. He also assumes (random) synergies from mergers, which as we argued above is not supported by empirical studies. Our approach puts entry and merger decisions into the context of a product life cycle, which emphasizes the role of the evolution of technology. Product life cycles have been studied in many industries including automobiles, televisions, tires and penicillin (Klepper and Simons (2005)). Klepper (1997) reviews the literature and concludes that the concept has validity in many cases. The literature generally finds a "shakeout" phenomenon where initial large scale entry gives way to a more concentrated market structure. Although it is not the purpose of our model to explain this phenomenon, our results do suggest that mergers can generate a similar effect and that future empirical work in this area should therefore distinguish between exit and mergers.

Our results depend on a number of crucial features which we now discuss. First, there is a complete spillover of knowledge in the sense that firms do not retain a private technological capability into the second period. This, along with the fact that spillovers do not depend on the capability of the frontier firm, means that first period investment decisions depend only on the first period market structure. Thus, first period entry unambiguously discourages early innovation. This may be different if firms retain a private technological capability. A firm that begins the second period with a higher capability would have a competitive advantage over rivals and would be able to bargain for a higher share of post-merger rents. Thus a more relaxed merger policy in the second period may even *increase* R&D in the first period rather than encourage entry, as firms escalate their spending in order to capture more of the rents in the second period. Another point is that R&D in the model is purely imitative so that spillovers do not depend on *aggregate* spending. If firms make discoveries that are to some extent complementary, the spillover may increase with entry even if spending per firm decreases.

A second important aspect of our model is that early R&D is important for future research in the industry. Although R&D in the model is formally identical in both periods, early R&D can be thought of as fundamental research which subsequent R&D merely develops and builds on. If early discoveries are limited, future R&D may be handicapped.

An alternative would be to see an industry as having a fixed potential for discovery over its lifetime, in which case later research could easily make up for any early deficiencies. The issue here is the importance of innovation within an industry versus the emergence of new industries/products based on new ideas. Certainly, there are many instances where important innovations have been associated with the emergence of new industries, for example the growth of IT based industries. In this case innovation within an industry may be less important and policy makers should instead focus on making it easier for new industries to emerge. However, many industries, such as motor vehicles, exhibit steady innovation over the long run. There is no reason to think that the innovative potential within these industries is fixed and therefore early innovation can have important implications for later research.

We also assume that the industry's life ends in a deterministic manner. This is to keep the model to two periods for reasons of simplicity, and it would be unlikely to make much difference to the qualitative results to have multiple periods and a stochastic end date. Mergers would still encourage early entry and this would reduce the productivity of later R&D. One important feature of our model, however, is that the end date is not affected by the actions of the incumbents. Firms' innovative efforts in the model takes the form of developing an existing product, not the creation of new industries. This can be justified by an Arrow "replacement-effect" argument; incumbents are earning rents in the second period and will not have a strong incentive to end the industry's life.

Finally, we assume that there is free entry in the first period. In reality there may be a number of factors that block entry in the early stages. It may be hard to obtain financing for a start up in a new industry and if this limits the extent to which first period entry responds to changes in merger policy it will affect the results of our model. It may also be the case that, initially, only a few entrepreneurs are aware of the potential opportunities in a new industry and have already built up a capability advantage over entrants before the latter become aware of the new industry.

Chapter 3

Technology choice and anti-competitive technology sharing agreements

Abstract

We demonstrate, in a model with deterministic process innovation and Cournot competition, how a duopoly can use an information sharing agreement to ensure that firms adopt different technologies prior to conducting research, thereby reducing product substitutability and softening competition. The model also shows how, once technology choice is taken into account, spillovers can be harmful even when R&D and output decisions are made simultaneously. Thus, unlike the rest of the literature, the result does not depend on the existence of the strategic motive to (over-)invest. Policy implications are discussed.

3.1 Introduction

Ever since the seminal paper by d'Aspremont and Jacquemin (1988) there has been an explosion in the literature on the effects of R&D cooperation among firms that compete in a product market. The literature has tended to focus on full R&D cooperation, often labelled Research Joint Ventures, where firms coordinate R&D budgets and maybe even set up a joint research lab. Because of the degree of cooperation involved, this clearly has potential for anti-competitive effects and the terms of such agreements are likely to be subject to close scrutiny by competition authorities. Less attention has been given to agreements or arrangements that merely affect spillovers, without fixing R&D budgets or coordinating research. Such agreements are likely to fall under competition authorities' radars as they would appear quite innocuous on the surface and may be very low key. Firms need not sign formal agreements but could, for example, organize a trade body to disseminate information, organize various conferences or develop a scheme of secondments of research staff to each other's facilities.

There is evidence that technology sharing between firms is widespread. Systematic data does not seem to be available, but there is considerable anecdotal evidence[1]. Baumol (2001) cites a number of interesting cases, including Pekins-Elmer Corporation's technology sharing agreements with various rivals, including Hitachi Corporation, and IBM's technology exchange agreements with all its major competitors. Interestingly, the Perkins-Elmer agreement provided for a *complete* sharing of technical information with rivals. Baumol also cites a study of US steel mills by Von Hippel (1988), which found that firms shared large amounts of technical information and frequently exchanged personnel, even training each others' employees. More recently, the Financial Times published an article announcing the formation of the Global Leadership and Technology Exchange, which brings together a variety of firms to share maritime engineering technology, including General Electric, Wilh Wilhelmsen and IBM[2]. The article recounts how executives from Wilh Wilhelmsen formed an agreement with General Electric to exchange engine technology. Other examples include the I3C consortium, whose members include GlaxoSmithKline and Pfizer, which aims to facilitate the spread of biotechnology research emanating from the Human Genome Project, and agreements between Boeing and several European defence companies to share missile technology[3].

In addition to its focus on Research Joint Ventures, the literature has also focused

[1] The MERIT-CATI database maintained by John Hagedoorn and colleagues contains data on a variety of cooperative R&D agreements. To our knowledge, information from this database specifically on information sharing agreements has not been published.

[2] See *Industry needs to collaborate in order to innovate*, Financial Times, 28th August, 2006

[3] See *International economy: Biotech alliance focuses on data sharing*, Financial Times, June 26, 2001, and *Defence deal to encourage collaboration,* Financial Times, July 24, 2002.

on the effects of cooperation on R&D expenditure decisions. Less attention has been paid to the effects on the choice of technology or "R&D approach", and where this is considered it only affects spillovers and not the degree of competition. In reality, firms' choices of technology are a crucial determinant of the nature of competition in the industry, affecting both the efficiency of R&D and product characteristics. The latter will affect the substitutability between firms' products and therefore the intensity of competition. When firms choose to develop more similar technologies it is likely that their products will have similar characteristics. For example, in the motor vehicle industry, electric vehicles (a very small niche in the market) do not compete directly against petrol driven cars, whereas vehicles employing hybrid technology, such as Toyota's Prius, do. Technology choice, therefore, is at least as important as the size of R&D budgets. While some firms do invest in exploratory research, without committing themselves to a particular technology or R&D approach, in general a firm that wishes to develop a product has to choose a technology up-front. For example, a firm that wishes to develop data storage devices for PCs has to decide whether to base their research on flash memory, hard drives or optical drives. These all have different properties and the one a firm chooses will determine which firms it competes against.

We investigate a scenario where, because of the superiority of a particular technology that we call the "core" technology, firms may be drawn into producing products that are close substitutes. We demonstrate how firms can use an information sharing agreement to coordinate their choices away from this core technology towards separate (inferior) technologies, so as to reduce product substitution and increase profits. This agreement is likely to harm consumers and decrease aggregate innovation, and net welfare may also decrease. Our paper differs from the existing literature in that we allow technology choice to affect fundamental product characteristics and the efficiency of R&D, not just the degree of spillovers. We also focus on information sharing agreements rather than full R&D cooperation. Finally, our results are obtained in a model with simultaneous R&D and output decisions. Consequently, unlike the existing literature, our results show that when technology choice is taken into account spillovers can harm R&D and innovation even when there are no strategic effects from R&D investment.

3.2 Existing literature

In a classic early paper, d'Aspremont and Jaquemine (1988) investigate the effects of two firms coordinating R&D budgets in a two-stage model where R&D precedes product market competition. Competition in the model takes a Cournot form and R&D reduces marginal costs of production. They find that such cooperation only increases cost reduction if spillovers are sufficiently strong. When spillovers are high, the incentive to invest is low because research confers large benefits on rival firms, reducing the cost advantage to the researching firm. Cooperation allows firms to take this into account and collectively increase R&D. However, when spillovers are low, the strategic nature of R&D (i.e. the fact that it precedes product market competition) means that, in the absence of cooperation, firms are over-investing in a futile effort to win market share from each other. Cooperation therefore allows firms to reduce expenditure and increase profits.

There is a huge literature essentially building on and extending these findings, for example by extending the results to Bertrand competition and an arbitrary number of firms. The early literature is surveyed by DeBondt (1996). Recent contributions include Amir, Estigneev and Wooders (2003) who consider very general functions and Amir (2000), who criticizes the representation of spillovers in d'Aspremont and Jaquemine's paper. Atallah (2003) considers the stability of R&D coalitions and Amir and Wooders (2000) consider one-way spillovers, that is spillovers that only flow from a lead firm to a technologically inferior one. The general conclusion of the literature is that R&D cooperation is beneficial when spillovers are sufficiently high, but harmful if spillovers are low.

An area of this literature of particular relevance to our paper investigates how firms' actions affect the degree of R&D spillovers. The early literature simply assumed that the degree of spillovers between firms is exogenous. More recent work endogenizes the spillover parameter so that it is a function of firms' individual actions. These actions include firms' investments in "absorptive capacity", that is, their ability to receive and exploit knowledge generated by rival firms, voluntary information sharing and firms' choices of technology or "R&D approach". Kamien and Zang (2000) investigate technology choice and absorptive capacity. Firms can choose to conduct either general research that is useful to rivals and thus transmits spillovers or more specific research that can not be used by rivals. They find that, without R&D cooperation, each firm conducts specific research in order to minimize spillovers. Cooperation is therefore particularly beneficial because it leads to a high level of information sharing. Similar models are developed by Poyago-Theotoky (1999) and Katzsoulacos and Ulph (1998). In general, these models show that cooperation in R&D results in full or high spillovers and increased cost-reduction.

Gil Molto, Georgantzis and Ortz (2005) consider a model where spillovers depend on how closely related the technologies chosen by the firms are. Unlike Kamien and Zang, a firm can not unilaterally retreat from transmitting spillovers without reducing the amount it receives. They find that non-cooperating firms may still move close to each other and generate high spillovers in a deliberate attempt to reduce the over-investment resulting from the strategic effect. Consequently, in equilibrium, spillovers are too high from the point of view of social welfare and consumer surplus. As the authors note, the process of technology choice in their model is equivalent to firms directly bargaining over the level of spillovers, since in equilibrium neither wants the level of spillovers to increase or decrease. As a result, they argue that government policy should be cautious of technology sharing agreements that do not entail the coordination of R&D expenditure.

In these models, the choice of technology has no bearing on anything other than spillovers. In particular, it does not influence the effectiveness of research or the substitutability between end products. Any harmful effects of R&D cooperation come from the reduction in the strategic motive to invest, which is a result of the sequential nature of the investment and output decisions in the model. Leahy and Neary (1997) show that when output/prices and R&D expenditure are chosen simultaneously cooperation in the setting of R&D budgets increases cost reduction whenever there are spillovers. Also, any increase in spillovers increases innovation.

In this paper, we argue that the choice of technology affects not only the degree of spillovers but also the effectiveness of R&D spending and the substitutability between products. When firms in an industry follow an identical technology, product substitutability is likely to be high and competition intense. In some cases this could lead to "commoditization", where goods are essentially homogeneous. In our model there is a single "core" technology which represents the most effective line of research. Both firms are naturally drawn to this technology because of its effectiveness but then suffer intense competition because their products become close substitutes. The firms essentially face a Prisoner's Dilemma; although they would prefer that both avoided the core technology each has an incentive to make a unilateral deviation to it. Firms clearly have an incentive to avoid this and in this chapter we investigate how an information agreement can be used to this effect.

Firms could avoid intense product market competition by explicitly agreeing to coordinate technologies. The anti-competitive potential of such an agreement is clear, however, and it would be highly likely to attract the attention of competition authorities. A simple agreement to share technical information, on the other hand, would be far less likely to arouse suspicion. We develop a simple model that demonstrates how firms can use an information sharing agreement to coordinate their choices of technology so as to limit product substitutability. An information sharing agreement can shift firms' technology choices from the core to "peripheral" ones that, while inferior, produce differentiated products and reduce the intensity of product market competition. The key elements are that technology choice affects both technological compatibility and demand substitution and that core research has applications to peripheral technologies. This means that, with an information sharing agreement, a firm adopting the peripheral technology can free-ride off the research effort of the core firm and remain competitive. This can eliminate the incentive to adopt the core technology. The model shows how, once the impact of technology choice is taken into account, spillovers can have detrimental impacts on R&D even when R&D and output are chosen simultaneously.

Before moving on to our model, we note that there is a strand of the literature that considers the impact of spillovers on firms' (physical) locations. Spillovers are assumed to be higher when firms are located close to each other. Although the authors' main focus is on industrial clustering, these models can be interpreted as models of product differentiation or technology choice. Piga and Poyago-Theotoky (2005) find that the existence of spillovers can outweigh the normal maximal differentiation result found in a Hotelling model with quadratic transport costs. However, they do not consider R&D cooperation. Van Long and Soubeyran (1998) look at location on a plane rather than a line and simply assume that a closer location reduces costs (there is no explicit R&D stage). Their results are varied and depend on whether spillovers are convex or concave in distance. Mai and Peng (1999) also develop a model without an explicit R&D stage where proximity reduces fixed costs. They find that whether firms locate close to each other depends on the ratio of spillovers to transport costs. As with our model, these papers highlight the impact that spillovers have on technology/location choice. However, none of these models consider how firms can agree on spillovers in order to coordinate their choice of technologies/spatial locations.

3.3 The Model

We develop a simple model to show how firms can use information sharing agreements to coordinate their choices of technology, thereby avoiding the intense competition that results when both have the same technology. The basic framework is the same as that found in d'Aspremont and Jacquemin (1988) and the wider literature, that is, deterministic cost-reducing R&D and Cournot competition. To this, we add a stage where firms choose their technologies and a stage where they decide whether to share the output of their research. Two firms play the following 3 stage game:

- Stage 1: firms agree whether to share the results of their research
- Stage 2: firms choose technologies
- Stage 3: firms simultaneously set R&D and output

The information sharing agreement is represented by $\alpha \in \{0, 1\}$, with $\alpha = 0$ when there is no agreement and $\alpha = 1$ when an agreement is made. In stage 1, firms simultaneously propose whether or not to form an agreement, and one is only signed if both propose that it is. Although we call this a technology sharing agreement, it could in reality reflect any mechanism jointly established by the firms which has the same effect. We assume that the agreement is completely enforceable, either via the courts or the instant detection of a refusal to follow its terms. Firms can only agree to share information, as we assume that a competition authority would ban any attempt to make direct agreements to coordinate technology choice. We also assume that firms can only agree to share *all* of their research output, or, where this can be identified in advance, all of the research that is relevant to the other firm's technology. It is not feasible to monitor and enforce (or even comply with) an agreement to share only a proportion of research output. We show in the Appendix that, when firms can agree to share a proportion of their research output, they will indeed choose to share all of their research in the central scenario that we are interested in.

If an information sharing agreement is signed, the strength of spillovers depends on the compatibility between the firms' technologies. Spillovers in our model take the form used by Kamien, Muller and Zang, where they are represented by bonus R&D *inputs* rather than outputs. In other words, spillovers are equivalent to bonus R&D expenditure in an individual firm's R&D production function. This approach is advocated by Amir (2000) for several reasons. In particular, spillovers in outcomes (as used in much of the literature including the seminal paper by d'Aspremont & Jaquemin) are highly complementary so that knowledge gained from a rival firm always adds to a firm's own discoveries. This has the counter-intuitive effect that cost reduction can increase with spillovers even if individual R&D spending decreases. Amir argues that the form used by Kamien, Muller and Zang is more realistic for the majority of industries.

In the second stage, firms choose which technologies to adopt. Technology choice affects both the productivity of R&D and product characteristics. Certain pairs of technologies are "closer" than others, that is, they are technologically more compatible and produce products that consumers regard as closer substitutes. In our model there is a single "core" technology that is superior to all others. We label the other technologies "peripheral" and assume that they all have identical properties. Thus, a firm chooses between either the core technology or a peripheral one. It is a trivial result that if both firms choose a peripheral technology, they will choose separate ones. We denote firm i's choice of technology by $\gamma_i \in \{C, P\}$, where C is the core technology and P is a peripheral one. Throughout, we refer to a firm that chooses a peripheral technology as a *peripheral firm* and a firm with the core technology as a *core firm*. We assume that any peripheral technology is "closer" to the core than any other peripheral one. An obvious interpretation is that the core technology is a hybrid of the peripheral ones.

In the third stage, R&D and output are set simultaneously. Because of this there is no strategic motive for investment; a firm sets R&D taking output as fixed and thus does not consider the effect on its market share. This feature focuses the model on technology choice, rather than the strategic effects of R&D.

The functional forms used in the third stage are as follows. The demand function is:

$$P_i = A - q_i - d\left(\gamma_i, \gamma_j\right) q_j, \tag{3.1}$$

where P_i is the price of firm i's product, q_i is firm i's own output and q_j is its rival's output. $d\left(\gamma_i, \gamma_j\right)$ determines the substitutability between the two products and is a function of technology choices. For simplicity, we assume that peripheral technologies are independent submarkets with respect to each other so that when both firms adopt peripheral technologies, $d = 0$. In the Appendix, section B.5, we show that our key result still holds when we relax this assumption and have competing peripheral technologies. When both firms adopt the core technology, products are homogeneous and $d = 1$, and when firms choose different technologies $d = \widehat{d}$ with $\widehat{d} \in [0, 1]$.

Marginal costs are B minus the firm's technological capability, s_i:

$$c_i = B - s_i = B - \sqrt{\left(D_i z_i + \alpha t\left(\gamma_i, \gamma_j\right) D_j z_j\right)} \tag{3.2}$$

Where z_i is firm i's R&D expenditure and D_i represents the efficiency of firm i's research. This depends on the choice of technology: when the firm adopts a peripheral technology $D_i = 1$ and when it has the core technology $D_i = D_c > 1$. Spillovers are equal to $\alpha t\left(\gamma_i, \gamma_j\right)$ where $\alpha \in \{0, 1\}$ is determined by whether an information sharing agreement is made in the first stage and $t\left(\gamma_i, \gamma_j\right)$ is a function representing the "closeness" or compatibility between the firms' technologies. When both firms adopt the core technology, $t = 1$, and when only one firm has the core technology, $t = \widehat{t}$. We assume that peripheral technologies are unrelated so that when both firms adopt peripheral technologies t is set to zero. As with product substitutability, we relax this assumption in the Appendix (section B.5). Finally, for simplicity, we set $\widehat{t} = \widehat{d}$, so that when peripheral technologies are technologically close to the core technology, they are also close product substitutes. This is a natural assumption to make. These assumptions mean that the two parameters $\widehat{d}$ and D_c entirely describe the nature of technology in the model.

We solve the model in the usual way, using backward induction to establish a Subgame Perfect Nash Equilibrium. First we solve for R&D and output decisions, including an important case where firms have different technologies and the non-negativity constraint on R&D binds for the firm with the peripheral technology. In this case the peripheral firm simply abandons its research and free-rides off the efforts of its core rival. Then we look at technology choices in the second stage, first for the case where an information sharing agreement is not signed in the first stage, and then when it is.

Given these outcomes, we then determine the circumstances under which firms will form an agreement in the first stage. Our main focus is on those cases where, in the absence of an agreement, both firms choose the core technology and where an agreement can induce both firms to adopt a peripheral technology instead. We show that this occurs whenever the core technology is sufficiently superior, and sufficiently "close", to peripheral technologies. Finally, we look at the optimal policy of a competition authority that seeks to promote either total welfare, consumer welfare or innovation.

Before proceeding, we introduce some notation and a couple of additional assumptions that will be used in our analysis. We denote a firm's strategy for the first two stages by $(x, (y, z))$, where $x \in \{Y, N\}$ is whether the firm proposes an agreement in the first stage (Y means that it does, N that it doesn't), $y \in \{C, P\}$ is technology choice in the second stage *without* an information sharing agreement, and $z \in \{C, P\}$ is technology choice *with* an information sharing agreement. In writing strategies this way, we have made the following assumption:

Assumption 1: *A firm's strategy in the second stage subgame only depends on whether an agreement is made, not the specific actions chosen in the first stage.*

This basically says that if one firm plays N in the first stage, so that an agreement is not made, strategies in the second stage do not depend on whether the other firm played Y or N. This basically rules out cases where, in the absence of an agreement and with multiple equilibria in the second period subgame, the equilibrium that is selected in the second period subgame depends on whether both or only one of the firms rejected the agreement.

We denote an equilibrium by square brackets containing the strategies (i.e. $[(.), (.)]$). As firms are ex-ante identical, we do not distinguish between them; either firm could adopt the first strategy in the square brackets. Finally, we adopt the following standard form of equilibrium selection for cases where there are multiple equilibria.

Assumption 2: *In any subgame, firms adopt the Pareto-preferred Nash equilibrium.*

These two assumptions are all that is needed for analyzing our central scenario, where an information agreement can be used to shift both firm's technology choices away from the core technology. When we come to look at other scenarios, for example where only one firm adopts the core technology in the absence of the agreement, we will impose some further assumptions in order to deal with multiplicity of equilibria.

We now solve the model.

3.4 Stage Three

Given the demand and cost functions, a firm has a net profit of:

$$\Pi_i = (A - q_i - dq_j)\, q_i - \left(B - \sqrt{(D_i z_i + D_j \alpha d z_j)}\right) q_i - z_i \tag{3.3}$$

Where D_i and d are functions of firms' technology choices. In the the third stage, firm i sets q_i and z_i simultaneously to maximize Π_i, subject to both of these variables being non-negative. The Kuhn-Tucker conditions are:

$$\frac{d\Pi_i}{dz_i} = \frac{D_i q_i}{2\sqrt{D_i z_i + \alpha d D_j z_j}} - 1 \leq 0 \tag{3.4}$$

$$\frac{d\Pi_i}{dq_i} = A - B - 2q_i - dq_j + \sqrt{(D_i z_i + \alpha d D_j z_j)} \leq 0 \tag{3.5}$$

$$\frac{d\Pi_i}{dz_i} z_i = 0, \quad z_i \geq 0 \tag{3.6}$$

$$\frac{d\Pi_i}{dq_i} q_i = 0, \quad q_i \geq 0 \tag{3.7}$$

We also require that marginal costs are non-negative. This and the second order conditions are dealt with in the Appendix (sections B.1 and B.3). The second order conditions simply require that $D_c < 4$, while the non-negativity of marginal cost places restrictions on the relative values of A and B. Relative values of A and B have no impact on technology choice, so from now on we simply assume they are set at levels that ensure marginal costs are non-negative.

To begin with we solve this stage for those cases where both firms have interior solutions to the first order conditions. This is relevant either when both firms choose the same technology, or when the core technology is not too superior and knowledge spillovers are not too high. We then examine an important case where there is a corner solution to R&D investment. In this case, the knowledge spillovers resulting from an information sharing agreement are so high that a peripheral firm abandons its own research and free-rides off a core rival. As we will see, this free-riding provides a powerful mechanism by which an information sharing agreement can eliminate the profitability of the core technology, and allows firms to coordinate technologies.

When equations (3.4) and (3.5) hold with equality, and z_i and q_i are positive, equations

(3.4) and (3.5) imply:

$$q_i = \frac{2}{D_i}\sqrt{D_i z_i + D_j z_j \alpha d} \tag{3.8}$$

and:

$$q_i = \frac{A - B - q_j d + \sqrt{D_i z_i + D_j z_j \alpha d}}{2} \tag{3.9}$$

The right hand side of equation (3.8) is the marginal cost of obtaining an extra unit of capability, s_i. The left hand side is the marginal benefit of this. As there is no strategic motive for investment this is just the reduction in costs of producing an output of q_i. Note that the marginal productivity of R&D depends on the amount of knowledge spillovers received from the other firm. Thus, R&D is duplicative in this model. If a firm receives a large amount of knowledge from a rival there is less to discover for itself. This contrasts with the approach contained in d'Aspremont and Jacquemin where spillovers are in R&D *outcomes* and each firm's research perfectly complements the other's.

We can obtain the following expression for firm i's equilibrium output using equation (3.9) and the equivalent first order condition for firm j:

$$q_i^* = \frac{A(2-d) + dc_j - 2c_i}{(2-d)(d+2)} \tag{3.10}$$

This is increasing in a rival's costs and decreasing in a firm's own costs. We can substitute this into equation (3.8) and rearrange to get firm i's capability (s_i) as a function of firm j's capability. Then we substitute the equivalent expression for firm j into this and rearrange to get:

$$s_i^* = \sqrt{D_i z_i + D_j z_j \alpha d} = \frac{(2(2-d) - D_j)(A-B)D_i}{D_i D_j - 4(D_i + D_j) + 4(2-d)(d+2)} \tag{3.11}$$

Marginal costs are simply $B - s_i$, and so follow immediately from this equation. As α is not present in equation (3.11), we can immediately derive the following Lemma:

Lemma 3.1 *When both firms invest a positive amount in R&D, an information sharing agreement does not affect equilibrium levels of capability.*

Because output and R&D are chosen simultaneously in our model, firms do not take into account the impact of their R&D on their rival's decisions and only consider the cost saving benefits. When a firm receives spillovers from its rival, its own marginal costs of research rise (because there is less productive research for it to carry out) and it reduces its own R&D expenditure. As a result capability and output are unaffected. By contrast, in the d'Aspremont and Jacquemin characterization of spillovers, R&D expenditure and capability actually increase. We note the following Corollary:

Corollary 3.1 *Assuming both firms adopt the core technology, profits and welfare are increased by a technology sharing agreement.*

By Lemma 3.1 the agreement does not affect capability and therefore will not affect output or gross revenue, but it does allow firms to avoid duplication of research and save on R&D costs. Given that output (and therefore consumer surplus) is unaffected, this is clearly an increase in welfare as well. Thus a competition authority that investigates the effects of an information-sharing agreement without taking technology choice into account may well conclude that it beneficial.

To work out the profit function, we will also need to solve for the equilibrium value of R&D expenditure, z_i^*. Using equation (3.11) we can solve for z_i^* as a function of z_j^* and vice versa. We then substitute the expression for z_j^* into that for z_i^* and simplify to obtain the following:

$$z_i^* = \frac{1}{D_i\left(1-(\alpha d)^2\right)} \frac{((2(2-d)-D_j)(A-B)D_i)^2 - \alpha d((2(2-d)-D_i)(A-B)D_j)^2}{(D_iD_j - 4(D_i+D_j)+4(2-d)(d+2))^2} \tag{3.12}$$

When both firms adopt the same technology, this expression simplifies to:

$$z_i^* = \frac{(B-A)^2 D}{(2d-D+4)^2(d\alpha+1)} \tag{3.13}$$

Where D is equal to 1 if both firms choose a peripheral technology and D_c if both firms adopt the core technology. We can use equations (3.11) and (3.10), and their equivalents for firm 2 to get the following reduced form expression for q_i :

$$q_i^* = \frac{2(2(2-d)-D_j)(A-B)}{(D_iD_j - 4(D_i+D_j)+4(2-d)(d+2))}. \tag{3.14}$$

As would be expected, this is increasing in a firm's own capability and decreasing in its rival's capability. As capability does not change with an information sharing agreement, neither does output.

Using equation (3.8) and its firm j equivalent and equation (3.3), we can obtain an expression for profits as a function of capability. We then substitute equation (3.11), and its equivalent for firm j, into this equation and simplify to get the following:

$$\Pi_i(\alpha) = \frac{(B-A)^2}{(d\alpha+1)(1-d\alpha)(D_iD_j - 4(D_i+D_j) + 4(2-d)(d+2))^2 D_i} \times$$
$$((16D_i((d-2)+D_j))(1-d\alpha)(d\alpha+1)(d-2) + 4D_jD_i^2(2-d) +$$
$$4D_j^2D_i(\alpha d(d-d\alpha-2)+1) + D_j^2D_i^2(d\alpha-1) - 4(d-2)^2(D_i^2 - d\alpha D_j^2)) \quad (3.15)$$

For certain cases that we are concerned with, this expression simplifies considerably. Denote by $\Pi^{\gamma_i\gamma_j}(\alpha)$ the profit of firm i when it has a technology γ_i and its rival has γ_j. Given our assumptions, when both firms choose a peripheral technology this is equal to:

$$\Pi^{PP}(\alpha) = \frac{(B-A)^2}{3} \quad (3.16)$$

When both firms choose the core technology the profit function is:

$$\Pi^{CC}(\alpha) = \frac{(4(\alpha+1) - D_c)(B-A)^2}{(D_c-6)^2(\alpha+1)} \quad (3.17)$$

This is positive as D_c must be less than 4 by the second order conditions.

We also note the profit functions when firms adopt different technologies in the absence of an information agreement ($\alpha = 0$). In this case, the profit function of the core technology firm is:

$$\Pi^{CP}(0) = \frac{(4-D_c)\left(2\widehat{d}-3\right)^2(B-A)^2}{\left(3D_c + 4\widehat{d}^2 - 12\right)^2}, \quad (3.18)$$

and the profit of the peripheral technology firm is:

$$\Pi^{PC}(0) = \frac{3\left(2\widehat{d} + D_c - 4\right)^2(B-A)^2}{\left(3D_c + 4\widehat{d}^2 - 12\right)^2}. \quad (3.19)$$

All the above expressions assume an interior solution to the first order conditions. There are two cases where there may be a corner solution. First, when firms adopt different technologies, and there is no information sharing agreement, a peripheral technology firm may not be able to compete against a core rival if the core technology is sufficiently superior. This case is discussed in the Appendix, section B.2. The second case occurs when there is an information sharing agreement, when the core technology is sufficiently superior to the peripheral technology and when peripheral and core technologies are sufficiently "close". In this case the peripheral firm abandons its own R&D programme and free-rides off its rival.

3.4.1 Free-riding

Equation (3.13) shows that both firms invest in a positive and equal amount of R&D when they adopt the same technology, regardless of the presence of knowledge spillovers. Firms respond to spillovers by reducing their own R&D and neither abandons its research programme. However, in the case where firms adopt different technologies, sufficiently high spillovers may cause the peripheral technology firm to cease R&D altogether. The firm receives so much knowledge from its rival that its own inferior research can not make a profitable contribution. Furthermore, the knowledge received from a rival allows the firm to produce a positive output and compete, something that may not otherwise be the case when the core technology is significantly superior (see the Appendix, section B.2). This free-riding effect is an important feature of our model and provides a strong mechanism by which an information sharing agreement can dissuade firms from adopting the core technology.

We have the following Lemma:

Lemma 3.2 *With an information sharing agreement, for any value of D_c greater than one, there exists a value of $\widehat{d}$ such that a peripheral-technology firm faced with a core-technology rival will abandon its R&D programme if $\widehat{d}$ exceeds this level.*

Proof. Using equation (3.12), the exact condition for firm i to abandon its R&D program when it adopts the peripheral technology and its rival adopts the core technology, is:

$$\frac{\left(2\left(2-\widehat{d}\right)-D_c\right)}{\left(2\left(2-\widehat{d}\right)-1\right)D_c} < \sqrt{\alpha\widehat{d}} \tag{3.20}$$

This condition says that if knowledge spillovers ($\alpha\widehat{d}$) are strong enough a peripheral firm will abandon its R&D. The derivative of the left hand side with respect to $\widehat{d}$ is negative (specifically, $\frac{df}{d\widehat{d}} = -2\frac{(D_c-1)}{D_c\left(2\widehat{d}-3\right)^2}$), while the right hand side is increasing in $\widehat{d}$. Also, while the right hand side always goes to 1 as $\widehat{d}$ approaches 1, the left hand side goes to a value strictly less than one (for $D_c > 1$). The boundary for this condition to hold is plotted below, in Figure 3.2 ■

To show in the next stage how Lemma 3.2 affects technology choices, we need to solve for the profit function of both firms when a peripheral firm free-rides off a core rival. First we determine the R&D investment of the core firm. When (3.20) holds and firm i does not invest in R&D, firm j's optimal investment becomes (using equation (3.8) and equation

(3.10), and its equivalent for firm i):

$$z_j^* = \frac{1}{D_c}\left(\frac{D_c(A-B)\left(2-\widehat{d}\right)}{\left(8-2\widehat{d}^2+\left(\widehat{d}\sqrt{\widehat{t\alpha}}-2\right)D_c\right)}\right)^2. \tag{3.21}$$

Note that, as it will be useful to identify the specific impact of spillovers, we have not set α to 1 and $\widehat{t}$ to $\widehat{d}$ in this equation and the profit functions shown below. Using equation (3.3), equation (3.8), equation (3.21) and firm i's equivalent of equation (3.10) we can obtain the following expression for firm j's equilibrium profit when firm i does not invest, but remains active:

$$\Pi_j^{CP}\Big|_{z_i=0} = \frac{(4-D_c)\left(2-\widehat{d}\right)^2(B-A)^2}{\left(8-2\widehat{d}^2+D_c\left(\widehat{d}\sqrt{\widehat{t\alpha}}-2\right)\right)^2} \tag{3.22}$$

We can do the same for firm i to get:

$$\Pi_i^{PC}\Big|_{z_i=0} = \frac{\left(2\left(2-\widehat{d}\right)+D_c\left(\sqrt{\widehat{t\alpha}}-1\right)\right)^2(B-A)^2}{\left(8-2\widehat{d}^2+D_c\left(\widehat{d}\sqrt{\widehat{t\alpha}}-2\right)\right)^2} \tag{3.23}$$

It is easy to see from equation (3.22) that an increase in spillovers (i.e. higher $\widehat{t\alpha}$) reduces the core firms' profits (note that, given our parameter restrictions, the term in brackets in the denominator is always positive). When the peripheral firm free-rides, the core technology firm faces increased competition from its rival as spillovers increase, and its own output decreases. Because of reduced economies of scale, this makes R&D less profitable and the core firm responds by reducing expenditure. This does not occur when both firms invest in R&D; as equation (3.11) clearly implies, the peripheral firm responds to spillovers by reducing its own research and the technological advantage of the core firm persists. As we will see, in some circumstances firms can exploit this free-riding effect to coordinate technology choices.

Next, we note the following Lemma:

Lemma 3.3 *A core firm that is faced with a peripheral rival is worse off under an information sharing agreement if, and only if, the agreement induces free-riding.*

Proof. If the different technologies are not sufficiently closely related (i.e. $\widehat{d}$ is not high enough) so that an information sharing agreement does not induce free riding, then by equations (3.10) and (3.11) gross profits are unchanged. However, the core firm will benefit from spillovers from the peripheral firm, reducing its R&D costs and increasing net profits.

To show that free-riding reduces profits, imagine for the moment that information

sharing, α, is a continuous variable between 0 and 1. We denote the value that induces free riding by $\overline{\alpha}$. This is given by (3.20), once the condition is set to equality and rearranged. Note that when $\alpha = \overline{\alpha}$, the interior solution and the corner solution coincide for the peripheral firm. This means that equilibrium capabilities for both firms are still given by equation (3.11). In turn, this suggests that when $\alpha = \overline{\alpha}$, the profits of a core firm faced with a peripheral rival are identical to the case where there is no information sharing agreement. In both cases, equilibrium capability and therefore gross profits are the same and in both cases the core firm receives no spillovers from its peripheral rival. Therefore its R&D expenditure and *net* profits must be the same. Next, notice from equation (3.22) that further increases in α beyond $\overline{\alpha}$ will reduce the profits of the core firm. We therefore conclude that when $\overline{\alpha} < 1$ (i.e. an information sharing agreement induces free riding) a core firm faced by a peripheral rival is worse off under an information sharing agreement.
■

This lemma states that, for a firm that is faced with a peripheral rival, the incentive to adopt the core technology is reduced under an information sharing agreement when the agreement induces free-riding. The free-riding effect demonstrates the importance of technology choice in the analysis of spillovers. Many models simply assume that firms have identical technologies and, when R&D and output decisions are made simultaneously, this means that spillovers always increase profits and welfare. Our model shows that, despite the lack of a strategic motive to invest in R&D, spillovers can harm the profits of a firm when technology choice, and the resulting potential for asymmetry, is taken into account. Next, we examine the implications of this for technology choice.

3.5 Stage Two

In this stage, firms choose which technology to adopt given their decision on whether to sign an information sharing agreement in the first stage. We first determine the equilibrium outcomes for various parameter values when an agreement is not made and then consider the outcomes when there is an agreement. When there is an agreement there are two possible cases: one where the agreement induces free-riding in the event that firms choose different technologies, and one where it does not. This gives us three cases to consider. In each of these, technology choices are determined by two conditions: one that determines whether it is an equilibrium for both firms to adopt the core technology and one that determines when it is an equilibrium for both to adopt a peripheral technology. Together with the condition that determines when free-riding will occur (i.e. condition (3.20)), this gives us seven conditions that fully determine technology choices in the second stage.

By plotting these conditions we can find the equilibrium outcomes for various parameter values and identify the impact of agreements in the various regions of our parameter space (this also reveals that two of our conditions are always satisfied)).

Our main focus throughout this chapter is on the case where, in the absence of an information sharing agreement, both firms are drawn to adopting the core technology, hence leading to a Prisoner's Dilemma. In this section we show that this occurs when the core technology is sufficiently superior, and is sufficiently close, to the peripheral technology (i.e. a high enough D_c and $\widehat{d}$). In this case, competition will be fierce and firms will seek to coordinate their technology choices. In the next section we show when firms will form an information sharing agreement in order to achieve this. We denote technology outcomes as (γ_i, γ_j),where γ_i is firm $i's$ choice of technology.

3.5.1 No information sharing agreement

With no information sharing agreement, the (C,C) outcome will be a Nash equilibrium of the stage two subgame whenever a unilateral deviation to the peripheral technology reduces a firm's profits. This condition can be written as $\Pi^{CC}(0) > \Pi^{PC}(0)$. Using equations (3.17) and (3.19) this condition becomes:

$$\frac{3\left(2\widehat{d}+D_c-4\right)^2(6-D_c)^2}{\left(3D_c+4\widehat{d}^2-12\right)^2(4-D_c)} < 1. \tag{3.24}$$

We plot this condition below in Figure 3.1, which shows that the boundary for it to hold is downward sloping in $\widehat{d}$ and D_c space. Increases in $\widehat{d}$ decrease profits in the (C,P) case. Holding $\widehat{d}$ constant, a lower D_c reduces the relative benefit of remaining at the core technology[4]. Thus, for low levels of D_c, $\widehat{d}$ needs to be large to dissuade a core firm from deviating to the peripheral technology. Note that, although the profit functions used in the condition assume interior solutions for both firms' first order conditions, the case where a peripheral firm cannot compete against a core rival is encompassed by this condition. That is, if a peripheral firm is inactive when faced with a core rival then condition (3.24) holds (see the Appendix, section B.2).

The (P,P) outcome will be a Nash equilibrium whenever a unilateral deviation to the core technology is unprofitable. This can be written as $\Pi^{CP}(0) < \Pi^{PP}(0)$, which, using

[4]Profits in the (C,C) case and (P,C) case are not necessarily increasing in D_c. However, its easy to determine from the profit functions that *relative* profits are increasing and that higher levels of D_c encourage firms to adopt the core technology over the peripheral technology.

equations (3.16) and (3.18) becomes:

$$\frac{3\left(4-D_c\right)\left(2\widehat{d}-3\right)^2}{\left(3D_c+4\widehat{d}^2-12\right)^2}<1 \tag{3.25}$$

As Figure 3.1 shows, this condition starts off upward sloping in $\widehat{d}$ and D_c space, before bending backwards. To begin with, as the core technology becomes increasingly superior, higher levels of product competition (that is higher $\widehat{d}$) are needed to dissuade a firm from adopting it, given that its rival adopts a peripheral technology. However, when competition is very intense a peripheral firm is less able to compete and the core firm's profits are not harmed significantly.

These two conditions determine equilibrium outcomes. These are summarized in the following proposition:

Proposition 3.1 *When there is no information sharing agreement, the equilibrium choices of technologies are as follows:*

i) When only condition (3.24) holds, both firms choose the core technology

ii) When condition (3.24) and condition (3.25) both hold, both firms choose a peripheral technology

iii) When neither condition (3.24) nor condition (3.25) holds, one firm will choose a peripheral technology and one firm will choose the core technology

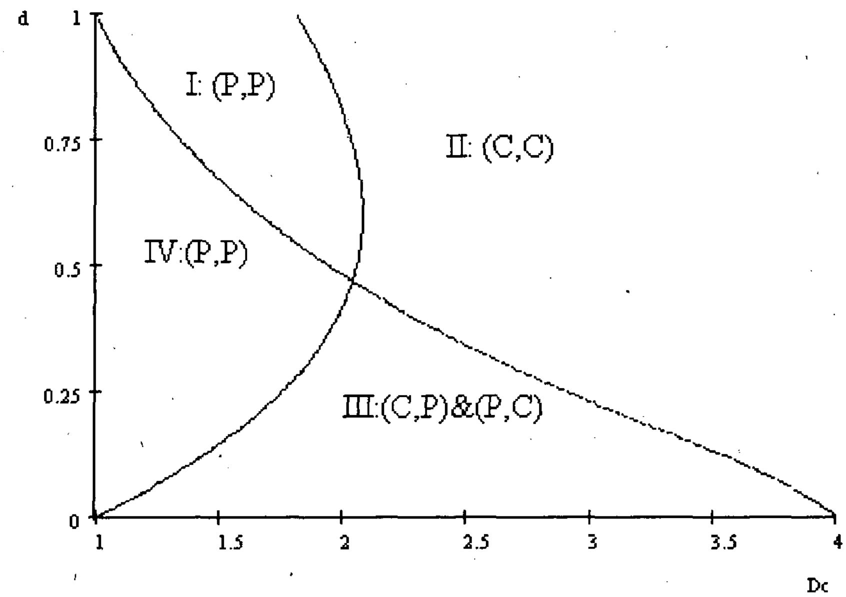
iv) When only condition (3.25) holds, both firms will choose a peripheral technology.

Note that part ii) uses the fact that the (P,P) outcome is Pareto-preferred to the (C,C) case. This is shown in the Appendix, section B.4. We can use conditions (3.24) and (3.25) to plot the graph below, which shows the equilibrium outcome for various values of $\widehat{d}$ and D_c.

Condition (3.24) holds above the downward sloping line and condition (3.25) holds to the right of the line that starts off upward sloping before bending backwards.

The central scenario of this paper occurs in region II. In this case, the core technology is so superior, and competition sufficiently intense, that both firms have no option but to adopt it (i.e. choosing the core technology is a dominant strategy). As we have mentioned, this region incorporates the case where a peripheral firm cannot even produce a positive output when faced with a core rival. This region essentially involves a Prisoner's Dilemma. Both firms prefer the (P,P) outcome to the (C,C) outcome, however each has an incentive to make a deviation to the core technology in order to benefit from more effective R&D

Figure 3.1: Stage one outcomes: no agreement



and greater cost reduction. The end result is that firms end up producing similar products and competition is intense.

Region I has multiple Subgame Perfect Nash Equilibria; a firm will want to adopt whichever technology is chosen by its rival. However as the (P,P) outcome is Pareto-preferred to (C,C) we select this. In region III, we have an asymmetric outcome. One firm will adopt the core technology but its rival will not follow. Substitutability between a core product and a peripheral one is fairly low so a peripheral firm is not harmed too much by its technological inferiority. A move to the core technology would cause such a large increase in substitutability that the firm's profit would fall. In region IV the core technology is not sufficiently superior to make up for the increased product substitutability and no firm will adopt it.

3.5.2 Information sharing agreements

Here we examine the outcome when firms sign an information sharing agreement in the first stage (so that $\alpha = 1$). Spillovers are now determined by $t(\gamma_i, \gamma_j)$, the degree of compatibility between technologies. We first look at the outcomes when the information sharing agreement induces free-riding and then look at the outcomes when it does not.

The condition for the (C,C) outcome to be a Nash equilibrium with an information sharing agreement is $\Pi^{CC}(1) > \Pi^{PC}(1)$. When an information sharing agreement induces free-riding (which is determined by condition (3.20)), we can use equations (3.17) and

(3.23) to obtain:

$$\frac{2\left(6-D_c\right)^2\left(2\left(2-\widehat{d}\right)+D_c\left(\sqrt{\widehat{d}}-1\right)\right)^2}{\left(8-D_c\right)\left(8-2\widehat{d}^2+D_c\left(\widehat{d}\sqrt{\widehat{d}}-2\right)\right)^2}<1 \tag{3.26}$$

The condition for (P,P) to be a Nash equilibrium when there is an agreement is $\Pi^{PP}(1) > \Pi^{CP}(1)$. This is the central condition in our paper as it shows when an information sharing agreement is able to support the low competition outcome. Assuming that the peripheral technology firm free-rides when faced with a core rival, we can use equations (3.16) and (3.22) to obtain the following:

$$\frac{\sqrt{3\left(4-D_3\right)}\left(2-\widehat{d}\right)+2\widehat{d}^2+2D_c-8}{\widehat{d}D_c\sqrt{\widehat{d}}}<1 \tag{3.27}$$

We plot this condition below. It basically requires that the two types of technology are sufficiently close. When this is the case, the free riding effect is enough to dissuade any firm from adopting the core technology.

When condition (3.20) does not hold, an information sharing agreement does not induce free-riding. In this case, the conditions $\Pi^{CC}(1) > \Pi^{PC}(1)$ and $\Pi^{PP}(1) > \Pi^{CP}(1)$ can be determined from equation (3.15). Using equation (3.15) and equation (3.17), the condition $\Pi^{CC}(1) > \Pi^{PC}(1)$ is given by:

$$\begin{aligned}&\frac{\left(D_c-6\right)^2 2}{\left(\widehat{d}+1\right)\left(1-\widehat{d}\right)\left(D_c-4\left(1+D_c\right)+4\left(2-\widehat{d}\right)\left(\widehat{d}+2\right)\right)^2\left(8-D_c\right)}\times\\ &\left(\left(16\left(\left(\widehat{d}-2\right)+D_c\right)\right)\left(1-\widehat{d}\right)\left(\widehat{d}+1\right)\left(\widehat{d}-2\right)+\right.\\ &\left.4D_c^2\left(1-2\widehat{d}\right)+4D_c\left(2-\widehat{d}\right)+D_c^2\left(\widehat{d}-1\right)-4\left(\widehat{d}-2\right)^2\left(1-\widehat{d}D_c^2\right)\right)\\ <\ & 1\end{aligned} \tag{3.28}$$

Using equation equation (3.15) and equation (3.16), the condition $\Pi^{PP}(1) > \Pi^{CP}(1)$ is given by:

$$\begin{aligned}&\frac{3}{\left(\widehat{d}+1\right)\left(1-\widehat{d}\right)\left(D_c-4\left(D_c+1\right)+4\left(2-\widehat{d}\right)\left(\widehat{d}+2\right)\right)^2 D_c}\times\\ &\left(\left(16D_c\left(\left(\widehat{d}-2\right)+1\right)\right)\left(1-\widehat{d}\right)\left(\widehat{d}+1\right)\left(\widehat{d}-2\right)+4D_c\left(1-2\widehat{d}\right)\right.\\ &\left.+4D_c^2\left(2-\widehat{d}\right)+D_c^2\left(\widehat{d}-1\right)-4\left(\widehat{d}-2\right)^2\left(D_c^2-\widehat{d}\right)\right)\\ <\ & 1\end{aligned} \tag{3.29}$$

The following proposition summarizes the equilibrium outcomes with an information sharing agreement:

Proposition 3.2 *When firms sign an information sharing agreement, when this induces free-riding (that is condition (3.20) is satisfied), and assuming that condition (3.26) does not hold, the equilibrium outcomes are as follows:*

i) When condition (3.27) holds, the equilibrium outcome is (P,P)

ii) When condition (3.27) does not hold, the equilibrium outcome is (C,P) or (P,C)

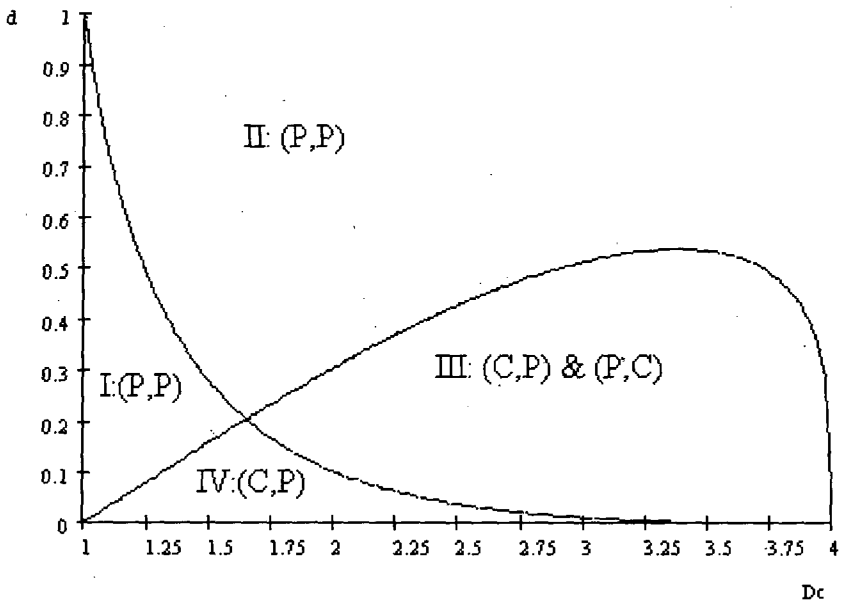
When condition (3.20) is not satisfied then, and assuming that condition (3.28) does not hold then:

iii) If condition (3.29) is satisfied, the equilibrium outcome is (P,P)

iv) If condition (3.29) is not satisfied, the equilibrium outcome is (C,P) or (P,C).

We plot the boundaries of the conditions contained in the proposition in Figure 3.2 to get equilibrium outcomes for various values of $\widehat{d}$ and D_c . This reveals that conditions (3.26) and (3.28) do not hold in the relevant regions, thus justifying the assumptions made in Proposition 3.2. When an information sharing agreement is signed, it is never an equilibrium for both firms to choose the core technology.

Figure 3.2: Stage one outcomes: with agreement



Condition (3.20) holds above the downward sloping curve. Thus in regions I and IV, there is no free riding. Condition (3.27) holds above the inverted U-shaped curve (and to the right of the boundary of condition (3.20)). Thus, in region II the free-riding effect deters any firm from adopting the core technology and the outcome is (P,P). The reason for the inverted-U shape is that, as the core technology becomes very effective, a core firm is induced to increase its R&D costs dramatically. Gross profits do not increase in step and net profits fall. The graph shows that, regardless of the superiority of the core technology (i.e. D_c) the free-riding effect can always eliminate the profitability of a move to the core technology if the core and peripheral technologies are sufficiently "close". This is intuitive for very high values of $\widehat{d}$, but the graph shows that, in general, modest values are sufficient. In region III, although the spillovers induce free-riding, the competition between a core product and a peripheral one is not sufficiently intense to dissuade one firm from adopting the core technology and, consequently, firms will choose different technologies. Condition (3.29) separates regions I and IV and holds in region I. Note that, although this looks like a continuation of the boundary of condition (3.27) in the graph, it is in fact different.

3.5.3 Impacts of information sharing agreements

Before proceeding to discuss the first stage it is useful to combine Figures 3.1 and 3.2 to show how an agreement affects technology choices for each combination of parameter values. The following proposition defines the various regions of Figure 3.3 (shown below) and states how an information sharing agreement changes technology choices in each case.

Proposition 3.3 *When condition (3.20) holds (i.e. there is free-riding) and assuming condition (3.26) does not hold, then:*

i) In region IV of Figure 3.3, conditions (3.27) and (3.24) hold and condition (3.25) does not hold, and an agreement shifts technology choices from (C,C) to (P,P)

ii) In region V , condition (3.24) holds and conditions (3.25) and (3.27) do not hold, and an agreement shifts technology choices from (C,C) to (C,P) or (P,C)

iii) In region VI, conditions (3.25) and (3.24) do not hold but condition ((3.27)) holds, and an agreement shifts technology choices from (C,P) or (P,C) to (P,P)

iv) In region VII, conditions (3.24), (3.25) and (3.27) do not hold, and the set of technology choices with and without an agreement is (C,P) and (P,C)

v) In region III, conditions (3.24), (3.25) and (3.27) all hold and technology outcomes are (P,P) with or without an agreement.

vi) In region II, conditions (3.25) and (3.27) hold and condition (3.24) does not hold, and technology outcomes are (P,P) with or without an agreement.

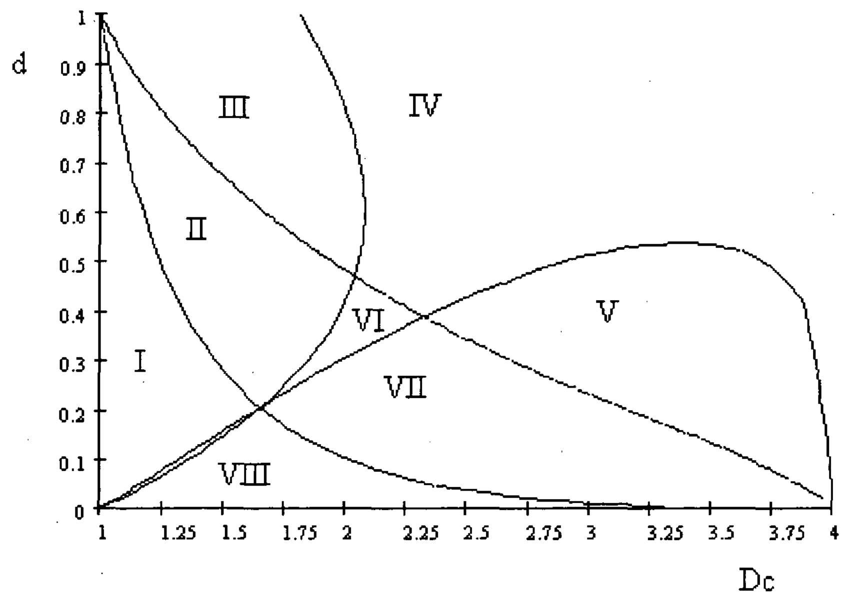
When condition (3.20) does not hold, when condition (3.24) does hold and assuming condition (3.28) does not hold then:

vii) In region I, conditions (3.25) and (3.29) hold, and technology outcomes are (P,P) with or without an agreement.

viii) In region VIII, conditions (3.25) and condition (3.29) do not hold and the set of technology choices with and without an agreement is (C,P) and (P,C)

ix) In region IX (not marked in figure 3.3), condition (3.25) holds, but condition (3.29) does not hold and an agreement shifts technology choices from (P,P) to (C,P) or (P,C).

Figure 3.3: Stage one: technology changes from agreement



As mentioned above, plotting reveals that conditions (3.26) and (3.28) never hold, thus justifying the assumptions made in Proposition 3.3. Region IV is the central scenario of our model. Without an agreement, both firms are drawn to adopt the core technology in what is basically a Prisoner's Dilemma. The agreement means that the incentive to adopt the core technology vanishes and both firms adopt a peripheral technology. In regions I, II and III, an agreement has no impact on technology choices and no firm will ever adopt the core technology. Although the core technology is slightly superior, it is not superior enough to make up for the increased competition that results when one firm adopts it. In regions VIII and VII, only one firm adopts the core technology both with and without an agreement. The only difference is that in region VII a core firm faces a free-riding rival when there is an information sharing agreement (in region VIII a peripheral firm still conducts research when there is an agreement). Nevertheless, because product substitutability is low, the core firm is not persuaded to switch to a peripheral technology despite this free-riding. In region VI, by contrast, substitutability is higher and although one firm will adopt the core technology in the absence of an agreement, an agreement means that both will adopt peripheral technologies. In region IX (between regions I and VIII - not labelled in the figure) both firms adopt a peripheral technology in the absence of an agreement and an agreement encourages one firm to shift to the core technology. Without an agreement, the core technology falls just short of being profitable, but the cost-saving benefit of spillovers means that, with an agreement, one firm will adopt the core technology. In region V, an agreement persuades one firm to abandon the core technology in favour of a peripheral one, however, as the degree of competition between the two technologies is not too high, the remaining core firm does not suffer too much.

The general message of these results is that a technology sharing agreement has an impact on technology choices whenever the core technology is reasonably superior to, and close to, peripheral technologies (i.e. when there are high values of D_c and $\widehat{d}$). The exception is region IX, which, as Figure 3.3 shows, is not very significant. We now consider the first stage, where each firm proposes whether to sign an agreement. We will show that whenever both firms adopt the core technology in the absence of an agreement, they will agree to share information in order to shift technology choices and reduce competition. In other cases, firms by-and-large do not sign agreements either because it has no impact or because one firm would lose out and so essentially veto an agreement. The exception is when substitutability between the core and peripheral technology is very low and firms will sign an agreement to save on the fixed costs of research (region VIII).

3.6 Stage One

In this stage firms agree on whether to sign an information sharing agreement. We assume that both firms simultaneously propose whether to sign an agreement and that one is only made if both propose that is it. We show that in all cases where the outcome is (C,C) in the absence of an agreement (i.e. region II in Figure 3.1), firms will sign an agreement in order to induce either one or both to switch to the peripheral technology, thereby reducing the intensity of competition and increasing profits. For completeness, we also look at equilibrium outcomes in other cases. In doing so, we use a number of additional assumptions to deal with issues of multiplicity of equilibria. We show that, unless substitutability between core and peripheral technologies is low, firms typically will not sign information sharing agreements in these cases. Throughout this section, we refer to the regions of Figure 3.3, as defined in Proposition 3.3.

We now show that, in regions IV and V, it is a unique equilibrium for firms to sign an information sharing agreement:

Proposition 3.4 *i) In region IV of Figure 3.3, equilibrium strategies are* $[(Y,(C,P)),(Y,(C,P))]$ *ii) In region V of Figure 3.3, equilibrium strategies are* $[(Y,(C,P)),(Y,(C,C))]$

Proof. For part i) we simply note that the (P,P) outcome is Pareto-preferred to the (C,C) outcome as shown in the Appendix, section B.4. As we rule out Pareto-dominated equilibria, both firms will propose an information sharing agreement. A deviation by either firm would result in both firms choosing the core technology and lower profits. For part ii) note that in region V, although an agreement only dissuades one firm from adopting the core technology, both firms still prefer this outcome. The core firm prefers it because $\Pi^{CP}(1) > \Pi^{PP}(1) = \Pi^{PP}(0) > \Pi^{CC}(0)$, where the first inequality comes from the fact that condition (3.27) does not hold in this region and the last inequality is from the fact that the (P,P) case is Pareto-preferred to the (C,C) outcome when there are no spillovers. The peripheral firm prefers it because $\Pi^{PC}(1) > \Pi^{CC}(1) > \Pi^{CC}(0)$, where the first inequality comes from the fact that condition condition (3.26) does not hold and the last inequality comes from Corollary 3.1. ■

This proposition shows that, whenever firms are both drawn to the core technology in the absence of information sharing, they will sign an agreement in order to induce one or both firms to switch to a peripheral technology, thereby reducing the intensity of product market competition and increasing profits. The mechanism that leads to this change in technologies is the free-riding effect. When a core firm is required to share the results of its research, it loses its technological advantage and its profits are reduced. In both cases, this effect means that at least one firm adopts a peripheral technology. In our central scenario, it means that both firms adopt a peripheral technology.

Before moving on we note that, although we have assumed that firms can only agree to share either all information or no information, this assumption can be relaxed without harming our central results. With a couple of extra mild assumptions we show in the Appendix, section B.6, that when firms are able to share only a proportion of their research, they will indeed choose to share all information in our central scenario.

3.6.1 Other outcomes

Before we consider the implications of our central scenario for government policy, we look at the equilibrium outcomes in the other regions of Figure 3.3. Because of multiplicity of equilibria we need to impose a few additional assumptions. First, we assume the following:

Assumption 3: *i) Firms do not sign an agreement if it has no impact on profits. ii) Firms choose symmetric actions in stage 1.*

This assumption is not strong. Part i) is relevant for regions I, II and III, and simply says that firms will not sign agreements when they are indifferent to them. Without this assumption any combination of proposals could be an equilibrium in these regions. Part ii) simply says that no firm will propose an agreement when it knows that its rival will not propose one. Because agreements are only made if both firms propose one (i.e. both play Y), there are many cases where one firm, faced with a rival that plays N, is indifferent between proposing and not proposing and either can be an equilibrium. This assumption just says that neither firm will propose an agreement in such cases.

Another assumption is needed to deal with regions VII and VIII. Here, regardless of the outcome in the first stage, the set of equilibrium outcomes in the second stage subgame consists of (C,P) and (P,C). To simplify the analysis of these cases, we make the assumption that the resolution of the outcome of the second stage is made before the game begins (for example, in pre-play communication) and is not affected by the information sharing agreement. In other words, an agreement is not taken as a signal to "swap places", with one firm adopting the core technology when there is an agreement and a peripheral one when there isn't. Our interest is in the impact of spillovers on technology choice in the industry and we are not interested in the use of agreements to coordinate outcomes when there are multiple equilibria.

Assumption 4: *When an information sharing agreement does not change the set of equilibrium outcomes in the second stage subgame, we assume that the same equilibrium is selected in this subgame with and without an agreement.*

This assumption basically rules out strategies of the type $[(., (C, P)), (., (P, C))]$.

Given these assumptions, we can now prove the following:

Proposition 3.5 *Referring to Figure 3.3:*

i) In region VI, equilibrium strategies are $[(N, (C, P)), (N, (P, P))]$.

ii) In region IX, if $\Pi^{PC}(1) < \Pi^{PP}(1)$ *then equilibrium strategies are* $[(N, (P, P)), (N, (P, C))]$, *if* $\Pi^{PC}(1) > \Pi^{PP}(1)$ *then equilibrium strategies are* $[(Y, (P, P)), (Y, (P, C))]$.

iii) In regions I, II and III, equilibrium strategies are $[(N, (P, P)), (N, (P, P))]$

iv) In region VII, equilibrium strategies are $[(N, (C, C)), (N, (P, P))]$.

v) In region VIII, equilibrium strategies are $[(Y, (C, C)), (Y, (P, P))]$

Proof. For part i) note that the fact that condition (3.25) does not hold means that the firm that chooses the core technology in the absence of an agreement prefers the (C,P) outcome to the (P,P) outcome. This firm will therefore always choose N in the first stage and an agreement will not be signed. By our symmetry assumption, its rival will also play N. For part ii), the firm that adopts the core technology when there is an agreement would prefer an agreement because condition (3.29) does not hold. The outcome therefore depends on whether the peripheral firm prefers the agreement or not, as stated in the proposition. Unfortunately, we have no analytical proof of whether this is the case. Part iii) is straightforward, given Assumption 3. For part iv), note that by Lemma (3.3) the firm that adopts the core technology is worse off with an agreement because of the free-riding effect. It would therefore never propose an agreement and again, by symmetry, its rival will not propose an agreement either. For part v) note that as we do not have free riding and as an agreement does not affect technology choices, an agreement does not change equilibrium levels of capability by Lemma 3.1. However, given that both firms receive spillovers, both must be spending less on R&D (otherwise equilibrium capability would have risen) and net profits must increase. ■

Regarding region IX, although we do not have an analytical proof of whether $\Pi^{PC}(1) < \Pi^{PP}(1)$, we can plot this condition using equations (3.15) and (3.16), which reveals that it always holds in this region. Consequently, we conclude that an agreement will not be signed in this region.

Proposition 3.5 basically says that when, in the absence of an information sharing agreement, neither firm or only one firm adopts the core technology, firms will only sign an information sharing agreement in the first stage if substitutability between the core and peripheral technologies is very low. In this latter case, the agreement has no impact on technology choice or on competition and is only used to avoid duplication of R&D costs. In the other cases, the agreement either has no impact or would, in effect, be vetoed by one of the firms.

3.7 Government policy

We now address the question of what policy a competition authority should adopt towards information sharing agreements. We focus our attention on the case where information sharing agreements are used to shift both firms' choices of technology from the core to peripheral technologies (i.e. region IV of Figure 3.3). We consider three possible aims of a competition authority. Firstly, the authority may be concerned about total welfare, that is the sum of producer and consumer surplus. In reality, however competition authorities, such the UK's Office of Fair Trading have a general legal obligation to focus on *consumer* welfare rather than total welfare. The fact that an agreement creates large profits is not a defence under UK and EU competition law if consumers are harmed[5]. Also, a government may wish to use competition law to promote innovation. The present UK government has strengthened competition law with the explicit aim of fostering R&D and innovation. The reasoning is that R&D generates a lot of spillovers and is thus valuable beyond the static benefits within a single market. Research generates both inter-sectoral spillovers, where R&D benefits other markets in the economy, and inter-temporal spillovers, where R&D helps the research of other firms in the future. Although such spillovers are outside the scope of our model, we also investigate government policy when its aim is to foster innovation.

We start with total welfare. We assume that there is a continuum of identical consumers with density 1. The utility function corresponding to our linear demand function is:

$$U = Aq_1 + Aq_2 - \frac{1}{2}q_1^2 - \frac{1}{2}q_2^2 - dq_1q_2 + y \tag{3.30}$$

Where y is expenditure on other goods. The budget constraint is:

$$p_1q_1 + p_2q_2 + y = m, \tag{3.31}$$

where m is total wealth. Substituting the demand function into the utility function, along with the expression for equilibrium output (3.14) and imposing symmetry yields:

$$U = \frac{4(B-A)^2(d+1)}{(D-2d-4)^2} + m \tag{3.32}$$

This is actually decreasing in product differentiability, d. Although competition reduces prices, consumers have a preference for variety and are harmed when this decreases. However, consumers do prefer higher values of D as this reduces prices. Combining this expression with those for firms' profits (equations (3.16) and (3.17)) and simplifying gives the following expressions for welfare in the (P,P) and (C,C) outcomes:

$$W^{PP} = \frac{10}{9}(B-A)^2 + m \tag{3.33}$$

$$W^{CC} = \frac{2(8-D)(B-A)^2}{(D-6)^2} + m \tag{3.34}$$

By banning information sharing agreements, a competition authority shifts the outcome

[5]For example Article 81(3) of the EC Treaty allows any agreement between firms "which contributes to improving the production or distribution of goods or promoting technical or economic progress, *while allowing consumers a fair share of the resulting benefit*" (emphasis added).

from (P,P) to (C,C). Using equations (3.34) and (3.33) it is easy to show that welfare is greater in the (C,C) case if D_c is greater than 3. If this holds then a competition authority would opt to ban information sharing agreements.

Proposition 3.6 *In region IV of figure 3.3, when* $D_c > 3$ *a competition authority that seeks to maximize total welfare would choose to ban agreements.*

A much more realistic depiction of the behaviour of competition authorities is that they aim to maximize consumer welfare. This is, after all, the legal standard which most competition authorities apply. An agreement that makes consumers worse off is illegal even if it has other benefits. Using equation (3.32) and Figure 3.3, we can obtain the following result:

Proposition 3.7 *In region IV of figure 3.3, a competition authority that seeks to maximize consumer welfare will ban information sharing agreements .*

Propositions 3.6 and 3.7 show that the decreased competition resulting form a move to the (P,P) outcome harms consumers if D_c is at a modest level or higher but the increase in profits can often make up for this leading to a net increase in welfare. The reason is that, under our utility function, consumers have a preference for variety. Even though R&D may be lower under the (P,P) outcome, the increased product diversity increases welfare, although this increase is capture by the firms. Proposition (3.7) suggests that we would frequently expect to see these agreements being banned even though they only harm total welfare in quite specific circumstances.

Another possible objective of a government is to promote R&D in the economy. The idea that competition policy can be used to promote R&D and innovation has been supported by a lot of empirical and theoretical work in the past decade or so (see Aghion and Griffith (2005) for an overview) and has gained the attention of policy makers. The Treasury in the United Kingdom has sought to strengthen competition policy with the explicit intention of boosting R&D. Innovation has benefits beyond the simple static gains in a single market, yielding both inter-sectoral and inter-temporal spillovers. In this context, a government may wish to encourage firms to adopt the most sophisticated core technology rather than the peripheral ones. Using equation (3.11) and Figure 3.3 we get the following:

Proposition 3.8 *In region IV of figure 3.3, a competition authority that wishes to promote technological progress, that is maximize* s*, will ban technological sharing agreements.*

For any value of D_c above 1.5, technological capability is higher in the (C,C) outcome than the (P,P) outcome and the competition authority will want to ban any agreements that deter firms from adopting the core technology. Additionally, inter-sectoral or inter-temporal spillovers could be stronger for the core technology than peripheral technologies, giving further reason to promote it, although such spillovers are clearly outside the scope of our static, partial-equilibrium model.

3.8 Discussion and Conclusions

Our model makes a number of contributions to the existing theoretical literature. It adds to the general conclusion that cooperation that leads to large knowledge spillovers without fixing R&D budgets is likely to be harmful. For example, in a model similar to d'Aspremont and Jaquemine (1988), Gil Molto, Georgantzis and Ortz (2005) find that consumer welfare is maximized at a spillover parameter equal to 0.5 (welfare is maximized at a slightly higher level) but that cooperating firms will collectively choose a spillover parameter equal to 1, which is invariably harmful. These results are driven by the strategic motive for investment: a high spillover can be used by firms to alleviate their strategic incentive to over-invest. Our results are similar but occur for very different reasons. With high spillovers, a firm is able to unilaterally retreat to an inferior technology and free-ride on the efforts of its rival. In effect, adopting the inferior technology is a commitment not to invest in R&D and this generates free-riding. This in turn eliminates the profitability of adopting the superior "core" technology and, in equilibrium, both firms adopt inferior, peripheral technologies. As a result, innovation and, when the core technology is sufficiently superior, consumer welfare will suffer. We also find parameter values for which total welfare suffers. Contrary to the existing literature, our results are obtained in a model with simultaneous R&D and output decisions, and do not rely on the existence of the strategic effect. As Vives (2005) notes[6], it is possible that the strategic effect has been over-emphasized in the literature and empirical evidence for its importance is lacking.

As mentioned in the introduction, there is much evidence that information sharing agreements between firms are widespread. Although much of the economics literature and the attention of policy makers has focused on full Research Joint Ventures, our model suggests that competition authorities should also pay attention to lesser forms of R&D cooperation. Specifically, agreements that commit firms to sharing large amount of technical information prior to the R&D being carried out should be subject to close scrutiny. Furthermore, such agreements should not be overlooked simply because the firms appear to be involved in very different sectors and do not compete head-on. The agreement may be an attempt to prevent both firms adopting a common technology. For example, in

[6] See Vives (2005) footnote 3.

the case of the information exchange between General Electric and Wilh Wilhelmsen an authority would want to check that there is no potential for the adoption of a hybrid technology that allows a firm to compete in both maritime and aircraft engines. The need to investigate *potential* markets as well as existing ones is a common theme in much of the recent writing on competition policy in high-tech industries[7].

Our results highlight the importance of free-riding on R&D decisions. This effect is absent in the existing literature because the focus tends to be on symmetric technologies and symmetric outcomes. Additionally, much of the literature adopts spillovers of the form used by d'Aspremont and Jacquemin, where information received from others perfectly complements a firm's own research. With our spillovers (of the form adopted by Kamien, Muller and Zang) a technologically inferior firm may receive so much information from a rival that there is nothing that its own research can profitably add. We believe that this is a plausible effect of information sharing that is over looked by much of the literature. By adopting a peripheral technology a firm is, in effect, committing itself not to carry out its own research when faced by a technologically superior rival and to free-ride instead. By eliminating the profitability of adopting a superior technology, this free-riding effect can have important consequences for the market.

The model does rely on some key assumptions, which we now discuss. One assumption is that the information sharing agreement precedes the choice of technologies and therefore influences it. If firms had already adopted their technologies prior to making an information sharing agreement, then neither would face the threat of a free-riding rival as it could always refuse to sign an agreement that resulted in this outcome. Then, in our scenario, both firms would be happy to choose the core technology and would share information to reduce R&D costs. However, there are a couple of reasons why it is plausible to think of the agreement as preceding technology choice. First, it may not be possible to commit to adopt a technology ahead of the agreement. In particular, if the benefits of switching to a peripheral technology and free-riding off a rival are large enough, firms would be willing to abandon an existing core-technology research programme despite having sunk certain costs associated with it. Second, firms may sign agreements in anticipation of a newly emerging "core" technology. Neither firm may be able to adopt it at the point when the agreement is signed but both would be aware of its future potential. Firms would sign an agreement in order to prevent either from adopting this technology once it becomes viable.

Another assumption of the model is that entry is blocked and the core technology

[7]For example see Pleatsikas and Teece (2001) *The analysis of market definition and market power in the context of rapid innovation.*

can not be adopted by a new entrant. Essentially we are assuming that technological opportunities are only available to incumbent firms. Outsiders will not have built up the experience or technological capability necessary to enter the market or may learn of the existence of a newly emerged "core" technology too late. This is a natural assumption when the core technology is related to existing ones, as in our model. It does not apply to completely new, unrelated technologies that supersede existing ones. The rise of the internet and digital technologies, for example, has allowed many new firms to encroach on the territory of incumbents. In these cases, information sharing agreements would not prevent the core technology from being adopted.

The fact that core research has applications to peripheral technologies is another important feature of our model. It is this that allows a peripheral firm to compete even when it does no research and merely free rides off the core firm. This assumption is reasonable in many cases, particularly if we interpret the core technology as being some kind of hybrid of the peripheral ones. Note, however, that a simple extension of our model could eliminate the profitability of a deviation to the core technology even where this is unrelated to peripheral ones. If the information sharing agreement allows instant *imitation* by the peripheral firm, that is the peripheral firm could instantly adopt the core technology too, a deviation could trigger a shift from both firms having the peripheral technology to both firms having the core technology. As our model shows, this would reduce profits and so prevent a deviation, thus maintaining the (P,P) outcome as an equilibrium. Note however, that this would not prevent the (C,C) outcome from being an equilibrium. Thus the mechanism in our model is more powerful; faced with a core rival, a firm would prefer to adopt the peripheral technology and free ride, reducing the profitability of the core technology.

Chapter 4

Absorptive capacity and the effects of tying on innovation in a systems market

Abstract

We show how an incumbent monopoly supplier of a primary product in a systems market can protect its position through the technological tying of complementary goods. The key feature is that the production of complementary goods allows rivals to build up an *absorptive capacity* and thus benefits from spillovers from the incumbent. This in turn helps them challenge the incumbent in an R&D race to produce a superior version of the primary product. Tying reduces the aggregate rate of innovation and a competition authority that seeks to promote innovation should therefore ban it. Unlike other models in the literature, we do not drop the Chicago-School assumption that the complementary market is perfectly competitive.

4.1 Introduction

In May 1998 the US Department of Justice, 20 individual States and the District of Columbia started legal action against Microsoft Corporation in one of the most high profile anti-trust cases of recent years. Microsoft was accused of engaging in various anti-competitive activities in order to exclude its rival, Netscape, from the internet browser market. In particular, Microsoft required that PC manufacturers who installed Windows also installed its Internet Explorer programme rather than Netscape's Navigator. In the 1998 version of Windows, this tie was automatic since Explorer was integrated into the operating system. The Department of Justice alleged that Microsoft viewed Netscape's browser as a platform that, over time, could take on more and more roles performed by the operating system (such as file and memory management) and constitute a threat to its near monopoly over the non-server operating system market (see Gilbert and Katz (2001) and Rubinfeld (2004)). More recently, the European Commission found Microsoft guilty of tying its Windows Media Player to its operating system, potentially excluding rivals such as Realplayer from the market (see Ayres and Nalebuff (2005)). Again, it was alleged that Microsoft was concerned about rival media players evolving into more complex programs that could challenge Microsoft's position.

Since these cases were brought, a number of number of papers have sought to explain how technological tying may be anti-competitive in markets where a primary product is combined with complements to form a system. In particular, a number of studies have attempted to show how tying can protect the monopoly position of an incumbent supplier of the primary product, in the above cases the Windows operating system, for example, Carlton and Waldman (2002) and Choi and Stefanadis (2001). Evidence presented at the trial by the Department of Justice made it clear that Microsoft regarded Navigator as a threat to its wider position and was not aiming to dominate the browser market simply to secure rents from browser sales[1]. In this chapter we add to this literature by showing how tying can have direct effects on an excluded firm's technological capability, in particular via its ability to benefit from knowledge spillovers. Our model has the particular advantage that we do not abandon the assumption that the complementary good market is perfectly competitive. Thus, unlike other models, it is not important that a challenger to the incumbent's position in the primary market can earn rents from the complementary market. The central feature is that producing complementary products helps rival firms gain an *absorptive capacity*, that is, an ability to receive and exploit spillovers. In addition to showing that tying can help protect the incumbent's monopoly position, we show that

[1] Microsoft's internal documents referred to Explorer as a "no-revenue product", see Rubinfeld (2004)

this reduces the rate of technological innovation in the market. A competition authority that seeks to foster innovation should therefore ban such ties. Our model benefits from having wide applicability in that it does not rely on specific parameters and is robust to a number of extensions. We begin by outlining the existing literature on bundling/tying[2]. We then describe the central ideas underlying our analysis before presenting the basic model. Finally, we consider a series of extensions before comparing our results to the existing literature and discussing the assumptions.

4.2 Existing literature

Accusations that bundling and tying could allow a firm with a monopoly over one market (product A) to leverage its market power into another market (product B) played a role in a number of anti-trust cases in the US prior to the Second World War (for example see *International Business Machines* v. *United States* (1936)). In the post-war era, however, these ideas were attacked by the influential Chicago-school of anti-trust analysis (for example Director and Levi (1956)). Under the assumption that the competitive B product is supplied at marginal cost before and after tying, it was argued that the monopoly can sell its bundle for an incremental value that is, at most, equal to what consumers would be prepared to pay for the monopolist's A product anyway. There is only "one monopoly profit" to exploit and the monopolist can not do any better through the tie. The implication is that observed tying must have efficiency benefits, such as efficiencies in production, and should not be challenged by competition authorities. Until the late 1980s, economists accepted these arguments and instead focused on price discrimination motives for bundling. By reducing the variation in consumers' valuations of a product, bundling can allow a firm to extract more surplus and increase its profits (see Adams and Yellen (1976) and McAfee, McMillan and Whinston (1989)).

The growth of game theoretic analysis in the 1980s led to a number of challenges to the Chicago view. By dropping the assumption that the B product is supplied competitively, a number of papers showed how a credible commitment to a tie can change the outcome of product market competition in favour of the tying firm. In an important early paper Whinston (1990) argued that, by tying, a firm with a monopoly over the A product could force the exit of a rival firm in a duopolistic market for the B product. Each sale the tying firm makes is worth more to it than a sale is worth to its rival, since it also includes the surplus from the value of the A product. This makes the tying firm a very aggressive competitor in the product market which can deter its rival from sinking the fixed costs of

[2] In this paper we use the terms bundling and tying interchangeably.

entry. In this model, tying is only profitable if it induces exit. In Carbajo, De Meza and Seidmann (1990) tying makes competition less intense, effectively by making goods more differentiated. Before tying, competition in the B market is intense and profits are driven to zero. After tying, the tying firm sells to those who place a high value on the A product while its rival in the B market sells to the rest. Both firms are able to raise prices since their customers are less willing to accept the other firm's offer. Nalebuff (2004) develops a similar model in which tying means that a rival firm is only able to sell to those who do not place a high value on the A product. This helps the tying firm capture market share and, in the presence of fixed costs, potentially force exit.

Choi (2004) argues that much of the literature on tying is too focused on price competition and instead investigates the impact on the incentives to conduct R&D. He assumes that an incumbent has a monopoly over the A product but competes in the B market with a rival firm. Competition in the B market takes a Hotelling form. By bundling the A product and the B product, a firm is induced to act more aggressively and capture a greater market share in the B market. Without R&D this strategy is never profitable in the model. However, when deterministic, non-tournament R&D is introduced, the increased market share makes R&D investment more profitable for the tying firm, since the fixed costs can be spread over a larger output. Similarly, R&D is less profitable for the firm's rival. When these effects are taken into account, bundling can be profitable. A similar model with stochastic R&D and vertical product differentiation is presented in Choi (2007).

The articles mentioned above all involve the leveraging of market power from one market to a second, unrelated one. In recent years, inspired by the Microsoft case as well as examples in other high-tech industries, economists have studied tying in systems markets, that is, markets where a primary good is combined with a complementary good to form an integrated product. The familiar example of operating systems and internet browsers is only one of many, including the bundling of iTunes with Apple's iPod and the online services of Xbox Live with the Microsoft's Xbox console. The models typically involve a monopoly supplier of an essential component (product A) and a potentially oligopolistic market for a complementary component (product B). The research divides into those papers that show how tying can be used by the monopolist to try and extract more rent from the industry and those that show how tying can be used to protect the firm's monopoly over the primary product.

Regarding rent extraction motives, Carlton and Waldman (2005) show how bundling can allow the monopoly supplier of a durable component to extract rents associated with future upgrades of complementary products. In general, the supplier of the primary component would not want to exclude complementary producers as it can extract some of the value they add to the system through the pricing of the durable A component. However, the value of future upgrades cannot be captured by the pricing of the A component and the firm has an incentive to bundle an A and B product together to ensure it is the one that sells upgrades in the future. This can damage innovation because the monopolist's B component may be inferior to that of its rival. Farrell and Katz (2000) also look at the issue of rent extraction in a system market and compare a variety of methods an incumbent can adopt including bundling and a price squeeze. Gilbert and Riordan (2007) explore the incumbent's incentives to tie when it is constrained in its pricing of the A product, for example by regulation or the fact that only some consumers value the complementary good.

The prosecutors' central argument in the Microsoft case was that Netscape constituted a long run threat to Microsoft's operating system. Documents presented during the case by the US Department of Justice made it clear that Microsoft regarded Explorer as a "no-revenue product" and was not simply aiming to capture rents in the browser market. A number of papers have investigated how tying can help a firm maintain its monopoly position over an essential component. Carlton and Waldman (2002) show how a rival that is able to enter the primary product market only after a time delay may be deterred from entering altogether if it cannot enter the complementary market earlier. Their model has two periods and entry involves fixed costs, which the incumbent does not have to pay. In the model a rival has a superior complementary product, but can only capture all the rents from this advantage if it is also active in the primary market. Under certain parameters, entry by the rival firm in the primary market in the second period is only possible if it is able to earn some rents in the first period to help contribute towards the total fixed costs of entry. In other words there are intertemporal economies of scale. Tying can thus help protect the incumbent's position. Although innovation is not explicitly considered, tying harms welfare because the rival firm is assumed to have a superior product. The authors further extend their model to show how network externalities can play a similar role to entry costs.

In Choi and Stefanadis (2001) an incumbent with an initial monopoly position in both the A and B components can simultaneously protect both segments from entry by tying. The key element is that risky R&D is needed to successfully enter each component market. Without the tie, success in only one component still yields profits. If the incumbent ties, however, an entrant can only earn profits if its R&D is simultaneously successful in both components. This reduces the incentive to invest in R&D and increases the probability that the incumbent remains the monopolist. The monopoly does face a trade-off, however, because tying prevents it from extracting rents generated by a rival's superior product when there is entry in only one component. Tying also harms innovation since, as with Carlton and Waldman, the entrant is assumed to have a superior product.

In this paper we present a model that also shows how tying in a systems market can help protect an incumbent's monopoly position. Unlike the rest of this literature, we do not abandon the Chicago-school assumption that the B market is perfectly competitive. The key feature is that being active in the complementary component market (the B component) yields benefits that are not available to outsiders who are not active in either market. Specifically, we assume that being active in the B component allows a firm to receive and exploit technological spillovers from the incumbent, which helps the firm challenge the incumbent's position in the primary component. In the commonly used terminology, being active allows a firm to develop an *absorptive capacity.* Tying reduces spillovers and directly damages the technological capability of potential entrants. We now discuss this concept in more detail.

4.3 Absorptive capacity

The concept of absorptive capacity was first discussed by Cohen and Levinthal (1989 and 1990) who defined it as "the ability of a firm to recognize the value of new, external information, assimilate it and apply it to commercial ends". They argued that knowledge spillovers were not an automatic public good, as traditionally assumed in the work of economists such as Arrow (1962), but required the receiving firm to have sufficient prior knowledge. In the same way as a radio is needed to exploit free broadcasts, a firm must have a specific capability to exploit external knowledge. In their 1989 paper, the authors argue that absorptive capacity is a product of a firm's own R&D efforts. In their 1990 paper they add that it may also be a by-product of the manufacturing process. Von Hippel (1988) stresses the importance of contact with buyers and suppliers as do Stock, Greis and Fischer (2003) in their case study of the modem industry. The movement of staff between firms may also be important, as mentioned by Arrow (1962) and demonstrated by Almeida and Kogut (1999) using patent data in the semi-conductor industry. Lim (2006), in a case study of the development of copper interconnects in semiconductors, stresses the importance of wider social networks including contacts with universities and trade associations (in this case the Sematech consortium). He also notes that contacts with equipment suppliers are important, especially for late adopters. Cockburn and Henderson (1998) find that, in the pharmaceutical industry, R&D is not enough to generate an absorptive capacity and that a firm must be connected to the wider scientific community. They measure this through coauthorships between a firm's scientists and academics in public institutions. Vinding (2006) also finds evidence for the importance of external linkages in a sample of 1544 firms in Denmark.

The notion of absorptive capacity has been used by economists in a number of areas. Kamien and Zang (2000) and Leahy and Neary (2004) study how it affects the impact of research joint ventures. Wiethaus (2005) studies how it allows an incumbent firm to maintain its position by imitating a challenger's innovations. Griffith, Redding and Van Reenen (2003) use the notion to help explain long run differences in countries' productivities. In this paper, we use the notion to show how an incumbent with a monopoly over the primary component in a systems market can use tying to prevent potential rivals from challenging its position. We argue that being active in the production of complementary products allows a firm to develop an absorptive capacity and benefit from technological spillovers from the incumbent. This in turn helps the firm to challenge the incumbent's monopoly position in the primary product by investing in R&D. By contrast, outsiders, who are not active in the market, are less able to develop an absorptive capacity and suffer a technological disadvantage relative to the incumbent. We now discuss the various sources of absorptive capacity and reasons why they may only be available to active firms.

First, as mentioned by Cohen and Levinthal, an absorptive capacity may be a by-product of the manufacturing process. Firms that produce a product naturally benefit from learning-by-doing over time and this can help them exploit external knowledge. In our case, a producer of complementary products may be in a better position to acquire and exploit external knowledge from the primary sector than an outsider. Clearly an assumption here is that the complementary product and primary products are, to some extent, technologically related. If the complementary product is a mere accessory to the primary product, for example stands for hi-fi speakers, manufacturing it may not provide a firm with the relevant absorptive capacity. For an industry such as software, however, it is more likely that manufacturing (or rather development) has these effects.

Second, the movement of staff between the incumbent and rivals may be an important factor in a firm's ability to exploit spillovers, as suggested by the studies mentioned above. Of course, outsiders could always attempt to hire experienced staff themselves while they conduct R&D and attempt to challenge the incumbent. However, as the firm would be inactive and produce no product, it may be unable to offer valuable on-the-job experience to workers, who may therefore be reluctant to accept employment with the firm. Active firms by contrast may be able to offer valuable experience.

Third, absorptive capacity may depend on contact with buyers and suppliers and with external bodies such as universities or trade associations. Again, an outsider could attempt to invest directly in acquiring these contacts, however its ability to do so may be limited because, as with the movement of staff, the firm has less to offer in return. For example universities may value contacts with active firms and be uninterested in outsiders who have less experience to share. Similarly, buyers and suppliers have less incentive to maintain contacts with firms they may never end up doing business with.

In all of these examples, an inactive firm may find it difficult to replicate the absorptive capacity obtained by an active firm. It could be argued that outsiders could always engage in R&D specifically directed at learning from active firms. However, knowledge is often not "codified", meaning that it is embedded in the experience and working practices within firms and is not easy to set down in a technical blueprint. While this knowledge can be acquired by the movement of staff or learning-by-doing, there may be limits to the extent to which R&D alone can achieve this. Even when this is possible, such R&D places a financial burden on an excluded firm that an active firm does not have to bear. The implications of this are discussed in an extension to our basic model.

In the next section we set out our basic model. In this, spillovers allow an active firm to keep abreast of the latest production techniques used by the incumbent. This means that if it successfully develops a superior primary component it will be able to produce it efficiently and profitably challenge the incumbent. In contrast, when a firm is excluded from producing complementary products as a result of tying, the firm has higher production costs and the returns from innovation are reduced. We employ a standard racing model to show that exclusion reduces the aggregate rate of innovation in the industry and increases the profits of the incumbent. We then consider a number of simple extensions, introducing intellectual property rights, free entry and allowing excluded firms to invest directly in obtaining an absorptive capacity.

Throughout our analysis we assume that a competition authority is aiming to boost the rate of innovation in the industry. Although racing models often produce instances of *excessive* R&D, we assume that the spillovers from the industry, either to other sectors in the economy or to future innovation that builds on initial discoveries, are large enough that the competition authority always wants to promote R&D.

4.4 The Model

We consider a market for a system comprising one unit of a primary component (product A) and one unit of a secondary component (product B). There is a single producer of the A component, whom we refer to as the incumbent.

The incumbent is also active in the B market where, unless it engages in technological tying, it faces n rival firms. We initially take this number to be fixed. If the incumbent engages in tying, it becomes the sole producer of the B component. When the incumbent's rivals are excluded by tying, we refer to them as *outsiders* whereas rival firms that are able to produce and sell B components are said to be *active*. All firms, whether active or not, are free to participate in a stochastic R&D race in order to develop an improved version of the A product. However, as we will see, outsiders suffer from a reduced level of technological know-how which reduces their incentives to invest.

We first outline the nature of product market competition and R&D in the model before determining the equilibrium. Using a method of equilibrium selection, we show how the incumbent will always choose to engage in tying and that this reduces the aggregate rate of innovation. Policy implications are discussed. We then consider some extensions, including free entry and allowing excluded rivals to invest in obtaining an absorptive capacity.

4.4.1 Product market

There is a continuum of identical consumers of density 1 who place a value, v, on a system comprising one unit of the A component and one unit of a B component. Neither component has any value when consumed on its own. Firms invest in stochastic R&D in order create a superior A component which increases the value of a system to $\overline{v} > v$. Developing a new A product (of any quality) costs a fixed amount, F, (the incumbent has already sunk the costs associated with its initial position at the start of the game). Entry into the B market is costless unless the incumbent engages in tying, in which case no rival can enter[3]. A successful innovator has a first call on whether to develop the superior A product (and pay the fixed cost, F). Other firms can subsequently decide whether to do the same. Thus, it is the first-mover advantage and sunk costs that allow a firm to profit from innovation, not patent protection. Later we consider the impact of intellectual property on the model.

Competition in the product market takes a Bertrand form. The incumbent and its rivals all have a marginal cost for the B product of c_B. The incumbent can produce the A product at marginal cost c_A. The key feature of the model is that active rival firms, who produce complementary products, gain knowledge spillovers that put them in a better position to challenge the incumbent in the primary market. Specifically, we assume that active rivals have the technological capability to produce an A product at the same marginal cost as the incumbent, c_A, while outsiders can only produce at $c_A^O > c_A$. To make things realistic, we assume that an outsider who produces an A product will, after

[3] As is usual in the literature we assume that the tie involves techologically incorporating the complementary product into the primary product, and that it is therefore a credible strategy.

T periods, have accumulated enough experience to produce at the efficient cost level, c_A.

In order to have the first call on the option of developing a superior A product a firm must win an R&D race. The nature of this race is outlined next.

4.4.2 R&D

The R&D race follows the specification initially created by Lee and Wilde (1980) and developed further by Reinganum (1983, 1985) in the context of a market with an incumbent firm. Firm i chooses its flow R&D expenditure x_i and receives a Poisson arrival rate of $h(x_i)$. This flow cost is incurred until one firm wins the race. This contrasts with the Loury (1979) specification where x is an up-front fixed cost. Following the literature we assume:

$$h'(x) > 0, \; h''(x) < 0, \; h(0) = 0$$

$$\lim_{x \to \infty} h'(x) = 0 \text{ and } \lim_{x \to 0} h'(x) = \infty$$

These say that the arrival rate is increasing in R&D expenditure but with diminishing marginal returns (plus some boundary conditions). The aggregate arrival rate is simply the sum of individual arrival rates, which we denote by H (i.e. $H = \sum h(x_i)$). As mentioned, we assume that the aim of competition authorities is to promote this aggregate arrival rate. As we will see, the key feature for our purpose is that reaction functions slope upwards. If a firm's rivals increase their R&D expenditure a firm will respond by increasing its own investment. Exclusion reduces the R&D conducted by an incumbent's rivals and in response the incumbent reduces its own R&D efforts. Consequently the aggregate rate of innovation falls.

4.4.3 Product market equilibrium

We first consider the outcomes in the product market before any firm has successfully innovated. If rivals are active, Bertrand competition drives the price of the B component to c_B and they receive zero profits. Regardless of whether rivals are active, the incumbent charges a price of $v - c_B$ per unit of the A component (and c_B for the B component) and makes a flow profit of $v - c_B - c_A$. We denote this as π_A. We denote the discounted value of an infinite stream of these profits as Π^A (i.e. $\Pi^A = \frac{\pi_A}{r}$, where $r > 0$ is the discount rate). Note that the incumbent captures all the surplus in this model and consequently has no rent-capturing motive for excluding rivals.

We now consider post-innovation outcomes. The first firm to successfully innovate has the option of paying F and producing a rival A product. Other firms subsequently have an option to do the same (the exact order does not matter and can be taken as random).

Next, we compare the profits of introducing a new product for the incumbent, active rivals and outsiders.

An incumbent who wins the race and introduces a new A product will charge a new price of $\overline{v}-c_B$, yielding a flow profit of $\overline{v}-c_B-c_A$, which we denote by π_A^I. The discounted value of an infinite stream of this flow, net of the fixed costs F, is denoted by Π^I. We assume the net incremental profits are positive, that is:

$$\Pi^I - \Pi^A = \frac{\overline{v}-v}{r} - F > 0 \tag{4.1}$$

Given this, the incumbent will pay F and introduce a new product. No other firm will subsequently choose to develop the product because Bertrand competition would drive their gross profits to zero, leading to a loss net of fixed costs.

An *active* rival who wins the race and develops a new product will become the new monopolist. However, its price is constrained by the existence of the incumbent. It has to offer consumers a surplus of at least $v-c_B-c_A$ (as the incumbent is willing to charge marginal cost) and can therefore only extract $\overline{v}-v$. We denote this flow profit by π_A^R. The discounted value of an infinite stream of this, net of F, is denoted by Π^R, that is:

$$\Pi^R = \frac{\overline{v}-v}{r} - F$$

Clearly $\Pi^R < \Pi^I$. However note that $\Pi^R = \Pi^I - \Pi^A$, that is, incremental gains from innovation are identical. Thus by condition (4.1) the firm will find it profitable to introduce the product. Again, no other firm will subsequently choose to pay F and introduce a version of the improved product.

An *outsider* who wins the race and introduces a new A product faces the possibility that the incumbent will also pay the development cost and compete against it. An incumbent can earn some rents for the first T periods because of its lower marginal costs. Specifically, it can charge a price of c_A^O and gain a flow profit of $c_A^O - c_A$ for T periods. The discounted value of this is $\left(c_A^O - c_A\right)\frac{(1-e^{-rT})}{r}$. After period T, Bertrand competition means both firms earn zero profits. The condition for this imitation *not* to be profitable is:

$$\left(c_A^O - c_A\right)\frac{(1-e^{-rT})}{r} < F \tag{4.2}$$

Unless this condition holds, an outsider cannot earn any profits from its innovation and would never choose to invest in R&D. If it does hold then the outsider will be able to extract a flow profit of $\overline{v}-v+c_A-c_A^O$ for T periods and $\overline{v}-v$ from then on. We denote by Π^O the discounted value of this flow net of F. This is positive when:

$$\Pi^O = \left(\overline{v} - v + c_A - c_A^O\right) \frac{\left(1 - e^{-rT}\right)}{r} + \frac{\overline{v} - v}{r} e^{-rT} - F > 0 \tag{4.3}$$

When (4.3) holds an outsider can earn profits from innovation. Note however that $\Pi^O < \Pi^R$. Exclusion always reduces the return from innovation.

We sum up the results of product market competition in the following proposition.

Proposition 4.1 *Assuming condition (4.1) holds, the profit function satisfies* $\Pi^I > \Pi^R > \Pi^O$. *Also,* $\Pi^R = \Pi^I - \Pi^A$. *If condition (4.2) or condition (4.3) does not hold then an outsider can never earn positive profits from introducing a new product.*

An outsider suffers from inferior technological knowledge compared to the incumbent and can earn less profits from introducing a new product. An idea for a new product is worth less to it because it does not have the knowledge to profitably exploit the idea. In the extreme case, it can not earn any profits at all. In this case it will clearly not engage in R&D.

4.4.4 R&D Equilibrium

Given the payoffs in the product market, the expected discounted value of profits for the incumbent is:

$$V_i^I = \Pi^A + \int_0^\infty e^{-(r+H)t} \left((\Pi^I - \Pi^A) h(x_I) - \Pi^A h(x_O) - x_I\right) dt$$

or,

$$V_i^I = \frac{\Pi^I h(x_I) + r\Pi^A - x_I}{r + H} \tag{4.4}$$

Note that this includes flow of profits from the incumbent's initial position as a monopolist in the market (i.e. $r\Pi^A$).

The expected discounted value of profits for a rival j is:

$$V_j^a = \int_0^\infty e^{-(r+H)t} \left(\Pi^a - x_j\right) h(x_j)\, dt$$

or,

$$V_j^a = \frac{\Pi^a h(x_j) - x_j}{r + H}, \tag{4.5}$$

where $a = R$ when the rival is active and $a = O$ when the incumbent engages in tying. Note that when Π^O is not positive (that is when neither condition (4.2) nor (4.3) holds) rivals will never invest in R&D.

Next we show that, when condition (4.2) or (4.3) holds (so that rivals can earn positive profits from innovating), there exists at least one Nash equilibrium. Although there may be multiple equilibria, we select the Pareto-dominant equilibrium, which yields straightforward comparative statics. Using equation (4.4), the first order condition for the incumbent is:

$$\left(h'(x_I)\Pi^I - 1\right)(r + h(x_I) + \alpha_I) - \left(\Pi^I h(x_I) + r\Pi_A - x_I\right)h'(x_I) = 0, \tag{4.6}$$

where α_I is the sum of the arrival rates of all other firms. For a rival firm, j, the first order condition is:

$$\left(h'(x_j)\Pi^a - 1\right)(r + h(x_j) + \alpha_j) - (\Pi^a h(x_j) - x_j)h'(x_j) = 0 \tag{4.7}$$

where $a = R$ when the rival is active and $a = O$ when the incumbent engages in tying. Given our assumptions on $h(.)$, under which the value functions are globally concave, it is easy to show that each first order condition has a solution and that this defines a global maximum (see Appendix, section C.1). We next make use of the following lemma, as proved in Reinganum (1985):

Lemma 4.1 *Any Nash equilibrium in the current stage is symmetric among the challengers, that is $x_j = x_a$ for all rivals.*

Given this, the first order condition for rival firms can be written as:

$$\left(h'(x_a)\Pi^a - 1\right)(r + h(x_I) + nh(x_a)) - (\Pi^a h(x_a) - x_a)h'(x_a) = 0 \tag{4.8}$$

The Nash equilibrium in R&D is therefore given by the solution to the system of equations given by (4.6) and (4.8). Each equation implicitly defines functions that determine optimal R&D spending. We denote these $x_I^*(x_a)$ for the incumbent and $x_a^*(x_I)$ for rivals. We shall refer to these as *equilibrium functions* (as technically they are not reaction functions). Where these functions cross is a Nash equilibrium. We now state the following proposition:

Proposition 4.2 *i) The functions $x_I^*(x_a)$ and $x_a^*(x_I)$ slope upwards. ii)There exists at least one Nash equilibrium in R&D expenditure.*

Proof. See Appendix, section C.2. ■

Our assumptions do not rule out multiple-equilibria. However, rather than imposing further restrictions on $h(.)$ we assume that the Pareto-dominant equilibrium is always selected. This outcome is a natural focal point in the game and it is not unreasonable to assume that firms will select this equilibrium. As we will see this provides us with straightforward comparative statics, regardless of the parameters of the product market. We now prove the following:

Lemma 4.2 *The Nash equilibrium defined by the first point at which the functions $x_I^*(x_a)$ and $x_a^*(x_I)$ cross is Pareto-dominant.*

Proof. This can be seen as follows. Let x_I^1 and x_a^1 denote the equilibrium values of the first Nash equilibrium and x_I^2 and x_a^2 denote the equilibrium values of an equilibrium with higher levels of R&D spending, that is $x_I^2 > x_I^1$ and $x_a^2 > x_a^1$. Denote by V_1^I and V_2^I the value of expected profits for the incumbent in each equilibrium. Then for the incumbent the following holds:

$$V_1^I = \frac{\Pi^I h\left(x_I^1\right) + r\Pi^A - x_I^1}{r + h(x_I^1) + nh(x_a^1)} > \frac{\Pi^I h\left(x_I^2\right) + r\Pi^A - x_I^2}{r + h(x_I^2) + nh(x_a^1)} > \frac{\Pi^I h\left(x_I^2\right) + r\Pi^A - x_I^2}{r + h(x_I^2) + nh(x_a^2)} = V_2^I$$

Consequently, $V_1^I > V_2^I$. The first inequality holds because x_I^1 is an optimal response to x_a^1 and the second inequality holds as $h(x_R^2) > h(x_R^1)$. Thus the equilibrium with the smaller levels of investment is preferred by the incumbent. A similar argument holds for rivals and this outcome is therefore Pareto-preferred. ■

The two key features of this equilibrium are that the functions cross each other from below and that, no matter how the functions shift, the equilibrium always exists. This makes the comparative statics straightforward.

4.4.5 Effects of exclusion

We now show that tying reduces the aggregate rate of innovation in the model and that it increases the profits of the incumbent. Thus, unless a competition authority intervenes, the incumbent will always choose to exclude and innovation will fall. The fact that the equilibrium functions $x_I^*(x_a)$ and $x_a^*(x_I)$ slope upwards immediately gives us our first result:

Proposition 4.3 *When neither condition (4.2) nor (4.3) holds, exclusionary behaviour by the incumbent reduces the aggregate rate of innovation.*

When neither condition (4.2) nor condition (4.3) holds, outsiders can never earn positive profits from innovation and will choose to abandon their R&D altogether following exclusion from the complementary product market. As the function $x_I^*(x_a)$ slopes upwards, the incumbent therefore reduces its own arrival rate in response with the result that the aggregate arrival rate falls. Because they are not active in the complementary product market, rival firms are now unable to keep up to date with the latest technology, and can not earn positive profits from the discovery of an idea for a superior product. This is quite an extreme case and, as we see below, cannot occur when we introduce simple extensions, such as intellectual property, into the model.

When condition (4.3) holds outsiders can still earn a positive return from a successful innovation. However, by Proposition 4.1 this return is less than the no-exclusion return. We now show that this reduction in return decreases the equilibrium R&D efforts of rivals and in response the incumbent:

Proposition 4.4 *When we assume that the Pareto-dominant Nash equilibrium is selected, exclusion reduces the aggregate rate of innovation in the industry.*

Proof. We have already shown that at the Pareto-dominant outcome, the equilibrium functions cross from below, so we only need to show that exclusion shifts the equilibrium function of rival firms to the left. Exclusion reduces the return from innovation for a rival from Π^R to Π^O. Therefore, if we can show that $\frac{dx_a^*}{d\Pi^a}$ is always positive then our proposition holds. Using implicit function theory on equation (4.7) we get:

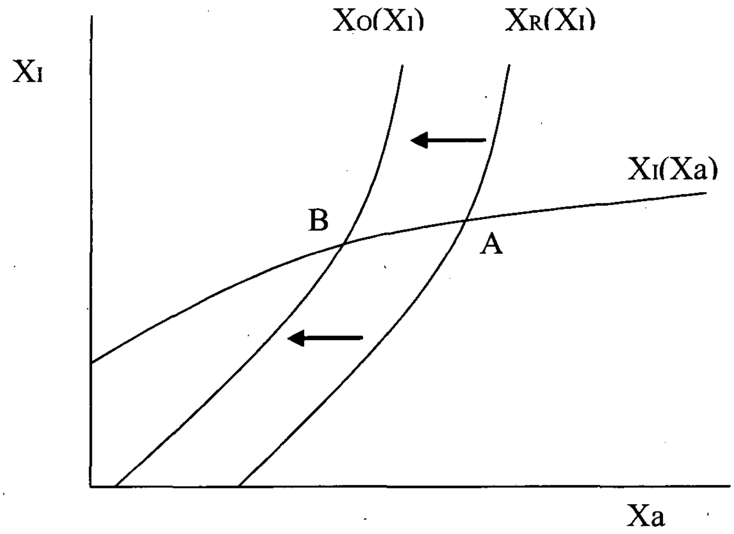
$$\frac{dx_a^*}{d\Pi^a} = -\frac{h'(x_a)(r + h(x_I) + (n-1)h(x_a))}{h''(x_a)(\Pi^a D - \Pi^a h(x_a) - x_a) + h'(x_a)n(h'(x_a)\Pi^a - 1) - h'(x_a)h'(x_a)\Pi^a}$$

Where $D = r + h(x_I) + nh(x_a)$. We have already shown in the proof of proposition (4.2) that the denominator is negative. It is also clear that the numerator is positive (as $h'(.)$ and $h(.)$ are always positive). This means that all marginal reductions in Π^a shift the reaction function of rivals to the left and the reduction from Π^R to Π^O reduces the aggregate rate of innovation in the industry. ■

Together both our propositions say that whenever tying reduces the profitability of innovation for an incumbent's rivals, the aggregate equilibrium rate of innovation will fall. This is true for all cases, except when outsiders are at no disadvantage, that is, when $c_A^O = c_A$. The comparative statics can be seen from the figure 4.1 below. The R&D expenditure of the incumbent is on the y-axis while the expenditure of each rival is on the x-axis. Prior to exclusion, the Pareto-dominant equilibrium (which is the only one shown) is at A. Exclusion shifts the equilibrium function for rivals to the left and at the new equilibrium, B, R&D expenditure of all firms and the aggregate arrival rate has unambiguously decreased.

These comparative statics are more robust than those found in Reinganum (1985). Reinganum simply assumes, without justification, that an equilibrium where the functions cross from below is selected. We are able to identify a specific such equilibrium, which we argue is a focal point of the game on the basis that it Pareto-dominates all others. Also,

Figure 4.1: Effects of exclusion on innovation



unlike other equilibria, we know this one will always exist and so the comparative statics are straightforward regardless of the size of the change in Π^a. In contrast, other equilibria may cease to exist when Π^a changes by a large amount.

We now show that tying increases the profits of the incumbent, who will therefore choose to do this unless prevented by a competition authority.

Lemma 4.3 *As long as $c_A^O > c_A$, tying always increases the profits of the incumbent*

Proof. This is essentially the same as the proof that the first equilibrium is Pareto-preferred. We have already shown that exclusion always reduces the expenditure of the representative rival firm. The incumbent's expenditure will fall too. Denote by x_I^* and x_R^* the equilibrium expenditure of the incumbent and representative rival without exclusion and by $\overline{x}_I$ and $\overline{x}_O$ the equilibrium expenditure of the incumbent and representative rival with exclusion. We have $x_I^* > \overline{x}_I$ and $x_R^* > \overline{x}_O$. Denote by V_1^I the post-exclusion expected profits of the incumbent and by V_2^I the pre-exclusion profits. Then we have:

$$V_1^I = \frac{\Pi^I h\left(\overline{x}_I\right) + r\Pi^A - \overline{x}_I}{r + h(\overline{x}_I) + nh(\overline{x}_O)} > \frac{\Pi^I h\left(x_I^*\right) + r\Pi^A - x_I^*}{r + h(x_I^*) + nh(\overline{x}_O)} > \frac{\Pi^I h\left(x_I^*\right) + r\Pi^A - x_I^*}{r + h(x_I^*) + nh(x_R^*)} = V_2^I$$

The first inequality holds by the because $\overline{x}_I$ not x_I^* is a best response to $\overline{x}_O$. The second holds because $h(x_R^*) > h(\overline{x}_R)$ ■

Taken together, Proposition 4.4 and Lemma 4.3 say that an incumbent will always find it profitable to tie and that this will reduce the aggregate rate of innovation in the industry. The incumbent is able to reduce the probability that a rival firm will dislodge it from its monopoly position by directly damaging the technological capability of rivals. In the extreme case where outsiders are significantly disadvantaged in production costs, an incumbent is able to secure its position completely. The monopolist responds to the reduced threat of entry by "resting on its laurels" and reducing its own R&D. We are assuming that spillovers are strong enough that a competition authority will want to promote R&D, so the clear policy implication is that tying in high-tech markets should be banned. By banning tying a competition authority can promote competition *for* the market, even though the outcomes of the product market are, initially, unchanged.

4.5 Extensions

We now consider a number of extensions to our basic case. These extensions show that our general result is quite robust. We begin by considering a number of alternative ways in which exclusion can reduce the value that rivals place on winning the R&D race, such as increased product development costs. We then consider the effects of introducing free entry into the model, the impact of outsiders being able to invest directly in obtaining an absorptive capacity, and the impact of intellectual property rights.

4.5.1 Alternative effects of exclusion on rival firms

The results in our basic model are based on the assumption that an excluded firm has higher production costs compared to an incumbent, leading it to reduce its R&D. However, the results also apply to any other effect from exclusion that also reduces the rival firm's payoff from innovating, that is, reduces Π^R. When marginal costs of all firms are identical, the expression for this is:

$$\Pi^R = \frac{\overline{v} - v}{r} - F$$

Clearly, Π^R can fall as a result of either an increased F or a reduced $\overline{v}$. In the case of an increased F, an outsider has a higher cost of developing a product once it has successfully innovated. For example, this could include the costs of establishing contacts with suppliers and customers. Active firms would already have formed these links and could arguably introduce a product more easily. This clearly reduces Π^R and the results of Proposition 4.4 apply. Similarly, an outsider may have less knowledge of consumer tastes or the latest technology and may only be able to create a product with a value of $\widetilde{v}$, where $\widetilde{v} < \overline{v}$. Again, the results of Proposition 4.4 apply directly. This case may be more relevant for industries like software, where marginal costs are very low and the differences in them between firms are unlikely to be important.

Although these cases produce similar results to our main model, note that if a rival's marginal cost for the A component is equal to the incumbent, then it can always earn at least some rents from innovation. It is never profitable for the incumbent to imitate the rival and consequently tying can never force rivals to abandon their R&D altogether. Thus the incumbent cannot completely secure its position and always faces some probability of being supplanted.

4.5.2 Free entry

In the basic model we assume that the incumbent faces a fixed number of rivals in the R&D race. We now assume that entry is endogenous. Each rival must pay a fixed cost K in order to enter the R&D race, which can be thought of as the initial start up costs of establishing a research laboratory[4]. We assume that the incumbent has already sunk this cost. Entry into the product B market is still costless. The number of rival firms is now determined by the condition that expected gross profits of a rival firm must equal K, or:

$$V_j^a = \frac{\Pi^a h\left(x_a^*\right) - x_a^*}{r + nh(x_a^*) + h(x_I^*)} = K \tag{4.9}$$

We denote the equilibrium number of firms by n_a^*. It is easy to see that expected profits are decreasing in the number of firms:

Lemma 4.4 *As the number of rival firms increases, expected profits decrease and the aggregate arrival rate increases.*

Proof. Using implicit function theory on the first order conditions we can see that an increase in n shifts the equilibrium function for the incumbent up and the equilibrium function for rivals down and to the right. For the incumbent, we have:

$$\frac{dx_I^*}{dn} = -\frac{h(x_a^*)\left(h'\left(x_I\right)\Pi^I - 1\right)}{h''(x_I)\left(r\left(\Pi^I - \Pi^A\right) + \Pi^I nh\left(x_a\right) + x_I\right)}$$

The denominator is negative because the value function is globally concave. The numerator can easily be shown to be positive using the first order conditions (equations (4.6) and (4.7)), therefore the whole expression is positive. For rival firms we have:

$$\frac{dx_a^*}{dn} = -\frac{h(x_a^*)\left(h'\left(x_a\right)\Pi^a - 1\right)}{h''(x_a)\left(D(\Pi^a - V^a)\right) + h'(x_a)h'(x_a)(nV^a - \Pi^a)}$$

We have shown in the Appendix, section C.2, that the denominator is negative and, again, it is easy to show that the numerator is positive. So, the equilibrium function for rivals

[4] The assumption of a fixed cost is necessary here as a firm's *gross* profits can never be driven to zero. Regardless of the aggregate arrival rate of a firm's competitors, a firm can always profitably invest an infinitessimal amount of R&D and earn positive expected profits.

shifts to the right and, as we are focusing on the Pareto-preferred equilibrium where the two equilibrium functions cross from below, the equilibrium levels of R&D expenditure for all firms will increase. We have already shown in the proof of proposition 4.2 above that an equilibrium involving higher levels of R&D expenditure by all firms has lower expected profits for each firm. ■

When the incumbent engages in tying, Π^a falls from Π^R to Π^O and expected profits will fall below K. As a result, by Lemma 4.4 the equilibrium number of firms must fall in order for equation (4.9) to hold. This reduction in the number of firms further reduces the aggregate rate of innovation. Thus, the effects are greater compared to the case where there is a fixed number of firms, set at the non-exclusion level n_R^*, and no fixed entry cost.

Proposition 4.5 *When the number of firms is initially equal to n_R^*, the impact of tying on aggregate innovation is greater under free entry.*

4.5.3 Outsiders' investment in absorptive capacity

Our basic model assumes that excluded firms have no method of acquiring an absorptive capacity once excluded from the B market. However, it is probably more realistic to assume that excluded firms do have some options for building up this capacity, for example, by investing in R&D specifically directed at monitoring and learning from the incumbent or by directly investing in relationships with suppliers and buyers. In this section we assume that an outsider can invest a fixed amount, G, and gain a marginal cost of production for the A product that is identical to the incumbent (i.e. c_A). When a firm does this, its expected profits are $V^R - G$ instead of V^O. We assume that it is always worth an outsider investing G. The condition for this is that $V^R - G > V^O$, or:

$$\frac{\Pi^R h\left(x_R^*\right) - x_R^*}{r + nh(x_R^*) + h(x_I^*)} - G > \frac{\Pi^O h\left(x_O^*\right) - x_O^*}{r + nh(x_O^*) + h(x_I^*)} \tag{4.10}$$

This will hold when Π^O is small enough, that is, when c_A^O or T is large enough. The immediate implication is that exclusion does not affect equilibrium R&D investments, as long as (4.10) holds and the number of rivals is fixed at n. Exclusion merely prompts rivals to invest in acquiring an absorptive capacity in order to keep up to date with the latest production technologies. Once they have done this, they remain aggressive competitors in R&D and the incumbent does not benefit.

Things are different, however, when we consider the case of free entry. Following exclusion, a firm must invest $K + G$ instead of just K. This means that exclusion, by increasing the right hand side of (4.9) must reduce the number of firms. In turn, this reduces the aggregate arrival rate of the incumbent's rivals and increases the incumbents profits.

These results gives us the following proposition:

Proposition 4.6 *If excluded firms can profitably invest in developing an absorptive capacity, tying has no effect when the number of rivals is fixed. However, when there is free entry, the cost of acquiring an absorptive capacity reduces the number of rivals and in turn reduces aggregate R&D.*

The mechanism here is somewhat different than in our main case. Each outsider is just as much of an aggressive competitor in the R&D race as an active firm (they value winning the race as much), but the cost of participation is higher and the number of entrants is lower.

4.5.4 Intellectual property

So far we have assumed that an innovator is protected from imitation by a first mover advantage in sinking development costs. Firms that lose the R&D race will not imitate the firm (unless condition (4.2) fails to hold) because the resulting Bertrand competition will drive gross profits to zero, leading to a loss net of development costs. This means that an excluded rival firm, which has high production costs, places a much lower value on winning the race. Things may be somewhat different if the winning firm has ownership of the knowledge it develops, either from a patent or through secrecy. An outsider (i.e. an excluded rival firm) may be able to sell the knowledge to the incumbent for a greater value than the knowledge is worth to itself. Similarly, the firm could agree to be taken over by the incumbent. This is a pattern that is often observed in high tech industries where an incumbent exists alongside small highly innovative firms who, presumably, are less able to develop their ideas into products that are produced and marketed on a large scale.

We follow a standard model of bargaining over the division of rents by assuming that both firms (the incumbent and the successful outsider) receive at least their outside option and split what is left according to a parameter $\beta \in [0,1]$, which is defined as the share received by the outsider. We assume that the new technology is sufficiently different that the incumbent can not demand licence fees from its ownership of the old technology. Outside values depend on whether condition (4.3) holds. If it does an outsider can earn positive profits Π^O from its innovation and the incumbent earns nothing. Therefore the two parties bargain over the extra value from having the more efficient incumbent produce the product, which is equal to $\left(c_A^O - c_A\right)\frac{(1-e^{-rT})}{r}$. As long as $\beta > 0$, the outsider is better off compared to the case with no intellectual property, receiving $\Pi^O + \beta\left(c_A^O - c_A\right)\frac{(1-e^{-rT})}{r}$ instead of just Π^O.

When condition (4.3) does not hold, the outside option of the excluded firm drops to zero because it can not recover the development cost, F. The incumbent's outside option is simply Π^A, the value of its existing profit flow. Therefore the outsider receives a profit of $\beta(\Pi^I - \Pi^A)$, while the incumbent receives a profit of $\Pi^I - \beta\left(\Pi^I - \Pi^A\right)$.

The first thing to note from these results is that outsiders will always place a positive value on winning the R&D race and therefore cannot be excluded from participating in it. Because the innovation has extra value to the incumbent (specifically, $\Pi^I - \Pi^A$) the outsider will be able to capture some of this from its ownership of the knowledge. The exact amount depends on the parameter β and the incumbent's outside option. In all cases the outsider is worse off under exclusion and will compete less aggressively in the R&D race, however, the presence of intellectual property rights means that the effects are mitigated, especially when an outsider can profitably produce the product itself and has a strong bargaining position (i.e. a high β). We summarize these results in the following proposition.

Proposition 4.7 *When firms own property rights over their innovations, the effects of exclusion are reduced. However, the incumbent will still choose to exclude rivals and the aggregate rate of innovation will fall.*

4.6 Discussion and Conclusions

We have shown how an incumbent with a monopoly over a primary component can increase its profits by tying complementary products. The key feature of the model is that active firms (i.e. those that produce complementary products) are more able to keep up with the latest technology in the industry than outsiders. In our basic model this takes the form of knowledge of the most efficient production processes. We then extend this by considering the effects of increased product development costs and reduced product quality. By selecting the Pareto-dominant equilibrium we are able to obtain straightforward comparative statics for the effects of tying. Tying reduces the aggregate rate of innovation in the industry and should therefore be blocked by a competition authority that seeks to promote innovation. These results hold under a wide range of conditions and do not rely on specific parameter values. All that is required is that an outsider has some cost disadvantage which reduces the return from innovation. Intellectual property rights can mitigate these effects, but they do not overcome them.

Our results complement those of Choi and Stefanidis (2001) and Carlton and Walman

(2002). In Choi and Stefanadis, tying prevents simultaneous entry into both components but, unlike our model, is not effective when there is free entry into one of the components. In Carlton and Waldman, tying prevents an entrant from exploiting intertemporal economies of scale in the complementary component. In our model by contrast, the results do not depend on potential entrants being able to earn rents from the complementary market. Also, unlike both of these models, we do not assume that the incumbent's rival has a superior complementary product. Although this is a common assumption in the literature, it is not explained. Certainly, returning to the Microsoft case, it is not clear that Netscape Navigator was significantly better than Internet Explorer.

The policy implications of our model are straightforward. A competition authority that seeks to promote innovation should be wary of tying in a systems markets when there is the potential for innovation in the primary market and when spillovers are important. Even if outsiders can still benefit to some extent from spillovers, tying is harmful as long as active firms benefit more. Thus the model does not depend on highly specific parameter values. The only case where tying has no effect is where being active in the complementary market yields no technological benefits.

It is worth noting that, by banning tying, the competition authority is not seeking to promote product market competition. The firm with a monopoly over the primary product is able to extract all rents in our model and the presence of multiple complementary producers does not bring down the price of a system for consumers. Instead, the competition authority is trying to promote competition *for* the market. There is a large debate in anti-trust circles about whether authorities should pay attention to potential competition in "innovation markets" rather than simply focusing on product markets (for example, see Davis (2003)). There are a handful of cases where the concept has been applied directly, for example the Department of Justice's action against the proposed take-over of Northrop Grumman by Lockheed Martin in 1998, however, the bulk of cases are still based on standard product markets. Whatever the legal issues, our analysis suggests that it is something competition authorities should take into account.

We now discuss some of the key assumptions underlying our model. First, we use a standard patent race formulation based on an exponential distribution of success over time. In this model, duplication is not an issue and the aggregate arrival rate is simply the sum of individual arrival rates. This means that extra R&D spending by any firm is useful. The model also has the important property that reaction functions slope upwards so that increased competition unambiguously stimulates innovation. By contrast, in a model such as that used in Cabral and Polak (2005) firms directly choose the probability that they succeed in innovating and time is not explicitly considered. This means that there is a risk of wasteful duplication (i.e. both firms succeeding). Cabral and Polak (2005) use this model to show the effects of firm dominance in an industry, defined as the premium value that consumers place on one firm's products. They find that an increase in dominance increases a firm's R&D while reducing that of its rival. When the possibility of duplication is considered, this shift in R&D can be beneficial, even though overall R&D spending may fall, because of the reduced duplication. These effects are not considered in the racing model that we use.

Second, we have assumed that more R&D is always beneficial to society because of spillovers to other sectors of the economy or to future research. Without this assumption excessive R&D is a real possibility. As in all racing models of R&D, much of the perceived benefit of an individuals firm's decision to invest in R&D comes at the expense of rival firms. This can lead to a situation where too much is invested in R&D. In this case, tying, by reducing equilibrium R&D levels could be beneficial. This means that a competition authority must make a judgement about the wider social return from innovation, something that will not be easy in most cases[5].

Third, we have not considered how the incumbent achieves its position in the first place. If this is the result of risky R&D then the possibility of being able to tie in the future may encourage early innovation, even though it discourages the subsequent invention of a superior primary component. In balancing these effects a competition authority must be able to weigh up the relative importance of early and later innovations. It also requires commitment on the part of the competition authority since after the first innovation it would always want to ban tying. These issues are discussed in the literature on patents and sequential innovations (see for example Green and Scotchmer (1995)).

In our model, we have assumed that the main threat to a monopolist is a superior version of its own product. However, if the main threat is from the emergence of a new market altogether based on a completely new technology, tying may be ineffective. For example the rise of digital electronics in sectors like stereos (mp3 players) and photography (digital cameras) allowed outsiders to challenge incumbent firms. In this case, the threat will come from outsiders with experience of the new technology, not necessarily those active in the current industry. For example the rise of mp3 players allowed software firms like Apple to challenge electronics producers like Sony. Tying to prevent firms from gaining a knowledge of the existing technology may be ineffective in such cases.

Another key assumption we have made is that the incumbent pays no price for tying. Other models, such as Choi and Stefanidis, point to the fact that tying prevents the

[5]In many racing models, additional R&D is also beneficial because monopolies cannot extract all of the surplus from their innovation. However, in our model firms appropriate all the surplus.

monopolist from extracting rent from a supplier of a superior complementary product. In cases where rival complementary producers add value to the system, an incumbent would have to balance the gain from protecting its position in the primary market with the gain from extracting rents from superior complementary products. As innovations will occurs in the future, and are thus discounted and uncertain, the immediate gains from extracting rents could easily outweigh the benefits from reducing rivals' R&D.

Our model focuses on absorptive capacity as the main benefit of being active in the production of complementary goods. However, there are other benefits of being active that could play a similar role. Producing complementary goods may generate knowledge via learning-by-doing, which could have direct relevance for the production of primary goods. In this case the above results would apply; an outsider would have fewer opportunities to gain this experience and may find it less profitable to invest in R&D. However, this mechanism does require that knowledge gained from the production of complementary goods is directly applicable to the production of primary goods, something that will not be true in many cases. The benefits from obtaining an absorptive capacity on the other hand would apply in more general cases.

Finally, being active may also help a firm obtain the financing necessary to conduct R&D. Only the incumbent can fund R&D out of retained earnings in our model, so all rivals will need to obtain loans. Banks may be reluctant to lend money to outsiders who are not able to demonstrate their general managerial competence. Successfully producing complementary products, by contrast, may signal that a firm is well run and make it easier to obtain funding. Whether this is a significant disadvantage would depend on whether outsiders have other mechanisms to signal their competence.

Appendix A

Chapter 2

A.1 Conditions for the symmetric outcome to be a global maximum

Here we show that, given our assumptions and restrictions, the outcomes identified in the main text are global maximums. The second order derivative of the profit function in the first period is:

$$\frac{d^2\Pi_i}{dk_i^2} = \frac{2SN_1^2}{(N_1+1)^2} - \beta\,(\beta-1)\,k_i^{\beta-2} \tag{A.1}$$

At the symmetric level of capability, k_1, given by equation (2.6), the condition for this to be negative is simply:

$$N_1 < \beta - 1$$

This is the condition contained in Lemma 2.1. The same condition also applies in period 2, however, it always holds here as $N_2 \leq \frac{\beta}{2}$. As discussed in the main text, we keep the number of active firms below $\beta - 1$ through restrictions on h. Therefore we can say the the symmetric outcome is always a *local* maximum for each firm. We now discuss when it is a global maximum.

Clearly, (A.1) becomes positive for low levels of k_i. From the profit function we can see that the corner solution where a firm invests the minimum capability necessary to obtain positive sales is always a *local* maximum (conditional on the firm being active). When other firms invest the symmetric level, k_t, this level of capability, which we call $k_{\min}$ is given by:

$$k_{\min} = \left(\frac{N_t - 1}{N_t}\right) k_t$$

This is determined from equation (2.3). The first derivative of profits at this outcome is simply:

$$\frac{d\Pi_i}{dk_i} = -\frac{dF_i(k_{\min})}{dk_i}$$

Which in the first period is $-\beta k_i^{\beta-1}$ and in the second period is $-\beta K^{-\theta} k_i^{\beta-1}$. Hence this is a local maximum (conditional on the firm being active). Profits here are simply:

$$\Pi_i(k_{\min}) = -F_i(k_{\min})$$

This will never be a global maximum when the symmetric outcome is associated with positive profits, which occurs when $N < \frac{\beta}{2}$. Therefore the symmetric outcome in the second period is a global maximum for each firm. However, in the first period when $N_1 > \frac{\beta}{2}$, this may exceed the profits from investing in the symmetric level, k_1. Using the profit and cost functions, the precise condition for a deviation to $k_{\min}$ not to be profitable is:

$$\left(\frac{N_1 - 1}{N_1}\right)^{\beta} < \left(1 - \frac{\beta}{2N_1}\right)$$

In general this only holds for values of N_1 that are only slightly larger than $\frac{\beta}{2}$. So, for large scale entry, a firm would want to deviate from the symmetric outcome. However, we impose the restriction that a firm in the first period must have a level of R&D spending sufficiently close to the other firms in order to receive the spillover, not that it must merely be active (i.e. have positive sales). Specifically, we require a firm to spend at least a proportion, g, of the median R&D spending in the industry. We now discuss how g is determined.

Given that a firm's rivals invest the symmetric level of capability, k_1^{β}, the profits of a firm that invests a proportion α of this R&D expenditure (and has a capability of $\alpha^{\frac{1}{\beta}} k_1$) is:

$$\Pi_1 = \frac{S}{(N_1+1)^2}\left(N_1\alpha^{\frac{1}{\beta}} - (N_1 - 1)\right)^2 \left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{2}{\beta-2}} - \alpha\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\beta}{\beta-2}}$$

Note that for the firm to be active (i.e. have positive sales) we require:

$$\alpha > \left(\frac{(N_1 - 1)}{N_1}\right)^{\beta}$$

We denote the right hand side as $\overline{\alpha}$. We can write this profit function as:

$$\Pi_1(\alpha) = \left(\frac{\left(N_1\alpha^{\frac{1}{\beta}} - (N_1-1)\right)^2 \beta}{2N_1} - \alpha\right)\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\beta}{\beta-2}}$$

Profits when the firm adopts the symmetric outcome (i.e. $\alpha = 1$) are:

$$\Pi_1(1) = \left(\frac{\beta}{2N_1} - 1\right)\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\beta}{\beta-2}}.$$

and the levels of α for which the profits of a deviating firm are less than this are therefore implicitly given by:

$$\left(\frac{\left(N_1\alpha^{\frac{1}{\beta}} - (N_1-1)\right)^2\beta}{2N_1} - \alpha\right) < \left(\frac{\beta}{2N_1} - 1\right) \tag{A.2}$$

We want to restrict a firm to deviations (values of α) that satisfy this condition. As k_1 is a *local* maximum we know this always holds for α close to 1. We restrict deviations by imposing the condition that whenever α is less than a specified value, g, the firm can no longer obtain the spillover, with $g \geq \overline{\alpha}$.

We can rewrite the condition as:

$$\frac{\beta - \left(N_1\alpha^{\frac{1}{\beta}} - (N_1-1)\right)^2\beta}{2N_1} - 1 + \alpha > 0 \tag{A.3}$$

We now show that the left hand side is decreasing in N_1. This means that if the condition holds for the maximum value of N_1, it will hold for all lesser values of N_1. The highest value of N_1 in our model, which we denote by $\overline{N}$ is determined by h (see equation (2.13))

The derivative of the left hand side of (A.3), which we denote f, is:

$$\frac{df}{dN_1} = -\frac{1}{2}\beta\left(\alpha^{\frac{2}{\beta}} - 2\alpha^{\frac{1}{\beta}} + 1\right)$$

It is easy to show that $\left(\alpha^{\frac{2}{\beta}} - 2\alpha^{\frac{1}{\beta}} + 1\right)$ is always positive for $\alpha \in [0,1)$ so this derivative is negative. So, if (A.3) holds at $N_1 = \overline{N}$, it will hold at all lesser values of N_1. This means we can restrict our attention to the following condition:

$$\frac{\beta - \left(\overline{N}\alpha^{\frac{1}{\beta}} - (\overline{N}-1)\right)^2\beta}{2\overline{N}} - 1 + \alpha > 0 \tag{A.4}$$

We know that condition (A.4) holds for α close to 1. We are interested in the highest value of α for which this *doesn't* hold. We call this g and impose the condition that a firm can only obtain the spillover if it spends an amount on R&D that is greater that a proportion g of the firm with the median R&D expenditure (if this is less than $\overline{\alpha}$, we set g to $\overline{\alpha}$). g will be uniquely determined (given h and β). Although we can not solve for it explicitly, numerical analysis gives the following values of g for various values of β and $\overline{N}$

(which is determined by h):

β	$\overline{N}$	$\overline{\alpha}$	g
10	6	0.16	0.17
10	8	0.26	0.63
30	20	0.21	0.26
30	28	0.34	0.89
100	70	0.24	0.31
100	90	0.32	0.74

This basically shows that, when $\overline{N}$ is modest (which corresponds to a modest value of h) g doesn't have to be significantly higher than $\overline{\alpha}$. For example when $\beta = 10$ and $\overline{N} = 6$ (this corresponds to an h of $\frac{1}{6}$) a deviating firm is only active if it invests at least 16% of the other firm's R&D and only receives the spillover if it invests 17% of their R&D. On the other hand when $\overline{N}$ is large, g becomes correspondingly larger.

Given our above assumptions the symmetric solution to the first order conditions is always a global maximum for each firm, for any merger policy. It is always a local maximum because beyond a certain level of entry, new firms enter as "learning firms" and do not develop products. It is always a global maximum because we only allow a firm to receive the spillover in the second period if it invests in a sufficient amount of R&D. The maximum number of firms is determined by h according to equation (2.13). The minimum R&D investment is implicitly determined by condition (A.4).

A.2 Proof of Lemma 2.2

$\frac{dN_1}{dN_2}$ is given by:

$$\frac{dN_1}{dN_2} = \frac{\left(N_2\left(4\left(N_2-\beta\right)-\beta^2+4\right)+\beta^2\right)\left(\beta-2\right)\left(\frac{N_2}{N_1}\right)^{\frac{2}{(\beta-2)}}\left(\frac{(N_1+1)}{(N_2+1)}\right)^{\frac{3\beta-2}{(\beta-2)}}\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\beta\theta}{(\beta-2)^2}}}{8N_1\left(N_1+1\right)+\beta\left(2\beta-12N_1+2\beta N_1-\beta^2-4N_1^2+\beta^2 N_1\right)+\beta\theta\left(N_1-1\right)\left(2N_1-\beta\right)}$$

We can show that in any symmetric solution $\frac{dN_1}{dN_2}$ is negative. This has the same sign as:

$$\frac{\left(N_2\left(4\left(N_2-\beta\right)-\beta^2+4\right)+\beta^2\right)\left(\beta-2\right)}{8N_1\left(N_1+1\right)+\beta\left(2\beta-12N_1+2\beta N_1-\beta^2-4N_1^2+\beta^2 N_1\right)+\beta\theta\left(N_1-1\right)\left(2N_1-\beta\right)}$$

The numerator is negative if:

$4\left(N_2+1\right)+\frac{\beta^2}{N_2}<\beta\left(\beta+4\right)$

Because N_2 can not exceed $\frac{\beta}{2}$, the Left hand side can at most be:

$4\left(\frac{\beta}{2}+1\right)+2\beta<\beta\left(\beta+4\right)$

Or

$(2-\beta)(\beta+2) < 0$

Which always holds as $\beta > 2$.

The denominator is positive if:

$8N_1(N_1+1)+\beta\left(2\beta-12N_1+2\beta N_1-\beta^2-4N_1^2+\beta^2N_1\right)+\beta\theta(N_1-1)(2N_1-\beta) > 0$

The last term is always positive (N_1 is greater than $\frac{\beta}{2}$) so it is sufficient that:

$8N_1(N_1+1)+\beta\left(2\beta-12N_1+2\beta N_1-\beta^2-4N_1^2+\beta^2N_1\right) > 0$

The left hand side is increasing in N_1. (The derivative is $(2-\beta)\left(8N_1-4\beta-\beta^2+4\right)$ which is always positive given our restriction that $N_1 < \beta-1$). So the smallest the LHS can be is when $N_1 = 1$. Substituting, this into $\left(8N_1(N_1+1)+\beta\left(2\beta-12N_1+2\beta N_1-\beta^2-4N_1^2+\beta^2N_1\right)\right)$ we get $4(\beta-2)^2$, which is clearly positive. So, we conclude that in any symmetric solution $\frac{dN_1}{dN_2}$ is negative.

A.3 Proof of Proposition 2.2

We are interested in when the following is positive:

$$\frac{dk_2}{dN_2} = \frac{\partial k_2}{\partial N_2} + \frac{\partial k_2}{\partial N_1}\frac{dN_1}{dN_2}$$

$\frac{dN_1}{dN_2}$ is given above. The other two derivatives are:

$$\frac{\partial k_2}{\partial N_2} = -\frac{(N_2-1)}{N_2(\beta-2)(N_2+1)}\left(\frac{2SN_2}{\beta(N_2+1)^2}\right)^{\frac{1}{\beta-2}}\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\theta}{(\beta-2)^2}}$$

$$\frac{\partial k_2}{\partial N_1} = -\frac{(N_1-1)\theta}{N_1(\beta-2)^2(N_1+1)}\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\theta}{(\beta-2)^2}}\left(\frac{2SN_2}{\beta(N_2+1)^2}\right)^{\frac{1}{\beta-2}}$$

Both of these are clearly negative. Substituting and simplifying gives the following condition for $\frac{dk_2}{dN_2}$ to be positive:

$$-\frac{\left(N_2\left(4(N_2-\beta)-\beta^2+4\right)+\beta^2\right)\theta\left(\frac{N_2}{N_1}\right)^{\frac{\beta}{(\beta-2)}}\left(\frac{(N_1+1)}{(N_2+1)}\right)^{\frac{2\beta}{(\beta-2)}}\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\beta\theta}{(\beta-2)^2}}}{8N_1(N_1+1)+\beta\left(2\beta-12N_1+2\beta N_1-\beta^2-4N_1^2+\beta^2N_1\right)+\beta\theta(N_1-1)(2N_1-\beta)} > \frac{(N_2-1)}{(N_1-1)}$$

Where the left hand side is positive (see proof of Lemma 2.2) and increasing in S. Although N_1 is also a function of S, this is bounded above by $\overline{N}$ as given by equation (2.13) above. It therefore follows that the above condition will always hold for large enough S.

Without an explicit solution for N_1 as a function of N_2 and S, it is not easy to determine the threshold for S explicitly, however, we can look at the case of a marginal relaxation in merger policy starting from a complete ban, where $N_1 = N_2 = \frac{\beta}{2}$. Substituting into the above condition and simplifying gives the following expression for the threshold level of S which we denote $\widetilde{S}$:

$$\widetilde{S} = \left(\frac{1}{2}\beta + 1\right)^2 \left(\frac{1}{\theta}(\beta - 2)\right)^{\frac{(\beta-2)^2}{\theta\beta}}$$

For reasonable parameter values, the threshold of S is not large, for example when $\beta = 6$ and $\theta = 4$, it is only 16.

A.4 Proof of Proposition 2.4

We need to show that $\left(\frac{dCS_1}{dN_1} + \frac{\partial CS_2}{\partial N_1}\right)$ is negative in sufficiently large markets. The derivatives are:

$$\frac{dCS_1}{dN_1} = \frac{SN_1(2\beta - N_1 - 3)}{2(\beta - 2)(N_1 + 1)^3}\left(\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{1}{\beta-2}}\right)$$

and,

$$\frac{\partial CS_2}{\partial N_1} = \frac{S}{2}\left(\frac{N_2}{N_2+1}\right)^2\left(\frac{2SN_2}{\beta(N_2+1)^2}\right)^{\frac{1}{(\beta-2)}} \frac{\theta(1-N_1)}{(\beta-2)^2 N_1(N_1+1)}\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\theta}{(\beta-2)^2}}$$

Our condition is $\frac{dCS_1}{dN_1} + \frac{\partial CS_2}{\partial N_1} < 0$. Substituting and simplifying gives the following condition:

$$(2\beta - N_1 - 3) < \left(\frac{N_2}{N_1}\right)^{\frac{2\beta-1}{(\beta-2)}}\left(\frac{(N_1+1)}{(N_2+1)}\right)^{\frac{2\beta}{\beta-2}}\frac{\theta(N_1-1)}{(\beta-2)}\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\theta}{(\beta-2)^2}}$$

Clearly this will hold when S is large enough (again, remember that N_1 is bounded above by $\overline{N_1}$). It is also immediately clear that the critical threshold of S is decreasing in θ and approaches infinity as θ goes to zero. As with the innovation case, we can get an explicit solution for the threshold of S, which we denote $\overline{S}$, for case of a marginal relaxation in merger policy starting from a complete ban, where $N_1 = N_2 = \frac{\beta}{2}$. Substituting into the above condition and simplifying gives the following expression for the threshold level of S:

$$\overline{S} = \left(\frac{1}{2}\beta + 1\right)^2\left(\frac{3}{\theta}(\beta - 2)\right)^{\frac{(\beta-2)^2}{\theta\beta}}$$

For any values of β and θ, this is larger that $\widetilde{S}$.

A.5 Proof that second period entry is blocked in large markets

Here we aim to show that when S is large enough, incumbent firms have such a cost advantage from the spillover that mergers do not induce entry. When incumbents expect an entrant to be unable to compete and to have zero output they will simply set their capability at the symmetric outcome given by equation (2.7) (after substituting for the spillover K given by equation (2.6)):

$$k_2 = \left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\theta}{(\beta-2)^2}} \left(\frac{2SN_2}{\beta(N_2+1)^2}\right)^{\frac{1}{(\beta-2)}} \tag{A.5}$$

This is an equilibrium if an entrant can not make positive profits given that incumbents invest k_2. We first show that there is a limit value of k_2 which we denote k_2^l such that the profits of an entrant is always zero if $k_2 > k_2^l$. We solve for k_2^l and show that as S becomes sufficiently large, k_2 will exceed k_2^l. Therefore, in sufficiently large markets, entry is blocked.

The profit of an entrant facing N_2 incumbents is:

$$\Pi_e(k_e, k_2) = \frac{S}{(N_2+2)^2}\left(k_e + N_2(k_e - k_2)\right)^2 - k_e^\beta \tag{A.6}$$

Where k_e is the entrant's capability. The entrant sets k_e to maximize profits, giving the following first order condition:

$$\frac{2S(N_2+1)}{(N_2+2)^2}\left(k_e + N_2(k_e - k_2)\right) - \beta k_e^{\beta-1} = 0 \tag{A.7}$$

The solution to this gives k_e^*. It is easy to show that second order conditions will hold whenever k_e^* is associated with a positive profit. k_2^l is given by the condition that an entrant's profits are equal to zero when it invests k_e^*:

$$\Pi_e(k_e^*, k_2) = \frac{S}{(N_2+2)^2}\left(k_e^* + N_2(k_e^* - k_2^l)\right)^2 - (k_e^*)^\beta = 0 \tag{A.8}$$

We can divide both sides of the first order condition by β, multiply by k_e^* and solve for $(k_e^*)^\beta$. We then substitute this into (A.8) to get the following:

$$\frac{2(N_2+1)k_e^*}{\left(k_e^* + N_2(k_e^* - k_2^l)\right)} = \beta$$

Which we can solve for k_e^* :

$$k_e^* = \frac{\beta N_2}{(\beta-2)(N_2+1)} k_2^l$$

We substitute this into equation (A.8) to get:

$$\frac{S}{(N_2+2)^2}\left(\frac{k_2^l N_2}{2\,(\beta-2)}\right)^2-\left(\frac{\beta N_2 k_2^l}{(\beta-2)\,(N_2+1)}\right)^\beta=0$$

We can solve this for k_2^l to get:

$$k_2^l=\left(\frac{S}{(N_2+2)^2}\left(\frac{N_2}{2\,(\beta-2)}\right)^2\left(\frac{\beta N_2}{(\beta-2)\,(N_2+1)}\right)^{-\beta}\right)^{\frac{1}{\beta-2}}$$

We can now show that, for S sufficiently large, $k_2 > k_2^l$. Dividing the expression for k_2^l by that for k_2 we get:

$$\frac{k_2^l}{k_2}=\frac{\left(\frac{N_2}{2(\beta-2)}\right)^{\frac{2}{(\beta-2)}}}{\left(\frac{2SN_1}{\beta(N_1+1)^2}\right)^{\frac{\theta}{(\beta-2)^2}}\left(\frac{\beta N_2}{(\beta-2)(N_2+1)}\right)^{\frac{\beta}{\beta-2}}}$$

This can be made arbitrarily small by setting S at a sufficiently high level (remember that N_1 is bounded by $\overline{N}$), so at some point it will be less that 1. We conclude that entry is blocked in sufficiently large markets.

Appendix B

Chapter 3

B.1 Second order conditions

When firm i invests a positive amount in R&D (so that both first order conditions hold with equality), the second order derivatives for that firm are:

$$\frac{d^2\Pi_i}{dq_i^2} = -2 \tag{B.1}$$

$$\frac{d^2\Pi_i}{dz_i^2} = -\frac{1}{4}\frac{q_i D_i^2}{z_i D_i\sqrt{z_i D_i + t\alpha z_j D_j} + t\alpha z_j D_j\sqrt{z_1 D_1 + t\alpha z_j D_j}} \tag{B.2}$$

$$\frac{d^2\Pi_i}{dz_i dq_i} = \frac{1}{2}\frac{D_i}{\sqrt{z_i D_i + t\alpha z_j D_j}}$$

Using the resulting Hessian matrix and the determinant based test for negative semi-definiteness (the first principal minor negative, the second one positive), we get the following condition:

$$\frac{\left(2q_i - \sqrt{z_i D_i + t\alpha z_j D_j}\right) D_i^2}{4\left(z_i D_i + t\alpha z_j D_j\right)\left(\sqrt{z_i D_i + t\alpha z_j D_j}\right)} > 0$$

From the numerator it is easy to see that this has the same sign as $2q_i - s_i$. However, using the first-order conditions (equations (3.4) and (3.5)) we can show that $q_i = \frac{2}{D_i}s_i$. From this it is straightforward to show that second order conditions for a maximum hold when $D_i < 4$. A corresponding condition holds for firm j. Note that this always holds when equation (B.4) below holds; that is, when we restrict the parameters such that output is always positive we do not need to worry about second order conditions.

Things are slightly different in the case where a firm does not invest a positive amount of R&D. Here, $\frac{d\Pi_i}{dz_i}$ is negative and the non-negativity constraint binds. We now need to use a bordered Hessian matrix assessed at $z_i = 0$:

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & -\frac{1}{4}\frac{q_i D_i^2}{t\alpha z_j D_j \sqrt{t\alpha z_j D_j}} & \frac{1}{2}\frac{D_i}{\sqrt{t\alpha z_j D_j}} \\ 0 & \frac{1}{2}\frac{D_i}{\sqrt{t\alpha z_j D_j}} & -2 \end{bmatrix}$$

The determinant of the whole matrix is simply 2 which is obviously positive (as required for a maximum) and the determinant of the second principal minor is -1 which, again, satisfies the condition for a local maximum. Thus, second order conditions always hold when a firm ceases to invest in R&D.

B.2 Positive output when firms choose different technologies and there is no information sharing agreement

From equation (3.10) the condition for firm $i's$ output to be positive is:

$$\frac{A(2-d)+dc_j}{2} > c_i \tag{B.3}$$

It is clear that in a symmetric outcome this will always hold (given that marginal costs are positive and $B < A$). In the asymmetric case, the peripheral firm only has positive output if D_c and $\widehat{d}$ are not too high. To show this we can use equation (3.14) and its firm j equivalent. Note that the denominator for this expression is the same for both firms. This means that for both outputs to have the same sign, both numerators must have the same sign, which is true if $(2(2-d)-D_i)$ and $(2(2-d)-D_j)$ have the same sign. As D is equal to 1 when a firm has the peripheral technology, this means that the numerator for one of them will definitely be positive, and therefore we require the other to be positive too. This means that both firms will produce a positive output if:

$$D_c < 2\left(2-\widehat{d}\right) \equiv \overline{D}_c \tag{B.4}$$

Finally, we need the denominator of equation (3.14) to be positive. This condition is:

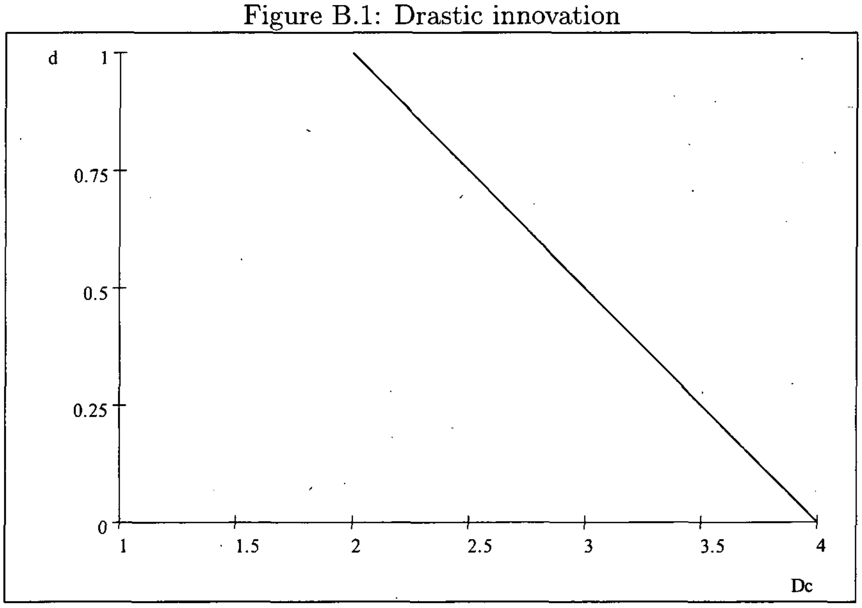
$$\frac{12-4\widehat{d}^2}{3} > D_c \tag{B.5}$$

It is straightforward to show that this is always holds if (B.4) holds. Furthermore, it is straightforward to show that if (B.4) does not hold then the first order derivative of profits with respect to a change in output for the peripheral-technology firm is negative at $q_i = 0$.

Thus, the peripheral firm produces nothing and the core technology firm enjoys monopoly profits.

We can plot condition (B.4):

Figure B.1: Drastic innovation



B.3 Non-negative marginal costs

Here we look at the conditions for marginal costs to be positive, that is for $B > s_i^*$ for each firm. To begin with we focus on the case where both firms invest in R&D. For firm i we can substitute for s_i^* from equation (3.11) and rearrange to get the following condition:

$$A < \frac{(2(2D_j + dD_i) - 4(2-d)(d+2))}{D_iD_j - 2D_i(2-d)}B \tag{B.6}$$

This places restrictions on how large A can be for a given B. For the symmetric case, this becomes:

$$A < \frac{2(d+2)}{D}B$$

Given that $A > B$, we require the coefficient on the right hand side to be greater than 1 in order for it to be possible that the condition holds. It is easy to see that this is true in the symmetric case as $D < 4$ by the second order conditions. For the asymmetric case, we only need to check the condition for the firm with the core technology as, looking at equation (3.11), it will have the higher s_i. With $D_j = 1$ equation (B.6) becomes:

$$A < \frac{2(6 - d(2d + D_c))}{D_c(2(2-d) - 1)}B \tag{B.7}$$

Again, we require the coefficient on the right hand side to be greater than 1. It can be shown that this is the case if equation (B.4) holds, that is if both firms' output is positive in equilibrium.

This gives us three conditions relating to each of the possible combinations of technology; two for the each symmetric case and one for the asymmetric case. For any given B we need to set A so that they all hold, which will be achieved if the case with the smallest coefficient on B in equation (B.6) holds.

We now check the conditions for marginal costs to be positive when one firm does not invest in R&D. The peripheral technology firm will always have higher marginal costs than the core-technology firm so we only need to check that marginal costs are positive for the latter. Using the expression for R&D expenditure in equation (3.21) we obtain the following:

$$A < \frac{\left(dD_c\sqrt{t\alpha} - 2d^2 - dD_c + 8\right)}{(2-d)\,D_c}B \tag{B.8}$$

As with equation (B.6) above this restricts the size of A relative to B. We need the coefficient on B to be greater than 1 and it is easy to show that this is the case.

To summarize, we now have a number of conditions limiting the size of A for a given B. Denote $\theta^{\gamma_i\gamma_j}$ as the coefficient on B in condition (B.6) when when firm i has a technology of γ_i and firm 2 chooses γ_j, and denote θ^* as the coefficient on B in equation (B.8). This gives the following:

$$A < \min\left\{\theta^{pp}, \theta^{cp}, \theta^{cc}, \theta^*\right\} \times B \tag{B.9}$$

Note from all the profit expressions we have derived in the main text that *relative* profits do not depend on the values of A and B. Thus we are able to set A and B such that marginal costs remain positive without affecting the second stage outcomes.

B.4 Pareto-preferred outcomes

Here we show that the (P,P) outcome (with or without spillovers) is preferred by both firms to the (C,C) outcome (without spillovers) for all permitted parameter values. The condition is $\Pi^{PP}(0) > \Pi^{CC}(0)$, which using equations (3.17) and (3.16) can be written as:

$$\frac{1}{3} > \frac{(4-D_c)}{(D_c-6)^2}$$

The right hand side is maximized at $D_c = 2$ which gives a value of $\frac{1}{8}$. As this is less than $\frac{1}{3}$ we conclude that firms always prefer the (P,P) outcome to the (C,C) outcome with no spillovers.

B.5 Competing peripheral technologies

In this section we show that even when peripheral technologies compete with each other, the free riding-effect almost always has the potential to make a deviation to the core technology unprofitable. We denote the product substitutability between two peripheral technologies as d^*. For simplicity we assume that the technological compatibility, t^*, is set equal to d^*. Using equation (3.15), profits in the (P,P) outcome are now:

$$\Pi^{PP}(\alpha) = \frac{(4(d^*\alpha + 1) - 1)(B - A)^2}{(d^*\alpha + 1)(2(d^* + 2) - 1)^2} \tag{B.10}$$

A unilateral deviation to the core technology is unprofitable if equation (B.10) exceeds equation (3.22), the profits of a core firm faced with a free-riding rival. Equation (3.22) is decreasing in $\widehat{d}$ (note we set $\widehat{t}$ to $\widehat{d}$) so we set $\widehat{d}$ to 1 and take the derivative with respect to D_c. This is:

$$\left.\frac{d\Pi_j^{CP}}{dD_c}\right|_{z_i=0,\widehat{d}=1} = \frac{(D-2)}{(D-6)^3} \tag{B.11}$$

and equation (3.22) is clearly maximised at $D_c = 2$, which results in a profit of $\frac{1}{8}(B-A)^2$. This means that, by setting $\widehat{d}$ close enough to 1 we can always drive profits down to at least this level. If we can show that the profits in the (P,P) outcome are always higher than this, no matter what value is placed on d^* we can conclude that the free-riding effect always has the potential to sustain the (P,P) outcome as an equilibrium as long as $\widehat{d}$ is sufficiently high. Equation (B.10) is decreasing in d^* (the derivative is $-\frac{(26d^*\alpha - 3\alpha + 16d^{*2}\alpha^2 + 12)}{(d^*\alpha+1)^2(2d^*+3)^3}$) so we can set d^* to 1 and evaluate the expression. This gives a value of $\frac{7}{50}(B-A)^2$, which is larger than $\frac{1}{8}(B-A)^2$. From this we conclude that, regardless of the value of D_c and regardless of the value of d^*, the free-riding effect can deter a deviation to the core technology if $\widehat{d}$ is sufficiently high. One immediate implication is that the free-riding effect does not rely on large "jumps" in product substitutability, that is high values of $\widehat{d} - d^*$. What is important is that the peripheral firm can commit not to do any R&D because of the information sharing agreement. When $\widehat{d}$ is high enough, this harms the core firm and renders a deviation from the (P,P) outcome unprofitable.

B.6 Partial information sharing agreements

We now assume that firms can agree to share any proportion of their research between 0 and 1. In the first stage, both firms simultaneously propose a value of $\alpha \in [0,1]$. An agreement is only made if both firms propose the same value. To rule out multiple equilibria we add the assumption that when both firms adopt the peripheral technology $t = \varepsilon > 0$. This means that there is a slight compatibility between peripheral technologies (we keep the assumption that the products are not demand substitutes, i.e. $d = 0$). We now show that when firms both adopt the same type of technology profits are increasing in spillovers. When firms adopt the same type of technology, profits are:

$$\Pi^{symmetric}(\alpha) = \frac{(4(t\alpha + 1) - D)(B - A)^2}{(t\alpha + 1)(2(d + 2) - D)^2} \tag{B.12}$$

The derivative of this with respect to α is:

$$\frac{d\Pi^{symmetric}(\alpha)}{d\alpha} = \frac{(B - A)^2 tD}{(t\alpha + 1)^2 (D - 2d - 4)^2} > 0 \tag{B.13}$$

We now prove the following:

Proposition B.1 *In region IV of Figure 3.3, when* $D_c < 3.36$, *and when firms can agree on any value of* α *between* 0 *and* 1, *firms will set* $\alpha = 1$. *This will shift equilibrium outcomes from (P,P) to (C,C).*

Proof. When spillovers can be variable, it is possible that firms would actually prefer the (C,C) outcome with *some* spillovers (so as not to change technology choices) to the (P,P) outcome. A *sufficient* condition for this not to be the case is that $D_c < 3.36$. This is determined by the condition that firms prefer the (P,P) outcome to the (C,C) outcome with full spillovers and can be derived from equation (B.12). There exists a critical value of α, which we call α^*, above which a firm would not want to deviate from the (P,P) outcome and adopt the core technology. We know this exists because a high enough value of α induces free riding, the profits of a core firm faced with a free-riding peripheral rival are decreasing in α (see equation (3.22)) and are less than the profits at the (P,P) outcome when $\alpha = 1$. This means that firms will always agree on a value of alpha of at least α^*. However, profits in the (P,P) outcome are increasing in α (as we assume t is strictly positive) and, as we rule out Pareto-dominated outcomes by Assumption 2, firms will both propose $\alpha = 1$ in the first stage. ■

Note that if we drop the assumption that there is always some technological compatibility between peripheral technologies, then it will still be an equilibrium for firms to set $\alpha = 1$, however, it will not be unique (any value between α^* and 1 is a potential equilibrium).

Appendix C

Chapter 4

C.1 Proof that first order conditions define a maximum

For both firms, the value function is globally concave. The second order derivative for an incumbent's value function is:

$$\frac{d^2V^I}{dx_I^2} = \frac{h''(x_I)(r\left(\Pi^I - \Pi^a\right) + \Pi^I nh\left(x_a\right) + x_I)}{(r+H)^2}$$

This is always negative as $h''(x)$ is always negative. Similarly, the second order derivative for a rival firm is always negative. It is easy to show that the value function always starts off positive and upwards sloping and eventually ends up downward sloping. Therefore there exists a unique solution to equation (4.6) for any value of x_a which yields a global maximum for the incumbent. Similarly, there is a unique solution to equation (4.7). These solutions are given by the implicit functions, $x_I^*(x_a)$ and $x_a^*(x_I)$.

C.2 Proof of Proposition 4.2

Equations (4.6) and (4.8) implicitly define a pair of functions in x_I, x_a space, which we call equilibrium functions. We denote these $x_I^*(x_a)$ and $x_a^*(x_I)$. Where these functions cross is a Nash equilibrium. We now show that these functions are upward sloping and must cross at least once. We also show that the first point at which they cross is Pareto-dominant. The slope of $x_I^*(x_a)$ is:

$$\frac{dx_I^*(x_a)}{dx_R} = -\frac{\left(h'\left(x_I\right)\Pi^I - 1\right) nh'(x_I)}{h''(x_I)\left(r\left(\Pi^I - \Pi^A\right) + \Pi^I nh\left(x_a\right) + x_I\right)}$$

The denominator is negative by the second order conditions. The numerator can be shown to be positive using the first order conditions and the value function. Therefore $x_I^*(x_a)$ slopes upwards.

The slope of $x_a^*(x_I)$ is:

$$\frac{dx_a^*(x_I)}{dx_I} = -\frac{\left(h'(x_a)\,\Pi^a - 1\right) h'(x_a)}{h''(x_a)\left(\Pi^a D - (\Pi^a h(x_a) - x_a)\right) + h'(x_a) n (h'(x_a)\Pi^a - 1) - h'(x_a) h'(x_a) \Pi^a}$$

Where $D = r + h(x_I) + nh(x_a)$. Again, the numerator can be shown to be positive using the first order conditions and the value function. We now show that the denominator is negative and therefore that the equilibrium function slopes upwards. Using the first order conditions and the value functions, the denominator can be written as:

$$h''(x_a)\left(D(\Pi^a - V^a)\right) + h'(x_a)h'(x_a)(nV^a - \Pi^a) \tag{C.1}$$

Using the expressions for the value function, V^a, it is straightforward to show that $D(\Pi^a - V^a)$ is positive and that $nV^a - \Pi^a$ is negative. Given this, (C.1) is negative and $x_a^*(x_I)$ slopes upwards.

Next we show that the equilibrium functions start off below each other. This simply means that $x_I^*(0)$ and $x_a^*(0)$ are strictly positive. When x_a is zero the derivative of the value function for the incumbent is:

$$\left.\frac{dV^I}{dx^I}\right|_{x_R=0} = \frac{h'(x_I)(r\left(\Pi^I - \Pi^A\right) + x_I) - r - h(x_I)}{(r + h(x_I))^2}$$

Because $h'(x_I)$ goes to infinity as x_I goes to zero, and $h(x_I)$ goes to zero, this implies that $x_I^*(0)$ is strictly positive. A similar argument holds for rivals.

Next we show that the equilibrium functions must cross at some point. The proof is a standard one found in the literature (for example see Reinganum (1983)). It shows that neither function will exceed a finite value. Given this and the fact that the equilibrium functions are upward sloping, continuous and start off below each other, they must cross at some point.

For the incumbent, the first order derivative of the value function is:

$$\frac{dV^I}{dx^I} = \frac{\left(h'(x_I)\Pi^I - 1\right) D - (\Pi^I h(x_I) + r\Pi^A - x_I) h'(x_I)}{D^2}$$

Which has the same sign as:

$$h'(x_I)(r\left(\Pi^I - \Pi^A\right) + nh(x_a)\Pi^I + x_I) - D$$

Which is negative if:

$$r\left(h'(x_I)\left(\Pi^I - \Pi^A\right) - 1\right) + nh(x_a)\left(h'(x_I)\Pi^I - 1\right) + \left(h'(x_I)x_I - h(x_I)\right) < 0$$

The last term is always negative by the definition of concavity. The whole expression is always negative whenever $h'(x_I)\Pi^I - 1 < 0$. Denote by $\widehat{x}_I$ the smallest value of x_I such that this holds. Then we can say that for any value of x_a, $x_I^*(x_a)$ is always less than $\widehat{x}_I$. A similar value can be found for the function . As reaction functions are upward sloping, continuous and start off below each other this implies that they must cross at least once.

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