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Effects of Piracy on Quality of Information Goods

Atanu Lahiri, Debabrata Dey
Michael G. Foster School of Business, University of Washington, Seattle, Washington 98195
{lahiria@uw.edu, ddey@uw.edu}

It is commonly believed that piracy of information goods leads to lower profits, which translate to lower incentives to invest in innovation and eventually to lower-quality products. Manufacturers, policy makers, and researchers all claim that inadequate piracy enforcement efforts translate to lower investments in product development. However, we find many practical examples that contradict this claim. Therefore, to examine this claim more carefully, we develop a rigorous economic model of the manufacturer's quality decision problem in the presence of piracy. We consider a monopolist who does not have any marginal costs but has a product development cost quadratic in the quality level produced. The monopolist faces a consumer market heterogeneous in its preference for quality and offers a quality level that maximizes its profit. We also allow for the possibility that the manufacturer may use versioning to counter piracy. We unexpectedly find that in certain situations, lower piracy enforcement increases the monopolist's incentive to invest in quality. We explain the reasons and welfare implications of our findings.

Key words: piracy; quality; pricing; information good; versioning
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1. Introduction

Piracy nowadays is one of the most important issues facing providers of information goods. According to a report by the U.S. Government Accountability Office (GAO 2010, p. 9), the investigative arm of the U.S. Congress, "counterfeiting and piracy have produced a wide range of effects on consumers, industry, government, and the economy as a whole, depending on the type of infringements involved and other factors." Some of the adverse effects listed in this GAO report are lost sales, lost tax revenues, erosion of brand values, and reduced incentives to innovate. It is the last one—the reduced incentives to innovate—that we examine in this research. The GAO believes that losses in revenues resulting from piracy discourage investments in innovation in the software and audiovisual sectors. It even claims that reduced innovation would impact the long-term growth rate of the U.S. economy.

A similar concern is echoed by a report from the Organisation for Economic Co-operation and Development (OECD 2008). This OECD report also identifies reduced incentives to innovate and potential fallouts on medium to long-term growth rates as some of the major socioeconomic impacts of piracy. It uses an argument, similar to that of the GAO, that lost revenues imply lower returns on investments in innovation and, hence, lower incentives to innovate.

The software industry is perhaps among the most severely impacted. In the United States, the piracy rate for software products is approximately 20% (Business Software Alliance (BSA) 2011). This alone amounts to $9.5 billion in lost revenues for the U.S.-based software manufacturers. When losses around the world are included, the estimate is even higher, around $59 billion. Software manufacturers frequently argue that such huge losses imply lower investments in research and development (R&D) (e.g., Adobe 2011). Recent academic research on piracy of information goods lends strong support to this claim as well (e.g., Cho and Ahn 2010, Jain 2008), the essential logic being that piracy lowers the return on investments in quality, which, in turn, leads to lower incentives to invest in quality. Whereas the above articles, as well as others that have studied quality in the context of piracy, suggest that more piracy implies less quality, we find many examples to the contrary, a few of which are discussed below. It appears that there is a discernible gap between the literature and practice.

In this debate, we take a slightly different view. We feel that even though piracy leads to lost revenues, it is not obvious that lower revenues automatically translate to lower-quality information goods. A case in point is the European unit of the cable TV channel HBO, which is fighting against unauthorized distribution of its content by raising the quality of its offerings. The piracy rate faced by HBO is estimated to be between 30% and 50%. HBO has responded to this high piracy rate by churning out new high-quality contents in different European languages (Briel 2010).

New contents are available through HBO's cable TV channels as well as its new Internet protocol television channels. HBO's innovative offerings have reduced piracy and brought in new subscribers. Valve, a video game manufacturer, has also adopted a similar strategy. Since releasing its game *Team Fortress 2* in 2007, it has made frequent quality enhancements, including addition of new weapons and avatars, available only to legal consumers. This strategy has encouraged enthusiastic gamers, who have a strong preference for the latest version, to switch to legal downloads.

Producers of movies face the twin threat of counterfeit disks and illegal torrent sites. Hollywood has been considering an interesting option to combat this threat, which is to offer high-definition legal downloads of its movies immediately following their releases in theaters (Kennedy 2011). Many consumers want new movies as soon as they are released; to them, quality is synonymous with immediate availability. If legal downloads are made available soon enough, they would not wait for the same content to be available through illegal torrent sites or counterfeit DVDs. American TV networks used a similar approach previously—they cut the lag between the American and European releases of their shows to fight piracy in Europe (Stone 2007).

Globally, the piracy rate is often the highest for end-user software products and console games, and, as mentioned already, these industries routinely claim that piracy leads to lower investments in R&D. To investigate this claim, we consider here R&D expenditures of several leading manufacturers. Table 1 shows the R&D investments by Electronic Arts, an American video game developer, along with the global piracy rate. As evident from this table, the R&D investments at Electronic Arts have increased markedly despite an upward trend in the global piracy rate. Besides, the R&D to revenue ratio for the fiscal year 2010 has also been the highest in recent years, which is noteworthy, especially, in light of the current global economic crisis. Software firms also show a similar trend over 2006–2010; for example, Adobe's annual R&D expenses have risen from \$0.54 to \$0.68 billion, an increase of more than 20%. As a percentage of the net revenue, Adobe's R&D expenditure has hovered around the 20% mark.[1] In short, despite increased piracy threats arising from their global expansions and the recent economic slowdown, there has been no visible decrease in R&D investments by many companies.

In the face of such compelling facts, it is difficult to subscribe to the usual claim about the adverse effect piracy has on innovation and investments in quality. Although one may be tempted to draw exactly the opposite conclusion, we believe that this issue requires a closer examination. In this research, we do just that—we investigate the *impact of piracy on quality* and search for reasons behind, for example, HBO's surprising response to piracy. We are interested in answering the following research questions:

- Is it possible that an optimal response to piracy is building higher-quality products?
- Could it ever be the case that lower enforcement and higher piracy would lead to more innovation and not less?
- If such surprising outcomes are indeed possible, under what conditions are they likely to happen?
- What are the welfare implications of such outcomes? How do they impact the welfare of consumers and that of the society in general?

Answering these questions is of much significance. First, it has important implications for manufacturers of information goods who are actively searching for appropriate responses to piracy. With answers to these questions, a manufacturer situated in a technical and legal context would be able to find the best response to deal with the piracy of its product. Second, these answers can also provide a policy maker with an understanding of the welfare implications associated with choosing a certain level of piracy enforcement.

Although there is a rich stream of literature investigating economic impacts of piracy, as discussed in details in the next section, we are unable to locate prior research that comprehensively examines optimal product line decisions for manufacturers of information goods in the context of piracy. It is this void that this paper attempts to fill: We model a monopolist's product line decision problem. We allow consumers to be heterogeneous in their preferences for quality. We start with a basic model, in which all consumers are potentially "unethical" (August and Tunca 2008) and the manufacturer offers only one version. We allow the quality and price of this version to be endogenously chosen by the manufacturer. This model characterizes important trade-offs associated with investments in quality. To address the limitations of this model and to test the applicability of our

Table 1 **Research and Development Investments at Electronic Arts**

Year	Global piracy rate (%)	R&D investments (\$)	R&D to revenue ratio (%)
2006	35	0.76B	26
2007	38	1.04B	34
2008	41	1.15B	31
2009	43	1.36B	32
2010	42	1.23B	34

Note. Global piracy rate is from Business Software Alliance (BSA 2011), R&D investments from 10-K statements of Electronic Arts.

[1] Although, perhaps, a portion of this expenditure is to respond to competitive pressures in the marketplace, the figures, both in absolute and relative terms, are still quite compelling.

results in a wider setting, we develop an extension in which there are some purely "ethical" consumers along with some potentially "unethical" consumers (August and Tunca 2008). We find that in both settings, lower piracy enforcement efforts can increase the manufacturer's incentive to invest in quality. This increase arises primarily out of the manufacturer's desire to differentiate the legal product from the pirated product. We finally extend our analysis to the setting where the manufacturer has the option to offer multiple versions. We find that in certain circumstances, versioning is indeed an appropriate strategy to mitigate piracy. However, in certain others, producing one version is optimal, and the monopolist still invests in a higher-quality product in response to a lower level of piracy enforcement.

Our results have interesting welfare implications. We show that when a manufacturer lowers quality in response to stricter enforcement, it can adversely impact the surplus of legal users. This adverse impact may even lead to a net negative impact on the total surplus of the manufacturer and legal users combined. Prior research has shown that stricter enforcement often reduces social welfare because it negatively influences the welfare of pirates (Chen and Png 2003, Novos and Waldman 1984). We augment prior findings by showing that even when the welfare of pirates is ignored, stricter enforcement can still lead to a decline in the social welfare. Our findings thus cast additional doubts on the social benefits of piracy enforcement, and, in this respect, contribute to the economic research on public policy toward piracy.

2. Literature Review

Prior analytical research on piracy of information goods spans several streams. One of these streams investigates manufacturers' attitudes toward tolerating piracy of their products. For example, Conner and Rumelt (1991) show that a manufacturer can actually gain from piracy when the positive network effect is strong. More recently, August and Tunca (2008) find that supporting pirates with security patches can increase profits, because doing so improves the security and welfare of legal users. A second stream investigates possible strategies for mitigating piracy. For example, Shy and Thisse (1999) show that in a duopoly setting where support is bundled with purchase, there are incentives for software manufacturers to not implement digital rights management (DRM). Chellappa and Shivendu (2005) find that offering free trials is often effective in reducing piracy of digital "experience" goods. Wu and Chen (2008) discuss the possibility of fighting piracy by offering cheaper versions to price-sensitive consumers. Other streams include pricing of digital goods in the presence of piracy (Sundararajan 2004) and impact of piracy on product quality (Bae and Choi 2006, Cho and Ahn 2010, Jain 2008, Jaisingh 2009). This paper belongs to the last stream.

Jain (2008) assumes that consumers are all homogeneous in their preferences for quality and concludes that piracy reduces a monopolist's incentive to invest in quality. Apparently, the assumption of consumer homogeneity is critical to this conclusion. In fact, in making this assumption, Jain (2008) departs from the established stream of research on information goods, which argues that different consumers value quality differently (August and Tunca 2006, 2008; Bhargava and Choudhary 2001, 2008; Chellappa and Shivendu 2005; Cho and Ahn 2010; Jones and Mendelson 2011; Wu and Chen 2008). Despite making the same assumption as Jain (2008), Jaisingh (2009) presents a more nuanced view of the impact of piracy on quality. Specifically, he considers the commercialization of piracy, that is, what would happen if there exists a pirate firm that sets the price of the pirated product strategically. Jaisingh (2009) finds that in limited circumstances, weaker enforcement leads to higher-quality legal products. It is, however, unclear whether this result is applicable when consumers are heterogeneous and there is no price-setting pirate firm.

Another important part of the product line decision with respect to quality is the versioning strategy, which has been explored by Wu and Chen (2008). They find that a cheaper version is often effective in combating piracy and increasing profits. The quality of this lower version is endogenous in their model, but that of the highest one is not. In that sense, the impact of piracy on the manufacturer's incentive to invest in the quality of the higher version is outside the scope of their work. This, however, is an important issue in itself, which we investigate in detail.

Cho and Ahn (2010) extend the prior work by endogenizing the highest quality level, with two types of consumers who differ in their tastes for quality. Despite the extended scope of their model, like Jain (2008), they still find that piracy adversely affects quality. They reach the same conclusion even after considering consumer heterogeneity, because the quality of their pirated product is the same as that of the legal product, a premise that is in conflict with many practical situations (Sundararajan 2004). Bae and Choi (2006), on the other hand, do consider the quality difference between the legal and pirated products, but limit their analysis to only one version. They show that the existence of piracy leads to inefficiently low levels of quality. Overall, prior research seems to have converged to a congruous position that piracy implies lower quality, a claim that we question in this paper.

We develop a parsimonious, yet comprehensive, economic model that combines all the relevant aspects in a rigorous manner. We consider the fact that consumers differ in their preferences for quality. We also follow the long stream of economic research on piracy, which assumes that piracy is costly, but does not assume the existence of price-setting pirate firms (August and Tunca 2006, 2008; Conner and Rumelt 1991; Chellappa and Shivendu 2005; Chen and Png 2003; Shy and Thisse 1999). We model the pirated product as a competing product having a lower quality than the legal product; many researchers have previously made the same modeling choice (August and Tunca 2006, 2008; Jaisingh 2009; Novos and Waldman 1984; Sundararajan 2004). Despite using an approach that is in line with the existing research, we get intriguing new results that provide a possible explanation for unexpected real-world observations regarding the relationship between piracy and quality.

3. Basic Model

We consider a model where a manufacturer offers a product of quality $\theta > 0$ at a price $p > 0$. Consumers choose from one of the three options available to them: (i) buy the legal product, (ii) obtain a pirated version of the product, or (iii) forgo use completely. As mentioned earlier, consumers in our model are heterogeneous in their preference for quality, denoted as v. Hence, the utility of the legal version to a consumer is $v\theta - p$. Each consumer knows his or her v, but the manufacturer only knows the distribution. We make the following assumption:

Assumption 1. *Consumers' preferences for quality, v, is uniformly distributed over* $[0, 1]$.

We denote the (expected) cost of piracy by $r > 0$. Following August and Tunca (2008), we view this cost as the "expected loss" resulting from potential legal liabilities—the probability that piracy gets detected times the expected penalty assessed on detection.[2] Because the *cost of piracy* is directly related to the *enforcement level*, henceforth, we use these two terms interchangeably and represent both by r. We argue that r largely depends on the political and legal environments in which a business operates. For example, the cost of piracy in certain developing nations is quite low because, in those countries, either governments are remiss in enforcing intellectual property laws and international treaties, or the penalty on detection is low under their judicial systems (BSA 2011). In contrast, there are hundreds of piracy-related criminal prosecutions in the United States every year, and the U.S. Federal Copyright Act (U.S. Code Title 17) allows a maximum of \$150,000 per infringement as statutory damages. The existence of such statutory limits makes us believe that r depends more on the legal context than the attributes of the product or the actual damage to the seller. A case in point is the set of 261 individual lawsuits filed by the Recording Industry Association of America (RIAA) in 2003 to combat the piracy of music (Bhattacharjee et al. 2006, Katz 2005). Although most of these cases were eventually settled outside courtrooms, often for undisclosed amounts, two prominent ones went to trial and resulted in vastly different amounts of penalty awarded per song (\$80,000 versus \$9,250). There is, however, no prima facie evidence that the qualities of the downloaded tracks or the damages to the music companies in those two cases were drastically different.

We do concede that antipiracy efforts exerted by a manufacturer might, at times, also have an impact on r. Such efforts could go toward either increasing the probability of detection through investments in technology or increasing the penalty through aggressive prosecution of pirates, or both. In fact, RIAA's investments in detecting individual offenders and its subsequent fierce legal action against them provide an example where a manufacturer invests significant amounts of resources toward enforcement. The interesting point to note here is that the RIAA has recovered only a tiny fraction of its legal costs in terms of penalty, but its much publicized legal action has perhaps paid dividends by educating consumers of a potentially higher r than what they believed earlier. Because legal actions by the RIAA (and lately by the Motion Picture Association of America) are one of a kind, and because most manufacturers take a fairly passive approach toward enforcement, we do not explicitly model these efforts and take r to be exogenous in this research; we discuss the implications of endogenizing it in the concluding section.

The quality of the pirated product is denoted as ϕ; accordingly, the utility of the pirated version to a consumer is $v\phi - r$. Based on prior literature, we assume that $\phi < \theta$. A few words are in order in support of this assumption, which is critical for our analysis. First, pirated products usually do not get product support from manufacturers, as in the case of a software product where illegal users are not offered updates and patches (e.g., Lahiri 2012). Second, pirated copies of software or video games may be missing certain important functionalities and may even contain embedded malicious codes (Jaisingh 2009). Third, examples abound where the physical quality of the pirated product is less than that of the original product, as in the case of pirated movies or music (e.g., Karaganis 2011). Even if the physical quality is the same, users of illegal torrent sites usually face a much higher download time (Sundararajan 2004). Finally, other considerations—such as higher search costs, existence of decoy files, and uncertainties about the product itself—may also diminish a consumer's perception of quality (Sundararajan 2004).

[2] Acquiring the pirated version may also involve additional costs, such as search costs and payments to illegitimate sellers. Usually, these costs are quite low compared to legal liabilities.

We further argue that ϕ cannot be independent of θ—pirated versions of two information products with widely differing quality levels are unlikely to be deemed identical quality-wise.[3] Naturally, ϕ should be an increasing function of θ, satisfying the conditions $\phi|_{\theta=0} = 0$ and $\phi < \theta$. For the sake of analytical tractability, we choose a linear form, though a strictly concave form would also yield similar results:[4]

Assumption 2. *The quality of the pirated product is $\phi = \beta\theta$, where $\beta \in (0, 1)$.*

Following well-known properties of digital goods, we assume that the manufacturer's marginal cost is negligible (e.g., Shapiro and Varian 1999, Jones and Mendelson 2011) and that the product development cost, $c(\theta)$, is a quadratic function of θ (e.g., Moorthy 1988, Jones and Mendelson 2011).

Assumption 3. *The manufacturer's marginal cost of producing an additional copy is* 0, *and its product development cost is $c(\theta) = c\theta^2/2$.*

Timeline. We assume the following timeline. The manufacturer decides on the product quality and announces the price. Consumers then decide whether to buy, pirate, or forgo use completely. As with other game-theoretic settings, solving this game requires traversing the timeline backward. We, therefore, begin by solving the consumer's decision problem and then solve the manufacturer's decision problem.

Consumer's Decision Problem. Consumers decide based on their individual rationality (IR) and incentive compatibility (IC) constraints. A consumer buys the legal version if the following IR and IC conditions are satisfied:

$$v\theta - p \geq 0 \quad \Rightarrow \quad v \geq \frac{p}{\theta}, \tag{IR-L}$$

$$v\theta - p \geq v\beta\theta - r \quad \Rightarrow \quad v \geq \frac{p-r}{(1-\beta)\theta}. \tag{IC-L}$$

Similarly, a consumer procures the pirated version if the following IR and IC conditions are satisfied:

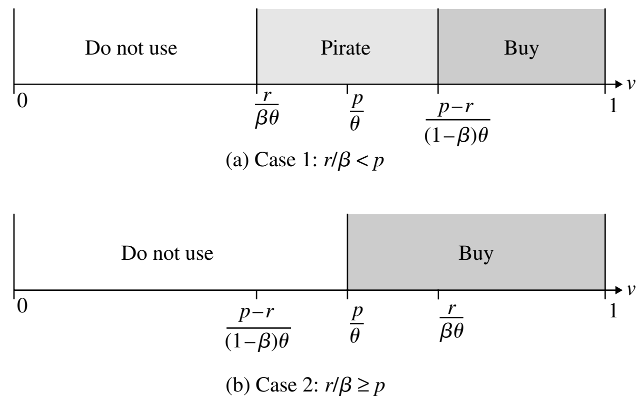
$$v\beta\theta - r \geq 0 \quad \Rightarrow \quad v \geq \frac{r}{\beta\theta}, \tag{IR-P}$$

$$v\beta\theta - r \geq v\theta - p \quad \Rightarrow \quad v \leq \frac{p-r}{(1-\beta)\theta}. \tag{IC-P}$$

[3] For counterfeit *physical* products, however, ϕ could be independent of θ. The quality of a fake *Rolex* watch does not necessarily have a relationship with the quality of the much costlier original watch.

[4] Both linear and strictly concave forms are quite reasonable in this context, as the gap between θ and ϕ often widens with θ. For instance, the value of forgone technical support is likely to be higher for the pirated copy of a software product that is feature rich and expensive. Similarly, a higher-quality movie or TV show, because of its larger file size, would impose a longer delay when downloaded from an illegal file-sharing site lacking adequate capacity and proper connections to content distribution networks.

Figure 1 **Consumers Self-Select Based on Their Relative Benefits**



Since $r/(\beta\theta) < p/\theta$ implies $p/\theta < (p-r)/((1-\beta)\theta)$, two cases arise, which are depicted in Figure 1. Accordingly, the legal demand, $q(p, \theta)$, can be written as

$$q(p, \theta) = \begin{cases} 1 - \dfrac{p-r}{(1-\beta)\theta} & \text{if } p > \dfrac{r}{\beta}, \\ 1 - \dfrac{p}{\theta} & \text{otherwise.} \end{cases} \tag{1}$$

We note that when $p \leq r/\beta$, no user finds it optimal to pirate the information good, and the entire demand of $1 - p/\theta$ is from legal users only.

Manufacturer's Decision Problem. In this monopoly setting, the profit maximization problem is

$$\max_{p,\,\theta} \pi(p, \theta) = pq(p, \theta) - \frac{c\theta^2}{2}.$$

It does not matter whether the manufacturer does this optimization simultaneously or sequentially (Boyd and Vandenberghe 2004, p. 133). For the sake of exposition, let us assume that the manufacturer chooses the quality first and then chooses the price. When this sequence is assumed, at the time of the pricing decision, the manufacturer knows the quality, and the optimal price is chosen accordingly. Let us denote this optimal price by $p^*(\theta) = \arg\max_p \pi(p, \theta)$. The following lemma characterizes this optimal price:

Lemma 1. *For a given quality level θ, the optimal price, $p^*(\theta)$, is as follows:*

$$p^*(\theta) = \begin{cases} \dfrac{(1-\beta)\theta + r}{2} & \textit{if } \theta > \dfrac{r(2-\beta)}{\beta(1-\beta)}, \\ \dfrac{r}{\beta} & \textit{if } \dfrac{2r}{\beta} \leq \theta \leq \dfrac{r(2-\beta)}{\beta(1-\beta)}, \\ \dfrac{\theta}{2} & \textit{otherwise.} \end{cases}$$

From Lemma 1, we can see that when $\theta \leq r(2-\beta)/(\beta(1-\beta))$, no user pirates the information good, and piracy ceases to exist. In other words, piracy exists only if the quality of the product is sufficiently high relative to the cost of piracy. Specifically, piracy exists if $\theta > r(2-\beta)/(\beta(1-\beta))$. Otherwise, the quality of the product is sufficiently low, and piracy is a suboptimal choice for every consumer.

We now rewrite the manufacturer's profit maximization problem as follows, with $p^*(\theta)$ being as specified by Lemma 1:

$$\max_{\theta} \pi(\theta) = p^*(\theta)q(p^*(\theta)) - \frac{c\theta^2}{2}.$$

Although it can be easily shown that $\pi(\theta)$ is a continuous function of θ, it turns out that it is not necessarily concave in θ. Yet, as the following proposition shows, the solution to this maximization problem is unique.

Proposition 1. *Let* $\rho = (\beta/c)((1-\beta)/(2-\beta))^3$. *Then, the optimal quality level,* θ^*, *can be found from the following*:

- Piracy Region. *When* $r < \rho$, *the manufacturer tolerates some level of piracy and sets* $\theta^* = \tilde{\theta}$, *where* $\tilde{\theta}$ *is the unique real solution of*

$$\pi'(\theta) = \frac{1}{4}\left(1 - \beta - \frac{r^2}{(1-\beta)\theta^2} - 4c\theta\right) = 0,$$

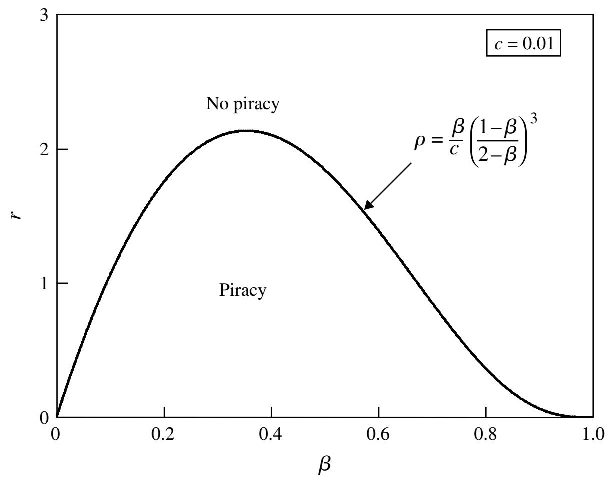
satisfying $\tilde{\theta} > r(2-\beta)/(\beta(1-\beta))$.

- No-Piracy Region With Threat. *When* $\rho \le r \le \beta/(8c)$, *there is no piracy, but the threat of piracy forces the manufacturer to set* $\theta^* = (r^2/(c\beta^2))^{1/3}$.
- No-Piracy Region Without Threat. *In all other cases, the threat of piracy disappears, and the manufacturer sets* $\theta^* = 1/(4c)$.

Proposition 1 partitions the (β, r) space into three regions: When $\rho \le r \le \beta/(8c)$, the cost of piracy is considered relatively high by all users and no one uses the pirated product. Even though there is no piracy in this region, the threat of piracy—piracy, in some sense, works as a "competitor" and reduces the monopoly power of the manufacturer—ensures that the manufacturer does not price the product too high and that it provides a sufficiently high quality level. On the other hand, when $r < \rho$, we are likely to see a mix of pirates and legal users. Finally, when r is very large, i.e., $r > \beta/(8c)$, piracy is extremely costly to users and they do not even consider it as a viable option. Consequently, the threat of piracy completely disappears, and the manufacturer is free to exert its full monopoly power in the market. From now on, we will exclude this last region from our discussion, because, without the threat of piracy, the market reduces to a traditional monopoly market, which is not the focus of this research.

In Figure 2, we show the two main regions of the (β, r) space for $c = 0.01$. It is quite interesting to

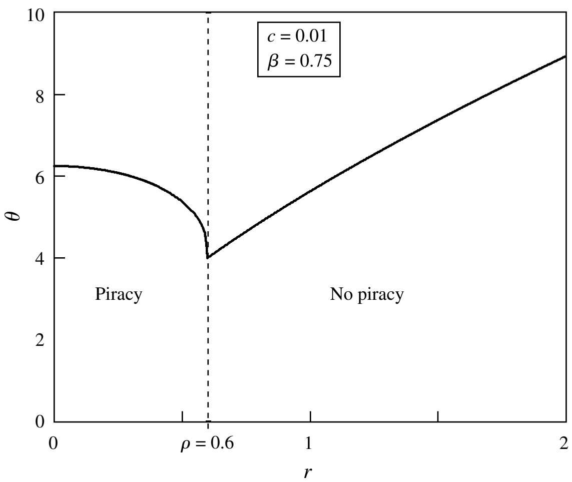
Figure 2 **Regions of Piracy**



observe that the threshold differentiating these two regions, ρ, is not a monotonic function of β, the quality degradation parameter. The value of ρ is small for extreme values of β and is large in the intermediate range. Although this may appear counterintuitive at first, a closer examination of the context reveals why this should indeed be the case. Recall that the quality difference between the original and pirated versions is $(1-\beta)\theta$ in our model. At low values of β, the pirated product is well differentiated from the original product, and the threat of piracy does not much diminish the manufacturer's monopoly power. Therefore, even at a low level of enforcement, the monopolist is able to eliminate piracy by slightly lowering the price. As β increases, however, the threat of piracy becomes more pronounced, and the manufacturer needs a higher level of enforcement to combat piracy. As β increases even further, $(1-\beta)\theta$ becomes quite small, and the pirated product becomes similar to the legal one in quality. Consequently, the marginal return from investing in θ diminishes sharply. In fact, the manufacturer, upon realizing that it is unable to differentiate on quality, decreases the price substantially to better compete with the pirated version. At the extreme, when $\beta = 1$, the manufacturer simply sets $p = r$, and piracy vanishes as long as $r > 0$.

Often, high prices of various information goods are cited as a reason for piracy, especially in emerging economies (Karaganis 2011), implying that a manufacturer can control piracy by pricing its product aggressively. Indeed, Proposition 1 indicates that when the enforcement level is sufficiently high ($r \ge \rho$), it is possible to price the product in such a way that no consumer has an incentive to pirate. However, when adequate enforcement is lacking, as might be the case with some emerging economies, pricing the product to fully eliminate piracy is suboptimal, and the best option for the manufacturer is to accept a piracy-tolerant approach. This is essentially the crux of this

Figure 3 **Optimal Quality of the Legal Product as a Function of Enforcement**



result. As we show in §§5 and 6, the basic insight from this proposition remains applicable even in more general settings, such as the one in which some consumers do not consider piracy to be an option.

We now turn our attention to the main question: How does the optimal quality change with the level of enforcement? To investigate this issue, we first plot the result in Proposition 1 as a function of r in Figure 3, for $c = 0.01$ and $\beta = 0.75$. As can be seen from this figure, the conventional wisdom that the incentive to invest in quality automatically decreases with piracy is not always true—the manufacturer produces a higher-quality product at $r = 0$ than it does at any positive r below ρ. We state this result as Theorem 1.

Theorem 1. *In the setting described above, in which the manufacturer serves a consumer market heterogeneous in its preference for quality, if $r \in [0, \rho)$, then $d\theta^*/dr < 0$, i.e., in the presence of piracy, the optimal quality level is decreasing in enforcement.*

Theorem 1 formally proves that prior intuitions regarding the impact of piracy on quality do not always hold. The reason behind this unexpected impact of piracy on quality is as follows: When faced with "competition" from the pirated product, the manufacturer increases the quality of the legal version to differentiate the product from its pirated version and secure consumers who value quality highly. As a result, when piracy enforcement decreases, the manufacturer finds it optimal to increase its investments toward building a higher-quality product despite, as we will show later, making lower profits. In other words, the lower the cost of piracy, the stronger is the manufacturer's incentive to differentiate the legal product from the pirated one. Perhaps this explains the surprising behavior by certain manufacturers of information goods, as discussed in §1, to enhance the quality of their offerings in the face of increasing piracy threats.

Earlier research has also assumed that consumers get a lower value from the pirated product (Jain 2008, Novos and Waldman 1984). However, there, it has been assumed that all consumers have the same preference for quality, which led to the conclusion that a monopolist typically underinvests in quality in the presence of piracy. As we show here, in a setting where consumers differ in their preferences for quality, this conclusion is no longer applicable. Therefore, we augment the literature in the following way: We show that often a monopolist's optimal response to a lower level of piracy enforcement is to invest more in quality.

Note that Theorem 1 establishes a relationship between quality and enforcement in the piracy region, but it does not shed any light on the relationship between the optimal quality and piracy rate—a relationship that was used to motivate this research. To that end, we examine how the piracy rate, which is endogeneously determined in our model, varies with the level of enforcement, r. The piracy rate is essentially the fraction of users who use the product illegally and is obviously zero in the no-piracy region. In the piracy region, it can be expressed as

$$\mu(r) = \frac{(p^*(\theta^*) - r)/((1-\beta)\theta^*) - r/(\beta\theta^*)}{1 - r/(\beta\theta^*)}.$$

Now, the relationship between the piracy rate and r can be formally stated as

Corollary 1. *In the piracy region, the piracy rate, $\mu(r)$, is monotonically decreasing in r.*

Corollary 1 clearly shows that the usual claim regarding the relationship between quality and piracy rate does not always hold. Indeed, at lower levels of enforcement, the piracy rate is higher, but the manufacturer still invests more in quality enhancement.

We have so far argued that the common wisdom that piracy works as a disincentive to invest in quality does not hold across the board. However, it does hold in the region $r \geq \rho$, i.e., in the no-piracy region. The lesson here is that when the manufacturer is capable of successfully combating piracy, it does have an incentive to increase quality with enforcement—because stricter enforcement helps the manufacturer turn a higher quality level directly into a higher demand and profit. This is different from what happens in the piracy region, where higher enforcement reduces the incentive to distinguish the legal product from its pirated version and results in a lower quality level.

It is imperative for us to note that this apparently counterintuitive relationship between the cost of piracy and the quality level does not involve positive network effects. We concede that positive network effects indeed present an opportunity to profit from piracy (Conner and Rumelt 1991), and higher profits may lead to higher incentives to invest in a better product. However, as we have shown, even without positive network effects, piracy potentially has a positive effect on quality, because the consumer heterogeneity in the preference for quality induces the manufacturer to differentiate the legal product from its pirated counterpart.

4. Consumer and Social Welfare

We now investigate the impact on the consumer and social welfare. In this analysis, we initially exclude illegal users, because it is unlikely that social planners or consumer advocates would be too interested in promoting the welfare of illegal users. Later, for the sake of completeness, we briefly examine the combined surplus including that of illegal users as well.

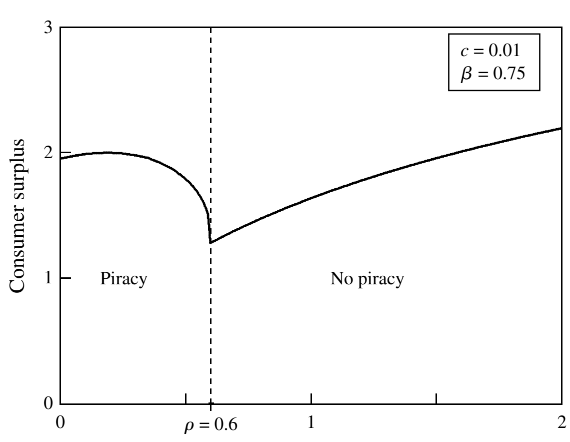
In this section, we argue that, contrary to the common perception, the consumer and social surpluses are not monotonically increasing in the level of enforcement. We further argue that the reason for this unexpected behavior is that stricter enforcement can lead to lower quality, adversely affecting legal users. This finding contradicts the common claim that weaker enforcement shrinks welfare and hinders economic growth (GAO 2010, OECD 2008).

First, we consider the surplus of the legal consumers; it can be found from

$$\int_{\max\{(p-r)/((1-\beta)\theta),\, p/\theta\}}^{1} (v\theta - p)\, dv.$$

Substituting the optimal price and quality from Lemma 1 and Proposition 1, we can easily obtain this surplus; Figure 4 shows how it changes with the enforcement level, for $c = 0.01$ and $\beta = 0.75$. As apparent from this figure, the insight that a stricter enforcement effort, or equivalently a larger piracy cost, increases the surplus of legal users is simply not true in the region in which piracy exists. The surplus is strictly lower at the point where piracy ceases to exist ($r = \rho$) than at no enforcement ($r = 0$). Although this may seem surprising, given what we already know, it is easy to explain why the consumer surplus behaves this way. It can be shown that as enforcement increases, the number of legal users increases sharply in the piracy region ($r < \rho$) and then declines gradually in the no-piracy region ($r \geq \rho$). On the contrary, the quality of the information good decreases with r in the piracy region but increases in the no-piracy region (see Figure 3). The average surplus to an individual legal consumer is directly linked with the quality and, therefore, increases or decreases with the latter. Because the total surplus of all legal users is a product of the average per-user surplus and the number of legal users, in the no-piracy region, the total surplus monotonically increases with r as the slight decrease in the number of consumers is amply compensated by the rapid increase in the per-user surplus. In the piracy region, on the other hand, the trend is somewhat more complicated. When r is very small, the sharp increase in the number of legal users may dominate and cause their total surplus to increase, even though the per-user surplus slowly declines. As r increases further, however, this reduction in the per-user surplus becomes sufficiently large to offset the expanding base of legal users, causing the total consumer surplus to decline. Below, we state this more formally:

Figure 4 **Surplus of Legal Consumers as a Function of Enforcement**



Proposition 2. *In the setting described above, in which the manufacturer serves a consumer market heterogeneous in its preference for quality, the consumer surplus of legal users is not monotonically increasing in the piracy cost or enforcement. This surplus is strictly decreasing in r in some parts of the region where $r \in [0, \rho)$.*

Proposition 2 has a clear implication for consumer advocacy groups and policy makers—it is not always better to have a high level of enforcement. Information goods, by their very nature, often afford their providers with some degree of monopoly power, which, in turn, can eat into the consumer welfare—a manufacturer may not invest adequately in the quality of the good or may raise the price. Piracy of information goods, although maligned heavily by most, has a contrary side—it somewhat reduces the monopoly power of a provider and increases the consumer welfare. Because the cost to a social planner for increasing the level of piracy enforcement is often substantial, a proper balance needs to be attained.

Even though the consumer surplus is not monotonic in enforcement, the manufacturer's profit is. To see this more clearly, in Figure 5, we plot the

Figure 5 Manufacturer's Profit as a Function of Enforcement

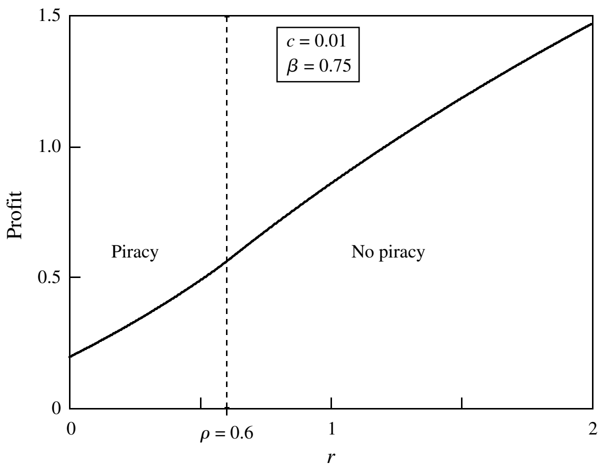
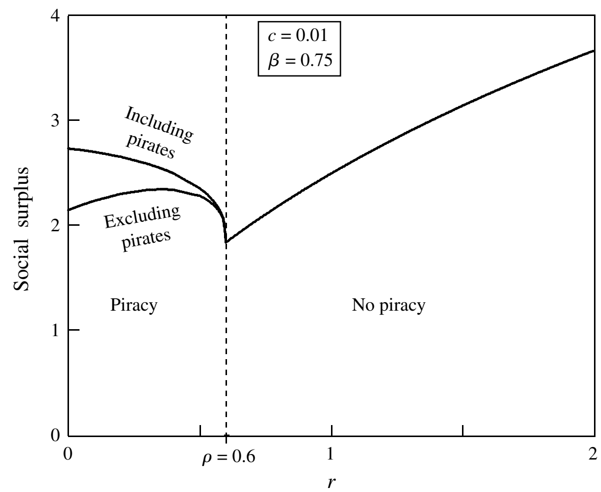


Figure 6 Social Surplus as a Function of Enforcement



manufacturer's profit as a function of r, for $c = 0.01$ and $\beta = 0.75$. It is clear from this figure that the manufacturer's profit monotonically increases with the enforcement level. This perhaps explains why the software industry constantly seeks more enforcement—a lower enforcement level does not always adversely impact quality, but it does hurt the profit. In contrast, a high level of enforcement allows a manufacturer to weed out piracy and regain portions of its monopoly power.

Of course, policy makers usually prefer to consider the social surplus in formulating policy debates. It is, therefore, imperative that we study how the social surplus (excluding illegal users) behaves. This surplus,

$$\int_{\max\{(p-r)/((1-\beta)\theta),\, p/\theta\}}^{1} v\theta\, dv - \frac{c\theta^2}{2},$$

can again be obtained from Lemma 1 and Proposition 1; we plot it in Figure 6 as a function of enforcement level, for $c = 0.01$ and $\beta = 0.75$. In this figure, for the sake of completeness, we also plot the total social surplus that even includes the pirates. Clearly, the implication for the social planner is that enforcing piracy does not always lead to a higher aggregate welfare for the manufacturer and legal users of its product. Only when r is raised to the level sufficient to eliminate piracy, the relationship between r and the social surplus is as commonly believed. In the region where piracy exists, the impact of stricter enforcement can be exactly the opposite of the intended impact. As long as the quality level is decreasing in enforcement, it is not safe to infer that the social surplus is increasing. Written more formally:

Proposition 3. *In the setting described above, in which the manufacturer serves a consumer market heterogeneous in its preference for quality, the social surplus excluding illegal users is not necessarily increasing in the piracy cost or enforcement. In particular, for $\beta \geq 0.6533$, this surplus is strictly decreasing in r in some parts of the region where $r \in [0, \rho)$.*

Because the manufacturer's profit increases with enforcement, the impact on the social surplus (excluding the illegal users) depends on whether this increase is sufficient to offset the decrease in the surplus of legal users. Proposition 3 suggests that when β is reasonably large, that is, the quality of the pirated product is sufficiently close to that of the legal product, the social surplus declines in some parts of the region where piracy exists. The intuition behind this anomalous behavior is as follows. When β is adequately large, the pirated product is quite competitive. Therefore, increased enforcement need not translate to large gains in the profit necessary to offset decreases in the consumer surplus.

Figure 6 also shows the combined surplus including the pirates. We find that when they are included in the total social welfare estimation, our results are strikingly consistent to those of Chen and Png (2003) and Novos and Waldman (1984), who find that stricter enforcement leads to a loss in social welfare in general. This loss is expected. Enforcement reduces the value generated through illegal use but does not have any bearing on production costs as the marginal cost is zero. However, we are of the opinion that an increase in welfare from an illegal activity should not influence a policy maker to embrace that activity.[5] Therefore, we feel that the correct yardstick for

[5] If the gentle reader is still not convinced of this argument, consider another one. It is well known that the marginal value of money to a poor individual is more than that to a rich individual. However, an illegal activity, such as stealing, aimed toward a redistribution of wealth cannot be supported, even if it may have its moral attraction to some. Perhaps, Robinhoods do not have a place in the modern society.

public policy debate should exclude the surplus of illegal users. In the end, whether or not illegal users are included, a salient implication of our analysis is that a stricter enforcement effort does not necessarily boost the social surplus, and an enforcement level should be chosen only after a careful analysis and not just based on claims from the industry.

5. A Mix of Ethical and Unethical Consumers

We now extend our basic model by introducing a group of purely "ethical" consumers, who either buy or forgo use but do not use illegally (August and Tunca 2008).[6] We assume that the fraction of consumers who are ethical is α. The remaining fraction, $1-\alpha$, is potentially "unethical" in the sense that they consider using the pirated version as an option. We now show that our earlier results are quite robust and carry over to this wider setting, with only slight modifications.

The demand from the ethical segment is always $\alpha(1-p/\theta)$. The demand from the unethical segment is $(1-\alpha)(1-p/\theta)$ if $p \le r/\beta$; otherwise, it is $(1-\alpha)\max\{0, 1-(p-r)/((1-\beta)\theta)\}$, because there are just two possibilities—one in which some unethical users buy the legal version, i.e., $(p-r)/((1-\beta)\theta) < 1$, and another where they all pirate, i.e., $(p-r)/((1-\beta)\theta) \ge 1$. As shown later in this section, the second possibility is relevant only in a limited situation where the quality degradation is minimal ($\beta \to 1$) and the piracy cost is small ($r \to 0$), essentially implying that the manufacturer has little chance of competing with the pirated version for a share of the unethical segment. For this reason, as well as for expositional simplicity, we consider only the first possibility for which the total legal demand, $q(p,\theta)$, can be expressed as

$$q(p,\theta)=\begin{cases}\alpha\left(1-\dfrac{p}{\theta}\right)+(1-\alpha)\left(1-\dfrac{p-r}{(1-\beta)\theta}\right) & \text{if } p>\dfrac{r}{\beta},\\[2ex] 1-\dfrac{p}{\theta} & \text{otherwise.}\end{cases}$$

Lemma 2. *For a given quality level θ, the optimal price, $p^*(\theta)$, is given by*

$$p^*(\theta)=\begin{cases}\dfrac{(1-\beta)\theta+r(1-\alpha)}{2(1-\alpha\beta)} & \text{if } \theta>\dfrac{r(2-\beta(1+\alpha))}{\beta(1-\beta)},\\[2ex] \dfrac{r}{\beta} & \text{if } \dfrac{2r}{\beta}\le\theta\le\dfrac{r(2-\beta(1+\alpha))}{\beta(1-\beta)},\\[2ex] \dfrac{\theta}{2} & \text{otherwise.}\end{cases}$$

[6] Ethical consumers can also be thought of as those who face an infinitely high piracy cost. In other words, a mixture of ethical and unethical consumers allows us to model some heterogeneity in the piracy cost faced by consumers.

Note that the threshold for θ, above which piracy exists, is now $r(2-\beta(1+\alpha))/(\beta(1-\beta))$; recall that this threshold was $r(2-\beta)/(\beta(1-\beta))$ for the basic model, which can also be obtained by simply setting $\alpha=0$ here. Using Lemma 2, we can reduce the manufacturer's optimization problem to a single decision variable, θ, which leads to the following result:

Proposition 4. *Let $\rho(\alpha)=(\beta/c)((1-\beta)/(2-\beta(1+\alpha)))^3$. Then, the optimal quality level, θ^*, is as follows:*

- Piracy Region. *When $r<\rho(\alpha)$, the manufacturer tolerates some piracy and sets $\theta^*=\tilde{\theta}(\alpha)$, where $\tilde{\theta}(\alpha)$ is the unique real solution of*

$$\pi'(\theta)=\frac{1}{4}\left(\frac{1-\beta}{1-\alpha\beta}-\frac{r^2(1-\alpha)^2}{(1-\beta)(1-\alpha\beta)\theta^2}-4c\theta\right)=0,$$

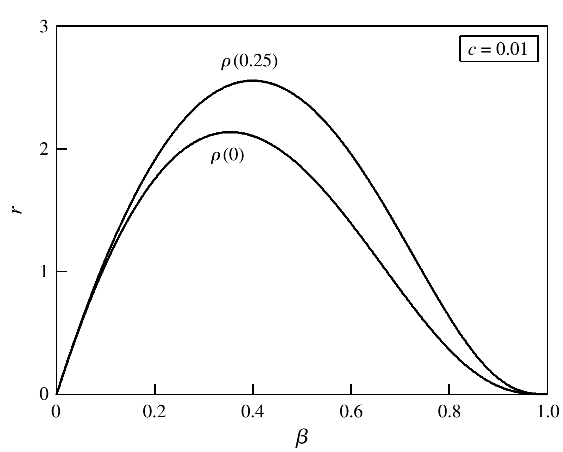
satisfying $\tilde{\theta}(\alpha)>r(2-\beta(1+\alpha))/(\beta(1-\beta))$.

- No-Piracy Region With Threat. *When $\rho(\alpha)\le r\le\beta/(8c)$, there is no piracy, but the threat of piracy makes the manufacturer set $\theta^*=(r^2/(c\beta^2))^{1/3}$.*
- No-Piracy Region Without Threat. *In all other cases, the threat of piracy disappears and $\theta^*=1/(4c)$.*

Similar to Proposition 1, Proposition 4 also partitions the (β, r) space into two main regions: When $r\ge\rho(\alpha)$, no one uses the pirated product. On the other hand, when r is below this threshold, we are likely to see a mix of pirates and legal users.

In Figure 7, we plot this threshold as a function of β for two different values of α, when $c=0.01$. It is interesting that this new threshold, $\rho(\alpha)$, is larger than the original threshold, $\rho=\rho(0)$. One would expect that the presence of ethical consumers should make the task of eliminating piracy easier, thereby making the threshold smaller for $\alpha>0$. However, we observe exactly the opposite—the task becomes more difficult, and this difficulty level increases as the fraction, α, of ethical consumers increases. Although apparently

Figure 7 Regions of Piracy with Ethical Consumers



counterintuitive, this result can be explained by examining how the manufacturer reacts to the presence of ethical consumers. Recall from our basic model that the manufacturer's incentive to lower price or invest in quality is driven by its desire to compete with the pirated version. However, when faced with a fraction of ethical users, who under no circumstances would choose the pirated version, this desire to compete with the pirated version lessens. Consequently, an unethical consumer finds pirating relatively more attractive, unless confronted by stricter enforcement. Therefore, a higher enforcement level is required to eliminate piracy completely. Below, we state this more formally:

Corollary 2. *The piracy region expands as the fraction of ethical consumers, α, increases, i.e., $\rho(\alpha)$ is an increasing function of α.*

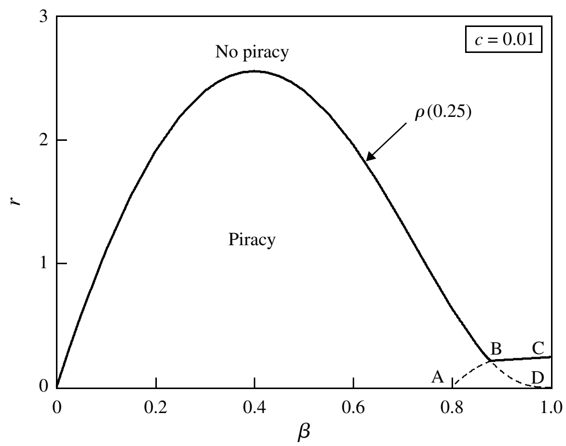
Even though the region of piracy expands as α increases, the original implication of Theorem 1—higher enforcement does not necessarily lead to higher incentives to invest in quality—remains applicable in this wider setting. Furthermore, as explained already, the presence of ethical consumers lessens the monopolist's desire to compete with the pirated product. Therefore, the incentive to adjust quality in response to a change in enforcement is lower in the presence of ethical consumers. We state these results in Theorem 2:

Theorem 2. *Consider a manufacturer serving a market with a mix of ethical and unethical consumers as described above. If $r \in [0, \rho(\alpha))$, then* (i) *$\partial\theta^*/\partial r < 0$, i.e., in the presence of piracy, the optimal quality level is decreasing in the enforcement level; and* (ii) *in this region, $\partial(\partial\theta^*/\partial r)/\partial\alpha > 0$, i.e., the extent of decrease in quality with r is decreasing in α.*

For completeness, we now consider the second possibility where β is so large or r is so small that it becomes optimal to choose p and θ such that $(p-r)/((1-\beta)\theta) \geq 1$. In such a situation, the solution in Proposition 4 and Lemma 2 is not optimal, because it is not feasible for the manufacturer to profitably attract any unethical consumer to the legal product. When that happens, the manufacturer would deliberately disregard the unethical fraction and target only the ethical segment of the market. Consequently, $q(p, \theta) = \alpha(1 - p/\theta)$, and it can be easily shown that $\theta^* = \alpha/(4c)$ and $p^* = \alpha/(8c)$, resulting in an optimal profit of $\alpha^2/(32c)$. If and only if this profit is π^* or higher, it is optimal for the manufacturer to target the ethical segment alone, where π^* denotes the profit obtained from Proposition 4 and Lemma 2. Stated formally:

Proposition 5. *If $\pi^* \leq \alpha^2/(32c)$, $\theta^* = \alpha/(4c)$ and $p^* = \alpha/(8c)$; otherwise, the optimal solution is given by Proposition* 4 *and Lemma* 2.

Figure 8 Revised Regions of Piracy with Ethical Consumers



Recall that Proposition 4 and Lemma 2 were derived under the implicit assumption that $(p-r)/((1-\beta)\theta) < 1$, but this constraint was not explicitly enforced; it is, therefore, possible that for some parameter values, that solution is not applicable. This is not a problem—Proposition 5 ensures that if such a solution does exist, it must be dominated by the solution where the manufacturer targets the ethical fraction alone. Viewed differently, when the solution in Proposition 4 and Lemma 2 is picked as the overall optimal, the solution would indeed abide by the implicit assumption of $(p-r)/((1-\beta)\theta) < 1$.

When Proposition 5 is incorporated into our analysis, the piracy region actually expands even further, albeit slightly; this expansion appears as region BCD in Figure 8, which is essentially a modified version of Figure 7 for $\alpha = 0.25$. In Figure 8, region ABCD represents the portion of the (β, r) space where the dominant strategy for the manufacturer is that of targeting only the ethical segment. Although the optimal quality level is flat at $\alpha/(4c)$ in region ABCD, when r is increased beyond this region, quality declines sharply along the edge ABC. In other words, even in this extended analysis, quality can decline with increased enforcement. Figure 8 also shows that the expanded piracy region is quite small and involves a portion of the (β, r) space where piracy has little downside to an unethical consumer, either in terms of quality (β) or the piracy cost (r), a scenario that is unlikely in practice. We preclude this region from our subsequent analysis.

We conclude this section with a word about the consumer and social welfare. It turns out that both the consumer and social surplus (excluding pirates) increase with α in the piracy region, but remain the same in the no-piracy region. Beyond that, however, all the insights obtained from the basic model are still valid in this wider setting. Proposition 2, which shows that the surplus of legal users is not monotonically increasing in the region where piracy exists, continues to be applicable. Proposition 3, which shows the behavior of the social surplus, continues to hold as well, for certain ranges of parameter values. For the sake of brevity, we omit restating these two propositions formally.

6. Versioning

The literature on piracy of information goods often ignores the possibility that a manufacturer can offer lower-quality versions of its product to combat piracy. Cho and Ahn (2010) and Wu and Chen (2008) are among exceptions who discuss this possibility. Perhaps the main reason why most researchers have ignored versioning in this context is that it has been shown to be suboptimal for an information good with zero marginal cost (Bhargava and Choudhary 2001). In this section, we consider this possibility and explore whether the insights obtained so far remain applicable.

Versioning of a product usually has two opposing effects. On one hand, it can capture marginal users who would not buy otherwise. On the other hand, it leads to cannibalization of the higher-quality version by the lower one. In our context, versioning has an additional benefit of converting some pirates to legal users. For most information products, versioning does not involve additional costs to the manufacturer; for example, a lower-quality version of a software product is easily produced by "turning off" features of its higher-quality version (Jones and Mendelson 2011, Shapiro and Varian 1999). Hence, we limit our discussion to the case in which versioning is costless. Incorporating additional costs, such as in Wu and Chen (2008), will bias the discussion in a predictable way.

We consider the possibility of offering an inferior version, V2, with quality $\gamma\theta$, $0<\gamma<1$, and price s such that some consumers find it incentive compatible to use it, i.e., $p>s/\gamma$; let us call the superior version V1. When V1 and V2 are offered simultaneously, the *ethical* segment would always use *both*. In contrast, with respect to the *unethical* segment, four possible cases can arise in the equilibrium:

Case 1. Both V1 and V2 are used, but a fraction still pirates.

Case 2. Both V1 and V2 are used, and no one pirates.

Case 3. Only V1 is used, and a fraction pirates.

Case 4. Only V1 is used, but no one pirates.

We now investigate how the manufacturer should chose γ and s, if it were to offer both V1 and V2. The following result is necessary:

Lemma 3. *If only purely ethical users are considered or if there is no threat of piracy, versioning is not an optimal strategy.*

Lemma 3 essentially restates the results obtained by Bhargava and Choudhary (2001), who prove that a manufacturer with zero marginal cost is not likely to offer a second version. An immediate implication of this lemma is that Cases 3 and 4 can be ruled out—unless V2 can lure some unethical consumers into becoming legal, its only impact would be to cannibalize V1 for the ethical segment.

Lemma 4. *When versioning is used, the manufacturer sets the quality and price of the inferior version* (*V*2) *at* $\gamma=\beta$ *and* $s=r$, *respectively.*

Lemma 4 states that if versioning is used at all, the manufacturer simply matches the pirated version in quality and charges a price equal to the piracy cost, thereby eliminating piracy completely. This, of course, implies that versioning and piracy cannot coexist and Case 1 can never arise. Therefore, to analyze versioning as a strategy, we need to consider Case 2 only for deriving the price and quality of V1. The final solution can be stated as follows:

Proposition 6. *Let* $\tilde{\theta}(\alpha)$ *and* $\rho(\alpha)$ *be as defined in Proposition* 4. *Let* $\hat{\theta}$ *be the unique real solution of*

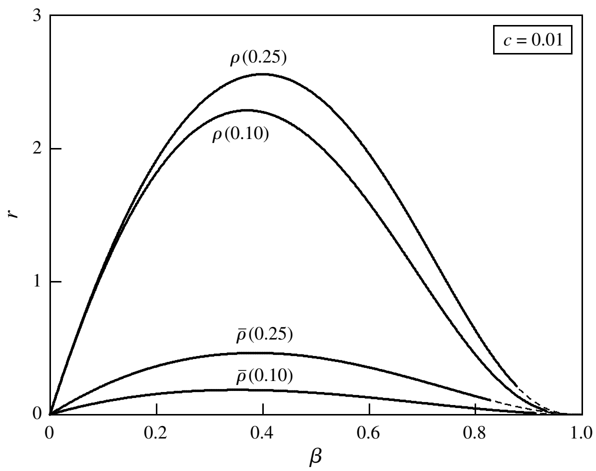
$$\frac{1-\beta}{4}+\frac{r^2}{\beta\theta^2}-c\theta=0.$$

Then, there exists a unique threshold for r *in* $[0,\rho(\alpha))$, *denoted* $\bar{\rho}(\alpha)$, *such that the optimal quality level,* θ^*, *is given by the following*:

- Piracy Region (No Versioning). *When* $r<\bar{\rho}(\alpha)$, *the manufacturer tolerates some piracy and offers only one version with* $\theta^*=\tilde{\theta}(\alpha)$.
- No-Piracy Region With Threat (Versioning). *When* $\bar{\rho}(\alpha)\le r\le\beta/(8c)$, *there is no piracy, but the threat of piracy compels the manufacturer to offer two versions, with* $\theta^*=\hat{\theta}$ *for the higher version.*
- No-Piracy Region Without Threat (No Versioning). *In all other cases, the threat of piracy disappears and the manufacturer, once again, offers only one version with* $\theta^*=1/(4c)$.

From Proposition 6, we observe that, similar to Propositions 1 and 4, exactly three regions emerge in this case as well. When the enforcement level is low ($r<\bar{\rho}(\alpha)$), only one version is offered and piracy exists at optimality. Here, the situation is so hopeless for the manufacturer that it has to tolerate some level of piracy. For moderate levels of enforcement ($\bar{\rho}(\alpha)\le r\le\beta/(8c)$), two versions are offered, and there is no piracy, as V2 replaces the pirated version. The observation that versioning and piracy cannot coexist in this region is just a byproduct of the discrete nature of the piracy cost in our model and, therefore, requires a conservative interpretation. Our result simply means that versioning would not be effective in combating

Figure 9 Regions of Piracy with Versioning



piracy unless enforcement is sufficiently strong. Further, in this region, although there is no piracy, the threat of piracy still remains; it is this threat that compels the manufacturer to offer two versions. When enforcement is even higher ($r > \beta/(8c)$), the threat of piracy disappears, and the manufacturer now enjoys the full monopoly power, where it offers only one version.

Proposition 6 indicates that $\bar{\rho}(\alpha) < \rho(\alpha)$, which is expected given that versioning provides the manufacturer an additional means to combat piracy. To see this clearly, we plot both $\rho(\alpha)$ and $\bar{\rho}(\alpha)$, for two values of α, in Figure 9. As can be seen from this plot, the piracy region shrinks significantly when the manufacturer considers offering a second version. Over a substantial portion of the (β, r) space, however, versioning is not optimal, and piracy still persists. Figure 9 also shows that $\bar{\rho}(0.10) < \bar{\rho}(0.25)$—as the fraction of purely ethical users increases, the relative efficacy of versioning declines. This is intuitive. The profit generated by offering two versions does not change with α, because there is no piracy with two versions. In contrast, the profit with a single version increases with α. Consequently, as α increases, $\bar{\rho}(\alpha)$ increases and versioning becomes less attractive as a strategy. We are now ready to state the final result of this paper:

Theorem 3. *Consider a manufacturer, capable of versioning costlessly, serving a market with a mix of ethical and unethical consumers as described above. If* $r \in [0, \bar{\rho}(\alpha))$, *then* (i) $\partial\theta^*/\partial r < 0$, *i.e., in the piracy region, the optimal quality level is decreasing in the enforcement level; and* (ii) *in this region,* $\partial(\partial\theta^*/\partial r)/\partial\alpha > 0$, *i.e., the extent of decrease in quality with* r *is decreasing in* α.

Theorem 3 further strengthens our earlier results in Theorems 1 and 2. It shows that even when versioning is a possibility, the relationship between the piracy cost and quality defies the common intuition. In all cases where piracy exists, the optimal quality level is surprisingly decreasing in the piracy cost. In other words, weaker piracy enforcement does not reduce the manufacturer's incentive to invest in quality so long as the manufacturer is able to differentiate the legal product from its pirated counterpart by increasing quality. Also, as discussed earlier, the presence of ethical consumers continues to reduce the manufacturer's incentives to compete in quality with the pirated product, resulting in smaller changes in the optimal quality level in response to changes in enforcement.

7. Conclusion

Piracy is recognized as a critical issue facing the providers of information goods and the society at large. The conventional wisdom is that piracy deters innovation and results in reduced investments in quality. In this paper, we develop an economic model to investigate, in the first place, whether or not this perception is indeed correct. We find that there is no clear monotonic relationship between the enforcement level and quality. More specifically, in the region where some piracy exists in the market for an information good, a higher enforcement level lowers a monopolist's incentive to invest in quality. When piracy enforcement increases beyond the above region, piracy is eliminated, but its threat persists, thus reducing the monopoly power of the manufacturer. It is in this region that the common perception about the relationship between piracy enforcement and quality is applicable. When the enforcement level becomes very high, the threat of piracy disappears from the market, and the manufacturer starts enjoying its full monopoly power. At these high levels of enforcement, the optimal quality is the same as the monopoly quality level and does not depend on enforcement.

Our model is motivated by, and our results are consistent with, several real-world observations, such as the ones related to HBO and Valve. In recent years, piracy has become a major concern for these manufacturers. On one hand, the proliferation of illegal torrent sites has made it easier to steal popular TV shows, putting many media companies, including bigger players such as NBC, into an extremely tricky situation (Soghoian 2007). On the other hand, Internet hackers have been helping gamers "jailbreak" their consoles, unlocking them for pirated versions of many top-selling games (Kalning 2007, Keller 2012). These games usually retail for more than $60 a piece, but their pirated versions can be obtained for as little as $4. The piracy rate faced by HBO in Europe indeed reflects a grim reality: Lately, this rate has been

32% for Italy and as high as 46% for Spain (Briel 2010). Likewise, the piracy rate for games and other types of software has also been stubbornly high across the world, in the range of 20%–30% for most developed economies and above 30% for most emerging ones (BSA 2011). Such high piracy rates are an indication that HBO and Valve are very likely operating in the piracy region, where enforcement is inadequate. Apparently, they have few options but to tolerate some level of piracy and to respond to it by enhancing quality to differentiate their products from the pirated counterparts. In this sense, our results have clear implications for manufacturers of information goods seeking appropriate responses to piracy. The key takeaway is that although lowering investments in quality may seem appealing as a response to widespread piracy and as a viable cost-saving measure in the face of reduced profitability, such a strategy is not necessarily profit maximizing. In the presence of "competition" from the pirated product, a manufacturer may find it optimal to produce a higher-quality product to incentivize consumers to give up the pirated version in favor of the legal one. Conversely, a lower quality level can make the legal version less distinguishable from its illegal counterpart, exacerbating the piracy problem and lowering profits even further.

We also perform an extensive welfare analysis in this context, the results of which have important implications for consumer advocacy groups and policy makers. We first examine the impact of piracy on the welfare of legal consumers. We find that when piracy exists, increasing enforcement leads to quality degradation sufficient to harm legal users. When β is high, i.e., the quality of the pirated product is close to that of the legal product, this degradation is severe, so much so that it causes the combined surplus of the manufacturer and legal users to decline. Therefore, when enforcement is costly and eliminating piracy is difficult, our research suggests that the social planner should prefer moderate or high rates of piracy to relatively low rates. This result that pirates can have a positive impact on the manufacturer and legal users—even in the absence of network effects—is new, and it shows that our current thinking about welfare issues does not hold when the quality decision is endogenous. The overall surplus, including that of the pirates, predictably declines in the piracy region, because the value obtained from illegally using a product with a zero marginal cost is forgone. This is consistent with prior literature, which, unlike this paper, has typically included pirates in the social welfare analysis.

We further extend our model to consider a more heterogeneous group of consumers, a portion of which is "purely" ethical in the sense that it never uses the pirated version. In the presence of ethical consumers, the piracy region surprisingly widens. Consequently, the counterintuitive relationship between the incentive to invest in quality and the enforcement level holds over a wider range of values of the latter. We also investigate the situation where the manufacturer may use versioning as a strategy to combat piracy. We find that versioning can be a valid strategy when the enforcement level is neither too low nor too high—in this region there is no real piracy, but its threat reduces the monopoly power of the manufacturer and forces it to offer two versions. The counterintuitive relationship between quality and enforcement persists in the region in which versioning is not optimal and tolerating some piracy is a better choice.

As discussed in §3 and evidenced by the example of RIAA litigations, at times, a manufacturer may be able to take antipiracy measures that can influence the enforcement level favorably. Although the enforcement level, r, is exogenous in our model, endogenizing it is conceptually straightforward; such an extension would nicely capture a manufacturer's dilemma between investing in enforcement versus quality enhancements. Let $\pi^*(r)$ be the manufacturer's optimal profit for a given r, as obtained from our model. Then, the manufacturer can find the optimal r by maximizing the net profit $\pi^*(r) - K(r)$, where $K(r)$ represents the cost of improving piracy enforcement. Under a quadratic $K(r) = kr^2/2$, this net profit has a unique maximum, and the resulting optimal r is monotonically decreasing in k. The implication is interesting: When the cost of antipiracy measures, k, is low, the manufacturer would invest more in enforcement but less in quality. Conversely, when k is high, the return from antipiracy efforts is not sufficient to induce the manufacturer to pursue that strategy to the same extent as before; instead, it would invest more of its resources in building better-quality products to regain portions of its monopoly power.

As is the case with any quantitative model, ours too makes certain assumptions. Some of them, such as the assumption of a quadratic cost function, can be easily relaxed. In fact, we can numerically—and in some cases analytically—show that all our results hold for other convex cost functions. In the basic model, we have assumed that the cost of piracy is the same for all consumers. In the extended models, we have relaxed that to consider purely ethical consumers with an infinite piracy cost in addition to potentially unethical consumers. This discrete nature of the piracy cost may be restrictive in some situations. Another issue that we have not considered is how the quality decision is impacted by piracy in the presence of positive network effects. We are investigating suitable modeling options to address these limitations. However, despite these limitations, we would have achieved our goal if this research has succeeded in drawing the attention of researchers and practitioners to the need to carefully examine the relationship between piracy and the quality of information goods.

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Appendix. Proofs

Proof of Lemma 1. If $q(p,\theta)=1-(p-r)/((1-\beta)\theta)$, then $\pi(p,\theta)=p(1-(p-r)/((1-\beta)\theta))-c\theta^2/2$, implying

$$\frac{\partial\pi}{\partial p}=1-\frac{2p-r}{(1-\beta)\theta}. \tag{2}$$

Since $\partial^2\pi/\partial p^2=-2/((1-\beta)\theta)<0$, the first-order condition, $\partial\pi/\partial p=0$, results in $p^*(\theta)=((1-\beta)\theta+r)/2$, which, according to Equation (1), must be greater than r/β, or $\theta>r(2-\beta)/(\beta(1-\beta))$ for this solution to be valid.

If, on the other hand, $q(p,\theta)=1-p/\theta$, then $\pi(p,\theta)=p(1-p/\theta)-c\theta^2/2$, resulting in

$$\frac{\partial\pi}{\partial p}=1-\frac{2p}{\theta}. \tag{3}$$

Since $\partial^2\pi/\partial p^2=-2/\theta<0$, the first-order condition, $\partial\pi/\partial p=0$, results in $p^*(\theta)=\theta/2$, which, according to (1), should be smaller than r/β, or $\theta<2r/\beta$ for this solution to be valid.

Since $0<\beta<1$, it follows that $r(2-\beta)/(\beta(1-\beta))>2r/\beta$, and we need to consider the range $2r/\beta\le\theta\le r(2-\beta)/(\beta(1-\beta))$. In this range, if $p\in[r/\beta,\infty)$, from (2), $\partial\pi/\partial p<0$, resulting in a boundary solution of $p^*(\theta)=r/\beta$. If $p\in[0,r/\beta]$, then (3) implies that $\partial\pi/\partial p>0$, and the same boundary solution, $p^*(\theta)=r/\beta$, results. Hence, if $2r/\beta\le\theta\le r(2-\beta)/(\beta(1-\beta))$, then the optimal price is simply r/β. □

Proof of Proposition 1. *No-Piracy Region Without Threat*. When $\theta<2r/\beta$, the optimal price is $\theta/2$ (by Lemma 1) and the corresponding profit is $\theta/4-c\theta^2/2$, which is clearly concave in θ. The optimal quality level is obtained from the first-order condition, which leads to $\theta^*=1/(4c)$. Clearly, this solution is applicable if $1/(4c)<2r/\beta$, i.e., if $r>\beta/(8c)$.

No-Piracy Region With Threat. When the optimal price is r/β, the profit is

$$\frac{r(\beta\theta-r)}{\beta^2\theta}-\frac{c\theta^2}{2}.$$

This profit function is also concave in θ, and the optimal quality level can be obtained from the first-order condition

$$\theta^*=\left(\frac{r^2}{c\beta^2}\right)^{1/3}. \tag{4}$$

According to Lemma 1, the solution given by (4) is applicable if $(r^2/(c\beta^2))^{1/3}\le r(2-\beta)/(\beta(1-\beta))$, i.e., if r is at least ρ. Also, $(r^2/(c\beta^2))^{1/3}$ must be at least $2r/\beta$, which leads to $r\le\beta/(8c)$.

Piracy Region. As is evident from the discussion above, when $r<\rho$, the only possibility is that the optimal price is $((1-\beta)\theta+r)/2$. According to Lemma 1, the profit would be

$$\pi(\theta)=\frac{(r+(1-\beta)\theta)^2}{4(1-\beta)\theta}-\frac{c\theta^2}{2}.$$

The first-order condition is $\pi'(\theta)=0$, where

$$\pi'(\theta)=\frac{1}{4}\left(1-\beta-\frac{r^2}{(1-\beta)\theta^2}-4c\theta\right). \tag{5}$$

We are interested in the optimal θ satisfying $\theta>r(2-\beta)/(\beta(1-\beta))$ (see Lemma 1). We note that (i) $\pi'(\theta)$ is strictly positive at $\theta=r(2-\beta)/(\beta(1-\beta))$ if $r<\rho$, and (ii) $\pi'(\theta)$ becomes negative as $\theta\to\infty$. It follows from (i) and (ii) that

- There must exist at least one $\theta\in(r(2-\beta)/(\beta(1-\beta)),\infty)$ where the first-order condition, $\pi'(\theta)=0$, is satisfied. Of all such possible solutions, consider the smallest one and denote it as $\tilde{\theta}$.
- Now, by the choice of $\tilde{\theta}$, $\pi'(\theta)$ must be positive to the left of $\tilde{\theta}$ because of (i). Evidently, $\tilde{\theta}$ is a local maximum, which also implies that $\tilde{\theta}$ must satisfy the second-order condition, $\pi''(\theta)|_{\theta=\tilde{\theta}}<0$.

We now show that $\tilde{\theta}$ is actually the unique maximum, even though $\pi(\theta)$ is not a concave function. Fortunately, its second derivative,

$$\pi''(\theta)=-c+\frac{r^2}{2(1-\beta)\theta^3},$$

is decreasing in θ. Therefore, because it is negative at $\tilde{\theta}$, it must also be so at any $\theta>\tilde{\theta}$. In other words, at all values of θ exceeding $\tilde{\theta}$, the first derivative is strictly negative. Hence, $\tilde{\theta}$ must also be the unique real maximum above $r(2-\beta)/(\beta(1-\beta))$, implying $\theta^*=\tilde{\theta}$. □

Proof of Theorem 1. In the region of interest, the optimal quality satisfies the first-order condition, i.e., $\pi'(\theta^*)=0$. Using the implicit function theorem, we get

$$\frac{d\theta^*}{dr}=-\frac{\partial\pi'(\theta)/\partial r|_{\theta=\theta^*}}{\partial\pi'(\theta)/\partial\theta|_{\theta=\theta^*}}.$$

Now, from (5), we get

$$\frac{\partial\pi'(\theta)}{\partial r}=-\frac{r}{2(1-\beta)\theta^2}<0.$$

And it is also clear from the proof of Proposition 1 that

$$\left.\frac{\partial\pi'(\theta)}{\partial\theta}\right|_{\theta=\theta^*}<0.$$

Therefore, $d\theta^*/dr$ must be negative. □

Proof of Corollary 1. From Lemma 1, the optimal price in the piracy region is given by $p^*(\theta)=((1-\beta)\theta+r)/2$. Substituting this into $\mu(r)$ and differentiating with respect to r, we get

$$\frac{d\mu(r)}{dr}=-\frac{\beta(\theta^*-r(d\theta^*/dr))}{2(1-\beta)(\beta\theta^*-r)^2},$$

which is clearly negative since $d\theta^*/dr<0$ by Theorem 1. □

Proof of Proposition 2. When piracy exists, the surplus of legal users is

$$\int_{(p-r)/((1-\beta)\theta)}^{1} (\theta v - p)\, dv.$$

At $r=0$, the optimal quality and price are $(1-\beta)/(4c)$ and $(1-\beta)^2/(8c)$, respectively. The surplus of legal users is, therefore, $(1+\beta-2\beta^2)/(32c)$.

At $r=\rho=\beta(1-\beta)^3/(c(2-\beta)^3)$, i.e., at the point piracy ceases to exist, the optimal quality and price are $(1-\beta)^2/(c(2-\beta)^2)$ and $(1-\beta)^3/(c(2-\beta)^3)$, respectively. The surplus of legal users is $\int_{r/(\beta\theta)}^{1}(\theta v-p)\,dv=(1-\beta)^2/(2c(2-\beta)^4)$.

Since $0<\beta<1$, it can be shown that $(1-\beta)^2/(2c(2-\beta)^4)<(1+\beta-2\beta^2)/(32c)$. Therefore, the surplus must be decreasing in r at least in some parts of $[0,\rho)$. □

Proof of Proposition 3. When piracy exists, the total surplus of the manufacturer and legal users is

$$\int_{(p-r)/((1-\beta)\theta)}^{1} \theta v\, dv - \frac{c\theta^2}{2}.$$

The total surplus at $r=0$ is $(1-\beta)(2+\beta)/(32c)$. The total surplus at $r=\rho=\beta(1-\beta)^3/(c(2-\beta)^3)$, where piracy ceases to exist, is $\int_{r/(\beta\theta)}^{1}\theta v\,dv-c\theta^2/2=(1-\beta)^2(2-\beta^2)/(2c(2-\beta)^4)$. By directly comparing this surplus with the surplus at $r=0$, we find that the surplus is higher at $r=0$ if $\beta>0.6533$. Therefore, if $\beta>0.6533$, the total surplus must be decreasing in r at least in some parts of $[0,\rho)$. □

Proof of Lemma 2. This proof is similar to the proof of Lemma 1.

If $q(p,\theta)=\alpha(1-p/\theta)+(1-\alpha)(1-(p-r)/((1-\beta)\theta))$, then $\pi(p,\theta)=pq(p,\theta)$ is concave in p. The first-order condition, $\partial\pi/\partial p=1-\alpha(2p/\theta)-(1-\alpha)((2p-r)/((1-\beta)\theta))=0$, results in $p^*(\theta)=((1-\beta)\theta+r(1-\alpha))/(2(1-\alpha\beta))$, which must be greater than r/β, or $\theta>r(2-\beta(1+\alpha))/(\beta(1-\beta))$, for this solution to be valid.

If, on the other hand, $q(p,\theta)=1-p/\theta$, then the first-order condition, $\partial\pi/\partial p=1-2p/\theta=0$, results in $p^*(\theta)=\theta/2$, which should be smaller than r/β, or $\theta<2r/\beta$ for this solution to be valid.

Since $0<\alpha,\beta<1$, $r(2-\beta(1+\alpha))/(\beta(1-\beta))>2r/\beta$. If $2r/\beta\le\theta\le r(2-\beta(1+\alpha))/(\beta(1-\beta))$, then the above partial derivatives imply that $p(1-p/\theta)$ is increasing in $p\in[0,r/\beta]$, but $p(\alpha(1-p/\theta)+(1-\alpha)(1-(p-r)/((1-\beta)\theta)))$ is decreasing in $p\in[r/\beta,\infty)$. Hence, the optimal price is r/β. □

Proof of Proposition 4. This proof is similar to the proof of Proposition 1.

No-Piracy Region Without Threat. When $\theta<2r/\beta$, the optimal price is $\theta/2$ (by Lemma 2) and the corresponding profit is $\theta/4-c\theta^2/2$, which is concave in θ. The optimal quality level is obtained through the first-order condition, which leads to $\theta^*=1/(4c)$. Clearly, this solution is applicable if $1/(4c)<2r/\beta$, i.e., if $r>\beta/(8c)$.

No-Piracy Region With Threat. When the optimal price is r/β, the profit is

$$\frac{r(\beta\theta-r)}{\beta^2\theta}-\frac{c\theta^2}{2}.$$

This profit function is also concave, and the optimal quality level can be obtained, from the first-order condition, as

$$\theta^*=\left(\frac{r^2}{c\beta^2}\right)^{1/3}. \tag{6}$$

According to Lemma 2, the solution given by (6) is applicable if $(r^2/(c\beta^2))^{1/3}\le r(2-\beta(1+\alpha))/(\beta(1-\beta))$, i.e., if r is at least $\rho(\alpha)$. Also, $(r^2/(c\beta^2))^{1/3}$ must be at least $(2r)/\beta$, which leads to $r\le\beta/(8c)$.

Piracy Region. It is now clear that when $r<\rho(\alpha)$, the only possibility is that the optimal price is $((1-\beta)\theta+r(1-\alpha))/(2(1-\alpha\beta))$. According to Lemma 2, the profit would be

$$\pi(\theta)=\frac{(r(1-\alpha)+(1-\beta)\theta)^2}{4(1-\beta)(1-\alpha\beta)\theta}-\frac{c\theta^2}{2}.$$

The first-order condition is $\pi'(\theta)=0$, where

$$\pi'(\theta)=\frac{1}{4}\left(\frac{1-\beta}{1-\alpha\beta}-\frac{r^2(1-\alpha)^2}{(1-\beta)(1-\alpha\beta)\theta^2}-4c\theta\right). \tag{7}$$

We would like to find the optimal θ satisfying $\theta>r(2-\beta(1+\alpha))/(\beta(1-\beta))$ (see Lemma 2). Similar to the proof of Proposition 1, we find that (i) $\pi'(\theta)$ is strictly positive at $\theta=r(2-\beta(1+\alpha))/(\beta(1-\beta))$ if $r<\rho(\alpha)$, and (ii) $\pi'(\theta)$ is negative when θ is large. Therefore, there exists a $\theta\in(r(2-\beta(1+\alpha))/(\beta(1-\beta)),\infty)$ that satisfies $\pi'(\theta)=0$. If there are multiple such values of θ, we pick the smallest one and denote it by $\tilde\theta(\alpha)$.

By its choice, $\tilde\theta(\alpha)$ is a local maximum and must, therefore, satisfy $\pi''(\theta)|_{\theta=\tilde\theta(\alpha)}<0$. However, this immediately implies that $\tilde\theta(\alpha)$ is also the unique maximum, because

$$\pi''(\theta)=-c+\frac{r^2}{2(1-\beta)(1-\alpha\beta)\theta^3}$$

is decreasing in θ. Since $\pi''(\theta)$ is negative at $\tilde\theta(\alpha)$, it is also so for all $\theta>\tilde\theta(\alpha)$. Consequently, for all those values of θ, the first derivative is strictly negative, implying that $\tilde\theta(\alpha)$ is the unique real maximum above $r(2-\beta(1+\alpha))/(\beta(1-\beta))$, or $\theta^*=\tilde\theta(\alpha)$. □

Proof of Corollary 2. This proof is straightforward from the observation that $\partial\rho(\alpha)/\partial\alpha=3\beta^2(1-\beta)^3/(c(2-\beta(1+\alpha))^4)>0$. □

Proof of Theorem 2. This proof is similar to the proof of Theorem 1.

In the region of interest, the optimal quality satisfies the first-order condition, i.e., $\pi'(\theta^*)=0$. Using the implicit function theorem, we get

$$\frac{\partial\theta^*}{\partial r}=-\frac{\partial\pi'(\theta)/\partial r|_{\theta=\theta^*}}{\partial\pi'(\theta)/\partial\theta|_{\theta=\theta^*}}.$$

Of course, from (7), we get

$$\frac{\partial\pi'(\theta)}{\partial r}=-\frac{r(1-\alpha)^2}{2(1-\beta)(1-\alpha\beta)\theta^2}<0.$$

And it is also clear from the proof of Proposition 4 that

$$\left.\frac{\partial\pi'(\theta)}{\partial\theta}\right|_{\theta=\theta^*}<0.$$

Therefore, $\partial\theta^*/\partial r$ must be negative.

To prove the second part of the result, we note that θ^* satisfies $\pi'(\theta)=0$ and Equation (7):

$$\frac{1}{4}\left(\frac{1-\beta}{1-\alpha\beta}-\frac{r^2(1-\alpha)^2}{(1-\beta)(1-\alpha\beta)\theta^{*2}}-4c\theta^*\right)=0.$$

Taking the derivatives of both sides with respect to r, we get

$$\frac{\partial\theta^*}{\partial r}=\frac{r(1-\alpha)^2\theta^*}{r^2(1-\alpha)^2-2c(1-\beta)(1-\alpha\beta)\theta^{*3}}.$$

Therefore,

$$\begin{aligned}\frac{\partial}{\partial\alpha}\left(\frac{\partial\theta^*}{\partial r}\right)&=[r(1-\alpha)(2c(1-\beta)(2-\beta(1+\alpha))\theta^{*4}\\&\quad+(\partial\theta^*/\partial\alpha)(r^2(1-\alpha)^3\\&\quad+4c(1-\alpha)(1-\beta)(1-\alpha\beta)\theta^{*3}))]\\&\quad\cdot[r^2(1-\alpha)^2-2c(1-\beta)(1-\alpha\beta)\theta^{*3}]^{-2}.\end{aligned}$$

The denominator is clearly positive, and so is the numerator if $\partial\theta^*/\partial\alpha>0$. We again invoke the implicit function theorem to obtain

$$\frac{\partial\theta^*}{\partial\alpha}=-\frac{\partial\pi'(\theta)/\partial\alpha|_{\theta=\theta^*}}{\partial\pi'(\theta)/\partial\theta|_{\theta=\theta^*}}.$$

As mentioned above, $\partial\pi'(\theta)/\partial\theta|_{\theta=\theta^*}<0$. Further, from (7)

$$\frac{\partial\pi'(\theta)}{\partial\alpha}=\frac{r^2(1-\alpha)(2-\beta(1+\alpha))+(1-\beta)^2\beta\theta^2}{4(1-\beta)(1-\alpha\beta)^2\theta^2}>0,$$

ensuring that $\partial\theta^*/\partial\alpha>0$. □

Proof of Proposition 5. Let $z_1(p,\theta)=p(\alpha(1-p/\theta)+(1-\alpha)(1-(p-r)/((1-\beta)\theta)))-c\theta^2/2$ and $z_2(p,\theta)=p\alpha(1-p/\theta)-c\theta^2/2$. Further, let $(p_1^*,\theta_1^*)=\arg\max z_1$ and $(p_2^*,\theta_2^*)=\arg\max z_2$.

Suppose that $\pi^*=z_1(p_1^*,\theta_1^*)\le\alpha^2/(32c)=z_2(p_2^*,\theta_2^*)$. We need to show that (p_2^*,θ_2^*) is a valid solution in the sense that no consumer from the unethical fraction purchases the legal version, i.e., (p_2^*,θ_2^*) satisfies $(p_2^*-r)/((1-\beta)\theta_2^*)\ge1$. Suppose not. Then, it results in a contradiction to the fact that $(p_1^*,\theta_1^*)=\arg\max z_1$:

$$\begin{aligned}z_1(p_2^*,\theta_2^*)&=z_2(p_2^*,\theta_2^*)+(1-\alpha)\left(1-\frac{p_2^*-r}{(1-\beta)\theta_2^*}\right)\\&>z_2(p_2^*,\theta_2^*)\ge z_1(p_1^*,\theta_1^*).\end{aligned}$$

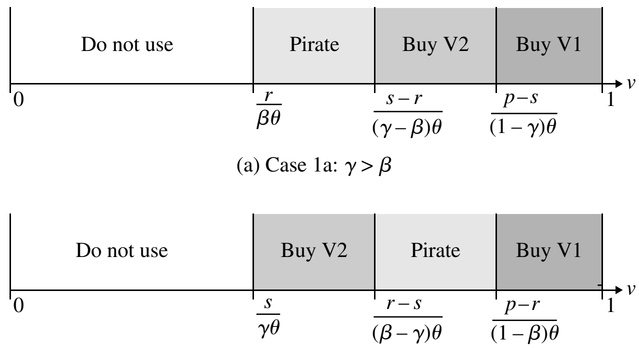
To prove the second part of the result, suppose that $\pi^*=z_1(p_1^*,\theta_1^*)>\alpha^2/(32c)=z_2(p_2^*,\theta_2^*)$. We now must show that (p_1^*,θ_1^*) is a valid solution that satisfies $(p_1^*-r)/((1-\beta)\theta_1^*)<1$. As before, assume that this is not true. Again, we reach a contradiction, this time, to our supposition that $(p_2^*,\theta_2^*)=\arg\max z_2$:

$$\begin{aligned}z_2(p_1^*,\theta_1^*)&=z_1(p_1^*,\theta_1^*)+(1-\alpha)\left(\frac{p_1^*-r}{(1-\beta)\theta_1^*}-1\right)\\&\ge z_1(p_1^*,\theta_1^*)>z_2(p_2^*,\theta_2^*).\end{aligned}$$

This completes the proof. □

Proof of Lemma 3. This lemma is a special case of the result in Bhargava and Choudhary (2001) that explains why versioning is suboptimal when all versions have the same marginal cost. Note that in our model, the marginal cost

Figure A.1 Unethical Consumers Self-Select Based on Their Relative Benefits



(a) Case 1a: $\gamma>\beta$

(b) Case 1b: $\gamma<\beta$

is zero for any version. When there are no unethical users, the profit function (assuming that some consumers buy the second version, or, equivalently, $p>s/\gamma$) is

$$p\left(1-\frac{p-s}{(1-\gamma)\theta}\right)+s\left(\frac{p-s}{(1-\gamma)\theta}-\frac{s}{\gamma\theta}\right).$$

The partial derivative of this function with respect to γ is easily shown to be strictly negative whenever $p>s/\gamma$, which means that the optimal γ is 0. □

Proof of Lemma 4. Because Cases 3 and 4 in §6 can be eliminated using Lemma 3, here, we analyze only Cases 1 and 2. Case 1 has two possibilities as to how the unethical segment self-selects; these possibilities are shown in Figure A.1.

We first show that an interior solution ($\gamma>\beta$) for Case 1a is not possible. In this case, the revenue function (or gross profit before the cost of development) is as follows:

$$\begin{aligned}\pi_{1a}(p,s,\gamma)&=\alpha\left(p\left(1-\frac{p-s}{(1-\gamma)\theta}\right)+s\left(\frac{p-s}{(1-\gamma)\theta}-\frac{s}{\gamma\theta}\right)\right)\\&\quad+(1-\alpha)\left(p\left(1-\frac{p-s}{(1-\gamma)\theta}\right)\right.\\&\qquad\left.+s\left(\frac{p-s}{(1-\gamma)\theta}-\frac{s-r}{(\gamma-\beta)\theta}\right)\right).\end{aligned}$$

Differentiating $\pi_{1a}(p,s,\gamma)$ with respect to p and s, and solving the first-order conditions, we get the optimal prices for a given γ:

$$p_{1a}(\gamma)=\frac{r\gamma(1-\alpha)+\theta(\gamma-\beta(\alpha+\gamma-\alpha\gamma))}{2(\gamma-\alpha\beta)},\quad\text{and}$$
$$s_{1a}(\gamma)=\frac{\gamma(r(1-\alpha)+(\gamma-\beta)\theta)}{2(\gamma-\alpha\beta)}.$$

We find that at these prices, the following hold:

$$\left[\frac{\partial^2\pi_{1a}(p,s,\gamma)}{\partial p^2}\frac{\partial^2\pi_{1a}(p,s,\gamma)}{\partial s^2}-\left(\frac{\partial^2\pi_{1a}(p,s,\gamma)}{\partial p\partial s}\right)^2\right]\Bigg|_{(p_{1a}(\gamma),\,s_{1a}(\gamma))}$$
$$=\frac{4(\gamma-\alpha\beta)}{(\gamma-\beta)(1-\gamma)\gamma\theta^2}>0,\quad\text{and}$$
$$\frac{\partial^2\pi_{1a}(p,s,\gamma)}{\partial p^2}\bigg|_{(p_{1a}(\gamma),\,s_{1a}(\gamma))}=-\frac{2}{\theta(1-\gamma)}<0.$$

Therefore, the second-order condition is satisfied, and $(p_{1a}(\gamma), s_{1a}(\gamma))$ is a local maximum for a given γ. Differentiating $\pi_{1a}(p_{1a}(\gamma), s_{1a}(\gamma), \gamma)$ with respect to γ, we find two possible values of γ satisfying the first-order condition:

$$\gamma_{1a,1} = \beta - \frac{r(1-\alpha)\beta}{r+\sqrt{\alpha}(\beta\theta - r)}, \quad \text{and}$$
$$\gamma_{1a,2} = \beta + \frac{r(1-\alpha)\beta}{\sqrt{\alpha}\beta\theta - r(1+\sqrt{\alpha})}.$$

The second root is a local minimum because

$$\left.\frac{d^2\pi_{1a}(p_{1a}(\gamma), s_{1a}(\gamma), \gamma)}{d\gamma^2}\right|_{\gamma_{1a,2}} = \frac{(r + r\sqrt{\alpha} - \sqrt{\alpha}\beta\theta)^4}{2r(1-\alpha)^2\sqrt{\alpha}\beta^3\theta(\beta\theta - r)} > 0,$$

and must be discarded. Furthermore, since $r < \beta\theta$ (see Figure A.1), $\gamma_{1a,1} < \beta$, which is a violation of the conditions of Case 1a. Therefore, this root must also be discarded, and there are no interior solutions in Case 1a.

In Case 1b, we will show that if an interior solution indeed exists, it would be dominated by the solution from Case 2. In Case 1b, the revenue function is as follows:

$$\begin{aligned}\pi_{1b}&(p, s, \gamma)\\ &= \alpha\left(p\left(1 - \frac{p-s}{(1-\gamma)\theta}\right) + s\left(\frac{p-s}{(1-\gamma)\theta} - \frac{s}{\gamma\theta}\right)\right)\\ &\quad + (1-\alpha)\left(p\left(1 - \frac{p-r}{(1-\beta)\theta}\right) + s\left(\frac{r-s}{(\beta-\gamma)\theta} - \frac{s}{\gamma\theta}\right)\right).\end{aligned}$$

In this case, the first-order conditions with respect to p and s lead to

$$p_{1b}(\gamma) = \frac{(1-\beta)(\alpha\gamma - \beta + (1-\alpha)\beta\gamma)\theta - r\beta(1-\alpha-\gamma+\alpha\gamma)}{2(\alpha\beta^2 + \alpha\gamma - \beta(1+2\alpha\gamma - \gamma))},$$

and

$$s_{1b}(\gamma) = \frac{\gamma(\alpha(1-\beta)(\gamma-\beta)\theta - r(1-\alpha-\gamma+\alpha\gamma))}{2(\alpha\beta^2 + \alpha\gamma - \beta(1+2\alpha\gamma-\gamma))}.$$

For now, we skip verifying the second-order condition and assume that this is an interior solution. Substituting the above into the profit function and solving the first-order condition with respect to γ, we get two roots:

$$\gamma_{1b,1} = \beta + \frac{r(1-\alpha)(1-\beta)\beta}{\sqrt{\alpha}(1-\beta)\beta\theta + r(\alpha - \sqrt{\alpha}(1-\beta) + \beta - 2\alpha\beta)}, \quad \text{and}$$
$$\gamma_{1b,2} = \beta - \frac{r(1-\alpha)(1-\beta)\beta}{\sqrt{\alpha}(1-\beta)\beta\theta - r(\alpha + \sqrt{\alpha}(1-\beta) + \beta - 2\alpha\beta)}.$$

It can be easily shown that $\gamma_{1b,1} > \beta$ and violates the conditions for this case. Therefore, we consider only the second root and substitute it into the profit function to obtain

$$\pi_{1b} = \frac{1}{4}\left(2r(1+\sqrt{\alpha}) - \frac{r^2(1+\sqrt{\alpha})^2}{\beta\theta} + \theta(1-\beta)\right).$$

Shortly, we will discard this solution, as well, because π_{1b} turns out to be less than the optimal profit from Case 2. Hence, irrespective of whether or not this is a valid maximum, this case is actually dominated by Case 2, and there is no need to verify the second-order condition for this solution.

Now we turn our attention to Case 2. In this case, no consumer uses the pirated product as the second version leads to a (weakly) higher net surplus for every unethical consumer vis-à-vis the pirated version. Our strategy here is to check for possible interior as well as three possible corner solutions ($\gamma = 0$, $\gamma = 1$, and $\gamma = \beta$). Two of the three corner solutions can be easily ruled out: $\gamma = 0$ means that a second version is not offered, and $\gamma = 1$ means that the second version has the same quality as the highest version does. We will now rule out the possibility of an interior solution as well. To that end, we note that when $\gamma \neq \beta$, the revenue function is given by

$$\pi_2(p, s, \gamma) = p\left(1 - \frac{p-s}{(1-\gamma)\theta}\right) + s\left(\frac{p-s}{(1-\gamma)\theta} - \frac{s}{\gamma\theta}\right).$$

It is now straightforward to show that $\partial\pi_2(p, s, \gamma)/\partial\gamma < 0$, which implies that there are no interior solutions.

When $\gamma = \beta$, s has to be less than or equal to r because otherwise the second version would not be used by anyone. Also, when $s < r$, $\partial\pi_2(p, s, \beta)/\partial\gamma > 0$ whenever $p > r/\beta > r > s$. Therefore, the optimal choice of s is r. When $s = r$, the revenue function simplifies to

$$\pi_2(p, r, \beta) = p\left(1 - \frac{p-r}{(1-\beta)\theta}\right) + r\left(\frac{p-r}{(1-\beta)\theta} - \frac{r}{\beta\theta}\right).$$

Differentiating this profit function with respect to p and solving the first-order condition, we find that the optimal p is $((1-\beta)\theta + 2r)/2$. Thus, the corner solution is given by

$$\gamma_2 = \beta, \quad p_2 = \frac{(1-\beta)\theta + 2r}{2}, \quad s_2 = r, \quad \text{and}$$
$$\pi_2 = r - \frac{r^2}{\beta\theta} + \frac{1}{4}(1-\beta)\theta. \tag{8}$$

As promised earlier, we now show that $\pi_2 > \pi_{1b}$ for all values of $\alpha \in (0, 1)$. Let $\Delta\pi(\alpha)$ be

$$\Delta\pi(\alpha) = \pi_2 - \pi_{1b} = \frac{r}{4}\left(2(1-\sqrt{\alpha}) + \frac{r}{\beta\theta}((1+\sqrt{\alpha})^2 - 4)\right).$$

Then,

$$\frac{\partial\Delta\pi(\alpha)}{\partial\alpha} = -\frac{r}{4\sqrt{\alpha}}\left(1 - \frac{r}{\beta\theta}(1+\sqrt{\alpha})\right) < 0. \tag{9}$$

The last inequality in (9) follows from the fact that $\alpha < 1$ and that the question of versioning arises only when $\theta \geq 2r/\beta$ (see Lemma 2). Since $\Delta\pi(1) = 0$, (9) immediately implies that, for all values of $\alpha < 1$, $\Delta\pi(\alpha) > 0$, or π_2 is larger. Therefore, the solution described by (8) above is optimal. □

Proof of Proposition 6. *No-Piracy Region Without Threat* (*No Versioning*). As is established by Proposition 4, the monopolist can exert its full monopoly power when $r > \beta/(8c)$, and, therefore, there is no need for it to consider other options.

No-Piracy Region With Threat (*Versioning*). We first look at the part of this region where $r \geq \rho(\alpha)$. Then, we look at the part where $r < \rho(\alpha)$.

When $\rho(\alpha) \leq r \leq \beta/(8c)$, the monopolist still has the option of offering one version and pricing it at r/β (as in Proposition 4 and Lemma 2). This option leads to a profit of

$$\pi_3(r, \theta) = \frac{r(\beta\theta - r)}{\beta^2\theta} - \frac{c\theta^2}{2}.$$

Henceforth, we will denote $\max_\theta \pi_3(r, \theta)$ by $\pi_3^*(r)$.

However, with versioning, we need to consider the other possibility, which is offering a lower version that is identical to the pirated version and a higher version for a price of

$((1-\beta)\theta+2r)/2$; see the proof of Lemma 4, Equation (8) in particular. This option leads to a profit of

$$\pi_2(r,\theta)=r-\frac{r^2}{\beta\theta}+\frac{1}{4}(1-\beta)\theta-\frac{c\theta^2}{2}.$$

By directly comparing $\pi_2(r,\theta)$ with $\pi_3(r,\theta)$, we can see that the strategy of offering two versions dominates that of offering only one version at every θ. Therefore, offering two versions must be the best strategy when $\rho(\alpha)\le r\le\beta/(8c)$. The profit function for this optimal strategy, $\pi_2(r,\theta)$, is concave in θ and has a unique maximum that is obtained by solving the first-order condition with respect to θ:

$$\frac{1-\beta}{4}+\frac{r^2}{\beta\theta^2}-c\theta=0.$$

As mentioned in the statement of the proposition, we denote the solution to this first-order condition by $\hat{\theta}$. Let us denote the corresponding maximum profit by $\pi_2^*(r)$. Note that at $r=\beta/(8c)$, $\pi_2^*(r)$ is identical to the profit that the manufacturer gets when it is able to exert its full monopoly power.

Before investigating the case in which $r<\rho(\alpha)$, we would also like to note that $\pi_2(r,\theta)$ is jointly concave in r and θ because (i) $\partial^2\pi_2(r,\theta)/\partial r^2=-2/(\beta\theta)<0$ and (ii) $(\partial^2\pi_2(r,\theta)/\partial r^2)(\partial^2\pi_2(r,\theta)/\partial\theta^2)-(\partial^2\pi_2(r,\theta)/\partial r\partial\theta)^2=2c/(\beta\theta)>0$. In other words, $-\pi_2(r,\theta)$ is jointly convex in r and θ. Minimizing a jointly convex function over a convex set leads to a convex function. Hence, $-\pi_2^*(r)=\min_\theta\{-\pi_2(r,\theta)\}$ is convex, which leads to the following result:

- $\pi_2^*(r)$ is concave in r.

When $r<\rho(\alpha)$, the monopolist has two options. One option is versioning, which leads to a maximum profit of $\pi_2^*(r)$. The other option, which is to offer one version for a price of $((1-\beta)\theta+r(1-\alpha))/(2(1-\alpha\beta))$ (as in Lemma 2). This option leads to a profit of

$$\pi_1(r,\theta)=\frac{(r(1-\alpha)+(1-\beta)\theta)^2}{4(1-\beta)(1-\alpha\beta)\theta}-\frac{c\theta^2}{2}.$$

The optimal quality level for this choice is $\tilde{\theta}(\alpha)$, which is as defined in Proposition 4. Let us denote the corresponding optimal profit by $\pi_1^*(r)$. Since $\pi_1(r,\theta)$ is convex in r and convexity is preserved under point-wise maximization, we have the following result:

- $\pi_1^*(r)$ is convex in r.

The optimal quality level characterized by Proposition 4 is continuous, as is the corresponding profit, which means that $\pi_1^*(\rho(\alpha))=\pi_3^*(\rho(\alpha))$. We have argued above that $\pi_3^*(\rho(\alpha))<\pi_2^*(\rho(\alpha))$. Therefore, $\pi_1^*(\rho(\alpha))<\pi_2^*(\rho(\alpha))$. Moreover, a quick comparison of $\pi_1(0,\theta)$ and $\pi_2(0,\theta)$ reveals that $\pi_1^*(0)>\pi_2^*(0)$ at all positive values of α. As a result, the following holds:

- $\pi_1^*(r)$ and $\pi_2^*(r)$ cross each other an odd number of times in $[0,\rho(\alpha))$.

However, since $\pi_1^*(r)$ is convex and $\pi_2^*(r)$ is concave, $\pi_1^*(r)-\pi_2^*(r)$ is convex. Therefore, $\pi_1^*(r)-\pi_2^*(r)=0$ can have at most two solutions. Because the number of crossings in $[0,\rho(\alpha))$ is odd, we can infer the following:

- $\pi_1^*(r)$ and $\pi_2^*(r)$ cross each other exactly once in $[0,\rho(\alpha))$.

We denote this crossing by $\bar{\rho}(\alpha)$, which completes the proof.

Piracy Region (No Versioning). It is clear from the discussion immediately above that when $r<\bar{\rho}(\alpha)$, the best option is tolerating piracy and offering only one version with quality $\tilde{\theta}(\alpha)$. □

Proof of Theorem 3. This proof is similar to the proof of Theorem 2. □

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