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DIGITAL RIGHTS MANAGEMENT AND HARDWARE MARKET POWER

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Abstract. Digital Rights Management (DRM) is employed by firms as a way of reducing illegal copying. In this paper we investigate the idea that it can also be associated with an increase in market power in the hardware market. In our main analysis content and hardware are complementary goods, where there are multiple hardware sellers and one of the hardware sellers owns a DRM technology that can be developed into a DRM system that makes legal content incompatible with hardware that does not employ the system. Our primary result is that the hardware producer who initially owns the DRM technology may employ closed DRM to gain market power in the hardware market because this is an efficient way to monetize its initial ownership of the technology. We also show that, depending on whether or not the content developer has positive bargaining power, the introduction of DRM may or may not result in an increase in content development. In addition to investigating these ideas in a number of related theoretical settings, we also consider the social welfare aspects of the argument and discuss its relevance for understanding the early history of Apple's iPod.

1. Introduction

The problem of illegal copying associated with the growth of creative works stored using a digital format has led to the introduction of technological tools designed to prevent such unauthorized copying. In particular, Digital Rights Management (DRM) refers to encryption technologies used to restrict access to content such as music, movies, or books distributed frequently over the internet, so that those without proper authorization cannot access it. In the standard case the content is distributed in an encrypted form and can only be accessed using devices with the capability of uncoding the content. It has become a popular practice in content industries where the stated goal is typically that it is employed to reduce illegal copying and increase incentives for the creation of content, but its restrictive nature has been

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a controversial subject.[1] In this paper we investigate from a theoretical perspective the idea that, in addition to or instead of the standard stated goals, DRM is also sometimes associated with increased market power in hardware markets.

There are significant reasons for thinking that DRM is sometimes associated with increased market power and profits of the hardware seller. For example, consider the case of Apple's iPod. After its introduction in 2001, the iPod quickly became the fastest selling music player in history. Its US market share among hard-drive-based portable music players exceeded 80 percent by 2004 and its online retail counterpart, the iTunes Store, accounted for more than 80 percent of US digital music sales.[2] As discussed in detail in Sharpe and Arewa (2007), Apple's early success in this market is often attributed at least partly to the fact that when the iPod was introduced its DRM system, known as FairPlay, was a proprietary product. That is, competing music players could not play protected content from the iTunes Store.

The logic is that a closed DRM system like the one initially employed by Apple when it introduced the iPod can increase the hardware seller's market power and profitability. For example, if a hardware seller employs a DRM system that it does not share with rival hardware sellers and content providers produce legal content that can only be consumed using devices that employ this DRM system, then it is as if legal content is tied to the hardware with DRM and users of rivals' products are sometimes forced to obtain illegal copies when legal copies are not available which can either increase the cost of using these rival systems or lower the functionality of those systems. The end result can be an increase in the market power and profitability of the hardware seller that employs DRM.[3]

[1]One of the legal arguments against DRM is that it restricts consumers' "fair use" rights which traditional copyright laws grant. That is, under fair use users do not need the copyright holder's permission to reproduce the work under some circumstances, but circumventing a DRM system is ruled illegal under the Digital Millenium Copyright Act (Pub. L. No. 105-304 (1998), codified at 17 U.S.C. Section 1201, et. seq.).

[2]These numbers are from the NPD Group, Inc. which is a leading North American market research company. For discussions of iPod's quick success see, for example, Guglielmo (2004) and Evans (2006).

[3]In a related class action suit, Apple iPod iTunes Antitrust Litigation, United States District Court for the Northern District of California, Case No. 4:05-cv-00037, Apple was found not guilty of an antitrust violation concerning its behavior of issuing software updates for the iPod that prevented iPods from playing songs not purchased on iTunes. The jury found that the updates were genuine product improvements and the instructions to the jury were that Apple must be found not guilty given that determination whether or not there was anticompetitive harm. Note that our analysis

In this paper we formally investigate this argument. We begin with a static model with homogeneous consumers and the assumption that one hardware producer owns a DRM technology that it can develop into a DRM system that the firm can share with its rival. We further assume that the hardware seller that owns the DRM technology has an effort choice that determines the probability the DRM system it develops is effective. We show that closed DRM emerges in equilibrium because the hardware seller that owns the DRM technology increases market power and profits by refusing to share its system with its rival and this is an efficient way for the firm to monetize its ownership of the technology. In particular, the alternative of selling the DRM system to the content provider and employing open DRM is less profitable due to a moral hazard problem associated with the hardware producer's effort choice concerning DRM effectiveness, where as discussed later this result can be thought of as an example of the determination of asset ownership in the property rights theory of the firm. We also show that, if the government forces the DRM system to be shared, then both social welfare and consumer welfare increase.

We then consider the same model but assume that the firm with the DRM technology can license the DRM system it develops to the other firm. Here we find two types of equilibria. In the first type the hardware seller with DRM does not license its DRM system and the result is basically identical to the equilibrium just described for the case where sharing rather than licensing is possible. In the other equilibria the firm with DRM licenses its system to the other hardware seller, where a high per unit price or royalty fee is used to achieve an outcome similar to the closed DRM equilibria. That is, consumption choices, firm profit levels, and consumer utilities are the same as in the closed DRM equilibria. Also, if the government forces the DRM system to be shared, then again both social welfare and consumer welfare increase.

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is related to Apple's practices that increased iPod's market power while the court case was mostly focused on whether Apple's practices increased iTunes' market power.

We then extend the analysis in various ways. For example, we introduce an investment stage at the beginning of the game where the content provider can invest in the development of content. The main result here is that adding this investment stage to our basic model yields that DRM has no effect on content development. However, that result depends on our assumption that the hardware producer with the DRM technology has all the bargaining power when bargaining with the content provider and DRM will increase content development when the content provider has positive bargaining power. We also consider what happens when each hardware producer at the beginning of the game is allowed to invest in the development of a DRM technology. Here we find that the equilibrium in our initial analysis can be thought of as one of the possible outcomes in this richer setting where initial ownership of a DRM technology is endogenous.

In summary, our basic argument is that, in addition to making copying more difficult, DRM can affect the nature of competition in the hardware market. For example, in our initial analysis the hardware seller with access to DRM employs closed DRM to monopolize the hardware market and in this way capture the incremental profits associated with legal copies when DRM is employed. Further, the reason the firm chooses this way of monetizing its ownership of a DRM technology is that, consistent with the property rights theory of the firm, closed DRM improves the firm's own incentives for optimally choosing the effort level that determines the probability the system will be effective.

We also find that when the DRM technology is owned by a hardware producer, in contrast to the standard argument, DRM does not necessarily result in increased content development. In that case whether or not content development increases depends on whether content developers have positive bargaining power when negotiating with the hardware producer. So the effect of DRM on content development when the technology is owned by a hardware producer is really an empirical question. Similarly, when the DRM technology is owned by a hardware

producer the price of legal content need not increase even if the DRM system is effective. Thus, a closed DRM system can primarily benefit the DRM owner.

The outline for the paper is as follows. Section 2 discusses the relevant literatures. Section 3 first sets forth and analyzes our basic model and then discusses a number of variants of our basic model. In Section 4 we consider two extensions. In the first we add a stage at the beginning of the game where the content provider invests in content development, while in the second we introduce an R&D stage at the beginning of the game where each hardware producer can invest in the development of a DRM technology. Section 5 relates our analysis to the early history of Apple's iPod and also discusses why Apple eventually dropped its use of DRM in that market. Section 6 presents concluding remarks.

2. Related literature

The economics literature on copyright has a long history and includes a variety of theoretical and empirical perspectives (which we do not attempt to fully summarize here; see, for example, Peitz and Waelbroeck (2006) and Novos and Waldman (2013) for surveys). From a theoretical perspective there are broadly two types of copyright protection available to owners of copyrighted goods. One is government enforced legislation, while the other consists of private actions – which are frequently technological in nature – taken by the owners themselves. Much of the early literature on the topic such as Novos and Waldman (1984) and Johnson (1985) focuses on government levels of protection and enforcement and finds that higher levels frequently enhance social welfare.[4] Recently, there has been growing attention to private copyright protection and, in particular, DRM.

Park and Scotchmer (2005) examine the effects on pricing and collusion of the use of DRM systems. They assume that content providers can deploy a DRM system and share the

[4]Landes and Posner (1989), however, argue that in some instances increased copyright protection can reduce social welfare by reducing the number of works in the public domain since such a reduction increases the costs of creating new works. See also Kim (2007) and Boldrin and Levine (2008) for other arguments concerning how increased copyright protection can reduce welfare.

fixed costs of the system. They find that a shared DRM system can facilitate collusion via cost sharing, while separate systems are less vulnerable to hacking so sellers are more likely to raise prices. Other papers that focus on DRM systems without modeling the hardware market include Yoon (2002), Bae and Choi (2006), and Ahn and Shin (2010), where most of the focus of this literature is how DRM affects product quality and profitability of content providers. In contrast, like in the iPod example, we focus on a DRM system owned by a hardware seller rather than a content provider and consider whether the seller has an incentive to share the system with a rival hardware seller.

The paper closest to ours is Bergemann et al. (2011) which also considers how DRM affects profits in the hardware market. Their main focus is the trade-off in setting up a DRM system between increasing the value of purchasing a legal copy of the content good with the increased probability that a non-paying customer gets access to the good. They also extend the analysis by introducing a platform or hardware good which is required to consume the content. They show how specific features of the DRM system affect the profitability of selling the hardware and, in turn, how whether or not the content and hardware products are sold by separate firms or an integrated firm affects the choice of how restrictive to make the DRM system. Our analysis is similar in that it also focuses on how DRM affects the hardware market. But the specifics of the two arguments are quite different because they focus on a setting with a single hardware producer while our focus is on how DRM affects market power when there are rivals in the hardware market.

One can think of closed DRM in our initial analysis as a type of tie that the hardware seller who owns the DRM technology uses to tie legal content to its hardware device. Thus, another literature relevant to our study is the extensive literature on tying and, in particular, the literature focused on the circumstances in which tying can have anticompetitive effects.[5]

[5]See Whinston (1990) which is discussed above, as well as Choi and Stefanadis (2001), Carlton and Waldman (2002, 2012), and Nalebuff (2004) for analyses focused on the potential anticompetitive effects of tying. Tirole (2005) and Carlton and Waldman (2014) survey this literature.

The analysis most similar to ours is one of the analyses in Whinston (1990) in which tying is used to increase market power and profits in the tying market. Whinston (1990) considers a primary good monopolist where there is a competitively supplied inferior substitute for the monopolist's primary product and a complementary good that can be produced both by the monopolist and a rival. Whinston shows that tying reduces the attractiveness of the rival's inferior primary product which can raise monopoly profitability.

Our analysis is related in that the hardware producer can use a closed DRM system as a type of tie that increases its market power and profitability in the hardware or tying market. But there are important differences. First, in our analysis licensing and a high royalty fee can serve as a substitute for closed DRM and there is no similar result in the tying literature. Second, our analysis introduces a new type of tying. In previous literature on the topic two goods produced by the same firm are physically or contractually tied together. In contrast, in our analysis the producer of one good – the hardware product – uses proprietary technology to tie another firm's complementary good and in this way increase its market power in the hardware market. Third, and most importantly, the motivation for tying in our analysis is different. That is, tying or closed DRM is chosen in our analysis because it is an efficient way to monetize the hardware seller's ownership of a DRM technology. There is no analogous argument in the tying literature.[6]

Finally, as mentioned briefly in the Introduction, our main analysis can be thought of as an example of the determination of asset ownership in the property rights theory of the firm (see Grossman and Hart (1986) and Hart and Moore (1990) for the seminal papers on the topic and Gibbons (2005) for a more recent discussion). The basic idea in that theory is that when there are non-contractible specific investments then asset ownership is determined by the need to create investment incentives. In particular, if only one party has the ability to

[6]Another related literature is the literature on systems competition and, in particular, the choice between having an open or a closed system (see, for example, Matutes and Regibeau (1988), Kende (1998), and Church and Gandal (2000)). An important difference between these papers and the models we consider is that in our models the hardware firm does not produce and sell the complementary good in which case it can directly choose to make the good incompatible with the rival's product, but rather the firm uses closed DRM to achieve this incompatibility.

invest, then that party is given full ownership of the asset because then that party receives the full surplus from investing and thus invests efficiently.

This is equivalent to what happens in our main model. In that analysis one hardware producer is endowed with a DRM technology and has to choose a non-contractible investment level that determines the effectiveness of the DRM system that it develops from the technology. Consistent with the basic insight of the property rights theory of the firm, the equilibrium outcome is that the hardware producer with initial ownership of the technology retains ownership rather than selling the asset to the content provider because this means the hardware firm receives the full surplus from its investment and as a result invests efficiently. Given that content industries are not specializing in the development of encryption technologies as hardware sellers are, this seems an important aspect of the software-hardware ecosystem.

3. Model and analysis

In this section we present our argument in a basic model with homogeneous consumers and two hardware producers, where only one is endowed with a DRM technology. We then consider bargaining power, hardware substitutability, and government enforced copyright protection in three variants of our basic model.

3.1. **The Model.** There are two firms ($j = A, B$) that sell hardware devices that consumers need in order to play digital content. There is a single content firm, call it firm C, that sells access to (a bundle of) content and owns its copyright. That there is a single content firm may be due to individual artists or authors transferring their copyrights to a single firm that specializes in managing content. Note, however, assuming a single content firm is not essential for our results but rather we impose the assumption in order to make our main arguments easier to follow. Both hardware devices are produced at a constant marginal cost of c, $c > 0$, while the content has a zero marginal cost of production. The content is subject to consumer

piracy, where we assume that consumers can obtain illegal copies at zero marginal cost in the absence of a DRM system. That is, there are two versions of content; one we refer to as "legal content" and the other as "illegal copies."

We assume that firm A owns a proprietary DRM technology that can encrypt digital content. When firm A designs its DRM system based on this technology there is an unobservable and unverifiable effort choice, d, that determines the probability the DRM system will be effective. Assuming that d is unobservable and unverifiable seems realistic since the effort that a firm expends in developing effective software code is unlikely to be observed by either competitors or the courts. Let $q(d)$ be the probability the system is effective. We assume $q(0) = 0$, $q'(0) = \infty$, $q'(d) > 0$ and $q''(d) < 0$ for all $d > 0$, and $q(\infty) < 1$. Further, the cost of effort choice d is $g(d)$, where $g(0) = 0$, $g'(0) = 0$, $g'(d) > 0$ and $g''(d) > 0$ for all $d > 0$.

When content is DRM protected and the protection is effective it is harder for individuals to make illegal copies. Specifically, we assume that effective DRM protection increases a consumer's copying cost from zero to h, $h > 0$, while with ineffective DRM protection the copying cost remains at zero.[7] When legal content is protected by a DRM system, firm A's hardware is by design compatible with it. However, firm B's hardware is compatible with protected content only if firm A shares or licenses its DRM system with or to firm B. Illegal copies, however, are not DRM protected, so both firms' hardware are compatible with illegal copies regardless of whether they can play DRM protected content.[8]

There are N identical consumers each of whom derives utility from consuming a system composed of hardware and content, where a consumer places zero value from consuming either component by itself or from a system composed of hardware and content where the two are incompatible.[9] Let $U_i = X - e_i - p_j^H$ denote consumer i's utility when he purchases a system

[7]Assuming that the copying cost given ineffective DRM protection is some value h_L, $0 < h_L < h$, would have no effect on the qualitative nature of the results as long as h_L is sufficiently small.

[8]This captures the idea that most portable music players, including the iPod, are compatible with plain MP3 files which is the standard format for illegal copies.

[9]The main qualitative results of the paper are robust to the introduction of consumer heterogeneity concerning either valuations consumers place on illegal copies or consumer copying costs. The main change asscociated with introducing

consisting of firm j's hardware and legal content that can be played on firm j's hardware, where X is the consumer's value for reading, watching, or listening to the legal content, e_i is the consumer's expenditure on content, and p_j^H is the price of firm j's hardware.[10]

Illegal copies are imperfect substitutes for legal content, where there are various factors that can lead to this result. Examples of such factors include copies being of lower quality, customer service not being available to consumers of illegal copies, the risk associated with violations of the law, and psychological costs and moral costs associated with illegal copying. To be specific, let $U_i = Y - e_i - p_j^H$ denote consumer i's utility when he purchases a system consisting of firm j's hardware and an illegal copy, where $Y < X$ captures that illegal copies are inferior to legal content and let $\Delta = X - Y$. We assume $Y > h + c$ which ensures both that the value of legal content exceeds the marginal cost of producing a system consisting of hardware and legal content and that the value of an illegal copy exceeds the marginal cost of producing a system consisting of hardware and an illegal copy even given effective DRM protection.

Let p_C denote the price of legal content. This means that when consumer i purchases legal content $e_i = p_C$. However, if instead the consumer obtains an illegal copy, $e_i = 0$ if the legal content is DRM free or there is ineffective DRM protection and $e_i = h$ if it is DRM protected and the protection is effective. The two hardware devices are homogeneous other than the compatibility issue related to the use of DRM and firms engage in Bertrand competition when more than one firm is active. Finally, let π_j, $j = A, B$, denote firm j's expected profitability and π_C denote firm C's expected profitability.

The timing of the game is as follows. First, firm A has the option of adopting DRM, choosing a value for d if it chooses adoption, and in the case of adoption choosing whether

either of these would be that some consumers would choose to copy in equilibrium and there would also be a monopoly deadweight loss given closed DRM.

[10]One might argue that a more realistic approach would be to model a consumer's choice of hardware as a one-time fixed expenditure and then content purchases would occur later and would be similar to a variable cost. Similar to the approach taken in various empirical papers concerning durable goods such as Dubin and McFadden (1984), this dynamic decision problem can be modeled as a static simultaneous choice problem if consumers are forward looking and firms face reputation considerations due to the repeated nature of the game.

to share or license its system with or to firm B. Second, if a licensing offer is made, then B either accepts or rejects the offer. We start by assuming that the license price is zero so firm A's choice is to share or not share its DRM system with B and we then consider the case in which it can offer a license to B at a positive price. Third, in the case of adoption firm A then offers to firm C a contract that specifies that C sells DRM protected content, where the contract includes a lump sum payment, z, C makes to A for its use of the DRM system and a price, p_C^+, that C can charge for its content. Fourth, in the case of adoption firm C chooses whether or not to accept the offer. Fifth, if DRM was adopted, then whether or not the DRM protection is effective is realized and observed by all parties.[11] Sixth, firms set prices simultaneously subject to any contractual terms and then consumption choices are made. Throughout the analysis we restrict attention to Subgame Perfect Nash equilibria.

Before proceeding to the analysis, it is worth noting that in the equilibrium of our model no copying or piracy actually occurs which is clearly unrealistic. Along the lines of the discussion in footnote 9, we could add a set of consumers with very low copying costs even given effective DRM who would copy in equilibrium. This would have no effect on the main results we focus on which concern the use of closed DRM by the hardware producer who initially owns the DRM technology where closed DRM emerges in equilibrium because it is the most efficient way for this firm to monetize its ownership of the technology. We have chosen not to include these low copying cost consumers in our analysis in order to make the logic behind our main results more transparent.

Another aspect of the model worth mentioning is that, if firm C accepts firm A's offer to sell DRM protected content, firm C has no incentive to then negotiate with firm B to make DRM free content available for firm B's hardware. In other words, even if we added a stage in the game in which such negotiation was possible, there would be no change in terms of

[11]We also assume that the terms in any contract between A and B and the terms in any contract between A and C cannot be made contingent on whether the DRM system is effective. The logic is that whether an encryption system is effective or ineffective may be hard to prove or verify in the courts, although it may be observed by the contracting parties.

equilibrium outcomes. Intuitively, this is the case because DRM protection creates product differentiation in the hardware market and this differentiation results in positive profits shared by the contracting parties (i.e., firms A and C). Similarly, if firm C accepts firm A's offer, firm C has no incentive to make DRM free content available for A's hardware. If it did, consumers could obtain an illegal copy at zero cost which could be consumed using B's hardware and this would also serve to reduce the profits shared by the contracting parties.[12]

3.2. **Analysis.** As indicated, we start with the assumption that firm A's choice is whether or not to share its DRM system with B. Further, we start by taking the value for d when A chooses to sell hardware with a DRM system as given. Consider first pricing and consumption choices as a function of the DRM choices made earlier and whether or not DRM protection is effective when it is adopted. There are three possibilities concerning the DRM choices. First, neither hardware seller employs a DRM system or the DRM system employed is ineffective. Second, firm A employs effective DRM and firm C agrees to sell its product with DRM encryption. We refer to this case as firm A selling hardware with a closed DRM system. Third, both firms employ DRM and firm C agrees to sell its product with DRM encryption.[13] We refer to this case as firm A selling hardware with an open DRM system.

Suppose neither firm employs DRM or the DRM system employed is ineffective. In this case the two hardware sellers are selling identical products and there is Bertrand competition, so $p_A^H = p_B^H = c$, $\pi_B = 0$, and $\pi_A = 0$ given no DRM and $\pi_A = z - g(d)$ given ineffective DRM. Firm C, on the other hand, faces potential competition from illegal copies which can be obtained in this case at zero cost. This means that firm C sets its price equal to its quality

[12]We also assume that pricing occurs after the effectiveness of the DRM system is observed. Having the price determination game occur after product characteristics are realized is standard in models of oligopoly interaction given that prices are typically easy to change.

[13]Another possibility is that one or both firms employ DRM but C sells legal content without encryption. In terms of the resulting pricing and consumption choices this case is equivalent to the first case where neither hardware seller employs a DRM system or the DRM system employed is ineffective.

advantage over illegal copies, i.e., $p_C = \Delta$, all consumers purchase legal content from C, and $\pi_C = N\Delta$ given no DRM and $\pi_C = N\Delta - z$ given ineffective DRM.[14]

Suppose firm A sells hardware with a closed DRM system and the DRM system is effective. If $p_C^+ > \Delta + h$, then consumers would obtain illegal copies rather than purchase legal content from C. In this scenario it is as if the two hardware firms are selling identical products, so we again have $p_A^H = p_B^H = c$, while $\pi_A = z - g(d)$ and $\pi_B = 0$. Further, since C does not sell legal content, we have $\pi_C = -z$.[15]

Now suppose $p_C^+ \leq \Delta + h$. If consumer i purchases firm A's hardware and legal content, then $U_i = X - p_C^+ - p_A^H$. The other possibility is that consumer i purchases firm j's hardware and obtains an illegal copy which yields $U_i = Y - h - p_j^H$ (consumer i will not purchase firm B's hardware and legal content because firm A sells hardware with a closed system). Given $p_C^+ \leq \Delta + h$, the consumer prefers to purchase firm A's hardware and legal content if the two firms choose equal hardware prices.[16] This set of parameterizations is therefore equivalent to Bertrand competition where firm A has a superior product. So $p_A^H = c + \Delta - (p_C^+ - h)$, $p_B^H = c$, and consumers purchase A's hardware and legal content from C. Also, $\pi_A = N[\Delta - (p_C^+ - h)] + z - g(d)$, $\pi_B = 0$, and $\pi_C = Np_C^+ - z$.

The final possibility is that firm A sells hardware with an open system and the DRM system is effective. In this case the two hardware sellers are again selling identical products and there is Bertrand competition, so $p_A^H = p_B^H = c$, $\pi_A = z - g(d)$, and $\pi_B = 0$. If $p_C^+ > \Delta + h$, then consumers prefer to obtain illegal copies and $\pi_C = -z$. If $p_C^+ \leq \Delta + h$, then consumers

[14] In the case where DRM is adopted but ineffective and $p_C^+ \neq \Delta$, we assume a renegotiation stage where firm C makes a take-it or leave-it offer to firm A that includes a payment from C to A and a new value for p_C^+. The unique Nash equilibrium to this renegotiation is a payment of zero and a new value for p_C^+ equal to Δ. So the outcome described above also holds in this case. Allowing for this type of renegotiation for other parts of the game would not change the equilibrium outcome.

[15] One concern here is that it is not clear how consumers obtain illegal copies if firm C sells no legal content. So implicitly we are assuming there is a small number of additional consumers – at least two – who have a higher cost of obtaining illegal copies with the result that copying is not an option for these consumers. This additional assumption rationalizes the behavior above as long as $p_C^+ \leq X - c$.

[16] To be precise, if $p_C^+ = \Delta + h$, then given equal hardware prices consumers are indifferent between purchasing firm A's hardware and legal content and purchasing either firm's hardware and obtaining an illegal copy. In this case behavior can be consistent both with what we describe for $p_C^+ > \Delta + h$ and with what we describe for $p_C^+ \leq \Delta + h$.

prefer legal content and $\pi_C = Np_C^+ - z$.[17] Note that open DRM with $p_C^+ = \Delta + h$ is basically equivalent to having firm A sell the DRM system to firm C.[18]

Table 1: Firms' choices leading up to final stage of the game

Firm A	Firm B	Firm A	Firm C	Regime
adopts DRM; and then decides whether to share it with B (or license it to B)	accepts	makes an offer to C to sell DRM protected content	accepts	If effective, then open DRM; If not, then no DRM protection
			rejects	No DRM protection
	rejects	makes an offer to C to sell DRM protected content	accepts	If effective, then closed DRM; If not, then no DRM protection
			rejects	No DRM protection
does not adopt DRM				No DRM protection

We now use these results to analyze the earlier stages of the game at which time firm A makes choices concerning DRM. From above we know that if neither firm employs DRM (or DRM is employed but firm C does not encrypt its legal content), then $\pi_A \leq 0$ and $\pi_B = 0$. So firm A has an incentive to employ either open or closed DRM if doing so achieves strictly positive expected profits. Table 1 above summarizes the firms' choices leading up to the last stage of the game which was analyzed above.

We start by focusing on closed DRM. If firm A chooses closed DRM and $p_C^+ > \Delta + h$, then $\pi_A = z - g(d)$, $\pi_B = 0$, and $\pi_C = -z$. Since firm C will not accept an offer where $\pi_C < N\Delta$ since $\pi_C = N\Delta$ if it turns down A's contract offer, we have $\pi_A < 0$ for any accepted contract so

[17]To be precise and similar to the discussion in footnote 16, if $p_C^+ = \Delta + h$, then consumers are indifferent between purchasing legal content and obtaining illegal copies. So π_C will be somewhere in the interval $[-z, Np_C^+ - z]$.

[18]To be precise, suppose we added a stage between firm A's choice of d and its choice of whether or not to share its technology with firm B where A makes a take-it or leave-it offer to C for the sale of the DRM system. We can show that selling the DRM system for some amount Z in this variant of our model is basically equivalent in terms of firms' profits, consumer utilities, prices, equilibrium value for d, etc., to firm A in the sharing version of our model sharing the technology with B and contracting with C where $z = Z$ and $p_C^+ = \Delta + h$.

this is not a candidate for equilibrium. Suppose firm A chooses closed DRM and $p_C^+ \leq \Delta + h$. From above we know that if firm C accepts the DRM contract offer and chooses to encrypt its content, then $\pi_A = q(d)N[\Delta - (p_C^+ - h)] + z - g(d)$ and $\pi_C = q(d)Np_C^+ + (1 - q(d))N\Delta - z$. On the other hand, if firm C turns down the offer, then $\pi_A = -g(d)$ and $\pi_C = N\Delta$. Clearly, the only candidate for equilibrium is that A offers a z, p_C^+ pair such that the contract is accepted and $\pi_C = N\Delta$. The reason we know $\pi_C = N\Delta$ is that, if $\pi_C > N\Delta$, then A could always increase profits by slightly increasing z.

Now consider open DRM. As before, it must be the case that $p_C^+ \leq \Delta + h$. From above we know that if firm C accepts the DRM contract offer, then $\pi_A = z - g(d)$ and $\pi_C = q(d)Np_C^+ + (1 - q(d))N\Delta - z$. As before, the only candidate for equilibrium is that A offers a z, p_C^+ pair such that the contract is accepted and $\pi_C = N\Delta$. Further, since this tells us that a higher value for p_C^+ within the relevant range also means a higher z, we now have $p_C^+ = \Delta + h$.

Finally, we consider the choice of d at the beginning of the game. Start with the case in which the firm anticipates employing open DRM. From above we have $\pi_A = z - g(d)$, so since firm A will take the subsequent value for z as given in making the decision concerning d the firm chooses $d = 0$ which means $\pi_A = 0$, $\pi_B = 0$, and $\pi_C = N\Delta$. This is a classic moral hazard problem. Firm A's investment in DRM effectiveness is unobservable and unverifiable and costly to firm A. If the firm plans to choose open DRM then it receives no return from a higher investment in d, so it chooses the minimum value for d, i.e., $d = 0$. This tells us that open DRM is not consistent with equilibrium behavior.

Now consider closed DRM. Let d^* be the value for d that would be chosen by a monopoly seller of hardware that is vertically integrated, i.e., firm A owns firm C. d^* satisfies $q'(d^*)Nh - g'(d^*) = 0$. Given this, consider the choice of d under closed DRM as a function of the anticipated contract between A and C. From above we have $\pi_A = q(d)N[\Delta - (p_C^+ - h)] + z - g(d)$. Comparing this expression with the equation that defined d^* yields that incentives for investing in DRM effectiveness are optimal when $p_C^+ = \Delta$. The logic is that, if the firm plans

to choose closed DRM and a contract that sets $p_C^+ = \Delta$, then the returns to a higher choice of d go fully to firm A and A then makes the efficient investment in DRM effectiveness. In other words, closed DRM where the content provider is not allowed to raise its price yields efficient effort incentives for firm A, so this is the equilibrium outcome.[19]

We state the result formally in Proposition 1. Proofs are in the Appendix.

Proposition 1: *If firm A's choice is whether or not to share its technology with firm B, then there is a unique Subgame Perfect Nash equilibrium characterized by 1 through 7.*

(1) *Firm A adopts DRM and chooses* $d = d^*$.
(2) *Firm A does not share its DRM system with firm B and offers a contract to firm C that sets* $z = 0$ *and* $p_C^+ = \Delta$.
(3) *Firm C accepts the contract.*
(4) *All consumers purchase hardware from A and legal content from C when the DRM system is effective, while consumers purchase hardware from A or B and legal content from C when the DRM system is ineffective.*[20]
(5) *In states of the world in which the DRM system is effective,* $p_A^H = c + h$, $p_B^H = c$, *and* $p_C = p_C^+ = \Delta$.
(6) *In states of the world in which the DRM system is ineffective,* $p_A^H = c$, $p_B^H = c$, *and* $p_C = \Delta$.
(7) $\pi_A = q(d^*)Nh - g(d^*)$, $\pi_B = 0$, *and* $\pi_C = N\Delta$.

In our analysis the hardware producer with access to DRM does not produce the complementary product and we do not consider the possibility of a merger. So the firm cannot unilaterally reduce the availability of complementary products that can be used with the

[19]This result is consistent with Mathewson and Winter (1984) which shows that under certain conditions franchise fees and resale price maintenance constitute a sufficient set of vertical restraints to achieve an efficient outcome.
[20]In describing the equilibrium as unique we are ignoring that when the DRM system is ineffective each consumer purchases hardware from either A or B.

rival's hardware system. Instead, the firm uses DRM to accomplish this goal, where this requires agreement by the content provider because a DRM system only works when the content provider agrees to encrypt its product. So what happens in equilibrium is that the hardware producer with access to DRM, firm A, makes a contract offer to firm C that sets the fixed payment equal to zero and a price for legal content such that firm C finds it (weakly) advantageous to adopt DRM. In other words, there is a type of tie accomplished through DRM and encryption that increases market power and profitability of the hardware seller with access to DRM, but because the tie requires the cooperation of the content provider this firm cannot be made worse off (and, as discussed further below, if the content provider has some bargaining power then this firm will be made better off when it adopts DRM).

But note that, as indicated earlier, the motivation for the tie achieved through closed DRM in our analysis is different than the related results in Whinston (1990). The basic issue that arises in our analysis which has no analogue in that earlier paper is that firm A owns a DRM technology which makes the expected cost of copying higher and from A's standpoint the question is what is the best way to monetize its ownership of this technology. It could, for example, employ open DRM and simply sell the DRM system it develops (see footnote 18) to the content firm but because of a moral hazard problem this is not the most effective approach. Rather, the firm monetizes the DRM technology through closed DRM and tying because this creates efficient incentives for investing in DRM effectiveness. As discussed earlier, this argument can be thought of as an example of how asset ownership is determined in the property rights theory of the firm.

The next question we consider is, how would a government policy that requires DRM systems to be shared or open affect social welfare? One reason this question is of interest is that in the case of Apple's iPod there was pressure from European regulators for Apple to share its DRM system with rival hardware producers.[21] This issue is considered in the

[21]In 2006 both France and Denmark moved towards requiring Apple to share its DRM system with rivals, but in each case the government stopped short of a mandate. For example, the French National Assembly passed a bill that required

following corollary where we analyze the exact same game considered above except that at the beginning of the game the government announces that firm A must share its DRM system with firm B. Also, social welfare is defined as the sum of firms' profits and consumers' utilities.

Corollary to Proposition 1: *Suppose that at the beginning of the game considered in Proposition 1 the government announces that firm A must share its DRM system with firm B. The result is both social welfare and consumer welfare rise.*

The logic here is as follows. If firm A is restricted to employing open DRM, then from above we know that $d = 0$ and so the outcome is basically the no DRM outcome. This means, in turn, that both social welfare and consumer welfare rise. The reason that social welfare rises is that with or without the government intervention all consumers purchase a system consisting of one hardware unit and legal content, so the decrease in the investment in DRM effectiveness means social welfare rises. Further, the price for content is unchanged while the expected price for hardware falls, so consumer welfare rises while aggregate firm profitability falls since firm A no longer derives positive expected profits from its initial ownership of the DRM technology.

We now consider what happens when, rather than firm A having the option of sharing its DRM system with B, we assume that A can offer to license its technology to B. Specifically, licensing requires B to make a two-part payment to A where F is the fixed payment and s is the per unit payment or royalty fee. For this case we make the additional assumptions that firm B does not accept contract terms which result in no hardware sales for B and $\pi_B = 0$ and that there are other hardware sellers each of whom has marginal cost c, but only B's product is capable of using A's DRM system. If we did not assume the existence of these other hardware sellers, then, in contrast to what we find in Proposition 2, firm A would prefer to license its DRM system over having a closed DRM system because by licensing the firm

Apple to share information about its DRM system with rival hardware sellers. However, the French Senate passed a bill that dropped key provisions and then a joint committee passed a compromise bill in which exemptions were granted as long as copyright owners agreed to a closed system.

could eliminate the sale of rival hardware that plays only unprotected content which, in turn, would allow the firm to increase the price of its own hardware that plays protected content.

Proposition 2 formally considers this case.

Proposition 2: *If firm A's choice is whether or not to license its technology to firm B, there are multiple equilibria.*

(1) *In some equilibria firm A does not license its DRM system to firm B, and in all respects other than the contract terms A offers to B these equilibria are equivalent to the Proposition 1 equilibrium where A has the option of sharing and employs a closed DRM system.*

(2) *In the other equilibria, A licenses its technology to B, where* $F = 0$, $s = h$, $d = d^*$, $z = 0$, $p_C = p_C^+ = \Delta$, p_A^H, $p_B^H \geq c + h$ *(and at least one equals* $c + h$*) when DRM is effective,* $p_A^H = p_B^H = c$ *when DRM is not effective,* $\pi_A = q(d^*)Nh - g(d^*)$, $\pi_B = 0$, *and* $\pi_C = N\Delta$. *Also, in these equilibria each consumer purchases hardware from either A or B and legal content from C.*[22]

The logic behind the equilibria where A employs closed DRM is the same as the logic for the equilibrium described in Proposition 1. By employing closed DRM firm A is able to monetize its ownership of its DRM system in an efficient manner. As stated in the proposition, however, now there are also other equilibria in which A licenses its technology to B, where $z = 0$, $p_C^+ = \Delta$, and the equilibrium license payments are $F = 0$ and $s = h$.

To see why there are equilibria with licensing consider what happens given $z = 0$, $p_C^+ = \Delta$, $F = 0$, and $s = h$ when firms set prices to charge consumers in states of the world in which DRM is effective. Because of the contract, firm C charges $p_C = p_C^+ = \Delta$. To determine the hardware prices we need to know the marginal costs for hardware. B's marginal cost is $c + h$ since it is the sum of the production marginal cost and the per unit payment that B makes

[22]There are multiple equilibria of the first type because there are multiple contract terms that A can offer to B that will be rejected, while there are multiple equilibria of the second type because p_A^H and p_B^H are not uniquely defined.

to A when it sells a hardware unit. In equilibrium A's marginal cost is also $c+h$ which is the sum of A's production marginal cost and the lost licensing fee equal to h that A incurs when it sells a unit because each unit A sells means one less sale for B. In turn, given Bertrand competition and a marginal cost for each hardware producer equal to $c+h$, in equilibrium p_A^H, $p_B^H \geq c+h$ (and at least one equals $c+h$). The final result is that every consumer purchases hardware from either A or B and legal content from C, $p_C^+ = \Delta$, p_A^H, $p_B^H \geq c+h$ (where at least one equals $c+h$), while $\pi_A = Nh - g(d)$, $\pi_B = 0$, and $\pi_C = N\Delta$.[23] In other words, this second type of equilibrium is almost identical to the first except that the DRM system is open and so consumers can purchase hardware from either hardware producer.[24]

One way to think about this result is that firm A can use licensing and a high royalty payment to achieve collusive pricing in the hardware market when the DRM system is effective, where the royalty payment from B to A means that A's profit in such an outcome is the same as A's profit given closed DRM found in Proposition 1 and Proposition 2(1). In this case it is not closed DRM acting as a tie that creates market power in the hardware market. Rather, it is the high royalty payment from B to A that raises the marginal cost for each firm so that the final price charged to consumers is the same as if firm A's device was the only one that could be used to consume legal content. And then the high royalty payment from B to A means that all the profits are received by A.[25]

We end this subsection by considering the social welfare implications of a government policy that requires DRM systems to be shared or open when licensing is a possibility. We formally consider this issue in the following corollary.

[23]The reason only one of firms A and B needs to charge $c+h$ for its hardware is that the threat of consumers purchasing hardware from a third firm and obtaining an illegal copy means that either A or B can deviate from a price of $c+h$ without creating an incentive for the other firm to deviate.

[24]That there are both licensing and no licensing equilibria in this version of the model is consistent with Apple employing closed DRM for the iPod while Microsoft employed licensing and open DRM for its "PlayForSure" DRM system.

[25]Note that introducing dynamic considerations might eliminate the multiple equilibria finding and result in only closed DRM equilibria. For instance, related to Carlton and Waldman (2012) on tying and Chen (2014) on refusal to deal, suppose there is potential competition between hardware devices over multiple periods, hardware upgrades, and consumer switching costs concerning the hardware devices. Then closed DRM can be preferred to licensing because it results in the rival hardware devices becoming less attractive alternatives in later periods.

Corollary to Proposition 2: *Suppose that at the beginning of the game considered in Proposition 2 the government announces that firm A must share its DRM system with firm B. The result is both social welfare and consumer welfare rise.*

The logic for this result is basically the same as the logic for the similar result when firm A's option was to share rather than license. That is, all the equilibria in Proposition 2 have the same consumer utilities and firm profitabilities as the unique equilibrium in Proposition 1. So the same argument given above concerning why this government intervention raised social welfare and consumer welfare when A's option was to share also applies here where A's option is to license.

3.3. **Three Variants.** In this subsection we consider three simple variants of this section's analysis. In the next section we consider larger changes which we label as extensions. The first variant involves bargaining between firms A and C. That is, by assuming that firm A makes a take-it or leave-it offer to firm C when offering to share its DRM technology, we give all the bargaining power in this exchange to firm A. As a result, firm C's profit in the unique equilibrium in Proposition 1 and all the equilibria in Proposition 2 is the same as the profit it receives in a setting with no DRM. If instead we assumed that each firm had positive bargaining power so that the added profits associated with DRM were shared between the firms, the result would be $z < 0$ and $p_C^+ = \Delta$, i.e., firm A would pay firm C to encrypt its content and p_C^+ would remain unchanged. The logic is that setting $p_C^+ = \Delta$ as in the Proposition 1 result yields that the incentives for investing in DRM effectiveness are optimized. So, if firm C has positive bargaining power, p_C^+ is unchanged and the higher profits for C are achieved through a negative value for z.[26]

This version of our model is related to Aghion and Bolton's (1987) analysis in which contracts between buyers and sellers are used to deter entry. In the Aghion and Bolton argument a buyer and seller extract rents from a potential entrant by signing a contract that specifies

[26]In this discussion we are assuming that the bargaining process leads to an efficient outcome.

damages if the buyer trades with the potential entrant, where the extra profitability of the seller is shared with the buyer so that the buyer is compensated for the reduced probability of entry. In our argument a hardware producer and content provider extract surplus from consumers by signing a contract that increases market power in the hardware market, where the extra profitability of the hardware producer is shared with the content provider and the sharing takes the form of a higher fixed payment to the content provider, $z < 0$.

The second variant concerns the substitutability of the two hardware products. In our basic analysis we assume that in the absence of DRM protection the two products are equally attractive to consumers. But another interesting case is what happens when consumers prefer one hardware product over the other. Suppose, for example, that consumers prefer firm A's hardware product, i.e., consumers prefer the product of the firm that owns the DRM technology. Consider this case and assume initially as a benchmark analysis that A does not own a DRM technology. Because consumers prefer A's hardware product, even in the absence of DRM, firm A would monopolize the hardware market where A's profit would reflect the added valuation that consumers place on A's hardware relative to B's.

Now start from the situation described above where A does not own a DRM technology and give A such ownership. The result is an equilibrium similar to the one described in Proposition 1, i.e., firm A adopts a closed DRM system and all consumers purchase hardware from A and legal content from C.[27] The question is, why does A adopt closed DRM given that it monopolizes the hardware market with or without DRM? And the answer is that, because the price that A can charge for its hardware is a function of how close a substitute B's product is for A's, firm A adopts closed DRM because in a sense closed DRM reduces the quality of B's product which allows A to raise its hardware price and in this way efficiently monetize its DRM technology.

[27]If consumers preferred firm B's hardware product rather than firm A's, then A would license its technology to B and B would employ a closed DRM system. Also, if some consumers preferred A's hardware and some preferred B's, then there is the possibility that all equilibria would be characterized by open DRM.

In the third variant we consider the effects of government enforced copyright protection on equilibrium behavior in our model. In our main analysis we implicitly assume that the level of government enforced copyright protection is zero and does not change when a DRM system is introduced. Given potential substitutability between government enforced copyright protection and DRM systems, however, how the introduction of government enforced copyright protection and more generally how changes in the level of such government enforcement affect equilibrium behavior in our model is an interesting question. Suppose in our basic analysis government enforced copyright protection creates an addititonal copying cost, k, $k > 0$. That is, a consumer's copying cost is $e_i = k$ if the legal content is not DRM protected or the DRM system is ineffective and $e_i = h + k$ if the legal content is DRM protected and the protection is effective.

With this change, if no DRM system is introduced, then firm C sets the price for legal content equal to the quality advantage over illegal copies plus the extra copying cost due to the government enforced copyright protection, i.e., $p_C = \Delta + k$. This change, in turn, increases firm C's equilibrium profit level from $\pi_C = N\Delta$ to $\pi_C = N(\Delta + k)$. From the standpoint of consumers, however, the difference in (gross) utility from using A's hardware together with DRM protected legal content and using B's hardware together with an illegal copy remains at h which is the increase in copying cost due to DRM protection. The result is that, as long as k is sufficiently small, the equilibrium characterization will be the same as in the above propositions, except firm C will capture more surplus from consumers. In other words, as long as government enforced copyright protection is limited, the introduction of such enforcement into our model or small changes in the enforcement level have little effect on the qualitative nature of our results.[28]

[28]On the other hand, if k is sufficiently high, i.e., $h + k + c > Y > k + c$, then the additional copying cost due to DRM protection will preclude the use of B's hardware with an illegal copy. In this case firm A can extract more surplus by employing a closed DRM system because B's hardware would then no longer be a viable option. As a result, firm A's investment in DRM effectiveness, d, can be larger than the equilibrium value, d^*, found in our main analysis.

4. Extensions

In this section we consider two extensions. First, we add a stage at the beginning of the game in which the content provider invests in content development and also a probability that firm A is endowed with a DRM technology. Second, we add an R&D stage at the beginning of the game where hardware producers can invest in the development of a DRM technology.

4.1. **Investing in Content Development.** In Section III we ignored what our model suggests concerning how DRM affects content development. This is an important question since the underlying rationale for the initial development of DRM is that by making copying more difficult it improves incentives for content development. This is the issue we consider in this subsection.

We start with our initial model where firm A's option is whether or not to share its system with firm B and make three changes. First, at the beginning of the game firm C chooses an investment level in content development. This investment level is denoted m, where X, Y, and thus Δ (since $\Delta = X - Y$) are all functions of m. Specifically, $\Delta(m)$ satisfies $\Delta(0) > 0$, $\Delta'(0) = \infty$, $\Delta'(m) > 0$ and $\Delta''(m) < 0$ for all $m > 0$, and $\Delta'(\infty) = 0$. That is, we assume the incremental gross benefit that a consumer receives from consuming legal content rather than an illegal copy increases but at a decreasing rate with investments in content development. The basic idea here is that an increase in m leads to more variety, or equivalently, a larger bundle of content, and then any of the factors mentioned earlier concerning why $X > Y$ can justify Δ being a positive function of m. For example, customer service not being available to consumers of illegal copies will constitute a larger cost the more content is in the bundle.

Second, the copying cost associated with effective DRM is given by $h(m)$, where $h'(m) \geq 0$ for all $m \geq 0$. This allows for the possibility that, if increased investment means a larger bundle of content, then the cost of copying content given effective DRM increases with the investment level. Third, there is now a probability α, $0 \leq \alpha \leq 1$, that firm A is endowed with a DRM technology at the beginning of the game. Further, the realization for whether firm

A is endowed with the technology occurs after C chooses m but before the rest of the game, where this realization is publicly observed.

To understand the nature of equilibrium in this extension we start by taking m as given and consider the outcome as a function of whether or not firm A is endowed with the DRM technology. Suppose the firm chooses m^+ in the first stage of the game. When firm A is endowed with the DRM technology then the equilibrium outcome is described in Proposition 1 where $\Delta(m^+)$ substitutes for Δ. When firm A is not endowed with the technology then the two hardware sellers are selling identical products, so $p_A^H = p_B^H = c$, $p_C = \Delta(m^+)$, and each consumer purchases hardware from either A or B and legal content from C.

Now consider the initial stage of the game where firm C chooses an investment level in content development and, in particular, how this investment level varies with α. Call m^* the investment level that would be chosen if the probability firm A is endowed with a DRM technology was zero, i.e., $\alpha = 0$. Analysis of this benchmark case yields that m^* satisfies $N\Delta'(m^*) = 1$. As captured below in Proposition 3 which describes equilibrium in this first extension of our model, firm C's investment level in content development is unchanged when the probability firm A is endowed with a DRM technology is positive, i.e., $0 < \alpha \leq 1$. And note that this also means that this investment level is independent of the probability firm A is endowed with a DRM technology when this probability is positive.

Proposition 3: *Suppose firm C chooses an initial investment in content development, m, and there is also a probability, α, that firm A is endowed with a DRM technology. If firm A's choice is whether or not to share its technology with firm B, then there is a unique equilibrium described by 1 through 3.*[29]

(1) *When firm A is not endowed with a DRM technology, then $p_A^H = p_B^H = c$, $p_C = \Delta(m)$, and each consumer purchases hardware from A or B and legal content from C.*

[29] As was the case for Proposition 1 (see footnote 20), in describing the equilibrium as unique we are ignoring that in some of the subgames on the equilibrium path consumers purchase hardware from either A or B.

(2) *When firm A is endowed with a DRM technology, then the equilibrium outcome is given by Proposition 1 where $\Delta(m)$ substitutes for Δ.*

(3) $m = m^*$.

To understand the logic here, note that firm C charges $\Delta(m)$ for legal content when firm A is not endowed with a DRM technology, when it is endowed with the technology but the resulting DRM system is ineffective, and when it is endowed with the technology and the resulting DRM system is effective. Given this, think about what happens when the possibility of DRM is introduced, i.e., α starts at zero and is increased to a strictly positive value. Since having effective DRM protection does not change the price of legal content and we also know that $z = 0$ when firm A is endowed with a DRM technology, the result is that the possibility of DRM protection does not increase how much content is developed. In other words, although content is harder to copy, since the increase in copying cost does not translate into higher revenues for the content provider, introducing the possibility of DRM does not translate into more content development.

Note that the correct interpretation of Proposition 3 is not that the use of DRM necessarily has no effect on content development, but rather that this is a possible outcome. In our analysis we assume that firm A makes a take-it or leave-it contract offer to firm C which is equivalent to giving all the bargaining power concerning the contract between the two parties to firm A. In this case, as we just showed, the introduction of DRM has no effect on content development. But if instead we assumed that firm C has positive bargaining power, then the introduction of DRM would increase content development. Specifically, increased content development would increase the value of the DRM technology and thus the payment A makes to C to encrypt legal content as long as $h'(m) > 0$ for all m. In that case, since C would anticipate a higher payment for DRM adoption when it develops more content, introducing the possibility of DRM protection would increase C's investment in content development.

In other words, the point of our analysis in this subsection is that when a hardware producer owns a DRM technology one should not assume that DRM necessarily increases content development which is the standard argument. Whether or not it increases content development depends on the bargaining power of the various parties. So it is in fact an empirical question whether or not a DRM system owned by a hardware seller has a positive impact on the quantity and quality of content available for consumption.

4.2. **R&D Investments in DRM Technology.** In Section III's model we assumed that one hardware producer was endowed with a DRM technology. We thus ignored the question of the incentive that hardware firms have to develop a DRM technology in the first place. This is what we focus on in this subsection.

Assume everything is the same as in Section III's initial model with sharing except that at the beginning of the game each hardware seller has the option of investing in the development of a DRM technology, where r_j is the expenditure of firm j, $j = A, B$, and $v(r_j)$ is the probability that firm j successfully develops a DRM technology. We assume $v(0) = 0$, $v'(0) = \infty$, $v'(r) > 0$ and $v''(r) < 0$ for all $r > 0$, $v(\infty) = 0$, and investment outcomes are independent events. These assumptions ensure that in equilibrium each hardware seller chooses the same R&D expenditure which we denote r^*, where $0 < r^* < \infty$. Below we describe the nature of equilibrium in this setting.

There are three possible outcomes in equilibrium. First, with probability $2v(r^*)(1 - v(r^*))$ one firm develops a DRM technology and the other firm does not. In this case the rest of the equilibrium is described by Proposition 1 of Section 3. That is, the outcome is a closed DRM system where the hardware seller with the DRM technology is able to increase its hardware price when the DRM protection is effective, while the contractually specified price for legal content remains at Δ. As before, this way of monetizing the DRM technology provides efficient incentives for investing in the effectiveness of the DRM system.

Second, with probability $(1 - v(r^*))(1 - v(r^*))$ neither firm develops a DRM technology. What happens in this outcome was also described in the previous section. Because the two hardware sellers are selling identical products and there is Bertrand competition, hardware prices are at marginal cost so each hardware seller earns profits equal to $-r^*$. Further, because DRM is not employed, illegal copies can be obtained at a zero price so the legal content provider, firm C, sets its price at the quality advantage of legal content which is Δ. Finally, each consumer purchases hardware from either firm A or firm B and purchases legal content from firm C.

Third, with probability $v(r^*)v(r^*)$ both firms develop a DRM technology. The firms then both choose effort levels that determine the probability the DRM system is effective and to improve effort incentives both also choose closed DRM. This means this third possibility is itself associated with three sub-cases. In the first neither DRM system is effective which is similar to the no DRM outcome. In the second one is effective and one is ineffective which is similar to the Proposition 1 outcome when DRM is effective. In the third both are effective which is similar to the case of open DRM described in the previous section since in this subcase the hardware sellers have in a sense identical products, so $p_A^H = p_B^H = c$.

In summary, the Proposition 1 equilibrium can be thought of as part of an equilibrium in a richer game where hardware sellers start the game by making expenditures on the development of a DRM technology. When only one of the firms is successful then the outcome is the Proposition 1 equilibrium, while there is also a positive probability of an outcome consistent with no DRM and a positive probability of an outcome in which both firms develop a DRM technology.

5. Discussion

In this paper we have presented a model and extensions showing why a DRM system developed by a hardware seller is frequently accompanied by an increase in the firm's market power in the hardware market. One potential real world example of this argument is Apple's

iPod which for a number of years following its introduction employed the DRM system called FairPlay. In this section we discuss the early part of the history of Apple's iPod when it did not face significant competition as it does today, where our focus is how that early history relates to our theoretical analysis.

The iPod was introduced in 2001 and quickly became the fastest selling music player in history. By 2004 its US market share reached over 80 percent in the market for hard-drive-based portable music players and its online retail counterpart, the iTunes Store, also accounted for more than 80 percent of US digital music sales (see footnote 2). When the iPod was introduced it employed the DRM system called FairPlay and Apple did not share the system with rival hardware sellers. That is, consistent with how we modeled a closed DRM system in our theoretical analysis, rival hardware devices could not play protected content bought from the iTunes Store.

Before Apple launched the iPod the market for portable music players was small and there was no dominant firm in the market. At the time the major record labels did not sell MP3 music online because of the ease with which illegal copies could be made and, as could be seen in the Napster lawsuit, they regarded MP3 files as something to be eliminated. Thus, the major record labels at the time required encryption technology in order to increase the difficulty of making a copy. Apple successfully persuaded the major labels to sell music using its DRM technology and then, as indicated above, did not share or license its DRM technology with rival hardware sellers.

At the time of the iPod's introduction, there were a few competitors employing competing DRM technologies but they used different strategies that with hindsight seem to have been mistakes. For example, Microsoft's Windows Media Audio format was mainly used on personal computers and it employed a subscription based pricing strategy that has not been popular with consumers.[30] Sony's Adaptive Transform Acoustic Coding system (ATRAC) was not

[30]Microsoft licensed their PlaysForSure DRM technology to a number of online music stores; however, most of them failed and were closed (e.g., AOL MusicNow, Yahoo! Music Unlimited, Spiralfrog, MTV URGE, Musicmatch Jukebox,

subscription based but, unlike the iPod, Sony's devices initially did not support MP3 files which reduced their popularity.[31] More serious challenges, like Microsoft's Zune (launched in 2006), were introduced only after Apple dominated the market.[32] Note that significantly after their introduction iPods were able to play music files from other online stores that did not employ DRM such as eMusic, but such platforms were introduced only after the iPod came to dominate the market or Apple no longer employed DRM for the iPod (see below for a related discussion).

Given the lack of viable competitors with an effective DRM technology, it seems quite plausible that Apple's decision not to share its DRM system with rival hardware sellers helped in its quick dominance of the market as suggested by our theoretical analysis. One possibility is that, along the lines of our first analysis in Section 3, by not sharing the technology Apple moved an industry that would have been quite competitive to something close to a monopoly. Another possibility is that because of its superior design the iPod would have been quite successful even in the absence of DRM. But along the lines of one of the variants of the Section 3 model discussed at the end of the section, even with its superior design Apple benefitted from closed DRM because it made the rival products worse substitutes and thus allowed Apple to charge a higher price for the iPod.

It is important to note that in 2009 Apple changed its policy and started selling DRM-free music at the iTunes Store. Clearly, one motivation for the change was that the firm was under pressure from European antitrust regulators to change its policy. But there were also other changes in the market that could have made its DRM system for the iPod less valuable to

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etc.), and a few remaining ones switched to selling MP3 files when major labels later decided to drop DRM (e.g., Rhapsody and Wal-Mart). Microsoft also launched its own MSN Music store in 2004, which was unpopular and was discontinued in 2006.

[31]Sony users had to convert their MP3 music to ATRAC3 for use on the Network Walkman. Later in 2005 Sony introduced the Walkman Core which supports MP3. Sony also commercialized Mini-Disc players using ATRAC which had limited impact outside of Japan.

[32]In 2004, RealNetworks introduced a DRM translation system called Harmony and licensed it to device manufacturers (e.g., Creative and Palm). However, Steve Jobs said "we are stunned that Real is adopting the tactics and ethics of a hacker and breaking into the iPod." And because of the risk of a lawsuit, no device employing Harmony became popular.

Apple. For example, around 2007 the major record labels had changed their policy concerning MP3 files and started selling MP3 files directly to consumers through Amazon's online music store. According to our theoretical analysis, this would eliminate the return to using a DRM system because, even if DRM content was harder to copy, the presence of non-DRM legal content would mean copies could be made at low cost so there would be little return to either the record labels or to Apple to retain DRM. In other words, it is possible that Apple dropped DRM for the iPod not primarily because of consumer or antitrust complaints, but because the market had changed in such a way that much or all of the increased profitability associated with DRM had disappeared.

Note that in addition to Apple initially using a closed DRM system for the iPod, there are a number of other aspects of the iPod example that are similar to the equilibrium in our main theoretical analysis. First, in our main analysis the introduction of DRM does not increase the price the content provider charges for legal content, i.e., both with and without DRM this price equals Δ which is the increased consumer gross benefit of consuming legal content rather than an illegal copy. This seems consistent with the fact that 99 cents was the standard price for a legally purchased song at the iTunes Store when DRM was in place and that after Apple dropped DRM in 2009 the modal price for DRM-free music remained the same, i.e., 99 cents.[33] Second, in our main analysis the content provider does not benefit from the introduction of DRM which in a sense is consistent with the major record labels in around 2007 starting to sell MP3 files directly to consumers as mentioned above.[34]

A final point concerns what would have happened to social welfare if Apple had been legally compelled to share its DRM system with other hardware manufacturers. As captured

[33]To be precise, after Apple dropped DRM in 2009, it changed to three-tiered variable pricing (69 cents, 99 cents, or $1.29 per song) based on popularity, where the modal price was 99 cents.

[34]We use the term "in a sense is consistent" since in our model firm A's take-it or leave-it offer should be lucrative enough for firm C to want to sell only DRM protected content. It is possible that in the Apple case the contract was initially sufficiently lucrative for the major record labels that initially they chose not to sell MP3 files to consumers. But possibly as the situation evolved this was no longer the case but Apple decided, because of the strong market position that Apple had acquired for the iPod and iTunes Store, that it was in Apple's best interests not to renegotiate the contract.

in Corollary 1, our main analysis suggests that such a policy would have improved social welfare because Apple would have decreased its investment in DRM effectiveness. But as was also discussed, in this analysis, because the hardware firm with the DRM system has all the bargaining power, a policy of forcing this firm to share its DRM system with rivals has no effect on content development. But if the content firm has some of the bargaining power, then the policy would reduce content development and the social welfare effect of the policy becomes ambiguous.

In terms of this discussion, it is interesting to note that Handke (2012) and Waldfogel (2012) provide empirical evidence consistent with digital copying, in fact, not reducing the supply of new copyrighted sound recordings. This finding suggests that our main analysis is the more empirically relevant one which, in turn, suggests that a government policy of forcing Apple to share its DRM system would indeed have increased social welfare.

6. Conclusion

In the age of the internet, which enables immediate access to a broad array of creative works, DRM has become an important technological tool in the market for copyrighted works. While previous literature on the subject has focused mostly on the use of DRM to reduce illegal copying, real world examples such as that of Apple's iPod suggest that DRM is also sometimes associated with an increase in the market power of a hardware seller with a DRM system. In this paper we have considered from a theoretical perspective the extent to which DRM is associated with increased hardware market power and also asked the extent to which the government can improve welfare by requiring a hardware seller with DRM to share the system with rivals.

Our main finding is that DRM will frequently be accompanied by an increase in the hardware seller's market power achieved through the use of closed DRM, although we also found that the hardware seller with DRM can achieve a similar outcome by licensing and using a high royalty fee. The logic is that, consistent with the insights of the property rights theory

of the firm, monetizing a DRM system through increased hardware market power is efficient due to a potential moral hazard problem associated with the design of the DRM system. We also considered the social welfare and consumer welfare implications of our basic analysis. For example, in our basic analysis the use of DRM reduces consumer welfare because consumers pay more for hardware, while there is also a reduction in social welfare due to investments made in the design of the DRM system. So a government rule forcing DRM to be shared increases both social welfare and consumer welfare.

We also investigated a number of extensions. Possibly the most interesting one concerns what happens when an initial stage is added to the game where the content provider makes investments in the development of content. The standard rationale for DRM is that it increases the costs of copying and thus increases incentives for the development of content. Our analysis shows that this is not necessarily the case. Rather, when the DRM technology is owned by a hardware producer and there is a contract between the hardware firm and the content producer or producers concerning encrypting the content, then whether or not DRM increases content development depends on the bargaining power of the parties. If the hardware producer has all the bargaining power like in our main analysis, then there is no increase in content development. But if content firms have positive bargaining power, then as in the standard argument DRM will result in increased investments in content development.

There are a number of directions in which the analysis in this paper could be extended. On the theoretical side we believe the most interesting direction would be to consider oligopoly hardware producers along the lines of what we see in the ebook market. We conjecture that an important motivation for the use of DRM in that market which is not captured in our analysis is that DRM is used as a way of increasing the degree of product differentiation by causing each hardware product to be associated with different selections of available ebooks.[35] With

[35]See Carbajo, de Meza, and Seidman (1990) and Chen (1997) for related analyses in which tying is used to increase profits in oligopoly settings through increased product differentiation.

this in mind we think that a formal theoretical investigation of DRM employed by oligopoly hardware producers is worthwhile.

On the empirical side we feel the most interesting direction for further study concerns whether or not closed DRM employed by hardware sellers increases the amount of content available. In the analysis in Section 4 introducing the possibility of DRM resulted in no increase in content availability, but as discussed above there would be an increase if content providers had positive bargaining power. To our knowledge, there is no systematic study that empirically examines the effect the removal of DRM from the iPod in 2009 had on the supply of sound recordings. Such an analysis would help determine whether or not closed DRM increases content development.

Appendix

Proof of Proposition 1: As in the informal discussion in the text, we begin by considering pricing and consumption choices as a function of earlier behavior. First, suppose neither hardware seller employs DRM. Then the two hardware firms sell identical products so prices equal marginal cost, i.e., $p_A^H = p_B^H = c$, $\pi_A = 0$, and $\pi_B = 0$. In turn, consumers can obtain an illegal copy at a price of zero, so firm C can charge $p_C = \Delta - \varepsilon$, $\varepsilon > 0$, and each consumer will purchase a legal copy from C. Further, if firm C charges $p_C = \Delta$, then consumers are indifferent between purchasing legal content and an illegal copy. Since the smallest ε, $\varepsilon > 0$, is not defined, every subgame perfect equilibrium for this subgame is such that $p_A^H = p_B^H = c$, $p_C = \Delta$, $\pi_A = \pi_B = 0$, $\pi_C = N\Delta$, and all consumers purchase hardware from A or B and legal content from C.

Suppose one or both of firms A and B employ DRM but firm C does not encrypt. Then everything is the same as in the previous case except $\pi_A = -g(d)$.

Suppose one or both of firms A and B employ DRM, C encrypts its content and the DRM system is ineffective. Then everything is the same as in the first case except $\pi_A = z - g(d)$, $\pi_B = 0$, and $\pi_C = N\Delta - z$ (see footnote 14).

Suppose only A employs DRM, C encrypts its content, and the DRM system is effective. If $p_C^+ > \Delta + h$, then consumers prefer to obtain an illegal copy at a price of zero which means $\pi_C = -z$. Given consumers obtain illegal copies, consumers place the same value on the two hardware products, so Bertrand competition again yields $p_A^H = p_B^H = c$, while $\pi_A = z - g(d)$ and $\pi_B = 0$.

Suppose $p_C^+ < \Delta + h$. From the standpoint of consumers, in this case firm A is selling a superior product so Bertrand competition yields $p_A^H = c + (\Delta + h - p_C^+)$, $p_B^H = c$, and consumers purchase A's hardware and legal content from C at p_C^+. Also, $\pi_A = N(\Delta + h - p_C^+) + z - g(d)$, $\pi_B = 0$, and $\pi_C = Np_C^+ - z$.

Suppose $p_C^+ = \Delta + h$. From the standpoint of consumers, in this case firms A and B are selling equivalent products. So each of the two outcomes just described are possible as well as outcomes in which some consumers purchase legal content and some purchase illegal copies.

The last possibility is that both A and B employ DRM, C encrypts its content, and the DRM is effective. Since the two hardware products are identical in this case, Bertrand competition yields $p_A^H = p_B^H = c$, $\pi_A = z - g(d)$, and $\pi_B = 0$. If $p_C^+ > \Delta + h$, then consumers purchase illegal copies and $\pi_C = -z$. If $p_C^+ < \Delta + h$, then consumers purchase legal content and $\pi_C = Np_C^+ - z$. If $p_C^+ = \Delta + h$, all consumers purchasing legal content, all consumers purchasing illegal copies, and some consumers purchasing each are all consistent with equilibrium. So in this case $0 \leq \pi_C \leq N(\Delta + h)$.

We now consider earlier choices concerning DRM, d, z, and p_C^+. We have from above that if neither firm employs DRM or one or both firms employ DRM but firm C turns down A's contract offer, then $\pi_A \leq 0$. So the equilibrium will be such that one or both hardware producers employ DRM and firm C accepts A's offer as long as there is a set of choices for A at the beginning of the game that yield strictly positive expected profits for A.

Consider first the case of open DRM. We have in this case $\pi_A = z - g(d)$ when the DRM is effective and also when it is ineffective, so $\pi_A = z - g(d)$. Since the choice of d is unobservable

and unverifiable, the choice does not affect subsequent equilibrium choices so we have that A maximizes by choosing $d = 0$ when it plans to choose open DRM. But if $d = 0$, then there is no benefit to encryption so $z \leq 0$. Thus, $\pi_A \leq 0$ with open DRM so this is not a candidate for equilibrium behavior assuming there is a set of choices associated with closed DRM that yield $\pi_A > 0$.

Now consider the case of closed DRM. From above we have $\pi_C = N\Delta - z$ when the DRM is ineffective while when DRM is effective $\pi_C = -z$ if $p_C^+ > \Delta + h$, $\pi_C = Np_C^+ - z$ if $p_C^+ < \Delta + h$, and $-z \leq \pi_C \leq Np_C^+ - z$ if $p_C^+ = \Delta + h$. If $p_C^+ > \Delta + h$, then C does not sell legal content which means $z \leq 0$, $p_A^H = c$, and so $\pi_A \leq 0$. So the only possible candidate for equilibrium is closed DRM and $p_C^+ \leq \Delta + h$.

Suppose firm A chooses closed DRM and makes a contract offer to A that is accepted and $\pi_C > N\Delta$. Then A could increase z at least a little, keep p_C^+ the same, and C would still accept the contract offer which means the intial offer was not consistent with equilibrium behavior. So the equilibrium offer must be such that $\pi_C = N\Delta$.

Focusing on closed DRM where C accepts A's contract offer and all consumers purchase legal content, we have $\pi_A + \pi_B + \pi_C = q(d)N(\Delta + h) + (1 - q(d))N\Delta - g(d)$. But we know that in equilibrium $\pi_B = 0$ and $\pi_C = N\Delta$, so $\pi_A = q(d)Nh - g(d)$. So π_A is maximized when $d = d^*$, where d^* satisfies $q'(d^*)Nh - g'(d^*) = 0$.

Given this, consider firm A's choice of d given closed DRM and a z, p_C^+ pair such that the contract offer is accepted, $p_C^+ \leq \Delta + h$, and $\pi_C = N\Delta$. Firm A will choose d to maximize $q(d)[N(\Delta + h - p_C^+) + z - g(d)] + (1 - q(d))[z - g(d)]$ or d maximizes $q(d)N[\Delta + h - p_C^+] + z - g(d)$. Taking the derivative with respect to d yields the first order condition $q'(d)N[\Delta + h - p_C^+] - g'(d) = 0$. Comparing this expression with the expression that defined d^* yields that firm A maximizes π_A by setting $p_C^+ = \Delta$ which in turn yields $d = d^*$. So in equilibrium $p_C^+ = \Delta$, $d = d^*$, and all consumers purchase hardware from A and legal content from C when DRM is effective. This completes the proof.

Proof of Corollary to Proposition 1: If the government announces firm A must share its DRM system, then from the proof of Proposition 1 we know $d = 0$, $\pi_A = \pi_B = 0$, $\pi_C = N\Delta$, and each consumer purchases hardware from A or B and legal content from C. Comparing this outcome with the equilibrium described in Proposition 1 yields that consumer welfare is higher because consumers purchase hardware at a lower price, while social welfare is higher because d is lower.

Proof of Proposition 2: Many of the steps in the proof of Proposition 2 are similar to arguments in the proof of Proposition 1. So to avoid redundancy, in a number of the parts of the proof we omit details and refer the reader to the proof of Proposition 1.

Firm A's profit in the unique equilibrium described in Proposition 1 is given by $\pi_A = q(d^*)Nh - g(d^*)$. Call this value π_A^*. The first step of the proof is to show that in the licensing game in equilibrium $\pi_A \leq \pi_A^*$. If neither firm adopts DRM, then an argument similar to one in the proof of Proposition 1 yields $\pi_A = 0$. So for π_A to exceed π_A^* it must be the case that one or both firms adopt DRM. Suppose one or both of A and B adopt DRM but C does not accept A's offer to encrypt its output. An argument similar to one in the proof of Proposition 1 yields that in this case $\pi_A \leq 0$. So for π_A to exceed π_A^* it must be the case that one or both of A and B adopt DRM and C accepts A's offer.

Suppose only A adopts DRM and C accepts A's offer. An argument like one in the proof of Proposition 1 yields $\pi_A = \pi_A^*$. Suppose both A and B adopt DRM and C accepts A's offer. We know $\pi_B = 0$ since B won't accept A's offer if accepting yields $\pi_B < 0$ while A can always raise F if B accepting yields $\pi_B > 0$. We also know from an argument like one in the proof of Proposition 1 that $\pi_C = N\Delta$. Let d^+ be firm A's equilibrium choice of d. If DRM is ineffective, then an argument like one in the proof of Proposition 1 yields $p_A^H = c$, $p_B^H = c$, and $p_C = \Delta$. If DRM is effective, then consumers will pay no more than $c + \Delta + h$ for hardware from A or B and legal content from C since a consumer can always purchase hardware from another firm at c and acquire an illegal copy at a cost of h. This means $\pi_A + \pi_B + \pi_C \leq$

$q(d^+)N(\Delta+h)+(1-q(d^+))N\Delta-g(d^+)$ or $\pi_A+\pi_B+\pi_C \leq q(d^+)Nh+N\Delta-g(d^+)$. Given $\pi_B=0$ and $\pi_C=N\Delta$, we now have $\pi_A \leq q(d^+)Nh-g(d^+)$. Since by definition this upper bound is maximized at d^* we now have $\pi_A \leq q(d^*)Nh-g(d^*)=\pi_A^*$.

Given this, any choice of whether or not firm A adopts DRM, a value for d when it chooses adoption, and a contract offer to B when it chooses adoption that result in $\pi_A=\pi_A^*$ is part of an equilibrium. Suppose firm A adopts DRM, chooses $d=d^*$, and chooses a contract offer to B that B does not accept. An argument like one in the proof of Proposition 1 yields that equilibrium to the resulting subgame is described by (2) through (7) of Proposition 1 (except B turns down A's offer rather than A not sharing). Since in this subgame equilibrium $\pi_A=\pi_A^*$, we now have that firm A adopting DRM, choosing $d=d^*$, choosing a contract offer to make to B that is not accepted, and (2) through (7) of Proposition 1 describe equilibria to the licensing game. This proves (1).

Suppose firm A adopts DRM, chooses $d=d^*$, and offers a contract to firm B that is accepted and is characterized by $F=0$ and $s=h$. Arguments like ones in the proof of Proposition 1 yield that all the equilibria to the resulting subgame are characterized by (2) of Proposition 2. Since $\pi_A=\pi_A^*$ and $\pi_B=0$ in these subgame equilibria, we now have that there are equilibria where A adopts DRM, chooses $d=d^*$, $F=0$, and $s=h$, and the equilibria also satisfy the other properties listed in (2) of Proposition 2.

The last step of the proof is to show that there are no other equilibria which, given what we have already shown, means showing that any behavior for firm A concerning DRM adoption, choice of d, and contract offer to B results in $\pi_A<\pi_A^*$. Based on arguments in the proof of Proposition 1 we know that the only sets of strategies in which firm B does not accept firm A's offer and $\pi_A=\pi_A^*$ are strategies consistent with (1). Also, previous arguments yield that if firm B accepts firm A's offer but C does not accept A's offer, then $\pi_A<\pi_A^*$.

So the only other possible equilibria are such that A adopts DRM, B accepts A's contract offer, and C accepts A's contract offer. Based on arguments put forth above we know that

if $d \neq d^*$, then $\pi_A < \pi_A^*$. So $d = d^*$. Suppose $s > h$. Then firm B will anticipate selling no units. If $F \geq 0$, then B will turn down the offer. If $F < 0$, then $\pi_B > 0$. But from earlier we know $\pi_B = 0$ in equilibrium. So $s \leq h$. Suppose $s = h$ and $F > 0$. Then $\pi_B < 0$ if the offer is accepted so B turns it down. Suppose $s = h$ and $F < 0$. Then $\pi_B > 0$ but from earlier we know $\pi_B = 0$ in equilibrium. The last possibility is $s < h$. Then it can be shown that A does not receive all of the benefits from a higher value for d so A does not choose d^* which from above means $\pi_A < \pi_A^*$. This completes the proof.

Proof of Corollary to Proposition 2: From Proposition 2 we know that all the equilibria in Proposition 2 are associated with the same value for social welfare, the same value for consumer welfare, and these values equal the values for social welfare and consumer welfare in the unique equilibrium in Proposition 1. Given this, the proof of Corollary 1 to Proposition 1 tells us that each of these equilibria is associated with values for social welfare and consumer welfare lower than the values that result if the government rules that A's DRM system must be shared.

Proof of Proposition 3: Consider a state of the world in which firm A is not endowed with a DRM technology. Competition between firms A and B yields $p_A^H = p_B^H = c$, while copies being available at a price of zero yields $p_C = \Delta(m)$. Further, given these prices each consumer purchases hardware from A or B and legal content from C. This proves (1).

Now suppose firm A is endowed with a DRM technology. Then the logic used to prove Proposition 1 yields that the outcome is given by Proposition 1 where $\Delta(m)$ substitutes for Δ. This proves (2).

Now consider firm C's choice of m in the first stage of the game. Given (1) and (2), the firm chooses m to maximize $\alpha N\Delta(m) + (1-\alpha)N\Delta(m) - m$. Taking the derivative with respect to m yields the first order condition $N\Delta'(m) = 1$, so $m = m^*$. This proves (3).

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