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R&D, Licensing and Patent Protection

by

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Date January 2002

Abstract This paper investigates the effect of different patent regimes on R&D investment and social welfare in a duopoly market with uncertain R&D process. We find that strong patent protection increases R&D investment of at least one firm but whether both firms R&D investment will be more under strong patent protection is ambiguous. While ex-ante welfare is more likely to be higher under strong patent protection, ex-post welfare may be higher under strong patent protection. Whether the possibility of licensing increases both firms' R&D investment is also ambiguous. Licensing with up-front fixed-fee can increase policy dilemma by increasing the possibility of higher ex-ante welfare under strong patent protection but higher ex-post welfare under weak patent protection. However, the results may be different for licensing contract with per-unit output royalty.

Keywords Knowledge spillover, Licensing, Patent protection, Uncertain R&D

J.E.L. Class D43, L13, O34

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1 Introduction

Technological progress is an important factor for development and growth of an economy. An economy can increase her technological capability through several ways. Two dominant ways to increase technological capability are indigenous research and development (R&D) and technology licensing.

Researchers working on industrial organization and international economics have already analyzed several issues on R&D investments and optimal R&D organizations in oligopolistic industries (see, e.g. Reinganum, 1983, d'Aspremont and Jacquemin, 1988, Marjit, 1991, Combs, 1992, Suzumura, 1992, Choi, 1993, Beath et al., 1998, Poyago-Theotoky, 1998 and Kabiraj and Mukherjee, 2000). It has been found that knowledge spillover and uncertainty in R&D are two major concerns to the firms doing R&D. While the strategy on R&D investment may help firms to overcome the problem of uncertainty, patent policy can influence knowledge spillover. However, the above papers did not pay attention to examine the role of different patent policies on the incentives for R&D and social welfare.

There is another literature examining the effects of different patent systems on R&D (see, e.g. Gilbert and Shapiro, 1990, Klemperer, 1990, Gallini, 1992 and Mukherjee and Pennings, 2001). But, these papers ignored the possibility of R&D by all the firms in the industry and concentrated on a pre-defined sequence of R&D. However, the above-mentioned two sets of papers share a common feature, viz., these papers more or less ignored the possibility of other business strategies such as technology licensing while analyzing R&D decisions.[1] Hence, while the possibility of tacit knowledge or higher cost associated with licensing can justify the previous works, those works are not completely relevant in those industries where licensing is not difficult. The present paper starts off with this background and examines the implications of different patent systems on R&D investment and social welfare with and without the possibility of licensing ex-post R&D.

In what follows, section 2 considers a duopoly model of R&D competition under different patent systems. For simplicity, we consider two different patent systems called weak and strong patent protections. We assume that knowledge spillover is possible only under weak patent protection.[2] We show that whether strong patent protection increases R&D investment of all firms compared to weak patent protection is ambiguous. If R&D functions of these firms are sufficiently asymmetric then strong patent protection can increase R&D investment of one firm but can reduce R&D

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1 In a model of R&D competition with no uncertainty in R&D, Kultti and Takalo (1998) looked at the possibility of cross licensing ex-post R&D.

2 It is well known that patents do not always prevent spillover of the research results (see, e.g., Levin et al., 1987). Further, the efficiency of a patent system depends on the nature of industries. Though, for simplicity, we assume that strong patent protection does not encourage knowledge spillover, our qualitative results will hold as long as one assumes higher knowledge spillover under weak patent protection compared to strong patent protection.

investment of the other firm. But, for more symmetric firms, R&D investment of both firms is higher under strong patent protection compared to weak patent protection. However, there will be no influence on R&D investment if, in case of unilateral success in R&D, the successful firm becomes the monopoly even under weak patent protection. Using a cross-country analysis with aggregative R&D data Varsakelis (2001) has shown that countries with a strong patent protection invest more in R&D. Hence, the present paper asks for firm level analysis and provides a testable hypothesis regarding the influence of different patent systems on R&D investment of individual firms.[3]

We show that the existence of uncertainty in R&D can lead to a conflict between ex-ante and ex-post social welfare. If cost reduction from R&D is sufficiently small or the degree of knowledge spillover is sufficiently large then ex-post welfare will be more under weak patent protection. But, for sufficiently large cost reduction and for sufficiently low knowledge spillover, ex-post welfare will be more under strong patent protection. However, as probability of innovation increases under strong patent protection, the ex-ante welfare is likely to be higher under strong patent protection when the effect of R&D investment on the probability of success is sufficiently strong.

The possibility of licensing ex-post R&D may encourage the firms to engage in technology licensing. We consider this possibility in sections 3 and 4 by incorporating the possibility of fixed-fee licensing and licensing with per-unit output royalty, respectively. With fixed-fee licensing we show that licensing is more likely to occur under weak patent protection. The possibility of fixed-fee licensing is likely to increase the difference of total R&D investment between these patent systems when licensing is privately profitable under both patent systems. But, if licensing is profitable only under weak patent protection then the difference of total R&D investment reduces between these patent systems. However, when licensing is profitable under both patent systems then by creating ex-post welfare likely to be higher under weak patent protection and ex-ante welfare likely to be higher under strong patent protection, the possibility of licensing may increase the policy dilemma. If licensing is profitable under weak patent protection only then both ex-ante and ex-post welfare are likely to be higher under weak patent protection.

If licensing consists of per-unit output royalty then royalty income will be higher under weak patent protection when cost reduction from R&D is sufficiently large. Therefore, unlike fixed-fee licensing, licensing contract with per-unit output royalty can have higher impact on R&D investment under weak patent protection than strong patent protection. The analysis on welfare shows that, unlike fixed-fee licensing contract, ex-ante welfare is likely to be higher under weak patent protection when cost reduction from R&D is not sufficiently low. Thus, this paper shows the importance of the type of licensing contract for our results.

[3] A recent overview on the benefits and costs of patent protection is given by Mazzoleni and Nelson (1998).

This paper can be related to the literature on licensing also (see, e.g. Rockett, 1990, Marjit, 1990, Kabiraj and Marjit, 1993, Mukherjee, 2001). One common feature of these papers on licensing is the absence of R&D process in their framework. Contrary to this, the present paper considers the dynamic effect of R&D and technology licensing.[4]

The rest of the paper is organized as follows. In the second section, we consider a two-stage game of R&D competition in section 2. Section 3 extends this two-stage game to a three-stage game by incorporating the possibility of a licensing contract ex-post R&D. In this section we concentrate on fixed-fee licensing contract. Then we examine the implication of a licensing contract with per-unit output royalty in section 4. Section 5 concludes the paper. Proofs are relegated to the appendix.

2 A two-stage game of R&D competition

Consider that there are two firms, say 1 and 2, in the industry competing for an innovation. Suppose the firms have a technology that corresponds to a constant average cost of production $\bar{c} > 0$ and they are trying to invent a technology that corresponds to a constant average cost of production c, where $\bar{c} > c \geq 0$. However, the success in R&D is probabilistic and the unconditional probability of success in R&D, $p_i(x_i)$, $i = 1,2$, increases with R&D investment, where x_i is firm i's R&D investment. We consider that $p_i'(x_i) > 0$, $p_i''(x_i) < 0$, $p_i'(0) = \infty$ and $p_i'(\infty) = 0$ for $i = 1,2$. So, we allow for the difference in probability functions between these firms. However, for simplicity we consider that if the two probability functions are different, there is no possibility of crossing of these functions. Without loss of generality, we consider that for same R&D investment probability of success in R&D for firm 1 is at least as good as that of for firm 2, i.e., $p_1(x_1) \geq p_2(x_2)$ for $x_1 = x_2$ and $x_i > 0$, $i = 1,2$.

Uncertainty in the R&D process can lead to unilateral success in R&D and generates technological difference ex-post R&D. We assume that knowledge spillover helps to reduce the cost of production of the unsuccessful firm in case of technological difference. Therefore, if both firms succeed or fail in R&D then there is no possibility of knowledge spillover. However, knowledge spillover depends on the type of patent protection of the economy. In the following analysis we will consider to different patent protections – (i) weak patent protection and (ii) strong patent protection. A relatively strong patent protection reduces knowledge spillover between the firms. For simplicity, here we assume that knowledge spillover is possible only under weak patent protection. Hence, in case of unilateral success in R&D, the effective constant average cost of

[4] In totally different context and framework Gallini and Winter (1985) and Katz and Shapiro (1985) focus on the effect of licensing on R&D. While Gallini and Winter (1985) identify the conditions for licensing in a search-theoretic model of R&D, Katz and Shapiro (1985) focus on the incentives to develop a process when there is a possibility of licensing by the patent holder to its competitor.

production of the unsuccessful firm is given by $\alpha\bar{c}$ with $\alpha \in [\frac{c}{\bar{c}}, 1]$, where α shows the degree of knowledge spillover. While $\alpha = \frac{c}{\bar{c}}$ implies perfect knowledge spillover, $\alpha = 1$ implies no knowledge spillover. Therefore, strong patent protection implies $\alpha = 1$.

We assume that the inverse market demand function is given by

$$P = a - q, \tag{1}$$

where the notations have usual meaning with $a > \bar{c}$.

2.1 Weak patent protection

First, consider optimal R&D investments under weak patent protection. Here, the firms experience a knowledge spillover in case of unilateral success in R&D and the effective cost of the unsuccessful firm is given by $\alpha\bar{c}$. Therefore, the net expected profit of the i th firm are

$$p_i(x_i)p_j(x_j)\pi_i(c,c) + p_i(x_i)(1 - p_j(x_j))\pi_i(c) + (1 - p_i(x_i))(1 - p_j(x_j))\pi_i(\bar{c},\bar{c}) - x_i,$$
$$\text{for} \quad \alpha\bar{c} \geq \frac{(a+c)}{2} \tag{2}$$

and

$$p_i(x_i)p_j(x_j)\pi_i(c,c) + p_i(x_i)(1 - p_j(x_j))\pi_i(c,\alpha\bar{c}) + (1 - p_i(x_i))p_j(x_j)\pi_i(\alpha\bar{c},c)$$
$$+ (1 - p_i(x_i))(1 - p_j(x_j))\pi_i(\bar{c},\bar{c}) - x_i, \ \text{for} \ \alpha\bar{c} \leq \frac{(a+c)}{2}, \tag{3}$$

where $i, j = 1,2$, $i \neq j$, the first and second argument of the π function show the marginal cost of i th and j th firm respectively and $\pi_i(c)$ shows the monopoly profit of firm i.

The maximization of (2) and (3) with respect to x_i gives us the following first order conditions respectively

$$p_i'(x_i)p_j(x_j)\pi_i(c,c) + p_i'(x_i)(1 - p_j(x_j))\pi_i(c) - p_i'(x_i)(1 - p_j(x_j))\pi_i(\bar{c},\bar{c}) = 1,$$
$$\text{for} \quad \alpha\bar{c} \geq \frac{(a+c)}{2} \tag{4}$$

and

$$p_i'(x_i)p_j(x_j)\pi_i(c,c) + p_i'(x_i)(1-p_j(x_j))\pi_i(c,\alpha\bar{c}) - p_i'(x_i)p_j(x_j)\pi_i(\alpha\bar{c},c)$$
$$- p_i'(x_i)(1-p(x_j))\pi_i(\bar{c},\bar{c}) = 1, \text{ for } \alpha\bar{c} \le \frac{(a+c)}{2}. \quad (5)$$

It is easy to check that the second order conditions for maximization are satisfied. Equation (4) and (5) implicitly define firm i's reaction functions $x_i^*(x_j)$, where $i,j=1,2$ and $i \ne j$. These reaction functions show the profit maximizing levels of x_i given x_j. Solving these reaction functions, we get the optimal R&D investments for these firms. We consider that the probability functions are such that we get unique equilibrium for R&D investment.

Proposition 1: *(a) The reaction functions are negatively sloped and the absolute slope of the reaction functions is less than 1.*
(b) If R&D productivity[5] *of firm* i *is more than firm* j, $i,j=1,2$ *and* $i \ne j$ *(i.e.,* $p_i' > p_j'$*) then equilibrium R&D investment of firm* i *is more than firm* j*. The equilibrium probability of success in R&D is also higher for firm* i *than firm* j*, i.e.,* $p_i > p_j$ *in equilibrium.*

Proof: See Appendix A for the proof. Q.E.D.

2.2 Strong patent protection

Now, we consider the R&D game under strong patent protection where knowledge spillover is not possible. Therefore, here the net expected profits of the ith firm are given by

$$p_i(x_i)p_j(x_j)\pi_i(c,c) + p_i(x_i)(1-p_j(x_j))\pi_i(c) + (1-p_i(x_i))(1-p_j(x_j))\pi_i(\bar{c},\bar{c})$$
$$- x_i, \quad \text{for } \bar{c} \ge \frac{(a+c)}{2} \quad (6)$$

and

$$p_i(x_i)p_j(x_j)\pi_i(c,c) + p_i(x_i)(1-p_j(x_j))\pi_i(c,\bar{c}) + (1-p_i(x_i))p_j(x_j)\pi_i(\bar{c},c)$$
$$+ (1-p_i(x_i))(1-p_j(x_j))\pi_i(\bar{c},\bar{c}) - x_i, \text{ for } \bar{c} \le \frac{(a+c)}{2}, \quad (7)$$

where $i,j=1,2$, $i \ne j$. Maximizing (6) and (7) we get the respective first order conditions for optimal R&D investment of the ith firm, $i=1,2$:

[5] Here by R&D productivity we mean the effect of R&D investment on the probability of success. Hence, higher productivity implies that same R&D investment can lead to higher probability of success in R&D.

$$p_i'(x_i)p_j(x_j)\pi_i(c,c) + p_i'(x_i)(1-p_j(x_j))\pi_i(c) - p_i'(x_i)(1-p_j(x_j))\pi_i(\bar{c},\bar{c}) = 1,$$

for $\bar{c} \geq \frac{(a+c)}{2}$ (8)

and

$$p_i'(x_i)p_j(x_j)\pi_i(c,c) + p_i'(x_i)(1-p_j(x_j))\pi_i(c,\bar{c}) - p_i'(x_i)p_j(x_j)\pi_i(\bar{c},c)$$

$$- p_i'(x_i)(1-p_j(x_j))\pi_i(\bar{c},\bar{c}) = 1, \text{ for } \bar{c} \leq \frac{(a+c)}{2}. \quad (9)$$

Second order conditions for maximization are satisfied. Further, we can have the finding similar to Proposition 1 even for strong patent protection.

2.3 Comparison between weak and strong patent protections

2.3.1 Effect on R&D investments

It is clear that if cost reduction from R&D is sufficiently large and knowledge spillover is sufficiently small then in case of unilateral success in R&D, the successful firm becomes a monopoly under both patent systems (see (4) and (8)). Hence, here patent protections do not have any influence on the R&D investments of these firms.

Now, consider the situation where in case of unilateral success in R&D, the unsuccessful firm can compete in the market under both weak and strong patent protections. Therefore, here (5) and (9) are the relevant first order conditions for optimal R&D investments. From these expressions we see that, given x_j, firm i will invest more in R&D under strong patent protection than weak patent protection. Therefore, the reaction function functions for both the firms will shift outward under strong patent protection compared to weak patent protection. However, whether the equilibrium R&D investment of both firms will be higher under strong patent protection compared to weak patent protection depends on the relationship between the probability of success in R&D and R&D investment. The outward movement of a firm's reaction function will be more when the marginal profitability of her R&D investment reduces slowly. Therefore, if a firm's incremental gain from higher R&D investment is more then it gives that firm higher incentive for R&D investment. So, if the probability functions of these firms differ significantly then it is more likely that the equilibrium R&D investment of one firm (other firm) will be more (less) under strong patent protection compared to weak patent protection. But, for firms with more symmetric R&D productivity, the similar outward movement of both the reaction functions will lead to higher R&D investment by both firms under strong patent protection.

Figure 1 shows the effect of different patent systems on the reaction functions for R&D investments with $\bar{c} < \frac{(a+c)}{2}$. The figure shows firm 1's and 2's reaction functions as NN and HH respectively under weak patent protection and Y shows the equilibrium R&D investments. Strong patent protection shifts the reaction functions of both firms towards right. If new equilibrium of R&D investments does not occur in the range XYZ then one firm's R&D investment increases under strong patent protection while the other firm's R&D investment decreases under strong patent protection. In this figure we show that MM and GG are the reaction functions of firm 1 and 2 respectively under strong patent protection. Therefore, new equilibrium is at K and firm 1's (firm 2's) equilibrium R&D is more (less) under strong patent protection compared to weak patent protection.

Figure 1

If, in case of unilateral success in R&D the unsuccessful firm can compete in the market under weak patent protection only then the relevant first order conditions are (5) and (8). The comparison of (5) and (8) shows that given the R&D investment of the competitor, it is always better for a firm to invest more in R&D under strong patent protection compared to weak patent protection. However, like the previous situation, whether equilibrium R&D investment of both firms will be more under strong patent protection is ambiguous (similar to Figure 1).

The following proposition summarizes the above findings.

Proposition 2: *(a) If knowledge spillover is not large enough and cost reduction from successful R&D is sufficiently large, i.e.,* $\alpha\bar{c} \geq \frac{(a+c)}{2}$*, then R&D investments under weak and strong patent protections are same.*
(b) If either cost reduction from R&D is not sufficiently large, i.e., $\bar{c} < \frac{(a+c)}{2}$*, or knowledge spillover is sufficiently large, i.e.,* $\alpha\bar{c} < \frac{(a+c)}{2}$*, then R&D investment of at least one firm is more under strong patent protection compared to weak patent protection.*

It has been argued in the literature that strong patent protection increases R&D investment in a country (see, e.g. Varsakelis, 2001). But, attention did not paid how patent protections can affect R&D investments of individual firms. The above result shows that in an economy with sufficient difference in R&D abilities, R&D investment of a firm can be less under strong patent protection compared to weak patent protection.

2.3.2 Impact on social welfare

Now, we would like to investigate how it affects social welfare. Here by social welfare we mean the summation of industry profit net of R&D investment and consumers surplus. We will show that the existence of uncertainty in R&D may lead to differences in ex-ante and ex-post welfare.

2.3.2.1 Ex-post welfare under weak and strong patent protections

We start our analysis by looking at the ex-post social welfare under both patent regimes. If both firms succeed or fail in R&D then both firms' cost of production will be same irrespective of the patent protection. The analysis in subsection 2.3.1 shows that R&D investment will change under these patent systems when the unsuccessful firm competes at least under weak patent protection in the case of unilateral success in R&D. Therefore, given a duopoly market structure under unilateral success in R&D, if both firms succeed or fail in R&D, we can say that with higher total R&D investment under strong patent protection,[6] ex-post welfare will be higher under weak patent protection relative to strong patent protection.[7]

Now, we examine what will happen if there is an unilateral success in R&D. If, in case of unilateral success, the successful firm becomes a monopolist under weak and strong patent protections then the effective cost of production and R&D investments of these firms are same under both patent systems. Hence, here ex-post social welfare remains same under these two patent systems.

Next, consider the situation where under unilateral success in R&D, the unsuccessful firm can compete in the market at least under weak patent protection. Hence, in this situation, it is clear that the cost asymmetry becomes more under strong patent protection than weak patent protection. Given the demand and cost specifications, in case of unilateral success in R&D, industry profit in the product market and consumers surplus under weak patent protection is given by

$$W_{ex}^{wp} = \frac{(a-2c+\alpha\bar{c})^2}{9} + \frac{(a-2\alpha\bar{c}+c)^2}{9} + \frac{(2a-c-\alpha\bar{c})^2}{18}. \tag{10}$$

But, under strong patent protection, the industry profit and consumer surplus is either

$$W_{ep}^{sp} = \frac{(a-2c+\bar{c})^2}{9} + \frac{(a-2\bar{c}+c)^2}{9} + \frac{(2a-c-\bar{c})^2}{18} \quad \text{for } \bar{c} \le \tfrac{(a+c)}{2}, \tag{11}$$

or,

$$W_{ep}^{sp} = \frac{(a-c)^2}{4} + \frac{(a-c)^2}{8} \quad \text{for } \bar{c} \ge \tfrac{(a+c)}{2}. \tag{12}$$

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[6] Total R&D investment increases under strong patent protection compared to weak patent protection if the absolute slope of the reaction functions for R&D investment is less than 1, which has been satisfied for this analysis (Proposition 1(a)).

[7] Ex-post welfare will be same when the successful firm becomes a monopoly in case of unilateral success in R&D as in this situation R&D investments will not be influenced by the patent systems.

Proposition 3: *(a) If in case of unilateral success in R&D, the successful firm becomes a monopoly under weak patent protection then ex-post social welfare is same under weak and strong patent protections irrespective of the number of successful firm in R&D.*
(b) Suppose that, in case of unilateral success in R&D, the successful firm cannot be the monopoly. Then, if either both firms succeed or neither firm succeeds in R&D, ex-post welfare is higher under weak patent protection.
(c) Suppose, in case of unilateral success in R&D, the unsuccessful firm can compete in the product market at least for weak patent protection. (i) Then ex-post welfare is more under weak patent protection than that of under strong patent protection when either cost reduction from R&D is sufficiently small or knowledge spillover is sufficiently large. (ii) But for sufficient large cost reduction from R&D and with sufficiently low knowledge spillover, ex-post welfare is more under strong patent protection than weak patent protection provided the difference between total R&D investments under these patent systems is not sufficiently large.

Proof: See Appendix B for the proof. Q.E.D.

The result shows that even if weak patent protection induces knowledge spillover, social welfare may be more under strong patent protection if the degree of knowledge spillover is sufficiently small. Knowledge spillover helps to raise consumer surplus by reducing the effective cost of the unsuccessful firm but, at the same time, it reduces the profit of the successful firm who has relatively better technology than the unsuccessful firm. This loss in production efficiency may be larger than the gain in consumer surplus.[8]

2.3.2.2 Ex-ante welfare under weak and strong patent protections

While ex-post social welfare depends only on the outcomes of R&D and R&D investment, probability of success is also important for ex-ante social welfare. For example, lower competition due to relatively higher cost of production of the unsuccessful firm under strong patent protection can reduce ex-post welfare under strong patent protection compared to weak patent protection. But, sufficiently higher R&D investment under strong patent protection can reduce the chance of lower competition under strong patent protection significantly and can provide higher ex-ante welfare under strong patent protection compared to weak patent protection.

It is easy to understand that ex-ante welfare is same under these patent systems when in case of unilateral success in R&D, the successful firm becomes monopoly

[8] The possibility of welfare of loss due to cost reduction in a Cournot oligopoly has also addressed in Lahiri and Ono (1988).

under weak patent protection. This is because here R&D investments are same under both patent protections.

Now, consider that even under unilateral success in R&D, the market becomes duopoly under weak patent protection. Hence, ex-ante welfare under weak patent protection will be

$$W_{ea}^{wp} = p_1(x_1^{wp})p_2(x_2^{wp})W_{ep}^{wp}(c,c) + [p_1(x_1^{wp})(1-p_2(x_2^{wp})) + (1-p_1(x_1^{wp}))p_2(x_2^{wp})]W_{ep}^{wp}(c,\alpha\bar{c}) + (1-p_1(x_1^{wp}))(1-p_2(x_2^{wp}))W_{ep}^{wp}(\bar{c},\bar{c}) - x_1^{wp} - x_2^{wp}. \quad (13)$$

But, ex-ante welfare under strong patent protection will be either

$$W_{ea}^{sp} = p_1(x_1^{sp})p_2(x_2^{sp})W_{ep}^{sp}(c,c) + [p_1(x_1^{sp})(1-p_2(x_2^{sp})) + (1-p_1(x_1^{sp}))p_2(x_2^{sp})]W_{ep}^{sp}(c,\bar{c}) + (1-p_1(x_1^{sp}))(1-p_2(x_2^{sp}))W_{ep}^{sp}(\bar{c},\bar{c}) - x_1^{sp} - x_2^{sp}, \text{ for } \bar{c} \le \tfrac{(a+c)}{2} \quad (14)$$

or,

$$W_{ea}^{sp} = p_1(x_1^{sp})p_2(x_2^{sp})W_{ep}^{sp}(c,c) + [p_1(x_1^{sp})(1-p_2(x_2^{sp})) + (1-p_1(x_1^{sp}))p_2(x_2^{sp})]W_{ep}^{sp}(c) + (1-p_1(x_1^{sp}))(1-p_2(x_2^{sp}))W_{ep}^{sp}(\bar{c},\bar{c}) - x_1^{sp} - x_2^{sp}, \text{ for } \bar{c} \ge \tfrac{(a+c)}{2} \quad (15)$$

where $W_{ep}^{sp}(c)$ shows ex-post welfare under strong patent protection when only the successful firm produces in the market.

Consider the following lemma, which will help us in the following analysis.

Lemma 1: *We have (a)* $W_{ep}(c,c) > W_{ep}(c,\bar{c}) > W_{ep}(\bar{c},\bar{c})$, *(b)* $W_{ep}(c,c) > W_{ep}(c) > W_{ep}(\bar{c},\bar{c})$, *where* $\bar{c} \ge \frac{(a+2c)}{2}$ *and (c)* $W_{ep}(c,c) > W_{ep}(c,\alpha\bar{c})$.

Proof: The proof is given in the Appendix C. Q.E.D.

Now, we are in a position to examine the effects of different patent systems on ex-ante welfare. First, consider a situation where in case of unilateral success in R&D, the summation of consumer surplus and total profit in the product market is more under weak patent protection (i.e., $W_{ep}^{wp}(c,\alpha\bar{c}) > W_{ep}^{sp}(c,\bar{c})$ and $W_{ep}^{wp}(c,\alpha\bar{c}) > W_{ep}^{sp}(c)$). Then from the expressions (13) – (15), it is clear that ex-ante welfare can be more under strong patent protection than weak patent protection only if the probability of at least one success in R&D (i.e., $\beta = p_1(x_1)p_2(x_2) + p_1(x_1)(1-p_2(x_2)) + (1-p_1(x_1))p_2(x_2)$), which is the summation of both-success in R&D (i.e., $\gamma = p_1(x_1)p_2(x_2)$) and only one success in R&D (i.e., $\delta = p_1(x_1)(1-p_2(x_2)) + (1-p_1(x_1))p_2(x_2)$), increases under strong patent protection. It is easy to check that probability of at least one success increases under strong patent protection.[9]

Next, consider the situation where ex-post welfare is more under strong patent protection under unilateral success in R&D (i.e., $W_{ep}^{wp}(c,\alpha\bar{c}) < W_{ep}^{sp}(c,\bar{c})$). Since, probability of at least one success is higher under strong patent protection, in this situation, ex-ante welfare will be more under strong patent protection.

Now, we see how the analysis will be affected with more asymmetric changes in R&D investments. As one firm's R&D investment increases, say firm 1's, it reduces the R&D investment of the other firm, i.e., firm 2. From Proposition 1 we know that firm 1's equilibrium R&D investment is more than firm 2 provided firm 1's R&D productivity is more than that of under firm 2 (i.e., $p_1^{'} > p_2^{'}$) and this also implies that the equilibrium probability of success is higher for firm 1 than firm 2 (i.e., $p_1 > p_2$). So, for higher total R&D investment under strong patent protection, it is clear that more asymmetric changes in R&D investments increases the probability of at least one success and probability of only one success in R&D. But, whether this will increase also the probability of both-success is ambiguous. If $\frac{p_1^{'}}{p_2^{'}} > \frac{p_1}{p_2}$, then more asymmetric changes in R&D investment under strong patent protection also increases the probability of both-success. So, if more asymmetric changes in R&D investment does not reduce the probability of both-success significantly we can say that it is more likely that more asymmetric changes in R&D investment increases the likelihood of higher ex-ante welfare under strong patent protection.

Hence, summarizing the above discussion, we can have the following proposition.

Proposition 4: *(a) Since probability of at least one success increases under strong patent protection, it is more likely that ex-ante welfare is higher under strong patent protection. If summation of consumer surplus and industry profit in the product market is higher under strong patent protection then ex-ante welfare is always higher under strong patent protection.*
(b) It is more likely that ex-ante welfare will be higher under strong patent protection with more asymmetric changes in R&D investments.

3 A three-stage game of R&D competition and licensing

[9] We have $d\beta = p_1^{'}(x_1)(1-p_2(x_2))dx_1 + p_2^{'}(x_2)(1-p_1(x_1))dx_2$, $d\gamma = p_1^{'}(x_1)p_2(x_2)dx_1 + p_2^{'}(x_2)p_1(x_1)dx_2$ and $d\delta = p_1^{'}(x_1)(1-2p_2(x_2))dx_1 + p_2^{'}(x_2)(1-2p_1(x_1))dx_2$.

In this section we will extend the analysis of the previous section by allowing the possibility of licensing ex-post R&D and will examine how the results are influenced with this modification. We define a technology by corresponding constant average cost of production and lower constant average cost of production implies better technology.

Technology licensing can take place when there is a difference in technology. Hence, like knowledge spillover, we assume that if both firms succeed or fail in R&D then there is no possibility of licensing ex-post R&D. In this section, following Katz and Shapiro (1985), Marjit (1990), Mukherjee (2001) and many others, we will consider that technology licensing takes place against an up-front fixed-fee.[10] Then, in section 4, we will briefly consider another popular licensing contract, viz., licensing with per-unit output royalty and will examine how the results are affected under this licensing contract compared to fixed-fee licensing contract.

Since technology licensing implies a deliberate knowledge transmission from the technologically superior firm to the technologically inferior firm, it is likely that the amount of knowledge transmission under licensing could be more than that of under knowledge spillover. But, the licenser may decide on the extent of knowledge transmission. However, as noted in Rockett (1990), the licenser will either transfer full knowledge or will not license at all when licensing consists of up-front fixed-fee. Hence, here we consider that in case of licensing complete knowledge transmission will take place and hence, ex-post licensing both firms will produce with same technology.

We consider the following game in this section. In stage one, firm 1 and 2 simultaneously invest in R&D. Outcome of R&D is realized. Then, in stage two, the firms decide whether to do licensing. In our framework, licensing will be an option ex-post R&D provided only one firm succeeds in R&D. In stage three, these firms compete like Cournot duopolists. We solve the game through backward induction. We will consider this game under weak and strong patent protections.

3.1 Technology licensing

Since, licensing acts as a deliberate way of sharing information between the firms, we have to find out when licensing is profitable. Licensing will be profitable provided industry profit under licensing is more than that of under no licensing.

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[10] It is often not possible to monitor a rival firm's output as is necessary to enforce a royalty provision in a patent licensing contract. This may be so for purely informational reasons. Alternatively, this can happen if after getting the licensed technology, the licensee can imitate or invent around the technology easily and produce output with the imitation, thereby avoiding royalty payments. This can be consistent with our assumption of weak and strong patent protections if one assumes that strong patent protection eliminates knowledge spillover but, does not prevent non-infringing inventing around (see Katz and Shapiro, 1985).

Proposition 5: *Suppose the licenser and the licensee have constant average cost c and $\bar{c}$ respectively without licensing and both of them have constant average cost c after licensing. Then licensing is profitable provided $\bar{c} < \frac{(2a+3c)}{5}$.*

Since, this result can be found in Marjit (1990) also, the readers may be referred to Marjit (1990) for the proof of this result. The above proposition shows that if the initial technologies of these firms are sufficiently close then technology licensing can take place. When initial technologies are sufficiently close then, under licensing, the licenser does not face much higher competition from the licensee but licensing helps to increase cost efficiency in the industry. Hence, the gain from cost reduction in licensee's firm outweighs the loss of profit of the licenser. So, licensing increases industry profit. But, if initial technologies are far away then the licenser becomes a near monopoly without licensing. In this situation, the loss of profit to the licenser's firm due to higher competition from the licensee outweighs the gain from cost reduction in licensee's firm. Therefore, if initial technologies of these firms are far away then licensing is not optimal.

From Proposition 5 it is clear that licensing will take place under weak patent protection whenever $\alpha\bar{c} < \frac{(2a+3c)}{5}$ but licensing can take place under strong patent protection when $\bar{c} < \frac{(2a+3c)}{5}$. Therefore, under fixed-fee licensing contract, licensing is more likely outcome under weak patent protection than strong patent protection. Though it looks slightly paradoxical, the reason is very simple. Weak patent protection induces knowledge spillover and hence, reduces the benefit from patent protection. Therefore, this increases the incentive for gaining from information sharing through licensing compared to a situation where higher benefit from patent protection reduces the gains from licensing. Further, this finding provides a testable hypothesis regarding the possibility of licensing in an industry with competing licenser and licensee for different patent systems.

The above proposition has looked at the profitability condition for technology licensing but did not consider the pricing of the technology. We assume that the price for the licensed technology will be decided through a Nash bargaining process. Assume that the bargaining power of the licenser is given by β and the bargaining power of the licensee is given by $(1-\beta)$. Further, we will assume that the bargaining powers of the licenser and the licensee are independent of the identity of these firms, i.e., whether firm 1 or firm 2 acts as licenser or licensee.

Proposition 6: *Assume that the bargaining powers of the licenser and the licensee are β and $(1-\beta)$ respectively. Denote the licensee's constant average cost of production before licensing by z, where $z = \bar{c}$ under no knowledge spillover and $z = \alpha\bar{c}$ under knowledge spillover. Suppose F shows the price of the technology. If firm i licenses to* *firm* j, *where* $i, j = 1,2$ *and* $i \neq j$ *then price of the licensed technology is* $F = \beta(\pi_j(c,c) - \pi_j(c,z)) + (1-\beta)(\pi_i(c,z) - \pi_i(c,c))$.

Proof: See Appendix D for the proof. Q.E.D.

From Proposition 6, it is easy to check that license fee increases with large difference in initial costs, whenever licensing is optimal. Higher cost of production of the licensee reduces the reservation payoff of the licensee, which, in turn, helps the licenser to extract more benefit from licensing through higher license fee.

3.2 Effect of licensing on R&D efforts

Since licensing will occur when the effective cost of the unsuccessful firm is greater than $\frac{(2a+3c)}{5}$, the analysis of the section 2 will not be influenced if cost reduction from R&D is sufficiently large and the degree of knowledge spillover is sufficiently small. In this section we concentrate on those costs and the degree of knowledge spillover such that licensing is an optimal decision at least under weak patent protection.

Hence, we can have the following proposition.

Proposition 7: *(a) Consider that licensing is profitable only under weak patent protection. Then the difference in total R&D investment as well as the asymmetry in R&D investment under weak and strong patent protection declines with the presence of licensing compared to no licensing.*
(b) Consider that licensing is profitable under weak and strong patent systems. Then the difference in total R&D investment as well as the asymmetry in R&D investment under weak and strong patent protection is likely to increase under licensing compared to no licensing.

Proof: Proof of this proposition is given in Appendix E. Q.E.D.

From Proposition 6 it is clear that higher bargaining power of the licenser increases license fee. Since, there is a positive relationship between the license fee and the amount of rightward shift of the reaction functions, higher bargaining power of the licenser is likely to create higher asymmetry in equilibrium R&D investments. Higher bargaining power increases the gain from licensing and encourages both firms to invest more in R&D. But, this will help a firm with more R&D capability to invest more aggressively in R&D compared to a firm with low R&D capability. As a result, higher bargaining power tends to increase the asymmetry in equilibrium R&D investments.

3.3 Effect on welfare

3.3.1 Effect of licensing on ex-post welfare

It is easy to understand that there will be no effect when either both firms succeed in R&D or neither firm succeeds in R&D. Further, even under unilateral success in R&D, the possibility of licensing may have an impact on ex-post welfare when licensing is a profitable option.

If licensing is profitable under both patent systems then it will make both firms symmetric in the product market. Hence, in this situation, the summation of consumer surplus and industry profit in the product market will be same under both patent systems. But, higher license fee under strong patent protection will help to increase total R&D investment under strong patent protection. So, here ex-post welfare is more under weak patent protection.

If licensing is profitable only under weak patent protection then the summation of consumer surplus and industry profit in the product market is given by $W_{ep}(c,c)$ and $W_{ep}(c,\bar{c})$ for weak and strong patent protection respectively. Here, $W_{ep}(c,c) > W_{ep}(c,\bar{c})$ (see Lemma 1). Further, it can be checked easily that here total R&D investment is more under strong patent protection, we can say that here also ex-post welfare is higher under weak patent protection. Hence, the following proposition is immediate.

Proposition 8: *Whenever licensing is privately profitable for at least weak patent protection, ex-post welfare is higher under weak patent protection compared to strong patent protection.*

In Proposition 3, we have seen that for $\bar{c} > \frac{(4a+7c)}{11}$ and for sufficiently low knowledge spillover, ex-post welfare becomes more under strong patent protection compared to weak patent protection. So, contrary to this, Proposition 9 shows that, in this situation, the possibility of licensing can change our qualitative conclusion regarding ex-post welfare and can make higher ex-post welfare under weak patent protection.

3.3.2 Effect of licensing on ex-ante welfare

First, consider the situation where in case of unilateral success in R&D, licensing is profitable under weak and strong patent systems. Hence, in this situation, the summation of consumer surplus and industry profit in the product market is same under both patent systems. But, higher license fee under strong patent protection will lead to higher total R&D investment under strong patent protection. Following the logic of the subsection 2.3.2.2, we see that here the probability of at least one success increases under strong patent protection. Therefore, if the difference in total R&D investment under weak and strong patent protection is not sufficiently large then, in this situation, ex-ante welfare is always higher under strong patent protection.

Now, consider that licensing is privately profitable only under weak patent protection. Here licensing will change the expression for ex-ante welfare from (13) to the following expression:

$$W_{ea}^{wp} = [p_1(x_1^{wp})p_2(x_2^{wp}) + p_1(x_1^{wp})(1-p_2(x_2^{wp})) + (1-p_1(x_1^{wp}))p_2(x_2^{wp})]W_{ep}^{wp}(c,c) \\ + (1-p_1(x_1^{wp}))(1-p_2(x_2^{wp}))W_{ep}^{wp}(\bar{c},\bar{c}) - x_1^{wp} - x_2^{wp}. \tag{16}$$

But, ex-ante welfare under strong patent protection is given by (14) or (15). From Lemma 1(c) and Proposition 7(a) we find that $W_{ep}(c,c)$ is greater than $W_{ep}(c,\alpha\bar{c})$ and $W_{ep}(c,c)$ and the difference in total R&D investment between weak and strong patent protection reduces under licensing compared to no licensing. While the former effect tends to increase the ex-post welfare under weak patent protection for given probability of at least one success, the latter effect reduces the difference between the probability of success under weak and strong patent systems. Thus, here it reduces the likelihood of higher ex-ante welfare under strong patent protection compared to weak patent protection.

We summarize the above discussion in the following proposition.

Proposition 9: *(a) Consider licensing is profitable under both weak and strong patent protections. Then ex-ante welfare is always higher under strong patent protection compared to weak patent protection when the difference in total R&D investments is not sufficiently large between strong and weak patent protections. Hence, here licensing increases the likelihood of higher ex-ante welfare under strong patent protection compared to a situation with no licensing.*
(b) Consider licensing is profitable only under weak patent protection. Then ex-ante welfare is more likely to be higher under weak patent protection under licensing relative to no licensing.

Therefore, unlike the effect on ex-post welfare, the effect of licensing on ex-ante welfare is ambiguous. If the cost reduction from R&D is not sufficiently higher so that, in case of unilateral success in R&D, licensing is a profitable option under both patent systems, the possibility of licensing helps to increase the ex-ante welfare under strong patent protection. But, the possibility of licensing helps to increase ex-ante welfare under weak patent protection when the cost reduction from R&D as well as knowledge spillover is sufficiently large. Thus, cost reduction from R&D becomes important to determine whether the possibility of licensing increases ex-ante welfare under weak patent protection.

4 Licensing with per-unit output royalty

In this subsection, we will briefly examine the importance of another dominant way of licensing, viz., licensing with per-unit output royalty. In fact, without any informational problem or the absence of opportunism on the part of the licensee, this could be the optimal licensing contract (see, Rockett, 1990 and Mukherjee and Balasubramanian, 2001). Further, for simplicity, in this section we will consider that the licenser has full bargaining power, which is enough for our purpose. Hence, it is clear that in this situation, licensing will be privately profitable for all values of $\bar{c} < \frac{(a+c)}{2}$ and the licenser will charge an output royalty $r = (z - c)$ where $z = \alpha\bar{c}$ under weak patent protection and $z = \bar{c}$ under strong patent protection.[11] Hence, licensing does not influence the effective cost of production of the licensee but helps the licenser to increase her profit through royalty income.

Proposition 10: *Royalty income is maximum at $\bar{c} = \frac{(a+3c)}{4}$. Effect of licensing with per-unit output royalty on equilibrium R&D investment will be more under strong patent protection if the cost reduction from R&D is sufficiently low (i.e., $\bar{c} < \frac{(a+3c)}{4}$). But, for not so low cost reduction from R&D and not large degree of knowledge spillover (i.e., $\alpha\bar{c} > \frac{(a+3c)}{4}$) the effect of licensing with per-unit output royalty will be more under weak patent protection. Otherwise, it will depend on the cost reduction from R&D and the degree of knowledge spillover.*

Proof: See Appendix F for the proof. Q.E.D.

As the effective cost of the firms are same under both the patent systems, it is clear that the summation of consumer surplus and industry profit in the product market except royalty income will be same under licensing and no licensing. The analysis without licensing (see subsection 2.3.2.1) shows that ex-post welfare is always higher under weak patent protection for $\bar{c} < \frac{(4a+7c)}{11}$ where $\frac{(a+3c)}{4} < \frac{(4a+7c)}{11}$. We know that royalty income is more under strong patent protection for $\bar{c} < \frac{(a+3c)}{4}$. Hence, for $\bar{c} < \frac{(a+3c)}{4}$, higher royalty income under strong patent protection reduces the likelihood of higher ex-post welfare under weak patent protection compared to a situation with no licensing if licensing does not increase sufficiently large asymmetry in total R&D investments under these patent systems.

If cost reduction from R&D is sufficiently large and the degree of knowledge spillover is not sufficiently large then we have seen in subsection 2.3.2.1 that ex-post welfare can be higher under strong patent protection. However, royalty income is more

[11] This assumes that up-front fixed-fee cannot be negative (see, e.g., Rockett, 1990 and Mukherjee and Balasubramanian, 2001).

under weak patent protection for $\bar{c} > \frac{(a+3c)}{4}$. Hence, for $\bar{c} > \frac{(a+3c)}{4}$, higher royalty income under weak patent protection reduces the likelihood of higher ex-post welfare under strong patent protection compared to a situation with no licensing if licensing does not increase sufficiently large asymmetry in total R&D investments under these patent systems. Hence, whether licensing with per-unit output royalty increases or reduces the likelihood of higher ex-post welfare under weak patent protection may depend on the cost of reduction from R&D and the degree of knowledge spillover.

When cost reduction from R&D is sufficiently low (i.e., $\bar{c} < \frac{(a+3c)}{4}$) then the effect of licensing on the R&D investment is more under strong patent protection, as here royalty income is higher under strong patent protection. This tends to raise the probability of success in R&D under strong patent protection compared to weak patent protection. Further, in case of unilateral success in R&D, higher royalty income under strong patent protection increases the summation of consumer surplus and industry profit in the product market. Thus, both these effects under licensing make ex-ante welfare more likely to be higher under strong patent protection compared to no licensing. But, for $\bar{c} > \frac{(a+3c)}{4}$, royalty income is higher under weak patent protection compared to strong patent protection. Hence, in this situation, the effect of licensing on R&D investment as well as the higher summation of consumer surplus and industry profit in the product market increases under weak patent protection. Thus, here ex-ante welfare more likely to be higher under weak patent protection with licensing compared to no licensing.

The following proposition summarizes the above discussion.

Proposition 11: *Consider licensing with per-unit output royalty compared to no licensing. For sufficiently (not sufficiently) low cost reduction from R&D (i.e.,* $\bar{c} < (>) \frac{(a+3c)}{4}$*), ex-ante and ex-post welfare are less (more) likely to be higher under weak patent protection compared to strong patent protection.*

From Propositions 8 – 11, we can have following conclusion showing the difference of these two licensing contracts on R&D investment and social welfare.

Corollary 1: *Effect of licensing on R&D investment and ex-ante welfare depends on the type of licensing contract and if the cost reduction from R&D is moderate (i.e.,* $\bar{c} \in (\frac{(a+3c)}{4}, \frac{(2a+3c)}{5})$*). Here, both higher impact of licensing on R&D investment and the likelihood of higher ex-ante welfare under strong (weak) patent protection is more if licensing involves up-front fixed-fee (per-unit output royalty).*

5 Conclusion

In a Cournot duopoly, we take a fresh look on the effect of different patent systems on R&D investments and social welfare. Further, we examine how the results are influenced with the existence of different types of licensing.

Whether strong patent protection increases R&D investment of both firms is ambiguous. However, R&D investment of at least one firm is higher under strong patent protection than weak patent protection. Thus, this paper provides a testable hypothesis for examining the effects of different patent systems on the firm level R&D investment. Without any possibility of licensing, whether ex-post welfare will be more under weak and strong patent protection is also ambiguous. However, in this situation, ex-ante welfare is likely to be higher under strong patent protection.

If licensing contract ex-post R&D consists of up-front fixed-fee only then the effect of licensing on R&D investment is higher under strong patent protection whenever licensing is profitable under both patent systems. But, if licensing is privately profitable only under weak patent protection then it reduces the difference in total R&D investment between weak and strong patent protections. While a profitable licensing contract makes the ex-post welfare more likely to be higher under weak patent protection, the possibility of licensing makes ex-ante welfare more likely to be higher under strong (weak) patent protection whenever licensing is profitable under both patent systems (under only weak patent system).

The results could be changed if licensing consists of per-unit output royalty only. Whether royalty income is higher under weak patent protection depends on the cost reduction from R&D as well as on the degree of knowledge spillover. While for sufficiently low cost reduction from R&D, the effect of this type of licensing on R&D investment is more under strong patent protection, the effect of licensing will be more under weak patent protection when cost reduction from R&D is sufficiently large and the degree of knowledge spillover is sufficiently small. Unlike fixed-fee licensing contract, ex-post welfare is likely to be higher under strong patent protection when cost reduction from R&D is sufficiently small, but ex-ante welfare is likely to be higher under weak patent protection when cost reduction is not sufficiently small.

Appendix

A Proof of Proposition 1: (a) Taking total differential of (4) and (5), we find the reaction function of the ith firm either as

$$\frac{dx_i}{dx_j} = -\frac{p_i'(x_i)p_j'(x_j)H}{p_i''(x_i)(\pi_i(c,\alpha\bar{c}) - \pi_i(\bar{c},\bar{c})) + p_i''(x_i)p_j(x_j)H}, \tag{A.1}$$

where $H = \pi_i(c,c) + \pi_i(\bar{c},\bar{c}) - \pi_i(c)$

or, as

$$\frac{dx_i}{dx_j} = -\frac{p_i'(x_i)p_j'(x_j)G}{p_i''(x_i)(\pi_i(c,\alpha\bar{c}) - \pi_i(\bar{c},\bar{c})) + p_i''(x_i)p_j(x_j)G}, \tag{A.2}$$

where $G = \pi_i(c,c) + \pi_i(\bar{c},\bar{c}) - \pi_i(c,\alpha\bar{c}) - \pi_i(\alpha\bar{c},c)$, $i, j = 1,2$ and $i \neq j$. We know that the denominator of (A.1) and (A.2) are negative due to the second order condition of maximization. Further, it is easy to check that both H and G are negative. Hence, the reaction functions are negative. Further, straightforward calculation shows that the absolute value of the reaction functions is less than 1.

(b) The proof is by contradiction. Consider the first order conditions of these firms mentioned above with $p_i' > p_j'$. Assume that in equilibrium $x_i = x_j$ and the first order condition is satisfied for firm j. Then it is easy to see that in this case the marginal benefit for firm i is higher than the marginal cost (i.e., the left hand side is greater than the right hand side for firm i). Therefore, for this value of x_j, the profit maximizing R&D investment will be higher for firm i. Hence, we can say that the reaction function of firm i will be to the right of point $x_i = x_j$ when x_j is on the reaction function of firm j. Since, the reaction functions are negatively sloped with an unique equilibrium, this proves the result.

Since, equilibrium R&D investment of firm i is more than firm j and $p_i' > p_j' > 0$, the probability of success for firm i will be more than firm j in equilibrium. Q.E.D.

B Proof of Proposition 3: (a) If in case of unilateral success in R&D the successful firm becomes a monopoly then the analysis in section 2.3.1 shows that total R&D investment will be same under both patent systems. Hence, here ex-post welfare will be same under both patent systems irrespective of the number of firms succeed in the R&D.

(b) If either both firms succeed or neither firm succeeds in R&D then both firms will operate with same marginal costs of production. Since, we consider a situation where the successful firm cannot be a monopoly in case of unilateral success in R&D, the analysis in the subsection 2.3.1 shows that here total R&D investment will be more under strong patent protection. Hence, here ex-post welfare will be more under weak patent protection.

(c) From (10) we find that

$$\frac{\partial W_{ep}^{wp}}{\partial(\alpha\bar{c})} = -\frac{(4a - 11\alpha\bar{c} + 7c)}{9} \quad \text{and} \quad \frac{\partial^2 W_{ep}^{wp}}{\partial(\alpha\bar{c})^2} = \frac{11\alpha\bar{c}}{9} > 0. \tag{B.1}$$

Therefore, W_{ep}^{wp} reaches minimum at $\alpha\bar{c} = \frac{(4a+7c)}{11}$. First, consider that $\bar{c} < \frac{(a+c)}{2}$. Therefore, in this case both firms compete in the product market irrespective of the patent systems. We know that $\alpha\bar{c} \in [c, \bar{c}]$. From (10) and (11) we see that $W_{ep}^{wp}(\alpha\bar{c} = c) > W_{ep}^{sp}$ and $W_{ep}^{wp}(\alpha\bar{c} = \bar{c}) = W_{ep}^{sp}$. Hence, we find that if $\bar{c} < \frac{(4a+7c)}{11}$ then $W_{ep}^{wp} > W_{ep}^{sp}$ for all $\alpha\bar{c} \in [c, \bar{c})$. Total higher R&D investment under strong patent protection reinforces this effect. Therefore, welfare under weak patent protection is more than that of under strong patent protection for all degrees of knowledge spillover when cost reduction from R&D is not sufficiently large.

Since, W_{ep}^{wp} as convex, quadratic and continuous over $\alpha\bar{c} \in [c, \bar{c}]$ with $W_{ep}^{wp}(\alpha\bar{c} = c) > W_{ep}^{sp}$ and $W_{ep}^{wp}(\alpha\bar{c} = \bar{c}) = W_{ep}^{sp}$, we can say that for $\bar{c} > \frac{(4a+7c)}{11}$ there is a value of α, say α^*, such that $\forall \alpha < \alpha^*$, $W_{ep}^{wp} > W_{ep}^{sp}$ and $\forall \alpha > \alpha^*$, $W_{ep}^{wp} < W_{ep}^{sp}$. Total higher R&D investment under strong patent protection helps further to increase ex-post welfare under weak patent protection. Hence, we find that even if cost reduction from R&D is sufficiently large then ex-post welfare is higher under weak patent protection when knowledge spillover is sufficiently large. But, for sufficiently large cost reduction from R&D and sufficiently low knowledge spillover, ex-post welfare is likely to be higher under strong patent protection.

Next, consider that $\bar{c} \geq \frac{(a+c)}{2}$ but, $\alpha\bar{c} < \frac{(a+c)}{2}$. So, here the unsuccessful firm cannot compete in the market under strong patent protection but can compete under weak patent protection. From (10) and (12) we find that $W_{ep}^{wp}(\alpha\bar{c} = c) > W_{ep}^{sp}$ and $W_{ep}^{wp}(\alpha\bar{c} = \frac{(a+c)}{2}) = W_{ep}^{sp}$. Since, W_{ep}^{wp} is convex, quadratic and continuous over $\alpha\bar{c} \in [c, \frac{(a+c)}{2}]$ with a minimum at $\alpha\bar{c} = \frac{(4a+7c)}{11}$, we can say that weak (strong) patent protection provides larger amount of consumer surplus plus industry profit in the product market provided degree of knowledge spillover is sufficiently large, say $\alpha < (>) \alpha^c$. Therefore, higher ex-post welfare is more (likely to be more) under weak (strong) patent protection for $\alpha < (>) \alpha^c$. This proves the result. Q.E.D.

C Proof of Lemma 1: We have

$$W_{ep}(c,c) = \frac{(a-c)^2}{9} + \frac{(a-c)^2}{9} + \frac{(2a-2c)^2}{18}$$
$$W_{ep}(c,\bar{c}) = \frac{(a-2c+\bar{c})^2}{9} + \frac{(a-2\bar{c}+c)^2}{9} + \frac{(2a-c-\bar{c})^2}{18}$$
$$W_{ep}(\bar{c},\bar{c}) = \frac{(a-\bar{c})^2}{9} + \frac{(a-\bar{c})^2}{9} + \frac{(2a-2\bar{c})^2}{18}$$
$$W_{ep}(c) = \frac{(a-c)^2}{4} + \frac{(a-c)^2}{8}$$

and $W_{ep}(c,\alpha\bar{c}) = \frac{(a-2c+\alpha\bar{c})^2}{9} + \frac{(a-2\alpha\bar{c}+c)^2}{9} + \frac{(2a-c-\alpha\bar{c})^2}{18}$.

Direct comparison of the above expressions proves the results. Q.E.D.

D Proof of Proposition 6: In case of licensing the average cost of production of the licensee will be c after licensing. Hence, the ith firm, as the licenser will maximize the following objective function while determining the price of the technology:

$$\underset{F}{Max}(\pi_i(c,c) + F - \pi_i(c,z))^{\beta}(\pi_j(c,c) - F - \pi_j(c,z))^{(1-\beta)},\ i,j = 1,2, i \neq j. \quad \text{(D.1)}$$

Maximizing (D.1) we find that $F = \beta(\pi_j(c,c) - \pi_j(c,z)) + (1-\beta)(\pi_i(c,z) - \pi_i(c,c))$. Second order condition for maximization is satisfied. Q.E.D.

E Proof of Proposition 7: (a) First, consider a situation where licensing is optimal under weak patent protection but not under strong patent protection, i.e., $\alpha\bar{c} < \frac{(2a+3c)}{5}$ and $\bar{c} > \frac{(2a+3c)}{5}$. Therefore, here the possibility of licensing will affect the reaction functions under weak patent protection only. So, the equilibrium R&D investments under strong patent protection will be same as it was without the possibility of licensing, i.e., by the first order conditions (8) or (9). However, with the possibility of licensing, the net profit of the i th firm under weak patent protection will be

$$p_i(x_i)p_j(x_j)\pi_i(c,c)+p_i(x_i)(1-p_j(x_j))(\pi_i(c,c)+F_w)+(1-p_i(x_i))p_j(x_j)(\pi_i(c,c)-F_w)$$
$$+(1-p_i(x_i))(1-p_j(x_j))\pi_i(\bar{c},\bar{c})-x_i, \qquad i,j=1,2,\ i\neq j, \qquad \text{(E.1)}$$

since $\alpha\bar{c}<\frac{(2a+3c)}{5}$ and F_w shows the licensing fee under weak patent protection. Therefore, the reaction function for R&D investment of the ith firm is given by

$$p_i'(x_i)p_j(x_j)\pi_i(c,c)+p_i'(x_i)(1-p_j(x_j))(\pi_i(c,c)+F_w)-p_i'(x_i)p_j(x_j)(\pi_i(c,c)-F_w)$$
$$-p_i'(x_i))(1-p_j(x_j))\pi_i(\bar{c},\bar{c})=1, \qquad i,j=1,2,\ i\neq j. \qquad \text{(E.2)}$$

So, in case of weak patent protection, both the reaction functions for R&D investment shift rightward under licensing compared to no licensing (compare the expressions (5) and (E.2)). However, like the subsection 2.3.1, it is not clear whether this possibility will increase the equilibrium R&D investment of both firms. If the probability functions are sufficiently different then the possibility of licensing will increase the equilibrium R&D investment of one firm only. However, we can say that total R&D investment under weak patent protection will be more under licensing compared to no licensing. Hence, given that the total R&D investment under weak patent protection increases with the possibility of licensing compared to no licensing, the difference in R&D investments between weak and strong patent protections reduces with the availability of licensing.

(b) Now, we look at the situation where licensing is optimal under weak and strong patent protections, i.e., $\bar{c}<\frac{(2a+3c)}{5}$. Following the previous argument, we can say that here the reaction functions of both firms shift rightward under both patent systems. Therefore, it is not clear whether the possibility of licensing will increase both firms' R&D investment for corresponding patent system. However, from Proposition 6, it is clear that license fee increases as the cost difference between the licenser and licensee increases. This implies that the license fee will be higher under strong patent protection compared to weak patent protection. Since, there is a positive relationship between the rightward shifts of the reaction functions and the license fee, it is likely that the difference in total R&D investment and asymmetry in R&D investment under strong and weak patent protection tends to increase with the possibility of licensing. Q.E.D.

F Proof of Proposition 10: The royalty income of the licenser will be $R=\frac{(z-c)(a-2z+c)}{3}$, as with the per-unit output royalty $r=(z-c)$, the optimal output of the licensee will be $\frac{(a-2z+c)}{3}$. The royalty income reaches maximum at $\frac{(a+3c)}{4}$ where $\frac{(a+3c)}{4}<\frac{(a+c)}{2}$.

This extra gain from royalty income will encourage both firms to invest more in R&D, given the R&D investment of the competitor. Hence, if cost reduction from R&D

is sufficiently small (i.e., $\bar{c} < \frac{(a+3c)}{4}$) then royalty income will be higher under strong patent protection. But, for not sufficiently small cost reduction from R&D and with sufficiently low knowledge spillover (i.e., $\alpha\bar{c} > \frac{(a+3c)}{4}$) royalty income will be higher under weak patent protection. Otherwise, it depends on the cost reduction from R&D and the degree of knowledge spillover. Following the analysis of section 3, we can say that the impact on equilibrium R&D investment will be more with higher royalty income. Hence, this proves the result. Q.E.D.

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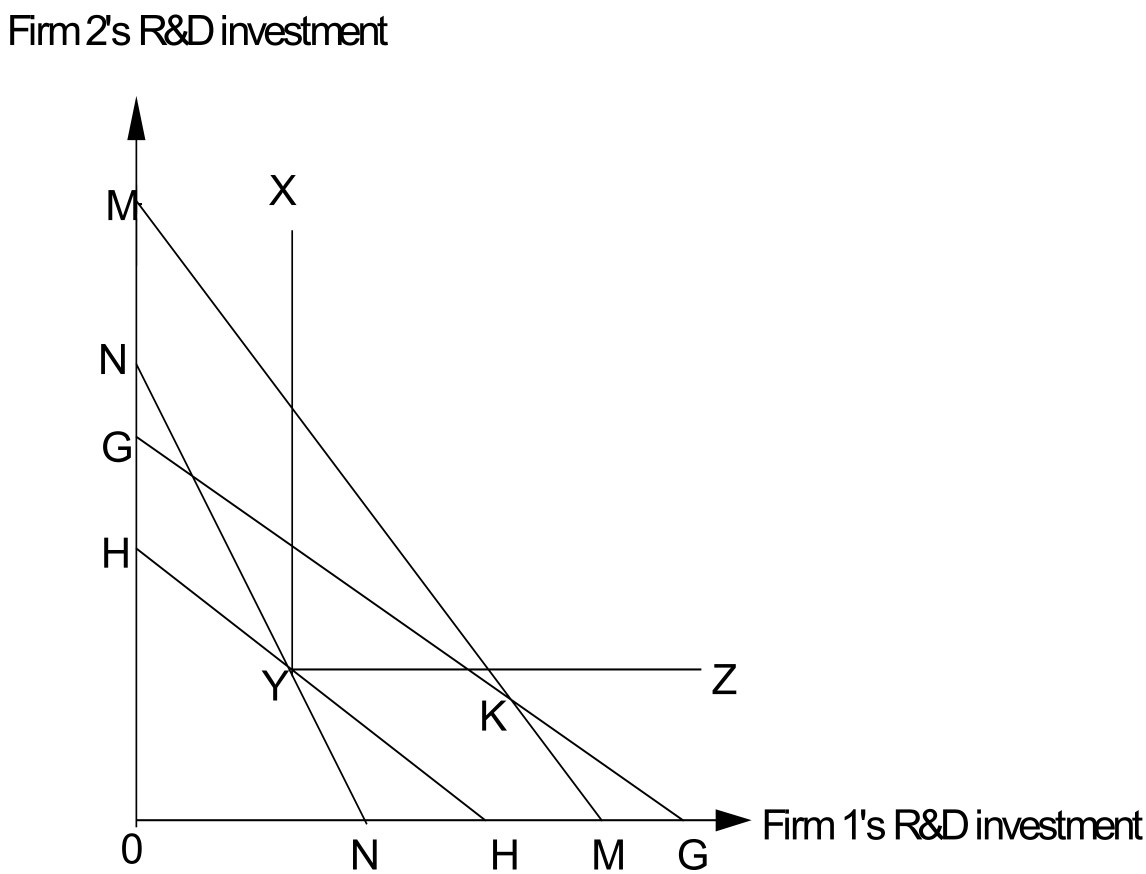

Figure 1

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