Essays on Investments in Research and Development

by

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CONTENTS

Introduction

The firm's choice of a research and development project (R&D project) resembles a scholar's choice of topic for his next paper. Should the researcher opt for a highly uncertain project, where the reward is large but the chance of success is small, or should he choose a more certain project where the chance of success is larger but the reward of success smaller? A firm's reward is a profitable patent or other profitable assets. An economist's reward is to be published in a well-known journal. Another example is that scholars, in the same way as firms, must decide whether to pursue a conventional approach or to pursue a more unusual approach. Despite the resemblance between decisions made by academic scholars and firms, investment in R&D has until recently been a relatively neglected research topic in mainline economics.[1]

I have divided the introduction into three parts. First, I briefly present the discussion of technological progress preceding the development of industrial economics. Second, I briefly discuss some of the contributions from industrial economics to the understanding of technological progress. The third and last part narrows the focus to the specific topics discussed in the thesis.

1. The discussion of technological progress before industrial economics.

Classical economists after Adam Smith and throughout most of the nineteenth century focused primarily on long-term growth. In seeking the causes of growth, non-Marxian economists emphasised the importance of

[1]Schmalensee (1988) p. 673: "It is also frequently noted that this subject [research and development] has received much less study than its importance warrants." Stiglitz (1989) p. 70: "Though [R&D and learning by doing] get far more attention today than they did a decade ago, the disparity between the importance attached to them by economists (at least revealed by their behaviour) and popular concern is remarkable".

resources like land, labour, and capital. A pessimistic view was taken of the prospects for future growth: economic growth was mainly attributed to an increase in resources, not to technological progress. Toward the end of the nineteenth century and during the first part of the twentieth, economists developed what is now referred to as neo-classical economics. Tools for analysing the optimisation of the use of scarce resources by firms were developed. The setting was mainly static: long-term growth was ignored, while much attention was paid to the study of shorter term business cycles.

Of course, not all economists have ignored the importance of technological innovation. Karl Marx, and later Joseph A. Schumpeter, forcefully argued that technological progress is essential for an understanding of the dynamism of capitalist growth. As Marx and Engels stated in *The Communist Manifesto*: "The bourgeoisie cannot exist without constantly revolutionizing the instruments of production, and thereby the relation of production, and with them the whole relations of society." (Marx and Engels (1848) Vol. 1, p. 36). Contrary to Marx, Schumpeter took a more disaggregated view when he argued for the importance of technological change in *Business Cycles* (1939) and in *Capitalism, Socialism and Democracy* (1942). Schumpeter traced all disrupting economic change to innovations, and identified the innovator with the entrepreneur. By focusing on the entrepreneur, which could be a firm and not necessarily a person, Schumpeter was able to highlight the importance of competition and industry structure for the innovating activities. Although the discussion does not easily lend itself to empirical testing, Schumpeter at first stimulated mainly empirical work.

The important role of technological progress in economic growth was not fully recognised until the publication of the seminal papers of Moses Abramovitz (1956) and Robert Solow (1957). In line with the classical tradition, Solow and Abramovitz wanted to study empirically how much growth in per capita output could be accounted for by an increasing quantity of capital and labour inputs. Both papers show that growth depended far more on increasing the productivity of resources than on using more resources. The methodologies were such that the residual captured all causes of rising output per capita other than rising input per capita. The residual turned out to be surprisingly large. Abramovitz considered it as a "measure of our ignorance".

The large residual discussed in the papers of Solow and Abramovitz provoked scholars to study its different components. This empirical research was conducted parallel to the empirical research stimulated by the works of Schumpeter.

2. The discussion of technological progress in industrial economics.

Before the development of industrial economics, there were relatively few theoretical investigations which addressed the questions raised by Schumpeter. Through applying game theory as a tool, industrial economics started to burgeon at the end of the seventies. With it a strand of the literature focusing on the relationship between industry structure, competition, and innovation has sprung up. As pointed out by Joseph E. Stiglitz (1989) investigation of competing firms' incentives to develop new technologies turned out to be a challenging part of industrial economics. The modelling difficulties can at least partly explain why relatively few focused on technological competition at first.[2] During the last ten years, the understanding of firms' incentives to develop new technologies has improved.

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[2] (1989) p. 70: "The difficulty of the topic – the absence of any consensus model – provides one of the explanations for the lack of research in this area".

Industrial economics is not the only branch of economics focusing on technological competition. Modern growth theory has also during the last ten years incorporated technological competition. Increasingly, a Schumpeterian approach is applied, where a firm's profit from its own innovation decreases when a competing firm introduces a better technology.[3]

Recent developments in modern growth theory and industrial economics show that the importance of technological progress for economic growth is increasingly reflected in economic theory.

Before turning to an overview of the topics discussed in the thesis, I briefly discuss some results obtained in industrial economics which may serve as a starting point for the discussion of the approach taken in the thesis.

Some questions on technological progress which have already been asked and answered

Research efforts to develop innovations can be seen as production of knowledge. Unlike conventional goods, knowledge can be used by all firms and consumers in an economy without any extra costs, except the costs of transmitting the information. Thus, knowledge is a public good in the sense that it yields non-rivalrous use. From a welfare perspective, a public good should be freely available to all agents in an economy.

However, profit maximising firms do not have an incentive to provide a freely distributed good. Unless it is able to appropriate some of the social gains generated by the resulting innovation or knowledge a firm will not be willing to undertake a research project. One means of appropriating a portion of the social gain is through a patent.

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[3]See Grossman and Helpman (1991), Aghion and Howitt (1992), and Segerstrom et. al. (1990)

Ever since the first patents were granted in fifteenth-century Italy, patents have been used to give innovators of new products and processes exclusive rights to their innovations for a specific period of time.[4] Patent law thus reflects the trade-off between stimulating entrepreneurs to develop useful knowledge (e.g. technology) on the one hand, and, on the other hand, maximising the social value of existing knowledge through unhindered dissemination and use of it. If the innovator is given exclusive rights to his newly developed knowledge, he can charge a price for letting other firms or consumers use the knowledge. With a strictly positive price for obtaining the technology from the patent holder, some potential users who would have gained by using the technology will refrain from paying the price. Hence, the welfare gain of the knowledge is reduced.

The theory of optimal design of patent law has focused on two questions: patents' length in time and their broadness of scope. The aim has been to design a law which optimally trades off the dead-weight loss of monopoly pricing with the need for providing incentives to develop new technologies.[5] Until recently, the theory has focused on single innovations, thereby ignoring the fact that an innovation often builds on other innovations. However, in recent years, there has been a growing interest in taking the cumulative aspect into account when analysing patent law. The profit from the latest innovation must somehow be shared between the firm with exclusive rights to the first innovation and the firm employing an earlier innovation in a new innovation.[6]

As pointed out by Kenneth J. Arrow (1962, p. 615): "However, no amount of legal protection can make a thoroughly appropriable commodity of something so intangible as information." It is impossible to enable a firm to

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[4]See Kaufer (1988) for a discussion of the early history of patent grants.

[5]See e.g. Nordhaus (1969) Chapter 5, Scherer (1972), and Klemperer (1990).

[6]See e.g. Scotchmer (1991) and Chang (1995).

capture the whole gain buyers have from using a new technology, or the whole gain later firms have from using the knowledge developed earlier. We may, thus, expect that the incentives for developing new technologies will be weaker than the socially optimal ones. However, this is not necessarily the case.

In the literature it has been shown that the way in which research units are compensated in the "market" may induce excessive research effort. The firm which secures itself a patent will often get most of the rent of the innovation.[7] Hence, the institution of patents approximately mimics a rather ruthless mode of compensation where the "the winner takes all". The social value of an innovation is, however, equal to the difference between the value of the best innovation and the technology which alternatively would have been used: the second best technology. If we leave out the quality of the innovations and focus only on the timing of new innovations, the value of an innovation is identical to the gain of obtaining the technology earlier than the innovation could have been introduced by any other firm. The patent system does not provide the best firm with a compensation for the innovation which is equal to the difference between the best and the second best technology. Instead, the innovator will get an exclusive right to his new technology. This exclusive right is often worth more than the difference between the best and second best technology. The second best firm gets nothing.

This observation about the incentive scheme induced by the patent system has been used to show divergence between firms' decisions regarding development of new technologies, and welfare maximising decisions. In the patent race literature, it has been shown that the firms can be induced to invest more in developing a new technology than the socially optimal level. This problem is related to the problem of the commons: an increase in a

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[7]Also in the absence of patents, the firm developing a technology first may reap a major share of the rent of the innovation.

firm's R&D effort will transfer some probability for obtaining the patent from its competitors to itself. Since a firm does not take into account rivals' losses due to its own increased R&D investment, all firms may overinvest. We may not only experience that all firms overinvest from a social point of view, but also that an excessive number of firms may be attracted to the market.[8]

Besides the level of investment, a firm often makes other decisions regarding its R&D project. A firm may, for instance, choose among uncertain projects. Due to the "winner takes all" form of compensation, risk-neutral firms will be induced to excessive risk-taking. The choice of a high-risk project is privately beneficial because it raises the chance of discovering a very valuable technology or of discovering the technology early *and*, thus, the chance of winning the patent race. Also a social planner will take into account that the expected value of a new patent will increase with a riskier project. However, contrary to the firms, the planner does not take into account that the firm undertaking a riskier project will more likely win. To the social planner the identity of the winning firm does not matter. Consequently, the firms have excessive incentives for risk-taking. The general conclusion is: Given that the firm developing the best technology captures more than the difference between the value of its own technology and the second best one, there will exist a gap between the firms' R&D incentives and the social optimal incentives.[9]

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[8]See Loury (1979) for a discussion of the problem of the commons and Reinganum (1989) for review of the patent race literature.

[9]See Dasgupta and Maskin (1987) for a more elaborated discussion of the firms' R&D incentives when compensation scheme is approximately of the form "the winner takes all". See also La Manna et al. (1989) for a discussion of patent races with multiple prizes.

3. The main topics in the thesis

Empirical work by Mansfield (1986) and Levin et al. (1987) has shown that in rather few industries is patent protection essential to the introduction of new inventions. Furthermore, their studies show that the principal reason for the limited effectiveness of patents is that competitors legally can "invent around" patents: patent protection is not broad enough to prevent relatively close substitutes from entering the market. One of the conclusions that may be drawn from the works of Mansfield and Levin et al. is that patent protection is seldom broad enough to ensure that "the market" compensation for inventive activities is of the form "the winner takes all". In line with these empirical results, the essays presented in the thesis assume that firms develop competing technologies and that the technologies are not similar enough to infringe the patents of the competitors. Since I mainly focus on R&D in typical hi-tech industries, where empirical evidence shows that patent protection is relatively inefficient in preventing introduction of competing technologies, this should not be considered a serious limitation.[10] The essays will point out other causes for differences between the private and socially best R&D incentives than those discussed in the existing "winner takes all" literature.

There is another significant feature that distinguishes four of the following five essays from most of the existing R&D literature. I discuss R&D incentives when standardisation and compatibility increase the utility a user derives from a product. Standardisation and compatibility are appreciated because they ensure that complementary products can operate together. Examples include computers and software, CD players and CDs, VCRs and movie cassettes for rental, camera and lenses. *Ceteris paribus*, buyers are willing to pay more for products which adhere to a dominant standard than

[10]See the empirical work of Mansfield et. al. (1981), Mansfield (1986).

for products that do not fit the standard. This extra willingness to pay for compatible or standardised products is often referred to as a *network externality*. The impact of network externalities on private incentives to innovate is studied and compared with the socially best incentives.

Several articles have focused on how network externalities can result in adoption of a standard other than the socially best.[11] Another area of interest has been how network externalities, from a welfare perspective, can induce the users to adopt a new technology too early or too late.[12] However, few articles have discussed how network externalities influence technological progress.

A firm that wants to develop a new technology needs to ask itself: How much should be spent on R&D? How risky should the R&D project be? When is the best time to introduce a new technology? In a major part of the thesis I study how the answers to these questions depend on the presence of network externalities. I also compare the firms' R&D incentives with the socially best incentives.

Outline of the thesis

In the first essay, "R&D in Markets with Network Externalities", I study an established firm's (incumbent's) and an entrant's choice among risky R&D projects. It is assumed that the entrant can only introduce incompatible technologies without infringing the patent of the incumbent firm. An R&D project becomes riskier if the chance of success diminishes and the value of the new technology in the event of success increases. I show that the firms' R&D incentives differ from the socially best incentives, since the rivalling

[11]See Katz and Shapiro (1986) and Farrell and Saloner (1986).

[12]See Katz and Shapiro (1990) and Farrell and Saloner (1985).

firms do not take into account the loss suffered by previous buyers as a result of the switch between technology standards.

In equilibrium, the entrant will choose an excessively safe R&D strategy. Contrary to the low risk R&D project chosen in equilibrium, a riskier R&D project would, if it succeeds, result in a technology constituting a sufficiently large improvement to justify the loss brought upon previous buyers through a switch of standards. Since the entrant ignores previous buyers' losses, he will, in equilibrium, choose an excessively safe project.

However, the incumbent will, in equilibrium, choose an excessively risky R&D strategy. By choosing a less risky R&D project, the incumbent would reduce the probability of failure. In the model, a lower probability of failure would make a switch of standard less likely. The incumbent's R&D strategy is excessively risky, since the previous buyers do not compensate the incumbent for making a switch of standards less likely.

In the second essay, "R&D Incentives in Compatible Networks" (co-authored with Marcel Thum), we explore firms' incentives to improve existing *compatible* technologies. Two firms are assumed to sell different, but compatible technologies. A buyer's willingness to pay for any of the two compatible technologies will, due to increased network externalities, increase with the number of buyers adopting one of the compatible technologies. We show that a firm may find it profitable to cover market segments which, viewed separately, are unprofitable. Covering such a segment can be profitable since it will increase the network externalities and, consequently, raise the profit in other segments of the market. If there is more than one firm in the market, firms prefer that other firms cover market segments which, viewed separately, are unprofitable. We show that a firm may strategically underinvest in R&D to induce another firm to cover the unprofitable market segments. Three different reasons for welfare losses are discussed: First, none of the firms may decide to cover the unprofitable market segment, since a single firm cannot reap the total increase in network externalities. Second, the firm best suited to cover the unprofitable market segment may induce the other firm to cover it. Third, given the firms' market shares in equilibrium, a firm may, due to strategic underinvestment, have a less valuable technology than the socially optimal one.

The third essay, "R&D in the Presence of Network Externalities: Timing and Compatibility", focuses on how network externalities influence the *timing* of R&D investments. Here I analyse the incentives for introduction of a new technology in an emerging market without any established technology or standard. I show that two rivalling firms will, due to network externalities, have excessive incentives to introduce a new technology early. Not only will a welfare maximising social planner prefer slower development, the firms may, in fact, also be better off if they develop their new technologies later. By agreeing on common standards before the new technologies are ready for market introduction, the firms can remove the incentives to introduce new technologies early. Hence, the firms' profits as well as social welfare increase by common standards. This result suggests that one of the motives for a growing number of alliances in the information technology industries might be to determine common standards (design features) in emerging markets. Common standards will reduce the firms' incentives to engage in an expensive R&D race.

In this essay, different government policy instruments are discussed. I point out how a standardisation policy imposed by a government agency can enhance social welfare given that the firm's R&D decisions are fixed. However, I also show that a such standardisation policy may reduce social welfare given that the firms can decide when to introduce new technologies. Moreover, compulsory licensing of a new technology for a defined reasonable per unit fee is shown to be a better public policy than a standardisation policy.

The last essay on R&D and network externalities, "Irreversible Choice of Uncertain Technologies with Network Externalities: Comment", is a comment on an article by Choi (1994). Choi studies an entrant's R&D decision in a market where early buyers can observe the entrant's R&D project and wait for the resulting new technology. He claims that from a welfare perspective the entrant should choose the most risky R&D project possible. The aim of my comment is twofold. First, in the setting introduced by Choi I show that, contrary to what Choi claims, it may be profit maximising as well as socially optimal for a firm to choose a low risk project. Second, in a plausible model without network externalities but with buyers who can wait, I show that a low risk project can be profit maximising as well as socially optimal. Hence, network externalities are not vital for showing that a low risk project can be welfare maximising as well as profit maximising.

In the final essay, "R&D when Adoption is Irreversible", I maintain an assumption often made in the literature about network externalities: the buyers adopt a technology only once. The impact of this assumption on the timing of R&D investments is discussed in a setting without network externalities. The new insight from this essay is that if buyers' adoptions are irreversible and they can wait for new technologies, in a market with price competition, the firms will have excessive incentives for early development of new technologies. It is shown that these incentives differ from the incentives for early introduction discussed in the literature about preemption and patent racing. Price competition leads to excessive profitability of temporal product differentiation.

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Chapter 1

R&D in Markets with Network Externalities*

Abstract

This paper studies the consequences of network externalities on R&D rivalry between an incumbent firm and a potential entrant. In the model, all differences between the R&D projects chosen in market equilibrium and the socially best projects are solely due to network externalities. From a welfare perspective, the incumbent chooses a too risky and the entrant a too certain R&D project. Rothschild and Stiglitz's mean preserving spread criterion is used as a measure of risk. Adoption of a new standard is more likely in equilibrium than in the social optimum.

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I. Introduction

Network externalities are the positive effects one owner has on other owners of the same or a compatible technology. Examples of such effects are found in markets for sophisticated goods such as computers and software, cameras and lenses and communication equipment. In these markets an owner will value a broad range of complementary goods and services. Hence, he will be willing to pay more for goods that have or are expected to have a large variety of related products. Usually, a large number of owners of the same good will ensure a broader supply of complementary goods than is the case with a smaller number of owners. The supply of software to a particular computer, for instance, will broaden when the number of buyers increases. A buyer will favour products owned by many to products owned by a few.[1] This phenomenon is frequently named network externality.

Markets with network externalities are often characterised by intense R&D rivalry. In the computer industry the rate of R&D investment to sales has been well above 10% for many years.[2]

Even though investment in R&D is very important in markets with network externalities, there have been few attempts to thoroughly discuss the possible impact of network externalities on firms' choice of R&D projects. So far the discussion has mainly focused on the adoption of new products, not on how new technologies came into existence in the first place: the invention of technologies.[3]

Since the existence of network externalities is of importance to the adoption of a new product, it will also influence how firms search for new technologies. Will network externalities induce firms to choose riskier

[1]See Katz and Shapiro (1985) for more examples.

[2]See Rosen (1991) for a discussion of R&D in the computer industry.

[3]See Katz and Shapiro (1986) (patented technology) and Farrell and Saloner (1985 and 1986) (not patented technology) for a discussion of the adoption decision.

projects, or will they instead choose projects that they are almost sure will succeed? The different R&D projects will be ranked according to the mean preserving spread criterion, see Rothschild and Stigliz (1970).[4] Besides discussing the market equilibrium, I shall also compare the market equilibrium with the welfare maximizing outcome. This will enable us not only to study the possible welfare loss related to the adoption or lack of adoption of a new technology, but also the welfare loss related to the firm's choice of socially inferior R&D projects.

In this paper it is assumed that an entrant can only enter with a new *incompatible* technology. However, the incumbent may introduce a new *compatible* generation of the existing technology. In this setting I show that the entrant's profit maximizing R&D project is less risky than the socially best project. The entrant will not take into consideration the *earlier* buyers' loss caused by a switch of standards. Hence, the entrant may choose an R&D project which, if it succeeds, does not constitute a technological improvement large enough to cover both the earlier and the new buyers' loss caused by a switch of standards (in addition to the R&D costs). A riskier project will, if it succeeds, result in a more valuable technology than the project chosen in equilibrium. Consequently, a riskier project will, if it succeeds, constitute an improvement sufficiently large to cover both the new and old buyers' losses caused by a switch of standards.

Like the entrant, the incumbent will focus on the new buyers and not take the earlier buyers' welfare into account when he decides which R&D project to pursue. If his R&D project fails and the entrant's succeeds, the entrant will enter the market with a new technology (standard). Since the incumbent will not take into account the earlier buyers' losses caused by the

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[4]A mean preserving spread may somewhat inaccurately be defined as moving probability weight from an outcome close to the mean to an outcome further away from the mean, keeping the mean constant.

adoption of a new standard, he will from a social welfare perspective choose a too risky project. A less risky project will increase the probability of success and thereby make adoption of a new technology less likely.

Katz and Shapiro (1992) and Choi (1994) discuss development of a new product in a market with network externalities. Katz and Shapiro focus on the timing of a product introduction in a market where both the incumbent and the entrant have exclusive rights to their technologies. The entrant's R&D decision is to decide when to develop the new technology given declining development costs over time. Katz and Shapiro show that with incompatible technologies an entrant will, since he is not taking into consideration the loss of network externality brought upon owners of the incumbent technology, have excessive incentives to develop a new technology. Not only does the entrant have excessive incentives to develop the new technology, the welfare loss is also enlarged by premature development.

Choi (1994) studies an entrant's choice among R&D projects with different risks. The incumbent technology is unchanging and supplied competitively. The buyers enter sequentially and the first buyer can observe the R&D project of the entrant. Choi shows that the private and social R&D incentives may differ. Assume that the expected value of the entrant's technology given it is used by only one user (stand-alone value), exceeds the incumbent technology's stand-alone value plus the network externality. If there is no uncertainty about the outcome of the R&D project, the entrant will always enter in the second period and the first buyer will always lose the benefits of compatibility by adopting in the first period. The anticipated loss of network externality may induce the first buyer to wait until the new technology is available.

Increased uncertainty may change the first buyer's decision. With an unfortunate R&D outcome in the second period, the entrant will stay out of the market. Consequently, even if the incumbent technology is bought in the first period, there is a strictly positive probability of reaping the compatibility benefits. Hence the first buyer may adopt the incumbent technology immediately. If the loss in demand reduces the profit more than the entrant gains by being able to choose the riskiest R&D project, the entrant will choose the riskiest R&D project that prevents the first buyer from buying immediately.[5] Since Choi shows that the riskiest R&D strategy is the socially optimal one, it follows that the entrant may choose a too safe R&D strategy. In the model presented in this paper a new reason for the entrant to choose a less risky R&D project than that which is socially optimal is identified.

The organization of the article is as follows: Section II presents a description of the model. The market equilibrium is analysed in Section III. Section IV characterizes the welfare optimum and compares it with the market equilibrium. Section V concludes.

II. The Model

2. 1 The buyers

The buyers enter the market in two groups. The first group consists of N buyers who enter market before a potential entrant can introduce a new technology. It is assumed to be infeasible or prohibitively costly for these buyers to postpone purchase until the entrant's technology is available. After the entrant may have introduced a new technology, the second group of buyers enters. To simplify, I have assumed that the last group consists of only one buyer.

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[5]Given the demand, the expected profit will increase by a mean preserving spread because the new technology will only be used if it is more valuable than the old one.

Let the stand-alone value of the incumbent's present technology (the technology bought by the first group of buyers) be a. If the incumbent succeeds in developing a new technology, it is assumed to be *compatible* with the old technology. However, the entrant will only be able to enter with a new *incompatible* technology.

The marginal gain or network externality from *one* new buyer is assumed to be independent of the number of earlier buyers and equal to b. Thus, a buyer's value of adopting a technology with x adopters at the end of the last period is bx.

2. 2 The R&D decision

Assume that an R&D project can only have one of two outcomes: success or failure. Only successful projects result in development of a new technology. The firms can choose among projects with different probabilities of success. A more uncertain project (i.e. lower probability of success) will, if it succeeds, lead to a larger technological improvement than a more certain project. Assume that the expected stand-alone value of the incumbent's new technology, t, is unaffected by the choice of R&D project such that

$$t = iV(i)$$

where $i \in (0,1]$ is the probability of success chosen by the incumbent, and where $V(i)$ is the stand-alone value given that the project succeeds. According to the mean preserving spread criterion, a project is riskier, the smaller i is. The production costs are ignored for simplicity; $V(i)$ should be interpreted as the net valuation of the new product.

If there are no R&D costs related to choosing a riskier R&D project, the incumbent will always seek to do so. Since he has already developed a technology, he will only apply the new technology when it is an improvement. Thus, he will, even in absence of competition, choose the most uncertain project.[6] These incentives will also prevail when the incumbent is facing competition. I will, as in Dasgupta and Maskin (1987), assume that the R&D costs are increasing in risk, and thereby avoid this corner solution (maximum risk). According to Dasgupta and Maskin (1987): "The intuitive idea behind this assumption is that [the riskier a project] the more "unusual" is the research strategy and thus the more costly in terms of materials and so forth." For simplicity, let the R&D costs be quadratic and a decreasing function of the success probability:

$$C(i) = \frac{1}{2}\gamma(1-i)^2.$$

γ is a parameter which is large if the cost of choosing a riskier project is large.[7]

Similarly, let $V(e)$ and $C(e)$ be respectively the consumer's stand-alone valuation of the entrant's technology (given a successful R&D project) and the entrant's increased costs from choosing an uncertain project given that e is the probability of a successful project.

$$t = eV(e) \qquad\qquad C(e) = \frac{1}{2}\gamma(1-e)^2 \qquad\qquad e \in (0,1].$$

Later we will need the following assumption about the cost function and the expected stand-alone value of a new technology:

Assumption 1

i. $\gamma > \dfrac{(t+bN)(t+a+bN)}{bN}$. ii. $t > a + 2bN$.

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[6]The incumbent will, by choosing the most uncertain project, (lowest i feasible) maximize expected consumer valuation in the next period: $(1-i)a + it/i$.

[7]Another approach is taken by Rosen (1991). He assumes that the expected value of the new technology is declining in risk. Applying this assumption instead of the chosen assumption will not change the qualitative conclusions in this paper.

Part (i) states that the parameter of the R&D cost function is above a certain level that is negatively related to the size of the network externalities. Part (ii) states that the expected value of the existing technology, including the network externalities of both buyer groups, is below the expected stand-alone value of a new technology.

2. 3 The firms

The firms will engage in the following two period game.

Period 1
The incumbent and the entrant simultanously choose one risky R&D project each. Both firms take into consideration that the incumbent has an installed base of size N.

Period 2
The outcomes of the R&D projects become known to both firms and the firms compete on price (Bertrand competition). The buyer chooses a technology.

Depending on the outcomes of the R&D projects, the Bertrand competition yields the following equilibrium prices in period 2:

Entrant	Incumbent	Entrant's price	Incumbent's price
Fails	Fails	0	$a+b(N+1)$
Fails	Succeeds	0	$V(i)+b(N+1)$
Succeeds	Fails	$V(e)-a-bN$	0
Succeeds	Succeeds	$Max[0, V(e)-V(i)-bN]$	$Max[0, V(i)+bN-V(e)]$

Knowing the equilibrium prices in the second period, it is straightforward to show that the following two functions are the incumbent and entrant's expected profit:

$$\pi_I(i;e) = (1-e)(1-i)[a + b(N+1)] + (1-e)i[V(i) + b(N+1)] + eiMax[0, V(i) + bN - V(e)] - C(i), \qquad i \in (0,1] \tag{1}$$

and

$$\pi_E(e;i) = e(1-i)[V(e) - a - bN] + eiMax[0, V(e) - V(i) - bN] - C(e), \qquad e \in (0,1] \tag{2}$$

Given that both firms have developed a new technology, the firm that can offer the largest consumer surplus will capture the buyer. Its profit is maximized by setting its price so that it matches the maximum consumer surplus the competing firm can profitably offer.

The incumbent's profit function is indexed with 1, (π_I^1) if $Max[0, V(i) + bN - V(e)]$ is replaced by its first element and 2 if it is replaced its second element (π_I^2). The entrant's profit function is indexed similarly.

The situation outlined in the two stages above can now be analysed as a static game where the firms solely choose the risk of their R&D projects (e and i) and where the profits are given by (1) and (2).

III. Equilibrium

To find the equilibrium (or equilibria), we need the two firms' reaction functions.

Given the other firm's choice of R&D project, a firm has to decide whether to choose a low risk project without profit opportunities if both firms succeed or a riskier project with profit opportunities. By choosing a risky project the firm will have a technology which is sufficiently valuable to capture the market even if the other firm succeeds as well.

Let $\bar{e}$ be defined as the entrant's project(s) which makes the incumbent indifferent between a project with and without profit opportunities if both firms succeed, i.e. $\max_i \pi_I^1(i;\bar{e}) = \max_i \pi_I^2(i;\bar{e})$. Let $\bar{i}$ be similarly defined.

Lemma 1.

i. *If $\bar{e}$ exists, it is unique. Given $e < \bar{e}$, the incumbent maximizes $\pi_I^1(i;e)$, otherwise he maximizes $\pi_I^2(i;e)$.*

ii. *If $\bar{i}$ exists, it is unique. Given $i < \bar{i}$, the entrant maximizes $\pi_E^1(e;i)$, otherwise he maximizes $\pi_E^2(e;i)$*

Proof. See the appendix.

The firms' reaction functions, $R_E(i)$ and $R_I(e)$, can now be derived from the first order conditions of the profit functions:[8]

$$R_E(i) = \arg\max_e \pi_E(e;i) = \begin{cases} 1-\frac{1}{\gamma}(1-i)(a+bN) & \text{if } \; i \le \bar{i} \\ 1-\frac{1}{\gamma}(t+(1-i)a+bN) & \text{if } \; i \ge \bar{i} \end{cases} \tag{3}$$

The incumbent's reaction function can be derived similarly:

$$R_I(e) = \arg\max_i \pi_I(i;e) = \begin{cases} 1-\frac{1}{\gamma}(1-e)a & \text{if } \; e \le \bar{e} \\ 1-\frac{1}{\gamma}((1-e)a+t-ebN) & \text{if } \; e \ge \bar{e} \end{cases} \tag{4}$$

The upward sloping reaction functions imply that i and e are *strategic complements.*[9] If a firm chooses a riskier project, the other firm will follow suit and choose a riskier project as well.

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[8]If $i \le \bar{i}$, $R_E(i)$ is given by the first order condition of $\pi_E^1(e;i)$.
If $i \ge \bar{i}$, $R_E(i)$ is given by the first order condition of $\pi_E^2(e;i)$.

[9]See Bulow et al. (1985) for a precise definition.

Proposition 1. Under assumption 1, there is a unique Nash equilibrium where the incumbent wins if both R&D projects succeed.

Proof. See the appendix.

The incumbent's installed base makes it unattractive for the entrant to choose a sufficiently risky project to win the market if both firms' R&D projects succeed. The entrant's profit will be larger if he chooses a less risky project with a larger probability of success. However, in the event of success it will not result in a sufficiently valuable technology to win if the incumbent's R&D project succeeds as well.

As discussed in Section II, a firm will always prefer a riskier project if it does not increase costs and if the firm already has a technology. The marginal income of choosing a riskier project is positive. In our case, the entrant's project is only profitable if the incumbent's project fails. The probability of failure is $(1-i)$. If the incumbent's project fails, the entrant is able to capture the (new buyer's) whole increase in consumer surplus caused by his own R&D project. The expected increase in the consumer surplus (the profit) is the difference between the expected value of the new technology less the expected loss from not buying the existing technology, $(1-i)(t-e(a+bN))$. The expected value of the entrant's technology is constant, but the expected gain from buying the new technology instead of the existing technology increases with the degree of risk. A risky project will seldom succeed and induce the new buyers to buy the new technology instead of the existing one. Hence, a riskier project will not increase the expected value of the new technology, but make the expected loss from not buying the existing technology less.

The incumbent will also be able to capture the entire increase in consumer surplus by providing the existing technology or an improved technology to the new consumers. As in the case of the entrant above, a riskier project will not increase the expected value of the new technology, t, but reduce the probability that the buyers have to give up the alternative purchase (which is the existing technology or the entrant's new technology).

Proposition 2.

Assume that the network externalities increase, (i.e. b or the size of the installed base, N, increases). In equilibrium,

a. *the entrant will choose a riskier R&D project.*

b. *the incumbent will choose a more certain project.*

c. *the adoption of a new technology will become less likely.*

Proof. From the reaction functions it follows that the equilibrium is

$$\hat{e} = \frac{\gamma^2 - (a+t)(a+bN)}{\gamma^2 - (a+bN)^2} \quad \text{and} \quad \hat{i} = \frac{\gamma^2 - (a+bN)^2 - \gamma(t-bN)}{\gamma^2 - (a+bN)^2}.$$

By differentiating $\hat{e}$ and $\hat{i}$ with respect to b and by using assumption 1, we get respectively $d\hat{e}/db < 0$ and $d\hat{i}/db > 0$ which prove proposition 2 a and 2 b; e declines and i increases as the network externalities grow. The same results are obtained by differentiating with respect to N instead of b.

A new incompatible technology will be adopted if the incumbent fails to improve the existing technology, and the entrant succeeds in his R&D project. The probability of this event is given by $(1-i)e$. By 2 a. and b. we know that this probability will decrease with an increase in b. Q.E.D.

The intuition for proposition 2 is as follows. An increase in the installed base will not influence the marginal cost of choosing a riskier project, i.e. $C'(e)$ is unchanged. Furthermore, we know that the entrant's profit is identical to the rise in expected consumer surplus resulting from his R&D project. Hence, we may infer that if the value of the existing technology is increased, the entrant's profit is reduced. By choosing a riskier project, the buyers' probability of having to give up the existing technology with its more valuable installed base declines and the value of the entrant's R&D project increases accordingly. Hence, a more valuable existing technology will increase the entrant's incentives to choose a riskier project.[10]

The consequences of a larger installed base advantage are quite different for the incumbent. Given that the entrant's R&D project fails, the incumbent will always capture the gain by having a larger installed base. In this case, the risk of the incumbent project will not matter. However, if the entrant succeeds the incumbent will only capture the gain if he succeeds as well. Hence, an increase in the installed base will increase the incentives for choosing a more certain project – a project which succeeds more often.

V. Welfare maximizing choices

In the previous section the equilibrium in the game is characterised. In this section the equilibrium strategies will be compared with the welfare maximizing R&D choices of a welfare maximizing social planner.

A social planner will not only maximize the expected value of the winning technology in the last period. Unlike the incumbent, he will also take account of the previous buyers' welfare. Adoption of an incompatible technology will, as discussed in the introduction, harm the owners of the obsolete technology.

Social welfare is defined by

$$\begin{aligned} W(i,e) = (1-e)(1-i)\left[a+b(N+1)+bN\right]+(1-e)i\left[V(i)+b(N+1)+bN\right]+ \\ e(1-i)\left[V(e)+b\right]+eiMax\left[V(i)+b(N+1)+bN, V(e)+b\right]-C(i)-C(e). \end{aligned} \tag{5}$$

[10]An increase in N will reduce the entrant's profit, $(1-i)(t-e(a+bN))$, and increase the profit of a marginally riskier project, $(1-i)(a+bN)$.

Let $W(i,e)$ be indexed by 1 (W^1) if the last square brackets are replaced by its first element (the incumbent's technology is adopted), and by 2 (W^2) if the brackets are replaced by its second element (the entrant's technology is adopted).

In the cases where the incumbent wins and a new technology does not capture the market, the existing buyers will obtain bN as increased network externalities.

Let $\tilde{i}$ be defined as the incumbent's choice of a project which makes a social planner indifferent between assigning a high risk project and a low risk project to the entrant, i.e. $\max_e W^1(\tilde{i},e) = \max_e W^2(\tilde{i},e)$. If a high risk project is assigned, it is always welfare maximizing to let the entrant capture the last buyer. However, if the low risk project is assigned to the entrant, the last buyer should only adopt the new standard if the incumbent's project ($\tilde{i}$) fails. Let $\tilde{e}$ be similarly defined.

Lemma 2.

i. If $\tilde{e}$ exists, it is unique. Keep e fixed. If $e < \tilde{e}$, the social planner maximizes $W^2(i,e)$ with respect to i, otherwise $W^1(i,e)$ is maximized.

ii. If $\tilde{i}$ exists, it is unique. Keep i fixed. If $i < \tilde{i}$, the social planner maximizes $W^1(i,e)$ with respect to e, otherwise $W^2(i,e)$ is maximized.

Proof. See the appendix.

The incumbent's *socially* best response to the other firm's R&D choice is given by

$$S_I(e) = \arg\max_e W(e;i)$$
$$= \begin{cases} 1 - \dfrac{1}{\gamma}(1-e)a & \text{if} \quad e \le \tilde{e} \\ 1 - \dfrac{1}{\gamma}\big((1-e)a + t - 2ebN\big) & \text{if} \quad e \ge \tilde{e} \end{cases} \tag{6}$$

Similarly, the entrant's *socially* best choice is

$$S_E(i) = \arg\max_i W(i;e)$$
$$= \begin{cases} 1 - \frac{1}{\gamma}(1-i)(a+2bN) & \text{if} \quad i \le \tilde{i} \\ 1 - \frac{1}{\gamma}\left(t + (1-i)a + 2bN\right) & \text{if} \quad i \ge \tilde{i} \end{cases} \tag{7}$$

Proposition 3. There is a unique pair of R&D projects which is socially optimal. In optimum, the incumbent has a superior technology and captures the last buyer if both projects succeed.

Proof. The proof is similar to the proof of proposition 1.

Without an installed base, the entrant will have to choose a very risky project to win if both projects succeed. It is better to assign a less risky project to the entrant and let him win only if the incumbent fails to improve his technology.

Before we continue, let us draw the socially best response functions and the firms' reaction functions in a figure.

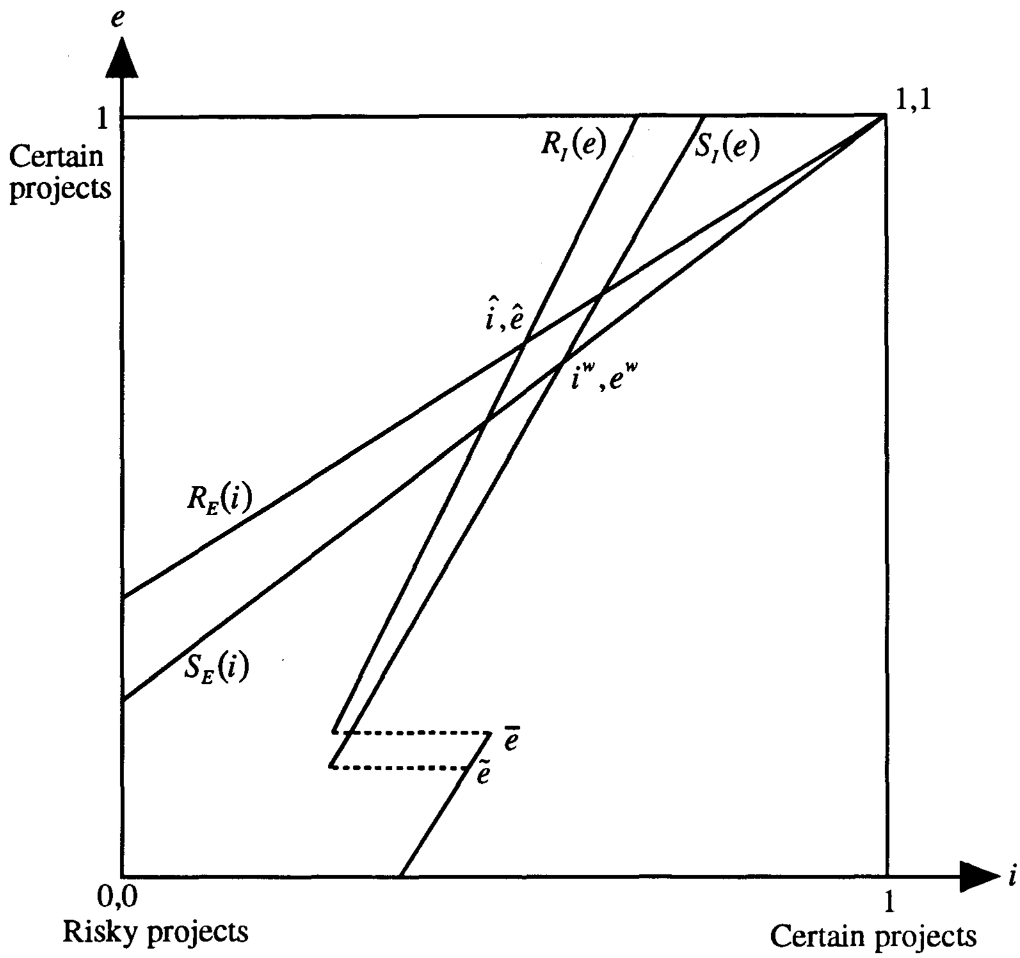

Figure 1. The market equilibrium and the socially optimal choice.

In Figure 1, the pair of R&D projects which are socially optimal is denoted (i^w, e^w) and the equilibrium is denoted $(\hat{i}, \hat{e})$.

We are now ready to compare the equilibrium with the social optimum.

Proposition 4. Without network externalities ($b = 0$) the social optimum and the market equilibrium are identical.

Proof. Compare (6) and (7) with (3) and (4). Q.E.D.

By substituting $2b$ for b in the firms' reaction functions, we get the *socially* best response functions. A social planner will not only take account of the new buyer's gain from compatibility, which is bN, but also the previous buyers' gain, which is also bN. Hence, the gain from compatibility is $2bN$ and not only bN as taken into consideration by the firms when they compete for the buyer in period 2.

Hence, in a market without network externalities, the profit maximizing firms will also maximize social welfare. The private and social incentives for choosing a particular R&D project correspond. This proposition enables us to focus solely on market failures due to network externalities.

Proposition 5.

(a) Compared to the socially best R&D choices, the incumbent chooses a too risky R&D project and the entrant chooses a too certain project.

(b) The probability of adoption of incompatible technology is larger in equilibrium than if social welfare is maximized.

Proof. The only distinction between the reaction functions and the first order condition of the welfare maximizing problem is that b is replaced by $2b$ in the first order conditions. By proposition 2, an increase in b induces the entrant to choose a riskier project and the incumbent to choose a less risky project in equilibrium. This establishes proposition 5. Q.E.D.

The probability of a loss of network externalities will decrease if the entrant chooses a riskier project. If a riskier R&D project succeeds, the size of the technological improvement may justify *both* the previous and the new buyers' loss of network externalities. Hence, social welfare increases if the entrant chooses a riskier project than that given by his reaction function.

Contrary to the entrant, the incumbent chooses a riskier project in equilibrium than that prescribed by the first order condition of the welfare maximizing problem. The incumbent does not take account of previous buyers' possible loss of network externalities when he makes his R&D

decision. The probability of a loss of network externalities (i. e. $e(1-i)$) will be reduced by a choice of a marginally less risky R&D project than that given by the incumbent's choice in equilibrium .

My results relate to the issue of excess momentum and excess inertia discussed in the literature, see for example Katz and Shapiro (1992) and Farrell and Saloner (1986). Like in Katz and Shapiro (1992), the entrant's incentives to introduce a new incompatible technology may in my model result in excess momentum – incompatible technologies are adopted too often from a welfare perspective. Excess inertia is possible if present buyers adopt the incumbent technology and ignore that future buyers might have gained if a new and incompatible technology had been adopted instead.[11] Since the model in this paper does not include buyers entering after period 2, excess inertia will never occur.

As discussed previously, Choi (1994) argues that the entrant *may* choose a less risky project than optimal from a welfare perspective. However, in Choi's paper the entrant does so to induce the first period buyers to wait until the entrant enters. This is, as we have seen above, not the argument in my model.

V. Conclusions and Extensions

In this paper I have developed a simple model of R&D decisions in markets with network externalities. Many markets with network externalities can be characterised by intense R&D rivalry and a key question is whether the incumbent's and entrant's R&D incentives differ from the socially optimal incentives.

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[11]Farrell and Saloner (1985) studies how asymmetric information among buyers or co-ordiantion problems may result in excess inertia.

In the paper I show that the incumbent chooses a too risky R&D project that too often lets a new firm with an incompatible technology enter. In addition, the entrant has an incentive to choose more certain projects than are socially optimal and these strengthen the possibility of adoption of an incompatible technology.

Our discussion might be extended in various directions. Contrary to many markets, in markets with network externalities a buyer's expectation about the others' choice of technology is important. If all buyers expect that the others will choose a particular technology, they may choose the same (or a compatible one) to obtain the network externalities. However, another (incompatible) technology may be chosen if it is expected to be the market standard. Hence, due to network externalities, there may be multiple equilibria for given prices (see Farrell and Saloner (1985). Here I have been able to ignore possible co-ordination problems by assuming that only one buyer enters in period 2.[12] However, the buyers' problems in co-ordinating on a particular standard may have an impact on the firms' R&D incentives. A thorough analysis of the formation of buyers' expectations in relation to the firms' R&D investments would be of great interest.

Another interesting extension would be to let an R&D project have more than two feasible outcomes (success or failure). A firm may very well develop a technology that is better than nothing but not as good as wanted when the R&D project was initiated. This possibility may alter both firms' R&D incentives.

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[12]In papers where there are many buyers, it has been common to assume that (identical) buyers are able to co-ordinate on the Pareto optimal equilibrium. See. e.g. Katz and Shapiro (1986).

Appendix

Proof of lemma 1. Let $g(e) \equiv \underset{i}{Max}\,\pi_i^1(i;e) - \underset{i}{Max}\,\pi_i^2(i;e)$, i.e. $g(e)$ is the profit difference if the incumbent does not capture the last buyer and if he does in the case where both R&D projects succeed. Hence, $g(\bar{e}) = 0$. Let i_1 maximize $\pi_I^1(i,e)$ and i_2 maximize $\pi_I^2(i,e)$. $\bar{e}$ is unique since

$$g(e) = -(1-i)(i_1 - i_2)a - (te + (ebN - t)i_2) + \frac{1}{2}\gamma(1-i_2)^2 - \frac{1}{2}\gamma(1-i_1)^2$$

and

$$g'(e) = (i_1 - i_2)a - t - bNi_2 < 0.$$

If $\bar{e} \notin (0,1]$, there is no feasible R&D project the entrant can choose to make the incumbent indifferent between capturing the period 2 buyer and not doing so given that both projects succeed. Because $g'(e) < 0$ the incumbent maximizes $\pi_I^1(i;e)$ if $e < \bar{e}$ and $\pi_I^2(i;e)$ if $e > \bar{e}$.

Similarly, it can be proved that $\bar{i}$ is unique (if it exists) and that the entrant maximizes $\pi_E^1(e;i)$ if $i < \bar{i}$ and $\pi_E^2(e;i)$ if $i > \bar{i}$. Q.E.D.

Proof of proposition 1. The entrant will independent of what project the incumbent chooses never find it profitable to capture the period 2 buyer if both projects succeed. This follows since by (3), the riskiest project that the entrant is willing to undertake if he intends to serve the period 2 buyer, given that both projects succeed, is

$$e^0 = 1 - \frac{1}{\gamma}(t + (1-0)a + bN)$$

which combined with assumption 1 (i), implies that $e^0 > 1 - \frac{bN}{t+bN}$ or equivalently,

$$V(e^0) = \frac{t}{e^0} < t + bN.$$

Hence, project e^0 will not result in a better technology (including the network externalities) even if the incumbent chooses the project $i = 0$ (the incumbent's project which results in the lowest stand-alone value given success). It follows that $R_E(i)$ is continuous and affine for $i \in (0,1]$.

Let $e^1 \equiv R_E(0^+)$. Now, $e^1 > e^0$ since by (3), the entrant will choose a less risky project given that he does not seek to capture the period 2 buyer if both projects succeed. Furthermore, $e^0 \geq \bar{e}$, since, for $e \geq e^0$, the incumbent always captures the period 2 buyer if both projects succeed. Hence, $e^1 > \bar{e}$. Since $e = \bar{e}$ is the only point of discontinuity for $R_I(e)$, (4) implies that $R_I(e)$ is continuous and affine on $[e^1,1]$.

By using Assumption 1 combined with (3) and (4), it is straightforward to show that $R_I(e^1) > 0$, $R_I(1) < 1$, and $R_E(1) = 1$. Hence, $R_E(R_I(e))$ is a continuous and affine function from $[e^1,1]$ to $[e^1,1]$, with $R_E(R_I(e_1)) > e^1$ and $R_E(R_I(1)) < 1$. By a standard fixed point argument it follows that there exists a unique equilibrium $(\hat{i},\hat{e})$ satisfying $\hat{e} = R_E(\hat{i})$ and $\hat{i} = R_I(\hat{e})$. Q.E.D.

Proof of lemma 2. Let $f(e) \equiv \underset{i}{Max}\, W^1(i;e) - \underset{i}{Max}\, W^2(i;e)$. Hence, $f(\tilde{e}) = 0$. Let i_1^* maximize $W^1(i;e)$ and i_2^* maximize $W^2(i;e)$. $\tilde{e}$ is unique because

$$f(e) = (1-e)(i_2^* - i_1^*)a + (i_2^* - i_1^*)(t + eb) + e(t + i_1^* b(2N+1)) - i_2^*(t+eb) - \frac{1}{2}(1-i_1^*)^2 + \frac{1}{2}(1-i_2^*)^2$$

and

$$f'(e) = -(i_2^* - i_1^*)a + t + 2i_1^* bN > 0.$$

Furthermore, we can infer that if $e < \tilde{e}$ the incumbent's socially best project is a low risk project which does not win the last buyer if both R&D projects succeed ($f'(e) > 0$). If $e > \tilde{e}$, the socially best project is a low risk project where the incumbent only captures the last buyer if the entrant's project fails.

Similarly, it can be proved that $\tilde{i} \in (0,1]$ is unique (if it exists) and that a social planner wants the incumbent to capture the last buyer if $i < \tilde{i}$ and the entrant if $i > \tilde{i}$. Q.E.D.

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Chapter 2

R&D Incentives in Compatible Networks*

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Abstract

Network externalities describe the phenomenon that a good becomes more valuable to each user the more other consumers use the same or a compatible product. Whereas most of the recent literature on network effects has focused on the direct market interaction of competing products, this paper shows that network externalities can have important feedback effects on the incentives to carry out research and development (R&D) in these markets. Even if the products are compatible, and the firms are not in direct competition, the firms may have too little incentive to carry out R&D for their products. The paper discusses three different reasons that can lead to a socially suboptimal R&D investment in compatible network markets.

JEL Classification: L10, O31, D43

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I. Introduction

In economic terms, a network effect occurs when a good becomes more valuable to a user as more consumers adopt it or a compatible product, i.e. when demand is interdependent. Examples include computers, communication networks and video equipment. The decision to join such a network involves an externality because the new buyer does not take into account the positive effect on other users. For instance, a buyer who considers joining a communication network will not take into account the fact that other users gain from having one more participant in the network.

Since the seminal papers of Farrell and Saloner (1985, 1986) and Katz and Shapiro (1985, 1986), the literature on network externalities has pointed out many market failures that are distinctive for demand interdependence. However, little has been said so far about the incentives to carry out R&D in these markets. Apart from a few exceptions, the existing literature has focused on the introduction of new products with given characteristics and with a given group of consumers.[1] This is especially surprising as innovations, cost reductions and the subsequent enlargement of markets, have strong spillovers into the related markets of compatible products (because of the network effect). Even if firms operate in different specialised markets and are not direct competitors, the network effect can create an important interdependence between disjoint market niches. A firm investing in R&D to cover new, previously unprofitable markets expands not only its own installed base but also the installed base for other compatible products.

To illustrate this point, take the emergence of computer reservation systems (CRS) as a highly stylized example. Computer reservation systems are used for booking flights, rental cars or accomodation. Initially, CRS were mainly designed for internal purposes. Airlines wanted to automate seat

[1]In the concluding part, we will relate the results of these few papers on R&D and network externalities to our own findings.

reservation and ticketing, car rentals wanted to optimize the utilization of their car pools. The computer reservation system ensures that each transaction is immediately accessible worldwide. As there was no intercommunicability between the systems, each reservation system was designed solely for a market niche of specialists. With a more widespread use of these systems, it was recognized that there is a significant potential for network benefits from communicability.[2] The gain from communicability, however, would only show off when there existed a broad access to the computer reservation systems. Therefore, the CRS had to create access for the big number of travel agents. This opened a new 'mass market' beyond the specialists' market niche. In order to reach the new clientèle, a huge investment in the CRS was necessary. Besides the expansion in the computing center, most resources were spent on the software improvement. The travel agents' software should be easily accessible and the travel agents should benefit from added features such as back-office accounting. Just to give an impression of the magnitude of the R&D costs: the initial development of the Apollo airline CRS cost $ 400 million; to improve the Apollo CRS for the travel agents $ 1 billion had to be put into R&D effort. This policy lead to a rapid diffusion of CRS among travel agents in the US; the CRS access of travel agents rose from a negligible number to 95 per cent during the 1980s [Katz (1988, p.88)].[3]

The expansion of a market like the one for CRS might require huge investments in R&D. Once the step is taken and the travel agents already

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[2]Of course, the data sets of the different CRSs were not fully compatible, but as all necessary information was already available in computerized form it was not prohibitively expensive to convert the data sets. That the development of *ex post* compatibility is a practicable way is shown by the manifold acitivities in Electronic Data Interchange (EDI).

[3]Competition between airline CRS is negligible as the regional differentiation of the market is very strong. We also neglect the problem of vertical integration between airlines and CRS which has led to several regulatory measures in the past. See Guerin-Calvert and Noll (1991) for a comprehensive survey of the CRS business.

have the computer facilities, it becomes relatively easy and inexpensive to establish links to further reservation systems. Other reservation systems than for the airlines (Apollo and Sabre in the US) have definitely benefitted from the efforts of airline CRS. Hotel chains and car rentals could either set up their own CRS access for travel agents or join an existing network by selling their products through the established CRS.[4] Because of this network effect, all CRS providers could benefit if the market can be extended to a mass market including the travel agents. However, the development of inexpensive and convenient CRS access may require huge investments in R&D and the question of which firm will leave its market niche and try to cover the mass market arises.

The relation between network effects and R&D efforts gives rise to a number of interesting questions for economists. To what extent will firms carry out R&D in order to expand their installed base? Can we expect the size of the installed base to be socially efficient? Why do we observe so many joint ventures in markets with large network externalities? Examples where firms are taking advantage of a common installed base can be found in the business news almost every day. Producers of consumer electronics co-operate with music and film companies, media giants search alliances in the telecommunication business, and software developers in different specialised segments establish coalitions. From all these issues, this paper will focus on the questions of which R&D incentives emerge in markets with network externalities and of whether private and socially optimal R&D efforts match. We will concentrate on cost reducing R&D, i.e. process innovations. However, our approach can easily be adapted to the case of (compatible) product innovation.

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[4]The first option was prevented by the airline CRS. Sabre and Apollo prohibited the travel agents to use their CRS terminals for other purposes. Hence, the airline CRS can almost completely control the access to other reservation systems.

We will show that network externalities are not only important when firms are competing face to face, but also when they invest in R&D in disjoint markets. Because of the positive externality, the innovating firms underestimate the value of larger future market shares. Successful R&D projects allow a firm to cover new markets that were unprofitable with the original high cost technologies. These innovations not only open new markets but also increase the value of the traditional market through the network effect. However, too little R&D is undertaken as the innovator ignores the positive effects such an expansion of markets creates for other firms with compatible products. While this effect on R&D is intuitively appealing, network externalities may also cause more, and less, obvious distortions. If a firm decides to invest in R&D to cover additional market segments, it will generate a public good benefiting all other firms with compatible products. Each firm might want other firms to provide the public good (network value) because it might not be profitable to serve the additional market segments itself. The question of who will provide this public good becomes a source for strategic considerations and investment in R&D can be used as commitment. As a result of this strategic behaviour, it cannot be taken for granted that the least cost innovator will cover the additional market segments and thereby provide the beneficial public good. Furthermore, firms may have strategic reasons for underinvestment in markets with network externalities and this underinvestment amplifies the inefficiency due to an inferior installed base mentioned above.

The paper is organized as follows. In part II, we will set up a simple two stage game where two specialised firms first decide on their R&D investments and thereafter sell to the consumers. Part III sets up the profit maximization problem of the firms. Part IV solves the game and discusses the market equilibria that may exist. Part V compares the market outcomes to the social optimum. Part VI concludes the paper and relates our findings to the existing literature on R&D in network markets.

II. The Model

We assume that two firms (A and B) are offering differentiated but compatible products. On the demand side, the market is split into three groups of buyers where each buyer considers to purchase one unit of the product or no unit at all. Two of these groups are highly specialized users who strongly prefer one of the two products. The first group includes α identical buyers who prefer the product of firm A (market segment A). The second user group is of the same size (α) but prefers firm B's product (market segment B). Assume for simplicity that the users in the two market segments put the same value on their favoured products. Let $\bar{s}$ denote the value of the good, if a representative buyer is the only user of the technology (stand alone value). Network benefits are not included in $\bar{s}$. We will further assume that these buyers are highly specialized and will never buy the non-favoured product, i.e. their valuation of the non-favoured product is always less than the minimum feasible cost of this product.

Besides the two groups which strongly favour one or other of the products, we have a group of less advanced buyers. We will refer to this third group as mass users. Let $\underline{s}$ be their stand-alone value and let the size of the group be $1-2\alpha$, i.e. the total number of buyers in the three groups together is normalised to 1. As they do not favour any of the special features, they are indifferent between the two products and value them less than the specialists ($\underline{s}<\bar{s}$).

A user's willingness to pay, however, is not only determined by this stand-alone value, it also depends on the number of compatible users. The network effect makes a good more valuable the more buyers that use a compatible product. Even though the firms are selling differentiated products, their products are compatible. Therefore, the buyers in one market segment will gain by an increase in the number of buyers in the other market segments. This interdependence between the market segments causes a network externality. The users' valuation of the network effect is assumed to be linear in the number of users with the same or a compatible product. If all three groups buy the same or compatible products, each buyer will be willing to pay v in addition to the stand-alone value of the product due to the network effect. If only the two advanced market segments purchase, each of the buyers will be willing to pay $2\alpha v$ in addition to the stand-alone value.[5]

On the supply side, the firms (A and B) face a two stage game. In stage 1, both firms invest in R&D projects that will determine their marginal costs.[6] If firm i (i = A, B) does not invest in R&D, its marginal cost will be $\hat{c}_i$ at stage 2. A reduction of the cost by d_i requires an investment of $I_i(d_i)$, with $I_i^{'}(d_i) > 0$ and $I_i^{''}(d_i) > 0$. Hence, the marginal cost of firm i at the second stage is $c_i = \hat{c}_i - d_i$.

This R&D investment will influence the market outcome in stage 2 of the game, where each firm sells to the buyers in its own specialized market segment. If the R&D investment is sufficiently large, the low cost firm may want to capture the mass users as well. This increase in the installed base will create spillover effects in the specialized market segments - on the firm's own market segment *and* on the competitor's segment.

The firms seldom take their R&D decision simultaneously. Instead of letting the timing of the R&D decisions be endogenously decided in the model,

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[5]By assuming full (instead of partial) compatibility between the two products, the niche buyers are indifferent about whether firm A or B covers the mass user market. In contrast to our introductory example, it is furthermore assumed that the network effect is also effective if only market niches prevail. This makes the model easier to manage without losing significant insight.

[6]The cost reducing investment does not need to be an R&D project, it can just as well be an investment in new capital equipment or training of the work force. However, R&D is the main source of cost reduction in the markets we are discussing.

we simply assume that the firms choose their R&D projects sequentially, and the firm to enter first is drawn randomly.[7] Our model requires that the first firm is able to commit itself to an R&D project. This assumption is plausible in markets where such commitment can be carried out by writing contracts with external R&D agencies or by choosing a particular direction for the R&D project which does not allow to serve the mass users. In the CRS example, the airlines may enter into contracts with software firms to develop the new software needed for their reservation systems. Since we cannot know which of the two firms will be the first mover we introduce an initial stage (stage 0) where the first mover in the investment process is randomly determined and this preplay randomization becomes public knowledge. We denote this stage the public randomization stage.[8] The timing of this game can be summarized as follows:

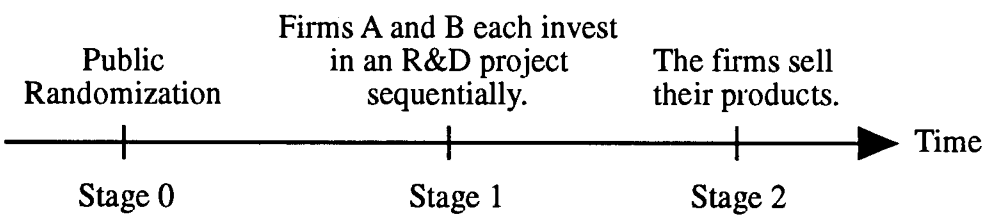


Figure 1. The time structure.

To narrow the focus of the paper to the impact of network externalities on R&D investments, we will make two further simplifying assumptions. First, the firms can discriminate between the two market segments by setting different prices. This assumption enables us to focus on the welfare

[7]To simplify the analysis we ignore the possibility that firms may consider to delay their R&D choice. Consequently, we avoid war of attrition types of equilibria; see, e.g., Fudenberg and Tirole (1986).

[8]See Fudenberg and Maskin (1986) for a discussion where the players make their actions contingent on the outcome of a public randomization device.

losses due to network externalities and to neglect market failures that are discussed thoroughly in the general literature on R&D investments.[9]

Second, we will assume that a firm will never find it profitable to serve the mass user market if the willingness to pay of its advanced segment does not rise (i.e. without the spillover effect in the specialized market segment). The firms never reduce the marginal cost of production ($\hat{c}_i - d_i$) below the maximum willingness to pay of the mass users ($\underline{s} + v$). Hence, the paper is restricted to cost reductions in the interval:

$$d_i \in [0, \hat{c}_i - \underline{s} - v) \qquad i = \mathrm{A, B} \tag{1}$$

Using this assumption, we can ignore situations where the firms compete for the mass user market.

III. The Firms' Decision

We solve the game backwards by starting with the second stage and later discuss the first stage. At the second stage, the firms take their marginal costs as given and set prices to maximize their profits. Knowing the second stage profit for different cost levels, the firms invest in cost reducing R&D at the first stage. In this multi-stage game with observed actions, we will restrict ourselves to subgame-perfect Nash equilibria in pure strategies.

Stage 2

If firm B does not serve the mass user market, firm A's profit at the second stage is the maximum profit from either serving only segment A or serving the mass users as well as segment A:

[9] For instance, investments in R&D might be too low, because firms cannot capture the incremental net social surplus accrueing to its own customers. This will be the case if a firm is unable to price discriminate and, therefore, has to lower the price for its niche buyers to capture the mass users.

$$\pi_A(d_A, d_B) = Max\{\alpha(\bar{s} + 2\alpha v - \hat{c}_A + d_A), \alpha(\bar{s} + v - \hat{c}_A + d_A) + (1-2\alpha)(\underline{s} + v - \hat{c}_A + d_A)\}$$

Firm A will be indifferent between the two alternatives if its marginal cost is $\bar{c} \equiv \underline{s} + (1+\alpha)v$, which implies a cost reduction by $\bar{d}_A = \hat{c}_A - \bar{c}$.

If the mass user market is served by firm B, the profit of firm A is $\alpha(\bar{s} + v - \hat{c}_A + d_A)$. By assumption (1) it will not be profitable to compete for the mass user market.

Firm B has a profit function similar to firm A. Given that the mass user market is not served, firm B will serve the mass user market only if its marginal cost is below $\bar{c}$, which implies that the firm has reduced the cost by more than $\bar{d}_B = \hat{c}_B - \bar{c}$.

Stage 1

At stage 1, the firms have to decide on the amount of cost reducing R&D investment. The investment of firm *i* may depend on whether or not the other firm is serving the mass user market.

Given that firm B does not serve the mass users, firm A will choose d_A to maximize:

$$\Pi_A(d_A, d_B) = \begin{cases} \alpha(\bar{s} + 2\alpha v - \hat{c}_A + d_A) - I_A(d_A) & \text{if} \quad \hat{c}_A - d_A > \bar{c} \\ \alpha(\bar{s} + v - \hat{c}_A + d_A) + (1-2\alpha)(\underline{s} + v - \hat{c}_A + d_A) - I_A(d_A) & \text{if} \quad \hat{c}_A - d_A \leq \bar{c} \end{cases}$$

The first line represents the profit if firm A serves market segment A only, and the second line represents the profit if the mass users are served as well. If firm A decides not to capture the mass users, the profit is maximized by a cost reduction of size d_A^*:

$$I_A'(d_A^*) = \alpha$$

If the profit is maximized by selling to the mass users as well, the optimal cost reduction is d_A^{**}:

$$I_A'(d_A^{**}) = (1-\alpha)$$

As the size of the specialized market segment α is smaller than the market share of mass users and specialized users together $(1-\alpha)$, the cost reduction will always be greater in the second case, $d_A^{**} > d_A^{*}$.

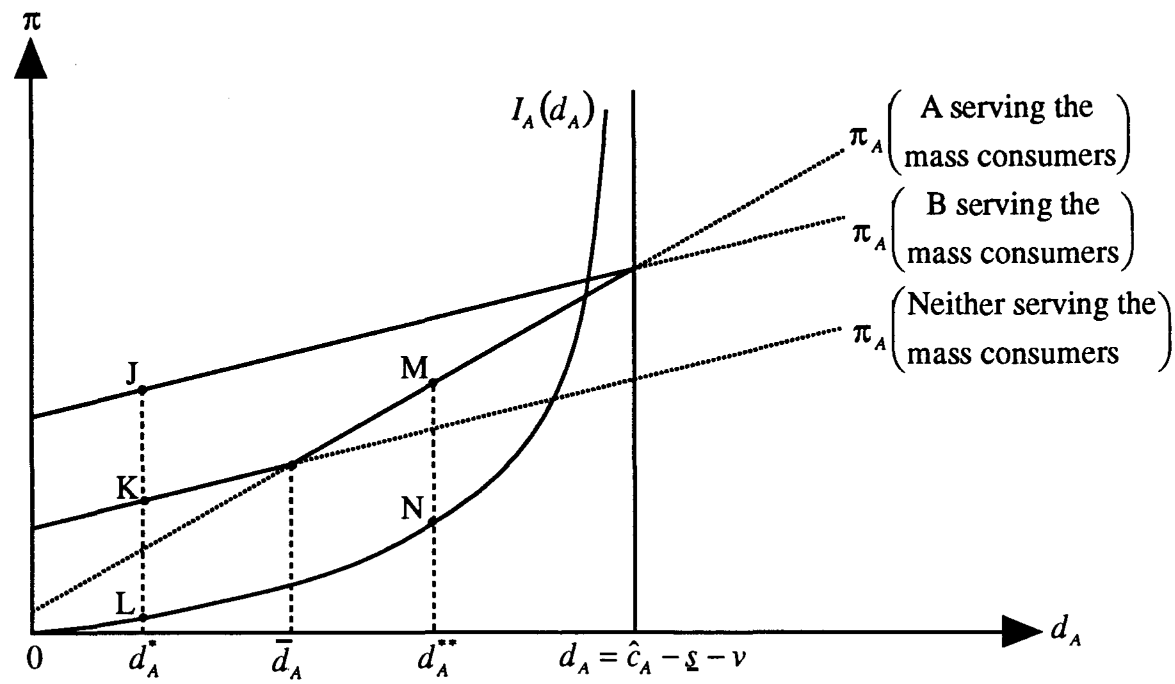
If firm B is expected to serve the mass users, by assumption (1), firm A will never consider capturing these buyers. In this case, the profit of firm A is given by:

$$\Pi_A(d_A, d_B) = \alpha(\bar{s} + v - \hat{c}_A + d_A) - I_A(d_A)$$

which is maximized by d_A^{*}. This level of cost reduction is the same as the optimal level of cost reduction in the case where the two firms only serve their own market segments.

Let $\Pi_i(d_A^{*}, d_B^{*})$, $\Pi_i(d_A^{**}, d_B^{*})$, and $\Pi_i(d_A^{*}, d_B^{**})$ be the maximum profits of firm i if neither of the firms serves the mass users, if firm A serves the mass users and if firm B serves the mass users, respectively.

We can now illustrate firm A's decision by showing the profits in the three cases. $\pi_A(\cdot)$ denotes the gross profits before the R&D investment is subtracted. The slopes of the gross profit curves are α and $(1-\alpha)$, depending on whether the firm in question is serving the mass users or not. The R&D costs are represented by the convex curve I. (Firm B's decision can be illustrated similarly.)



J-L: Firm A's net profit if firm B covers the mass user market.
K-L: Firm A's net profit if neither of the firms covers the mass user market.
M-N: Firm A's net profit if firm A covers the mass user market.

Figure 2. Firm A's profit.

If K-L is larger than M-N, firm A will not serve the mass user market even if the other firm stays out of that segment. In the opposite case, firm A will serve the mass user market. Of course, firm A always prefers B to cover the low price segment (the mass users), i.e. the profit J-L exceeds K-L and M-N.

It is worth noting that d_A^* might be larger than $\bar{d}_A$.[10] In this case, it is always optimal for firm A to choose d_A^{**} - given that firm B does not cover the low price segment. (We will later see that this situation may induce strategic underinvestment.) Moreover, if $d_A^* < d_A^{**} < \bar{d}_A$, firm A will never choose the large cost reduction d_A^{**}. It is not profitable to serve the mass users because profit

[10]Figure 2 illustrates the case where $d_A^* < \bar{d}_A < d_A^{**}$.

M-N is always smaller than profit K-L. Hence, in this case d_A^* will always be the profit maximizing cost reduction.

IV. The Market Equilibrium

We are now ready to discuss the different feasible market equilibria in the game. To obtain a better overview, the possible market outcomes are summarized in the following table:

case	investment in R&D for mass users?	Which firm will serve the mass market?
case 1	no investment	none
case 2	investment	low cost firm
case 3		depending on the timing
case 4	strategic provision	of the R&D investments

Table 1. Market outcomes

Case 1

First let us focus on the situation where neither of the firms invests enough to find it profitable to sell to the mass users at the second stage (i.e. K-L is larger than M-N in figure 2). Depending on the outcome of the public randomization, each firm can be assigned to the second mover position. Firm A and B's best response functions as second movers are drawn in figure 3. The two axes represent the decision variables d_A and d_B. The critical levels, $\bar{d}_i$, are drawn with dashed lines.

Given the initial production costs $\hat{c}_i$, the R&D costs are sufficiently large to make it unprofitable for any of the firms to capture the mass users. The best response function of the second mover is a straight line. As the first mover's choice has no influence on the second mover, the first mover will choose the optimal cost reduction for his market niche as well. Hence, none of the firms' decisions has an impact on the other firm's R&D investment. Whatever the competitor does, none of the firms can gain by deviating from the low R&D investment level. The unique market equilibrium is E_1, $\left(d_A^*, d_B^*\right)$, where the two firms stick to their respective market niches and neglect the mass user market.

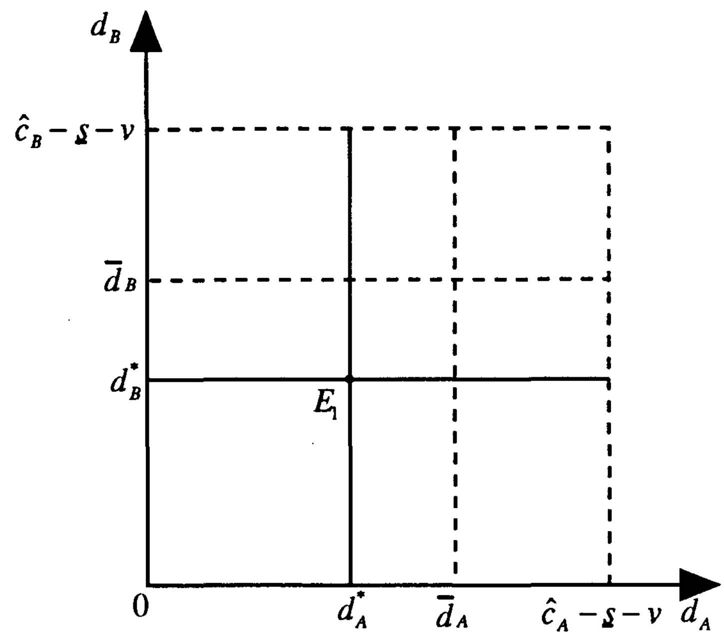


Figure 3. None of the firms covers the mass user market.

Case 2

In the second case, one of the firms has sufficiently low initial production costs $\hat{c}_i$ or R&D costs to find it profitable to cover the mass users (i.e. K-L is smaller than M-N in figure 2). Without loss of generality, let this be firm A. However, if firm B is covering the mass users firm A's best choice is to stick to its own market segment (i.e. J-L is larger than M-N). Moreover, we know that firm B only will cover the mass users if it reduces the cost by more than $\bar{d}_B$. Hence, if firm A is the second mover, its best response function will jump from d_A^{**} to d_A^* at this level.

Firm B is still assumed to have sufficiently large R&D costs to never find it profitable to cover the mass users. If firm B is the second mover, the best response function is the straight line at d_B^*. Whoever gets assigned to the first mover position, (d_A^{**}, d_B^*) will be the unique equilibrium (E_2 in figure 4).

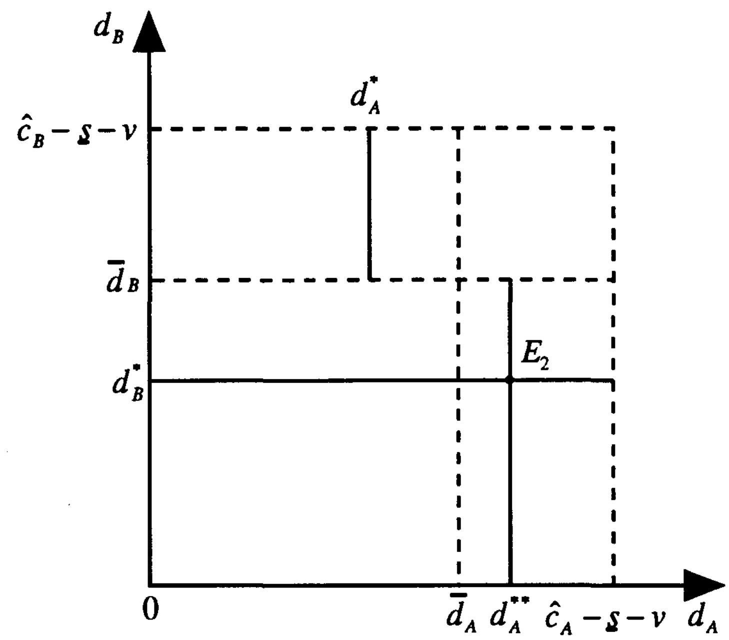


Figure 4. Firm A is covering the mass user market.

Case 3

In the last two cases, we have multiple equilibria. The market outcome depends on the public randomization. In this case, imagine that each firm finds it profitable to cover the mass user market if the other firm does not. Now, both firms have a discontinuous response function as the second mover. As shown in figure 5, there are two equilibria in pure strategies.

The market outcome will depend on the sequence of the firms' investment. Given that firm B can commit itself to an investment first, d_B^* is the optimal level of cost reduction. Firm B anticipates that the best response of firm A is a high investment level (d_A^{**}) where the mass users are served by firm A. The equilibrium is denoted E_3, (d_A^{**}, d_B^*) in figure 5. Moreover, there exists another equilibrium E_4 where firm A moves first and forces firm B to serve the mass users, (d_A^*, d_B^{**}). Generally, the first mover has the advantage of committing himself to the low investment level and forcing the follower to increase the installed base.

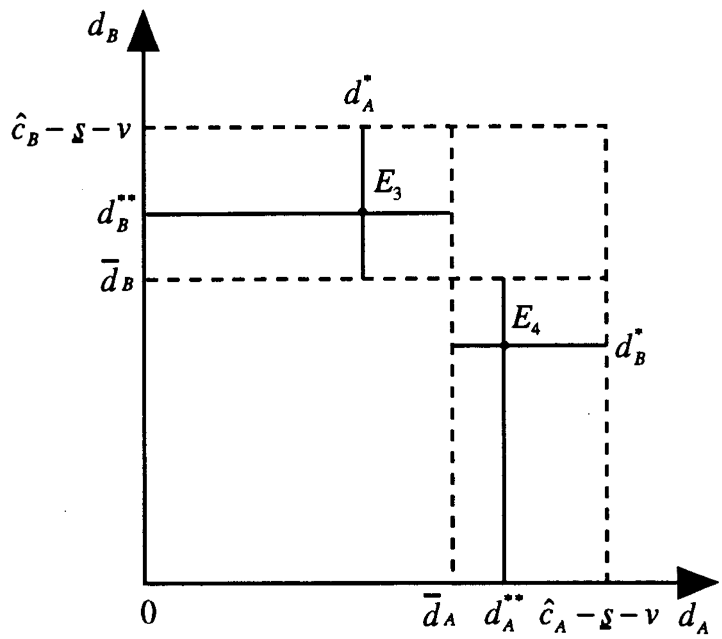


Figure 5. *Both firms are willing to serve the mass users.*

Case 4

In the discussion above, we have implicitly assumed that $d_i^* < \bar{d}_i$. As noted before, this may not be the case. By reversing the inequality for both firms we get a new situation where the firms might strategically underinvest in R&D.

Following the reasoning in case 3, one firm undertakes a large investment to cover the mass user market while the other firm only invests to cover its own specialized segment. As d_i^* is now above $\bar{d}_i$, even the firm which is not expected to serve the mass users will find it profitable to cover this market if the other firm refuses to do so. Despite a relatively small R&D investment, the firm is better off by covering the mass users.

Knowing this, (d_A^{**}, d_B^*) may not be an equilibrium. Firm A has the second mover position and is expected to serve the mass user market in this case. Instead, firm A could invest slightly below $\bar{d}_A$. This low cost reduction is a credible commitment by firm A indicating that it is not able to produce profitably for the mass market. Thereby, firm B is induced to cover the mass user market as both investment levels d_B^* and d_B^{**} are above the critical level $\bar{d}_B$. This strategy will pay for firm A if the profit at the underinvestment level $\bar{d}_A$ exceeds the profits at d_A^{**} where the firm would have to cover the mass user market. Suppose that each firm has a higher profit at the commitment level, $\bar{d}_i$, than with serving the mass market; then both firms will find the underinvestment strategy profitable.[11]

What is the new equilibrium? The first mover, i, will choose the underinvestment level $\bar{d}_i$ and the second mover j has to serve the mass market with a cost reduction of d_j^{**}, i.e. the only equilibria are $(\bar{d}_A, d_B^{**})$ and $(d_A^{**}, \bar{d}_B)$. To see this, assume there is a rule $R(d_A, d_B)$ determining which of the firms will serve the mass users at the second stage given both firms are above their critical levels, $\bar{d}_i$ (i=A,B). Such a rule may, for instance, say that the producer with the lowest production cost has to sell to the mass users. As long as there is an option of avoiding selling to the mass users, this cannot be an equilibrium. The firm which has to serve the mass users would have chosen a different investment level. If both firms invest above the critical level, there will be such an option. The firm which has to serve the mass users can choose the commitment level, $\bar{d}_i$. (It is never optimal to invest below $\bar{d}_i$ as this moves the firm further away from the profit maximizing level d_i^*.) The two possible equilibria are illustrated in figure 6.[12]

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[11]The cases where neither, or only one, firm or only one firm is willing to invest $I_i(\bar{d}_i)$ to induce the other firm to cover the mass user market is relegated to the appendix.

[12]The precise shape of firm A's and firm B's reaction functions in the interval $[\bar{d}_B, \hat{c}_B - \underline{s} - v]$ and $[\bar{d}_A, \hat{c}_A - \underline{s} - v]$ respectively depends on the rule $R(d_A, d_B)$.

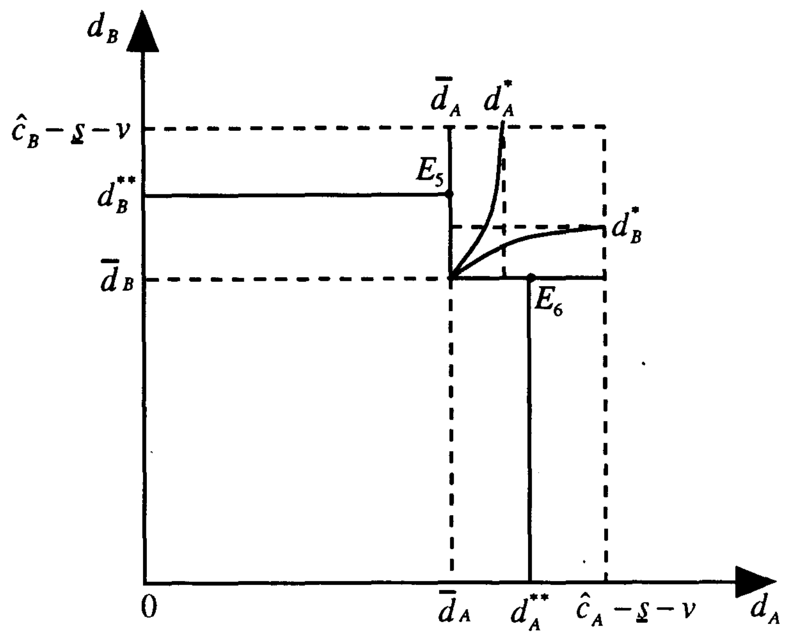

Figure 6. Strategic underinvestment.

In equilibrium E_5 $(d_A^{**}, \bar{d}_B)$, firm B is the first mover and will (as firm A did above) strategically underinvest in R&D. The production cost at the second stage will be larger than the level that maximizes the profit, given that firm B could commit itself to serving its own market segment only. The best response of the second mover is to invest $I_A\left(d_A^{**}\right)$ and to provide the public good (i.e. serve the mass users).

V. Welfare Analysis

We have seen above how network externalities make the R&D investments of firms more interdependent than in markets without this kind of externalities. In this section, we will show that this interdependence gives rise to welfare losses not previously discussed in the literature. This will be done by comparing the market equilibrium (or equilibria) with the choices of the social planner who maximizes the sum of consumer surplus and profits. As the firms can exert perfect price discrimination, all surplus will go to the producers and the buyers will be left without any consumer surplus. Hence, the social planner can use the sum of the two firms' profits as a measure of welfare.

Assuming perfect price discrimination, there will be no room for market failures apart from failures due to network externalities. The firms can appropriate all benefits from sale to their *own customers* (including the gain from lower costs) and in most markets there will be no additional benefits. However, in markets with network externalities, there are additional benefits that are not taken into account by a profit maximizing firm. In this section, we will point out which types of welfare losses may arise in network markets.

The discussion will focus on three types of social inefficiencies. First, the mass users may not be served even though welfare increases by including these users. Second, there are outcomes where the wrong firm, i.e. the one which has to do the most expensive R&D to serve the mass users, will do it. Third, one of the firms may invest less in R&D than is socially optimal in order to induce the other firm to cover the mass users. Put differently, strategic behaviour, which is facilitated by network externalities, might be socially harmful.

To analyse these inefficiencies we have to compare the welfare levels under three options for the social planner: neither of the firms covers the mass users (W_0), firm A (W_A) or firm B (W_B) covers the mass users. In each case, the welfare is given by the sum of the firms' profits. Given the number of buyers, the socially optimal level of cost reduction is the same as the profit maximizing level (d_i^* or d_i^{**}).

$$W_0 = \alpha\left(\bar{s} + 2\alpha v - \hat{c}_A + d_A^*\right) + \alpha\left(\bar{s} + 2\alpha v - \hat{c}_B + d_B^*\right) - I_A\left(d_A^*\right) - I_B\left(d_B^*\right)$$
$$W_A = \alpha\left(\bar{s} + v - \hat{c}_A + d_A^{**}\right) + \alpha\left(\bar{s} + v - \hat{c}_B + d_B^*\right) + (1-2\alpha)\left(\underline{s} + v - \hat{c}_A + d_A^{**}\right) - I_A\left(d_A^{**}\right) - I_B\left(d_B^*\right)$$
$$W_B = \alpha\left(\bar{s} + v - \hat{c}_A + d_A^*\right) + \alpha\left(\bar{s} + v - \hat{c}_B + d_B^{**}\right) + (1-2\alpha)\left(\underline{s} + v - \hat{c}_B + d_B^{**}\right) - I_A\left(d_A^*\right) - I_B\left(d_B^{**}\right)$$

We are now ready to compare the alternatives and discuss how the above mentioned welfare losses may occur in an unregulated economy.

Will the firms serve too few buyers in equilibrium?

By comparing W_0 and W_A, we can see whether it is socially optimal to let firm A serve the mass users - given firm *B* produces only for its specialized users. From a social point of view, the mass users should be covered if $W_0 < W_A$. In order to relate the social optimum to the private decision of firm A, we may rewrite the welfare functions by substituting in firm A's profit function:

$$W_0 < W_A$$
$$\Updownarrow$$
$$\Pi_A\left(d_A^*, d_B^*\right) < \Pi_A\left(d_A^{**}, d_B^*\right) + \alpha(1-2\alpha)v$$

Private and social rankings are identical except for the last term. $\alpha(1-2\alpha)v$ represents the gain that will accrue to the buyers in segment B, if firm A includes the mass users in the network.[13] We will, therefore, never get a market outcome where firm A is covering the mass users even though it reduces the social welfare. There is a bias toward not serving the mass users even if this increases social welfare. This bias is due to firm A's disregard of the benefits in the other market niche. The market failure will be more important (the loss will be larger) the larger the network externalities, and the more customers in segment B can gain by including the mass users in the installed base.[14]

[13]By covering the mass user market, the installed base is increased by $(1-2\alpha)$ new users. Hence, the additional network value for each of the α users in the B segment amounts to $(1-2\alpha)v$.

[14]The bias discussed above will be the same whether firm A or firm B is the candidate for serving the mass user market.

Will the wrong firm serve the mass users?

Besides the question whether the mass users should be served, there is a second source for welfare losses. Given that the mass users are served, will the socially best firm cover this segment? To answer this question we have to compare the welfare levels W_A and W_B where firm A or firm B respectively innovates for the mass user market. If the following condition is fulfilled, the welfare is maximized by firm A serving the mass users:

$$\begin{gathered} W_A \geq W_B \\ \Updownarrow \\ \alpha\left[\left(d_A^{**}-d_A^{*}\right)-\left(d_B^{**}-d_B^{*}\right)\right]+(1-2\alpha)\left[\left(\hat{c}_B-d_B^{**}\right)-\left(\hat{c}_A-d_A^{**}\right)\right]- \\ -\left[I_A\left(d_A^{**}\right)-I_A\left(d_A^{*}\right)\right]+\left[I_B\left(d_B^{**}\right)-I_B\left(d_B^{*}\right)\right]\geq 0 \end{gathered} \tag{2}$$

The first two terms represent the change in *production costs* by letting firm A serve the mass users instead of firm B.[15] The last two terms represent the change in *R&D costs*.

Depending on which of the two firms invests first, the socially inferior equilibrium might be the market outcome. The sum of the production costs and the R&D costs can be lower if the other firm is serving the mass users.

An example might help to illustrate the fact that the market might select the inefficient firm to sell to the mass users. To simplify the welfare discussion, we assume identical R&D cost functions for the two firms. Even though the two firms are starting from different initial cost levels $\hat{c}_i$ ($i = A, B$), both firms have to spend the same amount of R&D investment to achieve a cost reduction of d_i. This assumption also implies that both firms have the same optimal levels of cost reduction $d_A^{*} = d_B^{*}$ and $d_A^{**} = d_B^{**}$. Then (2) reduces to

[15]The three terms represent market segment A, segment B, and mass user segment, respectively.

$$W_A \geq W_B \quad \Leftrightarrow \quad \hat{c}_A \leq \hat{c}_B \tag{2'}$$

and the decision rule of the social planner is to choose

firm A if $\hat{c}_A \leq \hat{c}_B$ and

firm B if $\hat{c}_A > \hat{c}_B$.

Only initial cost differences matter. The firm with the lower initial production cost should cover the mass user market.

However, there is no mechanism to link the market outcome to this efficiency rule. The first mover - which is determined randomly and not according to cost considerations - can avoid the costly R&D investment and force the follower to serve the mass market. This dilemma describes the second type of R&D inefficiency in markets with network externalities. As there are no side payments between the two firms, the selection of the Pareto-dominant outcome in an unregulated economy is not certain. The firm with the largest innovation cost might be induced to provide the installed base as a public good.

Are the firms reluctant to invest the socially optimal level?

For the third type of inefficiency - the strategic underinvestment - it will not be necessary to set up the formal calculus of the social planner (see figure 6). Besides the welfare loss due to the inefficient firm serving the mass users, an additional welfare loss emerges immediately from the reduced R&D investment. If only the specialized market is to be served, d_i^* is the private and social optimal cost reduction. A strategic reduction of the R&D investment aimed at keeping the production costs sufficiently high (to avoid covering the mass users) increases only the profit of the firm, while it reduces the social surplus. The welfare will increase if the firm not serving the mass users increases its investment until the marginal R&D cost is equal to the marginal reduction in production cost at the second stage.

VI. Conclusion

This paper discusses how network externalitities create interdependence between firms' R&D decisions. Most of the R&D literature has focused on interdependence that emerges from positive technological spillovers across firms. Examples of such direct spillovers include imitation of non-patented technologies, hiring other firms' employees and re-engineering patented products to circumvent patent protection.[16] In this paper we point out that the network externality among buyers of compatible goods can create similar effects even in the absence of technological spillovers.

Even though little work has been done on R&D in network markets, there are some papers which are related to our paper. Katz and Shapiro (1992) discuss an entrant's timing in introducing an incompatible product.[17] Since an entrant ignores the loss of network externalities suffered by users of the incumbent technology, the incentives for the entrant to introduce the product early will be too strong. Moreover, a later entry would give the entrant more time for product development and make the new technology more valuable. An improved technology will, to a large extent, justify the loss of network externalities. Hence, the authors come to the same conclusion as we do; too little R&D is conducted in the market equilibrium. In contrast to our paper, however, the underinvestment emerges from competition with an incompatible innovation.

The papers by Choi (1994) and Kristiansen (1994) focus particularly on the risk of R&D projects. They show that network externalities may result in divergence between R&D projects which are socially or privately optimal.

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[16]See, e.g., Arrow (1962), Cohen and Levinthal (1989), and Griliches (1991) for a recent survey of the empirical literature.

[17]The paper analyses incentives to achieve compatibility as well.

In Kristiansen (1994), both an established firm with an installed base and an entrant can engage in R&D projects. If the R&D projects succeed, the entrant will have a new incompatible technology and the incumbent a new compatible technology. As in the paper of Katz and Shapiro, a welfare loss emerges because the incompatible technology succeeds too often. The network effect of the installed base is neglected by both the entrant and the incumbent. The incumbent firm chooses a too risky R&D strategy and - due to a large probability of having an unsuccessful R&D project - too often it leaves the market to the new incompatible technology. Moreover, the entrant chooses an R&D strategy that is too safe. If the entrant succeeds, the outcome is not innovative enough to make it socially worthwhile to relinquish compatibility with the installed base.

A similar result is obtained by Choi (1994) where the incumbent technology is competitively supplied and the (stand-alone) value of the good is stochastic. The buyers decide whether to adopt the incumbent technology immediately or to wait until the new incompatible technology is available. To induce the buyers to wait for the new technology, the entrant has to choose a sufficiently safe R&D strategy that will succeed with a large probability at the time it enters. The entrant will - as in Kristiansen (1994) - choose an R&D project that is too safe compared to the welfare optimum.

In contrast to these papers, we have focused on markets with compatible products. This is not to say that all products in markets with network externalities are fully compatible, but that network effects link different market segments even if the suppliers are not in direct competition. This setup may be especially relevant in the emergence of new markets. Leading a market from a minor market niche to a mass user market that can effectively exploit the network effects requires significant resources to be devoted to the development of new inexpensive products. Firms have first to invest in cost reducing R&D to be able to provide the public good 'installed base' later on. How this is done in network markets is the focus of this paper.

The network effect makes it valuable to develop products for a broad user market. Without the network effect, the mass user market might be privately and socially unprofitable. The incentive effects to carry out R&D in these markets resemble the problems known from the literature on the private provision of public goods.[18] First, the market participants underestimate the value of the public good 'installed base' because they neglect the network value for the other market niches. Therefore, too little R&D is undertaken. Second, even if both firms are willing to serve the mass users, each firm will prefer the other firm to do it. The question of who should provide the public good becomes the subject of strategic interaction, and the firm with high R&D costs might be induced to produce for the mass user market. Third, firms might strategically keep their production costs high so as to commit themselves to not serving the mass users.

Despite all the possible inefficiencies, it is difficult to observe the market failures directly. For instance, if the first type of inefficiency arises, the product will typically never become a mass user good - which is precisely the inefficiency. The public good is not provided, and the market can never take off because the network value remains too low. It is difficult to find simple empirical support. However, the mechanisms analysed might be helpful in understanding some of the merger activities in recent years. The integration of, for example, media and telecommunication business can be seen as a means of internalizing the positive effect that a firm's R&D efforts have on others (due to network externalities). These R&D investments will be necessary to develop products that are, at best, needed in minor market niches today but that might be dominant entertainment products (video-on-

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[18]See Bergstrom, Blume and Varian (1986) on the private provision of public goods and Konrad (1994) on the commitment effect.

demand, interactive TV) in the future. The trade-off between internalizing network externalities and the risks of market power may soon become relevant for the policy evaluation in regulation and anti-trust.

Appendix

In case 4 (part IV), we analyzed the situation where both firms have optimal levels of cost reduction above $\bar{d}_i$ and prefer underinvestment over serving the mass market. We chose this case because it most clearly shows the strategic motive of underinvestment. In this appendix, we discuss the outcome if at least one of the firms prefers the interior solution with a high cost reduction over the commitment strategy.

Case 4'

In contrast to the discussion in part IV, we assume that both firms are never willing to keep their costs at the commitment level $\hat{c}_i - \bar{d}_i$ to induce the other firm to cover the mass users. It is better to cover the mass user market than to move to the strategic position of underinvestment, i.e. $\pi_i(\bar{d}_i) < \pi_i(d_i^{**})$ for i=A,B.

Starting with stage 2, we solve the game backwards. As before, the rule R determines which firm has to cover the mass user segment if both firms have invested above the critical levels $\bar{d}_i$ at the first stage: $R{:}\{d_A, d_B\} \rightarrow \{A\} \vee \{B\}$.

The rule for stage 2 will have impact on the investment decision at stage 1. Let j denote the first mover and i denote the second mover. Given the investment level of the first mover (d_j), the second mover can choose an investment level which induces the first mover to cover the market or an investment level where he covers the mass market himself. Let $d_i^N(d_j)$ be the optimal reduction in costs given that the first mover covers the mass market

$$d_i^N(d_j) = \arg\max_{d_i \in D_j} \Pi_i(d_i) \qquad D_j = \{\forall d_j : R(d_i; d_j) = j\}$$

and let $d_i^S(d_j)$ be the optimal reduction in costs given that the second mover covers the mass market

$$d_i^S(d_j) = \arg\max_{d_i \in D_i} \Pi_i(d_i) \qquad D_i = \{\forall d_j : R(d_i; d_j) = i\}$$

Deciding whether to cover the mass user market or not, the second mover will compare the two profit levels. He will serve the mass market if $\Pi_i(d_i^N(d_j)) < \Pi_i(d_i^S(d_j))$, and not serve the market if $\Pi_i(d_i^N(d_j)) > \Pi_i(d_i^S(d_j))$.

The first mover can choose a cost reduction level $d_j \in E_i$ which induces the second mover to cover the mass user market, or he can choose a cost reduction level $d_j \in E_j$ where

$$E_j = \{\forall d_j : \Pi_i(d_i^N(d_j)) > \Pi_i(d_i^S(d_j))\} \text{ and } E_i = \{\forall d_j : \Pi_i(d_i^N(d_j)) < \Pi_i(d_i^S(d_j))\}.$$

The first mover will serve the mass users if

$$\max_{d_j \in E_j} \Pi_j(d_j) > \max_{d_j \in E_i} \Pi_j(d_j)$$

and the second mover will serve the mass users if the inequality is reversed.

If the first mover serves the mass users, he will invest $I_j(d_j^{**})$, i.e. he will not underinvest strategically. However, if $d_i^N(d_j^{**}) \neq d_i^*$, the second mover's cost reduction will be different from the optimal level for strategic reasons given that he serves his advanced segment only.

If the first mover chooses an investment level which implies that the second mover has to serve the mass users, i.e. $d_j \in E_i$, he may invest strategically. If $d_j^* \notin E_i$ and the first mover only covers his own advanced buyers, the chosen cost reduction will be different from the optimal cost reduction level due to strategic reasons.

Case 4''

So far, we have analyzed the cases where each firm preferred the commitment strategy of underinvestment (see case 4) and the case where neither of the firms is willing to invest only $I_i(\bar{d}_i)$ to induce the other firm to cover the mass market. The only case left is the intermediate one. One firm favours the commitment strategy of underinvestment at $\bar{d}$ and the other firm favours the large cost reduction of d^{**}. As this is a special case of the preceding analysis we can shorten the discussion. There are two cases to discuss:

(a) $\Pi_j(\bar{d}_j) < \Pi_j(d_j^{**})$ for the first mover and

$\Pi_i(\bar{d}_i) > \Pi_i(d_i^{**})$ for the second mover

If the second mover is willing to reduce his costs only by $\bar{d}_i$, the first mover cannot commit himself to not selling to the mass users. Hence, the only equilibrium is $\left(d_j^{**}, \arg\max_{d_i \in D_j} \Pi_i(d_i)\right)$. If $d_i^* \neq \arg\max_{d_i \in D_j} \Pi_i(d_i)$, the inefficiency from strategic underinvestment appears.

(b) $\Pi_j(\bar{d}_j) > \Pi_j(d_j^{**})$ for the first mover and

$\Pi_i(\bar{d}_i) < \Pi_i(d_i^{**})$ for the second mover

The first mover can commit himself to a cost level that induces the follower to cover the mass user market. This strategy pays for the first mover because he is willing to commit himself to a small cost reduction of $\bar{d}_j$ to avoid covering the mass user market. The equilibrium is $\left(\arg\max_{d_j \in D_i} \Pi_j(d_j), d_i^{**}\right)$. The inefficiency from strategic investment occurs if $d_j^* \neq \arg\max_{d_j \in D_i} \Pi_j(d_j)$.

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Chapter 3

R&D in the Presence of Network Externalities: Timing and Compatibility*

Abstract

Two rival firms must decide when to invest in R&D and whether the new products should be compatible. I show that network externalities may induce the firms to advance their introduction of new incompatible technologies. Early introduction of a new technology is socially harmful, because the R&D costs increase, and *de facto* standardisation becomes less likely. Compared with the equilibrium outcome, both firms may gain by delaying their introduction of incompatible technologies. By agreeing on common standards before product introduction, entry is delayed and the profit may increase. An *ex post* optimal standardisation policy may increase the incentives for early product introduction, and consequently be a undesirable policy *ex ante.*

JEL classification: O31, L13, L40.

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1. Introduction

This paper discusses how network externalities influence R&D in an emerging market where two prospective technologies will compete.[1] The main issues are: the timing of R&D investments, the incentives for achieving compatibility by *de facto* standardisation or by voluntary agreements between competing firms, and the impact of different public policy instruments.

Rapid technological progress is observed in many industries with network externalities. New technologies enable rivalling firms to introduce new products like interactive TV, video-CDs, and digital imaging. In emerging markets, extensive investments in R&D are usually needed to establish new standards or dominant designs. Firms like Microsoft and Intel have shown that the control of proprietary standards can be very valuable.

These features are captured in a model where the buyers enter sequentially, and two firms decide simultaneously the speed of their R&D projects. The outcome of an R&D project is uncertain, and it is more costly to complete a given R&D project early than late. None of the firms have a technology initially, and a buyer adopts a technology only once. An important feature is that early introduction of a new technology does not restrict the other firm's possibilities of introducing a different but competing technology later.[2]

From a welfare perspective, the extra costs of an early introduction of a new technology are, in the model, assumed to exceed possible benefits. I

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[1]The extra willingness to pay for compatible or standardised products is often referred to as a network externality.

[2]Mansfield (1986) and Levin et al. (1987) find evidence of limited effectiveness of patents, because competitors legally "invent around" patents. See also the literature on capital-embodied innovations, e.g. Reinganum (1981), Riordan (1992), and Katz and Shapiro (1992).

show that *without* network externalities, the firms will choose the socially optimal R&D strategy and introduce a new technology late. However, this may not be the outcome in a market *with* network externalities. Network externalities make it valuable to have an installed base facing an entrant. Consequently, a firm may find it profitable to enter early to establish an installed base before facing competition.

The question of when to develop a new technology is also studied in the literature about preemptive technology adoption.[3] Here, the argument for early introduction relies on the assumption that this prevents or delays competitors' development of competing technologies.[4] Contrary to the literature cited, I find that network externalities may induce firms to develop a new technology early, even when the competitors' R&D efforts are fixed.

I show that network externalities may induce both firms to introduce new technologies early, even though they might be better off by mutually delaying entry. If the firms anticipate that incompatibility will induce them to engage in a costly R&D race, they would be better off by agreeing on common standards and design features before the product is ready for the market, thus removing the racing incentives. Common design standards enable a buyer to take advantage of the complementary products initially offered to the competing technology. Thus, the firms' incentives to enter early to obtain an installed base are removed.

The above result suggest that one of the motives for the growing number of alliances in the information technology industries might be to

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[3]See e.g. Fudenberg and Tirole (1985), Gilbert and Newbery (1982), and Riordan (1992).

[4]Fudenberg and Tirole (1985): "[If] firms can observe and respond to their rivals' actions, firms have an incentive for "preemptive adoption". By this we mean that firms will adopt sooner than they would choose to were their rivals' adoption dates fixed."

determine common design features in emerging markets.[5] Compatibility weakens the advantage of incumbency and reduces the pace of the R&D race.

Given that the two competing firms do not agree on compatibility, how should a welfare maximising government act? The late entering buyers may prefer a technology which is incompatible with the technology already adopted by the first buyers. The new buyers take into account only their own, and not the previous buyers' loss of network externalities. If the new incompatible technology does not constitute a technological improvement large enough to justify *both* the previous and the new buyers' loss of network externalities, it might be tempting for a government agency to prevent a switch of standards.

However, I show that if the first buyers anticipate that the government may act in favour of the established technology, they become more willing to buy that technology at their time of entry. Consequently, such a standardisation policy may induce the firms to advance their development of new technologies. One of the results in this paper is that a public policy which at a first glance seems to be beneficial, may be socially harmful when one takes the firms' R&D decisions into account. I show that compulsory licensing can reduce the advantage of entering first and may, consequently, be an advantageous public policy.

Furthermore, if a government agency cannot renounce its power to introduce mandatory standards later, it may face a dynamic inconsistency problem: the firms make their development decisions before the agency can decide on a standardisation policy. Thus, the firms know that the best public policy, given the firms' introduction dates, may include mandatory standards.

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[5]Katz and Ordover (1990) points out that the telecommunication, computer, and semiconductor industries have a large share of the total number of cooperative R&D agreements registered under The National Cooperative Research Act of 1984.

Hence, without commitment to a standardisation policy before the firms choose their R&D strategies, the government's authority to impose mandatory standards at a later date, may induce the firms to engage in a socially harmful R&D race.

In the previous studies of network externalities and the adoption or innovation of new technologies, it has been assumed that the entry date of at least one of two competing technologies is fixed. Consequently, strategic R&D competition between firms in a new market, which is the main topic of this paper, is ignored. Katz and Shapiro (1992) discusses the impact network externalities may have on the entry date of the *second* technology in the market. Choi (1994) discusses the first buyers' incentives to adopt a new technology before information about alternative technologies is revealed. His paper discusses the buyers' actions, rather than focusing on strategic interaction between competing firms, which is one of the main topics here.

The paper is organised as follows: in section 2, the model is outlined. Section 3 characterises the equilibrium strategies and section 4 focuses on the impact different assumptions about buyers' expectations can have on the equilibrium outcome. Section 5 draws implications for public policy. Before the conclusion of the paper, the firms' incentives to agree on compatibility before the new products are ready for market introduction are discussed (section 6).

2. The basic model

The game has three stages. At stage 1, two firms, firm A and firm B, decide simultaneously for which stage a new technology should be developed and offered. The two technologies are incompatible. At the following two stages, two buyers enter sequentially. That is, the first buyer considers the potential technologies at stage 2 and decides whether to adopt or wait until stage 3.

The second buyer considers the technologies offered at stage 3, and adopts one of the technologies. Figure 1 presents a schematic diagram of the basic three stage game.

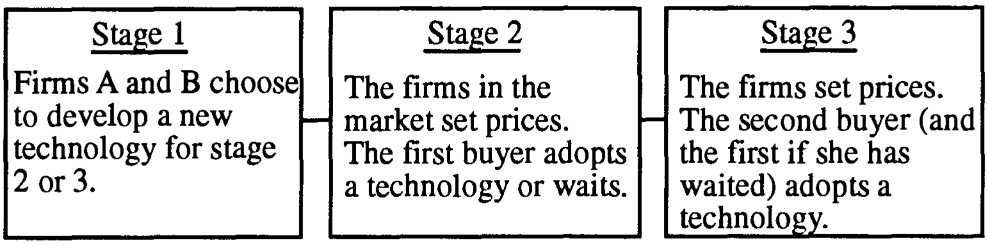

Figure 1. R&D timing in a three stage game

A. The buyers

The buyers are assumed to have identical preferences over alternative technologies. The adoption of a technology is irreversible.

A buyer's value of a technology consists of two components. One is the value of the product, given that the other buyer does not buy the same or a compatible technology, referred to as the *stand-alone value*. The second is the network externalities which only incur if the buyers use compatible technologies. Let Δ denote the value of the network externality, and let a or b denote the stand-alone value, depending on whether the product is produced by firm A or firm B, respectively.

Given that both buyers adopt at stage 3, for some prices there will be multiple equilibria. Similar to the approach taken by Katz and Shapiro (1986), I assume that the adoption decisions are made as if consumers could coordinate their adoption. That is, if there are multiple equilibria, then a Pareto optimal equilibrium is assumed to be realised.

To focus on the impact from network externalities on R&D, it is assumed that, *ceteris paribus*, the first buyer is indifferent between buying a given technology at stage 2 or at stage 3. Furthermore, I ignore discounting of prospective consumer surplus and profit. Discounting will introduce well-known incentives for early introduction of new technologies that are unrelated to the incentives due to network externalities. Relaxing these two assumptions would complicate the model without yielding substantially new insights.

B. The firms

Firms A and B are assumed to be identical *ex ante*. It is assumed to cost more to have a technology ready for introduction at stage 2 than at stage 3 (see Scherer (1967)). Let both firms have the same extra R&D costs if they develop a new technology for stage 2. Denote the extra costs C. For simplicity, there are no R&D costs if the firms enter at stage 3. The outcome or stand-alone value of an R&D project is stochastic. Assume that the firms' R&D projects result in stand-alone values which are non-negative real numbers with common support, $[0, \bar{v}]$. The probability distribution is given by $G(\cdot)$. The firms are assumed to be equally capable of developing a new technology and, consequently, the stand-alone values, a and b, have identical probability distributions.

If a firm introduces a new technology at stage 2, it does not develop another technology for stage 3.[6] It is often difficult to improve the existing technology or standard, while at the same time maintaining compatibility with the version owned by the existing users. Hence, this assumption is more likely to apply to markets where network externalities are present than to other markets (see Katz and Shapiro (1992)).[7]

The production costs are ignored for simplicity; the stand-alone values, a and b, should be interpreted as the net valuation of the new products. The firms engage in price competition.

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[6]This is a common assumption in the literature concerning capital-embodied innovations, see Fudenberg and Tirole (1985), Reinganum (1981), and Riordan (1992).

[7]By introducing a new *incompatible* technology, the incumbent gives up a competitive advantage.

3. Incompatibility and timing of entry

I examine the sub-game perfect equilibrium (or equilibria) in pure strategies. First, the equilibrium outcomes in the possible sub-games starting with stage 2 are examined. Then focus is on the firms' decisions at stage 1. Knowing the expected equilibrium profits in the different sub-games, the firms decide at stage 1 for which stage they will develop a new technology. There are four sub-games to consider: both firms enter at stage 2, both enter at stage 3, and the firms enter sequentially.

The expected profit in the sub-game where both firms enter at stage 3, will serve as a benchmark when the profit in the other three sub-games are analysed. As no technology is offered until stage 3, none of the firms obtain an installed base advantage before facing the buyers. The expected profits in the three other sub-games will differ from this benchmark by the follower's loss, $F(\Delta)$, the leader's benefits, $L(\Delta)$, or by the mutual benefits given that both firms offer a technology at stage 2, $M(\Delta)$. In the two last sub-games there is also a cost associated with rapid development.

Let $\Pi(i,j)$, $i,j \in \{2,3\}$, denote a firm's expected profit given that it chooses to introduce its new technology at stage i and that the competitor introduces its technology at stage j. Furthermore, let p_i and q_i, $i = 2,3$, respectively be firm A and firm B's price at stage i. In the following, I analyse the profit in the four different sub-games.

The expected profit if both firms introduce a technology at stage 3, $\Pi(3,3)$*:*

In this sub-game the firm with the best technology, i.e., the technology with the highest stand-alone value (a or b), will maximise its profit by offering the same consumer surplus as the largest consumer surplus the competitor can offer without a loss. Thus, if firm A (B) has the best technology, the market price will be $a-b$ $(b-a)$. The firms' expected profits are equal, because they *ex ante* have identical chances to develop the best technology. A firm's expected profit is equal to the number of buyers times the expected difference between its own stand-alone value and the competitor's stand-alone value, given that it has the best technology. Each firm's expected profit can be calculated as

$$\Pi(3,3) = 2\int_0^{\bar{v}}\int_0^{a}(a-b)dG(b)dG(a) = 2\int_0^{\bar{v}} G(a)(1-G(a))da. \qquad (1)$$

Here we let b take values below a for every possible realisation of a. The last equality follows by integration by parts. Note that there are two buyers at stage 3.

The expected profit if both firms introduce a technology at stage 2, $\Pi(2,2)$*:*

Here, we calculate the firms' mutual benefits if they both develop new technologies for stage 2, $M(\Delta)$. *Ex ante*, both firms have the possibility of capturing the buyers sequentially, and establishing an installed base for stage 3.

To calculate the *ex post* profit, the competition at stage 3 is analysed before the competition at stage 2. Without loss of generality, suppose firm A has the best technology, i.e., $a \geq b$. At stage 3, the firm that has captured the first buyer has an installed base advantage. There are two cases. The installed base advantage, Δ, may but must not exceed the difference in stand-alone values, $a-b$.

First consider the case where the difference in stand-alone values exceeds a possible installed base advantage, i.e., $a-b \geq \Delta$. Here, the second buyer adopts firm A's technology even if firm B has an installed base. The first buyer considers two alternatives. She can buy firm A's product at stage 2 and get a net benefit of $a+\Delta-p_2$. The benefits include the network externalities because firm A captures the last buyer. Alternatively, she can wait and get a net benefit of $b+\Delta$, which is the largest net benefit the loser at stage 3 (firm B) can profitably offer. Hence, firm A captures the first buyer by setting $p_2 = a-b$. Then, having obtained the installed base advantage, firm A also captures the second buyer by setting $p_3 = a+\Delta-b$. So, firm A earns a profit of $2(a-b)+\Delta$, given the stand-alone values, without taking into account the extra R&D cost, C, caused by entry at stage 2 instead of at stage 3.

Let $a-b<\Delta$. In this case, obtaining an installed base advantage is crucial for capturing the second buyer: The firm that captures the first buyer will also capture the second buyer. By capturing the first buyer, the sum of the firms' profit at stage 2 and 3 is, respectively, $p_2+a+\Delta-b$ and $q_2+b+\Delta-a$, for firm A and firm B. The lowest price that firm A can profitably offer is $b-a-\Delta$, and the lowest price that firm B can profitably offer is $a-b-\Delta$. Given that $a>b$, firm A is able to offer larger net consumer benefits than firm B. Firm A earns a profit of $(a+\Delta-(b+\Delta-(a-b-\Delta))+a+\Delta-b=3(a-b)$, given the stand-alone values, and excluding the extra R&D cost caused by rapid development of the new technology.

So far, the *ex post* profit has been analysed for the firm with the highest stand-alone value. At stage 1, however, the two firms do not know their future stand-alone values. They will base their decisions on the conditional expectation, which is identical for the firms:

$$\begin{aligned}\Pi(2,2) &= \int_0^{\bar{v}}\left\{\int_0^{a} 2(a-b)dG(b) + \int_0^{a-\Delta}\Delta dG(b) + \int_{a-\Delta}^{a}(a-b)dG(b)\right\}dG(a) - C \\ &= \Pi(3,3) + M(\Delta) - C \end{aligned} \tag{2}$$

where

$$M(\Delta) := \int_0^{\bar{v}}\left(\int_0^{a-\Delta}\Delta dG(b) + \int_{a-\Delta}^{a}(a-b)dG(b)\right)dG(a). \tag{3}$$

$M(\Delta)$ can be interpreted as the benefit of entering at stage 2 instead of at stage 3. The first integral in the brackets represents the benefits of early entry in the cases where $a-b \geq \Delta$, and the second integral represents the benefits of early entry if $a-b < \Delta$.

We see that without taking into account the extra costs, it is an advantage to capture the buyers sequentially, compared with facing all the customers simultaneously. *Given an early entry, the first buyer and the firms can share the benefits of being able to expropriate the second buyer's benefit of the network externality.*

The expected profit of the firm entering first, $\Pi(2,3)$*:*

Here, we calculate the benefits of developing a technology before the competitor, $L(\Delta)$. The firm introducing a new technology at stage 2 may establish an installed base before the competing firm enters.

Without loss of generality, suppose that firm A enters first. The first buyer cannot at stage 2 know the stand-alone value of the technology entering at stage 3. She will compare the expected net benefits of buying immediately with the expected benefits of waiting until the second firm enters.

i. Buying firm A's technology immediately: $a + \Delta G(a+\Delta) - p_2$

ii. Waiting until the second firm enters: $\Delta + \int_0^a b\,dG(b) + \int_a^{\bar{v}} a\,dG(b)$

If the buyer adopts firm A's technology at stage 2, she will only obtain the compatibility benefits if the technology firm B introduces at stage 3 has a stand-alone value less than $a+\Delta$. The probability of this outcome is $G(a+\Delta)$. Suppose the buyer waits until stage 3, then, given that firm A has the best technology, she will choose accordingly, and obtain net benefits equal to the expected stand-alone value of firm B' technology, $\int_0^a b\,dG(b)$. If firm B has the best technology, she obtains the stand-alone value of firm A, $\int_a^{\bar{v}} a\,dG(b)$.

For firm A to find it profitable to capture the first buyer at stage 2, its technology, a, must exceed a certain level $\bar{a}$. This is so, because given that a

is small, the first buyer will find it likely that the later buyer will buy firm B's technology at stage 3. Hence, the buyer will pay less as potential network externalities are lost. The price when $a \geq \bar{a}$ is given by

$$\bar{p}_2 = \int_0^a (a-b)dG(b) - \int_{a+\Delta}^{\bar{v}} \Delta dG(b).$$

The last term represents the buyer's expected loss of network externalities. Seen from stage 2, firm A's total profit is $\bar{p}_2$ plus the expected profit of having an installed base when facing the second buyer at stage 3:

$$\bar{p}_2 + \int_0^{a+\Delta} (a+\Delta-b)dG(b) = \int_0^a (a-b)dG(b) + \int_0^{a+\Delta} (a+\Delta-b)dG(b) - \int_{a+\Delta}^{\bar{v}} \Delta dG(b) \quad (4)$$

The cut-off value, $\bar{a}$, is determined such that the profit if the first buyer is captured at stage 2, equals the profit when the technology is not adopted at stage 2. Hence, $\bar{a}$, is given by the following equation:

$$2\int_0^{\bar{a}} (\bar{a}-b)dG(b) = \int_0^{\bar{a}} (\bar{a}-b)dG(b) + \int_0^{\bar{a}+\Delta} (\bar{a}+\Delta-b)dG(b) - \int_{\bar{a}+\Delta}^{\bar{v}} \Delta dG(b)$$

or

$$\int_0^{\bar{a}} \Delta dG(b) + \int_{\bar{a}}^{\bar{a}+\Delta} (\bar{a}+\Delta-b)dG(b) - \int_{\bar{a}+\Delta}^{\bar{v}} \Delta dG(b) = 0. \quad (5)$$

The first two integrals represent the expected price increase by having an installed base facing the second buyer. The third integral represents the first buyer's expected loss of network externalities if she adopts a new technology at stage 2. The expected loss of network externalities reduces the first buyer's willingness to pay for the technology at stage 2. Consequently, it represents a loss of profit for the firm. Given that firm A's stand-alone value is $\bar{a}$, the loss and the gain of capturing the first buyer at stage 2 are equal.

The *ex ante* expected profit, not knowing whether a is smaller or larger than $\bar{a}$, is:

$$\Pi(2,3) = 2\int_0^{\bar{a}}\int_0^a (a-b)dG(b)dG(a)$$
$$+\int_{\bar{a}}^{\bar{v}}\left(\int_0^a (a-b)dG(b) + \int_0^{a+\Delta} (a+\Delta-b)dG(b) - \int_{a+\Delta}^{\bar{v}} \Delta dG(b)\right)dG(a) - C \quad (6)$$

The first term represents the expected profit if the first firm's stand-alone value is not sufficiently large to capture the first buyer at stage 2, i.e., $a < \bar{a}$. The second term represents the profit if the stand-alone value is large enough to induce the first firm to capture the first buyer at stage 2, i.e., $a \geq \bar{a}$. The profit, $\Pi(2,3)$, can be written as

$$\Pi(2,3) = \Pi(3,3) + L(\Delta) - C$$

where $L(\Delta)$ represents the leader's benefits:

$$L(\Delta) := \int_{\bar{a}}^{\bar{v}} \left(\int_{0}^{a} \Delta dG(b) + \int_{a}^{a+\Delta} (a + \Delta - b) dG(b) - \int_{a+\Delta}^{\bar{v}} \Delta dG(b) \right) dG(a).$$

Interpretation is similar as for (5). It follows from the definition of $\bar{a}$ that $L(\Delta)$ is positive.

The expected profit of the firm entering last, $\Pi(3,2)$*:*

It remains to study the loss for the firm developing a technology for stage 3 given that the competitor offers a technology at stage 2, $F(\Delta)$.

If $a \in [\bar{a}, \bar{v}]$, firm A (which is assumed to enter first) captures the buyer entering at stage 2 immediately. In this case, the demand at stage 3 does only include the demand of the second buyer. However, if $a \in [0, \bar{a})$, firm A does not capture the first buyer at stage 2. Consequently, the demand at stage 3 includes the first buyer's demand. The profit of the firm entering last is

$$\begin{aligned} \Pi(3,2) &= 2 \int_{0}^{\bar{a}} \int_{a}^{\bar{v}} (b - a) dG(b) dG(a) + \int_{\bar{a}}^{\bar{v}} \int_{a+\Delta}^{\bar{v}} (b - (a + \Delta)) dG(b) dG(a) \\ &= \Pi(3,3) - F(\Delta) \end{aligned} \qquad (7)$$

where

$$F(\Delta) := \int_{\bar{a}}^{\bar{v}} \left\{ 2 \int_{a}^{a+\Delta} (b - a) dG(b) + \int_{a+\Delta}^{\bar{v}} (b - a) dG(b) + \int_{a+\Delta}^{\bar{v}} \Delta dG(b) \right\} dG(a).$$

$F(\Delta)$ is the expected loss of being the second firm compared with the outcome where both firms enter at stage 3. The first integral in the brackets represents the loss of not serving both buyers in the case where firm B would have won if firm A had waited until stage 3 to introduce its new technology, i.e., $a+\Delta > b > a$. The second integral represents the loss caused by reduced demand in the cases where firm A captures the first buyer and firm B captures the second. Firm B's installed base disadvantage is represented by the third integral.

A. Equilibrium outcomes

Having analysed the sub-games starting with stage 2, I now turn to stage 1. At stage 1, the two firms compare the expected profit levels calculated above and choose whether to develop the new technology for stage 2 or 3. See Figure 2.

Firm B

		2	3
Firm A	2	$\Pi(2,2)$; $\Pi(2,2)$	$\Pi(2,3)$; $\Pi(3,2)$
	3	$\Pi(3,2)$; $\Pi(2,3)$	$\Pi(3,3)$; $\Pi(3,3)$

Figure 2. Stage 1

The timing of entry depends on the comparison of different profit levels. Since I have assumed that the firms have identical distributions over stand-alone values and the same development costs, we only have to compare $\Pi(2,2)$ with $\Pi(3,2)$ and $\Pi(2,3)$ with $\Pi(3,3)$ to find the equilibrium outcome. Given that the competitor enters at stage 2, a firm enters at stage 2 if, and only if, $\Pi(2,2) \geq \Pi(3,2)$ or $M(\Delta)+F(\Delta) \geq C$. Moreover, given that the competitor enters at stage 3, the firm enters at stage 2 if, and only if, $\Pi(2,3) \geq \Pi(3,3)$ or $L(\Delta) \geq C$.

It is straightforward to prove the different equilibrium outcomes summarised in Table 1:

$\Pi(2,2)$ $M(\Delta)+F(\Delta)$ vs. $\Pi(3,2)$ C	$\Pi(2,3)$ $L(\Delta)$ vs. $\Pi(3,3)$ C	Equilibrium outcomes
>	>	(2,2).
>	<	(2,2), (3,3).
<	>	(2,3), (3,2).
<	<	(3,3).

Table 1. Equilibrium outcomes

In the right column, firm A's date of entry is stated first and firm B's entry date second, e.g. (3,2) means that firm A enters at stage 3 and firm B at stage 2.

There are assumed to be no social benefits from developing a technology for stage 2 instead of for stage 3 – the gross benefits of adopting a technology at stage 2 and at stage 3 are the same. However, there are two possible welfare losses associated with early introduction of a new technology. In addition to increasing the R&D costs, sequential entry may lead to loss of standardisation benefits. Given that the first buyer adopts the technology offered at stage 2, the standardisation benefits are lost if the technology developed last turns out to be a favourable choice of the second buyer. Hence, the socially best outcome is that both firms introduce their technologies at stage 3.

In the absence of network externalities ($\Delta = 0$), a firm will not benefit from early entry (stage 2) — there are no benefits attributed to establishing an installed base before the second firm's entry, i.e., $M(0)=0$, $F(0)=0$, and $L(0)=0$.[8] However, if a firm enters early, the R&D costs increase by $C>0$. Consequently, in the absence of network externalities, both firms will enter at

[8]The equalities follow from the definitions of $M(\Delta)$, $F(\Delta)$, and $L(\Delta)$.

stage 3, and the equilibrium outcome coincides with the socially best outcome.

Proposition 1

Mutual entry of the firms at stage 3 is the socially best outcome. In equilibrium, network externalities may induce one or both firms to enter at stage 2.

The formal proof is straightforward and hence omitted.[9]

Corollary 1

Increased network externalities, Δ, increase the gain of being first, $L(\Delta)$, the loss of being last, $F(\Delta)$, and the gain of mutually entering early, $M(\Delta)$.
To induce the firms to enter at stage 3, the extra cost attributed to early entry, C, needs to be larger if the network externalities increase.

Proof: See the Appendix.

There are two reasons why an increase in network externalities will increase the firms' advantage of entering first and the disadvantage of entering second. First, the total value of the incumbent technology increases compared to the entrant's technology. Second, given an increase in the network externalities, the firm which enters first will be more inclined (i.e., for lower stand-alone values) to capture the first buyer. Consequently, the loss of being second increases. However, an increase in the network externalities has a negative impact on the first firm's profit as well. Knowing that the second buyer may choose an incompatible technology, the first buyer will be

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[9]Given that the R&D project that leads to a new technology at stage 2 is equally costly as the project that ends at stage 3, and that the first project dominates the second by first order stochastic dominance, network externalities may still cause premature entry.

more reluctant to buy the first introduced technology (due to increased value of compatibility). Consequently, the first buyer is willing to pay less, and the profit is reduced. The proof of Corollary 1 shows that the positive impact of larger network externalities exceeds the negative impact on profit.

Compared with entering at stage 3, the firms' extra profits by entering mutually at stage 2, $M(\Delta)$, grow with an increase in the network externalities. At stage 3, larger network externalities increase the expected difference between the best offers the firms can profitably make. The firm with an installed base will be in a more advantageous position and earn more due to the increase in the value of the installed base. Since the two firms are identical *ex ante*, they have equal opportunities of becoming the firm with the installed base advantage. Hence, both firms' expected profits increase with an increase in the network externalities. Moreover, since it becomes more profitable to possess an installed base at stage 3, the competition at stage 2 will become more vigorous. However, the proof of Corollary 1 shows that the increase in the expected profit at stage 3 exceeds the loss due to tougher competition at stage 2.

Proposition 2

Given $M(\Delta)+F(\Delta)>C>M(\Delta)$, mutual entry at stage 2 is an equilibrium outcome although both firms get a larger profit if they mutually enter at stage 3. If, in addition, $L(\Delta)>C$, mutual entry at stage 2 is a unique equilibrium.

Proof: From Table 1, $M(\Delta)+F(\Delta)>C$ ensures that (2,2) is an equilibrium. $L(\Delta)>C$ ensures that (2,2) is a *unique* equilibrium. Given $C>M(\Delta)$, the fixed R&D costs attributed to rapid development of a new technology exceed the firms' benefits by entering at stage 2 instead of at stage 3.

Q.E.D.

Although both firms in equilibrium enter at stage 2, they might have earned more if they mutually delayed entry until stage 3. By developing the new technology more slowly, R&D costs are saved, and this cost reduction can exceed the benefits of entering at stage 2.

Given that the conditions stated in Proposition 3 hold, due to the network externalities both firms will enter the market at stage 2, although mutual entry at stage 3 is Pareto preferred.[10] In the cases where (2,2) is a unique equilibrium, the firms are facing a game that resembles the well-known prisoners' dilemma game. In a market without network externalities, these incentives for entering early disappear and the firms' profits are larger.

B. Consumer surplus

Early introduction of new technologies may have different consequences for the first and the second buyer.

Denote the buyer entering at stage k's consumer surplus $cs_k(i,j)$, given that the two firms enter at stages i and j, $i,j,k \in \{2,3\}$.[11]

Proposition 3

The first buyer:

$$cs_2(2,2) > cs_2(3,3) = cs_2(3,2).$$

The second buyer:

$$cs_3(3,3) \geq cs_3(2,3) > cs_3(2,2).$$

Proof: See the Appendix.

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[10]The well being of the buyers is not taken into account.

[11]The consumer surplus is independent of which firm that enters first, $cs_k(2,3) = cs_k(3,2)$.

The first buyer benefits from an early entry of both firms. Both firms are willing to take a loss at stage 2 to be able to profit from an installed base advantage at stage 3. The competition for the first buyer will be tougher the more equally valuable the two technologies are. If a firm finds it necessary to capture the first buyer to be able to profitably capture the second, i.e., $|a-b|<\Delta$, it will be willing to set the price below production costs. In the cases where the difference in the stand-alone values is sufficiently large to let a firm capture the last buyer independent of whether it has captured the first, $|a-b|\geq\Delta$, the first buyer will be offered the consumer surplus which the losing firm at most can offer profitably. For a given stand-alone value of firm A, the consumer surplus of the first buyer is illustrated in Figure 3.

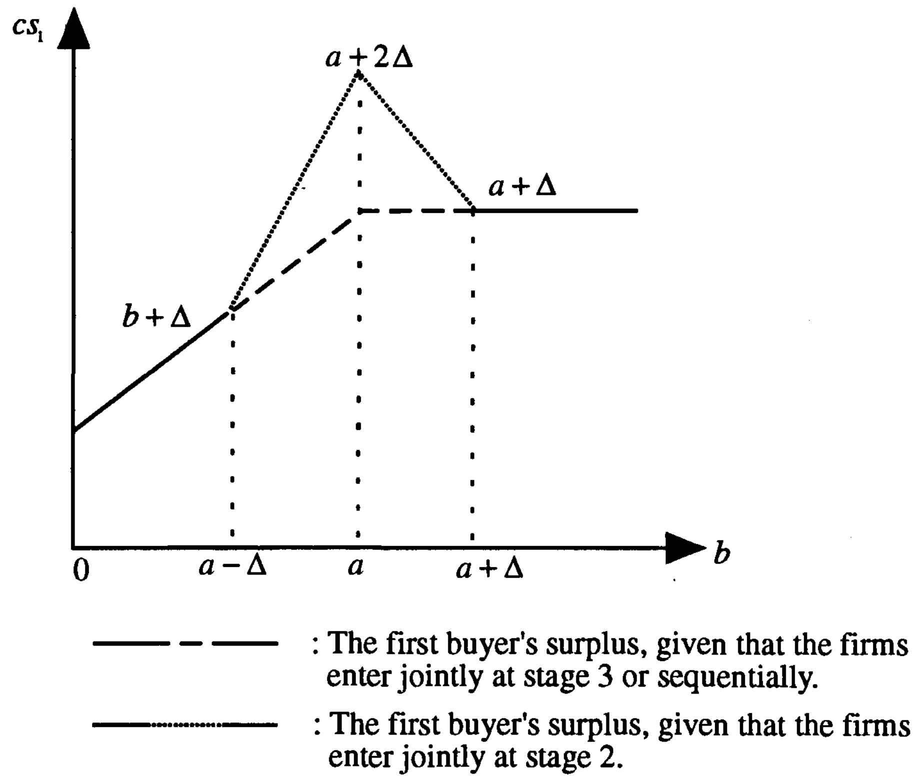
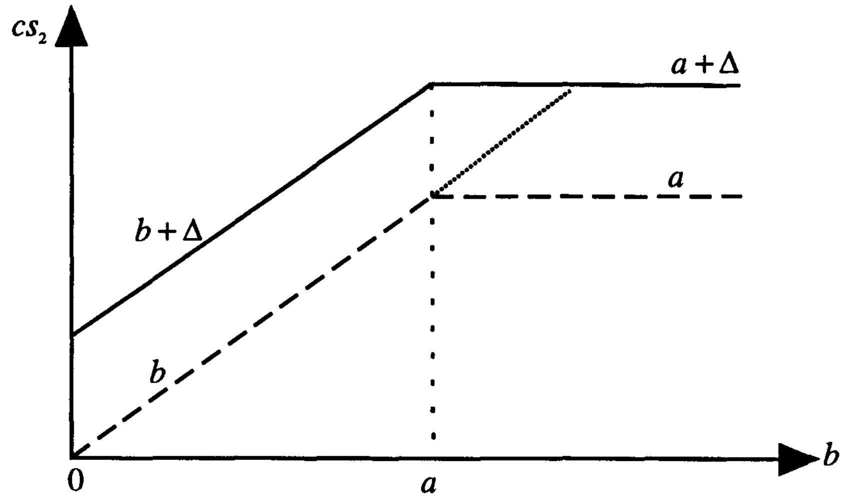


Figure 3. *The first buyer's consumer surplus*

The firms' entry decision will have a different impact on the second buyer's surplus than on the first buyer's surplus. The second buyer prefers that none of the firms have established an installed base before the second buyer arrives, and consequently that both firms enter at stage 3. Without an installed base, the competition is expected to be more vigorous because the firms are equally good competitors. Keeping firm A's stand-alone value fixed, the second buyer's surplus is illustrated in Figure 4.



———— : The second buyer's surplus, given that both firms enter at stage 3 or that the first entering firm does not capture the first buyer at stage 2.

– –······—— : The second buyer's consumer surplus, given that the firms enter sequentially and the first firm captures the first buyer.

– – – – – – : The second buyer's consumer surplus, given that both firms enter at stage 2.

Figure 4. The second buyer's consumer surplus

It is worth noting that the two buyers have conflicting interests regarding the pace of the product development. The first buyer favours that both firms enter early and engage in severe competition to capture the first buyer and consequently obtain an installed base advantage. The second buyer prefers that the competition at stage 3 is not curbed by an installed base advantage.

4. Expectations

In the above discussion there has been assumed to be only one buyer in each generation or at each stage. Possible co-ordination problems within each generation have, consequently, been ignored. Moreover, if the first buyer waits until the second buyer enters, it has been assumed that the two buyers co-ordinate on the Pareto preferred technology.

To focus on co-ordination failures within a generation of buyers, there is in this section assumed to be n identical buyers in each generation. Three alternative assumptions regarding the buyers' expectations about the other buyers' choice, are discussed and compared with the situation where the buyers co-ordinate on the Pareto preferred technology.

Alternative assumptions about the buyers' expectations:

1. Each generation co-ordinates on the Pareto optimal technology alternative.
2. The first generation of buyers adopts the Pareto preferred technology and the second generation adopts the same technology given that it is not a dominated strategy.
3. One of the technologies is expected to win throughout the game and will be adopted if it is not a dominated strategy.

Assumption 1 is similar to assuming that there is *only one* buyer in each generation. The discussion based on this assumption serves as a benchmark for the discussion of the following two assumptions.

If assumption 2 is adopted, it is a *focal* equilibrium for the second generation of buyers to choose the same technology as the first buyers.[12]

[12]See Schelling (1960).

Hence, the second generation of buyers will not necessarily adopt the technology which maximises their consumer surplus.

Moreover, in some cases, one of the competitors may have a reputation for being the firm which sets the standards in new markets. In these markets, assumption 3 may reflect the buyers' expectations. For instance, IBM previously benefited from having a reputation for being a, *de facto*, standard-setter in the computer market.

The notation has to be changed slightly to capture that there are more than one buyer in each generation:

	Network externalities given n buyers in each generation:	Network externalities given *1* buyer in each generation:
One buyer:	0	0
All buyers in one generation:	$\Delta(n)$	0
Both generations:	$\Delta(2n)$	Δ

The previous notation, where there is assumed to be only one buyer in each generation, is summerized in the right-hand column. The left-hand column contains the new notation with n buyers in each generation of buyers.

Given that the buyers' expectations are given by assumption $i \in [1,2,3]$, let $M^i(\Delta)$ be the benefits of a mutual entry at stage 2, $F^i(\Delta)$ be the loss of entering at stage 3 given that the competitor enters at stage 2, and $L^i(\Delta)$ be the gain of entering at stage 2 if the competitor enters at stage 3.

Proposition 4

If the buyers' expectations are given by assumption 2 instead of assumption 1, a firm's incentives to enter at stage 2 increase whether the competitor enters at stage 2 or at stage 3 (i.e. $L^2(\Delta) > L^1(\Delta)$ *and* $M^2(\Delta) + F^2(\Delta) > M^1(\Delta) + F^1(\Delta)$*).*

Proof: See the Appendix.

The main difference between assumptions 1 and 2 is that, if assumption 2 is adopted, the first generation's choice represents a signal to the next generation of buyers. The buyers in the second generation expect that the other buyers in her generation will adopt the same technology as the first buyers did, given that this technology is not a dominated choice. Consequently, selling to the second generation of buyers, the firm with the installed base is not only able to profit from the network externalities of the existing installed base, but also from the expected network externalities of the second generation.

It follows from Table 1 that if assumption 2 is adopted instead of assumption 1, the increase in R&D costs by early entry has to be larger to prevent a firm from entering early.

Even though none of the competing firms have a history in the emerging market, a firm can benefit from its reputation in an established market. A firm which is the dominating firm in other markets might be expected to also dominate a new market. Take Microsoft as an example. If Microsoft enters the interactive television market, the buyers may expect that its dominating position in the software industry will be transferred to the new market, and that its technology will be the dominating standard in the new market as well. In these cases, assumption 3 seems to be the best one.

If the buyers' expectations are given by assumption 3, the two firms will have different profit opportunities. Without loss of generality, let firm A have the technology which the buyers anticipate will be adopted as a market standard.

Proposition 5

Given that the buyers' expectations are given by assumption 3,

a. the firm having the technology expected to become the market standard will never benefit from entering before the other firm.

b. the firms will never enter sequentially.

Proof: See the Appendix.

The firm which is anticipated by the buyers to set the market standard, will not benefit from introducing its technology before its competitor. An early entry will only be profitable if it enables the firm to set a higher price facing the second generation of buyers. However, since the second generation of buyers expects that the dominating firm's technology will be the standard, independent of whether it enters early or not, the second generation of buyers' willingness to pay is independent of the timing of entry.

However, the firm which is *not* expected to set the market standard, may prefer to introduce its technology at stage 2. By entering early, it can capture the buyers sequentially. At stage 3, an installed base enables the firm to set a higher price to the second generation of buyers and still offer a product-price combination which dominates the best offer the competitor profitably can make.[13]

If the firm which is expected to set the market standard knows that its competitor enters at stage 2, it may decide to enter early as well. By entering early, the firm can prevent the competitor from establishing an installed base before facing competition, and hence reduce the competitor's advantage of having a reputation for being a standard setter in new markets. It is shown that the anticipated standard-setter's loss of entering after the other firm,

[13]Although a buyer expects that the others adopt the incompatible technology, she will stick to the same technology.

exceeds the competitor's benefits of entering first. Since the extra R&D costs of entering early are the same for the two firms, both firms enter early if the firm which is not the anticipated standard-setter finds it profitable to enter early.

In the following sections, I shall for simplicity return to the two-buyer assumption – there is only one buyer in each generation and co-ordination on the Pareto optimal equilibrium is achieved. However, it is shown above that if the buyers' expectations are not given by assumption 1, but by assumption 2, this will essentially increase the value of having an installed base. Consequently, in the following discussion we can infer that if the buyers' expectations are given by assumption 2 instead of by assumption 1, this will have the same impacts on the market outcome as an increase in the network externalities.

5. Public policy

Much of the research on network externalities and co-ordination problems has suggested that intervention of a government agency can solve the externality problem. Government agencies are to some extent aware of the need for standardisation in many markets, and have supported voluntary standardisation organisations as well as established agencies which hold the authority to impose mandatory standards, e.g. Federal Communication Commission in the US.

Assume that a government imposes mandatory standards if standardisation improves social welfare, but that it cannot regulate the firms' R&D efforts. Consequently, the timing of entry is chosen by the firms.

Proposition 6

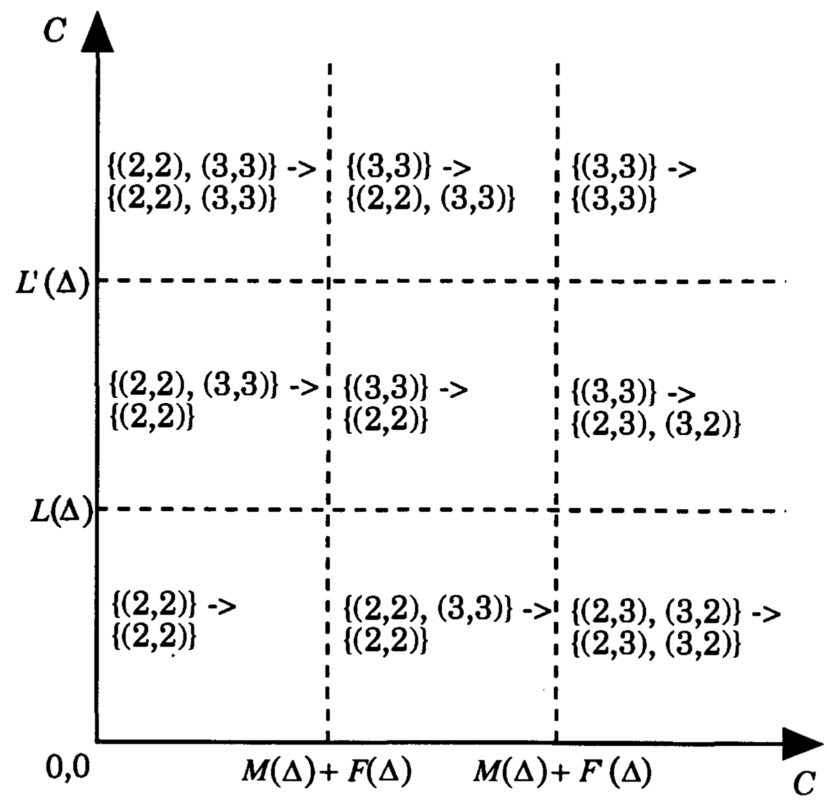
Suppose that the government chooses the incumbent technology as a mandatory standard whenever the market outcome implies a welfare reducing switch of standards. The firms' incentives to enter at stage 2 are strengthened even if the introduction of a mandatory standard is followed up by regulation to prevent the incumbent firm from charging a price above the production costs.

Proof: See the Appendix.

Although the technological improvement is too small to justify a switch of standards, the second buyer may favour the new technology instead of the incumbent one (i.e. $2\Delta > |a-b| > \Delta$). In these situations a benevolent government has incentives to impose the established technology as a mandatory standard for both buyers. The socially best standardisation policy when the introduction dates of the technologies are given, we refer to as the *ex post* efficient policy. However, if the buyers' adoption dates as well as the firms' entry dates are not given, the suggested standardisation policy can harm social welfare. An *ex ante* efficient standardisation policy might be different from an *ex post* efficient standardisation policy.

The first buyer's incentive to adopt the firstly introduced technology immediately, is strengthened by an *ex post* efficient public standardisation policy. The probability of buying a technology which is compatible with the next buyer's technology, increases if the government can intervene at stage 3. Consequently, the probability of a loss of network externalities is reduced, and the first buyer is less reluctant to adopt a new technology early. The firm entering first demands a lower stand-alone value to capture the first buyer (i.e., $\bar{a}$ is lower). Moreover, since early adoption makes incompatibility with the buyer entering last possible, an *ex post* efficient standardisation policy can be socially harmful. See Choi (1994) for a discussion of a similar result in a different model.

Besides strengthening the first buyer's incentives for adoption at stage 2, the *ex post* efficient public standardisation policy may also influence the firms' timing of R&D. Let $L'(\Delta)$ and $F'(\Delta)$, respectively, denote the first firm's gain by entering early and the last firm's loss of being second, given that the government agency follows the *ex post* efficient standardisation policy. The first buyer's increased willingness to adopt a new technology at stage 2 increases the profit of entering at stage 2 instead of at stage 3, i.e., $L'(\Delta) > L(\Delta)$ and $F'(\Delta) > F(\Delta)$.[14] Figure 5 illustrates how the timing of product introduction changes, due to *ex post* efficient standardisation policy.



{ the equilibrium outcomes without *ex post* standardisation policy} ->
{ the equilibrium outcomes with *ex post* standardisation policy}

Figure 5. Standardisation policy and timing of entry and R&D

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[14]See the proof of Proposition 6.

In cases where the timing of R&D alters due to the *ex post* efficient standardisation policy, the social welfare is never improved, but may be reduced. We can conclude that *ex post* efficient standardisation policy may be harmful, given that the government cannot regulate the firms' R&D.

Although the government knows that mandatory standards at stage 3 reduce welfare, it might find it impossible to commit itself to abstain from imposing standards at the time when the firms' R&D and entry decisions are made. If the firms make their R&D decisions before the government decides whether to introduce mandatory standards, they expect the government to introduce mandatory standards whenever it is welfare improving at the time when the decision is made. Consequently, the government will take the firms' R&D and entry decisions as given, and the *ex post* efficient standardisation policy can be socially harmful, as discussed previously. The government has to be able to commit itself to abstain from introducing mandatory standards later, to prevent the socially harmful impact *ex post* standardisation policy can have on the firms' R&D and entry decisions.[15]

An alternative public policy is to impose compulsory licensing of the best technology to the competing firm, for a license fee equal to or below the fee the licenser is willing to accept in an unregulated market.[16]

Proposition 7

The market outcome and the socially best outcome coincide if the government requires that the firms license their technologies for a per-unit fee of $Max\{|a-b|,0\}$.

[15]The issue of dynamic inconsistency in public policy was first raised by Kydland and Prescott (1977).

[16]There is an existing literature on compulsory licensing, see e.g. Tandon (1982).

Proof: If a firm enters at stage 2 and the competitor enters at stage 3, the first firm will never capture the first buyer at stage 2 (see equation (5)).

$$\int_0^{\bar{a}} 0 f(b)db + \int_{\bar{a}}^{\bar{a}+0} (\bar{a}+0-b)f(b)db - \int_{\bar{a}+0}^{\bar{v}} \Delta f(b)db = 0 \Leftrightarrow \bar{a} = \bar{v} \Rightarrow L(\Delta) = 0.$$

Since the first entering firm never captures the first buyer at stage 2, the second firm will never lose by entering at stage 3 instead of at stage 3, i.e., $F(\Delta) = 0$.

Given that both firms enter at stage 2, the firm capturing the first buyer will (due to the licensing regime imposed of the government) be unable to take advantage of its installed base at stage 3, i.e., $M(\Delta) = 0$. Proposition 7 follows. Q.E.D.

Above we have attributed the premature introduction of new technologies to the presence of network externalities. The firm capturing the first buyer obtains a strategic advantage at stage 3, which exceeds the difference in stand-alone values of the two technologies. Requiring that the firm with the best technology *always* licenses its technology for a per-unit fee equal to the difference in stand-alone values, weakens the property rights of the best technology. The firms cannot take advantage of the network externalities and, consequently, there will be no gains by entering at stage 2, mutually or alone. As in markets without network externalities, there will be no incentives for entering early.[17]

In some cases, the early buyers are concentrated in the firms' common home market, and the late buyers are mainly in foreign markets. If a government agency only takes into account the welfare of domestic buyers and firms, it may, contrary to the discussion above, prefer that one or both firms enter early. It follows from the discussion of consumer surplus, that

[17]Note that the government must be committed to enforce the licensing rule also if, given the stand-alone values, the unregulated market outcome does not involve a social loss.

early introduction of one or both technologies reduces the consumer surplus of the late buyers to the advantage of the firm(s) and buyers entering early.

6. Compatibility

Although products are different, they may work together with identical complementary goods, e.g. different computers can use the same software. In these cases, we say that the products or technologies are compatible. To achieve compatibility the firms have to agree on some common technological features.

The industries such as the information technologies display a striking pattern of co-operative alliances.[18] The firms in these alliances both compete and co-operate. As an example IBM and Apple have agreed upon the use of a common CPU in their computers, but produce different computers which compete in the market.

We have seen that network externalities create incentives for racing into emerging markets. In this section, I argue that these racing incentives can induce the firms to enter into alliances which seek to establish common standards.

Assume that the firms by agreeing on certain common technological features can ensure that *prospective* products are compatible. The firms' compatibility decision is taken at stage 0. See Figure 7.

If compatibility is agreed upon, the buyers can take advantage of the complementary products supplied for a competing technology. Consequently, the network externalities are not related to a particular technology, but can be taken advantage of by users of competing technologies as well.[19]

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[18]See Hagedoorn and Schakenraad (1992).

[19]The firms may at least reduce the difference in network externalities between the two technologies by letting a large part of the complementary product be common for the two technologies.

Stage 0	Stage 1	Stage 2	Stage 3
Firms A and B decide whether their technologies will be compatible or not	The firms choose to develop a new technology for stage 2 or 3.	The firms in the market set prices. The first buyer adopts a technology or waits.	The firms set prices. The second buyer (and the first if she has waited) adopts a technology.

Figure 7. *Compatibility and R&D*

It has been argued that standardisation and compatibility stimulate R&D and early development of new markets.[20] Although there are good reasons to believe that standardisation can stimulate innovation, standardisation may as well induce the firms to spend less on R&D and early development of new markets.

Proposition 8

If compatibility can be achieved without any costs, both firms will strictly favour compatibility if

$$M(\Delta)+F(\Delta)>C>M(\Delta) \qquad \text{and} \tag{8}$$

$$L(\Delta)>C. \tag{9}$$

Compatibility delays the development of new technologies from stage 2 to stage 3.

Proof: Given that (8) and (9) hold, in equilibrium both firms enter at stage 2 (see Table 1). Since $C>M(\Delta)$, both firms prefer entry at stage 3 instead of at stage 2.[21] Q.E.D.

Network externalities may induce both firms to develop their technologies early. This will happen if conditions (8) and (9) hold. Moreover, if the extra

[20]See e.g. David and Steinmueller (1994).

[21]Condition (9) is not necessary for having a mutual entry at stage 2 as an equilibrium, but it makes sure that (2,2) is a unique equilibrium.

R&D costs caused by an early introduction (C) exceed the benefits ($M(\Delta)$), the firms have incentives to enter early, although they would have been better off by mutually committing themselves to late entry. The situation resembles the well-known prisoners' dilemma game. (See Proposition 2.)[22]

Compatibility will remove the advantage of having an installed base. Consequently, the incentives for rapid development of a new technology disappear and the pace of the R&D race is reduced.[23] Riordan (1992) also points out the danger of too early development of new technologies. He shows that price and entry regulations (as imposed on many cable and telephone companies) can beneficially slow down technology development. Here, I argue that agreements about compatibility (or *ex ante* imposed standards) can have a similar impact on the development of new technologies.

Although there has been extensive co-operation in high-technology industries in recent years, and the co-operative agreements have often been subject to scrutiny by Federal agencies, there has been little antitrust enforcement. Given that some of the alliances are motivated by the need for compatibility, the argument above can be used to justify a lenient antitrust policy. The analysis of how mandatory standards can have adverse impacts on welfare, might further strengthen the need for a lenient antitrust policy.[24]

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[22] If compatibility can be achieved without the competing firm's consent, i.e., weak intellectual property rights, none of the firms have incentives to obtain an installed base by entering early. See Farrell (1989) for an interesting discussion on network externalities and intellectual property rights.

[23] National Bureau of Standards refused to write interface standards for the computer industry because they claimed standards would retard innovation. (See Hemenway (1975)) The analysis above can, to some extent, justify their claim that standards written before development of new technologies (*ex ante* standardisation policy) discourage rapid development of new technologies. However, note that slow development of new technologies is desirable in my model.

[24] Note that mandatory standards imposed by government agencies taking the firms' entry sequence as given, have a different impact on welfare than voluntary standards firms agree on before the development of new products are completed.

7. Conclusion and possible extensions

This paper has analysed how network externalities can influence the timing of R&D. It is shown that network externalities give the firms incentives to enter early in order to establish an installed base before the competitor enters the market. Consequently, network externalities can induce the firms to participate in an R&D race which increases the development costs of new technologies, and may cause incompatibility between early and late adopters.

Compared with the equilibrium outcome, both firms may favour that new technologies are developed less rapidly. The development costs decrease if the firms have more time to search for a new technology. It is shown that the firms, by agreeing on common features of prospective technologies which ensure compatibility, can delay the development of new technologies. Compatibility will remove the advantage of having an installed base and, consequently, the firms will not have incentives to develop new technologies quickly to capture buyers before the competitor enters. This may be one of several reasons why we see so many co-operative arrangements in the information technology industries.

In some cases, government agencies hold the authority to impose mandatory standards. A welfare maximising government will want to impose the incumbent technology as a mandatory standard, given that a new incompatible technology will be adopted by the last entering buyers and that it does not represent technological improvements sufficient to justify a switch of standards. Since the first buyers anticipate that the government may intervene in favour of the incumbent technology to ensure that network externalities are not lost, the first buyers are more willing to buy early. Consequently, the firms may be induced to enter early although accelerated entry reduces social welfare. Hence an *ex post* welfare optimal standardisation policy can be disadvantageous *ex ante*.

The market outcome and the welfare optimal outcome coincide if the government agency requires that the firm with the best technology licenses its technology for a reasonable license fee to the competitor. If the licensing fee per-unit is set to the difference in stand-alone values between the two competing technologies, the firms are unable to take advantage of an installed base advantage, and the firms' incentives for premature entry are removed.

There are several directions in which the analysis may be extended. One could allow the firm not entering early to decide whether to develop a new technology or not after the technology of the first entering firm is known. Given that there are fixed costs attributed to late entry as well as to early entry (e.g. R&D costs), the second firm will only enter if the expected income of developing a new technology, *given the established firm's technology,* exceeds the entry costs.

Another extension is to consider improvements of the first introduced technology. Improvements of the first technology may make the first buyer more reluctant to buy early because the expected consumer surplus of waiting increases. However, an improvement will also reduce the probability of a later switch of standards and, consequently, make early adoption more attractive.

Appendix

Proof of Corollary 1.

The corollary can be shown by differentiating $L(\Delta)$, $F(\Delta)$ and $M(\Delta)$ with respect to Δ.

a) Differentiation of $L(\Delta)$:

$$\frac{dL(\Delta)}{d\Delta} = \frac{\partial L(\Delta)}{\partial \bar{a}}\frac{d\bar{a}}{d\Delta} + \frac{\partial L(\Delta)}{\partial \Delta}. \tag{A1}$$

$\frac{\partial L(\Delta)}{\partial \bar{a}} = 0$ follows from the envelope theorem. Hence, the first term in (A1) is zero. The second term is positive:

$$\frac{dL(\Delta)}{d\Delta} = \frac{\partial L(\Delta)}{\partial \Delta} = \int_{\bar{a}}^{\bar{v}} (2G(a+\Delta) + \Delta g(a+\Delta) - 1)dG(a) > 0.$$

$g(\cdot)$ is the density function of $G(\cdot)$. It follows from equation (5) that the inequality holds:

$$\Delta G(\bar{a}+\Delta) + \int_{\bar{a}}^{\bar{a}+\Delta} (\bar{a}-b)dG(b) - \Delta(1-G(\bar{a}+\Delta)) = 0$$

$$G(\bar{a}+\Delta) = \frac{1 - \frac{1}{\Delta}\int_{\bar{a}}^{\bar{a}+\Delta}(\bar{a}-b)dG(b)}{2} > 0.5.$$

The advantage of being the leader increases with the amount of network externalities.

b) Differentiation of $F(\Delta)$:

$$\frac{dF(\Delta)}{d\Delta} = \frac{\partial F(\Delta)}{\partial \bar{a}}\frac{d\bar{a}}{d\Delta} + \frac{\partial F(\Delta)}{\partial \Delta}.$$

The first term is positive since $\frac{\partial F(\Delta)}{\partial \bar{a}} < 0$ and $\frac{d\bar{a}}{d\Delta} < 0$. The first inequality is obvious because the loss caused by being the follower is reduced if the first firm requires a larger stand-alone value to capture the first buyer. The second inequality can easily be established by differentiating (5) with respect to $\bar{a}$ and Δ:

$$\frac{d\bar{a}}{d\Delta} = \frac{1 - 2G(\bar{a}+\Delta) - \Delta g(\bar{a}+\Delta)}{\int_{\bar{a}}^{\bar{a}+\Delta} dG(b) + \Delta g(\bar{a}+\Delta)} < 0.$$

Note that I have used that $G(\bar{a}+\Delta) > 0.5$.

The second term is also positive:

$$\frac{\partial F(\Delta)}{\partial \Delta}=\int_{\bar{a}}^{\bar{v}}\left(\int_{a}^{\bar{v}}dG(b)+(a+\Delta-a-\Delta)g(a+\Delta)-\int_{a}^{a+\Delta}dG(b)\right)dG(a)>0.$$

An increase in the network externalities increases the loss of being second.

c) Differentiation of $M(\Delta)$:

$$\frac{dM(\Delta)}{d\Delta}=\int_{0}^{\bar{v}}G(a-\Delta)dG(a)>0.$$

The gains by mutually entering at stage 2 instead of at stage 3 grow with the amount of network externalities. Q.E.D.

Proof of Proposition 3:

Before the consumer surplus in the three different cases can be compared, they have to be calculated:

a) The consumer surplus, given that both firms enter at stage 2:

The first buyer's expected consumer surplus:

$$cs_2(2,2)=\int_{0}^{\bar{v}}\left(\int_{0}^{a}bdG(b)+\int_{a}^{\bar{v}}adG(b)\right)dG(a)+\Delta+\int_{0}^{\bar{v}}\int_{a-\Delta}^{a+\Delta}(\Delta-|a-b|)dG(b)dG(a).$$

The second buyer's expected consumer surplus:

$$cs_3(2,2)=\int_{0}^{\bar{v}}\left\{\int_{0}^{a}bdG(b)+\int_{a}^{\bar{v}}adG(b)\right\}dG(a).$$

b) Consumer surplus, given that both firms enter at stage 3:

$$cs_2(3,3)=cs_3(3,3)=\int_{0}^{\bar{v}}\left(\int_{0}^{a}bdG(b)+\int_{a}^{\bar{v}}adG(b)\right)dG(a)+\Delta.$$

c) Consumer surplus if the firms enter sequentially:

The first buyer will get the same consumer surplus whether she enters at stage 2 or at stage 3:

$$cs_2(2,3)=\int_{0}^{\bar{v}}\left(\int_{0}^{a}bdG(b)+\int_{a}^{\bar{v}}adG(b)\right)dG(a)+\Delta.$$

The second buyer's consumer surplus:

$$cs_3(2,3) = \int_0^{\bar{a}} \left\{ \int_0^a bdG(b) + \int_a^{\bar{v}} adG(b) + \Delta \right\} dG(a) + \int_{\bar{a}}^{\bar{v}} \left\{ \int_0^{a+\Delta} bdG(b) + \int_{a+\Delta}^{\bar{v}} adG(b) \right\} dG(a)$$

$$= \int_0^{\bar{v}} \left\{ \int_0^a bdG(b) + \int_a^{\bar{v}} adG(b) + \Delta \right\} dG(a) + \Delta G(\bar{a}) + \int_{\bar{a}}^{\bar{v}} \int_a^{a+\Delta} (b-a) dG(b) dG(a)$$

By comparison of the calculated consumer surplus in the three different cases, Proposition 3 follows. Q.E.D.

Proof of Proposition 4:

First, I show that the stand-alone value which makes the first entering firm indifferent between selling to the first buyers at stage 2 and waiting, is lower if the buyers' expectations are given by assumption 2 instead of by assumption 1. Let $\bar{a}^1$ and $\bar{a}^2$ denote the cut off, given that assumption 1 and assumption 2 respectively are applied. See (5). By comparing

$$\int_0^{\bar{a}^1} (\Delta(2n) - \Delta(n)) dG(b) + \int_{\bar{a}^1}^{\bar{a}^1 + \Delta(2n) - \Delta(n)} \left(\bar{a}^1 + \Delta(2n) - \Delta(n) - b\right) dG(b)$$
$$- \int_{\bar{a}^1 + \Delta(2n) - \Delta(n)}^{\bar{v}} (\Delta(2n) - \Delta(n)) dG(b) = 0$$

with

$$\int_0^{\bar{a}^2} \Delta(2n) dG(b) + \int_{\bar{a}^2}^{\bar{a}^2 + \Delta(2n)} \left(\bar{a}^2 + \Delta(2n) - b\right) dG(b) - \int_{\bar{a}^2 + \Delta(2n)}^{\bar{v}} (\Delta(2n) - \Delta(n)) dG(b) = 0,$$

it follows that $\bar{a}^1 \geq \bar{a}^2$. It is more valuable to have an installed base if the buyers entering at stage 3 expect that all buyers will adopt the same technology as the first entering buyers (assumption 2), than if they expect co-ordination on the Pareto optimal choice (assumption 1). Proposition 4 follows from comparisons of $M^1(\Delta)$ with $M^2(\Delta)$, $F^1(\Delta)$ with $F^2(\Delta)$, and $L^1(\Delta)$ with $L^2(\Delta)$:

$$n\int_0^{\bar{v}}\left\{\int_0^{a-\Delta(2n)+\Delta(n)}(\Delta(2n)-\Delta(n))dG(b)+\int_{a-\Delta(2n)+\Delta(n)}^{a}(a-b)dG(b)\right\}dG(a)$$
$$<n\int_0^{\bar{v}}\left\{\int_0^{a-\Delta(2n)}\Delta(2n)dG(b)+\int_{a-\Delta(2n)}^{a}(a-b)dG(b)\right\}dG(a)$$
$$\Updownarrow$$
$$M^1<M^2$$

$$n\int_{\bar{a}^1}^{v}\left\{2\int_{a-\Delta(2n)+\Delta(n)}^{a}(a-b)dG(b)+\int_0^{a-\Delta(2n)+\Delta(n)}(a-b)dG(b)-\int_0^{a-\Delta(2n)+\Delta(n)}(\Delta(2n)-\Delta(n))dG(b)\right\}$$
$$<n\int_{\bar{a}^2}^{v}\left\{2\int_{a-\Delta(2n)}^{a}(a-b)dG(b)+\int_0^{a-\Delta(2n)}(a-b)dG(b)-\int_0^{a-\Delta(2n)}\Delta(2n)dG(b)\right\}dG(a)$$
$$\Updownarrow$$
$$F^1<F^2$$

and

$$n\int_{\bar{a}^1}^{\bar{v}}\left\{\begin{array}{l}\int_0^{a}(\Delta(2n)-\Delta(n))dG(b)+\int_a^{a+\Delta(2n)-\Delta(n)}(\Delta(2n)-\Delta(n)+a-b)dG(b)\\-\int_{a+\Delta(2n)-\Delta(n)}^{\bar{v}}(\Delta(2n)-\Delta(n))dG(b)\end{array}\right\}dG(a)$$
$$<n\int_{\bar{a}^2}^{\bar{v}}\left\{\begin{array}{l}\int_0^{a}\Delta(2n)dG(b)+\int_a^{a+\Delta(2n)}(\Delta(2n)+a-b)dG(b)\\-\int_{a+\Delta(2n)}^{\bar{v}}(\Delta(2n)-\Delta(n))dG(b)\end{array}\right\}dG(a)$$
$$\Updownarrow$$
$$L^1<L^2$$

Proposition 4 follows. Q.E.D.

Proof of Proposition 5:

If the buyers' expectations are given by assumption 3, the two firms will have different profit opportunities. Without loss of generality, suppose that firm A has the technology which the buyers anticipate will be adopted as a market standard. Since the firms are asymmetric, let all functions have a subscript that tells which firms that are being studied (e.g. $\Pi_A^i(2,3)$ is the profit of firm A if firm A enters at stage 2 and firm B enters at stage 3). Propositions 5a and 5b will be shown sequentially.

Will firm A find it profitable to enter before firm B? Given that it wants to capture the first buyers at stage 2, firm A sets the price such that the consumer surplus by adopting firm A's technology equals the expected consumer surplus of waiting until stage 3.

$$a+\int_{0}^{a+\Delta(2n)}\Delta(2n)dG(b)+\int_{a+\Delta(2n)}^{\bar{v}}\Delta(n)dG(b)-p_A=\int_{0}^{a+\Delta(2n)}bdG(b)+\int_{a+\Delta(2n)}^{\bar{v}}(a+\Delta(2n))dG(b)$$

$$p_A=\int_{0}^{a+\Delta(2n)}(a+\Delta(2n)-b)dG(b)-\int_{a+\Delta(2n)}^{\bar{v}}(\Delta(2n)-\Delta(n))dG(b)$$

Consequently, firm A earns

$$np_A+n\int_{0}^{a+\Delta(2n)}(a+\Delta(2n)-b)dG(b)$$

$$=2n\int_{0}^{a+\Delta(2n)}(a+\Delta(2n)-b)dG(b)-n\int_{a+\Delta(2n)}^{\bar{v}}(\Delta(2n)-\Delta(n))dG(b)$$

given that it captures the first buyer.

Firm A compares the profit of capturing the first buyer at stage 2 with the profit of waiting until stage 3:

$$\Pi_A^3(3,3)=2n\int_{0}^{\bar{v}}\int_{0}^{a+\Delta(2n)}(a+\Delta(2n)-b)dG(b)dG(a)$$

A comparison of the expected profit of selling to the first buyer at stage 2 and the expected profit of selling to both buyers at stage 3, $\Pi_A^3(3,3)$, reveals that firm A, independent of its stand-alone value, will wait until stage 3 before selling its technology. Hence, there is no gain by entering first, i.e., $L_A^3(\Delta)=0$. In equilibrium, firm A will never want to introduce its technology before its competitor.

Above, we have shown the first part of the proposition (5a); in the equilibrium outcome firm A never enters before its competitor. The second part (5b) remains to be shown:

Will firm B enter before firm A in equilibrium? Firm B enters before firm A if $\Pi_A^3(2,2) < \Pi_A^3(3,2)$ and $\Pi_B^3(2,3) > \Pi_B^3(3,3)$, i.e. $M_A^3(\Delta) + F_A^3(\Delta) < C$ and $L_B^3(\Delta) > C$. It will be shown that both inequalities cannot be satisfied simultaneously.

a) Firm B's gain by being first, $L_B^3(\Delta)$:

If both firms enter at stage 3, firm B's profit is

$$\Pi_B^3(3,3) = 2n\int_0^{\bar{v}}\int_0^{b-\Delta(2n)}(b-a-\Delta(2n))dG(a)dG(b)$$

If firm B enters first and captures the first buyers, it will set the price such that the first buyer is indifferent between waiting and buying:

$$b + \int_0^{b-\Delta(2n)}\Delta(2n)dG(a) - p_B = \int_0^{b-\Delta(2n)}(a+\Delta(2n))dG(a) + \int_{b-\Delta(2n)}^{\bar{v}} b\,dG(a)$$

$$p_B = \int_0^{b-\Delta(2n)}(b-a)dG(a)$$

The profit, given that firm B captures the first buyers is:

$$np_B + n\int_0^b (b-a)dG(a) = n\int_0^{b-\Delta(2n)}(b-a)dG(a) + n\int_0^b (b-a)dG(a)$$

Independent of b, the expected profit of selling at stage 2 exceeds the expected profit of waiting, $2n\int_0^{b-\Delta(2n)}(b-a-\Delta(2n))dG(a)$. Hence, the profit of sequential entry is:

$$\begin{aligned}\Pi_B^3(2,3) &= 2n\int_0^{\bar{v}}\int_0^{b-\Delta(2n)}(b-a-\Delta(2n))dG(a)dG(b)\\ &\quad + n\int_0^{\bar{v}}\left\{2\int_0^{b-\Delta(2n)}\Delta(2n)dG(a) + \int_{b-\Delta(2n)}^{b}(b-a)dG(a)\right\}dG(b)\\ &= 2n\int_0^{\bar{v}}\int_0^{b-\Delta(2n)}(b-a-\Delta(2n))dG(a)dG(b) + L_B^3(\Delta)\end{aligned}$$

where

$$L_B^3(\Delta) := n\int_0^{\bar{v}}\left\{2\int_0^{b-\Delta(2n)}\Delta(2n)dG(a) + \int_{b-\Delta(2n)}^{b}(b-a)dG(a)\right\}dG(b).$$

b) Firm A's loss of being second, $F_A^3(\Delta)$:

Firm A's profit if they both enter at stage 3:

$$\Pi_A^3(3,3) = 2n\int_0^{\bar{v}}\int_0^{a+\Delta(2n)}(a+\Delta(2n)-b)dG(b)dG(a)$$

Firm A's profit if firm B enters before firm A:

It is shown above that firm B will always capture the first buyer if it enters first. Hence, firm A's profit is:

$$\Pi_A^3(3,2) = n\int_0^{\bar{v}}\int_0^{a}(a-b)dG(b)dG(a)$$

and the loss of being second is:

$$F_A^3(\Delta) = n\int_0^{\bar{v}}\left\{\begin{array}{l}\int_0^{a+\Delta(2n)}(a+\Delta(2n)-b)dG(b)+\int_0^{a}\Delta(2n)dG(b)\\ +\int_a^{a+\Delta(2n)}(a+\Delta(2n)-b)dG(b)\end{array}\right\}dG(a)$$

c) Firm A's benefits if both firms enter at stage 2, $M_A^3(\Delta)$:

$$\Pi_A^3(2,2) = 2n\int_0^{\bar{v}}\int_0^{a+\Delta(2n)}(a+\Delta(2n)-b)dG(b)dG(a) - C$$

By comparison with $\Pi_A^3(3,3)$, $M_A^3(\Delta) = 0$.

It follows that $L_B^3(\Delta) > C$ implies $F_A^3(\Delta) > C$. Hence, $M_A^3(\Delta) + F_A^3(\Delta) < C$ and $L_B^3(\Delta) > C$ cannot hold simultaneously. Q.E.D.

Proof of Proposition 6:

Compatibility will always be achieved if the firms enter simultaneously. Hence, the government will only act if the firms enter sequentially. Without loss of generality, let us assume that firm A enters first. A government agency will only enforce standardisation if $2\Delta > b-a > \Delta$. In all other cases, either standardisation will be the market outcome or incompatibility will be the socially best outcome. Let us assume that firm A at stage 3 does not profit from a sale to the second buyer in the case where the government acts, i.e., $2\Delta > b-a > \Delta$. (The technology offered by firm B at stage 3 is not allowed to be adopted, and the incumbent technology is licensed without a fee.) A more advantageous policy towards an early entrant will strengthen the incentives to enter early. The gain of being first will increase from

$$L(\Delta)=\int_{\bar{a}}^{\bar{v}}\left(\int_{0}^{a}\Delta dG(b)+\int_{a}^{a+\Delta}(\Delta+(a-b))dG(b)-\int_{a+\Delta}^{\bar{v}}\Delta dG(b)\right)dG(a)$$

to

$$L'(\Delta)=\int_{\bar{a}'}^{\bar{v}}\left(\int_{0}^{a}\Delta dG(b)+\int_{a}^{a+\Delta}(\Delta+(a-b))dG(b)-\int_{a+2\Delta}^{\bar{v}}\Delta dG(b)\right)dG(a).$$

It is straightforward to show that $\bar{a}\geq\bar{a}'$ (use equation (5)). Hence $L'(\Delta)>L(\Delta)$.

The loss of being the second firm increases from

$$F(\Delta)=\int_{\bar{a}}^{\bar{v}}\left\{2\int_{a}^{a+\Delta}(b-a)dG(b)+\int_{a+\Delta}^{\bar{v}}(b-a)dG(b)+\int_{a+\Delta}^{\bar{v}}\Delta dG(b)\right\}dG(a)$$

to

$$F'(\Delta)=\int_{\bar{a}'}^{\bar{v}}\left\{2\int_{a}^{a+2\Delta}(b-a)dG(b)+\int_{a+2\Delta}^{\bar{v}}(b-a)dG(b)+\int_{a+2\Delta}^{\bar{v}}\Delta dG(b)\right\}dG(a).$$

It follows that $F'(\Delta)>F(\Delta)$.

Since the loss of being second and the gain of being first increase, the incentive to enter early is strengthened. Q.E.D.

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Chapter 4

Irreversible Choice of Uncertain Technologies with Network Externalities: Comment*

Abstract

In the setting introduced by Choi (1994) I show that it may be profit maximising as well as socially optimal to choose a low risk R&D project. This result contradicts results in Choi (1994). Moreover, it is shown that this result stands in a plausible model without network externalities but with buyers who can delay their adoption of a technology.

JEL classification: O31, L13, L40.

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1. Introduction

In a recent paper published in this *journal*, Jay Pil Choi (1994) analyses the private and the socially optimal risks of R&D projects in the presence of network externalities. This paper discusses some of the conclusions in Choi (1994).

Choi assumes that there are two buyers who enter the market sequentially. In period 1, the first buyer enters the market. She has two options, to adopt the technology offered in period 1, or to delay her adoption until period 2 where a new technology is offered and the second buyer enters the market. If the first buyer adopts the incumbent technology in period 1, the second buyer can choose between adopting the same technology and capture the network externalities (standardisation benefits), or choose the new technology. Consequently, neither the first nor the second buyer gets the potential network externalities. Choi assumes that the first buyer can observe which project the entering firm chooses before she decides whether to wait or adopt the incumbent technology immediately. In such a setting Choi claims: even though the social planner cannot decide whether the first buyer should wait or not, he will choose the most risky project possible (Proposition 2), the socially best choice will not depend on whether the new technology entering in period 2 is sponsored or not (Proposition 3), and that an entering firm with exclusive rights to the new technology may choose a less risky R&D project than the socially optimal one (Proposition 5). Choi applies the same definition of increasing risk as first introduced by Rothschild and Stiglitz (1970); the mean preserving spread criterion.

The purpose of this comment is to show that Propositions 2 and 3 are incorrect. Since Choi uses Proposition 2 to prove Proposition 5, his proof of Proposition 5 is invalid. The setting in section 2 is identical to the setting in Choi (1994). In section 3, I show that in a plausible model *without* network externalities, a firm may choose a less risky R&D project than feasible. A low risk project can be used by the firm to commit itself to a level of consumer surplus which induces early buyers to wait until a new technology is available.

2. Choi's model

I use the same notation as Choi (1994). Let α be the value of using the incumbent technology in period 1 given that the technology is used by only one player (stand-alone benefit). Assume that the incumbent technology is mature and that its value, consequently, is unchanging over time.

The stand-alone benefit of adopting the new technology in period 2 is given by $\tilde{\beta}_2 \in [0, \bar{v}]$, where $\tilde{\beta}_2$ has a probability distribution $F(\cdot;\theta)$, whose density function has support contained in $[0, \bar{v}]$. Here $\theta \in [0, \infty)$ indicates the riskiness of the new technology. An increase in θ implies a mean preserving spread (MPS) in the initial probability distribution of $\tilde{\beta}_2$.

$$\int_0^x F(\tilde{\beta}_2;\theta_2)d\tilde{\beta}_2 \geq \int_0^x F(\tilde{\beta}_2;\theta_1)d\tilde{\beta}_2 \quad \forall x \in [0, \bar{v}] \qquad \text{if} \qquad \theta_2 > \theta_1 .$$

Let Δ denote the value each user attaches to the network externalities conferred when the other user adopts the same technology. The discount factor is denoted by δ.

2.1 Nonsponsored emerging technology

In Proposition 2, Choi concludes that the market-induced social welfare increases with an MPS in the distribution of $\tilde{\beta}_2$. This result is seemingly plausible since Klette and de Meza (1986), Bhattacharya and Mookherjee (1986), and Dasgupta and Maskin (1987) have achieved similar results in models where the buyers cannot wait. However, I will show that an MPS will not necessarily be welfare improving if buyers can wait. This result is maintained in a model without network externalities as well (see section 3).

Following Choi (1994), the first buyer has two options in period 1. If she decides to wait (W) until period 2, her expected payoff is given by

$$
\begin{aligned}
V(W;\theta) &= \delta\Delta + \delta\left[\alpha F(\alpha;\theta) + \int_{\alpha}^{\bar{v}} \tilde{\beta}_2 dF(\tilde{\beta}_2;\theta)\right] \\
&= \delta\Delta + \delta\left[\int_{0}^{\bar{v}} \tilde{\beta}_2 dF(\tilde{\beta}_2;\theta) + \int_{0}^{\alpha} F(\tilde{\beta}_2;\theta) d\tilde{\beta}_2\right]. \qquad (1)
\end{aligned}
$$

The last equality is shown in the appendix. If she decides to adopt (A) the incumbent technology in period 1, her expected payoff is given by

$$
V(A;\theta) = \alpha + \delta[\alpha + \Delta F(\alpha + \Delta;\theta)]. \qquad (2)
$$

Let $S_M(x;\theta)$ be the expected social surplus when action x is taken in period 1 subject to the constraint that the period 2 decisions are made in the market, where $x = A, W$. Then,

$$
S_M(W;\theta) = 2V(W;\theta) \qquad (3)
$$

and

$$
\begin{aligned}
S_M(A;\theta) &= \alpha + \delta\alpha + \delta\left[(\alpha + 2\Delta)F(\alpha + \Delta;\theta) + \int_{\alpha+\Delta}^{\bar{v}} \tilde{\beta}_2 dF(\tilde{\beta}_2;\theta)\right] \\
&= \alpha + \delta\alpha + \delta\Delta F(\alpha + \Delta;\theta) + \delta\left[\int_{0}^{\bar{v}} \tilde{\beta}_2 dF(\tilde{\beta}_2;\theta) + \int_{0}^{\alpha+\Delta} F(\tilde{\beta}_2;\theta) d\tilde{\beta}_2\right] \\
&= V(A;\theta) + \delta\left[\int_{0}^{\bar{v}} \tilde{\beta}_2 dF(\tilde{\beta}_2;\theta) + \int_{0}^{\alpha+\Delta} F(\tilde{\beta}_2;\theta) d\tilde{\beta}_2\right]. \qquad (4)
\end{aligned}
$$

The second equality in (4) follows from the result in the appendix. The third equality follows from (2).

I will here provide two independent arguments which separately make the proof of proposition 2 incorrect, and show that social welfare may decrease with increased risk.

First, given that the first buyer adopts the incumbent technology in period 1, $S_M(A;\theta)$, social welfare may – contrary to what Choi claims but does not show in the proof of proposition 2 – decrease with an MPS in the distribution of $\tilde{\beta}_2$.

Considering (4), it follows directly from the definition of MPS, that $(\alpha+\Delta)F(\alpha+\Delta;\theta)+\int_{\alpha+\Delta}^{\bar{v}}\tilde{\beta}_2 dF\left(\tilde{\beta}_2;\theta\right)$ increases with an MPS. However, it cannot be shown that this increase in general exceeds a possible reduction in $\Delta F(\alpha+\Delta;\theta)$. The following counter example establishes this claim.

Let $\tilde{\beta}_2$ be a uniform random variable on the interval $\left[\overline{\beta}_2-\theta,\overline{\beta}_2+\theta\right]$ where $\overline{\beta}_2$ denotes the expected stand-alone value of the new technology. Let the initial probability distribution be given by $\theta=1$ and the new probability distribution be given by $\theta=\theta_N>1$, i.e., the new probability distribution can be reached by an MPS of the initial distribution. Furthermore, let $\Delta>\frac{\theta_N-1}{2}$ and $\alpha+\Delta=\overline{\beta}_2+1$. Straightforward calculations show that $S_M(A;\theta_N)-S_M(A;1)<0$.

Hence, it is possible that $S_M(A;\theta)$ may decrease with an MPS in the distribution of $\tilde{\beta}_2$. The intuition for this result is as follows. An MPS may increase the probability of the second buyer adopting an incompatible technology and this loss may, as in above example, exceed the gain from the option effect discussed by Choi.

Second, Choi does not take into account that an MPS in the distribution of $\tilde{\beta}_2$ may induce the first buyer to adopt rather than wait, or *vice versa*. I will show that an MPS can reduce social welfare also if we restrict our attention to cases where social welfare, given adoption in period 1, increases with an MPS.

If an MPS induces the first buyer to adopt rather than wait, or *vice versa*, and this change reduces social welfare, the MPS may be disadvantageous from a welfare perspective. This is only feasible if the R&D project which makes the first buyer indifferent between waiting and adopting

, $\hat{\theta}$, differs from the project which makes waiting and adopting equally good from a social perspective, θ'.

Defining $\hat{\theta}$ by $V(W;\hat{\theta}) = V(A;\hat{\theta})$, it follows from (1), (3), and (4) that

$$S_M(W;\hat{\theta}) = V(A;\hat{\theta}) + V(W;\hat{\theta}) = S_M(A;\hat{\theta}) - \int_{\alpha}^{\alpha+\Delta} F(\tilde{\beta}_2;\hat{\theta})d\tilde{\beta}_2 + \delta\Delta.$$

Depending on the last two terms, the project which makes the buyer indifferent between waiting and adopting can be more or less risky than the project which makes a social planner indifferent between the alternatives, i.e., $\theta' \geq \hat{\theta}$ or $\theta' \leq \hat{\theta}$.

I will provide an example where $\theta' \geq \hat{\theta}$. Assume that development of a new technology in period 2 either succeeds or fails.

	Success	Failure
Probability:	$1/\theta$	$1-1/\theta$
Stand-alone value:	θ	0

Note that an increase in θ implies an MPS of the initial probability distribution. Suppose that the technological progress from period 1 to period 2 is represented by a probability distribution where either $\theta = 5$ or $\theta = 7$. Let $\delta = 1$, $\alpha = 4/3$, and $\Delta = 10/3$. The expected social welfare and the expected consumer surplus of the first buyer can be calculated:

	$\theta = 5$	$\theta = 7$
Consumer surplus		
Adopting:	$560/105$	$580/105$
Waiting:	$567/105$	$575/105$
Social welfare		
Adopting:	$1057/105$	$1105/105$
Waiting:	$1134/105$	$1150/105$

Table 1. Consumer surplus and social welfare

If the probability distribution given by $\theta = 5$ represents the technological progress from period 1 to period 2, the first buyer chooses to wait until period 2, and the market induced social welfare is $^{1134}\!/_{105}$. However, if the relevant probability distribution is given by $\theta = 7$, the first buyer chooses to adopt the incumbent technology immediately and the market induced social welfare is $^{1105}\!/_{105}$. Consequently, an MPS of the probability distribution reduces social welfare. The outcome is illustrated in Figure 1.

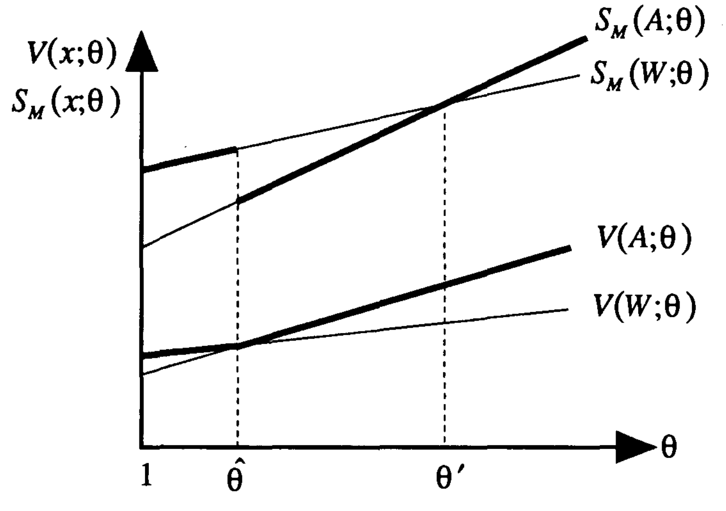

Figure 1. *Consumer surplus and market induced social welfare*

The bold lines indicate the first buyer's consumer surplus in equilibrium and the market induced social welfare. In the example, the probability distribution given by $\theta = 5$ is less risky than the one given by $\theta = \hat{\theta}$, and the other probability distribution is riskier, i.e., $5 < \hat{\theta} < 7$. As shown in Figure 1, a more risky project may reduce social welfare.

We can conclude that the market-induced social welfare may decrease with an MPS. This result contradicts Proposition 2 in Choi (1994).

2.2 Sponsored emerging technology

Propositions 3 and 5 in Choi (1994) apply Proposition 2. By using Choi's example from the proof of Proposition 5, I will show that my objection to Proposition 2 undermines the proofs of Propositions 3 and 5 as well.

Proposition 3 states that, given that the new technology introduced in period 2 is sponsored, a social planner who can only control the riskiness of the R&D project will prefer the most risky research strategy. To show that Proposition 3 is incorrect, I use an example provided by Choi (see Choi (1994) p. 394). Following Choi (1994), let $\alpha = 12$, $\Delta = 15$, $\bar{\beta}_2 = 30$, $\delta = 1$, and let $\tilde{\beta}_2$ be a uniform random variable on the interval $[30-\theta, 30+\theta]$.

Choi calculates that the most risky R&D project which induces the first buyer to wait, is given by $\theta = 5$ (a more risky project will induce the first buyer to adopt in period 1). He also shows that the firm's profit is maximised by choosing this low risk project. It can be shown that – as long as the first buyer waits until the second period – the market induced welfare increases with risk. Furthermore, given adoption of the incumbent technology in period 1, the market induced welfare will be maximised if the most risky project possible ($\theta = 30$) is chosen. Since (a) $\theta > 5$ induces the first buyer to adopt in period 1, and (b) it is straightforward to calculate that $S_M(W; \theta = 5) = 90$ and that $S_M(A; \theta = 30) = 66.83$, it follows that the firm's profit maximising choice is socially optimal.

This example shows that even if the new technology is sponsored, the market induced social welfare is not necessarily maximised by choosing the most risky R&D project. The example contradicts Proposition 3.

In Choi (1994), the above mentioned example is used to prove Proposition 5 – a firm may choose a less risky research strategy than the socially optimal one. Since I have shown that the firm's strategy in the example is, in fact, socially optimal, it follows that the proof of Proposition 5 is invalidated.

3. A model without network externalities but with waiting buyers

Choi (1994) shows that a firm may choose a low risk R&D project instead of a high risk project in a market with network externalities. The purpose of this section is to show that this is also a plausible outcome in markets without network externalities. I show that the expected consumer surplus may be larger if a low risk project is chosen than if a high risk project is chosen. By committing itself to a low risk project, a firm can in some cases induce buyers entering the market early to wait until a new technology is ready for market introduction.

As in the previous section, assume that the game consists of two periods and that an established technology is competitively offered in period 1. Most of the notation in section 2 is kept in this section.

In period 2 three technologies are offered – *two* new technologies in addition to the established technology. The two new technologies are sponsored by two firms with exclusive rights to one technology each. For simplicity, let the value of one of the new technologies be λ with certainty. The value of the second new technology, $\tilde{\beta}_2$, is stochastic. With probability, $1/\theta$, the R&D project succeeds and the value of the new technology is θ. With the complementary probability, $1-1/\theta$, the project fails and the value of the new technology is 0. An increase in θ implies an MPS of the initial probability distribution. This is similar to the second example introduced in section 2.1.

Furthermore, assume that the value of the certain technology (λ) is sufficiently large to justify from a welfare perspective that adoption is delayed until period 2, even if the uncertain R&D project does not succeed, i.e., $\delta\lambda \geq (1+\delta)\alpha$.

Since network externalities are absent in this model, it suffices to have one buyer who enters in period 1. Following Choi (1994), I will assume that the buyer observes which R&D project the firm chooses before she decides whether to wait or to adopt in period 1.

In a market with price competition, the buyer gets the maximum surplus that the firm with the second best technology can profitably offer. Hence, the firm with an uncertain R&D project earns a positive profit only if the project succeeds and the value of the technology (θ) exceeds the value of the best competing technology (λ). Therefore, the firm will always choose the level of risk such that $\theta > \lambda$.

The buyer considers the expected value of the second best technology in period 2 when she decides whether to adopt a technology immediately or wait. The second best technology in period 1 is either, α if the uncertain R&D project fails, or $\lambda (> \alpha)$ if the uncertain R&D project succeeds. Consequently, a buyer focuses only on the probability of success of the uncertain R&D project ($1/\theta$), while a firm's profit depends both on the probability of success ($1/\theta$) and on the difference between the value of its own technology and the value of the second best technology ($\theta - \lambda$).

The buyer will wait only if the expected surplus by waiting ($V(W)$) is larger than the surplus by adopting the established technology in period 1 ($V(A)$). Since $V(W) = (1 - 1/\theta)\delta\alpha + 1/\theta\,\delta\lambda$ and $V(A) = (1+\delta)\alpha$, it follows that the buyer adopts in period 1 if $\theta > \delta^{(\lambda-\alpha)}/\alpha$. Hence, the firm's profit, Π, as a function of the riskiness of the R&D project, θ, is given by:

$$\Pi(\theta) = \begin{cases} 1/\theta\,\delta(\theta - \lambda) & \text{if} \quad \theta \le \delta^{(\lambda-\alpha)}/\alpha \\ 0 & \text{if} \quad \theta > \delta^{(\lambda-\alpha)}/\alpha. \end{cases}$$

Since the profit is increasing with risk as long as the buyer waits, the profit is maximised by choosing the most risky R&D project that induces the buyer to wait: $\theta^* = \delta^{(\lambda-\alpha)}/\alpha$.

Also welfare is increased with risk as long as the buyer waits. Moreover, as noted above, from a welfare perspective it is desirable that the buyer waits. It follows that – if a social planner does not control the buyer's adoption decision – the socially optimal project is the most risky project that induces the buyer to wait. Hence, the firm's profit maximising low risk R&D decision is also socially optimal.

4. Conclusion.

First, I show that in the model introduced by Choi (1994), a welfare maximising social planner as well as a firm may prefer a low risk R&D project to a high risk project. This result contradicts Propositions 2 and 3 in Choi (1994). It also undermines the proof of Proposition 5.

Second, I introduce a simple model *without* network externalities. In this model, I show that, given that the social planner cannot control the buyers' adoption of a new technology, both the social planner and the firm may prefer a less risky R&D project to a more risky project available. Like in Choi (1994), the firm commits itself to a low risk R&D project in order to induce the first buyer to wait. Consequently, the choice of a low risk project is plausible in a market both with and without network externalities.

These results differ from the findings of Klette and de Meza (1986), Bhattacharya and Mookherjee (1986), and Dasgupta and Maskin (1987) who show that a risk neutral firm prefers the most risky R&D project available, given that the projects are equally costly. The background for this difference is that Choi (1994) and the present comment study models where it matters when the buyers' adopt. In such a setting it follows that a low risk R&D project can be chosen in equilibrium.

Appendix

Here, I show that $xF(x,\theta)+\int_x^{\bar{v}}\tilde{\beta}_2 dF(\tilde{\beta}_2,\theta)$ is equal to $\int_0^{\bar{v}}\tilde{\beta}_2 dF(\tilde{\beta}_2,\theta)+\int_0^x F(\tilde{\beta}_2,\theta)d\tilde{\beta}_2$:

$$
\begin{aligned}
xF(x,\theta)+\int_x^{\bar{v}}\tilde{\beta}_2 dF(\tilde{\beta}_2,\theta) &= xF(x,\theta)+\tilde{\beta}_2 F(\tilde{\beta}_2,\theta)\Big|_x^{\bar{v}}-\int_x^{\bar{v}}F(\tilde{\beta}_2,\theta)d\tilde{\beta}_2 \\
&= \bar{v}-\int_x^{\bar{v}}F(\tilde{\beta}_2,\theta)d\tilde{\beta}_2 \\
&= \bar{v}-\int_0^{\bar{v}}F(\tilde{\beta}_2,\theta)d\tilde{\beta}_2+\int_0^x F(\tilde{\beta}_2,\theta)d\tilde{\beta}_2 \\
&= \int_0^{\bar{v}}\tilde{\beta}_2 dF(\tilde{\beta}_2,\theta)+\int_0^x F(\tilde{\beta}_2,\theta)d\tilde{\beta}_2.
\end{aligned}
$$

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Chapter 5

R&D when Adoption is Irreversible*

Abstract

I study firms' timing of R&D in an emerging market where the buyers enter sequentially and adopt a technology only once. Contrary to in the preemption and patent race literature, early introduction of a new technology is assumed not to alter later firms' possibilities of introducing competing technologies. I show that the incentives for early introduction exceed the welfare optimal ones. Sequential development of new technologies implies temporal product differentiation which may benefit both firms. The firms may race into a new market, although they would have been better off by mutually entering later.

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1. Introduction

Often adoption of a technology is irreversible. Potential users of a technology have to decide whether to adopt a present technology or to wait until new technologies have been developed. If she waits the user loses the value of obtaining the existing technology now, but and gains the value of obtaining a possibly better technology later.

When users make irreversible adoptions of technologies, the future and present demand are interlinked. Buyers adopting a technology today do not adopt a future technology. Since demand conditions are important for firms' R&D efforts, it follows that there is a link between R&D decisions over time which is different from the interdependence due to technological spillovers or due to existing patents which restrict competitors' R&D efforts. This article studies how irreversible adoption decisions by users influence firms' R&D decisions and compares the firms' R&D incentives with the socially optimal ones.

I introduce a model with two periods, where buyers with identical preferences enter sequentially. Before two competing firms introduce their technologies in the last period, a firm may invest in an uncertain R&D project to introduce a new technology before it faces competition. Furthermore, I assume that the firms entering late are always able to offer better technologies than the one introduced early. The firms engage in price competition and are assumed to be unable to enter into sales contracts with buyers before their new technology is developed.

In the article, I show that if buyers make irreversible adoption decisions, a firm's incentive to develop a new technology before the competitors exceeds the socially optimal one. In a market with price competition the firm must have the best technology to be profitable, and the buyers get the maximum consumer surplus that the firm with the second best technology at most can offer profitably. However, if a firm introduces a new technology before its competitors, the firm achieves two advantages. First, the buyers are willing to pay more for obtaining a given technology earlier. Second, the firm will only need to compete with the second best technology introduced in the period in which the competitors enter. This is because the buyers anticipate that if they wait, they will only be offered the most consumer surplus the firm with the second best technology can profitably offer. The first reason for entering early is not only advantageous from the firm's perspective, but also from a social perspective. The second reason, however, does not represent a social gain. The buyers should wait if the *best* technology justifies waiting, not only if the expected value of the second best technology justifies waiting. Hence, I will show that a firm may have excessive incentives to develop a new technology early.[1]

We may note that these incentives to enter early differ from the incentives studied in the literature about preemption (see Fudenberg and Tirole (1985) Fudenberg et al. (1983), Gilbert and Newbery (1982), and Reinganum (1981)). In this literature the argument relies on the assumption that a firm's early introduction of a new technology prevents or delays competitors' development of competing technologies. In the patent race literature, an early discovery of a technology prevents competition until the patent expires (see Reinganum (1989) for a review of the patent race literature). My argument for early development of a new technology differs from the one put forward in this literature. Price competition leads to excessive profitability of temporal product differentiation.

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[1]The importance of technological expectations for the adoption decision has been pointed out by e.g. Rosenberg (1976), Balcer and Lippman (1984) and Kamien and Schwartz (1972). Contrary to these articles, I focus on oligopolistic pricing of prospective technologies and how this pricing influences the adoption of the present technology. (See also Ireland and Stoneman (1986) for a discussion of the pricing of prospective technologies in a different setting.)

This article is related to the growing literature on irreversible investments. In this literature optimal timing of an investment, in an irreversible project in which the value of the project follows a continuous time stochastic process, is studied. See McDonald and Sigel (1986), Baldwin (1982) and Dixit and Pindyck (1994). Unlike mine, however, the above studies do not analyse how the users' adoption decisions influence a firm's incentive to develop new technologies. The presence of investment opportunities is assumed to be exogenous in this literature.

In Section 2, the model is presented. In Section 3, I analyse the situation in which the firm developing the first technology is assumed to not make the transition to the next generation of the technology. Section 4 covers the situation where a firm considers when to develop a new technology given the introduction date of its competitor (the competitor's entry date is fixed). In Section 5, the model is extended to the situation where two competing firms decide simultaneously when to introduce a new technology. Section 6 presents the conclusions and suggests directions for further research and possible extensions of the model.

2. The model

To focus on how irreversible adoption decisions influence firms' R&D efforts, assume that there are two identical buyers who enter the market sequentially. The first buyer enters in period 1 and the second in period 2.[2]

If a technology obtained in period 1 generates x in total consumer benefits during the two periods, it is assumed that the total benefits can be

[2]Assuming only one buyer arriving in each period should not be considered as a serious limitation of this model. If we allowed for a certain number of buyers in each period, the analysis would be almost identical to the one presented here, and lead only to minor changes in the interpretation of the results.

divided into the benefits of using the technology in period 1, $\frac{1}{1+\delta}x$, and the benefits of using the technology in period 2, $\frac{\delta}{1+\delta}x$. Hence, the value of obtaining the same technology in period 2 is only $\frac{\delta}{1+\delta}x$.

Three different cases will be considered. First, we analyse the situation where a firm considers developing a new technology in period 1 knowing that two *other* firms will compete in period 2. This assumption applies in markets where the firm developing the first generation of a technology is different from the firms developing later generations.[3] Being successful in an emerging market may require different capabilities than being successful in a more mature market. For instance, the first entering firm may have an advantage in product innovation and the firms entering later may be better in process innovations.

In the second case, a firm's incentives to introduce a technology before its competitor are discussed. Knowing that the competitor will introduce a new technology in period 2, a firm decides whether to introduce its own technology in period 1 or 2.

In the third case, the situation where *two* competing firms can decide when to introduce a new technology is considered. The firms choose simultaneously period 1 or period 2 as the date for the introduction of their new technologies.

The following assumptions are common for all three cases. Given that two firms decide to develop a new technology in the same period, they are assumed to be equally capable of developing a new technology. An R&D project undertaken in period 2 is assumed to result in a better technology

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[3]Foster (1986) estimates that seven of every ten leaders in an established technology fail to make the transition to the next generation of technology. See also Rosen (1991) for a discussion of why small firms tend to make a disproportionately large share of major innovations while larger firms often concentrate on minor innovations.

than any technology introduced in period 1. General technological progress makes it possible to develop better technologies in period 1 than in period 2.

Let an R&D project in period 1 cost r. If a firm undertakes an R&D project, the outcome or the value of the resulting new technology is stochastic. Assume the value of a new technology is a non-negative real number with support $[0,\overline{\upsilon}]$. The probability distribution is given by $F(\cdot)$. An investment in R&D enables the firm to offer a new technology at the outset of period 1. Furthermore, let the value of a new technology in period 2 have support $[\underline{\omega},\overline{\omega}]$, where $\overline{\upsilon} \leq \underline{\omega}$ since a technology in period 2 is always better than a technology introduced earlier. The probability distribution is given by $G(\cdot)$. For simplicity, assume that there are no R&D costs in period 2.[4]

The production costs are ignored for simplicity; consequently, the value of a new technology should be interpreted as the net valuation of the new product.

The first buyer and a firm entering in period 2 are assumed to be unable to enter into a sales contract before the technology to be sold is developed.[5] The firms engage in price competition.

3. Case 1: Incentives to introduce a technology early

Consider a firm's decision to invest in an R&D project before other firms develop their technologies. Firm A_1 can invest r in an R&D project which results in a technology with value $a_1 \in [0,\overline{\upsilon}]$. The technology introduced in period 1 faces competition from the two technologies introduced in period 2, $a_2, b_2 \in [\underline{\omega},\overline{\omega}]$.

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[4]Scherer (1967) discusses why R&D costs are often larger in an early introduction of a new technology than in a late introduction.

[5]See Williamson (1985) for a discussion of why contracting about uncertain future events can be difficult to arrange. Also Aghion and Bolton (1987) discusses this assumption.

The firm's R&D decision

Firm A_1 will compare the expected revenue of developing a new technology with the fixed R&D costs, and invest if the revenue exceeds the R&D costs. The first buyer adopts a technology in period 1 if the net benefits of adoption exceed the expected net benefits of waiting until new technologies are developed in period 2. Since the firms engage in price competition, the buyer will, in period 2, obtain the expected benefits the firm with the second best technology at most can offer profitably, γ:

$$\gamma := \frac{\delta}{1+\delta} E[\min(a_2, b_2)].$$

Given that firm A_1 has a more valuable technology than the expected benefits of waiting, its profit will be $a_1 - \gamma$. Hence, the expected profit of an R&D investment in period 1 is

$$\Pi_{A_1} = E[(a_1 - \gamma)\mathbf{I}(a_1, \gamma)] - r = \int_{\gamma}^{\bar{v}} (a_1 - \gamma) dF(a_1) - r \qquad (1)$$

where $\mathbf{I}(\cdot)$ is an indicator function, defined as $\mathbf{I}(x,y) = 1$ if $x \geq y$, and $\mathbf{I}(x,y) = 0$ otherwise. Firm A_1 maximises its profit by investing in R&D if and only if the costs are less than

$$r_0 := E[(a_1 - \gamma)\mathbf{I}(a_1, \gamma)]. \qquad (2)$$

A welfare maximising social planner's incentive to invest in R&D may differ from the firm's incentive.

First best:

A social planner does not only take into account the profit of firm A_1, but also the other firms' profit and the buyers' net benefits. Let us first consider the *first best* situation, where a social planner can decide the pricing of the technology developed by firm A_1. Given that the first buyer waits until the prospective technologies are developed (period 2), the social welfare induced by the first buyer's adoption equals the expected benefits of adopting the *best* technology in period 2:

$$\chi := \frac{\delta}{1+\delta} E\left[\max(a_2, b_2)\right].$$

It is welfare maximising to let the first firm adopt the technology introduced in period 1 only if the value of this technology exceeds the expected social value of waiting. Hence, the expected welfare gain of an R&D project in period 1 is

$$w_{FB} = E\left[(a_1 - \chi)\mathbf{I}(a_1, \chi)\right] - r = \int_{\chi}^{\overline{v}} (a_1 - \chi)\, dF(a_1) - r. \qquad (3)$$

The social welfare is maximised given an R&D project is undertaken only if the R&D costs are less than:

$$r_{FB} = E\left[(a_1 - \chi)\mathbf{I}(a_1, \chi)\right]. \qquad (4)$$

If $a_1 < \chi$, the social planner chooses a price above $a_1 - \gamma$ to induce the first buyer to wait. However, if $a_1 \geq \chi$, a price equal to $a_1 - \chi$ will induce the first buyer to adopt the technology introduced first, and leave the first firm with a profit identical to the welfare gain of the adoption.[6] Hence, the firm's expected profit of an R&D project will coincide with the welfare gain of the project.

Second best:

Suppose that a social planner can only decide whether the first firm should invest in R&D or not. The firm chooses the profit maximising price.

A study of the optimal R&D incentives in second best might be relevant for a situation where a government agency has an impact on firms' R&D efforts, but does not control the firms' prices.[7]

The first firm will capture the first buyer if the value of its technology exceeds the buyer's expected benefits of waiting, i.e. $a_1 \geq \gamma$. Hence, the

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[6]Note that the social planner imposes a price that is lower than the price in an unregulated market, i.e. $a_1 - \gamma > a_1 - \chi$.

[7]Examples include R&D subsidies to firms, tax refunds for income spent on R&D, research undertaken by universities that help firms to introduce new technologies.

expected welfare gain of an R&D investment in period 1 given that a social planner controls the R&D decision, but not the price, is:

$$w_{SB} = E[(a_1 - \chi)\mathbf{I}(a_1, \gamma)] - r = \int_{\gamma}^{\bar{\upsilon}} (a_1 - \chi) dF(a_1) - r \tag{5}$$

A new technology should only be developed if the R&D costs are less than

$$r_{SB} := E[(a_1 - \chi)\mathbf{I}(a_1, \gamma)]. \tag{6}$$

Private R&D incentives compared to the socially best

We are now ready to compare the firm's R&D decision with the best decision seen from a welfare maximising social planner's point of view:

Proposition 1

From a welfare perspective, firm A_1 has excessive incentives to develop a new technology before the competing firms enter: $r_{SB} < r_{FB} < r_0$.

Proof: It follows from the definitions of γ and χ that $\chi > \gamma$. Hence, by (2), (4), and (6) it follows that $r_{SB} < r_{FB} < r_0$. Q.E.D.

The intuition for Proposition 1 can be explained as follows. The first buyer will compare the net benefits of adopting immediately with the expected net benefits of waiting. She does not take into account that waiting will increase the expected profit of later firms. Hence, the first buyer is willing to pay more for the technology offered in period 1 than the welfare gain induced by immediate adoption and, consequently, the first firm's incentives to develop a new technology exceed the socially optimal ones. By (1), (3), and (5), we can decompose the difference between profit and welfare gain of an R&D project in period 1:

$$\Pi_{A_1} = T + w_{FB} = T + w_{SB} + L \qquad \text{or} \qquad w_{SB} = \Pi_{A_1} - T - L \tag{7}$$

where

$$T := \int_{\gamma}^{\chi}(a_1 - \gamma)dF(a_1) + \int_{\chi}^{\bar{\upsilon}}(\chi - \gamma)dF(a_1) \qquad \text{and,}$$

$$L := \int_{\gamma}^{\chi}(\chi - a_1)dF(a_1).$$

T represents a transfer from the first buyer's consumer surplus to the first firm's profit, compared with the case where the buyer obtains the expected value of the best technology in period 2 by waiting. Viewed separately, this transfer does not result in a welfare loss. L represents the expected welfare loss due to the fact that the buyer adopts the first technology even when the socially welfare would have been larger if she had waited, i.e. $a_1 \in [\gamma, \chi]$.

Figure 1 illustrates the price, gross social gain ($w_{FB} + r$), transfer (T) and loss related to inefficient adoption of a new technology (L):

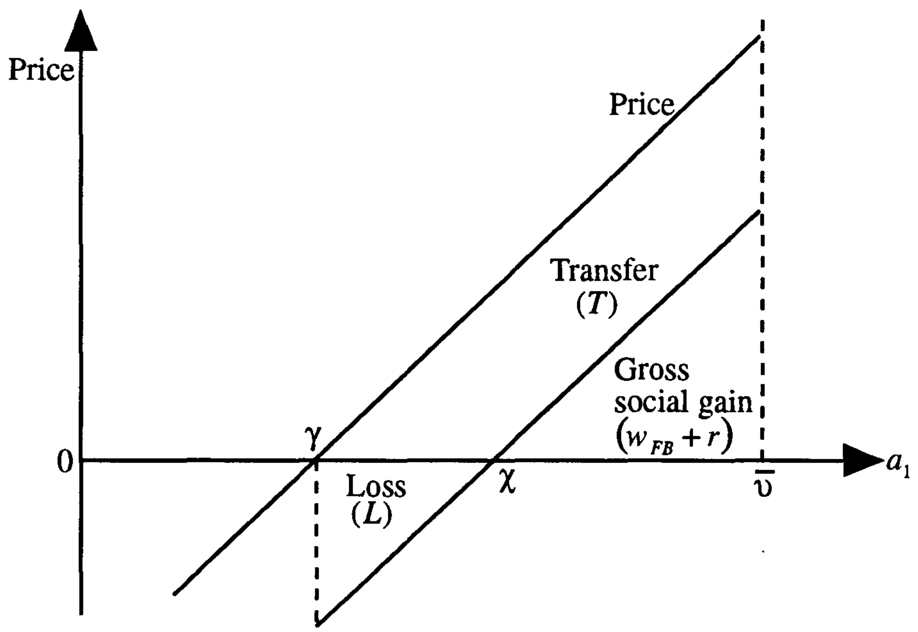

Figure 1. Welfare and profit of an R&D project in period 1

A social planner who does not control the adoption decision may prefer not to undertake an R&D project in period 1 even if there are no R&D costs ($r = 0$). If the expected welfare loss due to inefficient adoption in period 1 is large (i.e. if it is likely that $a_1 \in [\gamma, \chi]$), it follows that the expected social value of an R&D project not including the costs can be negative.

We may also note that the first firm competes with the later firms, but that the later firms do not compete with the first firm. The first firm's offer has to exceed the expected benefits of waiting. However, given that the first buyer waits, the firms entering in period 2 will compete with each other and ignore the first firm. This asymmetry between the first and later firms is an advantage for the first firm because it reduces the first buyer's expected benefits of waiting and, consequently, makes the first buyer more inclined to adopt the technology introduced early.

Suppose the first buyer buys a product in period 1 as well as period 2, e.g. the product is a consumer good. With this assumption, the supply and demand in periods 1 and 2 can be viewed as two separate markets. The firm entering first captures the buyer's value of having a product early, which is the same as the social benefits of introducing a product in period 1. Similarly, the later firms will only capture the social value of their technology introductions. Hence, in the case with a consumer good, the incentives for early development of a new technology will coincide with the socially optimal ones.

R&D incentives and the competition between prospective technologies

The first buyer's incentives to wait are weaker than the socially optimal ones, because she must share the welfare gain of waiting with the firms in period 2. Hence, if the first buyer obtains a larger share of the welfare gain induced by waiting (and the expected profit of the last firms decreases proportionally), the difference between the buyer's and the socially optimal incentives to wait will diminish. Let $n \in \{1,2\}$ be the number of buyers in period 2 and let Π_2 denote one of the two firms' profit:[8]

$$\chi - \gamma = \frac{\delta}{1+\delta} E\left[\left|a_2 - b_2\right|\right] = 2\frac{\Pi_2}{n}$$

[8]If the first buyer adopts a technology in period 1, there will be only one buyer in period 2. Otherwise, there will be two buyers.

It follows that an increase in the expected profit in period 2 increases the difference between the social and the buyer's gain from waiting and, consequently, the bias toward premature development of a new technology is amplified.

The riskiness of the R&D projects in period 2 may play an important role in the division of the social gain between the buyers and the firms. Let us assume that the probability distribution of a riskier R&D project can be reached by a mean preserving spread (MPS) in the probability distribution to a less risky R&D project (Rothschild and Stigliz (1970)).

We can now study the impact of riskier R&D projects in period 2:

Proposition 2

If the R&D projects in period 2 become riskier (i.e. an MPS in the probability distribution),

a) the welfare gain of an R&D investment in period 1 declines.

b) the profit of an R&D investment in period 1 rises.

Proof: See the Appendix.

The expected value of the *best* technology in period 2 will increase with the riskiness of the R&D projects (see the proof of Proposition 2). Consequently, from a social perspective, a better technology will be necessary in period 1 to justify immediate adoption instead of waiting until prospective technologies are available. Since the welfare induced by waiting increases, it follows that the social benefits of an R&D investment in period 1 diminish.

Moreover, the expected value of the *second best* technology in period 2 decreases with an MPS in the distribution of the outcome of the R&D projects. Consequently, the first buyer's expected benefit from waiting declines, and the firm introducing a technology in period 1 will face less competition from the technologies introduced later. Due to less competition, the expected profit of an R&D investment in period 1 grows. We can conclude that the more uncertain the R&D projects in period 2 become, the larger the difference between the first firm's incentives to invest in R&D and the socially optimal incentives will be.

4. Case 2: Incentives to develop a technology before a competitor

Suppose a firm anticipates when the competing firm will introduce its technology. The firm can choose whether it will introduce its own technology at the same date or earlier. Assume that firm B introduces its technology in period 2 and that firm A can advance its introduction of a new technology from period 2 to period 1. Furthermore, let firms A and B be the only firms in the market.

In order to decide the date for introduction of a new technology, firm A will compare the expected profit of entry in period 1, $\Pi(1)$, with the expected profit of entry in period 2, $\Pi(2)$:

Period 1: $$\Pi(1) = \frac{1}{1+\delta} E[a_1] - r = \frac{1}{1+\delta} \int_0^{\overline{\upsilon}} a_1 dF(a_1) - r. \tag{8}$$

Period 2: $$\begin{aligned} \Pi(2) &= 2\frac{\delta}{1+\delta} E[(a_2 - b_2)\mathrm{I}(a_2, b_2)] \\ &= 2\frac{\delta}{1+\delta} \int_{\underline{\omega}}^{\overline{\omega}} \int_{b_2}^{\overline{\omega}} (a_2 - b_2) dG(a_2) dG(b_2). \end{aligned} \tag{9}$$

Suppose firm A decides to develop a technology in period 1. To capture the first buyer it must offer larger net benefits than the buyer can obtain by waiting. Since the firms engage in price competition, and firm B in period 2 will introduce a better technology than the one already developed by firm A, the net benefit of waiting is $\frac{\delta}{1+\delta} a_1$. Hence, $\frac{1}{1+\delta} a_1$ is firm A's profit maximising price in period 1. This price equals the difference between the buyer's gross benefits of obtaining firm A's technology in period 1, a_1, and the benefits of waiting, $\frac{\delta}{1+\delta}a_1$. The expected profit is given by (8).[9]

Firm A maximises its profit by investing in R&D in period 1 if and only if $\Pi(1) > \Pi(2)$. By advancing the introduction of a new technology, firm A puts itself in a weaker position when facing the competition from firm B in period 2. Since firm A has a less valuable technology than it would have had by developing the technology later (in period 2), firm B can raise its price and still offer larger net benefits than firm A at most can offer profitably. Furthermore, a price increase in period 2 makes the first buyer willing to pay more for the technology offered in period 1, and, hence, firm A will earn more in period 1. A strategy where a firm profits from committing itself to a nonaggressive action and thereby induces a more favourable response from its competitor is often referred to as a "puppy dog" strategy (Fudenberg and Tirole (1984)).

The firm's timing of R&D can be compared with the socially best decision. Let $r_0(1)$, $r_{FB}(1)$, and $r_{SB}(1)$ denote the critical levels of extra R&D costs due to early development for, respectively, the firm, a social planner controlling prices (first best), and a social planner controlling the R&D decision (second best). Only if the extra R&D costs are less than the critical level will the decision-maker advance the development of a new technology to the first period.

[9]Recall that there is only one buyer in period 1.

Proposition 3

From a welfare perspective, firm A has excessive incentives to enter before firm B: $r_0(1) < r_{FB}(1) < r_{SB}(1)$.

Proof: See the Appendix.

If firm A develops a technology in period 2, its profit will be identical to the welfare gain of the R&D project: due to price competition, firm A will be able to capture the positive difference between the value of its own technology and firm B's technology. This difference is the same as the social benefits (not including the R&D costs) of an R&D project in period 2. However, if the firm advances its development of a new technology, the profit will exceed the welfare gain. The buyer does not get the total social benefits of waiting and will, hence, be inclined to pay more for the technology in period 1 than the social gain.

5. Case 3: Both firms can advance their development of new technologies.

In this section we consider the case where firms A and B decide simultaneously when to develop a new technology. To find the sub-game perfect Nash equilibrium in pure strategies in this setting, we need to analyse the firms' profits in four feasible outcomes: both firms enter in period 1, the firms enter sequentially, and both firms enter in period 2.

Let $\Pi(i,j)$ be the profit of a firm that develops a new technology for period $i \in \{1,2\}$ given the competitor develops his technology for period $j \in \{1,2\}$.[10] Furthermore, let the value of firm A's technology still be a_1 or a_2

[10]Since the firms *ex ante* are identical, the firms' profit functions are also identical.

depending on whether it is developed in period 1 or 2, respectively. Similarly, let the value of firm B's technology be b_1 or b_2.

The profit from entering before the competitor and the profit if both firms enter in period 2 were already calculated in (8) and (9), i.e. $\Pi(1,2)=\Pi(1)$ and $\Pi(2,2)=\Pi(2)$). The profit of entering after the competitor is

$$\Pi(2,1)=\frac{\delta}{1+\delta}\left(E[a_2]-E[b_1]\right), \tag{10}$$

and the profit of mutual entry in period 1 is

$$\Pi(1,1)=\left(1+\frac{\delta}{1+\delta}\right)E\left[(a_1-b_1)\mathbf{I}(a_1,b_1)\right]-r. \tag{11}$$

Having calculated the expected profit in the four feasible subgames where the timing of entry is taken as given, we can now focus on the timing of entry. Figure 2 illustrates the feasible outcomes:

		Firm B	
		1	2
Firm A	1	$\Pi(1,1)$ $\Pi(1,1)$	$\Pi(1,2)$ $\Pi(2,1)$
	2	$\Pi(2,1)$ $\Pi(1,2)$	$\Pi(2,2)$ $\Pi(2,2)$

Figure 2. *Timing*

The firms' timing of R&D depends on the comparison of the different profit levels. Since the firms' profit functions are assumed to be identical, we only have to compare $\Pi(1,1)$ with $\Pi(2,1)$ and $\Pi(1,2)$ with $\Pi(2,2)$, to find the equilibrium outcomes:

	$\Pi(1,1)$	$\Pi(2,1)$	$\Pi(1,2)$	$\Pi(2,2)$	Equilibrium outcomes
I	>		>		(1,1)
II	>		<		(1,1) (2,2)
III	<		>		(1,2) (2,1)
IV	<		<		(2,2)

Table 1. Equilibrium outcomes

In the brackets in the right-hand column, firm A's and firm B's timing of R&D are put first and second, respectively (e.g. (1,2) means that firm A develops a technology in period 1 and firm B develops a technology in period 2). There are four different situations:

I. Racing

Both firms develop a new technology early. Racing is a unique equilibrium outcome if investment in R&D in period 1 is a dominant strategy for both firms.

It follows from a comparison of the different profit levels that the incentives for early development of a new technology will be strengthened if the expected difference between two technologies developed in period 1 increases or the expected difference in period 2 decreases.[11] A reduction in the R&D costs related to early development of a new technology (r) will also strengthen the incentives to develop a technology early.[12]

[11] $\Pi(1,1)-\Pi(2,1)$ increases with an increase of $E[|a_1-b_1|]$. $\Pi(1,2)-\Pi(2,2)$ increases if $E[|a_2-b_2|]$ declines.

[12]Note also that the incentives to enter early also increase if the expected value of having a technology in period 1 increases, i.e. $\Pi(1,2)-\Pi(2,2)$ increases with an increase in $\frac{1}{1+\delta}E[a_1]$.

Both firms may have earned more if they mutually delayed their R&D investments until period 2, i.e. $\Pi(2,2) > \Pi(1,1)$. A situation such as this resembles the well-known prisoners' dilemma game.

II. Racing or late entry depending on the expectations.

This is the case where a firm will develop a new technology early if and only if it expects that the competitor will do so as well. In particular, if the firm expects that the competitor will develop a new technology late, it will do the same. Hence, the realised equilibrium outcome might be Pareto dominated by another equilibrium outcome.[13]

III. Temporal product differentiation

The firms choose to develop a technology at a different date than their rival. Temporal product differentiation weakens competition and increases the profit of at least one firm. Since $\Pi(1,2) > \Pi(2,2)$ holds in equilibrium, the firm which decides to advance its development of a new technology raises its profit. It is possible that both firms will earn more if one decides to enter in period 1. This will be the outcome if the profit increase of less competition in period 2 exceeds the loss due to the rival capturing the first buyer: both firms gain if one plays the "puppy dog" strategy.

IV. Late entry

If the extra R&D cost of early entry or the expected value of having a technology in period 1 is small, none of the firms will decide to develop a new technology early. Hence, late entry of both firms is a unique equilibrium outcome.

[13]The welfare of the buyers is not taken into account.

Welfare analysis:

The firm's profit maximising choice given the rival's action can be compared with the socially best choice assuming that the social planner controls the R&D decision but not the pricing decision (second best):

Proposition 4

If the firms enter sequentially, social welfare will never improve if the last firm advances its entry to period 1.

If both firms enter in period 2, social welfare will never improve if one of the firms advances its entry to period 1.

Proof: See the Appendix.

Proposition 5

If the firms enter sequentially, social welfare may improve if the first firm delays its entry to period 2.

If both firms enter in period 1, social welfare may improve if both firms delay their entries to period 2.

Proof: See the Appendix.

From a welfare perspective, there are two potential problems: First, if a firm expects that the competitor will enter late, it will have excessive incentives to enter early. However, if the competitor is expected to enter early, the firm's incentives to advance its entry coincide with the socially best ones. This can make mutual entry in period 1, and sequential entry equilibrium outcomes, although social welfare is maximised by mutual late entry. Second, there might exist two equilibria which induce different levels of social welfare. In case II (see Table 1) both mutual entry in period 1 and mutual entry in period

2 are equilibrium outcomes, but only one of the outcomes is the socially optimal one. Hence, the realised equilibrium outcome might be inferior from a social perspective.

6. Conclusion and further directions

This article examines firms' incentives to invest in R&D given that a buyer only adopts a technology once: adoption is irreversible. This feature makes the present demand and the future demand interdependent. If a technology is adopted today, the buyer will not buy a new technology tomorrow.

In a simple model where two buyers with identical preferences enter the market sequentially, three situations are studied: First, I focus on a firm's incentives to develop a new technology (invest in R&D) in an emerging market where an early firm anticipates that other firms will enter and capture the market when the market becomes more mature. It is shown that the firm's incentives to enter an emerging market early on exceed the socially best incentives.

In the second case, I study a firm's incentives to advance its development of a new technology from the date where the competitor enters to an earlier date. An early R&D investment is assumed to result in a less valuable technology than the technology introduced by a later rival, but the first firm will be able to capture the first buyer before the rival has introduced its technology. I show that the firm may prefer to enter early and, hence, have a less valuable technology than its rival when the last buyer enters. By being a weaker competitor when the rival enters than it would have been by entering at the same time, it induces the other firm to raise its price. The early firm's profit will increase because the first buyer is willing to pay more for the technology introduced first when it becomes more expensive to adopt the prospective technology. By using the terminology introduced by

Fudenberg and Tirole (1984), we may say that the firm follows a "puppy dog" strategy: the firm profits by committing itself to nonaggressive action since this induces a more favorable response from the competitor. The incentives to enter early will also in this case exceed the socially best ones.

The argument for premature development of a new technology presented here differs from the argument in the literature about preemption or patent races. Contrary to this literature, the argument here does not depend on the first mover's ability to delay or deter later firms' R&D investments by introducing a technology early. In this article, I show that price competition leads to excessive profitability of temporal product differentiation.

In the third case, the situation where both firms can choose their timing of R&D and, consequently, the date for introduction of a new technology, is studied. I show that both firms may choose to race into the market by entering early, although they both would have been better off entering late. It is also pointed out that sequential entry implies temporal product differentiation and less competition. Consequently, both firms may find it desirable that one of the firms advances its R&D investment. The equilibrium outcome is compared with the welfare maximising outcome.

There are various directions in which the analysis may be extended. First, the analysis can be extended to include technological spillovers. Second, the firms may decide on other characteristics of their R&D projects than timing (e.g. a firm may increase its R&D investment to raise the expected value of its new technology or the firms may influence the correlation between their R&D projects). Third, we may let R&D conducted early on influence the R&D decisions of later firms. Consequently, the first entering firms will take into account how their own R&D investments change the followers' investments. This extension will incorporate some of the features from the literature about preemption. Although these extensions will give further realism to the analysis in the model, it is still likely that the forces discussed in this article will prevail in an extended model.

Appendix

Proof of Proposition 2

Let probability function $G_2(\cdot)$ represent an MPS in the initial distribution function $G_1(\cdot)$: $\int_{\underline{\omega}}^{x} G_2(t)dt \geq \int_{\underline{\omega}}^{x} G_1(t)dt$. Given the first buyer chooses to wait until period 2, the induced social welfare is:

$$\frac{\delta}{1+\delta}E[\max(a_2,b_2)] = \frac{\delta}{1+\delta}\int_{\underline{\omega}}^{\overline{\omega}}\left\{\int_{\underline{\omega}}^{a_2} a_2 dG_i(b_2) + \int_{a_2}^{\overline{\omega}} b_2 dG_i(b_2)\right\}dG_i(a_2)$$
$$= \frac{\delta}{1+\delta}\int_{\underline{\omega}}^{\overline{\omega}}\left\{\overline{\omega} - \int_{a_2}^{\overline{\omega}} G_i(b_2)db_2\right\}dG_i(a_2). \qquad i=\{1,2\}$$

The second equality follows by integration by parts. An MPS in the probability distribution of a_2 and b_2 increases the expected value of the best technology at period 2:

$$\int_{\underline{\omega}}^{\overline{\omega}}\left\{\overline{\omega} - \int_{a_2}^{\overline{\omega}} G_1(b_2)db_2\right\}dG_1(a_2) \leq \int_{\underline{\omega}}^{\overline{\omega}}\left\{\overline{\omega} - \int_{a_2}^{\overline{\omega}} G_2(b_2)db_2\right\}dG_1(a_2) \leq \int_{\underline{\omega}}^{\overline{\omega}}\left\{\overline{\omega} - \int_{a_2}^{\overline{\omega}} G_2(b_2)db_2\right\}dG_2(a_2)$$

The first inequality follows from $\int_{\underline{\omega}}^{\overline{\omega}} G_1(b_2)db_2 = \int_{\underline{\omega}}^{\overline{\omega}} G_2(b_2)db_2$ and $\int_{\underline{\omega}}^{\overline{\omega}} G(b_2)db_2 = \int_{\underline{\omega}}^{x} G(b_2)db_2 + \int_{x}^{\overline{\omega}} G(b_2)de$, $x \in [\underline{\omega}, \overline{\omega}]$. The last inequality follows from the fact that $\overline{\omega} - \int_{a_2}^{\overline{\omega}} G_2(b_2)db_2$ is a convex function in a_2.

Since the expected value of the best technology in period 2 increases, the minimum value of the best technology in period 1 that makes immediate adoption socially beneficial increases. Consequently, the social value of investment in an R&D project in period 1 diminishes with an MPS in the probability distribution in period 2.

Part b) of Proposition 2 remains to be shown. In the market equilibrium, the consumer benefits of waiting are:

$$\frac{\delta}{1+\delta}E[\min(a_2,b_2)] = \frac{\delta}{1+\delta}\int_{\underline{\omega}}^{\overline{\omega}}\left\{\int_{\underline{\omega}}^{a_2} b_2 dG_i(b_2) + \int_{a_2}^{\overline{\omega}} a_2 dG_i(b_2)\right\}dG_i(a_2)$$
$$= \frac{\delta}{1+\delta}E[a_2] - \frac{\delta}{1+\delta}\int_{\underline{\omega}}^{\overline{\omega}}\int_{\underline{\omega}}^{a_2} G_i(b_2)db_2 dG_i(a_2) \qquad i=\{1,2\}.$$

The second equality follows by integration by parts. Recall that $E[a_2] = E[b_2]$. An MPS will not change the expected value of the outcome of an R&D project, but increase the last term and, consequently, reduce the expected consumer benefits of waiting:

$$\int_{\underline{\omega}}^{\overline{\omega}}\int_{\underline{\omega}}^{a_2} G_1(b_2)db_2dG_1(a_2) \leq \int_{\underline{\omega}}^{\overline{\omega}}\int_{\underline{\omega}}^{a_2} G_2(b_2)db_2dG_1(a_2) \leq \int_{\underline{\omega}}^{\overline{\omega}}\int_{\underline{\omega}}^{a_2} G_2(b_2)db_2dG_2(a_2)$$

The first inequality follows immediately from the definition of MPS. The last inequality follows from the fact that $\int_{\underline{\omega}}^{a_2} G_2(b_2)db_2$ is a convex function in a_2. A reduction of the expected consumer benefits of waiting increases the profit of the firm introducing a new technology in period 1 (see (1)). Q.E.D.

Proof of Proposition 3:

First let us calculate the social gain of an R&D project in period 1 given that the social planner controls the pricing (first best), $w_{FB}(1)$, and given that the social planner only controls the R&D decision (second best), $w_{SB}(1)$.

First best: $$w_{FB}(1) = \int_{\frac{\delta}{1+\delta}E[b_2]}^{\overline{v}} \left(a_1 - \frac{\delta}{1+\delta}E[b_2]\right)dF(a_1) - r \qquad \text{(A1)}$$

Second best: $$w_{SB}(1) = \int_{0}^{\overline{v}} \left(a_1 - \frac{\delta}{1+\delta}E[b_2]\right)dF(a_1) - r \qquad \text{(A2)}$$

Comparing (8), (A1), and (A2), it follows that $\Pi(1) > w_{FB}(2) > w_{SB}(2)$.

If both technologies are developed in period 2, the best technology will be adopted by both buyers. Hence, there will be no need for a social planner to act. Due to price competition, firm A will, given that it has the best technology, earn the difference between the values of the first and second best technologies. Hence, firm A's profit is identical to the social gain of entry in period 2: $\Pi(2) = w_{FB}(2) = w_{SB}(2)$. Since $r_0(1) := r|\Pi(1) = \Pi(2)$, $r_{FB}(1) := r|w_{FB}(1) = w_{FB}(2)$, and $r_{SB}(1) := r|w_{SB}(1) = w_{SB}(2)$, it follows from $\Pi(1) > w_{FB}(2) > w_{SB}(2)$ and $\Pi(2) = w_{FB}(2) = w_{SB}(2)$ that $r_0(1) < r_{FB}(1) < r_{SB}(1)$.

Q.E.D.

Proof of Proposition 4:

Suppose that a firm enters in period 1. The social gain if the other firm also enters in period 1 is identical to the expected difference between the value of its own technology and the competing technology value (given the difference is positive) subtracting the development costs, r. Hence, the social gain of early entry will be identical to the profit, $\Pi(1,1)$. Similarly, the social gain of entry in period 2 will be identical to the profit, $\Pi(1,2)$. It follows that if the firm (in equilibrium) enters in period 2, it will never improve social welfare by entering in period 1.

Suppose that a firm enters in period 2. It follows from the proof of Proposition 3 that the other firm has stronger incentives to advance the entry from period 2 to period 1 than the social optimal ones. Hence, we can conclude that if (2,2) is the equilibrium outcome, the social welfare will never improve given that one of the firms advances its entry.

Q.E.D.

Proof of Proposition 5:

From the proof of Proposition 3, we have that the profit of entering before the other firm exceeds the welfare gain. Hence, there exist values of r for which a firm enters before the competitor.

From Table 1, we have that if $\Pi(1,1) > \Pi(2,1)$, (1,1) is a feasible equilibrium outcome. If $\{\Pi(1,1) - \Pi(2,1)\} > 0 > w_{SB}(1,1) - w_{SB}(2,2)$, (2,2) is the socially best outcome, but (1,1) is an equilibrium outcome. Hence, the last part of the proposition can be established by an example satisfying the above inequality. The example: In period 1, an R&D project has only two feasible outcomes. The probability of success is 0.5 and the value of the technology is 32. If the project fails the value of the technology is 0. In period 2, all projects succeed and the value of the technology is 32. Let $r = 3$. Straightforward calculations show that (1,1) is a possible equilibrium outcome and that (2,2) is the socially best outcome. Q.E.D.

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