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# Fragmented property rights, R&D and market structure

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## Abstract

Fragmented property rights can be a factor that limits firms' willingness to invest in the development and commercialization of new products. This paper studies the interaction between markets for products and markets for intellectual property rights (patents) where product innovation requires several complementary patents, each of which is obtained as the result of a patent race. We show that the multiple patent product involves an important hold-up problem and we consider which market structure optimally balances the various incentives that emerge in such a system.

Keywords: fragmented property rights, patents, contests, hold-up, R&D, patent pools, licensing

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# 1 Introduction

Many modern consumer goods are produced using multiple, complementary technology components, which are often protected under a number of patents. This complementarity in production and in intellectual property generates several challenges. Heller and Eisenberg (1998), for instance, discuss that such fragmented property rights defined around gene fragments in biotechnology may reduce firms' incentives to invest and commercialize products:

Foreseeable commercial products, such as therapeutic proteins or genetic diagnostic tests, are more likely to require the use of multiple fragments. A proliferation of patents on individual fragments held by different owners seems inevitably to require costly future transactions to bundle licenses together before a firm can have an effective right to develop these products. (Heller and Eisenberg 1998, p.699.)

Other problems with fragmented property rights have been discussed. Firms that invest in a new product face the risk that, after sinking considerable resources in this, another firm may essentially blackmail this firm by claiming that this new product infringes on some patent held by this firm. Ziedonis (2004, p.806) reports the case of Intel in 1998: "After developing the architecture and tailoring its fabrication facilities to produce the new chip, Intel was sued by a small communications company, S3, for allegedly infringing patents S3 had purchased from a failed start-up company."

These examples illustrate that fragmentation of intellectual property rights is a widespread phenomenon and involves important strategic issues both for firms and policy makers. Shapiro (2001) discusses arrangements of trading, licensing or pooling patents to circumvent such problems, and Ziedonis (2004)

discusses whether firms may choose to acquire large sets of patents as 'bargaining chips' to deal with this problem. Lerner and Tirole (2004) discuss the welfare properties of patent pools. They briefly discuss the implications of patent pools for innovation, but mostly concentrate on a situation with a given set of patents.

Much of the literature that focuses on the implications of market structure for innovation effort considers a sequential structure of innovation, the incentives to spend R&D effort in a first or in a second stage of a cumulative innovation, and its policy implications for the allocation rules for the trading of patents (e.g., Scotchmer 1996, Green and Scotchmer 1995, Denicolo 2002).

We focus on the innovation incentives in a situation similar to the one discussed by Heller and Eisenberg (1998): several firms can make simultaneous investments in patents for several or even many technology components, all of which are needed to innovate and produce a new consumer product. Dynamic commitment issues which emerge in sequential R&D, or uncertainty about a possible infringement when commercializing a new product are absent from this consideration. We assume that the R&D processes for the different technology components are random and independent of each other. For this reason it will often be the case that one firm wins some patents and a competitor wins the complementary set of patents. In this case, none of the firms can produce without further arrangements or a reallocation of the rights to use the information that is protected by the patents. The competition between two firms,  $A$  and  $B$ , that takes place for  $n$  complementary patents has essentially three outcomes:  $A$  owns all patents and receives all rent,  $B$  owns all patents and receives all rent, or both firms own some patents and share the rent. In the first two cases the firm that owns all patents will typically produce and earn a monopoly profit. However, the outcome in the

third case depends on the rules and arrangements according to which patent rights can be traded between firms.

We analyze a benchmark case in which firms can freely trade exclusive rights to use single patents and three other, more restricted regimes. In the benchmark case, the sum of all contest efforts as a share in the firms' rents monotonically declines in the number of complementary patents, and quickly converges towards zero if the number of patents becomes large. We then compare this outcome with different patent trading regimes. Particularly, we consider a regime in which patents cannot be traded, a regime in which single patents can be licensed, but where the exclusive right to use the patent cannot be transferred, and a regime in which the only way patent rights can be traded is to form a patent pool that grants mutual rights to use all patents. We find that the incentives to spend contest effort are the same for all these arrangements, provided that the interior equilibrium exists. The firm profits under these arrangements differ, however.

For a description of the process of patent races we use a simple and elegant tool that has been developed in Baye and Hoppe (2003) who show that an elementary Tullock (1980) contest is an adequate description of patent races, and even fully equivalent to standard microeconomic descriptions of stochastic patent races. This tool makes the consideration of multiple parallel patent races between two firms particularly tractable.

## **2 The structure of the problem**

Consider two firms  $A$  and  $B$  that compete with each other in the following three stage game. In the first stage, the two firms spend efforts on R&D. They need to innovate and patent  $n$  essential components of a new consumer

good. Once these components are innovated and patented, the firms may negotiate with each other about who is allowed to use which set of patents; this is stage 2. Once these negotiations are over, if one or both firms are able and allowed to produce the new good, a market game takes place in which the firm(s) produce and sell the new good to consumers.

In the R&D stage, both firms simultaneously choose R&D expenditure  $x_i, y_i \geq 0$  for each of the  $n$  single component contests. These effort choices can be described by the vectors  $\mathbf{x} \equiv (x_1, \dots, x_n)$  and  $\mathbf{y} \equiv (y_1, \dots, y_n)$ . Further, we define each firm's aggregate R&D expenditure on all components as

$$x \equiv \sum_{i=1}^n x_i \quad \text{and} \quad y \equiv \sum_{i=1}^n y_i. \quad (1)$$

A firm's effort in an R&D contest typically has two effects that relate to two different sources of uncertainty, as described by Loury (1979). First, R&D is genuinely a risky activity, as it is uncertain whether and when own research effort will yield the desired information. This type of uncertainty may be called 'technological uncertainty'. Second, as other firms search for the same information, there is some uncertainty about who innovates first, and, hence, receives the patent. In line with Loury (1979) we call this the 'market uncertainty'. Both types of uncertainty are important.

In what follows we concentrate on market uncertainty. We assume that the information how to produce component  $i$  is eventually revealed, for any levels of effort. However, the probability that firm  $A$  gets hold of the relevant information about component  $i$  prior to firm  $B$  and wins the patent, is a function of the efforts in the respective component contest as follows:

$$p_i = \frac{x_i}{x_i + y_i} \quad \text{if} \quad \min\{x_i, y_i\} > 0, \quad \text{and} \quad p_i = 1/2 \quad \text{otherwise.} \quad (2)$$

This description of a firm's market uncertainty in the R&D contest between two firms can be justified using an important equivalence result that has

been developed by Baye and Hoppe (2003). They show that many types of innovation contest and patent race in which the process of innovation follows a stochastic process can be represented equivalently as a simple lottery contest in which the contestants' win probabilities equal their shares in aggregate expenditure, and in which the value of winning the lottery prize is a function of the aggregate contest efforts that depends more specifically on the properties of the stochastic process. For some stochastic processes the lottery prize is a constant with respect to aggregate efforts. We concentrate on this case which corresponds to considering only market uncertainty.

Once the efforts are chosen, the random process that is governed by win probabilities (2) allocates the patents on the components  $i = 1, \dots, n$  to the two firms. We assume that the random processes that determine the win probabilities in the different components are stochastically independent of each other.

When firms enter stage 2, the situation is described by effort vectors  $\mathbf{x}$  and  $\mathbf{y}$  and by a vector  $\mathbf{z} = (z_1, \dots, z_n)$  that describes the outcome of the  $n$  patent contests, where  $z_i = a$  if  $A$  wins the patent on component  $i$  and  $z_i = b$  if  $B$  wins the patent on component  $i$ . In stage 2 firms enter into negotiations in which they can reallocate their patent rights and pay each other compensation. We will consider several negotiation regimes, starting with a regime in which all firms are perfectly and completely informed and in which no contractual restrictions exist as regards the reallocation of patent rights and compare the outcome with a situation in which restrictions on contractual arrangements exist.

When the patent rights are finally allocated, the firms enter into a market stage. A firm may produce and compete in the market if it has the right to use all components. If none of the firms has the right to use all components,

then no production will take place. If only one firm has the right to use all components, this firm will be a monopolist. If both firms have these rights, they will both produce and compete in a duopoly.

### 3 Solving for an equilibrium

We now solve for a subgame perfect equilibrium and consider first the final stage.

**Product market competition** There are two firms and they are symmetric in all respects, except for their patent rights. Each firm can produce only if it holds the rights to use all  $n$  technology components. If none of the firms has access to all technology components, none of the firms can produce and both firms earn zero profits in the product market.

If only one firm has access to all technology components, this firm is a monopolist and will earn the monopoly rent which is denoted as  $F_M$ . Consumer rent under monopoly will be denoted  $C_M$ . By symmetry, these values do not depend on which firm is the monopolist.

If both firms have access to all technology components, the firms will compete and each firm will earn the equilibrium profit in duopoly, denoted by  $F_D$ . Aggregate consumer rent in the duopoly is denoted as  $C_D$ . We do not specify the market structure further, and the values of profits and consumer rents may result from Bertrand competition, Cournot competition or other types of competition in the product market. We will assume, however, that the firm's monopoly rent exceeds the sum of the firms' profits in a duopoly,



and that consumer rents in the monopoly are smaller than in the duopoly:

$$\begin{aligned} F_M &> 2F_D, C_M < C_D, \text{ and} \\ F_M + C_M &< 2F_D + C_D. \end{aligned} \tag{3}$$

These conditions are typically fulfilled, for instance, for Cournot or Bertrand competition.

**Unconstrained bargaining** Turn now to stage 2 that follows the R&D contests and that takes place prior to market competition. Firms enter into this stage with their respective collections of patents.<sup>1</sup> In the absence of information asymmetries or contractual constraints between firms, the two firms will end up with an allocation of their patents that maximizes the sum of the joint profits they can obtain in the market competition in stage 3.

If  $\mathbf{z} = (a, a, \dots a)$  or if  $\mathbf{z} = (b, b, \dots b)$ , then the firm that holds all patents will not turn all patent rights over to the other firm unless the price paid by the other firm is at least equal to  $F_M$  or higher, but  $F_M$  is the maximum of what the other firm is willing to pay. Hence, the payoffs of firms in the respective continuation games are

$$\left. \begin{aligned} \pi_A(\mathbf{x}, \mathbf{y}, \mathbf{z}) &= F_M - x \\ \pi_B(\mathbf{x}, \mathbf{y}, \mathbf{z}) &= -y \end{aligned} \right\} \text{ if } \mathbf{z} = (a, a, \dots a) \\ \left. \begin{aligned} \pi_A(\mathbf{x}, \mathbf{y}, \mathbf{z}) &= -x \\ \pi_B(\mathbf{x}, \mathbf{y}, \mathbf{z}) &= F_M - y \end{aligned} \right\} \text{ if } \mathbf{z} = (b, b, \dots b). \tag{4}$$

If each firm holds at least one patent, to determine side payments between firms, we need to adopt a more specific bargaining concept. Many bargaining concepts will yield the same outcome, given the assumption about risk

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<sup>1</sup>Implicitly we rule out that consumers take part in bargaining. While this is plausible, given their much higher transaction cost, it is not crucial for the qualitative findings we have on the R&D contest.

neutrality of firms and symmetry. For simplicity, we assume symmetric Nash bargaining among risk-neutral firms. Let firms have zero profits as their outside options. Then the surplus from efficient negotiations is the monopoly profit  $F_M$  and they share this evenly in the Nash bargaining solution. Hence, the firms' payoffs are

$$\pi_A = \frac{F_M}{2} - x \text{ and } \pi_B = \frac{F_M}{2} - y. \quad (5)$$

**The contest for patents** We now turn to the multi-component R&D contest in stage 1. With efficient bargaining after the patent contest, the expected profit of firm  $A$  is a function of the two firms' contest efforts. Using (4) and (5), it is given by:

$$\pi_A = \frac{F_M}{2} + \frac{\prod_{i=1}^{i=n} x_i}{\prod_{i=1}^{i=n} (x_i + y_i)} \frac{F_M}{2} - \frac{\prod_{i=1}^{i=n} y_i}{\prod_{i=1}^{i=n} (x_i + y_i)} \frac{F_M}{2} - x. \quad (6)$$

and  $x$  the sum of firm  $A$ 's component contest efforts as defined in (1). Firm  $A$  receives the monopoly rent if it wins all patents, which explains the additional payoff described by the second term in (6), and firm  $A$  does not receive any rent if firm  $B$  wins all patents, which explains the third, negative term on the right hand side. Finally, the firm has to pay the sum of its efforts in the  $n$  parallel component contests, and this constitutes the fourth term on the right-hand side. Equation (6) uses that the payoff is the same for all outcomes in which both firms win at least one patent, no matter how asymmetric is the distribution of patents in this case.<sup>2</sup> Maximizing (6) with

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<sup>2</sup>An interesting generalization of our approach addresses a situation in which the patents are not essential, in which case production cost may simply be a function of the number of patents which a firm is allowed to use. However, the linearly-limitational case we consider yields stark results and is of particular interest.

respect to  $x_k$  and then evaluating at a symmetric situation with  $x_k = y_k$  gives the equilibrium level of expenditure per patent as

$$x_i^* = y_i^* = \frac{F_M}{2^{n+1}} \text{ for all } i = 1, \dots, n. \quad (7)$$

This effort is strictly positive. Note also that this condition is sufficient to make the two firms' payoff strictly positive. The payoff is

$$\pi^* = \frac{F_M}{2} - n \frac{F_M}{2^{n+1}} > 0.$$

In the Appendix it is shown that the second order conditions for  $x_i^*$  as in (7) describe a local maximum. We summarize this result as follows.

**Proposition 1** *A subgame perfect equilibrium of the multi-component patent race with efficient bargaining between two firms is described by monopoly in the product market, and efficient bargaining that allocates patent rights such that only one firm can produce. An interior symmetric equilibrium in the patent race for  $n$  component patents is described by efforts as in (7)*

The two firms' total effort in all component contests sums up to

$$x^* + y^* = \frac{nF_M}{2^n}. \quad (8)$$

This sum has its maximum for  $n = 1$  and is strictly decreasing in  $n$ . Moreover, this sum converges towards zero if  $n$  becomes very large. Intuitively, if many complementary patents are needed to produce a particular good, even if one firm, say  $A$ , spends much effort on each of the component contests, it becomes very likely that both firms fail to obtain all patents. In each of these cases firm  $A$  receives  $F_M/2$ , independently of whether it holds 1, 2, or even  $n - 1$  patents. This makes it less worthwhile to spend much effort in the simultaneous contests.

Whether the reduction in effort that goes along with a larger  $n$  is desirable or not is difficult to evaluate. R&D effort is wasteful from a social point of view in this framework, as we focus on market uncertainty and disregard technological uncertainty. Firms would maximize their joint profits here if they choose the smallest possible amounts of efforts.<sup>3</sup>

## 4 Alternative patent trade regimes

In what follows we discuss deviations from the benchmark case in the previous section and consider regimes in which patent trade is restricted in different ways.

**No patent trade** Consider first the most severe patent trade restrictions one could think of: suppose patents cannot be traded at all. The only case in which production can take place in stage 3 is when one firm wins all patents. As this firm becomes a monopolist, the payoff of firm  $A$  becomes

$$\pi_A = \frac{\prod_{i=1}^{i=n} x_i}{\prod_{i=1}^{i=n} (x_i + y_i)} F_M - x, \quad (9)$$

and equivalently for firm  $B$ . A firm wins only if it wins all patents, and if the different component contests are mutually independent, this is the product of the win probabilities for all patents  $i = 1, \dots, n$ .

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<sup>3</sup>In a more general framework, there are also reasons why firms spend too little on R&D from a social point of view. Whether the different pieces of information that are needed to produce the product are found is often uncertain. The probability of innovation will typically be an increasing function in the R&D efforts of firms. Accordingly, the firms' monopoly rent and the consumer rents will typically be functions of R&D efforts. Profit maximizing firms take only some of these effects into consideration. From a social point of view, R&D effort may be too high or too low in a more general framework that adds technological uncertainty to the picture.

Maximization of this payoff with respect to  $x_k$  yields  $n$  identical first-order conditions of the type

$$\frac{\partial \pi_A}{\partial x_k} = \frac{\prod_{i \neq k} x_i \prod_{i=1}^{i=n} (x_i + y_i) - \prod_{i \neq k} (x_i + y_i) \prod_{i=1}^{i=n} x_i}{\left( \prod_{i=1}^{i=n} (x_i + y_i) \right)^2} F_M - 1. \quad (10)$$

Making use of the symmetry assumption, one obtains

$$y_k^* = x_k^* = \frac{F_M}{2^{n+1}}. \quad (11)$$

Efforts and aggregate effort in this equilibrium is exactly the same as in the equilibrium without any restrictions on patent trade:

**Proposition 2** *Prohibition of trade of exclusive patent rights between the firms does not change the contest effort in a symmetric interior equilibrium of the multi-patent contest.*

Despite this similarity with respect to the contest stage, the equilibrium payoffs differ from those in the benchmark case. Aggregate profit in the interior equilibrium with efforts for as in (11):

$$\pi_A = \pi_B = \frac{F_M}{2^n} - \frac{nF_M}{2^{n+1}} = \frac{F_M(2-n)}{2^{n+1}}. \quad (12)$$

For  $n = 2$ , this payoff is smaller than if patent trade is unconstrained. Firms spend the same amount of R&D, but each firm wins the monopoly rent only with probability 1/4, if patents cannot be traded. Firms and consumers are worse off ex-ante for  $n = 2$ , if patents cannot be traded. For  $n > 2$ , the profit (12) becomes negative, and symmetric effort as in (11) does not constitute an equilibrium in this case.

**Selective patent licensing agreements** Suppose now that firms can agree on sharing patents but cannot establish exclusive user rights on patents that have been traded, or restrict each firm's use of the patent in other ways.<sup>4</sup> Perhaps surprisingly, this leads to equilibrium R&D efforts and payoffs that are the same as in the unconstrained benchmark regime.

If one firm wins all patents, this firm will become a monopolist, like in the framework with free trade.

If, instead, each firm wins at least 1 patent, efficient negotiations will take place as follows. For each single patent, firms can negotiate the right to jointly use a patent for each single patent. An agreement that maximizes their joint surplus that is compatible with the restriction on patent sharing is as follows. Suppose firm  $A$  wins patents  $1\dots m$  and firm  $B$  wins patents  $m + 1, \dots n$ . In this case one of the firms may offer the other firm the right to join in the use of all its patents, or not vice versa, but not mutually. For instance,  $A$  may sell the right to make use of the technology components  $1, \dots m$ , and ask for a fee equal to  $\frac{F_M}{2}$  in this case, whereas firm  $B$  sticks to its exclusive rights to use patents  $m + 1, \dots n$ . As a result,  $B$  will be the only firm that is able to produce the good, and will earn the monopoly profit. This outcome is an equilibrium of any subgame in which both firms hold at least one patent. It maximizes the total payoff of the two firms, as it leads to the monopoly profit, and, as in the benchmark case, it shares this profit between the two firms. Accordingly, the objective functions of firms at the contest stage are the same as in the benchmark case. We summarize this as

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<sup>4</sup>One such restriction could be a limit on the number of units of the good which the licensee is allowed to produce using a particular technology component. Such licensing arrangements are not uncommon and are seemingly anti-competitive. Note, however, that such arrangements are not needed here to obtain the monopoly outcome in the equilibrium.

**Proposition 3** *Trade restrictions that allow only for selective patent licensing agreements between the firms do not change the contest effort in a symmetric interior equilibrium of the multi-patent contest.*

**Patent pools** Consider a different regime that is more restrictive with respect to which contractual arrangements are feasible. We again rule out contracts that transfer exclusive user rights for a patent from one firm to the other. We also rule out patent specific contracts as regards making use of a particular patent. Instead, firms may either keep the patents they have and use them exclusively, or they may pool all information and patent rights they have, like in a grand patent pool.

If one firm exclusively owns the patent rights for all  $n$  components, sequential rationality in stages 2 and 3 will imply that the firms do not form a patent pool, but the firm that owns all patents will produce as a monopolist in stage 3 and earn the monopoly profit  $F_M$ .

If each firm owns at least one patent, if they do not form a patent pool each firm will earn zero profits in the market game. If, instead, the firms form a patent pool, both firms can produce in the market game. The outcome in the market game is described by competition between duopolists. Each firm earns  $F_D$ .

Turning to stage 1, for reasons of symmetry, we can consider the payoff for one firm. Firm  $A$ 's objective function is

$$\pi_A = F_D + \frac{\prod_{i=1}^{i=n} x_i}{\prod_{i=1}^{i=n} (x_i + y_i)} (F_M - F_D) - \frac{\prod_{i=1}^{i=n} y_i}{\prod_{i=1}^{i=n} (x_i + y_i)} F_D - x. \quad (13)$$

Firm  $A$  receives the duopoly profit in all patent allocations that emerge from the contest stage, except if firm  $A$  wins all patents or if firm  $A$  wins none of the patents. The first exception yields an additional payoff for firm  $A$

equal to  $(F_M - F_D)$  and the exception occurs with the probability that is described by the ratio term in the second term on the right hand side of (13). The second exception yields firm  $A$  a payoff of zero, as the other firm has all patents. This is described by the third term in (13). Finally, and as in previous cases, the firm has to pay for the efforts in the  $n$  parallel R&D contests, and this constitutes the fourth term on the right-hand side.

Maximization of this payoff with respect to  $x_k$  for  $k = 1, \dots, n$  yields  $n$  identical first-order conditions

$$\frac{\prod_{i \neq k} x_i \prod_{i=1}^{i=n} (x_i + y_i) - \prod_{i \neq k} (x_i + y_i) \prod_{i=1}^{i=n} x_i}{(\prod_{i=1}^{i=n} (x_i + y_i))^2} (F_M - F_D) + \frac{\prod_{i \neq k} (x_i + y_i) \prod_{i=1}^{i=n} y_i}{(\prod_{i=1}^{i=n} (x_i + y_i))^2} F_D - 1 = 0$$

Using symmetry, this reduces to

$$x_k^* = y_k^* = \frac{F_M}{2^{n+1}}. \quad (14)$$

Again, the effort choice in a symmetric interior equilibrium is the same as in the regime in which exclusive patent rights can be traded freely, whereas the equilibrium payoffs differ. The payoff is equal to  $F_D + \frac{1}{2^n}(F_M - F_D) - \frac{1}{2^n}F_D - \frac{nF_M}{2^{n+1}}$  which is equal to

$$\pi_A = \pi_B = \frac{2F_D(2^{n-1} - 1)}{2^n} + \frac{F_M(2 - n)}{2^{n+1}}.$$

This payoff is positive for  $n = 1$  and non-negative for  $n = 2$ . Whether it is positive or negative for larger values of  $n$  depends upon the relative size of  $F_D$  and  $F_M$ . For  $n > 2$  it is positive for

$$\frac{F_D}{F_M} > \frac{n - 2}{2^{n+1} - 4}. \quad (15)$$

The ratio on the right hand side peaks at  $n = 3$  (it is about 0.0833), and decreases (rapidly) in  $n$  thereafter, and whether this condition is fulfilled



depends on the type of competition in a duopoly. Consumers gain from this regime compared to unconstrained trade of exclusive patent rights if the symmetric interior equilibrium exists, as the product is always supplied by at least one firm in both regimes, but the market is monopolized if exclusive patent rights can be traded without any restrictions, and a patent pool leads to a duopoly with a considerable probability which becomes ever larger if the number of patents is higher. This is summarized as a proposition:

**Proposition 4** *If firms cannot trade single patent rights, but can form a grand patent pool, condition (15) characterizes a necessary condition for the symmetric interior R&D contest equilibrium to exist. In this equilibrium they spend the same contest effort as with free patent trade. Firm payoffs are lower and consumer rents are higher than in the case with free patent trade.*

To get an intuition whether condition (15) is likely to hold, we consider Bertrand and Cournot competition with perfect substitutes. With Bertrand competition between identical firms,  $F_D = 0$ , and the condition fails, i.e., no interior symmetric equilibrium at the contest stage for  $n > 2$  exists. With Cournot competition with homogenous products, constant marginal cost and linear demand,  $F_D/F_M = 4/9$ , and participants make positive payoffs for all  $n$ .

## 5 Conclusions

The number of patents that are used for single consumer products is considerable, for many standard products. In this paper we considered R&D contests if firms need  $n$  complementary patent rights for components from which they can produce a consumer good. We show that this complemen-

tarity generally weakens the incentives to invest in R&D effort. If firms can freely trade the rights to use each single of these  $n$  patents, for large  $n$ , the sum of all R&D effort in all component contests reduces to zero. Intuitively, if many complementary patents are needed to produce a particular good, even if one firm spends much effort on each of the component contests, it becomes very likely each firm fails to obtain all patents. But if each of the firms obtains at least one patent, this patent yields veto power, and a firm's payoff is therefore the same whether it holds 1, 2, or even  $n - 1$  patents. This makes it less worthwhile to spend much effort in the  $n$  simultaneous contests.

We also show that this result is robust with respect to alternative trading regimes among patent holders. Particularly, if patent rights cannot be traded at all, or if exclusive rights in patents cannot be traded, but patents can only be licensed, or if firms can only enter into a general patent sharing arrangement (a 'patent pool'), the marginal incentives to spend effort in the simultaneous component contests remain unchanged. The profits for firms are lower in these regimes, however, and these marginal incentives need not characterize an interior equilibrium if the number  $n$  of components becomes large.

From a consumer point of view, among the regimes we study, the patent pool yields the highest consumer rents, provided that  $n$  is small enough such that the interior symmetric contest equilibrium is sustained under this regime.

Several extensions and generalizations would be interesting to look at. One would like to allow for more than two competing firms, or allow for asymmetry between firms. Further, it would be interesting to allow for technological uncertainty, in addition to the market uncertainty. However, in the context used here, the complexity of the problem increases more than

linearly in these dimensions, and we leave this to future research.

## 6 Appendix

A1: Consider the second-order conditions for  $x$  and  $y$  as in (7) to describe a local payoff maximum for the respective firm given that the other firm chooses their effort according to (7). The second order derivatives of the maximand (6), evaluated at the symmetric solution, are  $\frac{\partial^2 \pi_A}{(\partial x_i)^2} = -\frac{1}{2^n x^2}$ ,  $\frac{\partial^2 \pi_B}{(\partial y_i)^2} = -\frac{1}{2^n y^2}$  and  $\frac{\partial^2 \pi_A}{\partial x_i \partial x_j} = \frac{\partial^2 \pi_B}{\partial y_i \partial y_j} = 0$ . Hence, the Hessian is a diagonal  $(n \times n)$  matrix of the form

$$H_A = \begin{bmatrix} -\frac{1}{2^n x^2} & 0 & \cdots & 0 & 0 \\ 0 & -\frac{1}{2^n x^2} & & \vdots & \vdots \\ 0 & 0 & \ddots & 0 & 0 \\ \vdots & \vdots & & -\frac{1}{2^n x^2} & 0 \\ 0 & 0 & \cdots & 0 & -\frac{1}{2^n x^2} \end{bmatrix} \quad ((A1))$$

for firm  $A$ , and analogously for  $B$ . The determinant of this matrix is the product of the diagonal elements, so that the determinant of the first leading principal minor has negative sign, the second positive and so alternating. Hence, the conditions for a local maximum at the symmetric situation are fulfilled.

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