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Music Downloads and the Flip Side of Digital Rights Management Protection

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Digital rights management (DRM) is an important yet controversial issue in the information goods markets. Although DRM is supposed to help copyright owners by protecting digital content from illegal copying or distribution, it is controversial because DRM imposes restrictions on even legal users, and there are many industry practitioners who believe that the industry would be better off without DRM. In this paper, we model consumers' utilities and their incentives to purchase legal products versus pirate illegal ones. This allows us to endogenize the level of piracy and understand how it is influenced by the presence or absence of DRM. Our analysis suggests that, counterintuitively, download piracy might decrease when the firm allows legal DRM-free downloads. Furthermore, we find that a decrease in piracy does not guarantee an increase in firm profits and that that copyright owners do not always benefit from making it harder to copy music illegally. By analyzing the competition among the traditional retailer, the digital retailer, and pirated sources of information goods, we get a better understanding of the competitive forces in the market and provide insights into the role of digital rights management.

Key words: game theory; competitive analysis; piracy; entertainment marketing; digital music
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1. Introduction

According to the Recording Industry Association of America (RIAA), global piracy of music causes $12.5 billion in economic losses every year and has contributed to a 50% decline in CD sales over the last decade (RIAA 2009). As a result, the RIAA has paid particular attention to technological solutions that would make the sharing of music more difficult. On the other hand, EMI, a major record label, began selling some of its music in a downloadable format that does not include the key technological piracy-prevention component (EMI 2007). This presents an interesting conundrum: If the RIAA is right and global piracy is rampant, then why is EMI eliminating a key technology in preventing piracy? These conflicting views of the world are at the heart of the problem we address in this paper. In particular, we develop a formal model to address the following questions: As labels move away from designing technologies to thwart piracy, what will happen to the level of piracy, and how will it affect the profitability of the music industry—the record label as well as its retailers? We show that these technologies affect not only piracy and legal downloads but also the market for traditional CDs. By highlighting the role of competition not only between the legal and illegal channels but also within the legal channel, we offer fresh insights into the effect of piracy. Although we focus on the music industry, we also note that our conclusions are general and apply more broadly to the digital world of books, movies, video games, etc., where the basic problem of dealing with piracy is an ongoing issue.

As noted by Van Tassel (2006), "Content providers have always viewed piracy as a serious problem, but in the last few years, use of unlicensed content has undergone explosive growth and threatens to undermine the very foundations of both traditional businesses and electronic commerce." The belief is that if piracy can be reduced, both the traditional businesses and their online counterparts stand to benefit. As a result, a significant amount of effort has gone into developing digital rights management (DRM) technologies that make copying difficult. DRM controls how end users can access, copy, or convert information goods, such as software, music, movies, or books. For example, the original iTunes Fairplay DRM system restricted users from installing music on more than five authorized computers or burning a song more than seven times, and songs downloaded from Walmart Music can be played only on Windows PlaysForSure licensed products (Duchene et al. 2005).

Other digital goods also have some form of DRM—a movie purchased and downloaded from the iTunes store can only be played on an authorized computer, and books purchased for the Kindle cannot be read on any other device. All these constraints are designed to protect digital products from unauthorized copying and distribution and thus reduce the level of piracy.[1] The proponents of DRM believe that imposing DRM restrictions leads to a decrease in piracy that in turn leads to higher profits for the copyright owners.

Using DRM to combat piracy has many critics, such as Bill Gates and Cory Doctorow. A central problem with current DRM solutions is that although they may make piracy more costly and difficult, they also impose costs on legal users who have no intentions of doing anything illegal. Moreover, because a DRM-restricted product will only be purchased by a legal user, in a perverse sense, only the legal users pay the price and suffer from the restrictions; illegal users will not be affected because the pirated product does not have DRM restrictions. As a result, opponents of DRM argue that eliminating DRM will improve the value of the product for legal users, increase their willingness to pay, and thus increase industry profits.

To address the problem facing the music industry, we model a music distribution channel that allows for both traditional CD retailers and download services such as iTunes. Although this framework can be readily adapted to other information goods (e.g., books, videos), for simplicity of exposition this paper focuses on the music industry. The product for sale is a music album that is available to consumers in either a downloadable format (e.g., MP3 file) or a traditional (i.e., CD) format. Furthermore, music in the downloadable format can be either DRM-restricted or DRM-free. Consumers have heterogeneous preferences for downloaded music versus CDs, and they derive different utility from DRM-free and DRM-restricted music. A record label distributes music via iTunes-like download services and traditional retailers selling CDs. Consumers can legally download the music or purchase the CD from a retailer; if they choose to steal, they can get a pirated copy, but they also bear a moral and a technical cost of obtaining an illegal copy. Finally, consumers differ in their propensity to engage in piracy.

Our analysis suggests that under certain conditions piracy might decrease when the firm allows legal DRM-free downloads. This finding is in stark contrast to the view of DRM proponents that removing DRM will increase piracy. In particular, even when DRM imposes no constraints on legal users, the level of piracy can still go down when the firm eliminates DRM. This result stems from the competition among all three formats—legal downloads, traditional CDs, and illegal pirating. We also find that the record label does not necessarily benefit from making it harder to copy music illegally. In some cases, the record label may benefit from making piracy easier. Said differently, the record label can find it optimal to have some level of piracy.

The extant literature in this area also challenges the conventional belief that piracy decreases profitability, but in doing so, it simply assumes that DRM technologies reduce piracy. In particular, most of the research that shows a beneficial effect of piracy relies on the presence of positive demand externalities such that consumers' utility increases with the installed base (Xie and Sirbu 1995). Thus, tolerating a limited amount of piracy is a good idea in the presence of strong network externalities (Conner and Rumelt 1991, Takeyama 1994, Slive and Bernhardt 1998) or diffusion effects (Givon et al. 1995). Furthermore, in the context of experience goods, such as music or books, piracy can be viewed as a product sampling mechanism (Chellappa and Shivendu 2005) and positively affect profits through letting consumers learn the true perception of the product fit, i.e., through creating an "information advantage" (Villas-Boas 2006). Also, in a competitive situation, piracy can lead firms to increase their level of innovation (Jain 2008).

In this paper, we micromodel consumers' utilities and their incentives to purchase legal products versus pirate illegal ones. This allows us to endogenize the level of piracy and understand how it is influenced by the presence or absence of DRM. In the model we develop, the firm can make it harder to copy the product, but that imposes constraints not only on potential pirates but also on the legitimate buyers. Therefore, by anlyzing how DRM affects not only the level of piracy but also the competitive interaction between the competing firms, we get a more complete picture of the market.

Furthermore, the extant literature treats all legal sources of music, such as downloads and CDs, as one monolithic product that competes against illegal sources or pirates. In contrast, we note that although legal sources, such as downloads or CDs, compete against pirated versions, they also compete against each other. Thus, by analyzing the competition among the traditional retailer, the digital retailer, and pirated music, we get a better understanding of the competitive forces in the market. As a result, unlike the earlier literature, we endogenize consumers' choices among all the major sources of music.

The rest of this paper is organized as follows. In §2, we lay out the model and related assumptions. Section 3 analyzes the consequences of removing DRM restrictions. In §4, we compare the effect of removing

[1] Note that if DRM limits interformat operability, it also makes the market less competitive.

DRM restrictions on the record label and the retailers. In §5, we relax some of the assumptions of our general model, and in §6, we conclude the paper and suggest some directions for future research.

2. Model

We develop a model in which a record label distributes music through multiple retailers and consumers have the choice of either buying or pirating the music. Below, we detail our assumptions about the product, the consumers, and the firms.

2.1. Product

The product we consider is an album of music that consumers can obtain in either of two formats: *traditional* (i.e., CDs) and *downloadable* (e.g., MP3 or AAC files). Because CDs in the traditional format are sold without any DRM restrictions, we assume that the content is DRM-free. However, music that is sold in a downloadable format can be either DRM-restricted or DRM-free. Thus, DRM is an additional feature of the downloadable product that can either be on or off. We follow the timeline in the music industry by first analyzing the market with DRM-restricted downloads and then moving to analyzing DRM-free downloads.

2.2. Consumers

We develop demand functions for various products by developing a micromodel of consumers and then analyzing consumers' optimal product choices for a given set of prices. The base utility for a music album is given by $\theta > 0$, which reflects the pure joy of listening to that particular album. However, consumers' net utility is affected by their preferences for format (traditional or downloadable), their cost of stealing, and the restrictions imposed by DRM. We describe each of these next.

2.2.1. Format. Some consumers may like the portability of the downloadable music, whereas others might like the booklet and artwork or the ability to display a CD as a part of music collection. Preferences between these two formats are distributed uniformly on a Hotelling (1929) line segment in the $[0, 1]$ interval, such that the downloadable format is located at the left extreme and the traditional format is located at the right extreme. The transportation cost t captures consumers' disutility of choosing a format that is not their ideal format.

2.2.2. Cost of Stealing. Consumers can either purchase a legal copy (traditional or downloadable) or obtain an illegal copy from a variety of sources such as peer-to-peer networks (e.g., eDonkey) or music websites (e.g., http://www.guba.com/).[2] If they choose to obtain an illegal copy, they incur a moral, or a psychological, cost as well as the search cost of finding the music album (Hennig-Thurau et al. 2007). In particular, consumers may feel guilty about performing an illegal or unethical action or feel the threat of embarrassment or shame associated with being caught. Both these effects decrease the likelihood of consumers engaging in pirating activity (Sinha and Mandel 2008). Finally, on a more practical level, if they choose to pirate, consumers need to spend some time and effort in finding and downloading the illegal copy of the album (e.g., Hennig-Thurau et al. 2007).

We model the total costs of pirating through two components: the moral/psychological cost, e_M, and the technical/search cost, e_T. Clearly, we expect consumers to differ in their costs of pirating; e.g., a highly ethical consumer or a novice computer user will have a very high cost of pirating, whereas a consumer who does not see piracy as stealing or an expert computer user will have a much lower pirating cost. To capture this heterogeneity, we model two consumer segments that differ in their moral pirating effort. In the high (H) segment, consumers face a high moral pirating cost, e_M^H, and in the low (L) segment, they have a lower moral pirating cost, $e_M^L < e_M^H$. There are $\lambda \in (0, 1)$ consumers in segment H and $(1 - \lambda)$ consumers in segment L. We assume e_M^H is sufficiently high such that consumers in segment H will never choose to obtain pirated music, whereas some consumers in segment L may engage in piracy (see Figure 1).[3] This is consistent with empirical findings that certain consumers always buy digital goods, regardless of whether they are available on the Internet for free (Smith and Telang 2008).

Researchers have also noted a positive correlation between expertise with digital technology and usage of peer-to-peer networks (Zentner 2006). To incorporate this correlation, we assume that the technical component, e_T, is lower for technically sophisticated

[2] Because CDs are not DRM-restricted, music can be ripped off a CD and uploaded to a pirated music website or a peer-to-peer network, or it can be given to a friend. Thus pirated music can be downloaded even when digital music is not legally sold or sold only in DRM-restricted format. For example, in May 2002 (five years before the first DRM-free downloadable music album was sold) the International Federation of the Phonographic Industry (IFPI) estimated that there were 3 million simultaneous global users and 500 million files available for copying at any given time (IFPI 2002).

[3] More formally stated, we assume that

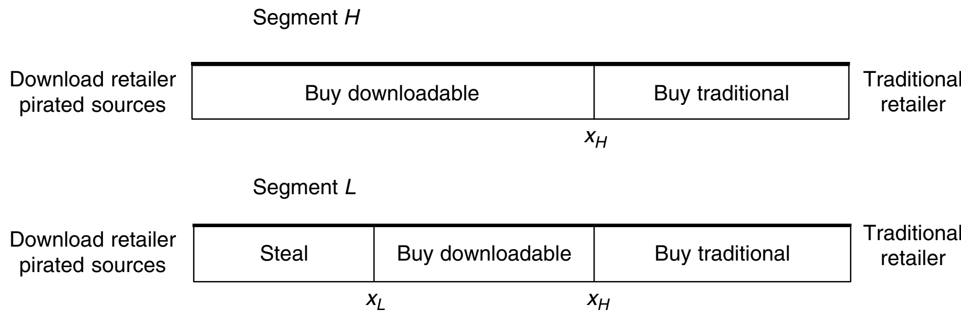
$$e_M^L < \delta e_T(3\delta e_T + 11t(1-\lambda))(3\delta e_T + 4t(1-\lambda))(1-\lambda)$$

and

$$e_M^H > \frac{3\delta e_T^2 + e_T(1-\lambda)(2\Delta_\theta + 11t) + 4t\Delta_\theta(1-\lambda)^2}{(3e_T + 4t(1-\lambda))(1-\lambda)}.$$

.

Figure 1 Equilibrium Demand for Legal and Illegal Versions



consumers who also tend to have stronger preferences for the downloadable format. Thus, the total pirating effort of a consumer located at point x on segment i, where $i \in \{H, L\}$, is equal to $e_i = e_T x + e_M^i$.

2.2.3. Restrictions Imposed by Digital Rights Management. The current state of DRM technologies is that they work by controlling how users can access, copy, or convert the music file. In this manner, they restrict how the product can be used, thus making it harder to pirate and increasing the cost of stealing. However, these restrictions also inconvenience legal buyers who have no intentions of engaging in piracy. We model both these effects below.

When an album has DRM restrictions, there are two ways for it to show up on pirated music websites or peer-to-peer networks: the pirates can break DRM restrictions or copy files from a CD and make them available on the Internet. The main option for a consumer who wants to pirate the album will be to search around for it. However, when legally available downloadable music is DRM-free, it can also be uploaded directly to the pirated networks by more people, thus increasing the supply and making it easier for consumers to find and download pirated music through technologies such as BitTorrent.[4] This suggests that the technical cost of pirating can decrease when DRM restrictions are removed. Specifically, with DRM restrictions, the total cost of piracy for segment i consumers is $e_i = e_T x + e_M^i$, and without DRM restrictions, it is $e_i^U = \delta e_T x + e_M^i$ (where $0 < \delta \leq 1$). The coefficient δ denotes the degree to which the search or technical part of the pirating effort decreases in the absence of DRM.[5]

[4] The waiting time associated with using the BitTorrent protocol decreases when there are a greater number of nodes because the overall download speed increases.

[5] As long as there is at least one service on the Internet that provides access to pirated music, eliminating DRM protection might not decrease consumers' cost of pirating by a significant amount. Indeed, some industry observers argue that consumers who truly want to download music illegally are not affected by DRM restrictions.

As noted earlier, the technological constraints of DRM inconvenience legal buyers and thus reduce the base utility that consumers can derive from the product. For example, DRM restrictions can limit usage of music to specific devices and/or operating systems, so consumers risk losing access to legally purchased content if their system crashes or their music player preferences change. Thus, consumers' ability to enjoy music in the downloadable format is affected by the presence or absence of DRM restrictions. As a result, with a DRM-free product, consumers get a utility of θ, and with a DRM-restricted product, they get a lower utility of $\theta_R = \theta - \Delta_\theta$, where $\Delta_\theta \geq 0$. We subsequently show in §5 that our results are robust to this assumption. Interestingly, when $\Delta_\theta = 0$, then the firm has the ideal DRM solution—it increases the cost of stealing without lowering the base utility for legal buyers.

2.2.4. Consumers' Options. In summary, consumers' options for obtaining music and their utilities from each option are as follows:

1. Buy the album in the traditional format at price p_T, and obtain the utility $U_T^B = \theta - t(1-x) - p_T$.
2. Buy the downloadable album and obtain the utility $U_{RD}^B(x) = \theta_R - tx - p_{RD}$ if the product is available in the DRM-restricted version at price p_{RD}, or obtain the utility $U_{UD}^B = \theta - tx - p_{UD}$ if the product is available in the DRM-free (unrestricted) version at price p_{UD}.
3. Steal the product in the downloadable format and obtain the utility $U_{RD}^S = \theta - tx - e_i$, $i = \{H, L\}$ if the legally available downloadable music comes with DRM restrictions or the utility $U_{UD}^S = \theta - tx - e_i^U$ if the legally available downloadable music comes without DRM restrictions.

2.3. Firms

We consider a distribution channel made up of a record label, an Internet retailer, and a traditional retailer. Considering only one retailer of each type is a simplification we make for tractability, but this parsimonious structure still allows us to capture (1) the differentiated competition between the two formats and (2) the positive profit margins enjoyed by each type of retailer. In §5, we relax this assumption and allow intraformat competition. We refer to the Internet (or download) retailer as retailer D and the traditional retailer as retailer T. The record label sells an album in the downloadable format through the Internet retailer and in the traditional format (CD) through the traditional retailer.

The record label owns the copyright and chooses whether or not to sell the downloadable version with or without DRM restrictions. The record label also chooses a wholesale price for each version that it sells: w_T for the traditional version and w_D for the downloadable version. Each retailer takes these wholesale prices as given and chooses its retail price. Although there are two segments of consumers (high and low pirating effort), neither the retailers nor the record label can identify consumers' locations or their pirating effort.

2.4. Sequence of Events

The game is played in three stages. During the first stage, the record label chooses the formats of the music album for sale and the wholesale prices for the formats it decides to sell. In the next stage, the retailers set their retail prices simultaneously. Finally, consumers maximize utility by choosing the optimal product available in the market. We adopt the notion of subgame-perfect Nash equilibrium to solve the game.

3. Equilibrium Prices and Sales

We begin our analysis by deriving equilibrium prices and sales volume separately for two cases: (1) the record label sells the album in the traditional and DRM-restricted formats; and (2) the record label sells the album in the traditional and DRM-free downloadable formats. Subsequently, in §4, we analyze which of these two cases would emerge in equilibrium. Comparing these two cases also allows us to analyze the impact of DRM protection on the level of piracy and the profitability of various players in the distribution channel.[6]

3.1. Selling Traditional Format and DRM-Restricted Downloads

In this case, retailer D sells the album in the DRM-restricted downloadable format and retailer T sells it in the traditional format. In the H segment, the cost of pirating is high enough to prevent piracy so that consumers choose between buying music from two retailers (see ??). In the L segment, the cost of pirating is low enough so that consumers choose between buying music from two retailers or stealing a digital copy from the Internet. The location of the consumer who is indifferent between buying the traditional version and the DRM-restricted version is exactly the same as x_H in the H segment.[7] The location of the L consumer who is indifferent between stealing a digital version and purchasing a DRM-restricted version is derived by equating $U^S_{RD}(x) = U^B_{RD}(x)$, which yields $x_L = (p_{RD} - e_M + \Delta_\theta)/e_T$. Because we only have to consider the L segment's moral cost, we simplify our notation and use e_M instead of e^L_M. Using backward induction, we first solve the retailers' and then the record label's optimization problems, yielding the optimal retail and wholesale prices:

$$p^*_{RT} = \frac{3e_T^2 + e_T(1-\lambda)(3e_M + 14t + \Delta_\theta) + 2t(5e_M + 6t + \Delta_\theta)(1-\lambda)^2}{2(1-\lambda)(3e_T + 8t(1-\lambda))},$$

$$p^*_{RD} = \frac{3e_T^2 + e_T(1-\lambda)(3e_M + 11t - 4\Delta_\theta) + 12t(e_M - \Delta_\theta)(1-\lambda)^2}{2(1-\lambda)(3e_T + 8t(1-\lambda))},$$

$$w^*_{RT} = \frac{e_T + (t + e_M)(1-\lambda)}{2(1-\lambda)},$$

$$w^*_{RD} = \frac{e_T + (e_M - \Delta_\theta)(1-\lambda)}{2(1-\lambda)}.$$

Equilibrium profits, prices, demand, and piracy volume are summarized in Table 1. Notice that with DRM protection, the piracy level is given by

$$S_{RD} = \frac{3e_T^2 + e_T(11t + 2\Delta_\theta - 3e_M)(1-\lambda) + 4t(1-\lambda)^2(\Delta_\theta - e_M)}{2e_T(3e_T + 8t(1-\lambda))}.$$

All else being equal,[8] if DRM restrictions are made more cumbersome (i.e., as Δ_θ increases), some consumers who were buying the legal version will shift toward stealing. Interestingly, even in the extreme case, when $\Delta_\theta = 0$, we still can see a positive level of piracy:

$$\frac{3e_T^2 + e_T(11t - 3e_M)(1-\lambda) - 4te_M(1-\lambda)^2}{2e_T(3e_T + 8t(1-\lambda))}.$$

This suggests that piracy is not driven simply by the disutility associated with DRM but also by the costs and benefits of the available alternatives and the proportion of consumers who might potentially engage in piracy.

[6] As we show in Appendix A, it is optimal for the record label to introduce some form of digital downloads. In other words, if the label only sells CDs through a traditional retailer, then it is optimal for the label also to sell through a retailer that only sells digital downloads.

[7] To see this, note that there is no difference in the utilities from either of these strategies across the two segments.

[8] One might argue that increasing Δ_θ would also lead to a higher technical cost of piracy, e_T. However, this is not necessarily the case. Note that Δ_θ includes the disutility of DRM restrictions that are unrelated to the cost of piracy, e.g., the fear of losing legally purchased songs as a result of accidents, the lack of interoperability. Therefore, there can be instances where increasing Δ_θ affects only the legal buyers and not the pirates. This is consistent with Doctorow's (2008) observation that the presence of a few sophisticated pirates can greatly facilitate piracy without having any impact on legal buyers.

Table 1 Equilibrium Outcomes with Two Competing Retailers

Traditional and restricted downloadable versions for sale	Traditional and unrestricted downloadable versions for sale
$p^*_{RT} = \dfrac{3e_T^2 + e_T(1-\lambda)(3e_M + 14t + \Delta_\theta) + 2t(5e_M + 6t + \Delta_\theta)(1-\lambda)^2}{2(1-\lambda)(3e_T + 8t(1-\lambda))}$	$p^*_{UT} = \dfrac{3\delta^2 e_T^2 + \delta e_T(1-\lambda)(3e_M + 14t) + 2t(5e_M + 6t)(1-\lambda)^2}{2(1-\lambda)(3\delta e_T + 8t(1-\lambda))}$
$p^*_{RD} = \dfrac{3e_T^2 + e_T(1-\lambda)(3e_M + 11t - 4\Delta_\theta) + 12t(e_M - \Delta_\theta)(1-\lambda)^2}{2(1-\lambda)(3e_T + 8t(1-\lambda))}$	$p^*_{UD} = \dfrac{3\delta^2 e_T^2 + \delta e_T(1-\lambda)(3e_M + 11t) + 12te_M(1-\lambda)^2}{2(1-\lambda)(3\delta e_T + 8t(1-\lambda))}$
$w^*_{RT} = \dfrac{e_T + (t + e_M)(1-\lambda)}{2(1-\lambda)}$	$w^*_{UT} = \dfrac{\delta e_T + (t + e_M)(1+\lambda)}{2(1-\lambda)}$
$w^*_{RD} = \dfrac{e_T + (e_M - \Delta_\theta)(1-\lambda)}{2(1-\lambda)}$	$w^*_{UD} = \dfrac{\delta e_T + e_M(1-\lambda)}{2(1-\lambda)}$
$\Pi^*_{RT} = \dfrac{(2t(e_M + 2t + \Delta_\theta)(1-\lambda) + e_T(3t + \Delta_\theta))^2}{8t(3e_T + 8t(1-\lambda))^2}$	$\Pi^*_{UT} = \dfrac{t(2(e_M + 2t)(1-\lambda) + 3\delta e_T)^2}{8(3\delta e_T + 8t(1-\lambda))^2}$
$\Pi^*_{RD} = \dfrac{(e_T + 2t(1-\lambda))(e_T(3t - \Delta_\theta) + 4t(e_M - \Delta_\theta)(1-\lambda))^2}{8te_T(3e_T + 8t(1-\lambda))^2}$	$\Pi^*_{UD} = \dfrac{t(\delta e_T + 2t(1-\lambda))(3\delta e_T + 4e_M(1-\lambda))^2}{8\delta e_T(3\delta e_T + 8t(1-\lambda))^2}$
$\Pi^*_{RL} = \dfrac{e_T^2(1-\lambda)(12e_M t + 13t^2 - 6t\Delta_\theta + \Delta_\theta^2) + 8t^2(e_M - \Delta_\theta)^2(1-\lambda)^3}{8e_T t(1-\lambda)(3e_T + 8t(1-\lambda))} + \dfrac{6e_T^3 t + 2e_T t(1-\lambda)^2(3e_M^2 + 10e_M t + 2t^2 - 4e_M\Delta_\theta - 6t\Delta_\theta + 3\Delta_\theta^2)}{8e_T t(1-\lambda)(3e_T + 8t(1-\lambda))}$	$\Pi^*_{UL} = \dfrac{6\delta^3 e_T^3 t + \delta^2 e_T^2(1-\lambda)(12e_M t + 13t^2) + 8t^2 e_M^2(1-\lambda)^3}{8\delta e_T t(1-\lambda)(3\delta e_T + 8t(1-\lambda))} + \dfrac{2\delta e_T t(1-\lambda)^2(3e_M^2 + 10e_M t + 2t^2)}{8\delta e_T t(1-\lambda)(3\delta e_T + 8t(1-\lambda))}$
$D^*_{RT} = \dfrac{2t(e_M + 2t + \Delta_\theta)(1-\lambda) + e_T(3t + \Delta_\theta)}{4t(3e_T + 8t(1-\lambda))}$	$D^*_{UT} = \dfrac{2t(e_M + 2t)(1-\lambda) + 3t\delta e_T}{4t(3\delta e_T + 8t(1-\lambda))}$
$D^*_{RD} = \dfrac{(e_T + 2t(1-\lambda))(e_T(3t - \Delta_\theta) + 4t(e_M - \Delta_\theta)(1-\lambda))}{4te_T(3e_T + 8t(1-\lambda))}$	$D^*_{UD} = \dfrac{(\delta e_T + 2t(1-\lambda))(3\delta e_T + 4e_M(1-\lambda))}{4e_T(3\delta e_T + 8t(1-\lambda))}$
$S^*_R = \dfrac{3e_T^2 - e_T(3e_M - 11t - 2\Delta_\theta)(1-\lambda) - 4t(e_M - \Delta_\theta)(1-\lambda)^2}{2e_T(3e_T + 8t(1-\lambda))}$	$S^*_U = \dfrac{3\delta^2 e_T^2 - \delta e_T(3e_M - 11t)(1-\lambda) - 4te_M(1-\lambda)^2}{2\delta e_T(3\delta e_T + 8t(1-\lambda))}$

3.2. Selling Traditional Format and DRM-Free Downloads

We now consider the case where retailer D sells the album in the DRM-free downloadable format and retailer T sells it in the traditional format. Following the same logic as in the previous section, we derive the optimal set of prices:

$$p^*_{UT} = \frac{3\delta^2 e_T^2 + \delta e_T(1-\lambda)(3e_M + 14t) + 2t(5e_M + 6t)(1-\lambda)^2}{2(1-\lambda)(3\delta e_T + 8t(1-\lambda))},$$

$$p^*_{UD} = \frac{3\delta^2 e_T^2 + \delta e_T(1-\lambda)(3e_M + 11t) + 12te_M(1-\lambda)^2}{2(1-\lambda)(3\delta e_T + 8t(1-\lambda))},$$

$$w^*_{UT} = \frac{\delta e_T + (t + e_M)(1+\lambda)}{2(1-\lambda)}, \quad w^*_{UD} = \frac{\delta e_T + e_M(1-\lambda)}{2(1-\lambda)}.$$

The equilibrium profits, prices, demands, and piracy levels are summarized in Table 1.

4. The Impact of Removing DRM Restrictions

Recall that the conventional wisdom in the record industry was that legal downloads would lead to a proliferation of copying, thus exacerbating the problem of piracy. As a result, all legal downloads were first made available strictly with DRM. In other words, the thinking in the industry was that DRM would fight piracy and protect the industry. In this section, we speak directly to the conventional wisdom of the industry: Would the industry be better off if DRM restrictions were removed? In what follows, we look at the impact of removing DRM on piracy and on record label and retailer profits.

4.1. Effect on Piracy

The most common argument put forward by proponents of DRM is that eliminating DRM restrictions will unconditionally increase the level of piracy. However, because the impact of removing DRM affects prices and quantities of both traditional CDs and online downloads, the full impact of eliminating DRM restrictions is not completely straightforward. Note that piracy exists regardless of whether the record label chooses DRM or not—so the issue is whether it is affected significantly by DRM. To fully understand the implications of removing DRM, we first focus on the case where there is no disutility imposed on legal buyers through the presence of DRM; i.e., $\Delta_\theta = 0$. As noted earlier, this is an ideal DRM scenario where the firm imposes a higher stealing cost without any adverse effects on legal buyers' utilities. This leads to the following proposition.

Proposition 1A. *When $\Delta_\theta = 0$, then removing DRM restrictions leads to a decrease in piracy when*

$$\delta > \delta^S = \frac{4e_M t(1-\lambda)(3e_T + 8t(1-\lambda))}{3e_T(3e_T(t-e_M) - 4e_M t(1-\lambda))};$$

otherwise, it results in an increase in piracy.

When $\Delta_\theta = 0$, the legal download provides the same product benefits as the traditional format and the pirated product; i.e., there is no disutility associated with the legal download. Therefore, removing DRM restrictions has only one effect—it decreases the technical cost of stealing from e_T to δe_T, $\delta \in (0, 1]$. In this case, we see that if δ is above a particular cutoff, then eliminating DRM leads to a reduction in piracy. In other words, even when we make stealing easier, we can still see a decrease in the level of piracy. The competition between the traditional format and the legal download does not change when DRM restrictions are removed. However, the competition between the digital download and the pirated version does change because the cost of piracy is lower without DRM. In particular, $\partial D_{RD}/\partial p_D = -(e_T + 2t(1-\lambda))/(2e_T t)$, and $\partial D_{UD}/\partial p_D = -(e_T + 2t(1-\lambda))/(2\delta e_T t)$. The download retailer's demand becomes more price sensitive when DRM restrictions are lifted, resulting in a lower price for the digital download and a lower level of piracy under some conditions. The important point to note is that in this case, legal consumers bear no direct disutility from the DRM version; only consumers who steal bear the cost of stealing but do not get any higher utility from the pirated good.

Now, consider the general case where $\Delta_\theta > 0$ and DRM imposes a cost by lowering the utility for the legal buyers of the product. This leads to Proposition 1B.

Proposition 1B. *Eliminating DRM leads to a decrease in piracy when*

$$\Delta_\theta > \Delta_\theta^S = \frac{(1-\delta)(9e_T^2\delta(e_M - t) + 12e_T e_M t(1+\delta)(1-\lambda) + 32e_M t^2(1-\lambda)^2)}{2\delta(3e_T\delta + 8t(1-\lambda))(e_T + 2t(1-\lambda))};$$

otherwise, it results in an increase in piracy.

The impact of removing DRM on piracy is determined by the competition among pirated music, legal downloads, and traditional music in terms of product benefits as well as prices. When legal downloads are sold with DRM protection, consumers face restrictions on their use of the product, whereas the pirated version is available without restrictions. In general, as the disutility from DRM restrictions ($\Delta_\theta = \theta - \theta_R$) increases, buying the legal restricted product becomes less attractive. Without DRM restrictions, the legal download provides the same product benefit as the pirated version and thus does not suffer a competitive disadvantage. All else being equal, when DRM restrictions are removed, it reduces consumers' incentives to engage in piracy.

The realized level of piracy, however, also depends on the price for the DRM-free legal download, which in turn is determined by the price competition among the three products. Removing DRM restrictions makes piracy easier through a reduction in the cost of piracy, creating incentives for the download retailer to decrease its price. Furthermore, without DRM restrictions, the legal download is on par with the traditional format in terms of the gross product benefits. This parity between the two formats removes the legal download's competitive disadvantage, creating incentives for the traditional retailer to reduce its price and for the download retailer to increase its price. The download retailer's equilibrium price is determined by the net of these effects.

The change in piracy volume is determined by the change in the download retailer's price relative to the reduction in the cost of piracy. When the download retailer's price falls more than the reduction in the cost of piracy, the net utility of legal download increases, and the piracy volume decreases. Interestingly, under some conditions, even when removing DRM leads to an increase in the download retailer's price and a decrease in the cost of piracy, the piracy level can be lower. When $\Delta_\theta < \Delta_\theta^S$, the cost of piracy declines when DRM is removed, but the benefits of product parity are limited, and the download retailer could still charge a higher price. This case supports the RIAA's fears that removing DRM will increase piracy.

Propositions 1A and 1B show that that the industry's belief that the removal of DRM leads to higher piracy is not always true when we consider the adverse impact of DRM restrictions on consumers' willingness to purchase legal downloads and the price competition among the three formats. It is important to note that this finding can exist even when DRM imposes no negative utility on legal purchasers.

4.2. Effect on Record Label

We now consider the impact of removing DRM restrictions on the profitability of the record label. As noted earlier, the ideal DRM mechanism would not penalize legal buyers, and yet it would impose a cost on pirates. When the label has a DRM mechanism with $\Delta_\theta = 0$, then legal purchasers are not penalized, but pirates still face a cost. In this case, removing DRM does not help the legal buyers, but it does make the cost of pirating easier. This would suggest that the firm could not gain from removing DRM when $\Delta_\theta = 0$. However, this is not the case. In particular, Proposition 2A. *When $\Delta_\theta = 0$, then removing DRM restrictions leads to an increase in profits for the record label iff*

$$\delta < \delta^{\Pi} = \frac{(1-\lambda)(\sqrt{A^2 + 48e_T e_M^2 t(1-\lambda)(3e_T + 8t(1-\lambda))^2} - A^2)}{6e_T^2(3e_T + 8t(1-\lambda))},$$

where $A = (24e_T^2 t - e_T(9e_M^2 - 18e_M t - 46t^2)(1-\lambda) - 12e_M^2 t(1-\lambda)^2$.

Proposition 2A shows that even when $\Delta_\theta = 0$, and the DRM product provides no disutility to legal buyers, it still might be optimal for the firm to remove the restrictions. This occurs because of the greater price sensitivity of the demand that comes when DRM is removed, resulting in higher profits for the label. Interestingly, in this case, the download retailer can also earn higher profits mainly because piracy decreases and it earns a higher margin on all sales. It is only the traditional retailer that stands to lose with a removal of DRM.

Now, we consider the general case when $\Delta_\theta > 0$ and the impact of removing DRM restrictions on the profitability of the record label.

Proposition 2B. *The record label earns a higher profit by removing DRM restrictions, iff $\Delta_\theta > \Delta_\theta^{\Pi}$, where*

$$\Delta_\theta^{\Pi} = \frac{t\gamma(e_T + 2t(1-\lambda)) - \sqrt{t\gamma\sigma(3e_T^2 + 14e_T t(1-\lambda) + 16t^2(1-\lambda)^2)}}{\gamma(e_T^2 + 6e_T t(1-\lambda) + 8t^2(1-\lambda)^2)},$$

$$\gamma = \delta(1-\lambda)(3e_T\delta + 8t(1-\lambda)),$$

and

$$\begin{aligned}\sigma &= e_T^3 t\delta(24\delta^2 - 16 + \delta)(1-\lambda) - 2e_T^2\delta(1-\lambda)^2 \\ &\quad \cdot (t^2(14 - 23\delta) + 6e_M t(1-3\delta) - 3e_M^2(1-\delta)) \\ &\quad + 8e_T e_M t(1-\lambda)^3(e_M(1+\delta) + 6t\delta) \\ &\quad + 32e_M^2 t^2(1-\lambda)^4 - 6e_T^4(1-\delta)\delta^2.\end{aligned}$$

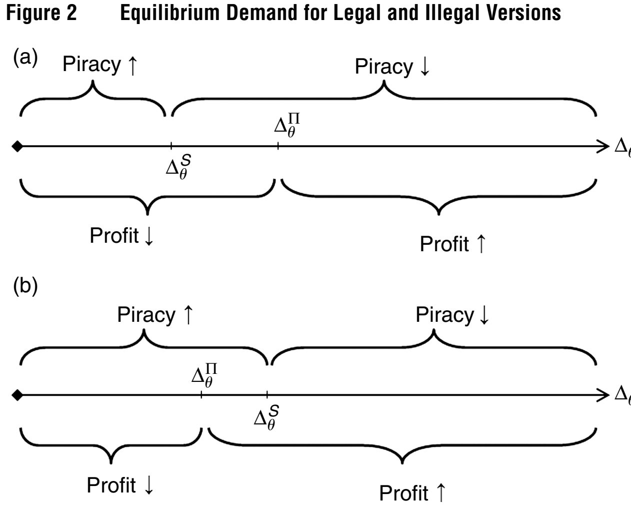
The record label's profit is determined by the sales of legal downloads as well as traditional CDs and the wholesale prices that it charges for the two formats. Proposition 1B shows that as long as Δ_θ is above a threshold, total sales of legal music increase when DRM restrictions are removed. In addition, the traditional format loses its competitive advantage over the legal downloads when DRM restrictions are removed. Therefore, with the removal of DRM, the sales mix for the record label shifts toward legal downloads, and this effect becomes stronger as Δ_θ increases. Although the wholesale price of the traditional music decreases when DRM restrictions are removed, the wholesale price for the legal downloads can go either way. The incentives to decrease the wholesale price arise because the demand for the legal download becomes more price sensitive when DRM is removed, whereas the incentives to increase it come from the higher product benefit enjoyed by the consumers. When Δ_θ is sufficiently high, the record label earns a higher profit without DRM because of either the higher total sales or the higher wholesale price for the legal download, or because of a combination of the two.

Propositions 1 and 2 show that record label profit and the overall piracy level can increase or decrease when DRM restrictions are removed. Furthermore, conventional wisdom suggests that an increase in piracy would lead to lower profits. However, the following proposition demonstrates that this is not always the case.

Proposition 3. (1) *If $\Delta_\theta^{\Pi} > \Delta_\theta^{S}$, then for $\Delta_\theta \in (\Delta_\theta^{S}, \Delta_\theta^{\Pi})$, piracy volume goes down, and the record label's profit goes down.* (2) *If $\Delta_\theta^{\Pi} < \Delta_\theta^{S}$, then for $\Delta_\theta \in (\Delta_\theta^{\Pi}, \Delta_\theta^{S})$, piracy volume goes up, and the record label's profit goes up.*

The threshold Δ_θ^{Π} could be higher or lower than the threshold Δ_θ^{S}. When $\Delta_\theta > \max\{\Delta_\theta^{\Pi}, \Delta_\theta^{S}\}$, the piracy level goes down with the removal of DRM restrictions, and the record label's profit goes up. When $\Delta_\theta < \min\{\Delta_\theta^{S}, \Delta_\theta^{\Pi}\}$, the piracy level increases with the removal of DRM restrictions, and the record label's profit goes down. Interestingly, when $\Delta_\theta^{\Pi} > \Delta_\theta^{S}$, then for $\Delta_\theta^{S} < \Delta_\theta < \Delta_\theta^{\Pi}$ the record label's profit is lower without DRM despite the piracy volume being lower (see Figure 2(a)). This is because the record label needs to charge a lower wholesale price for the traditional format album when DRM restrictions are removed. In addition, the record label may also charge a lower wholesale price for the legal download because of the increased price sensitivity of its demand. As Figure 2(b) shows, when $\Delta_\theta^{\Pi} < \Delta_\theta < \Delta_\theta^{S}$, the record label's profit increases when DRM restrictions are removed even though the piracy level goes up. This occurs because the record label is able to charge a higher wholesale price for the legal download, and its sales mix moves toward a higher fraction

Figure 2 **Equilibrium Demand for Legal and Illegal Versions**



of legal downloads compared with the traditional format albums.

Proposition 3 is important because it shows that the link between piracy volume and record labels' profits may not always work in the way that the recording industry believes: a reduction in piracy may or may not result in an increase of the record label's profits.

4.3. Effect on Retailers

We now examine how the removal of DRM restrictions affects the retailers in our analysis.

PROPOSITION 4. *When DRM restrictions are removed, the download retailer's profit increases, and the traditional retailer's profit may increase or decrease.*

Proposition 4 shows that the net effect of removing DRM is such that the download retailer is better off, whereas the traditional retailer may or may not be better off. This result is partly because of the changes that we have discussed earlier: the parity that the legal download achieves relative to the traditional format and the changes in price sensitivity of demand. In addition, the changes in the wholesale price also contribute to the results described in Proposition 4. Specifically, when the download retailer's price declines because of changes in the technical cost of piracy, e_T, reductions in the two wholesale prices mitigate the negative effects of lower retail prices for both retailers.

4.4. Impact of Piracy Costs

We have assumed that two components of the consumers' cost of piracy, moral cost, e_M, and technical costs, e_T, are outside the record label's control. It is, however, possible that the record label or recording industry trade associations can influence consumers' moral cost of piracy by educating them about unethical and illegal aspects of piracy. For example, in a popular advertising campaign, the message that "copying is stealing" was designed to reinforce the notion that downloading from pirates is illegal. The RIAA has also brought highly publicized lawsuits against consumers who have shared their music libraries online. Another commonly practiced option for the record label is to affect the technical costs of piracy, for example, by tracking bit torrent usage, creating fake bit torrent services, or infiltrating peer-to-peer networks with viruses and other malware. With the growing trend of providing DRM-free music, it is interesting to examine how the record label's profits are affected by the efforts to influence e_M and e_T.

Without DRM restrictions, the record label's profit increases with the moral costs of piracy but may increase or decrease with the technical costs of piracy.

Proposition 5 shows that increasing the moral costs may be a more profitable approach than trying to increase the technical cost of piracy primarily because of the predictability of its effect: increasing moral costs unambiguously increases the record label's profits, whereas higher technical cost might lead to lower or higher profits. Furthermore, if the industry is able to establish "copying is stealing" as a social norm, then it will probably not have to incur this cost repeatedly; on the other hand, each time pirates crack the code, firms will have to repeatedly incur the costs of developing new techniques to prevent copying.

5. Model Extensions

In this section, we analyze the effect of relaxing some of the assumptions of the basic model. In particular, there are three natural extensions to consider. First, DRM restrictions may yield a positive utility to legal buyers. Second, there is competition within format such that there are multiple firms selling CDs and legal downloads. And third, consumers face multiple options among stealing and buying legal products.

5.1. Positive Value of DRM Restrictions

As noted earlier, we represent a consumer's base valuation for the music album by $\theta > 0$. Earlier, we assumed that DRM restrictions lowered the utility for legal buyers by $\Delta_\theta > 0$. However, it could be argued that some legal buyers may feel even better knowing that they are playing a role in reducing piracy. To understand the consequences of this positive value of DRM, let the effect of DRM on consumers' base utility be denoted by $\theta^{\mathrm{DRM}} > 0$. As a result, when obtaining music in the restricted format, consumers who prefer DRM-restricted music get a higher utility of $\theta_R = \theta + \theta^{\mathrm{DRM}}$, whereas those who view DRM protection as a "frustrating impediment to lawful use" (Bridy 2009) obtain the lower utility of $\theta_R = \theta - \theta^{\mathrm{DRM}}$. The proportion of consumers that prefers DRM-free music is represented by $0 \le \beta \le 1$. We find that at the aggregate market level, this setup is equivalent to one where all consumers have $\theta_R = \theta - \Delta_\theta$, where $\Delta_\theta = (2\beta - 1)\theta^{\mathrm{DRM}}$ (see Appendix B for details).

Research suggests that a majority of consumers prefer digital music that does not have DRM restrictions (e.g., Berry 2002, Pfeiffer Consulting 2001). In particular, the IDC (2002) estimates that 73% of consumers reject any restrictions imposed by DRM. This is consistent with the comments of Eric Nicolli, the CEO of EMI Group: "In all of our research, consumers tell us overwhelmingly that they would be prepared to pay a higher price for digital music files that they could use on any player. It's clear to us that interoperability is important to music buyers, and is a key to unlocking and energizing the digital business." Within the context of our model, this implies that the majority of consumers do not see DRM as a positive (i.e., $\beta > 1/2$, and hence $\Delta_\theta > 0$), and our basic results all hold.

5.2. Perfect Intraformat Competition

In the main model setup, we considered one Internet and one traditional retailer. In other words, the main model captures interformat competition but not intraformat competition. In practice, there are multiple retailers selling the music in each format, with many of them enjoying downward sloping demands because of their differentiation strategies. Because some of our main results arise as a result of changes in prices when DRM restrictions are removed, it might appear that allowing for competition among the retailers may weaken those results. In this section, we explore this possibility.

We assume that there are many retailers selling each format and that they are engaged in Bertrand competition, so that the equilibrium retail prices are equal to wholesale prices. As before, the location of the digital music format is at the left extreme and the location of the traditional music format is at the right extreme of the Hotelling (1929) line segment. The rest of the model and our analysis approach remain unchanged.

In the case with DRM restrictions, the location of the consumer indifferent between the two formats is identified as in the basic model by equating the utilities $U_{RD}^{S}(x) = U_{RD}^{B}(x)$ and $U_{RD}^{B}(x) = U_{RT}^{B}(x)$ and then solving each for x. Because of the perfect competition within each format, the retail price for each format is the same as the wholesale price: $p_{RT}^{**} = w_{RT}^{**}$ and $p_{RD}^{**} = w_{RD}^{**}$. We then solve the record label's optimization problem to obtain the following optimal wholesale prices:

$$w_{RT}^{**} = \frac{e_T + (t + e_M)(1-\lambda)}{2(1-\lambda)}, \quad \text{and}$$

$$w_{RD}^{**} = \frac{e_T + (e_M - \Delta_\theta)(1-\lambda)}{2(1-\lambda)}.$$

The case when digital music is sold without DRM is solved in the same fashion, yielding the following optimal retail/wholesale prices:

$$p_{UT}^{**} = w_{UT}^{**} = \frac{\delta e_T + (t + e_M)(1+\lambda)}{2(1-\lambda)}, \quad \text{and}$$

$$p_{UD}^{**} = w_{UD}^{**} = \frac{\delta e_T + e_M(1-\lambda)}{2(1-\lambda)}.$$

The full solution is provided in Table 2.

From the above expressions, it is easy to see that with the elimination of DRM, the price for the album in the traditional format decreases, but the price for the music in the digital format may increase or decrease. Here again, the trade-off observed in the main model applies. On the one hand, legal digital music becomes more attractive to the consumers, which creates incentives for the label to increase the wholesale price for the digital album. On the other hand, the reduction in the technical cost of piracy leads to more intense competition between legal and pirated forms of digital music, creating a downward pressure on the wholesale price for the digital album. In terms of piracy, we have the following result.

Proposition 5. *In the case of perfect intraformat competition among retailers, removing DRM always leads to a decrease in piracy.*

Propositions 1A and 1B showed that without intraformat competition, the piracy volume might increase or decrease with DRM removal. Proposition 6 shows that with perfect intraformat competition, retailers are not able to increase price to take advantage of the incremental utility provided by the removal of DRM restrictions. As a result, the piracy volume always goes down. This result also implies that when the intraformat competition is not sufficiently strong, some of the benefits of removing DRM for the record label are reduced by the retailers' ability to charge higher prices for the DRM-free music.

When comparing record labels' profits in cases when the digital music is sold with and without DRM, we see that the result stated in Proposition 2B still holds, just with a different cutoff point:

$$\begin{aligned}\Delta_\theta^{\Pi} = {} & \frac{t(e_T + 2e_M(1-\lambda))}{e_T + 2t(1-\lambda)} \\ & - ((t\delta(2e_T^3(1-\delta)\delta - t\delta(4\delta-3)(1-\lambda) \\ & + 2e_T e_M(e_M(1-\delta) + 2t\delta)(1-\lambda)^2 \\ & - 4e_M^2 t(1-\lambda)^3)(1-\lambda))^{1/2}) \\ & \cdot (\delta(e_T + 2t(1-\lambda))(1-\lambda))^{-1}.\end{aligned}$$

The above cutoff point could be negative, which means that the record label's profit may increase with the elimination of DRM even when doing so does not lead to a higher utility for consumers. This is similar to the result in Proposition 2A in the basic model.

In summary, we find that the insights provided by our main model are preserved when we introduce intraformat competition among retailers. However, when removing DRM leads to a higher utility for consumers, the digital retailers are not able to capitalize on the higher utility by increasing prices. This means that removing DRM always leads to a bigger increase in the sales of legal music. It is easy to see that the retailers do not earn any economic profits even when DRM restrictions are removed, but any positive impact of removing DRM accrues to the record label.

5.3. Competition Between Pirated Digital and Legal Traditional Formats

In this section, we consider the final extension of our main model. In the main model, the legal downloadable format competed against either the legal traditional format or the illegal downloadable format

Table 2 Equilibrium Outcomes Under Perfect Competition

Traditional and restricted downloadable versions for sale	Traditional and unrestricted downloadable versions for sale
$p^{**}_{RT} = w^{**}_{RT} = \dfrac{e_T + (t + e_M)(1-\lambda)}{2(1-\lambda)}$	$p^{**}_{UT} = w^{**}_{UT} = \dfrac{\delta e_T + (t + e_M)(1+\lambda)}{2(1-\lambda)}$
$p^{**}_{RD} = w^{**}_{RD} = \dfrac{e_T + (e_M - \Delta_\theta)(1-\lambda)}{2(1-\lambda)}$	$p^{**}_{UD} = w^{**}_{UD} = \dfrac{\delta e_T + e_M(1-\lambda)}{2(1-\lambda)}$
$\Pi^{**}_{RL} = \dfrac{2e_T^2 t + e_T(4e_M t + (t-\Delta_\theta)^2)(1-\lambda) + 2t(e_M - \Delta_\theta)^2(1-\lambda)^2}{8e_T t(1-\lambda)}$	$\Pi^{**}_{UL} = \dfrac{4e_T e_M \delta(1-\lambda) + 2e_M^2(1-\lambda)^2 + e\delta(t + 2e\delta - t\lambda)}{8e\delta(1-\lambda)}$
$D^{**}_{RT} = \dfrac{t + \Delta_\theta}{4t}$	$D^{**}_{UT} = \dfrac{1}{4}$
$D^{**}_{RD} = \dfrac{e_T(t-\Delta_\theta) + 2t(e_M - \Delta_\theta)(1-\lambda)}{4e_T t}$	$D^{**}_{UD} = \dfrac{2e_M + e_T\delta - 2e_M\lambda}{4e_T\delta}$
$S^{**}_{R} = \dfrac{e_T - (e_M - \Delta_\theta)(1-\lambda)}{2e_T}$	$S^{**}_{U} = \dfrac{e_T\delta - e_M(1-\lambda)}{2e_T\delta}$

(see Figure 1). However, there was no direct competition between the legal traditional and the pirated downloadable formats. One might argue that some consumers choose between buying the legal traditional version and pirating the digital copy from the Internet. In this section we augment the main model by allowing direct competition between all three versions.

As before, the location of the downloadable music format is at the left extreme and the traditional music format is at the right extreme of the Hotelling (1929) line segment. We assume that φ proportion of consumers has a total cost of piracy as in the main model: $e_i = e_T x + e_M^i$ with DRM restrictions and $e_i^U = \delta e_T x + e_M^i$ (where $0 < \delta \le 1$, $i \in \{H, L\}$) without DRM restrictions. The remaining proportion of $(1-\varphi)$ consumers has a total cost of piracy that is $e_i = e_T + e_M^i$ with DRM restrictions and $e_i^U = \delta e_T + e_M^i$ without DRM restrictions. In other words, the piracy cost for φ consumers is related to their location, and for the remaining $(1-\varphi)$ consumers, it is independent of their location. Thus, for the φ proportion of consumers, the equilibrium demand will be as in Figure 1, and for the remaining $(1-\varphi)$ consumers, the equilibrium demand will be as depicted in Figure 3. The rest of the model and our analysis approach remain unchanged, and the full solution is presented in Table 3.

In this extended model, when we compare the piracy volume with and without DRM restrictions, we find that the result stated in Proposition 1B still holds, albeit with a different cutoff point:

$$\begin{aligned}&\big[2t(1-\delta)\tau(e_T^3\delta(3-v)(1-v)^2 v - 32e_M t^2\tau^2\\&\quad - 4e_T e_M t(1+\delta)\tau(1-v)(3+v))\\&\quad - e_T^2\delta(1-v)^2(e_M(9+v^2) - 3t(3-v))\big]\\&\cdot\big[\delta(8t^2\tau^2 + e_T^2(1-v)^2 v + 2e_T t\tau(1-v)(2+v))\\&\quad\cdot(8t\tau + e\delta(1-v)(3+v))\big]^{-1},\end{aligned}$$

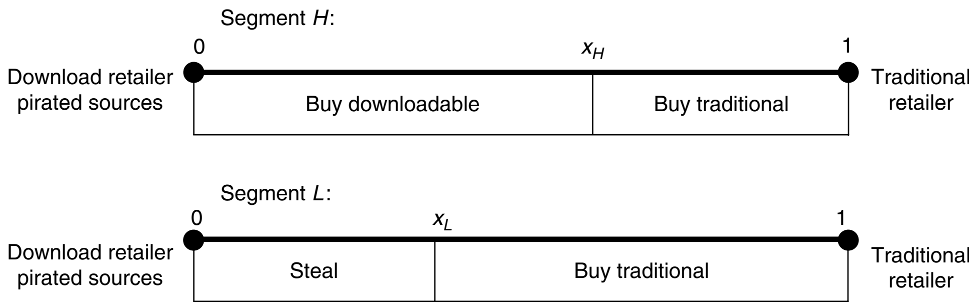
where $\tau = \varphi(1-\lambda)$ and $v = (1-\varphi)(1-\lambda)$.

When we the compare record label's profits in the two cases, the result in Proposition 2B holds as well, but with a different cutoff point, Δ_θ^1, which is defined in Appendix D. It can be shown that this cutoff point can be negative, which means that the record label's profit may increase with the elimination of DRM even when doing so does not lead to a higher utility for consumers (a result equivalent to the one in Proposition 2A). In summary, we find that the insights provided by our main model are robust when we introduce direct competition between traditional format and pirated digital versions.

6. Conclusion

Since music first began to be downloaded on the Internet, the recording industry has fretted about the long-term implications of online piracy. The industry pursued DRM as a partial solution because DRM restrictions make copying harder; they decrease piracy and that, in turn, improves industry profitability. On the other hand, DRM restrictions can potentially reduce the value for legal buyers of the product. In this paper, we show that even though DRM, piracy, and profits are all linked, the relationships among them are complex. The conventional line of thinking misses the impact of DRM technologies on the nature of competition in the legal music market, which in turn affects the consumers' proclivity to steal. Said differently, because DRM decisions by the label affect wholesale prices, retailer incentives, retail prices, the level of competition in the market, and the incentives of consumers to steal, the net effect on profitability depends on the conditions imposed by the DRM technology—in some cases, it improves profits for the label, and in other cases, it decreases them.

Figure 3 Impact of Removing DRM on Record Label Profits



Most of the existing research has focused on understanding the link between piracy and firm profitability. Not only do we look at the link between DRM and piracy, but we also consider the important role played by the retailers and how it affects upstream profits. Moreover, the extant literature looks at the competition between pirated sources versus legal music sales as a whole, whereas we model strategic behavior of download and traditional retailers as two different sources of legal music. By analyzing the competition among the traditional retailer, the download retailer, and pirated music, we get a better understanding of the competitive forces in the market. As a result, unlike the earlier literature, we endogenize not only piracy volume but also consumers' choices between traditional CDs and digital downloads.

In certain instances, we find that eliminating DRM restrictions can lead to an increase in sales of legal downloads, a decrease in sales of traditional CDs, and a decrease in piracy. This is in stark contrast to the view that removing DRM will unconditionally increase the level of piracy. This conclusion stems from the idea that by introducing DRM-free music, the music label increases the downstream competition between the traditional format and legal downloads. Because DRM-free music is a stronger competitor for traditional CDs, it forces the prices of CDs to move down, which in turn lowers the legal download price. This competition between the traditional and download formats lowers prices such that some consumers move from stealing music to buying legal downloads. Thus, removing DRM can lower the level of piracy. Furthermore, we find that this result can occur even when consumers do not see any difference in the utility they derive from DRM-free and DRM-restricted products.

Our analysis also generates several additional counterintuitive results. By removing DRM and making illegal copying easier, the record label can benefit from the intensified competition between pirated music

Table 3 Equilibrium Outcomes Under Direct Competition Between Pirated Digital and Legal Traditional Formats

Traditional and restricted downloadable versions for sale	Traditional and unrestricted downloadable versions for sale
$w_{RT}^{***}=\frac{2t(e_M+t)\tau+e_T^2(1-v)v+e_T(e_M(1-v)v+t(2-v(3-2\tau)+v^2))}{4t\tau+2e_T(1-v)v}$	$w_{UT}^{***}=\frac{2t(e_M+t)\tau+e^2\delta(1-v)v+e_T(e_M\delta(1-v)v+t(2\tau v+\delta(2-3v+v^2)))}{4t\tau+2e_T\delta(1-v)v}$
$w_{RD}^{***}=\frac{2t(e_M-\Delta_\theta)\tau+e_T^2(1-v)v+e_T(1-v)(2t+(e_M-\Delta_\theta)v)}{4t\tau+2e_T(1-v)v}$	$w_{UD}^{***}=\frac{2e_Mt\tau+e^2\delta(1-v)v+e_T\delta(1-v)(2t+e_Mv)}{4t\tau+2e_T\delta(1-v)v}$
$p_{RD}^{***}=\frac{4t(e_M+w_{RD}^{*}-\Delta_\theta)\tau+e_T^2(1-v)v+e_T(1-v)(3t+2w_{RD}^{*}+w_{RT}^{*}+e_Mv-\Delta_\theta(1+v))}{8t\tau+e_T(1-v)(3+v)}$	$p_{UD}^{***}=\frac{4t(e_M+w_{UD}^{*})\tau+e_T^2\delta(1-v)v+e_T\delta(1-v)(3t+2w_{UD}^{*}+w_{UT}^{*}+e_Mv)}{8t\tau+e_T\delta(1-v)(3+v)}$
$p_{RT}^{***}=\frac{2e_T^2(1-v)v+2t\tau(e_M(1+v)+2t+(w_{RD}^{***}+\Delta_\theta)(1-v)+2w_{RT}^{***})+e_T((1-v)((w_{RD}^{***}+\Delta_\theta)(1-v)+2(w_{RT}^{***}+e_Mv))+t(3-4(1+\tau)v+v^2)))}{8t\tau+e_T(1-v)(3+v)}$	$p_{UT}^{***}=\frac{2e_T^2\delta(1-v)v+2t\tau(e_M(1+v)+2t+w_{UD}^{*}(1-v)+2w_{UT}^{*})+e_T(t(\delta(3-v)(1-v)+4\tau v)+\delta(1-v)(w_{UD}^{*}(1-v)+2(w_{UT}^{*}+e_Mv)))}{8t\tau+e_T\delta(1-v)(3+v)}$
$D_{RT}^{**}=\frac{2e_T^2(1-v)v+2t\tau(2t+\Delta_\theta(1-v)+e_M(1+v))+e((1-v)(\Delta_\theta(1-v)+2e_Mv)+t(3-4(1-\tau)v+v^2))}{4t(8t\tau+e_T(1-v)(3+v))}$	$D_{UT}^{***}=\frac{2e_T^2\delta(1-v)v+2t\tau(e_M(1+v)+2t)+e_T(2e_M\delta(1-v)vt(4\tau v+\delta(3-4v+v^2)))\Big)}{4t(8t\tau+e_T\delta(1-v)(3+v))}$
$D_{RD}^{***}=\frac{(2t\tau+e_T(1-v))(4t(e_M-\Delta_\theta)\tau+e_T^2(1-v)v+e_T(1-v)(3t-\Delta_\theta(1+v)+e_Mv))}{4e_Tt(8t\tau+e_T(1-v)(3+v))}$	$D_{UD}^{**}=\frac{(2t\tau+e_T\delta(1-v))(4e_Mt\tau+e_T^2\delta(1-v)v+e_T\delta(1-v)(3t+e_Mv))}{4e_Tt\delta(8t\tau+e_T\delta(1-v)(3+v))}$
$\Pi_{RL}^{***}=w_{RT}^{***}D_{RT}^{***}+w_{RD}^{***}D_{RD}^{***}$	$\Pi_{UL}^{***}=w_{UT}^{***}D_{UT}^{***}+w_{UD}^{***}D_{UD}^{***}$

Note. Where $\tau=\varphi(1-\lambda)$ and $v=(1-\varphi)(1-\lambda)$.

and the download retailer. Furthermore, this suggests that DRM may protect the "traditional businesses," that is, retailers of CDs, more than they protect the download retailer. Finally, we also find that under certain conditions, piracy and label profits can both increase. It is important to note that this positive relationship between piracy and label profits occurs without any network effects in the model. That is, piracy does not contribute directly to consumer utility; instead, it has a positive effect based solely on how it affects prices of the legal products in the market.

Although the idea of eliminating DRM is still an anathema to some in the music industry, the idea of doing away with DRM restrictions is beginning to take hold. For example, the four major record labels (e.g., Sony, Universal, Warner, and EMI) are coming around to the idea of selling DRM-free music (Wortham 2008). The idea of eliminating DRM is also being suggested in the computer game industry. For example, an industry journal recently noted that a highly successful game, *Spore*, came with DRM restrictions that were so onerous that "the DRM encouraged thousands to get their copy illegally" (Ernesto 2008). Attributing abnormally high piracy levels to DRM is consistent with the analysis in our paper. Although our model is developed with the music industry as its principal backdrop, it can be readily extended to other information goods (e.g., movies, books) that can be digitized and distributed over the Internet.

The industry is clear that imposing DRM restrictions imposes costs on consumers; as long as these costs are not too onerous, then consumers will move away from piracy. However, it is important to be clear about the overall effect of these costs. If the record label sells DRM-restricted music, then the restrictions imposed by DRM lower the overall satisfaction from the downloaded product; furthermore, this cost is borne by all consumers, even those who purchase the download legally. Our analysis also suggests that record labels may be better off if they focused on increasing consumers' moral costs of copying rather than increasing their technical cost of copying. Furthermore, we find that removing DRM increases consumer welfare for all segments of the market. In particular, traditional consumers of CDs benefit from a lower price; consumers of legal downloads get higher utility with a DRM-free version even though the price of the legal version may increase; and, interestingly, consumers who obtain pirated versions benefit because it is easier to steal music when there is no DRM.

The present model also suggests several avenues for further research. First, we have treated our basic product as a music album and abstracted away from the bundling problem—a traditional CD is sold as a bundle of songs, whereas downloads can be bought either individually or as a bundle. It would be interesting to investigate the competition and profit implications of a bundling strategy for record labels that face the threat of piracy. Second, this model separates digital and traditional retailers; in future work, it would be worthwhile to allow each retailer to offer both the downloadable and traditional formats. This cannibalization can have interesting effects on the impact of DRM protection on music prices and profits. Third, it would be interesting to compare the role of copy protection in different industries and across different formats. As mentioned earlier, our model is applicable not only to the music industry but also to other information goods such as books and movies. In the absence of data on how these industries differ from one another, we are not able to develop comparative statics that capture the differential impact of DRM across industries. But as more data about these industries become available, it would be interesting to develop further industry-specific insights. Finally, it would be interesting to consider the role of DRM in the presence of network externalities. Existing literature on piracy as a positive network externality assumes that piracy volume depends inversely on the degree of DRM protection. Because our work challenges this assumption, further research should investigate whether eliminating DRM might have different effects in the presence of positive network externalities.

Appendix A. Optimality of Introducing a Digital Retailer

In this section we derive conditions under which introducing some form of digital downloads is optimal for the record label. We derive and compare the record label's profits in the following cases: (1) the record label sells the album exclusively in the traditional format, (2) the record label sells the album in the traditional and DRM-restricted formats, and (3) the record label sells the album in the traditional and DRM-free digital formats.

Consider the case when the only legally available albums are sold in the traditional format by retailer T. As discussed earlier, the moral cost of piracy for consumer in segment H is high enough ($e_M^H \geq \theta - t$) such that consumers prefer not buying music to pirating. The location of the consumer who is indifferent between buying the traditional version and not buying anything is derived by equating $U_T^B(x)$ to zero and solving for x. This location is given by $x_H = (p_T + t - \theta)/t$. The location of the L segment consumer who is indifferent between buying the traditional version and stealing the downloadable version is derived by equating $U_T^B(x)$ and $U_{RD}^S(x, e_L)$ and solving for x. This location is given by $x_L = (p_T + t - e_M)/(2t + e_T)$.

The overall demand for traditional version comes from both segments L and H and is given by

$D_T = \lambda(1-x_H) + (1-\lambda)(1-x_L)$. The traditional retailer chooses the retail price to maximize its profit:

$$\Pi_T = (p_T - w_T)\left(\lambda\frac{(\theta - p_T)}{t} + (1-\lambda)\frac{(e_T + e_M - p_T + t)}{e_T + 2t}\right).$$

As a function of wholesale price, the optimal retail price for traditional product is

$$p_T(w_T) = \frac{t(e_M(1-\lambda)+t(1-\lambda)+w_T(1+\lambda)+2\theta\lambda)+e_T(t(1-\lambda)+\lambda(w_T+\theta))}{2(t(1+\lambda)+e_T)}. \tag{A1}$$

The record label maximizes its profit by choosing the wholesale price:

$$\Pi_{RL} = w_T\left(\lambda\frac{(\theta - p_T(w_T))}{t} + (1-\lambda)\frac{(e_T + e_M - p_T(w_T) + t)}{e_T + 2t}\right).$$

This yields

$$w_T^* = \frac{e_T(t(1-\lambda)+\theta_U\lambda) + t((t+e_M)(1-\lambda)+2\theta_U.\lambda)}{2(t(1+\lambda)+e_T)}.$$

With this optimal wholesale price, the record label's profit is equal to

$$\Pi_{RL}^* = \frac{(t((e_M+t)(1-\lambda)+2\theta_U\lambda)+e_T(t(1-\lambda)+\theta_U\lambda))^2}{8t(e_T+2t)(e_T+t(1+\lambda))}. \tag{A2}$$

A straightforward comparison of (A1) with the record label's profit in cases when it sells DRM-restricted or DRM-free downloads (see Table 1) results in the following observation:

$$\Pi_{RL}^* < \max\{\Pi_{RL}^R, \Pi_{RL}^U\} \quad \text{when } \theta < \max\{\theta_1, \theta_2\},$$

where

$$\begin{aligned}\theta_1 = {}& ((t(t(1+\lambda)+e_T\lambda)(e_T\delta(6e_T^2\delta^2+13te_T\delta(1-\lambda)+4t^2(1-\lambda)^2)\\ &+4(1-\lambda)e_Me_T\delta(3e_T\delta+5t(1-\lambda))\\ &\cdot 2e_M^2(3e_T\delta+4t(1-\lambda))(1-\lambda)^2))\\ &\cdot(e_T\delta\lambda^2(1-\lambda)(e_T+2t)(3e_T\delta+8t(1-\lambda)))^{-1})^{1/2}\\ &-\frac{t(1-\lambda)(e_T+e_M+t)}{(e_T+2t)\lambda};\end{aligned}$$

$$\begin{aligned}\theta_2 = {}& ((6e_T^3t+e_T^2(1-\lambda)((12e_M+13t)t-\Delta_\theta(6t-\Delta_\theta))\\ &+2e_Tt(1-\lambda)^2(3e_M^2+10te_M+2t^2\\ &-\Delta_\theta(4e_M+6t-3\Delta_\theta))+8t^2(1-\lambda)^3(e_M-\Delta_\theta))\\ &\cdot(e_T(e_T+2t)(1-\lambda)(3e_T^2\lambda+et(3+11\lambda-8\lambda^2)\\ &+8t^2(1-\lambda^2)))^{-1})^{1/2}\\ &\times\frac{(1+\lambda(e_T+t))}{\lambda}-\frac{t(1-\lambda)(e_T+e_M+t)}{(e_T+2t)\lambda}.\end{aligned}$$

Because θ is the base utility of listening to the music, it is reasonable to assume that it cannot be infinitely high. So for reasonable values of the base utility, it is optimal for the record label to start selling legal digital downloads in order to capture the demand from the consumers who have strong preference for digital format.

Appendix B. Effect of DRM

In this appendix, we allow some consumers to see DRM as a positive and others to see it as a negative. The location of the consumer who is indifferent between buying the traditional version and buying the downloadable version is derived by equating $U_T^B(x)$ to $U_{RD}^B(x)$. Note that this location is the same for both segments H and L and is given by $x_H^+ = (p_T - p_{RD} + t - \theta^{\text{DRM}})/(2t)$ for those consumers who prefer the DRM-restricted version and $x_H^- = (p_T - p_{RD} + t + \theta^{\text{DRM}})/(2t)$ for those consumers who prefer the DRM-free version.

The location of the L segment consumer who is indifferent between buying the downloadable version and stealing it is derived by equating $U_{RD}^B(x)$ and $U_{RD}^S(x, e_L)$. For those consumers who prefer DRM-free music, this location is at $x_L^+ = (p_{DR} - e_L^M + \theta^{\text{DRM}})/e^T$, and for those consumers who prefer DRM-restricted version, it is at $x_L^- = (p_{DR} - e_L^M - \theta^{\text{DRM}})/e^T$.

Consumers who prefer the DRM-free version of the digital product produce the overall demand of

$$D_D^+ = \lambda x_H^+ + (1-\lambda)(x_H^+ - x_L^+) \quad \text{and} \quad D_T^+ = (1 - x_H^+) \tag{B1}$$

for digital and traditional versions of the product, respectively. Similarly, consumers who prefer the DRM-restricted version of the product have an overall demand of $D_D^- = \lambda x_H^- + (1-\lambda)(x_H^- - x_L^-)$ and $D_T^- = (1 - x_H^-)$. Therefore, the overall demand for the legal products D (digital) and T (traditional) is given by

$$\begin{aligned} D_D &= \beta(\lambda x_H^+ + (1-\lambda)(x_H^+ - x_L^+))\\ &\quad + (1-\beta)(\lambda x_H^- + (1-\lambda)(x_H^- - x_L^-)), \end{aligned} \tag{B2}$$

$$D_T = \beta(1 - x_H^+) + (1-\beta)(1 - x_H^-). \tag{B3}$$

Substituting the expressions for locations of indifferent consumers into (B2) and (B3) results in the following demand functions:

$$D_D(p_{DR}, p_T) = \frac{e_T(p_T - p_{DR} + t + \theta^{\text{DRM}} - 2\beta\theta^{\text{DRM}}) + 2t(1-\lambda)(e_M^L - p_{DR} + \theta^{\text{DRM}} - 2\beta\theta^{\text{DRM}})}{2e^Tt},$$

$$D_T(p_{DR}, p_T) = \frac{p_{DR} - p_T + t - \theta^{\text{DRM}} + 2\beta\theta^{\text{DRM}}}{2t}.$$

After defining the weighted impact of DRM as $\Delta_\theta = \theta^{\text{DRM}}(2\beta - 1)$, these demand functions can be rewritten as follows:

$$D_D(p_{DR}, p_T) = \frac{e_T(p_T - p_{DR} + t - \Delta_\theta) + 2t(1-\lambda)(e_M^L - p_{DR} - \Delta_\theta)}{2e^Tt}, \tag{B4}$$

$$D_T(p_{DR}, p_T) = \frac{p_{DR} - p_T + t + \Delta_\theta}{2t}. \tag{B5}$$

Now consider just the demand that comes only from consumers who prefer DRM-free version of the product. Substituting the locations of indifferent consumers into Equations (B1) results in the following demand functions for digital and traditional products:

$$D_D^+(p_{DR}, p_T) = \frac{e_T(p_T - p_{DR} + t - \theta^{\text{DRM}}) + 2t(1-\lambda)(e_M^L - p_{DR} - \theta^{\text{DRM}})}{2e^Tt}, \tag{B6}$$

$$D_T^+(p_{DR}, p_T) = \frac{p_{DR} - p_T + t + \theta^{\text{DRM}}}{2t}. \tag{B7}$$

Now compare (B4) and (B6). Note that if the overall weighted impact of DRM, Δ_θ, is positive, then our model formulation is equivalent to the model where all consumers derive utility $\theta_R = \theta - \Delta_\theta$ from a DRM-restricted product where $\Delta_\theta = \theta^{\mathrm{DRM}}(2\beta - 1)$. The weighted impact of DRM, $\Delta_\theta = \theta^{\mathrm{DRM}}(2\beta - 1)$, is positive if $\beta > 0.5$.

Appendix C. Allowing Direct Competition Between Pirated Digital and Legal Traditional Formats

Let $\tau = \gamma(1-\lambda)$ and $\upsilon = (1-\gamma)(1-\lambda)$. Consider the difference between record label's profit in the case when it sells DRM-restricted digital music and the case when it sells DRM-free digital music:

$$\Pi_{RL}^U - \Pi_R L^R = A * \Delta_\theta^2 + B\Delta_\theta + C,$$

where

$$A = -\frac{(e_T(1-\upsilon)+2t\tau)(e_T(1+2\tau^2-\upsilon^2)+4t\tau)}{8e_T t(8t\tau + e_T(3+\upsilon)(1-\upsilon))},$$

$$B = \frac{(2t\tau + e_T(1-\upsilon))(4e_M t\tau + e_T(1-\upsilon)(e_T\upsilon + (3t+e_M\upsilon)))}{4e_T t(8t\tau + e_T(3+\tilde{o}\tilde{o})(1-\upsilon))},$$

and

$$\begin{aligned}
C = {} & (1-\delta)\tau\big[128e_M^2t^4\tau^4 - e_T^6\delta^2(1-\upsilon)^4\upsilon^2(9+6\upsilon-\upsilon^2)\\
& + 16e_Te_M^2t^3(1+\delta)\tau^3(1-\upsilon)(3+5\upsilon)\\
& - 2e_T^3t\delta\tau(1-\upsilon)^2(2e_Mt(3-\upsilon)\upsilon(2\tau+3(1+\delta)(1-\upsilon))\\
& - 3e_M^2(1+\delta)\upsilon(1-\upsilon)(3+2\upsilon+\upsilon^2)\\
& + 2t^2(24-(25-52\tau)\upsilon+\upsilon^2+\delta(24-\upsilon)(1-\upsilon)))\\
& + 4e_T^2t^2\tau^2(1-\upsilon)^2(-46t^2\delta - 6e_Mt\delta(3-\upsilon)\\
& + e_M^2(2\upsilon(1+\delta^2)(3+\upsilon)+\delta(9+12\upsilon+13\upsilon^2)))\\
& - 2e_T^5\delta(1-\upsilon)^3\upsilon(e_M\delta\upsilon^2(3-\upsilon)(1-\upsilon)\\
& + 2t(\tau\upsilon(6+\upsilon)+\delta(9-3(1-2\tau)\upsilon-(8-\tau)\upsilon^2+2\upsilon^3)))\\
& + e_T^4\delta(1-\upsilon)^2(e_M^2\delta(1-\upsilon)^2\upsilon^2(9+\upsilon^2)\\
& + 2e_Mt\upsilon^2(3-4\upsilon+\upsilon^2)(-2\tau-\delta(3+2\tau-3\upsilon))\\
& + 2t^2(4\tau\upsilon((11-7\tau)\upsilon-12+\upsilon^2)-\delta(1-\upsilon)(18+6(8\tau-1)\upsilon\\
& + (4\tau-19)\upsilon^2+7\upsilon^3)))\big]/\big[4e_T\delta(2t\tau+e_T\upsilon(1-\upsilon))\\
& \cdot(3e_T+8t\tau-e_T\upsilon(2+\upsilon))(2t\tau+e_T\delta\upsilon(1-\upsilon))\\
& \cdot(3e_T\delta+8t\tau-e_T\delta\upsilon(2+\upsilon))\big].
\end{aligned}$$

The difference is quadratic in Δ_θ, and it is easy to see that $A < 0$.

Solve the equation $\Pi_{RL}^U - \Pi_{RL}^R = 0$ for Δ_θ and denote the two roots as Δ_θ^1 and Δ_θ^2:

$$\Delta_\theta^1 = \frac{B - \sqrt{B^2-4AC}}{-2A}, \quad \text{and} \quad \Delta_\theta^2 = \frac{B + \sqrt{B^2-4AC}}{-2A}.$$

Since $A < 0$, the difference $\Pi_{RL}^U - \Pi_{RL}^R$ is positive if and only if Δ_θ is located between the two roots of equation; i.e.,

$$\Pi_{RL}^U - \Pi_{RL}^R \ge 0 \;\Leftrightarrow\; \Delta_\theta \in [\Delta_\theta^1, \Delta_\theta^2].$$

However, the feasibility condition $D_{RD}^* \ge 0$ implies that

$$\Delta_\theta = \frac{4e_Mt\tau + e_T(1-\upsilon)(e_T\upsilon + (3t+e_M\upsilon))}{4t\tau + e(1-\upsilon^2)} = \bar{\Delta}_\theta.$$

Next we show that $\bar{\Delta}_\theta < \Delta_\theta^2$. Indeed, it is easy to see that $\partial(\Pi_{RL}^U - \Pi_{RL}^R)/\partial\Delta_\theta$ is equal to 0 with $\Delta_\theta = \bar{\Delta}_\theta$; hence, it is the case that $\Delta_\theta^1 < \bar{\Delta}_\theta < \Delta_\theta^2$, i.e., the root Δ_θ^2 is outside of the feasible set of parameters.

Thus $\Pi_{RL}^U - \Pi_{RL}^R \ge 0$ for all feasible $\Delta_\theta = \Delta_\theta^1$.

In other words, when $\Delta_\theta < \Delta_\theta^1$, the record label's profit decreases with elimination of DRM, and when $\Delta_\theta = \Delta_\theta^1$, the record label's profit increases with elimination of DRM.

Appendix D. Proofs of Propositions

Proposition 1A. *With $\Delta_\theta = 0$, the difference $S^U - S^R$ is equal to*

$$S^U - S^R = \frac{(1-\delta)(1-\lambda)(9e_T^2(-e_M+t)\delta - 12e_Te_Mt(1+\delta)(1-\lambda) - 32e_Mt^2(1-\lambda)^2)}{2e_T\delta(3e_T+8t(1-\lambda))(3e_T\delta+8t(1-\lambda))}.$$

It is easy to see that $S^U < S^R$ as long as

$$\delta > \frac{4e_Mt(3e_T+8t(1-\lambda))(1-\lambda)}{3e_T(3e_T(t-e_M)-4eMt(1-\lambda))} = \delta^S.$$

Proposition 1B. *The difference*

$$\begin{aligned}
S^U - S^R = {} & (3e_T^2\delta(3e_M(1-\delta)-3t(1-\delta)+2\delta\Delta_\theta)\\
& + 4e_Tt(3e_M(1-\delta^2)+\delta(4+3\delta)\Delta_\theta)(1-\lambda)\\
& - 32t^2(e_M(1-\delta)+\delta\Delta_\theta)(1-\lambda)^2)(1-\lambda)\\
& \cdot(2e_T\delta(3e_T+8t(1-\lambda))(3e_T\delta+8t(1-\lambda)))^{-1}
\end{aligned}$$

is linear and decreasing in Δ_θ. Solving $S^U - S^R = 0$ for Δ_θ results in the cutoff point

$$\Delta_\theta^S = \frac{(1-\delta)(9e_T^2\delta(e_M-t)+12e_Te_Mt(1+\delta)(1-\lambda)+32e_Mt^2(1-\lambda)^2)}{2\delta(3e_T\delta+8t(1-\lambda))(e_T+2t(1-\lambda))}.$$

Proposition 2A. *Consider the difference between the record label's profit in the case when it sells DRM-restricted digital music and the case when it sells DRM-free digital music with $\Delta_\theta = 0$:*

$$\begin{aligned}
\Pi_{RL}^U - \Pi_{RL}^R = {} & \big[-9e_T^4\delta^2 - 24e_T^3t\delta(1+\delta)(1-\lambda)\\
& + e_T^2\delta(9e_M^2 - 18e_Mt - 46t^2)(1-\lambda)^2\\
& + 12e_Te_M^2t(1+\delta)(1-\lambda)^3 + 32e_M^2t^2(1-\lambda)^4\big]\\
& \cdot\big[4e_T\delta(3e_T+8t(1-\lambda))(3e_T\delta+8t(1-\lambda))(1-\lambda)\big]^{-1}.
\end{aligned}$$

It is easy to see that this difference has the same sign as the numerator of the expression above, which in turn is quadratic in with negative quadratic coefficient. Hence $\Pi_{RL}^U - \Pi_{RL}^R > 0$ when $\delta \in (\delta_1, \delta_2)$, where

$$\delta_1 = \frac{(1-\lambda)\Big(-\sqrt{A^2+48e_Te_M^2t(1-\lambda)(3e_T+8t(1-\lambda))^2)} - A^2\Big)}{6e_T^2(3e_T+8t(1-\lambda))}$$

and

$$\delta_2 = \frac{(1-\lambda)\Big(\sqrt{A^2+48e_Te_M^2t(1-\lambda)(3e_T+8t(1-\lambda))^2)} - A^2\Big)}{6e_T^2(3e_T+8t(1-\lambda))},$$

where $A = (24e_T^2t - e_T(9e_M^2 - 18e_Mt - 46t^2)(1-\lambda) - 12e_M^2t(1-\lambda)^2$.

It is easy to demonstrate that δ_1 is always negative; hence, $\Pi_{RL}^U > \Pi_{RL}^R$ iff $\delta < \delta_2$. Let $\delta_2 = \delta^\Pi$.

Proposition 2B. *Consider the difference between the record label's profit in the case when it sells DRM-restricted digital music and the case when it sells DRM-free digital music*:

$$\begin{aligned}
&\Pi^U_{RL}-\Pi^R_{RL}\\
&=\big[64e_M^2t^3(1-\delta)(1-\lambda)^4-18e_T^4t(1-\delta)\delta^2\\
&\quad-48e_T^3t^2\delta(1-\delta^2)(1-\lambda)+2e_T^2t\delta(1-\delta)(1-\lambda)^2\\
&\quad\cdot(9e_M^2-18e_Mt-46t^2)+24e_Te_M^2t^2(1-\delta^2)(1-\lambda)^3\big]\\
&\quad\cdot\big[8e_Tt\delta(1-\lambda)(3e_T+8t(1-\lambda))(3\delta e_T+8t(1-\lambda))\big]^{-1}\\
&\quad+\Delta_\theta((18e_T^3\delta^2t(1-\lambda)+12e_T^2\delta t(1-\lambda)^2(2e_M\delta+t(4+3\delta))\\
&\qquad+96e_T\delta t^3(1-\lambda)^3+16e_Te_Mt^2\delta(4+3\delta)(1-\lambda)^3\\
&\qquad+128e_M\delta t^3(1-\lambda)^4)\\
&\qquad\cdot(8e_Tt\delta(1-\lambda)(3e_T+8t(1-\lambda))(3\delta e_T+8t(1-\lambda)))^{-1})\\
&\quad-\Delta_\theta^2((3e_T^3\delta^2(1-\lambda)+2e_T^2\delta t(4+9\delta)(1-\lambda)^2\\
&\qquad+24e_T\delta t^2(2+\delta)(1-\lambda)^3+64t^3\delta(1-\lambda)^4)\\
&\qquad\cdot(8e_Tt\delta(1-\lambda)(3e_T+8t(1-\lambda))(3\delta e_T+8t(1-\lambda)))^{-1}).
\end{aligned}$$

This difference is quadratic in Δ_θ *with a negative quadratic coefficient. Solve the quadratic equation*

$$\Pi^U_{RL}-\Pi^R_{RL}=0 \qquad \text{(D1)}$$

for Δ_θ *and denote the two roots as* Δ^1_θ *and* Δ^2_θ, *where* $\Delta^1_\theta<\Delta^2_\theta$:

$$\begin{aligned}
\Delta^1_\theta&=\big[t\delta(3e_T+4e_M(1-\lambda))(3e_T\delta+8t(1-\lambda))\\
&\quad\cdot(e_T+2t(1-\lambda))(1-\lambda)-(t\delta(1-\lambda)(3e_T\delta+8t(1-\lambda))\\
&\quad\cdot(3e_T^2+14e_Tt(1-\lambda)+16t^2(1-\lambda)^2)\\
&\quad\times(e_T^3t\delta(24\delta^2-16+\delta)(1-\lambda)-2e_T^2\delta(1-\lambda)^2\\
&\quad\cdot(t^2(14-23\delta)+6e_Mt(1-3\delta)-3e_M^2(1-\delta))\\
&\quad+8e_Te_Mt(1-\lambda)^3(e_M(1+\delta)+6t\delta)+32e_M^2t^2(1-\lambda)^4)\\
&\quad-6e_T^4(1-\delta)\delta^2))^{1/2}\big]\\
&\times\frac{1}{\delta(3e_T\delta+8t(1-\lambda))(e_T^2+6e_Tt(1-\lambda)+8t^2(1-\lambda)^2)(1-\lambda)}\\
\Delta^2_\theta&=\big[t\delta(3e_T+4e_M(1-\lambda))(3e_T\delta+8t(1-\lambda))\\
&\quad\cdot(e_T+2t(1-\lambda))(1-\lambda)+(t\delta(1-\lambda)(3e_T\delta+8t(1-\lambda))\\
&\quad\cdot(3e_T^2+14e_Tt(1-\lambda)+16t^2(1-\lambda)^2)\\
&\quad\times e_T^3t\delta(24\delta^2-16+\delta)(1-\lambda)-2e_T^2\delta(1-\lambda)^2\\
&\quad\cdot(t^2(14-23\delta)+6e_Mt(1-3\delta)-3e_M^2(1-\delta))\\
&\quad+8e_Te_Mt(1-\lambda)^3(e_M(1+\delta)+6t\delta)+32e_M^2t^2(1-\lambda)^4)\\
&\quad-6e_T^4(1-\delta)\delta^2))^{1/2}\big]\\
&\times\frac{1}{\delta(3e_T\delta+8t(1-\lambda))(e_T^2+6e_Tt(1-\lambda)+8t^2(1-\lambda)^2)(1-\lambda)}.
\end{aligned}$$

Since the Equation (D1) has a negative quadratic coefficient for Δ_θ, *the left-hand side of (D1) is positive if and only if* Δ_θ *is located between the two roots of equation (D1); i.e.,*

$$\Pi^U_{RL}-\Pi^R_{RL}\ge 0 \;\Leftrightarrow\; \Delta_\theta\in[\Delta^1_\theta,\Delta^2_\theta].$$

However, the feasibility condition

$$D^*_{RD}=\frac{(e_T+2t(1-\lambda))(e_T(3t-\Delta_\theta)+4t(e_M-\Delta_\theta)(1-\lambda))}{4te_T(3e_T+8t(1-\lambda))}\ge 0$$

implies that

$$\Delta_\theta=\frac{t(3e_T+4e_M(1-\lambda))}{e_T+4t(1-\lambda)}=\bar\Delta_\theta.$$

Next we show that $\bar\Delta_\theta<\Delta^2_\theta$. *Indeed, notice that the middle point between two roots of Equation (D1), given by* $(\Delta^1_\theta+\Delta^2_\theta)/2$, *is equal to*

$$\begin{aligned}
&\frac{\Delta^1_\theta+\Delta^2_\theta}{2}\\
&=\frac{1}{\delta(3e_T\delta+8t(1-\lambda))(e_T^2+6e_Tt(1-\lambda)+8t^2(1-\lambda)^2)(1-\lambda)}\\
&\quad\times[t\delta(3e_T+4e_M(1-\lambda))(3e_T\delta+8t(1-\lambda))(e_T+2t(1-\lambda))(1-\lambda)]\\
&=\frac{t(3e_T+4e_M(1-\lambda))}{e_T+4t(1-\lambda)}=\bar\Delta_\theta.
\end{aligned}$$

Thus it is the case that $\Delta^1_\theta<\bar\Delta_\theta<\Delta^2_\theta$; *i.e., the root* Δ^2_θ *is outside of the feasible set of parameters.*

Thus $\Pi^U_{RL}-\Pi^R_{RL}\ge 0$ *for all feasible* $\Delta_\theta=\Delta^1_\theta$.

In other words, when $\Delta_\theta<\Delta^1_\theta$, *the record label's profit decreases with elimination of DRM, and when* $\Delta_\theta=\Delta^1_\theta$, *the record label's profit increases with elimination of DRM. Denote this cutoff point as* $\Delta^\Pi_\theta=\Delta^1_\theta$.

Proposition 3. *It is easy to see that the difference* $\Delta^\Pi_\theta-\Delta^S_\theta$ *can be both positive and negative. Therefore, it can be the case that* $\Delta^\Pi_\theta\le\Delta^S_\theta$ *or* $\Delta^\Pi_\theta\ge\Delta^S_\theta$.

Proposition 4. *Consider the difference*

$$\begin{aligned}
&\Pi^U_D-\Pi^R_D\\
&\quad=\frac{t^2(3e_T\delta+4e_M(1-\lambda))^2(e_T\delta+2t(1-\lambda))}{8e_Tt\delta(3e_T\delta+8t(1-\lambda))^2}\\
&\qquad-\frac{(e_T+2t(1-\lambda))(e_T(3t-\Delta_\theta)-4t(e_M-\Delta_\theta)(1-\lambda))^2}{8e_Tt(3e_T+8t(1-\lambda))^2}.
\end{aligned}$$

It is easy to see that it is quadratic in e_M *with a positive quadratic coefficient. The equation* $\Pi^U_D-\Pi^R_D=0$ *has the following two roots when solved for* e_M:

$$\begin{aligned}
e^1_M&=\frac{t(3e_T+4e_M(1-\lambda))}{e_T+4t(1-\lambda)}-(t(3e_T\delta+4e_M(1-\lambda))\\
&\quad\cdot(3e_T+8t(1-\lambda))\sqrt{\delta(e_T+2t(1-\lambda))(e_T\delta+2t(1-\lambda))})\\
&\quad\cdot(\delta(3e_T\delta+8t(1-\lambda))(e_T^2+6e_Tt(1-\lambda)+8t^2(1-\lambda)^2))^{-1},\\
e^2_M&=\frac{t(3e_T+4e_M(1-\lambda))}{e_T+4t(1-\lambda)}+(t(3e_T\delta+4e_M(1-\lambda))\\
&\quad\cdot(3e_T+8t(1-\lambda))\sqrt{\delta(e_T+2t(1-\lambda))(e_T\delta+2t(1-\lambda))})\\
&\quad\cdot(\delta(3e_T\delta+8t(1-\lambda))(e_T^2+6e_Tt(1-\lambda)+8t^2(1-\lambda)^2))^{-1}.
\end{aligned}$$

Hence $\Pi^U_D-\Pi^R_D<0$ *if and only if* $e_M\in(e^1_M,e^2_M)$.

The feasibility condition $x^U_L<x^U_H$ *implies that*

$$e_M\ge\frac{3e_T^2+e_T(11t+2\Delta_\theta)(1-\lambda)+4t\Delta_\theta(1-\lambda)^2}{(3e_T+4t(1-\lambda))(1-\lambda)}=\underline{e}_M.$$

It is easy to see that $e^2_M<\underline{e}_M$; *hence,* $\Pi^U_D-\Pi^R_D>0$ *for all feasible values of* e_M.

Proposition 5. *It is easy to see that* $\partial\Pi_{RL}^{U}/\partial e_M > 0$, *whereas* $\partial\Pi_{RL}^{U}/\partial e_T$ *can be greater or smaller than zero. Hence, the record label's profits always increase when the moral cost of pirating increase but can increase or decrease when the technical cost of piracy goes up.*

Proposition 6. *The difference in piracy volumes,* $S^U - S^R = -((e_M(1-\delta)+\delta\Delta_\theta)(1-\lambda))/(2e_T\delta)$, *demonstrates that* $S^U < S^R$ *always.*

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