Department of Economics

Issn 1441-5429

Discussion paper 26/09

On the impact of piracy on innovation in the presence of technological and market uncertainty

Dyuti Banerjee[*] and Ishita Chatterjee[†]

Abstract:

This paper analyses the effect of piracy on innovation in the presence of R&D competition with technological and market uncertainty. With a single innovating firm facing technological uncertainty, piracy unambiguously retards innovation. However, with R&D competition where firms face market and technological uncertainties, we show that piracy may enhance overall innovation. We also show that if the difference between the probabilities of success of the innovating firms is relatively large then piracy enhances the R&D investment and profit of the less efficient firm.

JEL Classification: D21, D43, L13, L21, L26, O3.

Keywords: Innovation, market uncertainty, R&D race, technological uncertainty

[*] Department of Economics, Monash University, Clayton, VIC 3800, Australia.
Email: dyuti.banerjee@buseco.monash.edu.au. **Corresponding author.**
[†] Department of Economics, Monash University, Clayton, VIC 3800, Australia.
Email: ishita.chatterjee@buseco.monash.edu.au.

The authors thank Kunal Sengupta and participants in the Australian Conference of Economists, 2009, for valuable comments. The usual disclaimer applies.

1. Introduction:

In this paper we analyse the impact of piracy on innovation, especially in the digital industry, when innovation is associated with both technological and market uncertainties[1]. The literature on piracy and innovation only looks at the technological uncertainty aspect of innovation where the R&D investment of a firm materialises into a new product with some probability. However, innovation also has a market uncertainty aspect when multiple firms compete simultaneously to develop a new product but the success of a firm in patenting its product is stochastic. We attempt to bridge this gap and bring together these two strands of the literature.

Piracy has generally been perceived as having a damaging influence on software and media industry sectors that have high information and digital content since such products can be copied at a low cost (Marshall, 1999; Straub and Nance, 1990). This issue assumes importance not only because of the high magnitude of immediate loss in retail sale but also of its possible detrimental effects on the incentive to innovate. Business Software Alliance (BSA) believes that “local software industries crippled from competition with high-quality pirated software” and International Federation of the Phonographic Industry (IFPI) in its 2005 Commercial Piracy Reports argues that “the illegal music trade is destroying creativity and innovation”[2]. In an empirical study, Ding and Liu (2009) show that under weak IPR regimes piracy dissuades the legal firms to continue research on the development of new technologies. Park and Ginarte (1996) also supports this observation.

In this paper we show that piracy unambiguously retards the incentive to innovate and has adverse effects on profit if there is a single innovating firm facing technological uncertainty. However, if we introduce R&D competition that creates

[1] The terms technological uncertainty and market uncertainty have been introduced by Shy (2000).
[2] BSA in their 2005 Piracy Study claims US$34 billion in worldwide losses. BSA further projects that in the next five years almost US$200 billion worth of software will be pirated globally.

market uncertainty along with technological uncertainty then piracy may result in a higher level of R&D investment and profit of a firm. This follows from the fact that piracy lowers the competing firms' reaction functions with respect to the level of R&D investment. The equilibrium R&D investment in the presence of piracy thus depends on the relative size of the shifts in the reaction functions. We also show that if the difference between the probabilities of success of the innovating firms is relatively large then piracy enhances the R&D investment and profit of the firm with the lower probability of success.

The literature addressing the impact of piracy on innovation focuses on single innovating firm and show that piracy can have both detrimental and beneficial impact on innovation. Novos and Waldman (1984) show that increases in copyright protection could increase social welfare loss due to underproduction. Qiu (2006) shows that, if copyright protection is weak, software is not developed for general use but only for custom demands. Jaisingh (2009) shows that stricter regulatory enforcement policies raise the legitimate product quality which can be used as a measure of innovation.

A beneficial aspect of piracy can be in the form of providing insight into emerging market trends and specific consumer requirements. Easley et al. (2003) empirically show that the presence of piracy in the music industry induces firms to develop internet technologies and electronic modes of distributing music files.[3] Connor and Rumelt (1991) show that piracy can be a channel of advertising the legal product directed at target consumers.

[3] The gaming company Valve Software, when hackers used their Half Life game engine to develop a game called Counter Strike, Valve took the illegal game software and marketed it themselves, selling over 1.5 million copies (Barnes, 2005). Apple Computer, in a strategic reaction to P2P file sharing technologies, launched the iTunes online music library that was easy to navigate and explore, with free music previews, and allowed flexible download and copying for personal use. See Choi and Perez (2007) for anecdotal evidences on legal firms adopting technologies used by illegal P2P file sharers.

Piracy can also generate a positive feedback effect on innovation with the pirate modifying and improving on the original product thereby inducing further innovation by the legitimate firms (Kolm 2006; Harbi and Grolleau, 2008).[4] In such situations, the legal producers sometimes do not insist on severe punishments against pirates (Barnett, 2005; Barnett et al., 2008; Raustila and Sprigman, 2006).

The above literature, to the best of our knowledge, has not looked at R&D competition between innovating firms. The closest work in the spirit of our paper is by Shapiro (2006) who models simultaneous and independent inventions, in the context of prior rights, when two firms successfully realize the targeted innovation, but only one file for the patent.

There are incentive and strategic relations between patent race and innovation. Incentive relation points at the positive two-way causal relation between patents and innovations. That is, a change in patenting cost has a direct effect on the incentive to innovate and applications for patents and vice versa. So in this case R&D and patents are treated as complements in the production process.[5] Hunt (2006) shows that in the presence of R&D competition and costless imitation, reduction of patent costs may lower R&D activity under certain conditions.[6] Kultti et al. (2006) observes that too much patent race reduces innovation[7].

Strategic relations involve firms using patents to deter entry of competing firms. This literature treats R&D and patents as strategic substitutes. In a study on the computer industry in the U.S., Bessen and Hunt (2003) show that lowering of patent

[4] This is especially true for design based industries where being pirated is a signal of the high quality of the legal product, and products which ‘are not faked are considered too weak to generate consumer demand and are consequently not produced’ (WhiteHall, 2006). Ritson (2007) says that pirated goods are indicative of heralding a brand’s renaissance and a brand dies if no copies appear in the market.

[5] See Maurer and Scotchmer (2002) for a review.

[6] This ‘counterintuitive’ phenomenon can be observed in industries that are highly technology intensive such as, semiconductors, electronics and computers (Hunt 2004, 2006).

[7] Cohen et al. (2000) and Gallini (2002) suggest secrecy is a better strategy than patents in protecting innovation and the role of patents lie in encouraging information disclosure rather than R&D investments.

standards raises firms' propensities to file for more patents. In this paper we try to link the literature on patent race and innovation to that on innovation and piracy.

This paper is arranged as follows. In Section 2 we present the model with a single innovating firm. In Section 2 we present the model with single innovating firm. In Section 3 we introduce R&D competition. In section 4 we present an example using specific functional form and Section 5 contains the concluding remarks.

2. The model

Let us consider the market for a product like software that faces piracy. We first consider the case where there is only one firm investing in R&D technology in order to increase its profit over and above a reservation level, $\overline{\pi}_i$. For simplicity we assume $\overline{\pi}_i = 0$. Let R_i be the R&D investment of a firm F_i, and the probability that F_i is successful in developing the product is $k_i \alpha(R_i)$ with the properties $\alpha'(R_i) > 0$ and $\alpha''(R_i) < 0$.[8] k_i can be viewed as the R&D efficiency parameter.

There is a continuum of consumers indexed by $\theta, \theta \in [0,1]$. θ is assumed to follow a uniform distribution. We assume there is no resale market for used software. Each consumer is assumed to purchase only one unit of the software. The utility of a type-θ consumer is,

$$U(\theta) = \begin{cases} \theta - p_m & \textit{if the consumer buys the software,} \\ 0 & \textit{if the consumer does not buy.} \end{cases} \tag{1}$$

θ is the consumer's valuation of the software and p_m is the price of one unit of the software. Thus, in the model, consumers differ from one another on the basis of their valuation of the software. θ_m is the marginal consumer who is indifferent between buying and not buying:

[8] These properties ensure that the second order condition for profit maximization hold.

$$U(\theta_m) = \theta_m - p_m = 0 \Rightarrow \theta_m = p_m . \tag{2}$$

From equation (2) we get the demand function as,

$$D(p_m) = \int_{\theta_m}^{1} d\theta = 1 - p_m . \tag{3}$$

So F_i's expected profit is,

$$E\pi_i = k_i \alpha(R_i)(1 - p_m) p_m - R_i \tag{4}$$

F_i's realised profit conditional on successful innovation, is the monopoly profit, $r_i^* = \frac{1}{4}$. So the expected profit is, $E\pi_i = \frac{k_i \alpha(R_i)}{4} - R_i$. The first order condition for maximization yields $\frac{\partial E\pi_i}{\partial R_i} = 0 \Rightarrow \alpha'(R_i) = \frac{4}{k_i}$. The results for the equilibrium R&D investment and the expected profit denoted as R_i^* and $E\pi_i^*$ is summarised in Lemma 1 and the proof is given in the Appendix.

Lemma 1. *R_i^* satisfies $\alpha'(R_i^*) = \frac{4}{k_i}$ and $E\pi_i^* = \frac{k_i \alpha(R_i^*)}{4} - R_i^*$. R_i^* and $E\pi_i^*$ are increasing in k_i and $k_i \geq \frac{4R_i^*}{\alpha(R_i^*)}$.ensures non-negative profit.*

Let us now introduce piracy in the model. In the first stage F_i chooses a level of R&D investment R_i and in the second stage engages in price competition with the commercial pirate who sells illegal copies of F_i's product.

With the availability of the pirated product, a consumer can either purchase F_i's product or the pirated product or nothing. Let q denote the quality of the pirated product which is common knowledge and we assume $q \in (0,1)$.[9] The utility of a type-θ consumer is as follows.

[9] See Banerjee (2003) and Takeyama (1998) for more on the assumption that the legitimate and the pirated products are imperfect substitutes which is captured by the parameter *q*.

$$U(\theta) = \begin{cases} \theta - p_m, & \textit{if the consumer buys the original software,} \\ q\theta - p_c, & \textit{if the consumer buys the pirated software,} \\ 0 & \textit{if the consumer does not buy.} \end{cases} \tag{5}$$

$q\theta$ is the type-θ consumer's effective valuation of the pirated software. p_m and p_c are the prices of the legitimate and the pirated software.

The marginal consumer indifferent between purchasing the legitimate product from F_i and the pirated product copy is denoted as θ_{cm} and it satisfies,

$\theta_{cm} - p_m = q\theta_{cm} - p_c \Rightarrow \theta_{cm} = \dfrac{p_m - p_c}{1-q}$. The marginal consumer indifferent between purchasing the pirated product and not buying anything, denoted as θ_{c0}, satisfies,

$q\theta_{c0} - p_c = 0 \Rightarrow \theta_{c0} = \dfrac{p_c}{q}$. Using the expressions for θ_{cm} and θ_{c0} we get the demand functions for the legitimate and the pirated products as follows.

$$\begin{aligned} D_m(p_m, p_c, q) &= \int_{\theta_{cm}}^{1} d\theta = 1 - \theta_{cm} = 1 - \frac{p_m - p_c}{1-q} \\ D_c(p_m, p_c, q) &= \int_{\theta_{c0}}^{\theta_{cm}} d\theta = \theta_{cm} - \theta_{c0} = \frac{qp_m - p_c}{q(1-q)} \end{aligned} \tag{6}$$

The expected profit of F_i and the pirate are,

$$\begin{aligned} E\pi_i &= k_i\alpha(R_i)r_i - R_i, \\ E\pi_c &= k_i\alpha(R_i)\left(\frac{qp_m p_c - p_c{}^2}{q(1-q)}\right), \end{aligned} \tag{7}$$

where $r_i = p_m D_m = p_m - \dfrac{p_m^2 - p_m p_c}{1-q}$ is the realized stage 2 profit of F_i conditional on successful innovation in stage 1. The pirate can compete with F_i only if the latter is successful in innovation.

We solve for the game using the method of backward induction. In stage 2 of the game, F_i and the pirate competes in price. The reaction functions are

$p_m = \frac{1-q+p_c}{2}$ and $p_c = \frac{qp_m}{2}$. Solving the reaction functions yield the equilibrium prices and F_i's realised second stage profit which are,

$$p_m^{**} = \frac{2(1-q)}{4-q},\ p_c^{**} = \frac{q(1-q)}{4-q}, \text{ and } r_i^{**} = \frac{4(1-q)}{(4-q)^2}. \tag{8}$$

Substituting the expressions in (8) in F_i's expected profit function in equation (7) and differentiating with respect to R_i and equating to zero yields the equilibrium R&D investment, denoted as R_i^P, and the equilibrium expected profit of F_i, denoted as $E\pi_i^P$.The results are summarized in Lemma 2 and the proof is in the Appendix.

Lemma 2. *The equilibrium R&D investment and the expected profit of F_i satisfies,* $\alpha'(R_i^P) = \frac{1}{k_i r_i^{**}}$ and $E^P\pi_i = k_i\alpha(R_i^P)r_i^{**} - R_i^P$. R_i^P *and* $E\pi_i^P$ *are increasing in k_i and decreasing in q.* $k_i \geq \frac{R_i^P}{\alpha(R_i^P)r_i^{**}}$ *ensures non-negative profit.*

From Lemma 2 we observe that an improvement in the quality of the pirated software reduces a firm's incentive to innovate. Let us now compare the R&D levels with and without piracy to have an understanding of the impact of piracy on the incentive to innovate when there is a single innovating firm facing technological uncertainty. This leads us to Proposition 1.

Proposition 1. *Piracy reduces the incentive to innovate when there is a single innovating firm.*

Proof of Proposition 1. $\alpha'(R_i^*) - \alpha'(R_i^P) = \frac{-(8q+q^2)}{k_i r_i^{**}(4-q)^2} = \frac{-q(8+q)}{4k_i r_i^{**}(1-q)} < 0.$ Since $\alpha'(R_i) > 0$ and $\alpha''(R_i) < 0$ it implies $R_i^* - R_i^P > 0$ for all $k_i > 0$ because by assumption, $q \in (0,1)$. *Q.E.D.*

3. R&D race and piracy

Let us now introduce R&D competition between two firms F_1 and F_2. Hereafter, we will refer to this as R&D race and denote it as the *R-game*. In stage one the firms compete in R&D investment and the winner of the race receives the patent and is the monopolist in stage 2. So in stage 2 the winner of the R&D race faces the demand function as given in equation (3) and the stage 2 realized monopoly profit is $r_i^* = \frac{1}{4}$.

A firm can win the race if it is successful in innovation and the rival firm is unsuccessful or if both firms are successful then each firm receives the patent with equal probability. So the probability of F_i $i = 1, 2,$ receiving the patent is,

$$\mu_i(R_i, R_j) = k_i\alpha(R_i)(1 - k_j\alpha(R_j)) + \frac{k_i\alpha(R_i)k_j\alpha(R_j)}{2}, i.j = 1,2, i \neq j. \tag{9}$$

Hence, the expected profit of F_i $i = 1, 2,$ is

$$E\pi_i = \left(k_i\alpha(R_i)(1 - k_j\alpha(R_j)) + \frac{k_i\alpha(R_i)k_j\alpha(R_j)}{2} \right) r_i^* - R_i,\ i, j = 1,2,\ i \neq j. \tag{10}$$

The first order conditions yield,

$$\frac{\partial E\pi_i}{\partial R_i} = k_i\alpha'(R_i)\left(1 - \frac{k_j\alpha(R_j)}{2}\right) r_i^* - 1 = 0 \Rightarrow k_i\alpha'(R_i)(2 - k_j\alpha(R_j)) = \frac{2}{r_i^*}, \tag{11}$$

$$\frac{\partial E\pi_j}{\partial R_j} = k_j\alpha'(R_j)\left(1 - \frac{k_i\alpha(R_i)}{2}\right) r_j^* - 1 = 0 \Rightarrow k_j\alpha'(R_j)(2 - k_i\alpha(R_i)) = \frac{2}{r_j^*}. \tag{12}$$

Let (R_i^R, R_j^R) be the solution to equations (11) and (12).

Let us now consider R&D race in the presence of piracy. We will denote this as the *RP-game*. In stage 1 of the game two firms F_1 and F_2 compete in R&D investment. The winner of the patent competes in price with the commercial pirate in stage 2. The probability that a firm F_i wins the patent is the same as in equation (9).

The utility function and the demand functions facing the winner of the patent and the pirate are the same as given in equations (5) and (6). So the realised stage 2 profit of the winner of the R&D race is $r_i^{**} = \dfrac{4(1-q)}{(4-q)^2}$ as given in equation (8). The expected profit of F_i is,

$$E\pi_i = \left(k_i\alpha(R_i)(1-k_j\alpha(R_j)) + \frac{k_i\alpha(R_i)k_j\alpha(R_j)}{2} \right) r_i^{**} - R_i,\ i,j = 1,2,\ i \neq j. \tag{13}$$

The first order conditions yield,

$$\frac{\partial E\pi_i}{\partial R_i} = k_i\alpha'(R_i)\left(1 - \frac{k_j\alpha(R_j)}{2}\right) r_i^{**} - 1 = 0 \Rightarrow k_i\alpha'(R_i)(2-k_j\alpha(R_j)) = \frac{2}{r_i^{**}}, \tag{14}$$

$$\frac{\partial E\pi_j}{\partial R_j} = k_j\alpha'(R_j)\left(1 - \frac{k_i\alpha(R_i)}{2}\right) r_j^{**} - 1 = 0 \Rightarrow k_j\alpha'(R_j)(2-k_i\alpha(R_i)) = \frac{2}{r_j^{**}}. \tag{15}$$

Let (R_i^{RP}, R_j^{RP}) be the solution to equations (14) and (15). [10]

Now $r_i^{**} = r_j^{**} = \dfrac{4(1-q)}{(4-q)^2} < r_i^* = r_j^* = \dfrac{1}{4}$. Hence, $\dfrac{2}{r_i^{**}} = \dfrac{2}{r_j^{**}} > \dfrac{2}{r_i^*} = \dfrac{2}{r_j^*}$.

Dividing equation (14) by (11) we get at the optimum,

$$\frac{k_i\alpha'(R_i^{RP})(2-k_j\alpha(R_j^{RP}))}{k_i\alpha'(R_i^{R})(2-k_j\alpha(R_j^{R}))} = \frac{r_i^*}{r_i^{**}} > 1. \tag{16}$$

This implies,

$$\frac{\alpha'(R_i^{RP})}{\alpha'(R_i^{R})} > \frac{(2-k_j\alpha(R_j^{R}))}{(2-k_j\alpha(R_j^{RP}))}. \tag{17}$$

Similarly, dividing equation (15) by (12) we get at the optimum,

$$\frac{k_j\alpha'(R_j^{RP})(2-k_i\alpha(R_i^{RP}))}{k_j\alpha'(R_j^{R})(2-k_i\alpha(R_i^{R}))} = \frac{r_j^*}{r_j^{**}} > 1. \tag{18}$$

This implies,

[10] The superscript “RP” denotes the game where there is R&D race and piracy.

$$\frac{\alpha'(R_j{}^{RP})}{\alpha'(R_j{}^{R})} > \frac{(2-k_i\alpha(R_i{}^{R}))}{(2-k_i\alpha(R_i{}^{RP}))}. \tag{19}$$

Using (17) and (19) we can provide some comparison between $R_i{}^{RP}$ and $R_i{}^{R}$ and the result is summarized in Proposition 2. We include the proof in the main text as it is instructive.

Proposition 2. *(i) If* $R_j{}^{RP} \geq R_j{}^{R}$ *then* $R_i{}^{RP} < R_i{}^{R}$. *(ii) If* $R_j{}^{RP} < R_j{}^{R}$ *then* $R_i{}^{RP} \geq R_i{}^{R}$ *holds.*

Proof of Proposition 2. (i) Suppose $R_j{}^{RP} \geq R_j{}^{R}$ then $\frac{(2-k_j\alpha(R_j{}^{R}))}{(2-k_j\alpha(R_j{}^{RP}))} \geq 1$ implying that $\frac{\alpha'(R_i{}^{RP})}{\alpha'(R_i{}^{R})} > 1.$ This we get from condition (17). This means that $R_i{}^{RP} < R_i{}^{R}$ since by assumption $\alpha'(R_i) > 0$ and $\alpha''(R_i) < 0$ for all $i, j = 1,2,\ i \neq j.$ Now suppose $R_i{}^{RP} < R_i{}^{R}$ holds. This means that $\frac{2-k_i\alpha(R_i{}^{R})}{2-k_i\alpha(R_i{}^{RP})} < 1.$ Then, from (19), we have $\frac{\alpha'(R_j{}^{RP})}{\alpha'(R_j{}^{R})} > \frac{2-k_i\alpha(R_i{}^{R})}{2-k_i\alpha(R_i{}^{RP})}$ and either $\frac{\alpha'(R_j{}^{RP})}{\alpha'(R_j{}^{R})} < 1$ or $\frac{\alpha'(R_j{}^{RP})}{\alpha'(R_j{}^{R})} > 1$. If $\frac{\alpha'(R_j{}^{RP})}{\alpha'(R_j{}^{R})} > 1$ then $\alpha'(R_j{}^{RP}) > \alpha'(R_j{}^{R}) \Rightarrow R_j{}^{RP} > R_j{}^{R}$. This cannot be true since we started with the contention that $R_j{}^{RP} \geq R_j{}^{R}$. If $\frac{\alpha'(R_j{}^{RP})}{\alpha'(R_j{}^{R})} < 1$ then $\alpha'(R_j{}^{RP}) < \alpha'(R_j{}^{R}) \Rightarrow R_j{}^{R} > R_j{}^{RP}$. This conforms to our starting premise. (ii) Suppose $R_j{}^{RP} < R_j{}^{R}$ holds then $\frac{(2-k_j\alpha(R_j{}^{R}))}{(2-k_j\alpha(R_j{}^{RP}))} < 1.$ In this case either (a) $\frac{\alpha'(R_i{}^{RP})}{\alpha'(R_i{}^{R})} > 1$ or (b) $\frac{\alpha'(R_i{}^{RP})}{\alpha'(R_i{}^{R})} \leq 1$ such that $\frac{(2-k_j\alpha(R_j{}^{R}))}{(2-k_j\alpha(R_j{}^{RP}))} < 1.$ (a) If $\frac{\alpha'(R_i{}^{RP})}{\alpha'(R_i{}^{R})} > 1$ then $R_i{}^{RP} < R_i{}^{R}$, implying that

$\frac{2-k_i\alpha(R_i^{\ R})}{2-k_i\alpha(R_i^{\ RP})}<1.$ Using (19) this implies that $\frac{\alpha'(R_j^{\ RP})}{\alpha'(R_j^{\ R})}>\frac{(2-k_i\alpha(R_i^{\ R}))}{(2-k_i\alpha(R_i^{\ RP}))}$ and either

$\frac{\alpha'(R_j^{\ RP})}{\alpha'(R_j^{\ R})}<1$ or $\frac{\alpha'(R_j^{\ RP})}{\alpha'(R_j^{\ R})}>1$. If $\frac{\alpha'(R_j^{\ RP})}{\alpha'(R_j^{\ R})}<1$ then $R_j^{\ RP}>R_j^{\ R}$. This contradicts our

starting premise. Hence the solution is where $\frac{\alpha'(R_j^{\ RP})}{\alpha'(R_j^{\ R})}<1$ such that $R_j^{\ RP}<R_j^{\ R}$.

(b) If $\frac{\alpha'(R_i^{\ RP})}{\alpha'(R_i^{\ R})}\le 1$ then $R_i^{\ RP}\ge R_i^{\ R}$ implying that $\frac{2-k_i\alpha(R_i^{\ R})}{2-k_i\alpha(R_i^{\ RP})}>1.$ This means that

$\frac{\alpha'(R_j^{\ RP})}{\alpha'(R_j^{\ R})}>\frac{(2-k_i\alpha(R_i^{\ R}))}{(2-k_i\alpha(R_i^{\ RP}))}>1$ implying that $R_j^{\ RP}<R_j^{\ R}$. *Q.E.D.*

The intuition behind this result follows from the fact that the reaction functions in the *R-game* as given in equations (11) and (12) are below the reaction functions in the *RP-game* as given by the equations (14) and (15) because $\frac{2}{r_i^{**}}>\frac{2}{r_i^{*}}$. This means that for given level of R_j , F$_i$ needs a lower level of R_i in the *RP-game* compared to that in the *R-game*, that is, piracy shifts the reaction functions of the two firms in the downward direction. Hence, the equilibrium R&D investment of the two firms in the presence of piracy will depend on the relative size of the shifts of the reaction functions. This is diagrammatically represented in Figure 1.

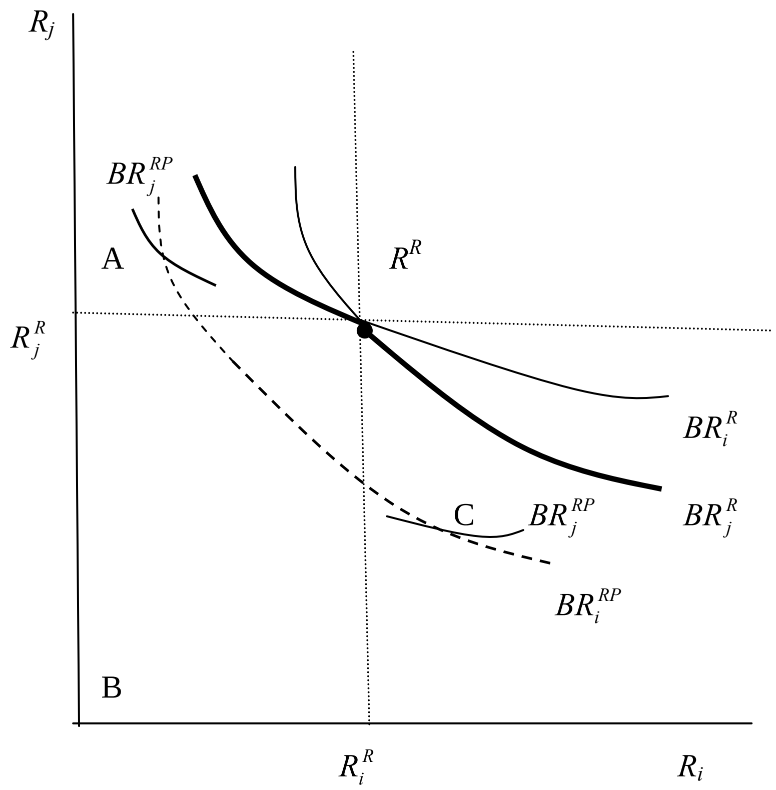

Figure 1: Reaction Curves

R^R is the equilibrium point of the *R-game* and the reaction functions are denoted as BR_i^R and BR_j^R. The reaction functions of the *RP-game* lies below the ones in the The intersection of the reaction functions of the *RP-game* must be below the curve drawn in bold which is the envelope of the top part of F_i's reaction function in the *R-game* labelled as BR_i^R and the bottom part of F_j's reaction function labelled as BR_j^R. This is because the reaction functions in the *RP-game* lies below those in the *R-game*.

Let us fix the reaction function of F_i in the *RP-game* at BR_i^{RP} represented by the dashed curve. Now we consider a relatively "small" shift in the reaction function of F_j compared to the shift in the reaction function of F_i when we move from the *R*-game to the *RP*-game. Then the equilibrium is at the point A where $R_j^{RP} > R_j^R$ and $R_i^{RP} < R_i^R$. This explains part (i) of Proposition 2. Next we consider a relatively “large” shift in the reaction function of F_j due to piracy, denoted as BR_j^{RP}, to intersect BR_i^{RP} at the point C that satisfies $R_j^{RP} < R_j^{R}$ and $R_i^{RP} > R_i^{R}$. This explains part (ii) of Proposition 2.

The precise location will depend on the relative positions of each firm’s reaction functions in the two games. The contention of this study, as summarised in proposition 2, is that it is not optimal for both the innovating firms to increase their R&D investment in the presence of piracy. Below we try to provide an intuitive explanation of Proposition 2.

R&D decision is associated with two costs – the loss of the R&D investment in the event of technological failure and the loss of the entire profit in the event of a market failure of the innovation. Hence, provided that the profit exceeds the cost of innovation, the objective of a firm would be to increase the probability of success of the R&D. Market uncertainty being same for both firms and the presence of piracy affecting the profits of the innovating firms similarly, they should push to minimise technological uncertainty. An innovating firm with higher efficiency can reach the same probability of technological success with a lower level of R&D effort compared to an innovating firm with lower efficiency. Thus, as the less efficient firm increases its innovation level (such that its expected profit is positive) to increase the probability of a technological success the best response of the more efficient firm will be to reduce cost through a lower innovation level and vice versa. Thus no equilibrium is possible in the area B (excluding the dotted lines) as it is not optimal for both firms F_i and F_j to increase R&D investments in the presence of a pirate in the output market. This leads us to Proposition 3.

Proposition 3. *If* $R_j^{RP} < R_j^{R}$ *and* $R_i^{RP} > R_i^{R}$ *holds then piracy increases the equilibrium R&D investment of* F_i *and there is an overall increase in the R&D investment by the two firms if* $R_i^{RP} + R_j^{RP} > R_i^{R} + R_j^{R}$.

Proposition 3 suggests that piracy can enhance the overall R&D investment under certain conditions where the increase in R&D effort by one firm exceeds the decrease in R&D investment by the other innovating firm given competition from the pirate in the product market. In the next section we provide an example using a specific functional form of $\alpha(R_i)$.

4. An Example

In this section we provide an example for the above general analysis. We assume that $k_i\alpha(R_i) = k_i\sqrt{R_i}$. Using this form we get the equilibrium R&D investments and expected profits of F_i for the *R* and *RP* games. The results are summarised in Lemmas 3 and 4.

Lemma 3. *In the R-game,* $R_i^{R} = E\pi_i^{R} = \dfrac{4k_i^2(16-k_j^2)^2}{(256-(k_ik_j)^2)^2}$, $i, j = 1,2, i \neq j$. R_i^{R} *and* $E\pi_i^{R}$ *are increasing in* k_i *and decreasing in* k_j.

We get the equilibrium R&D investments by solving equations (11) and (12) using $k_i\alpha(R_i) = k_i\sqrt{R_i}$. The second order condition of maximization requires,

$$\frac{d^2E\pi_i}{dR_i^2} = -\frac{k_i(2-k_j\sqrt{R_j})r_i^*}{8R_i^{3/2}} < 0.$$ This implies $2-k_j\sqrt{R_j} > 0 \Rightarrow \sqrt{R_j} < \dfrac{2}{k_j}$.

Similarly, $2-k_i\sqrt{R_i} > 0 \Rightarrow \sqrt{R_i} < \dfrac{2}{k_i}$. Substituting $\sqrt{R_i^{R}} = \dfrac{2k_i(16-k_j^2)}{256-(k_ik_j)^2}$ in the condition $\sqrt{R_i} < \dfrac{2}{k_i}$ yields $k_i < 4$.

Lemma 4. *The equilibrium R&D investments and expected profits of F_i in the RP-game are,* $R_i^{R,P} = E\pi_i^{R,P} = \left(\frac{2k_i r_i^{**}(4-k_j^2 r_i^{**})}{(16-k_i^2 k_j^2 r_i^{**2})}\right)^2, i, j = 1,2; i \neq j$.

We get the result by solving equations (14) and (15) using $k_i\alpha(R_i) = k_i\sqrt{R_i}$.

The second order condition of maximization requires,

$\frac{d^2 E\pi_i}{dR_i^2} = -\frac{k_i(2-k_j\sqrt{R_j})r_i^{**}}{8R_i^{3/2}} < 0$. This implies $2-k_j\sqrt{R_j} > 0 \Rightarrow \sqrt{R_j} < \frac{2}{k_j}$.

Similarly, $2-k_i\sqrt{R_i} > 0 \Rightarrow \sqrt{R_i} < \frac{2}{k_i}$. Substituting

$\sqrt{R_i^{RP}} = \frac{2k_i r_i^{**}(4-k_j^2 r_i^{**})}{(16-k_i^2 k_j^2 r_i^{**2})}, i, j = 1,2; i \neq j$ in the condition $\sqrt{R_i} < \frac{2}{k_i}$ yields

$k_i^2 < \frac{4}{r_i^{**}} < \frac{4}{r_i^{*}} = 16$ because $r_i^{**} = \frac{4(1-q)}{(4-q)^2} < r_i^{*} = \frac{1}{4}$. Hence, $k_i < 4, i, j = 1,2, i \neq j$

also satisfies the second order conditions in the *RP-game* and hence this assumption will be retained for the rest of the analysis.

Comparison of $\sqrt{R_i^{R}} = \frac{2k_i(16-k_j^2)}{256-(k_i k_j)^2}$ and $\sqrt{R_i^{RP}} = \frac{2k_i r_i^{**}(4-k_j^2 r_i^{**})}{(16-k_i^2 k_j^2 r_i^{**2})}$ will allow us to determine the effect of piracy on innovation when there is R&D race. The result is summarized in Proposition 4. We include the proof in the main text as it is instructive.

Proposition 4. *Piracy enhances R&D investment of F_i in the presence of R&D race if* $r_i^{**}(256-k_i^2k_j^2) - 4k_j^2(16-k_i^2)r_i^{**2} - 4(16-k_j^2) > 0$.

Proof of Proposition 4.

$$\sqrt{R_i^{R,P}} - \sqrt{R_i^{R}} = \frac{2k_i r_i^{**}(4-k_j^2 r_i^{**})}{(16-k_i^2 k_j^2 r_i^{**2})} - \frac{2k_i(16-k_j^2)}{256-k_i^2 k_j^2} \equiv A_i, i, j = 1,2; i \neq j$$

$A_i = 2k_i\left(\dfrac{r_i^{**}(4-k_j{}^2 r_i^{**})(256-k_i^2k_j^2)-(16-k_j{}^2)(16-k_i^2k_j^2r_i^{**2})}{(16-k_i^2k_j^2r_i^{**2})(256-k_i^2k_j^2)}\right)$. The denominator in A_i is always positive because $k_i, k_j < 4$ and $r_i^{**} = \dfrac{4(1-q)}{(4-q)^2} < \dfrac{1}{4}$. So the sign of A_i depends on the sign of the numerator. Simplifying the numerator we get $B_i \equiv r_i^{**}(256-k_i^2k_j^2)-4k_j^2(16-k_i{}^2)r_i^{**2}-4(16-k_j^2)$ which can be either positive zero or negative. If $r_i^{**}(256-k_i^2k_j^2)-4k_j^2(16-k_i{}^2)r_i^{**2}-4(16-k_j^2)>0$ it implies $\sqrt{R_i{}^{R,P}}-\sqrt{R_i{}^{R}}>0$. *Q.E.D.*

Let us discuss the implications of Proposition 4 by analysing the impact of the different strengths of k_i and k_j on the incentive to innovate in the presence of piracy when there is R&D race. We will be focusing on the expression B_i for the analysis.

Consider the symmetric case $k_i = k_j$. So, $B_i = (16-k_i{}^2)(4-k_i^2r_i^{**})(4r_i^{**}-1)$. Now $(16-k_i{}^2)>0$, $(4-k_i^2r_i^{**})>0$ and $(4r_i^{**}-1)<0$, since by assumption $k_i<4$ and $r_i^{**} = \dfrac{4(1-q)}{(4-q)^2} < \dfrac{1}{4}$. Therefore, $B_i = (16-k_i{}^2)(4-k_i^2r_i^{**})(4r_i^{**}-1)<0$.

Next let us look at the combinations of k_i and k_j that keeps the value of B_i unchanged. We will call them the B_i-curves. Total differentiation of $B_i \equiv r_i^{**}(256-k_i^2k_j^2)-4k_j^2(16-k_i{}^2)r_i^{**2}-4(16-k_j^2)$ with respect to k_i and k_j yields, $2k_ik_j{}^2r_i^{**}(4r_i^{**}-1)dk_i + 2k_j(1-4r_i^{**})(4+(16-k_i^2)r_i^{**})dk_j = 0$. The first expression on the L.H.S is negative because $(4r_i^{**}-1)<0$. The second expression on the L.H.S is positive because $(1-4r_i^{**})>0$ and $k_i<4$. Therefore, $\dfrac{dk_i}{dk_j}>0$. Now

$$\frac{dB_{\mathrm{i}}}{dk_{\mathrm{i}}} = 2k_ik_j^2r_i^{**}(4r_i^{**}-1)<0 \text{ and } \frac{dB_i}{dk_j} = 2k_ik_j^2r_i^{**}(4r_i^{**}+1)+8k_j(1-16r_i^{**2})>0$$

because $4r_i^{**} < 1$. This means an increase in k_i for a given k_j reduces B_i. The B_i-curves are represented diagrammatically in Figure 2 and the intuition is provided subsequently. Along the k_i=k_j line B_i<0. So the B_i=0 curve which is

$$k_j = 8\sqrt{\frac{1-4r_i^{**}}{4-k_i^{\;2}r_i^{**}-64r_i^{**2}+4k_i^2r_i^{**2}}}$$

lies above the k_i=k_j line. The B_i-curves are upward sloping because $\frac{dk_i}{dk_j} > 0$.[11] Since $\frac{dB_i}{dk_\mathrm{i}} < 0$ and $\frac{dB_i}{\mathrm{dk}_\mathrm{j}} > 0$ it means that higher values of B_i are associated with higher B_i-curves.

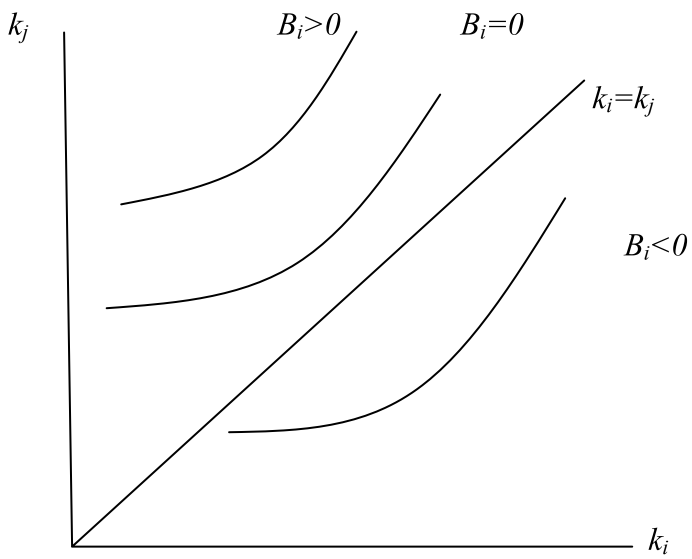

Figure 2: *B_i*-curves

To understand the intuition behind the result that $\frac{dB_i}{dk_\mathrm{i}} < 0$ let us consider the rate of change of $\sqrt{R_i^{R,P}}$ and $\sqrt{R_i^{R}}$ with respect to k_i and k_j.

[11] The concavity of the B_i-curves as shown in Figure 1 is only for illustrative purpose. The concavity is not necessary for the analysis.

$$\frac{\partial(\sqrt{R_i^{R,P}})}{\partial k_i} = \frac{r_i^{**}(4-k_j^{\ 2}r_i^{**})(2r_i^{**}(16-k_i^2k_j^2r_i^{**2})+4k_i^2k_j^2r_i^{**2})}{(16-k_i^2k_j^2r_i^{**2})^2} > 0 \text{ and}$$

$$\frac{\partial(\sqrt{R_i^{R,P}})}{\partial k_j} = -\frac{16k_ik_jr_i^{**2}(4-k_j^{\ 2}r_i^{**})}{(16-k_i^2k_j^2r_i^{**2})^2} < 0 \text{ since } k_i^2, k_j^2 < 16,\ r_i^{**} < \frac{1}{4}, \text{ thereby}$$

$k_j^{\ 2}r_i^{**} < 4$ and $16-k_i^2k_j^2r_i^{**2} > 0$. By similar reasoning,

$$\frac{\partial(\sqrt{R_i^{R}})}{\partial k_i} = \frac{2(256+k_i^2k_j^2)(16-k_j^{\ 2})}{(256-k_i^2k_j^2)^2} > 0 \text{ and}$$

$$\frac{\partial(\sqrt{R_i^{R}})}{\partial k_j} = -\frac{64k_ik_j(16-k_j^{\ 2})}{(256-k_i^2k_j^2)^2} < 0.$$

The upward sloping property of the B_i-curves is because the rate at which $R_i^{R,P}$ increases due to an increase in k_i is less than that of R_i^{R}. Consequently, an increase in k_i reduces the gap between $R_i^{R,P}$ and R_i^{R} thereby lowering the value of B_i. The opposite is the case for k_j. An increase in k_j reduces both $R_i^{R,P}$ and R_i^{R} but the rate of reduction of the former is less than that of the latter resulting in an increase in B_i. Thus a decrease in k_i and an increase in k_j results in higher values of B_i. This means that if the difference between k_i and k_j is "sufficiently high then $\sqrt{R_i^{R,P}} - \sqrt{R_i^{R}}$ is positive.

The following table provides a numerical example for certain values of q (which is the quality of the pirated product) and k_j. We have fixed k_j at 3.9 for the entire analysis which satisfies the second order condition $k_i < 4, i, j = 1,2, i \neq j$. For any given q, we observe that an increase in k_i reduces B_i and increases both $\sqrt{R_i^{R,P}}$ and $\sqrt{R_i^{R}}$ but the increase in $\sqrt{R_i^{R,P}}$ is less than the increase in $\sqrt{R_i^{R}}$. Also, as q

decreases from 0.9 to 0.8 to 0.7 we see that the negativity of B_i begins at progressively higher values of k_i. That is for lower qualities of the pirated product the asymmetricity between k_i and k_j required for the enhancement of R&D investment in the presence of piracy decreases. This example shows that if a firm's probability of success in innovation is relatively small compared to its rival then its incentive to invest in innovation is higher in the presence of piracy than in its absence.

Table: Comparative Static Analysis of $\mathbf{R_{i,j}}$ with the Probability Parameter $\mathbf{k_{i,j}}$

q	r_i^{**}	k_i	k_j	**B**	$\sqrt{R_i^{R,P}}$	$\sqrt{R_i^{R}}$
0.9	0.0416233	3.3	3.9	0.06259	0.0588643	0.0577005
0.9	0.0416233	3.31	3.9	0.02771	0.0590492	0.0585266
0.9	0.0416233	3.32	3.9	-0.00728	0.0592342	0.0593734
0.9	0.0416233	3.33	3.9	-0.04237	0.0594192	0.0602419
0.9	0.0416233	3.7	3.9	-1.41493	0.0663107	0.122365
0.9	0.0416233	3.75	3.9	-1.61149	0.067249	0.140705
0.8	0.078125	3.6	3.9	0.311008	0.106887	0.0966059
0.8	0.078125	3.65	3.9	0.014866	0.108619	0.108068
0.8	0.078125	3.7	3.9	-0.285361	0.110361	0.122365
0.8	0.078125	3.75	3.9	-0.589672	0.112116	0.140705
0.7	0.110193	3.7	3.9	0.397967	0.140668	0.122365
0.7	0.110193	3.75	3.9	0.048829	0.1433	0.140705
0.7	0.110193	3.8	3.9	-0.304997	0.14597	0.165092
0.7	0.110193	3.85	3.9	-0.663509	0.14868	0.199118

5. Conclusion

The literature on piracy and innovation shows that piracy can have both beneficial and adverse impacts on innovative efforts by firms. This paper attempts to link the literature on piracy and innovation to that on innovation and patent race by analysing the impact of piracy on R&D decision of a firm under the assumptions of technological and market uncertainties. In an environment where the success of R&D investment is stochastic, we show that piracy unambiguously retards innovation under technological uncertainty when there is one innovating firm. However, in the presence of R&D competition, or market uncertainty, we show that piracy may enhance innovation.

The last result depends on the relative position of the innovating firms' reaction functions in the case of R&D race without piracy to that in the R&D race with piracy. We showed that it is possible for one firm's R&D to increase in the presence of piracy. Using a specific functional form of the probability of success we showed that piracy enhances the R&D investment and profit of a less efficient firm if the difference between the probability of success of the two innovating firms is sufficiently large.

Appendix

Proof of Lemma 1. $\alpha''(R_i)\dfrac{dR_i^*}{dk_i} = \dfrac{-4}{k_i^{\,2}}$. Since $\alpha''(R_i) < 0$ hence, $\dfrac{dR_i^*}{dk_i} > 0$ and

$\dfrac{dE\pi_i^*}{dk_i} = \dfrac{\alpha(R_i^*)}{4} > 0$. $E\pi_i^* = \dfrac{k_i\alpha(R_i^*)}{4} - R_i^* \geq 0 \Rightarrow k_i \geq \dfrac{4R_i^*}{\alpha(R_i^*)}$. *Q.E.D.*

Proof of Lemma 2. $\dfrac{\partial E\pi_i}{\partial R_i} = k_i\alpha'(R_i)r_i^{**} - 1 = 0 \Rightarrow \alpha'(R_i^P) = \dfrac{1}{k_i r_i^{**}}$.

$\alpha''(R_i^P)\dfrac{dR_i^P}{dk_i} = \dfrac{-1}{k_i^{\,2} r_i^{**}} \Rightarrow \dfrac{dR_i^P}{dk_i} > 0$ because by assumption $\alpha''(R_i^P) < 0$.

$\dfrac{\partial E\pi_i^P}{\partial k_i} = \alpha(R_i^P)r_i^{**} > 0$. $\alpha''(R_i^P)\dfrac{dR_i^P}{dq} = \dfrac{-1}{k_i\ r_i^{**2}}\dfrac{dr_i^{**}}{dq} > 0$ because

$\frac{dr_i^{**}}{dq} = \frac{-4(2+q)}{(4-q)^3} < 0.$ Since $\alpha''(R_i^{\,P}) < 0$ so $\frac{dR_i^P}{dq} < 0.$ $\frac{\partial E\pi_i^{\,P}}{\partial q} = k_i \alpha(R_i^{\,P}) \frac{dr_i^{**}}{dq} < 0.$

Q.E.D.

Proof of Lemma 3: Maximizing equation (6) with respect to R_i yields F_i's reaction function which is $\sqrt{R_i} = \frac{k_i(2 - k_j\sqrt{R_j})}{16}$, $i, j = 1,2, i \neq j.$ Solving the two gives us $R_i^{\,R}$ which when substituted in equation (6) gives $E\pi_i^{\,R}$. Differentiating $R_i^{\,R} = E\pi_i^{\,R}$ with respect to k_i and k_j yields $\frac{dR_i^R}{dk_i} = \frac{dE\pi_i^R}{dk_i} > 0, \frac{dR_i^R}{dk_j} = \frac{dE\pi_i^R}{dk_j} < 0.$ *Q.E.D.*

References

Banerjee, D. S. (2003), “Software Piracy: A Strategic Analysis and Policy Instruments” *International Journal of industrial Organization*, Vol 21, 97-127.

Banerjee, D. S. (2006), “Lobbying and Commercial Software Piracy”, *European Journal of Political Economy*, 22, 139-155.

Banerjee, S., and Lin, P. (2003), “Downstream R&D, Raising Rivals’ Cost, and Input price Contracts, *International Journal of Industrial Organization*, Vol 21, 79-96.

Barker, G. (2009), “Ahoy! Pirates at work”, *The Age*, *Livewire*, p23, May 21, 2009.

Barnes, D. (2005), “Washington DC-area universities look for legal file sharing options”, *GW Hatchet, U-Wire DC Bureau*, Issue: 4/21/05, Paper 332.

Barnett, J.M. (2005), “Shopping for Gucci on Canal Street: Reflections on Status Consumption, Intellectual Property, and the Incentive Thesis”, *Virginia Law Review*, 91(16), 1381-1423.

Barnett, J.M., Grolleau, G., and El Harbi, S. (2010), “The Fashion Lottery: Cooperative Innovation in Stochastic Markets” *Journal of Legal Studies,* (forthcoming).

Chen, Y, and Png, I. (2003), "Information Goods Pricing and Copyright Enforcement: Welfare Analysis”, *Information Systems Research*, Vol. 14 No. 1, 107-123.

Choi, D.Y. and Perez, A., (2007), “Online Piracy, innovation, and legitimate business models”, *Technovation*, 27, pp 168-178.

Conner, K.R., and Rumelt, R.P. (1991), “Software Piracy: An Analysis of Protection Strategies”, *Management Science*, Vol. 37, No 2, 125-139.

Ding, C.G. and Liu, N., (2009), "Productivity changes of Asian economies by taking into account software piracy", *Economic Enquiry*, 47(1), pp 135-145.

Easley R.F., Michel, J.G., and Devaraj, S., (2003), "The MP3 open standard and the music industrys technological response to internet piracy", *Communications of the ACM*, November, 46(11), 91-96.

El Harbi, S. and Grolleau, G., (2008), "Profiting from Being Pirated by 'Pirating' the Pirates," *Kyklos*, Blackwell Publishing, 61(3), 385-390

Iwata, E., (2001), "Software piracy takes toll on global scale", USA Today, August 2001. http://www.usatoday.com/tech/techreviews/2001-08-01-software-piracy.htm.

Jaisingh, J., (2009), "Impact of piracy on innovation at software firms and policy implications for piracy policy", *Decision Support Systems*, 46, pp 763-773.

Kolm, S., and Ythier, J.M. (ed.), (2006), Handbook of the Economies of Giving, Altruism and Reciprocity, Elsevier, Edition 1, 1(1), 371-544.

Marshall, K.P., (1999), "Has technology introduced new ethical problems?", *Journal of Business Ethics*, 19(1), 81-90.

Novos, I.E., and Waldman, M., (1984) "The Effects of Increased Copyright Protection: An Analytic Approach," *Journal of Political Economy*, 92(2), 236-246.

Park, W.G., and Ginarte, J.C., (1998), "Intellectual Property Rights in a North-South economic context", *Science Communication*, 17(3), pp 379-87.

Qiu, L.D., (2006), "A general equilibrium analysis of software development: implications of copyright protection and contract enforcement", *European Economic Review*, 50, 1661-1682.

Raustiala, K. and Sprigman, C.J., (2006), "The Piracy Paradox: Innovation and Intellectual Property in Fashion Design", *Virginia Law Review*, December, 92(8), 1687-1777.

Ritson, M. (2007), "Fakes Can Genuinely Aid Luxury Brands," *Marketing*, *July 25*, 21-21.

Shapiro, C., (2006), "Prior User Rights", *American Economic Review*, 96(2): 92–96.

Shy, O. (2000). Industrial Organization: Theory and Applications Cambridge, Mass., MIT Press.

Shy, O. and Thisse, J. F., (1999), "A Strategic Approach to Software Protection". *Journal of Economics and Management Science*, 8(2), 163-190.

Straub, D.W. and Nance, W.D., (1990) "Discovering and disciplining computer abuse in organizations: a field study", *MIS Quarterly*, 14(1), pp 45-60.

Takeyama, L. N. (1994) "The Welfare Implications of Unauthorized Reproduction of Intellectual Property in the Presence of Demand Network Externalities". *Journal of Industrial Economics*, No. 2, 155-165.

WhiteHall, S. (2006) "Brand piracy: faking it can be good" *Brand Strategy*, 15 May 2006. http://www.intangiblebusiness.com/Brand-Services/Marketing-Services/News/Brand-piracy-faking-it-can-be-good~290.html