Lessons from the Sony CD DRM Episode

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Abstract

In the fall of 2005, problems discovered in two Sony-BMG compact disc copy protection systems, XCP and MediaMax, triggered a public uproar that ultimately led to class-action litigation and the recall of millions of discs. We present an in-depth analysis of these technologies, including their design, implementation, and deployment. The systems are surprisingly complex and suffer from a diverse array of flaws that weaken their content protection and expose users to serious security and privacy risks. Their complexity, and their failure, makes them an interesting case study of digital rights management that carries valuable lessons for content companies, DRM vendors, policymakers, end users, and the security community.

1 Introduction

This paper is a case study of the design, implementation, and deployment of anti-copying technologies. We present a detailed technical analysis of the security and privacy implications of two systems, XCP and MediaMax, which were developed by separate companies (First4Internet and SunnComm, respectively) and shipped on millions of music compact discs by Sony-BMG, the world's second largest record company. We consider the design choices the companies faced, examine the choices they made, and weigh the consequences of those choices. The lessons that emerge are valuable not only for compact disc copy protection, but for copy protection systems in general.

The security and privacy implications of Sony-BMG's CD digital rights management (DRM) technologies first reached the public eye on October 31, 2005, in a blog post by Mark Russinovich [21]. While testing a rootkit detector he had co-written, Russinovich was surprised to find an apparent rootkit (software designed to hide an intruder's presence [13]) on one of his systems. Investigating, he found that the rootkit was part of a CD DRM system called XCP that had been installed when he inserted a Sony-BMG music CD into his computer's CD drive.

News of Russinovich's discovery circulated rapidly on the Internet, and further revelations soon followed, from us,[1] from Russinovich, and from others. It was discovered that the XCP rootkit makes users' systems more vulnerable to attacks, that both CD DRM schemes install risky software components without obtaining informed consent from users, that both systems covertly transmit usage information back to the vendor or the music label, and that none of the protected discs include tools for uninstalling the software. (For these reasons, both XCP and MediaMax seem to meet the consensus definition of spyware.) These and other findings outraged many users.

As the story was picked up by the popular press and public pressure built, Sony-BMG agreed to recall XCP discs from stores and to issue uninstallers for both XCP and MediaMax, but we discovered that both uninstallers created serious security holes on users' systems. Class action lawsuits were filed soon after, and government investigations were launched, as Sony-BMG worked to repair relations with its customers.

While Sony-BMG and its DRM vendors were at the center of this incident, its implications go beyond Sony-BMG and beyond compact discs. Viewed in context, it is a case study in the deployment of DRM into a mature market for recorded media. Many of the lessons of CD DRM apply to other DRM markets as well.

Several themes emerge from this case study: similarities between DRM and malicious software such as spyware, the temptation of DRM vendors to adopt malware tactics, the tendency of DRM to erode privacy, the strategic use of access control to control markets, the failure of ad hoc designs, and the force of differing incentives in shaping behavior and causing conflict.

Outline The remainder of the paper is structured as follows. Section 2 discusses the business incentives of

record labels and DRM vendors, which drive their technology decisions. Section 3 gives a high-level technical summary of the systems' design. Sections 4–9 each cover one aspect of the design in more detail, discussing the design choices made in XCP and MediaMax and considering alternative designs. We discuss weaknesses in the copy protection schemes themselves, as well as vulnerabilities they introduce in users' systems. We cover installation issues in Section 4, recognition of protected discs in Section 5, player software in Section 6, deactivation attacks in Section 7, uninstallation issues in Section 8, and compatibility and upgrading issues in Section 9. Section 10 explores the outrage users expressed in response to the DRM problems. Section 11 concludes and draws lessons for other systems.

2 Goals and Incentives

The goals of a CD DRM system are purely economic: the system is designed to protect and enable the business models of the record label and the DRM vendor. Accordingly, any discussion of goals and incentives must begin and end by talking about business models. The record label and the DRM vendor are separate actors whose interests are not always aligned. Incentive gaps between the label and the DRM vendor can be important in explaining the design and deployment of CD DRM systems.

2.1 Record Label Goals

We first examine the record label's goals. Though the label would like to keep the music from the CD from being made available on peer-to-peer (P2P) file sharing networks, this goal is not feasible [4]. If even one user can rip an unprotected copy of the music and put it on a P2P network, it will be available to the whole world. In practice, every commercially valuable song appears on P2P networks immediately upon release, if not sooner. No CD DRM system can hope to stop this. Real systems do not appear designed to stop P2P sharing, but seem aimed at other goals.[2]

The record label's goal must therefore be to retard disc-to-disc copying and other local copying and use of the music. Stopping local copying might increase sales of the music—if Alice cannot copy a CD to give to Bob, Bob might buy the CD himself.

Control over local uses can translate into more revenue for the record label. For example, if the label can control Alice's ability to download music from a CD into her iPod, the label might be able to charge Alice an extra fee for iPod downloads. Charging for iPod downloads creates new revenue, but it also reduces the value to users of the original CD and therefore reduces revenue from CD sales. Whether the new revenue will outweigh the loss of CD revenue is a complex economic question that depends on detailed assumptions about users' preferences; generally, increasing the label's control over uses of the music will tend to increase the label's profit.

Whether the label would find it more profitable to control a use, as opposed to granting it for free to CD purchasers, is a separate question from whether copyright law gives the label the right to file lawsuits relating to that use. Using DRM to enforce copyright law exactly as written is almost certainly not the record label's profit-maximizing strategy.

Besides controlling use of the music, CD DRM can make money for the record label because it puts software onto users' computers, and the label can monetize this installed platform. For example, each CD DRM album includes a special application for listening to the protected music. This application can show advertisements or create other promotional value for the label; or the platform can gather information about the user's activities, which can be exploited for some business purpose. If taken too far, these become spyware tactics; but they may be pursued more moderately, even over user objections, if the label believes the benefits outweigh the costs.

2.2 DRM Vendor Goals

The CD DRM vendor's primary goal is to create value for the record label in order to maximize the price the label will pay for the DRM technology. In this respect, the vendor's and label's incentives are aligned.

However, the vendor's incentives diverge from the label's in at least two ways. First, the vendor has a higher risk tolerance than the label, because the label is a large, established business with a valuable brand name, while the vendor (at least in the cases at issue here) is a start-up company with few assets and not much brand equity. Start-ups face many risks already and are therefore less averse to taking on one more risk. The record label, on the other hand, has much more capital and brand equity to lose if something goes horribly wrong. Accordingly, we can expect the vendor to be much more willing to accept security risks than the label.

The second incentive difference is that the vendor can monetize the installed platform in ways the record label cannot. For example, once the vendor's DRM software is installed on a user's system, the software can control use of other labels' CDs, so a larger installed base makes the vendor's technology more attractive to other labels. This extra incentive to build the installed base will make the vendor more aggressive about pushing the software onto users' computers than the label would be.

In short, incentive differences make the vendor more likely than the label to (a) cut corners and accept security risks, and (b) push DRM software onto more users'

computers. If the label had perfect knowledge about the vendor's technology, this incentive gap would not be an issue—the label would simply insist that the vendor protect the label's interests. But if, as seems likely in practice, the label has imperfect knowledge of the technology, then the vendor will sometimes act against the label's interests. (For a discussion of differing incentives in another content protection context, see [9].)

2.3 DRM and Market Power

DRM affects more than just the relationships among the label, the vendor, and the user. It also impacts the label's and vendor's positions in their industries, in ways that will shape the companies' DRM strategies.

For example, DRM vendors are in a kind of standards war—a company that controls DRM standards has power to shape the online music business. DRM vendors fight this battle by spreading their platforms widely. Record labels want to play DRM vendors off against each other and prevent any one vendor from achieving dominance.

Major record companies such as Sony-BMG are parts of larger, diversified companies, and can be expected to help bolster the competitive position of their corporate siblings. For example, parts of Sony sell portable music players in competition with Apple, so Sony-BMG has an incentive to take steps to weaken Apple's market power.

Having examined the goals and motivations of the record labels and DRM vendors, we now turn to a description of the technologies they deployed.

3 CD DRM Systems

CD DRM systems must meet difficult requirements. Copy protected discs must be reasonably compliant with the CD Digital Audio standard so that they can play in ordinary CD players. They must be unreadable by almost all computer programs in order to prevent copying, yet the DRM vendor's own software must be able to read them in order to give the user some access to the music.

Most CD DRM systems use both passive and active anti-copying measures. Passive measures change the disc's contents in the hope of confusing most computer drives and software, without confusing most audio CD players. Active measures, in contrast, rely on software on the computer that actively intervenes to block access to the music by programs other than the DRM vendor's own software.

Active protection software must be installed on the computer somehow. XCP and MediaMax use Windows autorun, which (when enabled) automatically loads and runs software from a disc when the disc is inserted into the computer's drive. Autorun lets the DRM vendor's software run or install immediately.

Once the DRM software is installed, every time a new CD is inserted the software runs a recognition algorithm to determine whether the disc is associated with the DRM scheme. If it is, the active protection software will interfere with accesses to the disc, except those originating from the vendor's own music player application. This proprietary player application, which is shipped on the disc, gives the user limited access to the music.

As we will discuss further, all parts of this design are subject to attack by a user who wants to copy the music illegally or who wants to make uses allowed by copyright law but blocked by the DRM. The user can defeat the passive protection, stop the DRM software from installing itself, trick the recognition algorithm, defeat the active protection software's blocking, capture the music from the DRM vendor's player, or uninstall the protection software.

The complexity of today's CD DRM software offers many avenues of attack. On the whole, today's systems are no more resistant to attack than were simpler early CD DRM systems [10, 11]. When there are fundamental limits to security, extra complexity does not mean extra security.

Discs Studied Sony deployed XCP on 52 titles (representing more than 4.7 million CDs) [1]. We examined three of them in detail: Acceptance, *Phantoms* (2005); Susie Suh, *Susie Suh* (2005); and Switchfoot, *Nothing is Sound* (2005). MediaMax was deployed on 37 Sony titles (over 20 million CDs) as well as dozens of titles from other labels [1]. We studied three albums that used MediaMax version 3—Velvet Revolver, *Contraband* (BMG, 2004); Dave Matthews Band, *Stand Up* (Sony, 2005); and Anthony Hamilton, *Comin' from Where I'm From* (Arista/Sony 2005)—and three albums that used MediaMax version 5—Peter Cetera, *You Just Gotta Love Christmas* (Viastar, 2004); Babyface, *Grown and Sexy* (Arista/Sony, 2005); and My Morning Jacket, *Z* (ATO/Sony, 2005). Unless otherwise noted, statements about MediaMax apply to both version 3 and version 5.

4 Installation

Active protection measures cannot begin to operate until the DRM software is installed on the user's system. In this section we consider attacks that either prevent installation of the DRM software, or capture music files from the disc in the interval after the disc has been inserted but before the DRM software is installed on the computer.

4.1 Autorun

Both XCP and MediaMax rely on the autorun feature of Windows. Whenever removable media, such as a floppy

disc or CD, is inserted into a Windows PC (and autorun is enabled), Windows looks on the disc for a file called `autorun.inf` and executes commands contained in it. Autorun is commonly used to pop up a splash screen or simple menu (for example) to offer to install software found on the disc. However, the autorun mechanism will run any program that the disc specifies.

Other popular operating systems, including MacOS X and Linux, do not have an autorun feature, so this mechanism does not work on those systems. XCP ships only Windows code and so has no effect on other operating systems. MediaMax ships with both Windows and MacOS code, but only the Windows code can autorun. The MacOS code relies on the user to double-click an installer, which few users will do. For this reason, we will not discuss the MacOS version of MediaMax further.

Current versions of Windows ship with autorun enabled by default, but the user can choose to disable it. Many security experts advise users to disable autorun to protect against disc-borne malware. If autorun is disabled, the XCP or MediaMax active protection software will not load or run. Even if autorun is enabled, the user can block autorun for a particular disc by holding down the Shift key while inserting the disc [11]. This will prevent the active protection software from running.

Even without disabling autorun, a user can prevent the active protection software from loading by covering up the portion of the disc on which it is stored. Both XCP and MediaMax discs contain two sessions, with the first session containing the music files and the second session containing DRM content, including the active protection software and the autorun command file. The first session begins at the center of the disc and extends outward; the second session is near the outer edge of the disc. By covering the outer edge of the disc, the user can prevent the drive from reading the second session's files, effectively converting the disc back to an ordinary single-session audio CD. The edge of the disc can be covered with non-transparent material such as masking tape, or by writing over it with a felt-tip marker [19]. Exactly how much of the disc to cover can be determined by iteratively covering more and more until the disc's behavior changes, or by visually inspecting the disc to look for a difference in appearance of the disc's surface which is often visible at the boundary between the two sessions.

4.2 Temporary Protection

Even if the copy protection software is allowed to autorun, there is a period of time, between when a protected disc is inserted and when the active protection software is installed, when the music is vulnerable to copying. It would be possible to have the discs immediately and automatically install the active protection software, minimizing this window of vulnerability, but legal and ethical requirements should preclude this option. Installing software without first obtaining the user's consent appears to be illegal in the U.S. under the Computer Fraud and Abuse Act (CFAA) as well as various state anti-spyware laws [2, 3].

Software vendors conventionally obtain user consent to the installation of their software by displaying an End User License Agreement (EULA) and asking the user to accept it. Only after the user agrees to the EULA is the software installed. The EULA informs the user, in theory at least, of the general scope and purpose of the software being installed, and the user has the option to withhold consent by declining the EULA, in which case no software is installed. As we will see below, the DRM vendors do not always follow this procedure.

If the discs didn't use any other protection measures, the music would be vulnerable to copying while the installer waited for the user to accept or reject the EULA. Users could just ignore the installer's EULA window and switch tasks to a CD ripping or copying application. Both XCP and MediaMax employ temporary protection mechanisms to protect the music during this time.

4.2.1 XCP Temporary Protection

The first time an XCP-protected disc is inserted into a Windows machine, the Windows autorun feature launches the XCP installer, the file `go.exe` located in the `contents` folder on the CD. The installer displays a license agreement and prompts the user to accept or decline it. If the user accepts the agreement, the installer installs the XCP active protection software onto the machine; if the user declines, the installer exits after ejecting the CD, preventing other applications from ripping or copying it.

While the EULA is being displayed, the XCP installer continuously monitors the list of processes running on the system. It compares the image name of each process to a blacklist of nearly 200 ripping and copying applications hard coded into the `go.exe` program. If one or more blacklisted applications are running, the installer replaces the EULA display with a warning indicating that the applications need to be closed in order for the installation to continue. It also initiates a 30-second countdown timer; if any of the applications are still running when the countdown reaches zero, the installer ejects the CD and quits.[3]

This technique might prevent some unsophisticated users from copying the disc while the installer is running, but it can be bypassed with a number of widely known techniques. For instance, users might kill the installer process (using the Windows Task Manager) before it can eject the CD, or they might use a ripping or copying ap-

plication that locks the CD tray, preventing the installer from ejecting the disc.

The greatest limitation of the XCP temporary protection system is the blacklist. Users might find ripping or copying applications that are not on the list, or they might use a blacklisted application but rename its executable file to prevent the installer from recognizing it. Since there is no mechanism for updating the blacklist on existing CDs, they will gradually become easier to rip and copy as new applications not on the blacklist come into widespread use. Application developers may also adapt their software to the blacklisting technique by randomizing their process image names or taking other measures to avoid detection.[4]

4.2.2 MediaMax Temporary Protection

MediaMax employs a different—and highly controversial—temporary protection measure. It defends the music while the installer is running by installing, and at least temporarily activating, the active protection software *before* displaying the EULA. The software is installed without obtaining consent, and it remains installed (and in some cases, permanently active) even if the user explicitly denies consent by declining the license agreement.

MediaMax discs install the active protection driver by copying a file called `sbcphid.sys` to the Windows drivers directory, configuring it as a service in the registry, and launching it. Initially, the driver's startup type is set to "Manual," so it will not re-launch the next time the computer boots; however, it remains running until the computer is shut down, and it remains installed permanently [11]. Albums that use MediaMax version 5 additionally install components of the MediaMax player software before displaying a license agreement. These files are not removed if the EULA is declined.

Even more troublingly, under some common circumstances—for example, if the user inserts a MediaMax version 5 CD and declines the EULA and later inserts a MediaMax CD again—the MediaMax installer will permanently activate the active protection software (by setting its startup type to "Auto," which causes it to be launched every time the computer boots). This behavior is related to a mechanism in the installer apparently intended to upgrade the active protection software if an older version is already installed.

We can think of two possible explanations for this behavior. Perhaps the vendor, SunnComm, did not test these scenarios to determine what their software did, and so did not realize that they were activating the software without consent. Or perhaps they did know what would happen in these cases and deliberately chose these behaviors. Either possibility is troubling, indicating either a deficient design and testing procedure or a deliberate decision to install software after the user denied permission to do so.

Even if poor testing is the explanation for *activating* the software without consent, it is clear that SunnComm deliberately chose to *install* the MediaMax software on the user's system even if the user did not consent. These decisions are difficult to reconcile with the ethical and legal requirements on software companies. But they are easy to reconcile with the vendor's platform building strategy, which rewards the vendor for placing its software on as many computers as possible.

Even if no software is *installed* without consent, the temporary *activation* of DRM software, by both XCP and MediaMax, before the user consents to anything raises troubling ethical questions. It is hard to argue that the user has consented to loading running software merely by the act of inserting the disc. Most users do not expect the insertion of a music CD to load software, and although many (but not all) of the affected discs did contain a statement about protection software being on the discs, the statements generally were confusingly worded, were written in tiny print, and did not say explicitly that software would install or run immediately upon insertion of the disc. Some in the record industry argue that the industry's desire to block potential infringement justifies the short-term execution of the temporary protection software on every user's computer. We think this issue deserves more ethical and legal debate.

4.3 Passive Protection

Another way to prevent copying before active protection software is installed is to use passive protection measures. Passive protection exploits subtle differences between the way computers read CDs and the way ordinary CD players do. By changing the layout of data on the CD, it is sometimes possible to confuse computers without affecting ordinary players. In practice, the distinction between computers and CD players is imprecise. Older generations of CD copy protection, which relied entirely on passive protection, proved easy to copy in some computers and impossible to play on some CD players [10]. Furthermore, computer hardware and software has tended to get better at reading the passive protected CDs over time as it has become more robust to all manner of damaged or poorly formatted discs. For these reasons, more recent CD DRM schemes rely mainly on active protection.

XCP uses a mild variety of passive protection as an added layer of security against ripping and copying. This form of passive protection exploits a quirk in the way Windows handles multisession CDs. When CD burners came to market in the early 1990s, the multisession CD format was introduced to allow data to be appended to

partially recorded discs. (This was especially desirable at a time when recordable CD media cost tens of dollars per disc.) Each time data is added to the disc, it is written as an independent series of tracks called a session. Multisession compatible CD drives see all the sessions, but ordinary CD players, which generally do not support the multisession format, recognize only the first session.

Some commercial discs use a variant of the multisession format to combine CD audio and computer accessible files on a single CD. These discs adhere to the Blue Book or "stamped multisession" format. According to the Blue Book specification, stamped multisession discs must contain two sessions: a first session with 1–99 CD audio tracks, and a second session with one data track. The Windows CD audio driver contains special support for Blue Book discs. It presents the CD to player and ripper applications as if it were a normal audio CD. Windows treats other multisession discs as data-only CDs.

XCP discs deviate from the Blue Book format by adding a second data track in the second session. This causes Windows to treat the disc as a regular multisession data CD, so the primary data track is mounted as a file system, but the audio tracks are invisible to player and ripper applications that use the Windows audio CD driver. This includes Windows Media Player, iTunes, and most other widely used CD applications. We developed a procedure for creating discs with this passive protection using only standard CD burning hardware and software.

This variety of passive protection provides only limited resistance to ripping and copying. There are a number of well-known methods for defeating it:

- *Advanced ripping and copying applications* avoid the Windows CD audio driver altogether and issue commands directly to the drive. This allows programs such as Nero and Exact Audio Copy to recognize and read all the audio tracks.
- *Non-Windows platforms,* including MacOS and Linux, read multisession CDs more robustly and do not suffer from the limitation that causes ripping problems on Windows.
- The *felt-tip marker trick*, described above, can also defeat this kind of passive protection. When the second session is obscured by the marker, CD drives see only the first session and treat the disc as a regular audio CD, which can be ripped or copied.

5 Disc Recognition

The active protection mechanisms employed by XCP and MediaMax regulate access to raw CD audio, blocking access to the audio tracks on albums protected with a particular scheme while allowing access to all other titles.

To accomplish this, the schemes install a background process that interposes itself between applications and the original CD driver. In MediaMax, this process is a kernel-mode driver called `sbcphid.sys`. XCP uses a pair of filter drivers called `crater.sys` and `cor.sys` that attach to the CD-ROM and IDE devices [21]. In both schemes, the active protection drivers examine each disc that is inserted into the computer to see whether access to it should be restricted. If the disc is recognized as copy protected, the drivers monitor for attempts to read the audio tracks, as would occur during a playback, rip, or disc copy operation, and corrupt the audio returned by the drive to degrade the listening experience. MediaMax introduces a large amount of random jitter, making the disc sound like it has been badly scratched or damaged; XCP replaces the audio with random noise.

Each scheme's active protection software interferes with attempts to rip or copy any disc that is protected by the same scheme, not merely the disc from which the software was installed. This requires some mechanism for identifying discs that are to be protected. In this section we discuss the security requirements for such a recognition system, and describe the design and limitations of the actual recognition mechanism employed by the MediaMax scheme.

5.1 Recognition Requirements

Any disc recognition system detects some distinctive feature of discs protected by a particular copy protection scheme. Ideally such a feature would satisfy four requirements: it would *uniquely* identify protected discs without accidentally triggering the copy protection on other titles; it would be *detectable* quickly after reading a limited amount of audio from the disc; it would be *indelible* enough that an attacker could not remove it without significantly degrading the quality of the audio; and it would be *unforgeable*, so that it could not be applied to an unprotected album without the cooperation of the protection vendor, even if the adversary had access to protected discs.

This last requirement stems from the DRM vendor's platform building strategy, which tries to put the DRM software on to as many computers as possible and to have the software control access to all marked discs. If the vendor's identifying mark is forgeable, then a record label could mark its discs without the vendor's permission, thereby taking advantage of the vendor's platform without paying.[5]

5.2 MediaMax Disc Recognition

To find out how well the disc recognition mechanisms employed by CD DRM systems meet the ideal re-

quirements, we examined the recognition system built into MediaMax. This system drew our attention because MediaMax's creators have touted their advanced disc identification capabilities, including the ability to identify individual tracks within a compilation as protected [16]. XCP appears to use a less sophisticated disc recognition system based on a marker stored in the data track of protected discs; we did not include it in this study.

We determined how MediaMax identifies protected albums by tracing the commands sent to the CD drive with and without the active protection software running. These experiments took place on a Windows XP VMWare virtual machine running on top of a Fedora Linux host system, which we modified by patching the kernel IDE-SCSI driver to log all CD device activity.

With this setup we observed that the MediaMax software executes a disc recognition procedure immediately upon the insertion of a CD. The MediaMax driver reads two sectors of audio at a specific offset from the beginning of audio tracks—approximately 365 and 366 frames in (a CD frame stores $1/75$ second of sound). On unprotected discs, the software scans through every track in this way, but on MediaMax-protected albums, it stops after the first three tracks, apparently having detected an identifying feature. The software decides whether or not to block read access to the audio solely on the basis of information in this region, so we inferred that the identifying mechanism takes the form of an inaudible watermark embedded in this part of the audio stream.[6]

Locating the watermark amid megabytes of audio might have been difficult, but we had the advantage of a virtual Rosetta Stone. The actual Rosetta Stone—a 1500 lb. granite slab, unearthed in Rosetta, Egypt, in 1799—is inscribed with the same text written in three languages: ancient hieroglyphics, demotic (simplified) hieroglyphics, and Greek. Comparing these inscriptions provided the key to deciphering Egyptian hieroglyphic texts. Our Rosetta Stone was a single album, Velvet Revolver's *Contraband*, released in three different versions: a U.S. release protected by MediaMax, a European release protected by a passive scheme developed by Macrovision, and a Japanese release with no copy protection. We decoded the MediaMax watermark by examining the differences between the audio on these three discs. Binary comparison revealed no differences between the releases from Europe and Japan; however, the MediaMax-protected U.S. release differed slightly from the other two in certain parts of the recording. By carefully analyzing these differences—and repeatedly attempting to create new watermarked discs using the MediaMax active protection software as an oracle—we were able to deduce the structure of the watermark.

The MediaMax watermark is embedded in the audio of each track in 30 *clusters* of modified audio samples. Each cluster is made up of 288 marked 16-bit audio samples followed by 104 unaltered samples. Three mark clusters exactly fit into one 2352-byte CD audio frame. The watermark is centered at approximately frame 365 of the track; though the detection routine in the software only reads two frames, the mark extends several frames to either side of the designated read target to allow for imprecise seeking in the audio portion of the disc (a typical shortcoming of inexpensive CD drives). The MediaMax driver detects the watermark if at least one mark cluster is present in the region read by the detector.

A sequence of 288 bits that we call the *raw watermark* is embedded into the 288 marked audio samples of each mark cluster. A single bit of the raw watermark is embedded into an unmarked audio sample by setting one of the three least significant bits to the new bit value (as shown in bold below) and then setting the two other bits according to this table:[7]

Original bits	Marked bits					
	0__	_**0**_	__**0**	**1**__	_**1**_	__**1**
____________111	**0**11	1**0**1	11**0**	**1**11	1**1**1	11**1**
____________110	**0**11	1**0**1	11**0**	**1**10	1**1**0	11**1**
____________101	**0**11	1**0**1	10**0**	**1**01	1**1**0	10**1**
____________100	**0**11	1**0**0	10**0**	**1**00	1**1**0	10**1**
____________011	**0**11	0**0**1	01**0**	**1**00	0**1**1	01**1**
____________010	**0**10	0**0**1	01**0**	**1**00	0**1**0	01**1**
____________001	**0**01	0**0**1	00**0**	**1**00	0**1**0	00**1**
____________000	**0**00	0**0**0	00**0**	**1**00	0**1**0	00**1**

The position of the embedded bit in each sample follows a fixed sequence for every mark cluster. Each of the 288 bits is embedded in the first-, second-, or third-least-significant bit position of the sample according to this sequence:

```
2,3,1,1,2,2,3,3,2,3,3,3,1,3,2,3,2,1,3,2,2,3,2,2,
 2,1,3,3,2,1,2,3,3,1,2,2,3,1,2,3,3,1,1,2,2,1,1,3,
3,1,2,3,1,2,3,3,1,3,3,2,1,1,2,3,2,2,3,3,3,1,1,3,
 1,2,1,2,3,3,2,2,3,2,1,2,2,1,3,1,3,2,1,1,2,1,1,1,
2,3,2,1,1,2,3,2,1,3,2,2,2,3,1,2,1,3,3,3,3,1,1,1,
 2,1,1,2,2,2,2,3,1,2,3,2,1,3,1,2,2,3,1,1,3,1,1,1,
1,2,2,3,2,3,2,3,2,1,2,3,1,3,1,3,3,3,1,1,2,1,1,2,
 1,3,3,2,3,3,2,2,1,1,1,2,2,1,3,3,3,3,3,1,3,1,1,3,
2,2,3,1,2,1,2,3,3,2,1,1,3,2,1,1,2,2,1,3,3,2,2,3,
 1,3,2,2,2,3,1,1,1,1,3,2,1,3,1,1,2,2,3,2,3,1,1,2,
1,3,2,3,3,1,1,3,2,1,3,1,2,2,3,1,1,3,2,1,2,2,2,1,
3,3,1,2,3,3,3,1,2,2,3,1,2,3,1,1,3,2,2,1,3,2,1,3
```

The active protection software reads the raw watermark by reading the first, second, or third bit from each sample according to the sequence above. It determines whether the resulting 288-bit sequence is a valid watermark by checking certain properties of the sequence (represented below). It requires 96 positions in the sequence to have a fixed value, either 0 or 1. Another 192 positions are divided into 32 groups of linked values (denoted a–z

and α–ζ below). In each group, three positions share the same value and three share the complement value. This allows the scheme to encode a 32-bit value (value A), though in the discs we studied it appears to take a different random value in each mark cluster of each protected title. The final 32 bits of the raw watermark may have arbitrary values (denoted by _ below) and encode a second 32-bit value (value B). MediaMax version 5 uses this value to distinguish between original discs and backup copies burned through it proprietary player application.

$$0, a, b, c, d, e, 0, 0, f, 0, g, 0, h, 0, i, d, j, \bar{j}, k, 0, l, m, 0, n,$$
$$o, p, \bar{e}, q, \bar{e}, r, 0, \bar{p}, s, d, \bar{m}, t, u, v, w, t, \bar{l}, a, x, c, u, 0, \bar{r}, l,$$
$$f, \bar{d}, v, 0, m, 0, \bar{q}, 0, y, c, z, 0, j, \bar{i}, \bar{g}, \alpha, \bar{s}, \bar{w}, \bar{h}, v, y, n, 0, 0,$$
$$\bar{h}, \bar{j}, \bar{u}, a, \beta, 0, \bar{v}, g, j, 0, 0, \bar{\beta}, \bar{i}, e, \bar{z}, 0, r, \gamma, \bar{a}, \delta, \bar{d}, \bar{z}, 0, \bar{v},$$
$$\epsilon, 0, x, s, \bar{g}, \bar{r}, 0, \bar{b}, o, b, r, 0, y, \bar{\beta}, \bar{m}, h, 0, \bar{a}, n, \bar{f}, \bar{t}, 0, \bar{o}, 0,$$
$$\bar{\gamma}, \bar{\epsilon}, \bar{e}, 0, 0, \bar{k}, \bar{c}, \bar{x}, 0, \bar{f}, p, z, \bar{x}, i, 0, 0, \alpha, \bar{g}, 0, 1, w, \bar{t}, \bar{n}, \bar{w},$$
$$i, 0, 0, \bar{j}, m, x, \beta, \bar{y}, \bar{p}, \bar{q}, 0, 0, 0, e, \bar{\beta}, 0, 0, 1, g, 0, p, l, 0, \bar{\alpha},$$
$$t, h, \bar{d}, \bar{\epsilon}, \bar{w}, \gamma, \bar{\delta}, 0, \bar{p}, q, \bar{f}, 0, 1, \zeta, 0, \bar{c}, \zeta, \bar{\alpha}, \bar{s}, \bar{b}, \bar{\gamma}, \beta, 0, o,$$
$$0, q, \bar{i}, 0, 0, \bar{\alpha}, s, \epsilon, \bar{\epsilon}, \bar{h}, 0, \bar{k}, \bar{n}, \bar{\zeta}, \alpha, \bar{s}, \bar{z}, \bar{n}, \bar{c}, \bar{o}, \bar{b}, 0, \bar{t}, 0,$$
$$\bar{y}, \bar{v}, 0, \zeta, \bar{o}, 0, \bar{\zeta}, 0, u, \gamma, 0, \bar{y}, k, \bar{u}, z, \bar{\delta}, \bar{q}, k, \bar{r}, \bar{u}, \bar{\zeta}, \bar{\gamma}, \bar{l}, \bar{l},$$
$$w, \bar{k}, \bar{a}, 0, \bar{\delta}, 0, \epsilon, \bar{m}, b, f, 0, 0, \bar{x}, \delta, \delta, 0, \rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow$$
$$\rightarrow$$

5.3 Attacks on the MediaMax Watermark

The MediaMax watermark fails to satisfy the indelibility and unforgeability requirements of an ideal disc recognition system. Far from being indelible, the mark is surprisingly brittle. Most advanced designs for robust audio watermarks [7, 6] manipulate the audio in the frequency domain and try to resist removal attempts that use lossy compression, multiple conversions between digital and analog formats, and other common transformations. In contrast, the MediaMax watermark is applied in the time domain and is rendered undetectable by even minor changes to the file. An adversary without any knowledge of the watermark's design could remove it by converting the tracks to a lossy format like MP3 and then burning them back to a CD, which can be accomplished easily with standard consumer applications. This would result in some minor loss of fidelity, but a more sophisticated adversary could prevent the mark from being detected with almost no degradation by flipping the least significant bit of one carefully chosen sample from each of the 30 watermark clusters, thereby preventing the mark from exhibiting the pattern required by the detector.

The watermark also fails to satisfy the unforgeability requirement. The mark's only defense against forgery is its complicated, unpublished design, but as is often the case this security by obscurity has proved tedious rather than impossible to defeat. As it turns out, an adversary needs only limited knowledge of the watermark—its location within a protected track and its confinement to the three least significant bits of each sample—to forge it with minimal loss of fidelity. Such an attacker could transplant the three least significant bits of each sample within the watermarked region of a protected track to the corresponding sample from an unprotected one. Transplanting these bits would cause distortion more audible that that caused by embedding the watermark since the copied bits are likely to differ by a greater amount from the original sample values; however, the damage to the audio quality would be limited since the marked region is only 0.4 seconds in duration. A more sophisticated adversary could apply a watermark to an unprotected track by deducing the full details of the structure of the watermark, as we did; she could then embed the mark in an arbitrary audio file just as well a licensed disc producer.

Though MediaMax did not do so, it is straightforward to create an unforgeable mark using digital signatures. The marking algorithm would extract a segment of music, compute its cryptographic hash, digitally sign the hash, and write the hash into the low-order bits of audio samples elsewhere in the music file. The recognition algorithm would recompute the hash, and extract and verify the signature. Though unforgeable, this mark would be no more indelible than the MediaMax scheme—making an indelible mark is a more difficult problem.

6 CD DRM Players

Increasingly, personal computers—and portable playback devices that attach to them—are users' primary means of organizing, transporting, and enjoying their music collections. Sony-BMG and its DRM vendors recognized this trend when they designed their copy protection technologies. Rather than inhibit all use with PCs, as some earlier anti-copying schemes did [10], XCP and MediaMax provide their own proprietary media players, shipped on each protected CD, that allow certain limited uses of the music subject to restrictions imposed by the copyright holder.[8]

The XCP and MediaMax players launch automatically using autorun when a protected disc is inserted into a PC. Both players have similar feature sets. They provide a rudimentary playback interface, allowing users to listen to protected albums, and they allow access to "bonus content," such as album art, liner notes, song lyrics, and links to artist web sites. The players access music on the disc, despite the active protection, by using a special back door interface provided by the active protection software.

XCP and MediaMax version 5 both permit users to burn copies of the entire album a limited number of times (typically three). These copies are created using a proprietary burning application integrated into the player. The copies include the player applications and the same active (and passive, for XCP) protection as the original al-

bum, but they do not allow any subsequent generations of copying.

Another feature of the player applications allows users to rip the tracks from the CD to their hard disks, but only in DRM-protected audio formats. Both schemes support the Windows Media Audio format by using a Microsoft product, the Windows Media Data Session Toolkit [17], to deliver DRM licenses that are bound to the PC where the files were ripped. The licenses allow the music to be transferred to portable devices that support Windows Media DRM or burned onto CDs, but the Windows Media files will not be usable if they are copied to another PC. Because XCP and MediaMax create Windows Media files, they are vulnerable to any attack that can defeat Windows Media DRM. Often, DRM interoperation allows attacks on one system to defeat other systems as well, because the attacker can transfer protected content into the system of her choice in order to extract it.

The XCP and MediaMax version 5 players both exhibit similar spyware-like behavior: phoning home to the vendor or record label with information about users' listening habits despite statements to the contrary from the vendors. Whenever a protected disc is inserted, the players contact web servers to retrieve images or banner ads to display. Part of the request is a code that identifies the album. XCP discs contact a Sony web site, `connected.sonymusic.com` [20]; MediaMax albums contact `license.sunncomm2.com`, a site operated by MediaMax's creator, SunnComm. These connections allow the servers to log the user's IP address, the date and time, and the identity of the album. This undisclosed data collection, in combination with other practices—installation without informed consent and the lack of an uninstaller—make XCP and MediaMax fit the consensus definition of spyware.

6.1 Attacks on Players

The XCP and MediaMax version 5 players were designed to enforce usage restrictions specified by content providers. In practice, they provide minimal security because there are many ways that users can bypass the limitations. Perhaps the most interesting class of attacks targets the limited number of burned copies permitted by the players. Both players are designed to enforce this limit without communicating with any networked server; thus, the player must keep track of how many allowed copies remain by storing state on the local machine.

It is well known that DRM systems like this are vulnerable to rollback attacks. A rollback attack backs up the state of the machine before performing the limited operation (in this case, burning the copy). When the operation is complete, the old system state is restored, and the DRM software is not able to determine that the operation has occurred. This kind of attack is easy to perform with virtual machine software like VMWare, which allows the entire state of the system to be saved or restored in a few clicks. XCP and MediaMax both fail under this attack, which allows unlimited copies to be burned with their players.

A refined variation of this attack targets only the specific pieces of state that the DRM system uses to remember the number of copies remaining. The XCP player uses a single file, `%windir%\system32\$sys$filesystem\$sys$parking`, to record how many copies remain for every XCP album that has been used on the system.[9] Rolling back this file after a disc copy operation would restore the original number of copies remaining.

A more advanced attacker can go further and modify the `$sys$parking` file to set the counter to an arbitrary value. The file consists of a 16 byte header followed by a series of 177 byte structures. For each XCP disc used on the machine, the file contains a whole-disc structure and an individual structure for each track. Each disc structure stores the number of permitted copies remaining for the disc as a 32-bit integer beginning 100 bytes from the start of the structure.

The file is protected by primitive encryption. Each structure is XORed with a repeating 256-bit pad. The pad—a single pad is used for all structures—is randomly chosen when XCP is first installed and stored in the system registry in the key `HKLM\SOFTWARE\$sys$reference\ClassID`. Note that this key, which is hidden by the rootkit, is intentionally misnamed "ClassID" to confuse investigators. Instead of a ClassID, it contains the 32 bytes of pad data.

Hiding the pad actually doesn't increase the security of the design. An attacker who knows only the format of the `$sys$parking` file and the current number of copies remaining can change the counter to an arbitrary value without needing to know the pad. Say the counter indicates that there are x copies remaining and the attacker wants to set it to y copies remaining. Without decrypting the structure, she can XOR the padded bytes where the counter is stored with the value $x \oplus y$. If the original value was padded with p, the new value will be $(x \oplus p) \oplus (x \oplus y) = (y \oplus p)$, y padded with p.

Ironically, Sony itself furnishes directions for carrying out another attack on the player DRM. Conspicuously absent from the XCP and MediaMax players is support for the Apple iPod—by far the most popular portable music player. A Sony FAQ blames Apple for this shortcoming and urges users to direct complaints to them: "Unfortunately, in order to directly and smoothly rip content into iTunes it [sic.] requires the assistance of Apple. To date, Apple has not been willing to cooperate with our protection vendors to make ripping to iTunes and to the iPod a

simple experience." [23]. Strictly speaking, it is untrue that Sony requires Apple's cooperation to work with the iPod, as the iPod can import MP3s and other open formats. What Sony has difficulty doing is moving music to the iPod while keeping it wrapped in copy protection. This is because Apple has so far refused to support interoperation with its FairPlay DRM.

Yet so great is consumer demand for iPod compatibility that Sony gives out—to any customer who fills out a form on its web site [22]—instructions for working around its own copy protection and transforming the music into a DRM-free format that will work with the iPod. The procedure is simple but cumbersome: users are directed to use the player software to rip the songs into Windows Media DRM files; use Windows Media Player to burn the files to a blank CD, which will be free of copy protection; and then use iTunes to rip the songs once more and transfer them to the iPod.

6.2 MediaMax Player Security Risks

Besides suffering from several kinds of attacks that expose the music content to copying, the MediaMax version 5 player makes the user's system more vulnerable to attack. When a MediaMax CD is inserted into a computer, Windows autorun launches an installer from the disc. Even before displaying a license agreement, MediaMax copies almost twelve megabytes of files and data related to the MediaMax player to the hard disk. Jesse Burns and Alex Stamos of iSEC Partners discovered that the MediaMax installer sets file permissions that allow any user to modify its code directory and the files and programs in it [5].

As Burns and Stamos realized, the lax permissions allow a non-privileged user to replace the executable code in the MediaMax player files with malicious code. The next time a user plays a MediaMax-protected CD, the attack code will be executed with that user's security privileges. The MediaMax player requires Power User or Administrator privileges to run, so it's likely that the attacker's code will run with almost complete control of the system.

Normally, this problem could be fixed by manually correcting the errant permissions. However, MediaMax aggressively updates the installed player code each time the software on a protected disc autoruns or is launched manually. As part of this update, the permissions on the installation directory are reset to the insecure state.

We discovered a variation of the attack suggested by Burns and Stamos that allows the attack code to be installed even if the user has never consented to the installation of MediaMax, and to be triggered immediately whenever the user inserts a MediaMax CD. In our attack, the attacker places hostile code in the `DllMain` procedure of a code file called `MediaMax.dll`, which MediaMax installs even before displaying the EULA. The next time a MediaMax CD is inserted, the installer autoruns and immediately attempts to check the version of the installed `MediaMax.dll` file. To do this, the installer calls the Windows `LoadLibrary` function on the DLL file, which causes the file's `DllMain` procedure to execute, along with any attack code placed there.

This problem is exacerbated because parts of the MediaMax software are installed automatically and without consent. Users who have declined the EULA likely assume that MediaMax has not been installed, and so most will be unaware that they are vulnerable. The same installer code performs the dangerous version check as soon as the CD is inserted. A CD that prompted the user to accept a license before installing code would give the user a chance to head off the attack.

Fixing this problem permanently without losing the use of protected discs requires installing a patch from SunnComm. Unfortunately, as we discovered, the initial patch released by Sony-BMG in response to the iSEC report was capable of triggering precisely the kind of attack it was supposed to prevent. In the process of updating MediaMax, the patch checked the version of `MediaMax.dll` just like the MediaMax installer does. If this file was already modified by an attacker, the process of applying the security patch would execute the attack code. Prior versions of the MediaMax uninstaller had the same vulnerability, though both the uninstaller and the patch have since been replaced with versions that do not suffer from this problem.

7 Deactivation

Active protection methods install and run software components that interfere with accesses to a CD. Users can remove or deactivate the active protection software by using standard system administration tools that are designed to find, characterize, and control the programs installed on a machine. Deactivating the protection will enable arbitrary use or ripping of the music, and it is difficult to stop if the user has system administrator privileges. In this section, we discuss how active protection may be deactivated.

7.1 Deactivating MediaMax

The MediaMax active protection software is easy to deactivate, being comprised of a single device driver named `sbcphid`. The driver can be removed by using the Windows command `sc delete sbcphid` to stop the driver, and then removing the `sbcphid.sys` file containing the driver code. MediaMax-protected albums can then be accessed freely.

7.2 Defenses Against Deactivation

To counter deactivation attempts, a vendor might try technical tricks to evade detection and frustrate removal of the active protection software. An example is the rootkit-like behavior of XCP, discovered by Mark Russinovich [21]. When XCP installs its active protection software, it also installs a second program—the rootkit—that conceals any file, process, or registry key whose name begins with the prefix `$sys$`. The result is that XCP's main installation directory, and most of its registry keys, files, and processes, become invisible to normal programs and administration tools.

The rootkit is a kernel-level driver named `$sys$aries` that is set to automatically load early in the boot process. When the rootkit starts, it hooks several Windows system calls by modifying the system service dispatch table (the kernel's `KeServiceDescriptorTable` structure) which is an array of pointers to the kernel functions that implement basic system calls. The rootkit modifies the behavior of four system calls: `NtQueryDirectoryFile`, `NtCreateFile`, `NtQuerySystemInformation`, and `NtEnumerateKey`.[10] These calls are used to enumerate files, processes, and registry entries. The rootkit filters the data returned by these calls to hide items whose names begin with `$sys$`.

On intercepting a function call, the rootkit checks the name of the calling process. If the name of the calling process begins with `$sys$`, the rootkit returns the results of the real kernel function without alteration so that XCP's own processes have an accurate view of the system.

The XCP rootkit increases users' vulnerability to attack by allowing any software to hide—not just XCP. Malware authors can exploit the fact that any files, registry keys, or processes with names beginning in `$sys$` will be hidden, thereby saving the trouble of installing their own rootkits. Malware that lacks the privileges to install its own rootkit can still rely on XCP's rootkit.

Only kernel-level processes can patch the Windows system service dispatch table, and only privileged users—normally, members of the Administrators or Power Users groups—can install such processes. (XCP itself requires these privileges to install.) Malicious code running as an unprivileged user can't normally install a rootkit that intercepts system calls. But if the XCP rootkit is installed, it will hide all programs that adopt the `$sys$` prefix so that even privileged users will be unable to see them. This vulnerability has already been exploited by at least two Trojan horses seen in the wild [15, 14].

The rootkit opens at least one more security vulnerability. The modified functions do not check for errors as carefully as the original Windows functions do, so the rootkit makes it possible for an ordinary program to crash the system by calling one of the hooked functions, for example by calling `NtCreateFile` with an invalid `ObjectAttributes` argument. We do not believe this vulnerability can be exploited to run arbitrary code.

7.3 Deactivating XCP

Deactivating XCP's active protection is more complicated because it comprises several processes that are more deeply entangled in the system configuration, and are hidden by the XCP rootkit. Deactivation requires a three-step procedure.

The first step is to deactivate and remove the rootkit, by the same procedure used to deactivate MediaMax (except that the driver's name is `aries.sys`). Disabling the rootkit and then rebooting exposes the previously hidden files, registry entries, and processes.

The second step is to edit the registry to remove references to XCP's filter drivers and CoDeviceInstallers. XCP uses the Windows filter driver facility to intercept commands to the CD drives and IDE bus. If the code for these filter drivers is removed but the entries pointing to that code are not removed from the registry, the CD and IDE device drivers will fail to initialize. This can cause the CD drives to malfunction, or, worse, can stop the system from booting if the IDE device driver is disabled. The registry entries can be eliminated by removing any reference to a driver named `$sys$cor` from any registry entries named `UpperDrivers` or `LowerDrivers`, and removing any lines containing `$sys$caj` from any list of CoDeviceInstallers in the registry.

The third step is to delete the XCP services and remove the XCP program files. Services named `$sys$lim`, `$sys$oct`, `$sys$drmserver`, `cd_proxy`, and `$sys$cor` can be deactivated using the `sc delete` command, and then files named `crater.sys`, `lim.sys`, `oct.sys`, `$sys$cor.sys`, `$sys$caj.dll`, and `$sys$upgtool.exe` can be deleted. After rebooting, the two remaining files named `CDProxyServ.exe` and `$sys$DRMServer.exe` can be removed.

Performing these steps will deactivate the XCP active protection, leaving only the passive protection on XCP CDs in force. The procedure easily could be automated to create a point-and-click removal tool.

7.4 Impact of Spyware Tactics

The use of rootkits and other spyware tactics harms users by undermining their ability to manage their computers. If users lose effective control over which programs run

on their computers, they can no longer patch malfunctioning programs or remove unneeded programs. Managing a system securely is difficult enough without spyware tactics making it even harder.

Though it is no surprise that spyware tactics would be attractive to DRM designers, it is a bit surprising that mass-market DRM vendors chose to use those tactics despite their impact on users. If only one vendor had chosen to use such tactics, we could write it off as an aberration. But two vendors made that choice, which is probably not a coincidence. We suspect that the vendors let the lure of platform building override the risk to users.

7.5 Summary of Deactivation Attacks

Ultimately, there is little a CD DRM vendor can do to stop users from deactivating active protection software. Vendors' attempts to frustrate users' control of their machines are harmful and will trigger a strong backlash from users. In practice, vendors will probably have to provide some kind of uninstaller—users will insist on it, and some users will need it to deal with the bugs and incompatibilities that crop up inevitably in complex software. Once an uninstaller is released, users can use it to remove the DRM software. Determined users will be able to keep CD DRM software off of their machines.

8 Uninstallation

The DRM vendors responded to user complaints about spyware-like behavior by offering uninstallers that would remove their software from users' systems. Uninstallers had been available before but were very difficult to acquire. For example, to get the original XCP uninstaller, a user had to fill out an online form involving personal information, then wait a few days for a reply email, then fill out another online form and install some software, then wait a few days for yet another email, and finally click a URL in the last email. It is hard to explain the complexity of this procedure, except as a way to deter users from uninstalling XCP.

The uninstallers, when users did manage to get them, did not behave like ordinary software uninstallers. Normal uninstallers are programs that can be acquired and used by any user who has the software. The first XCP uninstaller was customized for each user so that it would only work for a limited time and only on the computer on which the user had filled out the second form. This meant, for example, that if a user uninstalled XCP but it was reinstalled later—say, if the user inserted an XCP CD—the user could not use the same uninstaller again but would have to go through the entire process again to request a new one.

Customizing the uninstaller is more difficult, compared to a traditional uninstaller, for both vendor and user, so it must benefit the vendor somehow. One benefit is to the vendor's platform building strategy, which takes a step backward every time a user uninstalls the software. Customizing the uninstaller allows the vendor to control who receives the uninstaller and to change the terms under which it is delivered.

As user complaints mounted, Sony-BMG announced that unrestricted uninstallers for both XCP and MediaMax would be released from the vendors' web sites. Both vendors chose to make these uninstallers available as ActiveX controls. By an unfortunate coincidence, both uninstallers turned out to open the same serious vulnerability on any computer where they were used.

8.1 MediaMax Uninstaller Vulnerability

The original MediaMax uninstaller uses a proprietary ActiveX control, `AxWebRemove.ocx`, created and signed by SunnComm. Users visiting the MediaMax uninstaller web page are prompted to install the control, then the web page uninstalls MediaMax by invoking one of the control's methods.

This method, `Remove`, takes a URL and a numeric key as arguments. `Remove` contacts the URL, passing it the key. If the server finds the key to be valid, it returns another URL for the uninstaller. The ActiveX control downloads code from the uninstaller URL and then executes it. After running the uninstaller, the ActiveX control contacts the server again to notify it that the key had been used. MediaMax has been removed, but the ActiveX control remains on the user's system.

At this point, a malicious attacker's web page can invoke the control's `Remove` method, passing it a URL pointing to a malicious server controlled by the attacker. The control could contact this server, and then download and run code from a location supplied by the malicious server. By this method, an adversary could run arbitrary code on the user's system.

The flaw in this design, of course, is that MediaMax ActiveX control does not validate the URL it is passed, and does not validate the downloaded code before running it. Validating these items, perhaps using digital signatures, would have eliminated the vulnerability.

8.2 XCP Uninstaller Vulnerability

The original XCP uninstaller contains the same design flaw and is only slightly more difficult to exploit. XCP's ActiveX-based uninstaller invokes a proprietary ActiveX control named `CodeSupport.ocx`. Usually this control is installed in the second step of the three-step XCP

uninstall process. In this step, a pseudorandom code generated by the ActiveX control is sent to the XCP server. The same code is written to the system registry. Eventually the user receives an email with a link to another web page that uses the ActiveX control to remove XCP, but only after verifying that the correct code is in the registry on the local system. This check tethers the uninstaller to the machine from which the uninstallation request was made. Due to this design, the vulnerable control may be present on a user's system even if she never performed the step in the uninstallation process where XCP is removed.

Matti Nikki first noted that the XCP ActiveX control contains suspiciously-named methods, including `InstallUpdate(url)`, `Uninstall(url)`, and `RebootMachine()` [18]. He demonstrated that the control was still present after the XCP uninstallation was complete, and that its methods (including one that rebooted the computer) were scriptable from any web page without further browser security warnings.

We found that the `InstallUpdate` and `Uninstall` methods have an even more serious flaw. Each takes as an argument a URL pointing to a specially formatted archive that contains updater or uninstaller code and data files. When these methods are invoked, the archive is retrieved from the provided URL and stored in a temporary location. For the `InstallUpdate` method, the ActiveX control extracts from the archive a file named `InstallLite.dll` and calls a function in this DLL named `InstallXCP`.

Like the MediaMax ActiveX control, the XCP control does not validate the download URL or the downloaded archive. The only barrier to using the control to execute arbitrary code is the proprietary format of the archive file. We determined the format by disassembling the control. The archive file consists of several blocks of gzip-compressed data, each storing a separate file and preceded with a short header. At the end of the archive, a catalog structure lists metadata for each of the blocks, including a 32-bit CRC. The control verifies this CRC before executing code from the DLL.

With knowledge of this file format, we were able to construct an archive containing (benign proof-of-concept) exploit code, and a web page that would install and run our code on a user's system without any browser security warnings, on a computer containing the XCP control. The same method would allow a malicious web site to execute arbitrary code on the user's machine. Like the MediaMax uninstaller flaw, this problem is especially dangerous because users who have completed the uninstallation may not be aware that they are still vulnerable.

Obviously, these vulnerabilities could have been prevented by careful design and programming. But they were only possible at all because the vendors chose to deliver the uninstallers via this ActiveX method rather than using an ordinary download. We conjecture that the vendors made this choice because they wanted to retain the ability to rewrite, modify, or cancel the uninstaller later, in order to further their platform building strategies.

9 Compatibility and Software Updates

Compared to other media on which software is distributed, compact discs have a very long life. Many compact discs will still be inserted into computers and other players twenty years or more after they are first bought. If a particular version of DRM software is shipped on a new CD, that software version may well try to install and run decades after it was developed. The same is not true of most software, even when shipped on a CD-ROM. Very few if any of today's Windows XP CDs will be inserted into computers in 2026; but today's music CDs will be, so their DRM software must be designed carefully for future compatibility.

The software should be designed for *safety*, so as not to cause crashes or malfunction of other software, and may be designed for *efficacy*, to ensure that its anti-copying features remain effective.

9.1 Supporting Safety by Deactivating Old Software

Safety is easier to achieve, and probably more important. One approach is to design the DRM software to be inert and harmless on future systems. Both XCP and MediaMax do this by relying on Windows autorun, which is likely to be disabled in future versions of Windows for security reasons. If the upcoming Windows Vista disables autorun by default, XCP and MediaMax will be inert on most Vista systems. Perhaps XCP and MediaMax used autorun for safety reasons; but more likely, this choice was expedient for other reasons.

Another safety technique is to build in a sunset date after which the software will make itself inert. A sunset would improve safety but would have relatively little effect on record label revenue for most discs, as we expect nearly all revenue from the disc to have been extracted from the customer in the first three years after she buys it. If in the future more copies of the album are pressed, these could have updated DRM software with a later sunset.

9.2 Updating the Software

When a new version of DRM software is released, it can be shipped on newly pressed CDs, but existing CDs cannot be modified retroactively. Updates for existing

users can be delivered either by download or on new CDs. Downloads are faster but require an Internet connection; CD delivery is slower but can reach non-networked machines.

Users will generally cooperate with updates that help them by improving safety or making the software more useful. But updates to retain the efficacy of the software's usage controls will not be welcomed by users.

Users have many ways to stop updates from downloading or installing, such as write-protecting the software's code so that it cannot be updated, or using a personal firewall to block network connections to the vendor's download servers. System security tools, which are designed generally to stop unwanted network connections, downloads, and code installation, can be set to treat CD DRM software as malware.

A DRM vendor who wants to deliver unwanted updates has two options. First, the vendor can simply offer updates and hope some users will not bother to block them. For the vendor and record label, this is better than nothing. Alternatively, the vendor can try to force users to accept updates.

9.3 Forcing Updates

If a user has the ability to block DRM software updates, a vendor who wants an update must somehow convince the user that updating is in her best interest. One approach is to make a non-updated system painful to use.

Ruling out dangerous and legally risky tactics such as logic bombs that destroy the user's system or hold her (unrelated) data hostage, the vendor's strongest tactic for forcing updates is to make the DRM software block all access to protected CDs until the user accepts an update. The DRM software might check with a network server, which periodically would produce a digitally signed and dated certificate listing allowed versions of the DRM software. If the software on the user's system found that its version number was not on the list (or if it could not get a recent list), it would block all access to protected discs. The user would then have to update to a new version to get access to her protected CDs.

This approach would convince some users to update, and would thereby prolong the DRM's efficacy for those users. But it has several drawbacks. If the computer is not networked, the software will eventually lock down because it cannot get certificates. (If the software kept working in this case, users could avoid updates by preventing the DRM software from making network connections.) A bug in the software could cause an accidental but irreversible lockdown. Or the software could lock itself down if the vendor's Internet site is shut down, for example if the vendor goes bankrupt.

Strong-arm tactics can also be counterproductive, by giving the user further reason to defeat or remove the DRM software.[11] The software is more likely to remain on the user's system if it does not behave annoyingly. Trying to force updates can reduce the DRM system's efficacy if it convinces users to remove the DRM altogether. From the user's standpoint, every software update is a security risk—a possible vector for hostile or buggy code.

Given the problems with forced updates, and the user backlash they likely would have triggered, we are not surprised that neither XCP nor MediaMax tried to force updates.

10 User Outrage, and the Fight to Control Users' Computers

One notable aspect of the Sony CD DRM episode was the level of outrage expressed by users. All too frequently, bugs in popular software products endanger users' security or privacy, and users just grumble and update their software. Users' anger over the CD DRM episode was much more intense. What made this issue so different?

There are three answers. First, many users did not expect audio CDs to contain software. Users did not want the software, and they recognized that Sony-BMG chose to include it anyway. Unlike (say) an email client, which necessarily includes complex software components that might have bugs, CDs need not include software, so users are less willing to accept the risk of security problems in order to get CDs.

Second, some harmful aspects of the CD DRM software reflected deliberate choices by the vendors (and by extension, Sony-BMG). Users who might be willing to forgive implementation errors will not accept the deliberate introduction of security and privacy risks. There can be little question that XCP's rootkit functionality, the installation without consent of MediaMax software, the lack of uninstallers, and phone-home behavior were put in place deliberately by the vendors.

Third, when the vendors did make apparent implementation errors, the errors were compounded by the products' aggressive installation and reluctant uninstallation mechanisms. For example, the file permission problem discovered by Burns and Stamos was difficult to fix because the MediaMax autorun program aggressively reset the permissions to dangerous values, without asking the user for permission, every time a disc was inserted. Similarly, the vendors' apparent desire to limit use of their uninstallers led to designs that relied on downloading code using ActiveX controls—leaving users just one bug away from critical code-download vulnerabilities.

These factors led some users to conclude that Sony-BMG and the DRM vendors not only put their own busi-

ness interests ahead of their customers' interests, but also made deliberate choices that endangered customers' security and privacy. Users who would have forgiven a few implementation mistakes by a well-intentioned vendor were not so quick to forgive when they felt the vulnerabilities were less than accidental.

Though Sony-BMG and other copyright owners will presumably tread more carefully in the future, there remains a fundamental tension between DRM vendors' desire to control and limit how computers are used, and the need of users to manage their own systems. Users and DRM distributors will continue to struggle for control of users' computers.

11 Conclusion

Our analysis of Sony-BMG's CD DRM carries wider lessons for content companies, DRM vendors, policymakers, end users, and the security community. We draw six main conclusions.

First, the design of DRM systems is driven strongly by the incentives of the content distributor and the DRM vendor, but these incentives are not always aligned. Where they differ, the DRM design will not necessarily serve the interests of copyright owners, not to mention artists.

Second, DRM, even if backed by a major content distributor, can expose users to significant security and privacy risks. Incentives for aggressive platform building drive vendors toward spyware tactics that exacerbate these risks.

Third, there can be an inverse relation between the efficacy of DRM and the user's ability to defend her computer from unrelated security and privacy risks. The user's best defense is rooted in understanding and controlling which software is installed, but many DRM systems rely on undermining this understanding and control.

Fourth, CD DRM systems are mostly ineffective at controlling uses of content. Major increases in complexity have not increased their effectiveness over that of early schemes, and may in fact have made things worse by creating more avenues for attack. We think it unlikely that future CD DRM systems will do better.

Fifth, the design of DRM systems is only weakly connected to the contours of copyright law. The systems make no pretense of enforcing copyright law as written, but instead seek to enforce rules dictated by the label's and vendor's business models. These rules, and the technologies that try to enforce them, implicate other public policy concerns, such as privacy and security.

Finally, the stakes are high. Bad DRM design choices can seriously harm users, create major liability for copyright owners and DRM vendors, and ultimately reduce artists' incentive to create.

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Notes

[1] As news of the rootkit spread, we added to the public discussion with a series of 27 blog posts analyzing XCP and MediaMax. This paper provides a more systematic analysis, along with much new information. Our original blog entries can be read at http://www.freedom-to-tinker.com/?cat=30&m=2005.

[2] Music industry *rhetoric* about DRM often focuses on P2P, and some in the industry probably still think that DRM can stop P2P sharing. We believe that industry decision makers know otherwise. The design of the systems we studied in this paper supports this view.

[3] Similar application blacklisting techniques have been used in other security contexts. The client software for World of Warcraft, a massively multiplayer online role playing game, checks running applications against a regularly updated blacklist of programs used to cheat in the game [12].

[4] An extreme extension of this would be to adopt rootkit-like techniques to conceal the copying application's presence, just as XCP hides its active protection software.

[5] Forging a mark is probably not copyright infringement. Unlike the musical work in which it is embedded, the mark itself is functional and contains little or no expression, and therefore seems unlikely to qualify for copyright protection. In principle, the mark recognition process could be covered by a patent, but we are unaware of any such patent relating to XCP or MediaMax. Even if the vendor does have a legal remedy, it seems worthwhile to design the mark to prevent forgery if the cost of doing so is low.

[6] By locating the watermark nearly five seconds after the start of the track rather than at the very beginning, MediaMax reduces the likelihood that it will occur in a very quiet passage (where it might be more audible) and makes cropping it out more destructive.

[7] This design seems to be intended to lessen the audible distortion caused by setting one of the bits to the watermark value. The change in the other two bits reduces the magnitude of the difference from the

original audio sample, but it also introduces a highly uneven distribution in the three least significant bits that makes the watermark easier to detect or remove.

[8]The restrictions imposed by the DRM players only loosely track the contours of copyright law. Some uses that could be prohibited under copyright—such as burning three copies to give to friends—are allowed by the software, while some perfectly legal uses—like transferring the music to one's iPod—are prevented.

[9]This file is hidden and protected by the XCP rootkit. Before the user can access the file, the rootkit must be disabled, as described in Section 7.2. We did not determine how the MediaMax player stores the number of copies remaining.

[10]The rootkit also hooks `NtOpenKey` but does not alter its behavior.

[11]Users could also mislead the DRM software about the date and time, but most users with the inclination to do that would probably just remove the DRM software altogether.

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