Patents, Imitation and Licensing In an Asymmetric Dynamic R&D Race

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Abstract

R&D is an inherently dynamic process which typically involves different intermediate stages that need to be developed before the completion of the final invention. Firms are not necessarily symmetric in their R&D abilities; some may have an advantage in early stages of the R&D process while others may have advantages in other stages of the process. This paper uses a two-firm asymmetric-ability multistage R&D race model to analyze the effect of patents, imitations and licensing arrangements on the speed of innovation, firm value and consumers' surplus. By using numerical analyses to study the MPE of the R&D race, the paper demonstrates the circumstances under which a weak patent protection regime, which facilitates free imitation of any intermediate technology, may yield a higher consumers' surplus and total surplus than a regime that awards a patent for the final innovation. The advantage of imitation may hold even when the length of the patent is optimally calculated or when we allow for voluntary licensing of intermediate technologies.
1. Introduction

Patents are designed to provide incentives for innovation. The conventional wisdom is that by protecting innovators from imitation we encourage R&D investment and promote innovation. Recently this rationale has been challenged. There is evidence that the software and computer industries were most innovative in particular during period of weak patent protection through which these industries experienced rapid innovation (see Bessen and Maskin (2002), Bessen and Hunt (2004), Hunt (2004), Gallini (2002)). The standard argument for patents may not hold in industries in which there is a sequential structure of the innovation process. In such industries, although imitation reduces the firms' current profits, imitation may spur innovation and may lead to more efficient R&D processes.

R&D races are inherently dynamic processes that take place over time and may involve several intermediate stages. Firms may adjust their R&D investments over time given their assessments regarding their relative success in the race. The race typically involves development of different intermediate inventions or complementary technologies that may enable the firms to complete the invention. Firms are not necessarily symmetric in their R&D abilities. Some firms may display better abilities in several stages of the R&D race while other firms may exhibit better abilities in other stages of the race. The multistage race is a convenient setting that captures the knowledge accumulated process during the race. In these settings each firm needs to go through several stages of R&D in order to complete the invention (see Fudenberg et al. (1983), Harris and Vickers (1985, 1987), Grossman and Shapiro (1987), and Lippman and McCardle (1987)).

The focus of this paper is on the effect of possible technology imitation on an asymmetric-ability multistage innovation race. We consider a two-firm multistage R&D race in which one firm has a technological advantage in the early stages of the race while the second firm has a similar advantage in the last stages of the race. We consider three possible patent policies: (i) a race which awards a patent for the final innovation, (ii) a race which awards a patent only for several periods - the length of the patent is determined optimally as to maximize consumers' surplus, (iii) a race in which any intermediate technological

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3 See also the survey in Cohen, Nelson and Walsh (2000).
discovery by one firm can be costlessly imitated by its competitors (hereinafter CTI). Clearly free and costless imitation is not always feasible, thus we view it as a benchmark case.\textsuperscript{5} We then introduce the possibility of licensing intermediate technologies and compare the CTI case with an R&D race with licensing of intermediate technologies.

We provide a numerical analysis of these R&D races using a variant of the value function algorithm developed in Pakes and McGuire (1994). We solve for the Markov perfect equilibrium of these races for a wide range of parameters' value, for each of the above patent regimes. We then compare the speed of innovation, firms' value, consumers' surplus and investment strategies for each type of race. Our main finding is that whenever the product market is small relative to the cost of innovation, the CTI regime does not provide sufficient incentives to invest in R&D. However when the market is large enough, the CTI regime yields higher consumers' surplus than R&D races with patent protection.\textsuperscript{6} Similarly whenever there is an intense duopolistic competition the CTI does not provide sufficient incentives for innovation; then again whenever the market competition is less intense, the CTI regime leads to higher consumers' surplus as well as higher value for firms than regimes which provide patent protection. These results are closely related to the nature of asymmetry between the firms. When the firms have identical or similar abilities the advantage of the CTI regime disappears.\textsuperscript{7} But whenever the R&D race is characterized by a sufficiently large asymmetric ability we show that the CTI may provide higher consumers' surplus and higher value for firms than regimes that provide patent protection.

The intuition behind our results is as follows: The R&D race with a CTI regime always ends up with a duopoly—implying a lower prize at the end of the race. On the other hand the R&D process is more efficient. The ability to imitate an intermediate technology is a form of cooperation where one firm gains from the success of its rival. Moreover, one firm may gain when its discovery is imitated as it provides it with an opportunity to imitate future discoveries by its rival. When the abilities are identical the free rider problem reduces the firms' incentives to invest in R&D which implies a slow pace of innovation and consequently

\textsuperscript{5} An interesting case that we do not discuss is when only the final innovation can be imitated. In a one stage R&D race the two regimes are equivalent but in a multistage race this regime would provide lower incentives to innovate without facilitating specialization and more efficient R&D investment.

\textsuperscript{6} The size of the product market determines the prize that firms get upon completion of the innovation and thus affects their incentives to innovate.

\textsuperscript{7} Symmetry in this context corresponds to firms with identical abilities. It is still possible that the early stages of the innovation are more difficult and more costly for both firms than the other stages of the innovation.
low consumers' surplus and low value for firms. But sufficient ability asymmetry induces firms to specialize in developing the technologies they are better at. Thus, one can think of the cost asymmetry as a coordination device that facilitates specialization and alleviates the free riding problem.

The possibility of licensing intermediate technologies may also enable the firms to specialize and take advantage of their asymmetric R&D abilities. We, therefore, consider an R&D race in which firms may license their intermediate technologies. Licensing occurs whenever it creates a surplus and we assume that the firms equally share this surplus. We find that, in the symmetric-abilities case there is no voluntary licensing. In the asymmetric case, however, the possibility of licensing indeed facilitates specialization resulting in a more efficient R&D process. We compare the equilibrium performance of the R&D race with licensing to the performance of the race under the CTI regime and demonstrate that when the product market is large and when there are sufficient asymmetries the CTI regime yields higher consumers' surplus than the race with licensing. Nevertheless, licensing considerably enhances the value of the firms.

Our paper is closely related to Bessen and Maskin (2002) who consider an innovation process which is both sequential and complementary. Bessen and Maskin define a sequential innovation process to be a sequence of potential innovation each built on its immediate predecessor and each can be sold in the market—contributing an additional incremental value for the firms. They further define the innovation process to be complementary in the sense that each firm takes a different research line and thereby enhances the probability of developing further innovations. Their paper considers a model in which an R&D investment generates a fixed probability of success. Once there is a failure the innovation process stops unless the firm is able to imitate the success of another firm. In such a setup imitation may reduce the firm's current profit but it raises the probability of further innovation and improves the prospect of capturing higher values. Our R&D model is different. We assume a multistage innovation process with a fixed final value rather than sequential innovation. Investment effort is endogenous and failure in one period leads to continuation of effort in the next period.

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8 Licensing at the last stages of the race will not occur as it reduces the prize that the firms obtain. Since firms have the same abilities there is no specialization that they can exploit, and licensing does not occur at earlier stages as well.
Our main result is that in such R&D processes, imitation is beneficial only in the asymmetric case where firms have different abilities.

Our paper is also related to Judd, Schmedders and Yeltekin (2002). Their paper focuses on dynamic multistage innovation races in which patents may be awarded at one of the intermediate stages. Using a numerical analysis, the paper considers the optimal innovation stage at which the patent is awarded and the optimal magnitude of the prize to the winner. The paper studies how the details of the innovation race and the planner's objectives affect the optimal patent rules.

Cumulative innovation has also been studied by Scotchmer (1991, 1996) and Green and Scotchmer (1995). In this setup the innovations are not isolated discoveries. Each innovation is built on prior discoveries. In such an environment there can be insufficient incentives for R&D investment if successful firms earn market profits only until competitors develop the next generation of products. This literature considers the solution of transferring some of the profits from the second generation innovators to the initial innovators in order to induce sufficient incentives for R&D investment for the early innovators.\(^9\)

The rest of the paper is organized as follows. Section 2 provides the details of the R&D races that we consider in this paper. In Section 3 we present the results of the numerical analysis and discuss the role of cost asymmetry and the possibility of imitating intermediate technologies. Section 4 presents details of the firms' strategies and descriptive statistics of the asymmetric race with patents and with the possibility of imitation. In section 5 we introduce the possibility of licensing and examine whether licensing may have the advantage of imitation but without reducing the incentive to imitate.

### 2. Asymmetric R&D Races

We start by presenting our benchmark multistage R&D race model in which firms are required to complete the development of several stages prior to completion of the invention. In the benchmark case, a patent is awarded to the first firm who completes this process and imitation is either not feasible or prohibited. We then specify different modifications of the benchmark case allowing for different patent and licensing possibilities.

\(^9\) See also O'Donoghue (1998) which discuss patentability requirement to solve this problem.
2.1 Benchmark Model: A Multistage R&D Race with End Patents

Our benchmark model is a two-firm asymmetric-cost $n$-stage R&D race in which a patent is awarded to the first firm that completes the development of the $n$ intermediate stages. Moving from step $l$ to step $l+1$ is a stochastic process depending on the firm’s investment. Letting $x_i \geq 0$ be firm $i$’s investment, we assume that the probability of success, i.e., $p(l+1|x_i, l)$ denoted by $p(x_i, l)$, is increasing in $x_i$. If a firm is unsuccessful in moving from $l$ to $l+1$ in one period, it can try again in the next period.\(^{10}\)

We assume that the firms are not symmetric in their R&D abilities, and capture this asymmetry by allowing for different cost profiles. Let $c_i = (c_i^1, \ldots, c_i^n)$ be firm $i$’s cost profile, which captures the firm’s abilities at different stages of the R&D process. Firm $i$’s cost of investing $x_i$ at stage $l$ is $c_i^lx_i$. A lower $c_i^l$ implies therefore a greater ability in developing intermediate technology $l+1$.

A two firm R&D race will be defined as $R \equiv \{n, (c^1, c^2), \pi^M\}$ where $n$ is the number of intermediate technologies, $(c^1, c^2)$ are the firms’ costs profiles and $\pi^M$ is the monopolistic profits in the product market - the prize at the end of the race.\(^{11}\) We assume that the two firms are symmetric in the product market. If a single firm holds the patent, then its reward is the monopolistic profits $\pi^M$, while the other firm makes zero profit. When both firms reach the patent stage at the same period, we assume that each obtains the patent with probability $0.5$. We further assume that firms maximize discounted payoffs and we let $\beta$ be the firms’ common discount factor. When we allow for imitation and licensing such that the innovation race ends up with a duopolistic industry we let the prize be the duopolistic profits, $\pi^D$; where $\pi^D < \pi^M/2$.

We consider the Markov Perfect Equilibrium (MPE) of the race (as in Maskin and Tirole (2001)). The state of the race is defined as $(l, m)$; i.e., firm 1 is at stage $l$ and firm 2 is at stage $m$. At every period, firms need to decide, simultaneously on their investment level given the state of the race $(l, m)$ and their respective cost profile regardless of how this state has been reached. Firm $i$’s strategy is denoted as $x_i(l, m)$.

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\(^{10}\) An alternative formulation would be to consider a race with learning such that any attempt to move from one stage to the other provides information on the likelihood of having at the end a successful innovation, see Malueg and Tsutsui (1997).

\(^{11}\) A multi-firm R&D race can be defined analogously.
A Markov Perfect Equilibrium for a two-firm R&D race is defined by

- Investment strategies $x^*_i(l, m)$ for $i=1, 2$ and every possible $(l, m)$.
- Value functions $V_i(l, m)$ for $i=1, 2$ and very possible $(l, m)$ (for convenience, we suppress dependence of the value function on the firms' cost structures and the different prizes).

Such that:

(i) The strategies $x^*_i(l, m)$ are optimal given the value functions $V_i(l, m)$.

(ii) For every state $(l, m)$, the value functions describe the present value of profits realized when both firms play the equilibrium strategies $x^*_i(l, m)$.

In calculating the value functions $V_1(l, m)$ and $V_2(l, m)$, we make repeated use of the following Bellman equation:

$$
V_i(l, m) = \begin{cases} 
\pi^M & l = n, m < n \\
0.5\pi^M & l = n, m = n \\
\max_{x_i \geq 0} \left\{ -c^i_i x_i + \beta \sum_{l', m'} V_i(l', m') p(l'|x_i, l) p(m'|l, m) \right\} & l < n, m < n \\
0 & l < n, m = n 
\end{cases}
$$

Where $p(l'|x_i, l) = p(x_i, l)$ if $l'=l+1$ and $p(l'|x_i, l) = 1 - p(x_i, l)$ if $l'=l$ and $p(m'|l, m) = p(x^*_2(l, m), m)$ if $m'=m+1$ and $p(m'|l, m) = 1 - p(x^*_2(l, m), m)$ if $m'=m$.

2.2 Patent Policy, Imitation and R&D Races

In general, the characteristics of the R&D race are governed not only by the patent regime itself, but also by the realities of each industry. In some industries it is possible to observe the intermediate technologies obtained by rival firms and thus to condition R&D investments on these observations. In other industries only some (or none) of the intermediate technologies are observable. Intermediate technologies may be patentable in some industries while in others they may not. There are industries in which imitation is relatively easy (either of intermediate steps or of the final innovation). In other industries trade secrets provide a relatively strong protection and imitation is not feasible. We consider in this paper several
R&D races with different types of patent protection and licensing. The list is clearly not exhaustive; however we try to provide the basic intuition on the effect of imitation and patenting in an asymmetric-ability multi-stage R&D race.

1. **R&D Race with an End Patent (hereinafter E-Pat):** This is the standard multistage R&D setting which is our benchmark model described in Section 2.1. In this case each firm must independently complete all the innovative stages to achieve the final innovation. Patent is awarded to the first firm that completes all the stages.

2. **R&D Race with End Patent of Optimal Length (hereinafter Opt-Pat):** The E-Pat regime may provide a patent protection which is too strong. We thus consider also the case in which a patent is awarded to the first firm that completes the invention, where the patent is awarded for \( \tau \) periods which are followed by a free imitation and a duopolistic market. The length of the patent affects the firms' incentives to innovate but also limits the period in which the firm can exploit its monopolistic power. Finding the optimal patent length is the balancing of these two forces. We use consumers' surplus as the criterion for calculating the length of the optimal patent.\(^{13}\)

   In most countries patents are awarded for a fixed number of years regardless of their type or scope. However in our analysis of Opt-Pat regime, the optimal patent length, \( \tau \), may vary with the parameters of the R&D race. Consequently, the Opt-Pat regime in our analysis cannot be implemented as a general patent protection regime but provides a benchmark for comparison with the CTI. We do not provide here the details of the Markov Perfect Equilibrium and the Bellman equation for the Opt-Pat case, in general given a \( \tau \), it requires only a small modification of our benchmark case.\(^{14}\)

3. **R&D Race with Complete Technology Imitation (hereinafter CTI):** We consider a race in which it is possible to imitate any intermediate technology developed by other firms. This may be an extreme assumption but we would like to examine the role of complete open

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\(^{12}\) For a discussion on optimal patent policy see for example Nordhaus (1969), Klemperer (1990), Gilbert and Shapiro (1990) and Denicolo (1999, 2000).

\(^{13}\) Clearly another option would be to define optimal patent as the regime that maximizes total welfare. Such a change would reduce the consumers' surplus derived from the race.

\(^{14}\) The procedure that we use searches for the optimal \( \tau \) for every set of parameters.
environment in which every development is imitable. The other extreme possibility is that only the final innovation can be imitated while intermediate technologies are not imitable. In a simple one stage race there is no difference between the two cases. Since the emphasis of this paper is a multi-stage race, we do not consider both scenarios and only focus on an R&D race in which firms may imitate, without any delay or cost, any intermediate technology invented by their competitors.\textsuperscript{15}

Among the cases examined in this paper, the CTI regime probably represents the weakest patent protection scenario. As imitation is free at any stage, firms cannot lead the race nor can they enjoy monopolistic profits. The CTI case resembles a type of research joint venture (RJV) arrangement in which firms commit at the outset of the race to share any intermediate innovation but without building a joint R&D lab.

The above cases are merely examples for different feasible scenarios. The relevant rules of R&D races are dictated by the patent regimes as well as by the detailed realities of each industry and innovation process. Imitation, for example, is not always feasible. Sometimes imitation is a costly process and a success of one firm is only partially diffused to other firms in the industry. In other cases firms may not observe the intermediate technologies that have been developed by their rival and thus are not able to condition their R&D effort on the state of the race.

3. Analysis of R&D races

3.1 Details of the Numerical Analysis

We adopt Pakes and McGuire (1994) algorithm to calculate the Markov Perfect equilibrium of the different races that we study in this paper. For each state, the algorithm calculates the value functions by using the relevant monopolistic and duopolistic profits and the Bellman equation (1).

The algorithm is iterative and works as follows: First, the algorithm initiates the value function \(V^0(l,m)\) and investment level \(x^0(l,m)\) for states \((l,m)\) with \(\max\{l,m\}=n\). \(V^0(l,m)\) is initiated with the corresponding monopolistic and duopolistic profits based on the patent

\textsuperscript{15} For simplicity, we focus on the extreme case of free imitation. Clearly, there are cases in which imitation is costly and requires some reverse engineering. This can be captured by a framework that assume that any success of one firm reduce the cost of innovation (of the same technology) for the other firm.
regime, and \( x^0(l,m) \) is set to zero. States \((l,m)\) where \( l,m<n \) are initiated with an arbitrary value function \( V^0(l,m) \) and investment level \( x^0(l,m) \). The algorithm then works iteratively. To move from iteration \( k \) to iteration \( k+1 \), the algorithm takes the value function \( V^k(.) \) and policy function \( x^k(.) \) as its input and uses the Bellman equation (1) to generate updated value and policy functions, separately for each firm. In each iteration, the algorithm first uses \( V^k_1(.) \) and \( x^k_1(.) \) from memory and solves equation (1) to calculate firm 1's investment strategy, \( x_1^{k+1}(.) \). It then takes the calculated \( x_1^{k+1}(.) \) and computes firm 1's value function, \( V_1^{k+1}(.) \). The same calculations are then done to compute firm 2's \( \{V_2^{k+1}(.),x_2^{k+1}(.)\} \). The algorithm iterates over the value functions and the investment strategies, and stops when \( \{V^k(,),V^{k+1}(.)\} \); and \( \{x^k(,),x^{k+1}(.)\} \) are very close point-wise between iterations.\(^{16}\)

The equilibrium investment strategies \((x^*(.)\)) are then used to construct the transition probabilities matrix, i.e., the probability distribution over tomorrow’s state \((l',m')\) given today's state \((l,m)\). This allows us to use tools from stochastic process theory to analyze the equilibrium Markov process and the appropriate descriptive statistics.

**Existence:** Pakes and McGuire (1994) consider an infinite horizon dynamic game. In such a setup existence and uniqueness is not guaranteed, see Doraszelski and Satterthwaite (2005) for a discussion on the existence and uniqueness of MPE in dynamic games. Our setup is simpler as we study a finite race with known prizes. The race will end (with probability 1) at a finite number of periods. The values at the end of the game are well defined by the rules of the race. One can therefore use these values together with the iterative algorithm and backward induction to calculate the value of firms and the equilibrium strategies at other states of the race. Since we have a finite stage race the existence of Markov Perfect Equilibrium is guaranteed for our setting.

**Parameter Values:** For our benchmark case we consider the following parameterization:

- The number of innovation steps is \( n=6 \).

\(^{16}\) Our stopping criteria is \( \varepsilon=10^{-6} \)
The cost profile is set to be $c^1 = (1,1,\gamma,\gamma,\gamma)$; $c^2 = (\gamma,\gamma,\gamma,1,1,1)$ where $\gamma \geq 1$, (we will repeat the analysis for different values of $\gamma$ in order to focus on the role of cost asymmetry).

The monopolistic payoffs $\pi^M$ is derived from the demand function $p=20-q$; assuming no production cost yields $\pi^M=100$. The consumers’ surplus associated with the same demand function and a monopolistic price is $CS^M=50$.

The duopolistic profits are assumed to be $\pi^D = \mu \pi^M$, where $0 \leq \mu \leq 0.5$. Given this structure, the collusive duopolistic case would be captured by $\mu=0.5$ while Bertrand price competition is captured by $\mu=0$. When we change $\mu$ we make the necessary modifications in consumers surplus $CS^D(\mu)$.

We let the probability of success at every stage of the race be $p(x_i) \equiv 0.1x_i/(1+0.1x_i)$.

The common discount factor $\beta = 0.97$.

In the Opt-Pat case, where the “winning” firm enjoys monopolistic payoffs for $\tau$ periods, followed by duopolistic payoffs, we take the per-period monopolistic payoff to be $r\pi^M$; where $r$ is the discount rate, such that $\beta=(1+r)^{-1}$.

We consider the effect of three different variables on the outcome of the race. (i) $\alpha$ - market size (the market prizes are simply set to $\alpha \pi^M$ and $\alpha \pi^D$, and consumers’ surplus is adjusted accordingly). (ii) $\gamma$ – the degree of cost asymmetry. (iii) $\mu$ - the intensity of the market competition i.e., the portion of the monopolistic payoffs that is captured in a duopolistic competition.

While the choice of cost structure seems arbitrary it is designed to capture the case in which the first firm has a technological advantage at the first stages of the R&D while the second firm has a technological advantage at the last stages. We choose this specific cost profile in order to incorporate two aspects of our analysis; cost asymmetry and multistage R&D race. We will compare our results with the outcome of a symmetric multistage race, i.e., with $c^1=(\gamma,\gamma,\gamma,1,1,1)$; $c^2=(\gamma,\gamma,\gamma,1,1,1)$. Changing the structure of the cost function may clearly

\[
CS^*(\mu) = \left[ 20 + \sqrt{20^2 - 2\mu20^2} \right] / 4
\]

Studying the effect of $\mu$ on the race allows us to analyze the effect of higher (lower) degree of competition without the need to change the number of firms in the race.
change the outcome of the race and the relative advantage of different patent regimes. Note that while we fixed the cost position we consider different levels of the market size $\alpha$. Increasing $\alpha$, for example, would be equivalent to reducing all costs by the same proportion.

3.2 The Performance of the different Patent Regimes.

We start by comparing the performance of the E-Pat, Opt-Pat and the CTI patent regimes without getting into details regarding the firms' investment strategies (which will be examined in the next section). We compare the consumers' surplus, the value for firms, total welfare and the duration of the race. We vary the values of the parameters $\alpha$, $\gamma$ and $\mu$ to obtain a better understanding of the race characteristics.

3.2.1 The effect of the size of the market

Figures 1a,b,c,d present the performance of E-Pat, CTI and Opt-Pat as a function of the market multiplier $\alpha$ or the prize at the end of the race. We maintain the cost asymmetry at $\gamma=2$, and the duopolistic competition intensity at $\mu=0.25$.\(^{19}\) The figures on the left present the symmetric case in which the cost structure of both firms is $c^1=(\gamma,\gamma,\gamma,1,1,1)$; $c^2=(\gamma,\gamma,\gamma,1,1,1)$ and on the right side we present the performance of the R&D race with asymmetric cost such as $c^1=(1,1,1,\gamma,\gamma,\gamma)$; $c^2=(\gamma,\gamma,\gamma,1,1,1)$.

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\(^{19}\) We will vary these parameters in the coming subsections.
Figure 1b: Duration

Figure 1c: Firms' Value

Figure 1d: Total Welfare
Figure 1a illustrates the standard argument justifying the need for patent protection. In the symmetric case for $1.5<\alpha<4.5$ the Opt-Pat and the E-Pat regimes induce R&D investment, while the CTI regime does not provide sufficient incentives for the firms to invest in R&D. For these parameter values investment in R&D is socially optimal, consequently offering no patent protection results in an inefficient outcome. Furthermore, when firms do invest in R&D, whenever $\alpha>4.5$, the duration of the race in the CTI case is much longer than under the other two regimes.

Comparing the symmetric and the asymmetric parts of Figure 1a demonstrate the effect of cost asymmetry in sequential R&D races. While the Opt-Pat and the E-Pat are not much affected by the cost asymmetry, the performance of the CTI case is greatly improved. In particular, R&D investment in the CTI case starts at much lower levels of $\alpha$ and for $\alpha>3$ the CTI regime yields higher consumers’ surplus than the E-Pat or the Opt-Pat regimes.

Consumers' surplus is determined in R&D races by two factors: the duration of the race and the resultant market game. When the outcome of market game is determined by the number of competitors (in our case monopoly vs. duopoly) and the intensity of the duopolistic competition. In the E-Pat case the race ends up with a monopolistic market, in the Opt-Pat it ends up with several periods of monopolistic market and then a switch to a duopolistic market, while in the CTI case the market is always duopolistic.

The duration of the race is depicted in Figure 1b. The curves depict the time until first invention and the curve Opt-Pat 2 depicts how long it takes in the Opt-Pat case from the first invention to the entry of the second firm.\(^{20}\) In the symmetric case the CTI does not provide sufficient incentives to invest in R&D, therefore even when firms invest it takes many period until the invention is completed. In the asymmetric case the race with CTI regime is much faster and generates a duopolistic market immediately after the innovation while in the Opt-Pat case the duopolistic period starts only after the patent expires (see the curve Opt-Pat 2 in the Figure). As the figure shows, for $\alpha>2.7$ the market structure effect dominates the duration effect and the CTI regime leads to higher consumers' surplus.

Figure 1c depicts the firms' value. These values are the equilibrium discounted expected profits minus discounted investment. The firms' cost asymmetry implies different

\(^{20}\) The time between Opt-Pat and Opt-Pat 2 is $\tau$. This time period is not constant as it is endogenously determined for every set of parameters and calculated as to maximize consumers' surplus.
equilibrium value for the firms. We present in Figure 1c only the sum of values and postpone the discussion on the effect of cost asymmetry on the firms' value to Section 4. As the figure indicates, the value of firms under the CTI regime is lower than under the E-Pat or the Opt-Pat cases. This result clearly depends on $\mu$ - the intensity of the duopolistic competition.

Figure 1d depicts the evaluation of the total welfare derived from the three regimes. In the symmetric case the CTI is dominated by the other regimes. However for the asymmetric case, for $\alpha>2.8$, it is the CTI that yields the higher total welfare.

### 3.2.2 The effect of market competition

We now turn to discuss the effect of $\mu$, the intensity of the duopolistic competition, on the performance of the three patent regimes. A low value of $\mu$ implies a tougher duopolistic competition, lower duopolistic payoffs but high consumers' surplus. On the other hand when $\mu$ is close to 0.5, the duopolistic firms share the monopolistic profits. In Figure 2 we present the performance of the three patent regimes as a function of $\mu$ fixing the other parameters at $\alpha=3$ and $\gamma=2$.

![Figure 2a: Consumers' Surplus](image)

Figure 2a: Consumers' Surplus
Figure 2b: Duration

Symmetric

Asymmetric

Figure 2c: Value

Symmetric

Asymmetric

Figure 2d: Investment

Symmetric

Asymmetric
The E-Pat R&D race is not affected by μ as it never ends up with a duopolistic market. In contrast, the intensity of the duopolistic competition has a large effect on the incentives to invest in the CTI case, as it always ends up in a duopolistic competition. In the Opt-Pat case the effect of μ is more complex. Since the patent is awarded for only a fixed number of periods, which are then followed by a duopolistic market, the level of μ affects the size of the (first and second) prizes and thus the incentives to invest. Furthermore, the length of the patent is endogenously calculated such as to maximize consumers' welfare and these calculations are affected by μ as well.

In the symmetric case, again, the CTI regime is dominated by the E-Pat and the Opt-Pat regimes which yield higher consumers surplus (see Figure 2a). For low levels of μ the possibility of imitation in the CTI case implies that firms do not invest in R&D, and the race does not start. Higher μ induce more R&D investment but the investment is always below the investment levels at the other two regimes (see Figure 2d). As before, the cost asymmetry has a huge effect on the incentives to invest in the CTI case, still at low levels of μ the CTI case induces no investment and the Opt-Pat regime dominate—yielding higher consumers' surplus.

In the asymmetric case, whenever μ>0.225 it is mostly the CTI regime that yields a higher consumer surplus. As μ increases the duration of the race converges under the three regimes, but in the CTI case there is immediately a duopolistic market where in the Opt-Pat case consumers need to wait τ periods until a second firm is allowed to enter the market; resulting in lower consumers’ surplus.

When μ approaches 0.5 the duopolistic firms share the monopolistic profits and the duopolistic market structure yields the same consumers' surplus as the monopolistic market. In this case the consumers' surplus generated by the CTI regime falls sharply, as there is no advantage in having a duopolistic market. Interestingly, as Figure 2b indicates, for such μ the length of the optimal patent increases dramatically as maximization of consumers' surplus implies putting more emphasis on the incentives to innovate rather than on the resultant markets structure.

In the symmetric case the CTI regime yields always the lowest value for firms (see Figure 2c). This is however not the case in the asymmetric race. Under the CTI regime the value of the firm is monotonically increasing with μ as a larger μ implies less market competition and higher profits. Interestingly for μ>0.36 the firms' value under the CTI regime...
is larger than under the E-Pat or the Opt-Pat regimes. The higher value is a result of a more efficient R&D investment. For large $\mu$ the overall market profits are similar and, as Figure 2b indicates, the duration of the race is also similar. But the advantage of the CTI regime is derived from a more efficient R&D investment (see Figure 2d). Under the CTI regime there is a much lower R&D expenditure but the duration until invention is not much different. This result is derived from a more efficient race in which the firms avoid duplication of effort and exploit their relative advantage in the different steps of the race.21

3.2.3 The effect $\gamma$ - the degree of cost asymmetry.

We now turn to discuss the effect of $\gamma$ - the degree of cost asymmetry, on the performance of the three patent regimes. A larger $\gamma$ implies greater R&D cost as well as greater cost asymmetry. As $\gamma$ is larger the advantage of the first firm in the first three steps of the race is larger and similarly the relative advantage of the second firm in the last three steps is larger. In the symmetric case, a larger $\gamma$ implies that both firms have higher costs in developing the first three steps of the invention. The effect of different $\gamma$ is depicted in Figure 3; we fix the value of the other parameters at $\alpha=3$ and $\mu=0.25$. As suggested in Figures 1 and 2, given these parameters values the symmetric case does not provide sufficient incentives to invest in the CTI regime. We, therefore present only the asymmetric case.

![Figure 3a: Consumers' Surplus](image1.png)  
![Figure 3b: Firms' Value](image2.png)

21 The CTI regime yields higher total surplus than the other two patent protection regimes whenever $\mu>0.22$. This range includes the Cournot equilibrium which is at $\mu=0.44$. 

18
As figure 3a-d shows, in the asymmetric case it is the CTI regime that yields higher consumers’ surplus and higher total welfare for most of the relevant range of $\gamma$.\(^{22}\)

An increase in $\gamma$ implies higher cost of R&D. Since imitation is not possible in the E-Pat and Opt-Pat cases, one would expect the higher cost of investment to have a direct effect on firms’ values. The lower expected value implies lower incentives to invest and thus longer duration of the innovation process which results in lower consumers' surplus. The CTI regime, on the other hand, facilitates a complete specialization; when $\gamma$ goes up each firm invests only in developing the technologies it has an advantage in. The non-monotonicity in the consumers' surplus and the value for firms in the CTI case is indeed due to a switch from a regime in which the two firms invest in R&D to a regime characterized by a complete specialization. Consequently, beyond that critical level of $\gamma$ a further increase of $\gamma$ does not affect the firms' investment strategies.

4. Strategies and Values of the Asymmetric R&D Race

So far we presented the summary performance of the R&D race under the E-Pat, Opt-Pat and CTI regimes without going into details regarding the strategic interaction between the firms. In this section we examine the details of the strategic race under a specific set of parameters. We choose parameters values where, in the asymmetric case, the CTI provides higher consumers' surplus than the E-Pat and Opt-Pat regimes. This allows us to explain the

\(^{22}\) Note that for the same parameters values in the symmetric case the CTI regime does not provide sufficient incentives for R&D investment.
superiority of the CTI regime (for these parameters). We examine two sets of parameters values that differ only with respect to the duopolistic competition intensity. Tables 1-2 present the summary statistics of the R&D race for the parameters \((\alpha=3, \gamma=2, \mu=0.25)\) and \((\alpha=3, \gamma=2, \mu=0.45)\). Tables 3-4 then present the investment strategies and value function of the race for the CTI and the E-Pat cases.

In Table 1-2 we let Inv1 and Inv2 be the investment of each of the two firms; TotInv is the firms’ total investment. Dur_Prod1 is the average duration of the race prior to first production while Dur_Race is the number of periods until the race ends and the second firm enters the market. The lines "Value" and "CS" provide the expected discounted total value of the firms and discounted consumers' surplus. Prob_1 and Prob_2 show the probability that firm 1 or 2 is the first firm to complete the invention and \((V1,V2)\) provides the expected initial value of the two firms in the race.

<table>
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<td>19.2</td>
<td>19.5</td>
<td>12.2</td>
<td>18.55</td>
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</tbody>
</table>

** - denotes the regime that provides the highest consumers’ surplus and total value.

Table 1: R&D race, \(\alpha=3, \gamma=2, \mu=0.25\)
As Tables 1 and 2 indicate, in the symmetric case the CTI regime is dominated by the E-Pat and the Opt-Pat regimes, both in terms of consumers' surplus and in terms of value for firms. The benefits from the CTI regime materialize only when there is a sufficiently asymmetric cost structure, and the prize is large relative to the cost of R&D. For example, when \((\alpha=3, \gamma=2, \mu=0.45)\), the CTI yields higher consumers' surplus and higher value than the regimes which provide patent protection. When there is more competitive duopolistic interaction, as in \(\mu=0.25\), the CTI regime yields lower value for the firms but still higher consumers surplus. The higher level of duopolistic competition (lower prices) generates higher consumers' surplus sufficient to compensate for the slower pace of innovation. Under the CTI regime there is a much lower level of investment in R&D which is partially due to lower incentives but also derived from a more efficient process that exploits specialization and avoids duplication of effort. The lower investment contributes to the values of firms and for high \(\mu\) this savings are sufficient to compensate for the lower profits implied by the duopolistic market structure.

Note that the cost asymmetry has also the role of a coordination devise. With cost symmetry, the CTI regime exhibits the standard free riding problem. Each firm wants the other firm to invest as they both share the rewards. As a result, at equilibrium they both reduce their investment. However with a large enough cost asymmetry, the optimal allocation of effort is clear to both firms. They specialize—each develops the intermediate technology it has an advantage in.

Our setup of cost asymmetry implies that the first firm is more efficient in the early three stages of the technology development while the second firm is more efficient in the last three stages of the race. All six stages are necessary for the completion of the invention and beside their order, are totally identical. The question is whether such an asymmetry implies an

<table>
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Table 2: R&D race with a less competitive duopolistic market, \(\alpha=3, \gamma=2, \mu=0.45\)
advantage to one of the firms? Tables 1 and 2 indicate that the answer to this question depends on the patent regime. In the E-Pat and Opt-Pat races, the firm that has better abilities at the first steps of the race has an advantage in the entire race; even though its total level of investment is higher, it has a greater value than the second firm i.e., $V_1 > V_2$. Furthermore, it has a higher probability to be the first to complete the innovation (i.e., Prob_1 > Prob_2). On the other hand in the CTI regime, it is the second firm - the firm with the better abilities in the last three stages of the race - which has the higher value. Note that this advantage is derived from lower investment in the R&D process as both firms share the same prize.

The fact that the cost asymmetry affects the race with E-Pat (or Opt-Pat) is somewhat surprising. After all each firm needs to independently develop three intermediate technologies with lower costs and three intermediate technologies with higher costs. Yet, there is a difference between the symmetric case and the asymmetric case. The probability that the firm that has the early advantage will be the one that will get the patent is much larger than the probability that the second firm would win the race. This is a direct result of the first firm’s higher level of investment, which in turn also increases its value of the race.

We now turn to present the strategies and value functions for the E-Pat and the CTI cases.

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Table 3a: Investment, $\alpha=3$, $\gamma=2$, $\mu=0.25$, E-Pat
Comparing Tables 3 and 4 provides more details on the effect of the different patent regimes on the R&D race. Under the CTI regime the investment is lower as the reward for success is lower (compare Tables 3b and 4b). On the other hand, the investment process is more efficient as the firms exploit their relative technological advantage and each firm invest only in the technologies in which they have superior abilities. In the E-Pat case there is no specialization; both firms invest heavily at the beginning even in technologies that they have disadvantage in.

Furthermore, in the CTI case both firms benefit from any success in the innovation process. The value function of both firms increases any time there was a successful innovation, regardless which firm did it (see Table 4b). Thus, while the firms compete at the end in the product market, the possibility of imitation at every stage of the race induces a type of "cooperative" innovation process even though there is no explicit cooperation or coordination between the firms.

5. Licensing and Asymmetric R&D Race

In our setting the CTI regime provides a more efficient innovation process as firms have comparative advantage in different stages of the process and the CTI regime facilitates specialization and sharing. This raises an interesting question: Is imitation the only mechanism that allows firms to gain from their complementary advantages? Sharing intermediate technologies may also occur in an environment in which it is possible to license
these technologies. Licensing will allow firms to share their discoveries and benefit from specialization. The focus of this section is the effect of licensing of intermediate technologies on the R&D race and in particular on the comparison of the CTI regime with a race in which licensing is allowed.

The possibility of licensing intermediate technologies affects the incentives facing the firms. Firms, for example, may decide to develop only the intermediate technology, license it and exit the race. Licensing intermediate technologies may generate “intermediate payoffs” but it also affects the continuation of the race and the probability of winning. One can distinguish between different possible scenarios depending of the details of the race. When it is possible to patent intermediate technologies then such a patent blocks the continuation of the race, and the race ends before the innovation process is completed. Licensing this patented technology may prolong the race and ultimately shorten the duration of the innovation process. Clearly, in the symmetric case there are no incentives for licensing of intermediate technology. However in the asymmetric case, licensing may enable firms to take advantage of their different skills.

5.1 Voluntary Technology Transfer.

Let us start by examining the possibility of a voluntary transfer of intermediate technologies. In Section 3 we showed that for a wide range of parameters values the CTI yields a higher value for firms than the E-Pat or the Opt-Pat regimes. In these cases, if imitation is not feasible, the firms can adopt a policy of voluntarily transmission of intermediate innovation. This policy is equivalent to licensing without compensation. If the firms can commit, at the outset of the race, to reveal all their intermediate innovation the outcome will be indeed equivalent to the CTI regime.

Consider now the race without a commitment to a voluntary transmission of intermediate technologies, rather at each stage firms can choose whether to voluntarily reveal their invention.\(^{23}\) Obviously, at the last stage of the race firms will not share their innovation with rival firms, as such sharing would reduce their value. Given that there is no sharing in the last stage, we can argue that there is no voluntary sharing of technology in the stage

\(^{23}\) We solve for the MPE of such a race but provide here only the final conclusion of this study. The details can be obtained from the authors upon request.
before the last one. One can use backward induction to argue that there is no voluntary
technology transfer at any stage, even though the firms may benefit from such a behavior.

5.2 A Multistage R&D Race with Intermediate Technology Licensing.

We consider an R&D race in which patent is awarded only at the end of the race. Firms may, however, voluntary license their intermediate technology to their competitors. We assume that licensing takes place only if both firms agree to do it. Licensing is a form of technology transfer and it is not exclusive. Once an intermediate technology is licensed, both firms may continue with the race for developing the next step of the innovation.

The timeline of this race is as follows. Each period \(t\) starts with a state \((l,m)\) which describes the intermediate technologies that had been developed by the two firms prior to period \(t\). After realizing the state of the race \((l,m)\), firms decide whether to sign a licensing agreement. The firms then realize the new state of the race, and make their investment decision. The outcome of these investments is realized at the beginning of the next period. We let \(V_i(l,m)\) be the value of the game for firm \(i\) at the beginning of a period after the realization of the outcome of the R&D investment from the previous period. \(V_i(l,m)\) is the value of firm \(i\) after licensing decisions were made and realized.

Assume that \(l > m\) such that firm 1 is ahead in the race of firm 2. If it licenses its intermediate technology to firm 2, it will lose its advantageous position implying a loss of \(V_1(l,m) - V_1(l,l)\). On the other hand, the gain of firm 2 from the licensing is \(V_2(l,l) - V_2(l,m)\). Since licensing is voluntary, licensing would occur only when it creates a surplus that is, whenever \(V_2(l,l) - V_2(l,m) > V_1(l,m) - V_1(l,l)\). We assume that once the surplus is positive, a licensing agreement is concluded and the firms share the licensing surplus equally between them. Let \(T_{1,2}(l,m)\) be the amount paid by firm 2 to firm 1 for the license of intermediate technology \(l\). Then, the licensing term is assumed to be:

\[
T_{1,2}(l,m) = \frac{1}{2}[V_1(l,m) - V_1(l,l)) + (V_2(l,l) - V_2(l,m))].
\]

Let \(I_L\) be an indicator function where \(I_L(l,m) = 1\) if licensing occurred and \(I_L(l,m) = 0\), otherwise. The Bellman equation is then
\[ V_1(l, m) = \max_{x_i \geq 0} \left\{ -c_i^l x_i + \beta \sum_{l', m'} \tilde{V}_1(l', m') p(l'| x_i, l) p(m'| x_i, l') \right\} \]

where

\[
\tilde{V}_1(l, m) = \begin{cases} 
V_1(l, m) & \text{if } I_1(l, m) = 0 \\
T_{1,2}(l, m) + V_1(l, l) & \text{if } I_1(l, m) = 1 
\end{cases}
\]

The value functions \( V_2(l, m) \) and \( \tilde{V}_2(l, m) \) are similarly defined for firm 2.

5.3 R&D Races with Licensing: Numerical Analysis

We use the same algorithm to calculate the Markov Perfect Equilibrium of this game (see details in Section 3.1). For the numerical analysis we maintain the value of the parameters as in our benchmark case (i.e., \( \alpha = 3, \mu = 0.25, \gamma = 2 \) and 5). Table 5 presents the summary statistics for the R&D race with licensing in comparison to the CTI and the E-Pat regimes.\textsuperscript{24} We compare the different regimes for two values of cost asymmetries; \( \gamma = 2 \) and \( \gamma = 5 \). We do not present the symmetric case as there is no intermediate technology licensing in the symmetric cost case. Firms have the same abilities and, therefore, there are no technological or strategic advantages from such licensing.\textsuperscript{25} Licensing in our model is therefore closely related to the asymmetries between the firms' R&D abilities.

<table>
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<td>5.3</td>
<td>29</td>
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</table>

\textsuperscript{24} We compare to the E-Pat regime because under our formulation when there is no licensing the race is identical to the E-Pat case.

\textsuperscript{25} All the equilibria with the symmetric case ended with no licensing. We do not present these results here but they can be obtained upon request from the authors.
Table 5 specifies the states in which licensing will take place. We specify only the relevant states, i.e., those states which are reached with positive probability on the equilibrium path. When $\gamma=5$ the possibility of licensing implies that firms specialize in their R&D investment. The first firm develops the first three intermediate technologies; it then licenses these technologies to the second firm which completes the R&D process. When $\gamma=2$ (lower level of cost asymmetry), both firms participate in the development of the different stages of the race. Firm 1 has a higher value but this value is the outcome of successful licensing and is not derived from the final market as the probability that firm 1 will get the final patent is only 38%.

Interestingly, even when there is a possibility of voluntary licensing at every stage of the race the CTI regime still provides a higher CS than the race with the licensing option. Note that the possibility of licensing enables the firms to adopt a more "cooperative" R&D race and to guarantee themselves higher values than in the CTI case. This creates a fast and efficient development process, yet consumers are still better off under the CTI regime as the shorter development process does not compensate for the monopolistic market structure.

The degree of cost asymmetry has an interesting effect on the race. Raising $\gamma$ is a form of a cost increase (for both firms). Yet as Table 5 indicates, when there is licensing firms are better off in the $\gamma=5$ case than with the lower cost of $\gamma=2$. For $\gamma=2$ there is no complete specialization in the R&D process. The probability that firm 1 would be the first firm to complete the innovation is 38% even though this firm has no advantage in the later stages of the race.

Table 5 shows that the possibility of licensing has an interesting effect on the R&D race. For example, when $\gamma=5$ the E-Pat regime, without the possibility of licensing, results in a long race characterized by large inefficient investment and very low firms' value. Firm 2 does not participate in the race, while firm 1 is left to develop all the intermediate technologies even those it has disadvantage in. In contrast, the possibility of licensing facilitates specialization as in the CTI case which results in higher firms' values.
the R&D process. On the other hand, when $\gamma=5$ the asymmetry is sufficiently high and “forces” the firms to completely specialize. The first firm develops the first three stages licenses the technology out to the second firm which then completes the innovation. This transforms the structure of the race. The firms do not race against each other. An early discovery by one firm benefits both firms. Consequently, even though there are higher R&D costs, the firms' invest more efficiently; their investment goes down and their value goes up.

We now turn to discuss the effect of the parameters $\alpha$ and $\gamma$ on the R&D race and on the comparison between the CTI and the licensing cases.

![Figure 4a: CS ($\gamma=2$, $\mu=0.25$).](image1)

![Figure 4b: Firms' Value ($\gamma=2$, $\mu=0.25$).](image2)

Figures 4a and 4b present the consumers' surplus and firms' value as a function of the market size $\alpha$ (holding $\gamma$ at 2). When $\alpha$ is above 2.5 the CTI regime yields higher consumer surplus than the R&D race with licensing of intermediate technology. On the other hand the CTI provides lower value for the firms than the race with licensing. The possibility of licensing enhances both consumers' surplus and firms' value in particular in low values of $\alpha$. For high levels of $\alpha$, the prize is sufficiently high, and firms choose not to license at all and the race with licensing coincides with the E-Pat case.
Figures 5a and 5b describe the consumers' surplus and the firms' value as a function of the degree of cost asymmetry $\gamma$ (holding $\alpha$ at $\alpha=3$). For $\gamma$ close to 1 the CTI does not provide sufficient incentives to invest but for most of the range of $\gamma$, the CTI provides higher consumers' surplus than the race with the licensing option. The possibility of licensing enhances the firms' value. For $\gamma < 1.5$ there is no licensing and the outcome is identical to the E-Pat regime. When $1.5 < \gamma < 2.2$ firm 1 licenses to firm 2 (but only when firm 2 is one stage behind it; i.e. close enough to catch-up by itself), and keeps investing in the hope to achieve the patent. When $2.2 < \gamma < 4.6$ firm 1 licenses the intermediate technology to firm 2 even when firm 2 is couple of stages behind. In this case, however, firm 1 does not drop out of the race after the licensing as long as it is neck-to-neck with firm 2. Once firm 1 is one step behind firm 2, it drops out of the race). Finally, for $\gamma > 4.6$ there is complete specialization in the R&D process. As a result of this pattern of licensing, we can see that the total value of firms increases with $\gamma$.

6. Concluding Remark

R&D races have many details; the technology may be complex, involving the development of different intermediate technologies and complement parts. There might be different degrees of spillovers, and firms may have different abilities, different labs and different personnel. Furthermore, firms may have different evaluations of the final prize.
There are R&D races in which firms may get signals regarding the success and failure of other competitors while in other races they are totally in the dark without the ability to infer their relative position in the race. The effect of different patent regimes on the race would depend very much on the detailed characteristics of the race. Clearly, one cannot find one regime which dominates all the others for all possible R&D races. Thus finding the "right" regime is a compromise that should take into account the distribution of possible types of R&D races.

Analytical tools are somewhat limited when the environment is so complex. On the other hand, numerical analyses are limited in theirs generality. What can be generalized beyond our numerical observations? This is a standard and debated question whenever a numerical analysis is presented. Clearly a general claim about the appropriate optimal patent policy is beyond the scope of this paper. But the numerical simulation allows us to examine the interplay between the complex structure of the R&D race and the performance of different patent regimes. In our case, the numerical analysis shows that whenever the R&D is sequential and firms have asymmetric-abilities the performance of the CTI regime may dominate other possible regimes. This conclusion, like any other claims about the optimal patent policy, depends very much on the details of the race and on the relevant parameters.
References


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<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2007</td>
<td>Elhanan Helpman, Pol Antrás</td>
<td>Contractual Frictions and Global Sourcing</td>
</tr>
<tr>
<td>3-2007</td>
<td>David Zvilichovsky</td>
<td>Technology Adoption, Bubbles and Productivity</td>
</tr>
<tr>
<td>4-2007</td>
<td>Yoram Weiss, Pierre Andre Chiappori, Murat Iyigun</td>
<td>Investment in Schooling and the Marriage Market</td>
</tr>
<tr>
<td>5-2007</td>
<td>Efraim Sadka, Assaf Razin</td>
<td>Productivity and Taxes as Drivers of FDI</td>
</tr>
<tr>
<td>6-2007</td>
<td>Itzhak Gilboa, Offer Lieberman, David Schmeidler</td>
<td>A Similarity-Based Approach to Prediction</td>
</tr>
<tr>
<td>7-2007</td>
<td>Itzhak Zilcha, Bernard Eckwert</td>
<td>The effect of Better Information on Income Inequality</td>
</tr>
<tr>
<td>8-2007</td>
<td>Itzhak Gilboa, Offer Lieberman, David Schmeidler</td>
<td>On the Definition of Objective Probabilities by Empirical Similarity</td>
</tr>
<tr>
<td>9-2007</td>
<td>Ariel Rubinstein, Yuval Salant</td>
<td>Choice with Frames</td>
</tr>
<tr>
<td>10-2007</td>
<td>Anat Bracha, Dan Ariely, Stephan Meier</td>
<td>Doing Good or Doing Well? Image Motivation and Monetary Incentives in Behaving Prosocially</td>
</tr>
<tr>
<td>11-2007</td>
<td>Chaim Fershtman, Sarit Markovich</td>
<td>Patents, Imitation and Licensing In an Asymmetric Dynamic R&amp;D Race</td>
</tr>
</tbody>
</table>

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