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Analysis of Compact Disc Digital Rights Management

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Abstract

Music publishers using the compact disc standard have introduced various copy protection schemes into the marketplace in the past several years, ostensibly in an effort to reduce sagging sales that the industry blames on illegal distribution of high-quality copies of compact discs. Over the course of three years, we performed a battery of tests against dozens of discs from various parts of the world to understand how these systems work.

Each of these schemes has unique features but a common thread emerges: exploiting differences between computer technology and basic players for compact disc digital audio. In some cases, the protected discs fail to meet the specifications established for interoperability of compact disc media. We also identified problems with computer software that failed to recognize certain types of standards-compliant discs that led consumers to report incorrectly that the discs were faulty.

Copy protection schemes come with several side-effects. These include a loss of functionality on some types of equipment, impaired playback quality on standard audio equipment, and risk of consumer privacy invasion.

The most important issue, however, is in the 'ownership' of digital media standards. Where such standards were once governed by the producers of recording and playback equipment, an attempt to get consumers accustomed to a standard established by the recording industry itself seems underway.

This paper is the first in a series to document the findings of Interhack's Digital Media Project.

1 Introduction

Widespread use of digital media has radically impacted the music industry. The industry claims that it is losing significant amounts of money due to people using technology to make digital copies of their product and to distribute such copies without further compensation.

In recent years, the industry has undertaken several efforts to prevent users' ability to make copies of data from digital media. Starting in 2002, we began to investigate compact discs to understand where copy protection technology, which systems were being used, how those systems worked, and what side-effects those systems might introduce.

2 Methodology

We compiled a master list of discs that were reported to have problems. We purchased discs from that master list. In cases where it was widely reported that only certain "batches" of discs were "bad," we purchased several copies of the discs, generally from different states.

We worked from a set of seventy-two discs in all. The discs came from the United States (California, New Mexico, and Ohio) and the United Kingdom. Tables 1, 2, and 3 shows the complete list of discs tested, broken down by "set," that is, group purchased at the same time and location. Sets are named according to the state of purchase; the set named "X" came to us from an unknown state; "UK" sets were purchased in London, England. (Discs appearing more than once in a single set are not duplicates, but indicators of multi-disc sets.)

In addition to the discs that were reported as problematic, we collected a list of the symptoms reported.

After collecting the data, we then began analysis through several mechanisms. Because functionality problems were first reported with computers in particular, we looked at the discs from the perspective of a computer: why functionality of one disc would differ from the functionality of another disc on the same computer. We wrote a software package called *CD Verity* (which is open-source and available for download from our Web site) to perform a variety of tests against the disc.

In addition to software-based analysis on a computer system, we looked at various CD peripheral devices and noticed minor differences of behavior from one system to another.

Finally, in an effort to understand why a CD-ROM drive would read the data differently from another CD-ROM drive, we performed an extremely low-level analysis of the discs themselves, examining such issues as compliance to Red Book specification for lead-in time, lead-out time, pit/land geometry limitations, and so on. This analysis was performed with a specialized testing device (model QA-201) produced by Clover Systems.

Set	*Artist*	*Album*
ca1	Alanis Morissette	Under Rug Swept
ca1	Bob Dylan	Love and Theft
ca1	Dream-Theater	Six Degrees of Inner Turbulence
ca1	Dream-Theater	Six Degrees of Inner Trbulence
ca1	Natalie Imbruglia	White Lilies Island
ca1	Sarah Brightman	Classics
ca1	Strange Little Girls	Tori Amos
ca1	Toby Keith	Pull My Chain
ca2	Delerium	Odyssey The Remix Collection
ca2	Delerium	Odyssey The Remix Collection
ca2	Gorillaz	(self)
ca2	Pink Floyd	Echoes The Best of Pink Floyd
ca2	Pink Floyd	Echoes The Best of Pink Floyd
ca2	Richard Elliot	Chill Factor
ca2	Sarah Brightman	Classics
ca3	(various)	More Fast and Furious: Music From and Inspired by the Motion Picture The Fast and the Furious
ca3	Aerosmith	Just Push Play
ca3	NSYNC	Celebrity
ca4	Aerosmith	Young Lust: The Aerosmith Anthology
ca4	Aerosmith	Young Lust: The Aerosmith Anthology
ca5	soundtrack	Atlantis The Lost Empire
ca6	Natalie Cole	Unforgettable
ca6	No Doubt	Rock Steady
ca6	Roger Waters	Flickering Flame
ca6	Staind	Break the Cycle
ca7	Toby Keith	Pull My Chain

Table 1: Discs from California Used in Testing

Set	*Artist*	*Album*
nm	Natalie Imbruglia	White Lilies Island
nm	Sheryl Crow	The Globe Sessions
nm2	Celine Dion	A New Day Has Come
nm2	soundtrack	The Fast and the Furious

Table 2: Discs from New Mexico Used in Testing

3 Compact Disc Background

Understanding the copy protection schemes in use will require having a basic understanding of how compact discs work, and knowing the types of media that are generally called "compact disc."

3.1 Types of Compact Disc

Consumers typically will refer to optical media that play in compact disc players, without any more precise description of the media type. The optical media most generally known as "compact disc" has a variety of standards, each of which has particular capabilities. Knowing about these standards is critical to understanding the mechanisms of copy protection and the consequences of using he media in various playback devices.

Compact Disc Digital Audio (CD-DA) is the most common type, that which most consumers expect when discussing audio CDs. These contain a *Table of Contents* and then tracks of waveform bitstreams. The specification is sometimes called "Red Book."[10]

Compact Disc Read-Only Memory (CD-ROM) is the specification for "data" discs, such as those used to distribute computer software. It is noteworthy that although most CD-ROM drives can play compact disc digital audio, there is no technical requirement for CD-ROM drives have that capability.[4, 5]

Multisession Compact Disc is a specification that will allow discs to support multiple sets of data on the same disc.[9]

Set	*Artist*	*Album*
oh1	(various)	Final Fantasy X
oh1	Aerosmith	Young Lust: The Aerosmith Anthology
oh1	Aerosmith	Young Lust: The Aerosmith Anthology
oh1	Alanis Morissette	Under Rug Swept
oh1	Bare Naked Ladies	Maroon
oh1	Dream-Theater	Six Degrees of Inner Turbulence
oh1	Dream-Theater	Six Degrees of Inner Turbulence
oh1	Joe Satriani	Engines of Creation
oh1	Seal	Hu Manbe In G
oh2	(various)	O Brother, Where Art Thou?
oh2	Bob Dylan	Love and Theft
oh2	Collective Soul	7 Year Itch Greatest Hits 1994-2001
oh2	Collective Soul	Dosage
oh2	Enya	A Day Without Rain
oh2	Howard Shore	The Lord of the Rings The Fellowship of the Ring Original Motion Picture Soundtrack
oh2	Lisa Loeb	Cake and Pie
oh2	The Cranberries	Bury the Hatchet The Complete Sessions
oh2	The Cranberries	Bury the Hatchet The Complete Sessions
oh2	The Doors	The Best of the Doors
oh2	The Doors	The Best of the Doors
oh2	Van Halen	Van Halen Best of Volume 1
oh3	Celine Dion	A New Day Has Come
oh3	Natalie Imbruglia	White Lilies Island
oh4	Delerium	Odyssey The Remix Collection
oh4	Delerium	Odyssey The Remix Collection
oh4	Richard Elliot	Chill Factor
oh4	Sarah Brightman	Classics

Table 3: Discs from Ohio Used in Testing

Enhanced Music CD (CD Enhanced) is a specific type of multisession disc, one that has an audio session and a second session of computer data with content related to the audio session.[8]

Philips licenses the specifications and related intellectual property around the compact disc standards, including logo and how to use them. Such specifications are available only to licensees who agree not to disclose technical detail. There are many other specifications, but only these were considered for the present research. Figure 1 shows the Compact Disc Digital Audio and Enhanced Music CD logos, respectively.

Figure 1: Philips Compact Disc Digital Audio and Enhanced Music CD Logos

Of particular interest is that many discs using the Enhanced Music CD format do not use the Philips logo created for the purpose; the most frequent logo is some variation of the one shown in Figure 2. This is apparently connected to a standard created not by the makers of media devices, but the Recording Industry Association of America (RIAA).

Figure 2: RIAA 'EnhancedCD' Logo

RIAA asserts that the purpose of the Enhanced CD Voluntary Specification is twofold: "The primary purpose of this document is to define the disc-player interface needed to improve compatibility. A secondary purpose is to provide general recommendations for CD-ROM readers concerning these products." [6] The same document says that the Enhanced CD specifications "are not intended to supersede, preclude or replace the existing Philips/Sony Compact Disc Specifications for CDDA, CD-ROM, CD-ROM XA, Multisession, CD-I, and 'CD-Extra', but are intended to insure a compatible interface between an Enhanced CD disc and CDDA audio players."

3.2 Compact Disc Digital Audio Basics

Digital audio is created by capturing a sound wave (such as created by a musical instrument) in a *sample*, encoded in a binary form to create a *frame*. A machine can read that frame at a later time to reconstruct the *waveform* and play it exactly as it was captured in the first place. Just as a motion picture is replayed by rapidly moving a film from one frame to another, sound is replayed by rapidly moving from one sound waveform to the next at the *sample rate*. In the case of compact disc digital audio, this is 44,100 samples per second.

The compact disc is an optical media format that uses *pits* on an otherwise smooth reflective surface (*land*) to encode data in a digital (binary) form. A compact disc player directs a laser beam against the reflective component of the disc and looks for the beam to be reflected back. The beam will reflect back brightly across land; when the beam moves across a pit, the reflection will be directed elsewhere, causing an interruption in the light back into the reader. A transition from land to pit or from pit to land represents a binary 1; moving from one sector to another without a transition represents a binary 0.

Once the data are read from the disc and demodulated back to the binary data stream, eight bits per frame are available for control and "display." These bits are referred to in the specification as channels P, Q, and so on, through W.

Channel P is a simple separator flag for music tracks, allowing cheap search systems to be implemented by scanning for this flag.

Channel Q is used by more sophisticated players for control purposes, such as a microcomputer. Data such as track number and time are encoded into Channel Q.

Channels R...W contain the display data, typically unused on audio CDs.

3.3 Compact Disc Error Correction

More than half of the data present on a compact disc are there to ensure that playback devices read the data properly and to provide help for the device to fix errors during playback. Additionally, the data are interleaved on the disc to enhance error correction.

Error correction in CD players works in two stages. The error correction chip used in the QA-201 unit used for testing uses the "Superstrategy" algorithm that can correct two bad symbols per block in the first stage and two bad symbols per block in the second stage.

Errors reported by the unit use a shorthand notation E11, E21, and E31 to refer to errors detected in the first stage of error correction; E12, E22, and E32 refer to errors detected in the second stage of error correction. E11 and E21 indicate one bad symbol in the block; E21 and E22 indicate two bad symbols in the block. E31 is uncorrectable at the first stage, but because data are de-interleaved between error correction stages, the three (or more) bad symbols go into separate blocks for the second stage, and thus might be correctable.

E32 is uncorrectable at the second stage, i.e., at the end of the error correction process. Interestingly, as technology improves, both the legitimacy of errors encoded in the discs and their impact decreases. Modern recording and encoding equipment can easily produce discs with very few errors, and our testing has shown many discs of excellent quality in circulation. Some of the earliest CD players reportedly could not correct E22 errors, while some modern equipment can correct even some E32 errors.

Thus, while compact discs are a significant technical improvement over vinyl records—since they can detect and correct many errors during playback—they are not indestructible; heavy scratches, bad fingerprints, and so on can lead to uncorrectable (E32) errors, which will cause imperfect reproduction of the recorded sound.

3.4 Computers and CD Enhanced

The CD Enhanced format was designed to allow producers to include computer data on the discs along with the Compact Disc Digital Audio. CD Enhanced is an important format for copy protection schemes to work on computers. This format allows a single disc to appear as compact disc digital audio and to a traditional CD player and as a CD-ROM to a computer's CD-ROM drive.

How computers deal with removable media such as compact discs will vary from one operating system to another. Generally speaking, operating systems will automatically recognize when a disc has been inserted into the CD-ROM drive. If an ISO 9660 filesystem can be found, it will be mounted. Operating systems such as Microsoft Windows and Apple's MacOS have features that allow them to look for specially-designated executable programs to be run on insertion of the disc. If such a file is not present, the filesystem will simply be mounted and presented to the user like any other directory structure. If no filesystem is present, the disc is generally assumed to be compact disc digital audio and playback can begin.

Of particular note here is that if executable software is started at disc insertion, many new features are possible. Since the computer has not recognized the disc as compact disc digital audio, producers can create a disc that will play on a computer only with the producer's special software. By taking advantage the differences between how data would be read on CD-ROM drives and traditional CD players, producers can even make discs that will not work properly on CD-ROM drives without their special software, but will apparently work in traditional CD players.

An early mechanism to foil copy protection schemes worked by using a black felt-tip marker to blacken the outer edge of the disc. This works because it makes the data session of a Multisession (specifically, CD Enhanced) disc unreadable to the CD-ROM drive, causing the computer to treat the disc as CD-DA.

4 Results

We found several issues with compact discs, each of which can explain the problems reported by users online. For comparison, we used test discs provided by Clover Systems with the QA-201 unit.

4.1 Encoding Errors

Errors encoded into the disc would impact the ability for error-correcting computer hardware to be able to read the disc properly. Traditional CD players, on the other hand, would likely throw out erroneous frames and replace them with a new frame created by the player by *interpolating* the previous and next frame together.

Some might claim that such errors are indiscernible to the listener on standard playback equipment, that the effect is no worse than *lossy* compression used in popular digital encoding methods like MPEG2 Layer III ("MP3").[1] On CD-ROM drives making a copy of the data, however, the situation is different. Instead of interpolating to replace the erroneous frames, the frames are easily audible noise, making the audio stream full of annoying pops. This is clearly the objective, as listeners will not want to listen to music with annoying pops.

The error rates in such schemes are significant. As noted earlier, E32 errors are generally considered uncorrectable and discs we tested typically had zero instances of them. A few breathtaking examples of high error rates stand out, including Natalie Imbruglia's *White Lilies Island*, which had over 32,000 separate E32 errors on each of the copies of the disc that we tested at double-speed. Figure 3 shows the frequency of E32 errors of that disc from the OH3 set.

Also of interest is how the E31 errors on a brand new disc compare with those that we introduced by scratching a disc with a metal key. Figure 4 shows the results.

4.2 Disc Geometry

The Compact Disc Digital Audio standard establishes boundaries for geometry of discs. In general, analysis of the geometry is most useful to look into the reason behind errors that are either high frequent or high impact.

Examination of the geometry of discs with high error rates suggests that the errors are not due to errors in the disc geometry, that is, the errors are encoded into the disc. We should note that our measurements of geometry were taken during playback on the QA-201 unit, which means that our test would measure not only the disc but the playback device as well. Since we don't have an electron microscope to take these measurements without also measuring the playback device, we show the results of the disc geometry analysis of our test disc provided by Clover Systems.

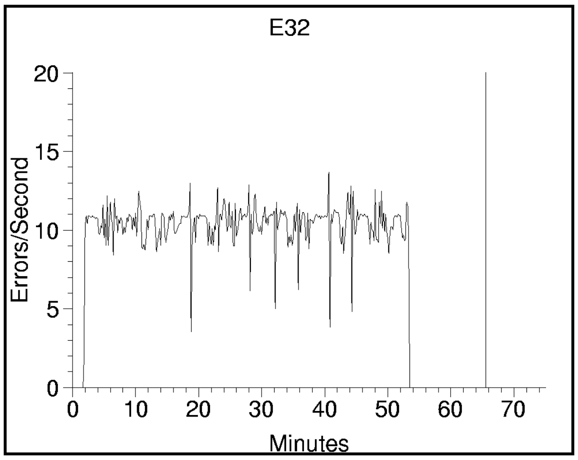


Figure 3: Instances of E32 (Uncorrectable) Errors on Natalie Imbruglia *White Lilies Island*

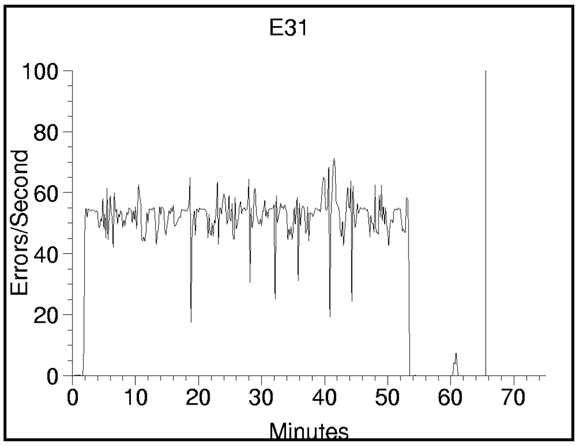
Figure 5 shows a pit and land geometry histogram for the disc *White Lilies Island*. Note that these measurements much more closely resemble the known-good test disc, qualification disc 6E from Clover Systems, shown in Figure 6. The same analysis on Philips test disc SBC444A (which has two built-in defects: missing data in the disc encoding and black spots on the disc surface) shows a very different result (Figure 7).[2]

4.3 Errors in Table of Contents

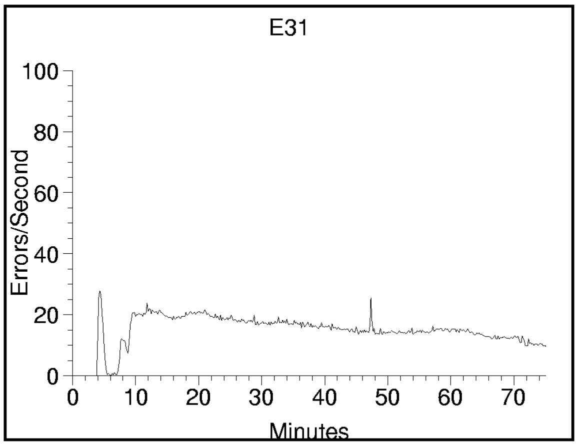
In addition to the audio waveforms, the Compact Disc Digital Audio standard requires a Table of Contents (TOC) that identifies the number of tracks on the disc,

[1] It is probably worth noting that some listeners and musicians who complain about the quality MP3-encoded music, so that the matter of impact is at least a subject for debate. Study of the merits these arguments is beyond the present scope.

[2] These graphs show the lengths of each pit and land in the disc and how they are distributed. There are nine discrete "effect lengths" in the Eight-to-Fourteen Modulation (EFM) used in encoding digital audio to compact disc, and each line in these histograms shows a different effect length. A disc with no deviation from the mean will show nine straight lines; a disc with high deviation from the mean will show wider distribution in these bell curves.



Brand New *White Lilies Island*



Disc Scratched with Metal Key

Figure 4: Comparison of E31 (Correctable) Errors: Brand New Disc vs. Intentionally Scratched

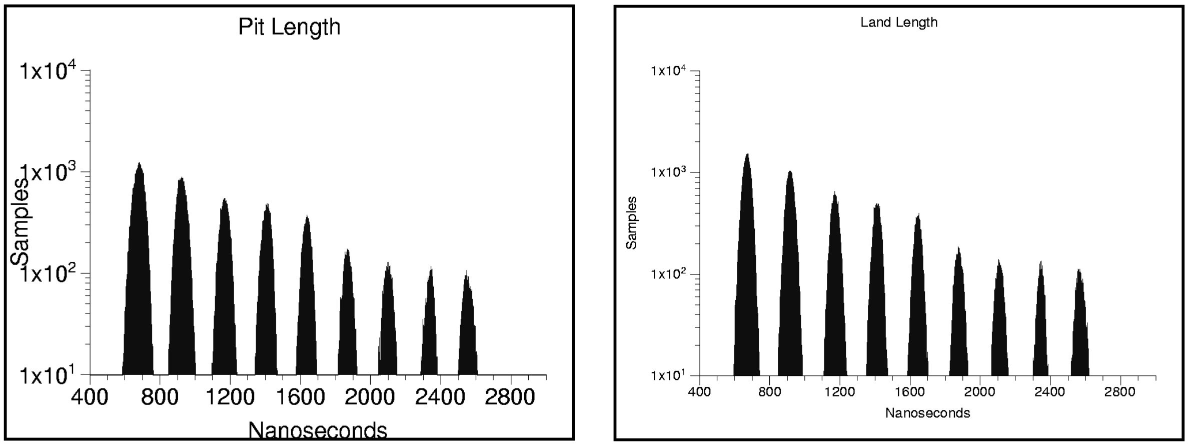


Figure 5: Pit and Land Geometry for *White Lilies Island*

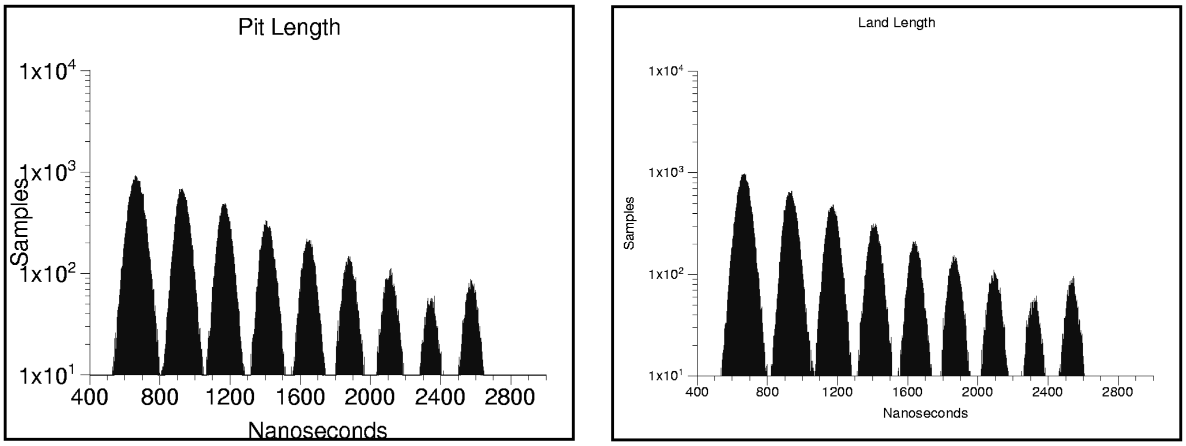


Figure 6: Pit and Land Geometry for Clover Qualification Disc 6E

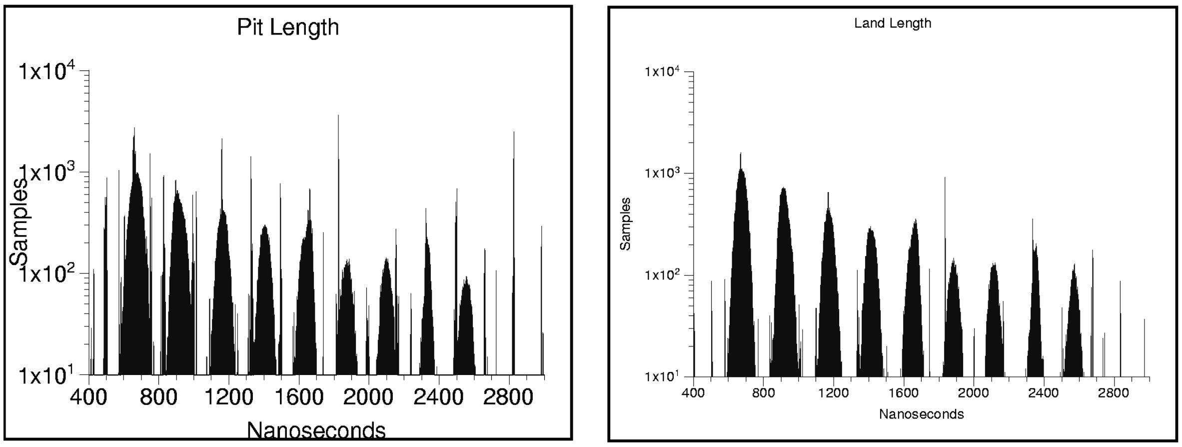


Figure 7: Pit and Land Geometry for Philips (Bad) Test Disc SBC444A

along with the points at which each track will start and stop. Our results seem to confirm what has been previously reported. [3]

CD players that display the total disc time and number of tracks will typically gather this information by reading the table of contents. This can also aid in specific track selection. Cheaper players can ignore the table of contents, relying solely on P-channel data to allow the user to advance from one track to another. More sophisticated players, such as computers, can use the table of contents, but can also or instead use the additional Q-channel control data.

An example of a disc with bad TOC data is *More Fast and the Furious*. Compact Discs have two modes of determining TOC data, known as Mode 0 and Mode 2. Note that in the case of the *More Fast and the Furious*, the data disagree. In the *Counting Crows* disc that we pulled from a personal collection, the data agree.

We are continuing analysis on a larger data set to determine just what the impact of the bad TOC data is and whether Mode 0 and Mode 2 TOC difference are a side-effect of a Multisession CD.

4.4 Software Errors

It was widely reported in 2002 that large numbers of Enhanced CD titles created usability problems in computers. After testing numerous titles with common software used to rip CD audio, we saw a common pattern where discs would rip properly—until the end of the last track, at which point the CD-ROM drive would stop and the operating system would report an I/O error or some other error related to the media or device. In fact, this is a problem in the software, which incorrectly assumed that the entire disc was Compact Disc Digital Audio. The software would read past the last audio track and instead of stopping, would continue on to the data session. The I/O error comes from the software trying to read the data section (which is encoded with 2048-byte blocks on an ISO 9660 filesystem)[4] as CD-DA audio (which is encoded with 2352-byte blocks). Software used to rip audio from compact discs should be able to detect the proper boundaries for each track by reading the disc's table of contents (assuming that it is properly encoded). Of course, on discs where the TOC data are incorrect, such attempts will be frustrated.

4.5 Privacy Implications

The use of computer technology for playback of digital media carries a separate set of risks, largely in the form of side-effects of enabling content playback to require interaction with systems outside of the user's control—such as Web sites put in place by the producers. We discussed these issues in the context of DVDs and outlined some specific problems in the *PC Friendly* system in early 2002. [2]

Determining the privacy risks associated with Enhanced CDs is an area for additional study.

5 The Future of Digital Media

Clearly, a significant battle over the future of digital media lies ahead. On one hand, producers of content want to control how such content can be copied, while users expect to be able to use their computers as they see fit.

We see no feasible way to prevent data from being freely copied from one source to another. After early debacles in copy protection (perhaps most famously through the Secure Digital Music Initiative) [1], the industry apparently now agrees with this view, shifting away from copy protection and toward control of playback mechanisms.

We emphasize that producers used to label their discs as "Compact Disc Digital Audio," a standard controlled by Philips to ensure compatibility among manufacturers' equipment, but now label their discs to advertise compliance with a voluntary standard of their own making (through their industry association). This move puts both content production and specifications for proper playback into the hands of the same parties.

In a broader context, we see these technical mechanisms being introduced to apparently familiar media (discs that look and largely work like Compact Disc Digital Audio) in addition to new formats (such as DVD) that bring with them their own set of protections that producers (incorrectly) claim are to stifle copy protection. Going as far as using cryptography to limit access to data that consumers have legitimately licensed, such producers have organized themselves into a cartel to use their position as the producers of content to estab-

Track	*Start*	*Length*	Type
1/1	16777365 [144:18.15]	-16758565 [116:249.216]	Audio POSITION
2/1	18801 [04:10.51]	15132 [03:21.57]	Audio POSITION
3/1	33934 [07:32.34]	13206 [02:56.06]	Audio POSITION
4/1	47141 [10:28.41]	7907 [01:45.32]	Audio POSITION
5/1	55049 [12:13.74]	15636 [03:28.36]	Audio POSITION
6/1	70686 [15:42.36]	14572 [03:14.22]	Audio POSITION
7/1	85259 [18:56.59]	19131 [04:15.06]	Audio POSITION
8/1	104391 [23:11.66]	17257 [03:50.07]	Audio POSITION
9/1	121649 [27:01.74]	14911 [03:18.61]	Audio POSITION
10/1	136561 [30:20.61]	18999 [04:13.24]	Audio POSITION
11/1	155561 [34:34.11]	16342 [03:37.67]	Audio POSITION
12/1	171904 [38:12.04]	13746 [03:03.21]	Audio POSITION
13/1	185651 [41:15.26]	15284 [03:23.59]	Audio POSITION
14/1	200936 [44:39.11]	41079 [09:07.54]	Audio POSITION
15/1	242016 [53:46.66]	90984 [20:13.09]	Data POSITION

Table 4: Mode 0 TOC, *More Fast and the Furious*

Track	*Start*	*Length*	*Type*
1/1	149 [00:01.74]	18651 [04:08.51]	Audio POSITION
2/1	18801 [04:10.51]	15132 [03:21.57]	Audio POSITION
3/1	33934 [07:32.34]	13206 [02:56.06]	Audio POSITION
4/1	47141 [10:28.41]	7907 [01:45.32]	Audio POSITION
5/1	55049 [12:13.74]	15636 [03:28.36]	Audio POSITION
6/1	70686 [15:42.36]	14572 [03:14.22]	Audio POSITION
7/1	85259 [18:56.59]	19131 [04:15.06]	Audio POSITION
8/1	104391 [23:11.66]	17257 [03:50.07]	Audio POSITION
9/1	121649 [27:01.74]	14911 [03:18.61]	Audio POSITION
10/1	136561 [30:20.61]	18999 [04:13.24]	Audio POSITION
11/1	155561 [34:34.11]	16342 [03:37.67]	Audio POSITION
12/1	171904 [38:12.04]	13746 [03:03.21]	Audio POSITION
13/1	185651 [41:15.26]	15284 [03:23.59]	Audio POSITION
14/1	200936 [44:39.11]	41079 [09:07.54]	Audio POSITION
15/2	242016 [53:46.66]	90984 [20:13.09]	Data POSITION

Table 5: Mode 2 TOC, *More Fast and the Furious*

Track	*Start*	*Length*	*Type*
1/1	150 [00:02.00]	24841 [05:31.16]	Audio POSITION
2/1	24992 [05:33.17]	16454 [03:39.29]	Audio POSITION
3/1	41447 [09:12.47]	20437 [04:32.37]	Audio POSITION
4/1	61885 [13:45.10]	22566 [05:00.66]	Audio POSITION
5/1	84452 [18:46.02]	20337 [04:31.12]	Audio POSITION
6/1	104790 [23:17.15]	23604 [05:14.54]	Audio POSITION
7/1	128395 [28:31.70]	19176 [04:15.51]	Audio POSITION
8/1	147572 [32:47.47]	20212 [04:29.37]	Audio POSITION
9/1	167785 [37:17.10]	18229 [04:03.04]	Audio POSITION
10/1	186015 [41:20.15]	21119 [04:41.44]	Audio POSITION
11/1	207135 [46:01.60]	25935 [05:45.60]	Audio POSITION

Table 6: Mode 0 TOC, *Counting Crows*

Track	*Start*	*Length*	*Type*
1/1	150 [00:02.00]	24841 [05:31.16]	Audio POSITION
2/1	24992 [05:33.17]	16454 [03:39.29]	Audio POSITION
3/1	41447 [09:12.47]	20437 [04:32.37]	Audio POSITION
4/1	61885 [13:45.10]	22566 [05:00.66]	Audio POSITION
5/1	84452 [18:46.02]	20337 [04:31.12]	Audio POSITION
6/1	104790 [23:17.15]	23604 [05:14.54]	Audio POSITION
7/1	128395 [28:31.70]	19176 [04:15.51]	Audio POSITION
8/1	147572 [32:47.47]	20212 [04:29.37]	Audio POSITION
9/1	167785 [37:17.10]	18229 [04:03.04]	Audio POSITION
10/1	186015 [41:20.15]	21119 [04:41.44]	Audio POSITION
11/1	207135 [46:01.60]	25935 [05:45.60]	Audio POSITION

Table 7: Mode 2 TOC, *Counting Crows*

lish, in effect, a monopoly on playback devices. This year, producers have made such a move, even asserting control over their customers' computers, requiring that their software be used for playback and other uses. These not only impeded normal and legal uses of the media, but opened the way for vulnerabilities in system stability and security. [7]

6 Acknowledgments

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