Evaluating New Copy-Prevention Techniques for Audio CDs

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Several major record labels are adopting a new family of copy-prevention techniques intended to limit "casual" copying by compact disc owners using their personal computers. These employ deliberate data errors introduced into discs during manufacturing to cause incompatibility with PCs without affecting ordinary CD players. We examine three such recordings: *A Tribute to Jim Reeves* by Charley Pride, *A New Day Has Come* by Celine Dion, and *More Music from The Fast and the Furious* by various artists. In tests with different CD-ROM drives, operating systems, and playback software, we find these discs are unreadable in most widely-used applications today. We analyze the specific technical differences between the modified recordings and standard audio CDs, and we consider repairs to hardware and software that would restore compatibility. We conclude that these schemes are harmful to legitimate CD owners and will not reduce illegal copying in the long term, so the music industry should reconsider their deployment.

1. Introduction

Many computer users take for granted the ability to play compact discs in their CD-ROM drives, store and transport music with MP3 compression, and create copies or customized mixes from their CDs. While these technologies have many legal and beneficial applications, they are often used to produce illegal duplicates of copyrighted music and distribute them around the world. The recording industry is extremely concerned about revenue lost to this so-called "consumer piracy" (though the resemblance to murder on the high seas is unclear), and they are battling the issue in the courts and in Congress as well as in the technological arena.

Record companies have been waiting anxiously for the deployment of SDMI (the Secure Digital Music Initiative watermarking system) and other next-generation digital rights management proposals, but these technologies will have little effect on the millions of PCs already capable of copying music. As an interim solution, several record labels and third parties have independently developed a family of copy-prevention techniques that can be implemented immediately and are effective—temporarily, at least—against existing computers. In general, these work by introducing intentional errors into the audio data or other structures on compact discs when they are manufactured. The errors are carefully designed to ensure that the discs work correctly in almost all CD players but are unusable in most PCs. A small number of titles incorporating such schemes have been sold this past year, but several labels are considering applying them much more extensively in coming months.

The music industry has an economic interest to reduce infringement, but these new anti-copying measures go beyond the protections granted by the law and pose disadvantages to legitimate record customers and to society. Copyright law creates a careful balance between content producers, who are provided an incentive to create new art, and consumers, who are guaranteed equitable access to a diverse body of works. As part of this compromise, only certain kinds of copying are prohibited. For example, under the doctrine of "fair use," record owners have the right to make copies in many circumstances, such as for backups (in case the original is lost or damaged), for time and space shifting (to play in a car or on a portable MP3 player), and to make personal compilations (by

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mixing songs from several CDs) [16]. These new schemes make no distinction between legal and illegal copying and block them both indiscriminately. Furthermore, copyright protection is only granted for a limited period of time after which the work passes into the public domain and may be used freely. In contrast, these copy-prevention systems remain in effect indefinitely and create a *de facto* permanent copyright. These extra-legal restrictions significantly reduce the value of the protected recordings to consumers and threaten to upset the balance established by the law.

Users who do attempt to make lawful copies of protected discs face significant hardships ranging from software errors to computer crashes and malfunctioning CD drives. One company marketing copy prevention technology actually holds a patent for a system capable of "damaging audio output circuitry" when copies (even legal ones) are played [14], and Apple Computer reports that another scheme can harm certain iMac systems so severely that they require service [1]. Consumer advocates have complained that labeling these recordings "Compact Discs" is misleading, and Philips, inventor of the CD format, has requested that record producers remove the official CD audio logo [9]. Critics also complain that the new techniques violate principles of good engineering. Their success relies on consistently flawed hardware design and buggy software. The errors they introduce may degrade sound quality and shorten the lifetime of protected discs by compounding the effects of errors caused by normal scratches and dirt. Most importantly, by deliberately violating the compact disc specification, they defeat the central purpose of any standard: interoperability.

Perhaps these severe drawbacks explain why such schemes have been the subjects of more rhetoric than scientific scrutiny. However, sound policy decisions can only be made on the basis of a deeper technical understanding, including answers to a number of interesting questions that we will address in this report:

— *Are they effective?* Since few albums have been confirmed to use these technologies, accounts on the Internet of uncopyable CDs have become both numerous and unreliable (one site lists over a hundred suspect discs [4]), but further analysis would presuppose that these schemes are reasonably effective. We hope to determine whether they actually do prevent copying with typical PCs, how their effects appear to users, and which systems, if any, are unaffected.

— *How do they work?* If they really are effective, these copy-prevention methods warrant further technical study. We wish to know how the modified discs differ from regular albums at the binary level. Few details have been published to date, and producers are guarding their inner workings carefully to provide "security through obscurity." We also want to understand how a simple data carrying medium like a CD can differentiate between playback devices and what features or flaws in these devices facilitate such behavior.

— *Can they be defeated?* Policy makers, record labels, and CD owners are interested in whether these techniques can be readily bypassed. If there is no simple work-around today, how easily can hardware and software adapt to cope with protected discs? If the barriers to circumvention are few, it will be only a matter of time before these methods lose their effectiveness, and their disadvantages will more clearly outweigh their limited ability to stop infringement.

2. Discs Studied

Our study was constrained by the small number of recordings known to employ copy-prevention techniques available in early 2002. We tested three titles that used schemes from different manufacturers. These were:

1. Charley Pride, *A Tribute to Jim Reeves* (Music City Records, 2001)

   Fine print on the back cover reads "...protected by SunnComm™ MediaCloQ™ Ver 1.0" and warns: "...designed to play in standard Audio CD players only and not intended for use in

DVD players." There are 15 audio tracks and a data track containing a Windows application for downloading compressed, encrypted tracks. The same SunnComm technology is also being evaluated by BMG music. We will refer to this disc as CP-1.

2. *More Music from The Fast and the Furious* (Universal Music, 2001)

   A sticker on the case says: "This audio CD is protected against unauthorized copying. It is designed to play in standard audio CD players and in computers running Windows..." There are 14 audio tracks and a data track that contains compressed, encrypted copies of the songs and proprietary player software. This title uses copy-prevention technology called 'Cactus Data Shield' marketed by Midbar Technologies, which claims its scheme had been applied to over 10 million CDs by February 2002 [11]. We will refer to this disc as CP-2.

3. Celine Dion, *A New Day Has Come*, UK release (Columbia/Sony, 2002)

   Tersely labeled "will not play on PC/MAC," the disc is reported [2] to use a technique developed by Sony called 'key2audio.' Sony says their technology is used by more than 50 customers with over 10 million units on the market as of January 2002 [15]. The CD contains 17 tracks, but there is no option to download or play encrypted versions. We will refer to this disc as CP-3.

We used two other discs as controls: a normal audio CD, *Made in the USA* by Pizzicato Five, and a multisession CD with audio and data tracks, the *Romeo & Juliet* film soundtrack. All albums were purchased from Amazon.com or the Sam Goody store in Princeton, New Jersey.

3. Testing Effectiveness

Our first goal was to determine under what circumstances the schemes used in these discs effectively prevent playing, "ripping," and copying in PC systems. This will indicate their usefulness for reducing copyright infringement and help reveal their underlying methods of operation.

3.1 Test procedures

We tested all three CDs with several computer configurations using a variety of operating systems, CD drives, and application programs. The test systems were:

- Dell Inspiron 3500 Pentium II laptop running Windows 98 with a Toshiba SD-C2202 DVD drive
- Compaq Presario 5184 AMD K-6 desktop running Windows 2000 Professional service pack 2 with an IBM CD-ROM drive and a Sony CRX0811 CD recorder
- Dell Dimension XPS Pentium III desktop running Windows 2000 Professional service pack 2 with a Hitachi GD-5000 DVD drive and a Plextor PX-W1210A CD recorder
- Generic Pentium III desktop running RedHat Linux 7.3 (kernel release 4.2.18-3) using the same Hitachi and Plextor drives

These machines represent a range of currently deployed hardware and operating systems. Due to architectural similarities, results under Windows 95 or ME would likely be similar to those on Windows 98, and results with Windows XP are expected to resemble those on Windows 2000.

All the drives in our tests connected to the IDE (Integrated Drive Electronics) interface and supported standard ATAPI (AT Attachment Packet Interface) commands. On the Windows systems we used the device drivers included in the operating system or shipped with the computer, except with the Plextor model, which was packaged with its own software. The Linux system used the open-source drivers compiled into the kernel.

We tested with several popular applications for playing, "ripping" (extracting tracks as audio files), and copying CDs. Before each test, we booted the computer, inserted the sample recording into the drive, and waited for the drive's "ready" indicator to come on if one was present. We first tested each configuration with our control CDs to verify correct operation with standards-compliant discs. Tests were declared successful if all tracks played, extracted, or copied correctly. On the Windows systems we tested:

- *Windows CD Player*, the CD player bundled with Windows 98 and 2000; we tested using the default configuration by attempting to play and seek among the tracks.
- *MusicMatch Jukebox 7.2*, a popular free application for "ripping" audio tracks in MP3 format; we tested by opening the Record window and clicking the Record button.
- *Nero Burning ROM 5.5.9.0*, a commercial application for creating and copying CDs that comes bundled with many CD recorder packages; we tested by attempting to copy each disc to an image file on the hard drive using the default copy options.
- *CloneCD 4.0*, a sophisticated commercial application for making low-level copies of audio and data CDs, including discs with unusual features and subchannel data; we tested by attempting to copy each album to an image file on the hard drive using the 'Audio CD' copy mode.

The first three programs represent typical user applications, and the fourth is a more complex utility intended for advanced users. CloneCD support for Windows 98 was limited, so we tested this program with Windows 2000 only.

On the Linux system we tested three popular open-source applications that are included with many desktop Linux distributions. These were:

- *CDPlay 0.33*, a basic audio CD player; we tested in interactive mode with the `cdp` command by attempting to play and seek among the tracks.
- *CD Paranoia III 9.8*, widely regarded as the most robust application for "ripping" CDs under Linux; we tested with the command:
  `$ cdparanoia -d [device] -B`
- *CDR-DAO 1.1.5*, a command line CD copying application; we tested with the command:
  `$ cdrdao read-cd --device [device] [file]`

We also attempted to play the discs using three regular audio CD players: a Panasonic portable player, model SL-S650; a Technics component system player, model SL-PG4; and a Delco-Bose car CD player. The recordings played correctly in all cases with no apparent loss of fidelity or difficulty seeking among the tracks.

3.2 Test results

Our test results are summarized in Table 1 of the Appendix. The copy-prevention techniques proved generally effective in these configurations, but there were several notable exceptions.

All our Windows system tests failed to read the CDs with the applications most likely to be chosen by mainstream users: CD Player, MusicMatch, and Nero. On Windows 98 with the Toshiba drive, CD Player complained that CP-1 and CP-2 were not audio CDs, MusicMatch identified CP-1 as a data CD and would not recognize that CP-2 was present in the drive, and Nero began to copy CP-1 and CP-2 but immediately aborted with an "invalid track info" error message. We were unable to test CP-3 in this machine because the drive would not accept the disc. It attempted to read CP-3 for several seconds before aborting and signaling an error with its status lights, and after failing it could not read any other disc until the computer was rebooted.

In our Windows 2000 test systems, the Hitachi, IBM, Plextor, and Sony drives encountered similar problems reading CP-1 and CP-2 with CD Player, MusicMatch, and Nero. These drives recognized CP-3, but the software failed with the same errors as with CP-2 on Windows 98. We encountered mixed results with CloneCD. The Hitachi, IBM, and Sony drives successfully copied CP-1 and CP-2. They attempted to copy CP-3, but the copies contained no usable data. The Plextor model copied all three discs successfully.

In our Linux system, the CDPlay software had partial failures with CP-1 and CP-2 on both the Hitachi and the Plextor drives. The discs would begin playing and continue to the end, but the on-screen track listings contained mostly erroneous lengths and showed many tracks as data instead of audio. This severely impaired navigation among the songs. With CP-3, CDPlay crashed with an assertion failure using the Hitachi drive and did not recognize the CD at all with the Plextor model. CDR-DAO also failed in all test cases. Using both drives, it saw invalid track listings for CP-1 and crashed with an assertion failure for CP-2 and CP-3. While CD Paranoia saw invalid track listings too, it successfully read CP-1 with the Hitachi drive and all three discs with the Plextor.

These results indicate that the copy-prevention techniques applied to the test discs are at least temporarily effective for disrupting CD playing, "ripping," and copying operations on many current computer configurations. Out of 75 trials, only 13 were conclusively successful. The distribution of the successes indicates that hardware and software design—or mis-design—is crucial to the operation of these schemes. Drive hardware showed varying degrees of robustness ranging from the Toshiba model, which failed severely with CP-3, to the Plextor, which was the only drive to read all three discs. We also observed two distinct classes of software: program that consistently failed (including the most popular Windows applications) and ones that were usually successful (CloneCD in 9 of 12 cases and CD Paranoia in 4 of 6 cases). Variations in modes of hardware failure with CP-3 using different drives and software failure with the Linux applications also suggest that each disc uses slightly different mechanisms to prevent copying.

4. Technical Analysis

Our second goal was to determine how these copy-prevention techniques work. Their effects seem enigmatic: CD drives support a greater variety of formats than CD audio players, so how can they be *less* compatible with these new recordings? We find the answers in the complex origins of CD standards and the fragile design of many drives and applications.

4.1 CD data formats

The compact disc digital audio (CDDA) format was invented by Sony and Philips in the late 1970s as a replacement for vinyl records. Although it stores audio in digital form, CDDA makes no provisions for data applications. In the early 80s, compact disc read-only memory (CD-ROM) was developed to specify discs that could be accessed from a computer and store data as well as audio. These held far more information than PC hard drives at the time, but the discs had to be pressed from glass masters at the factory, so it was impossible for CD drives to write them. Recordable and rewritable CD formats (CD-R, CD-RW) were finally created in the late 80's and early 90's by replacing the pitted aluminum in regular CDs with specialized dyes that could be marked by low-power lasers [10]. To this day the official specifications for CDDA, CD-ROM, and CD-R/W (known as the Red Book, Yellow Book, and Orange Book) remain carefully guarded trade secrets, but many details are publicly available in equivalent international standards (IEC-908 [8] for CDDA and ECMA-130 [6] for CD-ROM) or can be deduced from the programming interfaces for CD drives (such as the SCSI Multimedia Command specification [13]).

The information stored on a compact disc is organized into functional units called *tracks*. A typical audio CD contains one audio track for each song, and CD-ROM discs can contain audio and data tracks. Tracks are subdivided into blocks called *frames*, which hold 1/75 second of audio or around 2048 bytes of digital data along with error correction bits. Multiplexed with the main data stream in each frame are eight *subchannels*. Only two subchannels, designated P and Q, are commonly used. The *P subchannel* marks divisions between tracks. The *Q subchannel* holds the current track number, the track type (audio or data), and the time signature of the frame relative to the start of the disc. This data is displayed by players and allows seeking to a specific time position. There are two special regions: the *lead-in area* before the first track and the *lead-out area* after the last one. These consist of several empty frames that contain no audio but may include subchannel data describing the rest of the disc. The Q subchannel in the lead-in area holds a *table of contents* (TOC) specifying the number of tracks, their starting positions, and whether each contains audio or data. This is the basic CD format understood by CD audio players and CD-ROM drives. [6, 8]

The CD-R and CD-RW writable disc formats have more complicated structures. CD-R media cannot be erased, so the standards were designed to allow data to be written incrementally until the whole disc is filled. One way to do this is to write several *sessions* to the disc, each with its own lead-in, lead-out, and tracks. Every session has its own TOC that describes all of its tracks. A new Q subchannel code is defined to point to the beginning of the previous session area and included in each session's TOC. Discs encoded in this way are called *multisession* CDs [13]. Modern CD drives support the multisession format by starting with the last session TOC and following the links to previous ones, but audio CD players and older CD-ROM devices read only the initial TOC and just see the first session. While the multisession concept was intended for recordable media, many commercial albums now use it to deliver "enhanced" multimedia content on a second session that can be played in PCs.

4.2 Basic read mode TOC errors

The copy-protected CDs in this study retain compatibility with regular CD audio players, so they must incorporate changes at the data level rather than the physical level of disc design. We needed to read the discs to understand how they are protected, but of course this is made intentionally difficult by the copy-prevention technologies. In our tests, the Plextor hardware was the most robust to these schemes and successfully read from all three discs using CloneCD and CD Paranoia, so we analyzed the discs with the Plextor drive. We worked under Linux, but we passed commands directly to the drive, so the results are system independent.

Most of the software we tested encountered problems seeing correct lists of tracks, so we first attempted to read the table of contents from each disc. For various reasons there is no standard method for reading raw TOC data directly with a CD drive. The lead-in area resides in an unaddressable region of the disc, so applications must rely on the drive's firmware to process it. We used the SCSI Multimedia Command interface (which translates directly into ATAPI commands for the IDE drive). The command for returning TOC entries is called `READ TOC`. It can be called in several modes, of which mode 0 and mode 2 are useful for our purposes.

In mode 0, the `READ TOC` command returns a processed list of the tracks on the CD with their types (audio or data) and start times. The drive builds this list by reading the TOC from the lead-in area of each session. This is most commonly used by CD player and "ripper" applications, which only need a basic list of tracks [13]. The data returned by `READ TOC` mode 0 for the test CDs are presented on the left side of Tables 2, 3, and 4 in the Appendix. The TOC from CP-1 listed all the correct start times, but the first 15 tracks were mis-marked as data instead of audio (track 16 is an actual data track containing the Windows downloading application). CP-2 also reported that its audio tracks contain data, but its start times were incorrect too (except for track 15, which contains the compressed copies of the songs). CP-3 listed false types and start times for some tracks but not others, and which tracks were erroneous seemed to vary each time the disc was inserted into the drive. The incorrect track types in the CP-1 and CP-2 listings explain why some CD player and

MP3 extractor applications fail—they simply don't see any audio tracks in the TOC, and this may partially explain the failures for CP-3 in configurations where the drive accepted the disc. We also see why the tracks allowing encrypted versions to be played remained accessible. These results do not show why the discs are uncopyable, since CD copying software will copy data and audio, nor how regular CD players handle the discs correctly.

4.3 Advanced read mode TOC errors

To get a more complete picture of the TOC data, we tested with the `READ TOC` command in mode 2. In this mode the drive returns Q subchannel entries from each session separately. Besides track start times, mode 2 returns session pointers that link each lead-in area to the next. This mode is used by certain advanced "ripper" applications and most CD copying software, which needs to know the layout of the entire disk. It provides the most detailed information about the multisession TOC that the drive can report.

The entries returned by this method for the test CDs are listed on the right side of Tables 2, 3, and 4. The results for CP-1 aren't very informative. All the times and track types are the same as in mode 0, although we now see that the disc is in multisession format, with the audio portion in session 1 and the data track in session 2. The entries for CP-2 are more revealing. The disc is divided into two sessions like CP-1, and unlike the mode 0 results, those returned in mode 2 appear to be correct for nearly all tracks. The only exception is track 1, which has start time 00:01.74. The CDDA specification requires a pause of at least two seconds before the start of the first track [8], so 00:02.00 is the earliest allowed time. The block addressing scheme used by CD drives actually specifies 00:02.00 as frame 0, so this start time translates to the invalid frame address -1. This will cause many programs to fail while copying the disc or reading track 1, and it made CDR-DAO crash with an assertion failure in some of our tests. Normal CD players do not use this address scheme and are unlikely to be affected.

The mode 2 data from CP-3 warrants extended discussion. These entries list the correct types and start times for all the audio tracks, but strangely they also include multiple sessions with a data-mode track 18 as part of session 2. This CD claims to be completely unusable in PCs, so a real data track would be surprising. We observe that the lead-in time for the second session, 75:02.62, is only a few frames before the last accessible address on the disc, 75:02.68, and that track 18 begins even later. The session 2 TOC also includes a pointer to a *third* session that begins later still than the mysterious track 18.

This elaborate construction is the mechanism behind CP-3's total incompatibility with some configurations we tested. Since the third session begins before the end of the disc but has no TOC or lead-out, it is in an "open" or incomplete state. Sessions on recordable CDs are sometimes left open to allow more tracks to be written later, but most drives cannot recognize the disc until the session is "closed" by writing a complete TOC and lead-out [10]. Some drives, including the Toshiba in our tests, are unable to read open discs because they cannot locate a usable TOC in the final session. Others, like the Plextor used for these readings, are designed to handle open discs and have a more robust failure mode that returns the tracks from sessions 1 and 2 only, as in the mode 2 results. Even on such drives, the non-existent track 18 may cause problems for many CD copying programs which fail when they are unable to read it.

4.4 Concealing audio tracks

These TOC errors explain why the protected discs thwart most PC hardware and software, but the question remains how they still work in normal CD players. In fact, this is closely related to why we find different results reading the TOC in mode 0 and mode 2. It's no coincidence all three discs contain multiple sessions (even CP-3, which has no actual content outside of session 1). When a multisession-aware CD drive compiles a list of tracks with `READ TOC` mode 0, it reads TOCs from the last session to the first, ignoring duplicate track entries. The modified discs could place correct data in the first session TOC and erroneous entries for the same tracks in the second session TOC. The mode 0 results would then contain only the false track listings. In `READ TOC` mode 2, however, each session's TOC is processed individually and entries referring to tracks outside the current session are discarded, so just the correct session 1 entries would be visible. Audio CD players read only the first session TOC, so they would also be unaffected.

We performed a simple experiment to test whether the copy-prevention schemes for CP-2 and CP-3 use this method to hide their audio tracks. Three small pieces of non-transparent tape were affixed to the data side of discs CP-2 and CP-3 roughly 120 degree apart beginning at the outer edge and extending inward radially for approximately 3/4 inch. This prevented the drive from reading the TOC in the second session, which begins in the region under the tape, so we expected that the drive would now return only the correct TOC entries from session 1. When the taped discs were examined with `READ TOC` mode 0, the audio tracks were listed with the proper types and start times as in mode 2 without the tape, confirming our theory. Unfortunately, the tape covered portions of later audio tracks too, so the discs were not entirely usable. This multisession trick also explains why DVD players, video game systems, and certain car audio systems reportedly fail to read the discs, since many of these devices are multisession aware and read the later TOCs just like computer CD drives. Last May, several weeks after we completed these tests, reports appeared in the popular press that writing around the outer edge of certain discs with a felt-tipped marker would defeat the copy protection [17]. This works by obscuring the last session TOC just like the tape but leaves the audio tracks accessible when carefully applied.

We did not test CP-1 in this way because the entries returned by `READ TOC` in either mode were the same for the audio tracks on this disc. The start times were all correct, but the tracks were marked as data instead of audio. The designers of the scheme used on this disc relied on the fact that most audio CD players ignore the track types listed in the TOC and use types from the track subchannels instead. This variation makes this particular scheme more likely to defeat CD reader software that uses the `READ TOC` mode 2 method and may confuse CD copying software that will attempt to treat the audio tracks as data. It represents a different trade off between greater copy resistance and increased chances of incompatibility with audio CD players.

4.5 Other errors

In addition to TOC errors, copy prevention schemes may place errors in the track data area, either in the subchannel codes or in the audio data and its error correction bits. For instance, the makers of the protection technology applied to CP-2 hold a patent describing one such scheme that injects corrupt audio samples but conceals them from audio CD players using bits in the P subchannel [14]. Other proposed techniques involve writing corrupt audio samples along with incorrect error correction codes to simulate scratches on the disc. These errors are unrecoverable, so audio CD players interpolate over them. Most CD drives designed for data access have no audio interpolation capability and would return the faulty samples instead.

To test for subchannel errors we used the `PLAY CD` command to seek to each frame and then called `READ SUBCHANNEL` to retrieve the data. We found no invalid entries in the P or Q subchannels for these discs. This either indicates that the discs contain no such errors or that the drive firmware recognized and corrected them before returning the samples. We listened to copies made by CloneCD for evidence of faulty error correction codes, but they contained no noticeable loss of fidelity compared to the output from an audio CD player. However, another study reports an unusually high C1 error rate in the audio portion of the CP-2 disc [3]. These are low-level errors corrected by drive hardware and not normally visible to applications, but at the reported frequency certain drives might be unable to read the audio data, drastically slow down during copying, or return reduced quality samples.

5. Repairing Broken Hardware and Software

Our third and final goal was to determine whether hardware and software can be adapted to read discs with copy-prevention technology. As we have shown, these schemes take advantage of bugs and poor error handling in existing hardware and software. Now that these problems have been pointed out, we expect manufacturers to improve such fragile designs and produce more robust products that will gradually reduce the effectiveness of these methods.

Hardware compatibility is essential for reading the CDs successfully, since the worst case hardware failures (as illustrated by CP-3 in the Toshiba model) prevent the drive from accepting the disc at all. Our tests reveal that many current CD drives are poorly designed to cope with unusual conditions, but the robustness of the Plextor model demonstrates that greater compatibility is possible today. In addition to handling the TOC errors gracefully, well-built drive hardware should correct errors in the audio data stream during reading as CD players do or report specific data and subchannel errors to applications using the C2 and C3 feedback mechanisms [10] so that errors can be corrected in software. The Plextor drive and other recent models optimized for audio extraction do both. These changes are not specific to copy-prevention systems but improve operation with all damaged or poorly recorded discs.

Software can adapt more easily to changing conditions, and we expect future applications will fix problems that prevent them from supporting discs like these with almost any drive that does not reject them outright. As for hardware, the most important improvements for software are increased robustness and better modes of failure. For maximum compatibility, CD reading and copying programs should be modified to detect and correct data errors and to recover gracefully even when certain tracks or frames are unreadable. Obvious subchannel and TOC errors should simply be ignored. Since many drives might not report TOC information correctly even with `READ TOC` mode 2 and future copy-prevention techniques may include more persistent faults, applications for reading audio data should include an option to ignore the TOC entirely and derive a table of contents directly from the track data like some audio CD players do. Analyzing individual frames shows whether they contain audio data or are a transition between songs, and a simple binary search can reveal where each track begins and ends. This approach and improved error correction would allow playback under nearly any copy-prevention scheme that remains usable in audio CD players.

How easily can existing software be repaired to work with these CDs? To find out, we examined the source code of the CDR-DAO copying program [12]. Debugging revealed that our test CDs caused errors in just a few procedures, mostly related to reading the TOC. The program combines `READ TOC` mode 0 and mode 2 results, but the differences between them caused problems in logic for detecting the format of the start times. This could be corrected by using mode 2 data only or by using a subchannel scan to derive the correct TOC. The invalid start time of 00:01.74 on CP-2 was caught by a safety check and forced the program to abort. A better recovery would have been to guess the earliest valid start time, 00:02.00. Audio tracks incorrectly reported as data caused faults when CDR-DAO tried to read frames from the disc, but the actual types could instead be determined from the track subchannel codes or by analyzing data in the track. Finally, unreadable frames such as the contents of track 18 on CP-3 caused the whole copy operation to abort. This error could be changed to a warning and the invalid frames replaced by empty ones. All these modifications would be straightforward for someone familiar with the source code. Of course, other software would require different changes that might be more challenging, but it is unlikely that any would require significant rewriting to achieve compatibility with copy-protected CDs.

Recent developments indicate that changes like these are already being implemented. In May, the makers of two "ripper" applications released new versions with specific fixes for working around copy-prevention schemes. Feurio 1.64 adds special routines for defective CDs [7], and EAC 0.9x can detect CD structure by track subchannel analysis, bypassing the TOC [3]. Both already supported extended error correction mechanisms. Version 4.0 of the CloneCD copying software includes a special mode for audio CDs, and this greatly improved its success rate in our tests compared to earlier releases. Although all these programs are more obscure than MusicMatch, Nero, and other mainstream applications, they demonstrate that greater compatibility is possible through better software design. Drive hardware is adapting too. Philips is reportedly considering adding support for reading and copying these discs to future versions of its products [5], and market demand may induce competing manufacturers to do the same.

Hardware and software are becoming more resistant to these copy-prevention techniques even before they have been widely adopted. Given the relatively simple modifications needed to achieve full compatibility, it seems unlikely that these schemes will enjoy lasting effectiveness. Record producers might also adapt their practices to changing technology, but their options are limited by the need to maintain compatibility with audio CD players. Once more robust CD hardware becomes dominant, support for any new protection mechanism will require only software upgrades, which can be delivered easily using the Internet, and this will permanently undermine the usefulness of audio CD copy prevention. It may be proposed to prohibit such adaptations through legislation, but to do so would be to mandate buggy software and poor hardware design.

6. Conclusions

The development of inexpensive, user-friendly computer recording devices has pitted the technology industry versus the music industry in a battle for consumer dollars. Yet there is far more at stake than economics. These copy-prevention schemes threaten fair use and the future of the public domain, and pressure to preserve their effectiveness by prohibiting circumvention could limit the freedom of hardware and software manufacturers to improve their products and correct bugs.

While the techniques we studied prevented copying and playback in a high percentage of our test systems, it seems they have done little to reduce "piracy." A quick search on the Kazaa and Gnutella file trading networks in May 2002 revealed copies of nearly every track freely available for downloading. Instead of combating copyright infringement, these schemes harm legitimate record owners. Their inflexible copy controls prevent many legal uses, they cause hardware and software errors, and they threaten to damage PCs and stereo systems. As long as just a few computer configurations can read new CDs, they will inevitably be redistributed, and with so many disadvantages for consumers, these measures may actually encourage users to resort to illegal copying instead of purchasing CDs.

The concept of audio CD copy-prevention is fundamentally misguided. It is based on the false premise that specific deviations within the framework of a standard data format could result in lasting incompatibility. Yet hardware and software adaptation is an inevitable and natural extension of improved design and bug fixing. These ill-conceived schemes will amount to little more than a temporary speed bump for copyright infringement and promise to further alienate customers from the record industry.

7. Acknowledgments

I am grateful to Andrew Appel for his guidance throughout this project, and to Edward Felten, Brian Kernighan, and Scott Aaronson for valuable comments and support.

One likes to believe in the freedom of music,
But glittering prizes and endless compromises
Shatter the illusion of integrity.

—Rush, "The Spirit of Radio"

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Appendix. Test Results and Tables of Contents

Table 1. Summary of test results under various system configurations

O.S.	Drive	Album	Software	Results
Windows 98	Toshiba	CP-1	CD Player	Failure: No audio CD in drive
			MusicMatch	Failure: Data CD detected
			Nero	Failure: Invalid track info
		CP-2	CD Player	Failure: No audio CD in drive
			MusicMatch	Failure: CD-ROM drive is empty
			Nero	Failure: Invalid track info
		CP-3	—	Failure: Disc won't spin up; drive non-functional until reboot
Windows 2000	Hitachi IBM Sony	CP-1	CD Player	Failure: No audio CD in drive
			MusicMatch	Failure: Data CD detected
			Nero	Failure: Invalid track info
			CloneCD	Success
		CP-2	CD Player	Failure: No audio CD in drive
			MusicMatch	Failure: CD-ROM drive is empty
			Nero	Failure: Invalid track info
			CloneCD	Success
		CP-3	CD Player	Failure: No audio CD in drive
			MusicMatch	Failure: CD-ROM drive is empty
			Nero	Failure: Invalid track info
			CloneCD	Failure: Copy contains no data
	Plextor	CP-1	CD Player	Failure: No audio CD in drive
			MusicMatch	Failure: Data CD detected
			Nero	Failure: Invalid track info
			CloneCD	Success
		CP-2	CD Player	Failure: No audio CD in drive
			MusicMatch	Failure: CD-ROM drive is empty
			Nero	Failure: Invalid track info
			CloneCD	Success
		CP-3	CD Player	Failure: No audio CD in drive
			MusicMatch	Failure: CD-ROM drive is empty
			Nero	Failure: Invalid track info
			CloneCD	Success
Linux	Hitachi	CP-1	CDPlay	Failure: Bad track listing
			CD Paranoia	Success
			CDR-DAO	Failure: Invalid TOC data
		CP-2	CDPlay	Failure: Bad track listing
			CD Paranoia	Failure: Doesn't recognize tracks
			CDR-DAO	Failure: Assertion failure
		CP-3	CDPlay	Failure: Assertion failure
			CD Paranoia	Failure: Doesn't recognize tracks
			CDR-DAO	Failure: Assertion failure

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O.S.	Drive	Album	Software	Results
Linux	Plextor	CP-1	CDPlay	Failure: Bad track listing
			CD Paranoia	Success
			CDR-DAO	Failure: Invalid TOC data
		CP-2	CDPlay	Failure: Bad track listing
			CD Paranoia	Success
			CDR-DAO	Failure: Assertion failure
		CP-3	CDPlay	Failure: No audio CD in drive
			CD Paranoia	Success
			CDR-DAO	Failure: Assertion failure

Table 2. Table of contents entries from disc CP-1

`READ TOC` mode 0			`READ TOC` mode 2			
Track†	Type	Start‡	Track†	Session	Type	Start‡
1	Data*	00:02.00	1	1	Data*	00:02.00
2	Data*	02:21.08	2	1	Data*	02:21.08
3	Data*	05:13.30	3	1	Data*	05:13.30
4	Data*	08:25.54	4	1	Data*	08:25.54
5	Data*	10:51.46	5	1	Data*	10:51.46
6	Data*	13:05.04	6	1	Data*	13:05.04
7	Data*	15:59.74	7	1	Data*	15:59.74
8	Data*	18:08.67	8	1	Data*	18:08.67
9	Data*	21:32.66	9	1	Data*	21:32.66
10	Data*	23:41.49	10	1	Data*	23:41.49
11	Data*	25:58.07	11	1	Data*	25:58.07
12	Data*	28:26.10	12	1	Data*	28:26.10
13	Data*	31:04.41	13	1	Data*	31:04.41
14	Data*	33:31.01	14	1	Data*	33:31.01
15	Data*	35:55.55	15	1	Data*	35:55.55
			`0xa2`	1	Audio	38:21.42
			`0xb0`	1	Data	40:51.42
16	Data	40:53.42	16	2	Data	40:53.42
`0xaa`	Data	40:59.44	`0xa2`	2	Data	40:59.44

† Special track number codes—
Mode 0: `0xaa` Final lead-out start time
Mode 2: `0xa2` Session lead-out start time
`0xb0` Next session start time

‡ Start time from the beginning of the disc in minutes, seconds, and frames (75 per second).

* Denotes invalid or erroneous value.

Table 3. Table of contents entries from disc CP-2

READ TOC mode 0			READ TOC mode 2			
Track†	Type	Start‡	Track†	Session	Type	Start‡
1	Data*	00:02.00*	1	1	Audio	00:01.74*
2	Data*	00:06.00*	2	1	Audio	04:10.51
3	Data*	00:10.00*	3	1	Audio	07:32.43
4	Data*	00:14.00*	4	1	Audio	10:28.41
5	Data*	00:18.00*	5	1	Audio	12:13.74
6	Data*	00:22.00*	6	1	Audio	15:32.36
7	Data*	00:26.00*	7	1	Audio	18:56.59
8	Data*	00:30.00*	8	1	Audio	23:11.66
9	Data*	00:34.00*	9	1	Audio	27:01.74
10	Data*	00:38.00*	10	1	Audio	30:20.61
11	Data*	00:42.00*	11	1	Audio	34:34.11
12	Data*	00:46.00*	12	1	Audio	38:12.04
13	Data*	00:50.00*	13	1	Audio	41:15.26
14	Data*	00:54.00*	14	1	Audio	44:39.11
			0xa2	1	Audio	51:14.66
			0xb0	1	Audio	53:44.66
15	Data	53:46.66	15	2	Data	53:46.66
0xaa	Audio	74:00.00	0xa2	2	Audio	74:00.00

Table 4. Table of contents entries from disc CP-3

READ TOC mode 0			READ TOC mode 2			
Track†	Type	Start‡	Track†	Session	Type	Start‡
1	Audio	00:10.00	1	1	Audio	00:10.00
2	Audio	03:40.65	2	1	Audio	03:40.65
3	Audio	07:54.45	3	1	Audio	07:54.45
4	Audio	12:02.60	4	1	Audio	12:02.60
5	Audio	15:28.42	5	1	Audio	15:28.42
6	Audio	19:48.25	6	1	Audio	19:48.25
7	Audio	23:26.00	7	1	Audio	23:26.00
8	Audio	28:45.30	8	1	Audio	28:45.30
9	Audio	34:19.55	9	1	Audio	34:19.55
10	Audio	39:08.12	10	1	Audio	39:08.12
11	Data*	00:08.00*	11	1	Audio	43:25.22
12	Data*	00:08.00*	12	1	Audio	47:42.37
13	Data*	00:08.00*	13	1	Audio	51:52.50
14	Data*	00:08.00*	14	1	Audio	55:44.55
15	Data*	00:08.00*	15	1	Audio	59:14.52
16	Data*	00:08.00*	16	1	Audio	63:04.47
17	Data*	00:08.00*	17	1	Audio	68:47.17
			0xa2	1	Audio	72:32.62
			0xb0	1	Audio	75:02.62
*18	Data*	00:08.00*	*18	2	Data	75:04.62*
*19	Data*	00:08.00*				
0xaa	Data	75:12.62*	*0xa2	2	Data	75:12.62*
			*0xb0	2	Audio	76:42.62*