Chapter 24

Copyright and DRM

Be very glad that your PC is insecure – it means that after you buy it, you can break into it and install whatever software you want. What YOU want, not what Sony or Warner or AOL wants.
– JOHN GILMORE

24.1 Introduction

Copyright has been among the highly contentious issues of the digital age, and drove the development of *digital rights management* (DRM). The big fight was between Hollywood and the tech industry in the 1990s and 2000s; by 2010 it had essentially been resolved. We won; power in the music and film industry passed from firms like EMI and Universal to firms like Apple, Spotify, Amazon and Netflix, while Amazon cornered the market in books – first physically and then with e-books. Technically, the world moved from enjoying music and video from local media such as CDs and DVDs (which many people used to share) and satellite broadcast TV (which some people used to hack), to broadband streaming services where subscription management is fairly straightforward. I thought seriously about dropping this chapter from the third edition and just referring you to the second edition chapter online, as there's not a lot more to say technically. On reflection I decided to edit it to give the context as seen from 2020. Just as the multilevel secure systems I describe in chapter 9 are largely obsolete but drove the development of military computer security and influenced today's security landscape in many subtle ways, so also the copyright wars left their mark. DRM is still used: in the Fairplay system on your iPhone to make it harder to copy songs, and in html5 in your browser to make it harder for you to copy Netflix videos. Very similar techniques are used in gaming platforms to make it harder for players to use aimbots, in protecting user data on cloud platforms, and in mobile phone security where *Runtime Application Self-Protection* (RASP) is used to defend banking and other apps against malware that roots the phone. My final reason to spare this chapter is that the copyright wars became part of our shared security culture, and even if you're too young to have taken part, you may occasionally find it helpful to understand what we greybeards are blethering on about.

At the political level, the control of information has been near the centre of government concerns since before William Tyndale (one of the founders of the Cambridge University Press) was burned at the stake for printing the Bible in English. The sensitivity continued through the establishment of modern copyright law starting with the Statute of Anne in 1709, through eighteenth-century battles over press censorship, to the Enlightenment and the framing of the US Constitution. The link between copyright and censorship is obscured by technology from time to time, but has a habit of reappearing. Copyright mechanisms exist to keep information out of the hands of people who haven't paid for it, while censors keep information out of the hands of people who aren't trusted with it. Where ISPs are compelled to install filters that prevent their customers from downloading copyrighted material, these filters can also be used to block seditious material too.

Over the twentieth century, the great wealth accruing to the owners of literary copyright, films and music created a powerful interest in control. As the Internet took off, the music and film industries feared losing sales to digital copying, and lobbied for sweetheart laws – the DMCA in America in 1998, and a series of IP Directives in Europe – that give special legal protection to mechanisms that enforce copyright. These laws have since been used and abused for all sorts of other purposes, from taking down phishing websites to stopping people from refilling printer cartridges and even from repairing broken devices.

The ostensible target of these laws was the DRM used from the 1990s in products such as Windows Media Player, and since 2017 in browsers compliant with HTML5, to control the copying of music and videos. The basic idea in DRM is to make a file uncopiable by encrypting it, and then providing separately a 'license' which is the key to the media file encrypted using a key unique to the user, plus some statements in a 'rights management language' about what the user can do with the content. The app that renders the media content is trusted to abide by these. I'll also give a quick tour of the history and describe some interesting variants such as satellite TV encryption systems, copyright marking and traitor tracing. DRM is less relevant now than in 2008 when the second edition of this book came out, but there are still some applications, which I'll describe later.

Some serious policy issues are mixed up in all this. It's hard to make DRM compatible with open-source software unless you have either trustworthy hardware such as enclaves or TPMs, or closed-source sandboxes that are patched as soon as they are reverse engineered. The computer industry resisted DRM but Hollywood and the music industry forced us to introduce it, saying that without it they'd be ruined. We warned them that DRM would ruin them, and they didn't listen. Music is no longer run by firms like Universal and EMI but by firms like Apple and Amazon – and the move to streaming let new firms like Spotify join the party. DRM introduced serious privacy issues, though, which have not gone away with streaming. Do you really want a license management server in Redmond or a streaming service in Cupertino to know every music track you've ever listened to, and every movie you've ever watched?

24.2 Copyright

The protection of copyright has for years been an obsession of the film, music and book publishing industries. There were long and acrimonious disputes in many countries about whether blank audiocasettes, and then videocassettes, should be subjected to a tax whose proceeds would be distributed to copyright owners. Going back to the nineteenth century, there was alarm that the invention of photography would destroy the book publishing trade; the eighteenth saw book publishers trying to close down public lending libraries, until they realised they were creating mass literacy and driving sales; while in the sixteenth, the invention of movable type printing was considered subversive by most of the powers of the day, from princes and bishops to craft guilds.

We'll come back to these historical examples later. But I'm going to start by looking at software protection – as most of the copyright issues that led to DRM played out in the PC and games software markets from the 1980s.

24.2.1 Software

Software for early computers was given away free by the hardware vendors or by users who'd written it. IBM even set up a scheme in the 1960s whereby its users could share programs they'd written. (Most business programs were too specialised, too poorly documented, or just too hard to adapt. But software used in research was widely shared.) So protecting software copyright was not an issue. Almost all organizations that owned computers were large and respectable; their software tended to require skilled maintenance. There were also computer bureau services – the forerunner of today's cloud computing – where the owner of a mainframe who used it to work out their own payroll would offer this as a service to other firms. There, you bought the service, not the software. The hardware costs were the dominant factor.

When minicomputers arrived in the 1960's, software costs became significant. Hardware vendors started to charge extra for their operating system, and third-party system houses sprang up. To begin with, they mostly sold you a complete bespoke system – hardware, software and maintenance – so piracy was still not much of an issue. By the mid-1970's, some of them had turned bespoke systems into packages: software originally written for one bakery would be parametrized and sold to many bakeries. The most common copyright dispute in those days was when a programmer left your company to join a competitor, and their code suddenly acquired a number of your features; the question then was whether he'd taken code with him, or reimplemented it.

One way to resolve such a problem is to look at *software birthmarks* – features of how a particular implementation was done. For example, litigation over whether people had copied software from the ROM of the early IBM PCs turned on the order in which registers are pushed and popped, as the software had been written in assembler. This merged with the field of *stylometry* in which humanities scholars try to attribute authorship by analysis of writing styles[1]. More

[1]The great cryptanalyst William Friedman and his wife Elizabeth were once hired by an eccentric millionaire to figure out whether Bacon wrote Shakespeare. They concluded that he

recently, the natural-language processing community has written plagiarism detection tools, which typically recognise a passage of text by indexing it according to the least common words that appear in it [857]; by the 1990s this had led to tools that try to identify malware authors from their coding style [1069]. Code stylometry is still an active area of research [360].

With time, people invented lots of useful things to do with software. So a firm that had bought a minicomputer for stock control (or contracted for time on a bureau service) might be tempted to run a statistical program as well to prepare management reports. Meanwhile, the installed base of machines got large enough for software sharing to happen more than just occasionally. So some system houses started to design enforcement mechanisms. A common one was to check the processor serial number; another was the *time bomb*. When I worked in 1981 for a company selling retail stock control systems, we caused a message to come up every few months saying something like "Fault no. WXYZ – please call technical support". WXYZ was an encrypted version of the license serial number, and if the caller claimed to be from that customer we'd give them a password to re-enable the system for the next few months. (If not, we'd send round a sales person.) This mechanism could have been defeated easily if the 'customer' understood it, but in practice it worked fine: most of the time it was a low-level clerk who got the fault message and called our office.

Software copyright infringement really started to become an issue when the arrival of microcomputers in the late 1970's and early 80's created a mass market, and software houses started to ship products that didn't need technical support to install and run. Initial responses varied. There was a famous open letter from Bill Gates in 1976, a year after Microsoft was founded, in which he complained that less than 10% of all microcomputer users had paid them for BASIC [704]. "Who cares if the people who worked on it get paid?" he asked. "Is this fair?" His letter concluded: "Nothing would please me more than being able to hire ten programmers and deluge the hobby market with good software."

Appeals to fair play only got so far, and the industry next tackled the main difference between minis and the early micros – the latter had no processor serial numbers. There were three general approaches tried: to add uniqueness on to the machine, to create uniqueness in it, or to use whatever uniqueness happened to exist already by chance.

1. The standard way to add hardware uniqueness was a *dongle* – a device attached to the PC which could be interrogated by the software. The simplest just had a serial number; the most common executed a simple challenge-response protocol; while some top-end devices actually performed some critical part of the computation.

2. A very common strategy in the early days was for the software to install itself on a PC's hard disk in a way that resisted naive copying. For example, a sector of the hard disk would be marked as bad, and a critical part of the code or data written there. Now if the product were copied from the hard disk using the standard utilities, the bad sector wouldn't be copied and the copy wouldn't work. A variant on the same theme was to require

hadn't. [974].

the presence of a master diskette which had been customized in some way, such as by formatting it in a strange way or even burning holes in it with a laser. In general, though, a distinction should be drawn between protecting the copy and protecting the master; it's often a requirement that people should be able to make copies for backup if they wish, but not to make copies of the copies (this is called *copy generation control*).

3. 1988 saw the arrival of the *license server*, basically a machine programmed to act as a dongle shared by all the machines on a company network, which supported more complex business models such as enabling a company to buy the right to run a program on up to 20 machines at once, and enabling multiple software companies to license their products via the same license server.

4. A product I worked on in 1989 fingerprinted the PC – what extension cards were present, how much memory, what type of printer – and if this configuration changed too radically, it would ask the user to phone the helpline. It's quite surprising how many unique identifiers there are in the average PC; ethernet addresses and serial numbers of disk controllers are only the more obvious ones. Provided you have some means of dealing with upgrades, you can tie software to a given machine fingerprint.

A generic attack that works against most of these defenses is to go through the software with a debugger and remove all the calls made to the copy protection routines. Many hobbyists did this for sport, and competed to put unprotected versions of software products online as soon as possible after their launch. Even people with licensed copies of the software often got hold of unprotected versions as they were easier to back up and often more reliable generally. You can stop this by having critical code somewhere uncopiable (such as in a dongle, a license server, or nowadays in the cloud) but this arms race taught everyone that if you don't do something like that then kids with debuggers will always break your scheme eventually. It's one reason why closed platforms, like games consoles and the iPhone, only run signed code.

The vendors also used psychological techniques.

- The installation routine for many business programs would embed the registered user's name and company on the screen, for example, in the toolbar. This wouldn't stop a pirate distributing copies registered in a false name, but it will discourage legitimate users from giving casual copies to colleagues. To this day, when I download papers from many academic journals, my university's name and a serial number are visible in the pdf. These are examples of *copyright marking* which I'll discuss in more detail later.
- Industry people delighted in telling tales of organizations that had come unstuck when they failed to get a critical upgrade they hadn't paid for.
- If early Microsoft software (Multiplan, Word or Chart) thought you were running it under a debugger, it would put up the message 'The tree of evil bears bitter fruit. Now trashing program disk.' It would then seek to track zero on the floppy disk and go 'rrnt, rrnt, rrnt'.

In the late-1980s, the market split. The games market moved to hardware protection, and ended up dominated by consoles with closed architectures whose software was sold in proprietary cartridges. As consumers are more sensitive about the sticker price of a product than about its total cost of ownership, it makes sense to subsidise the console out of later sales of software (a strategy then adopted by printer makers who subsidise the printers from the ink cartridges). This strategy led to *accessory control* in which hardware protection was used to prevent competitors selling software or other add-ons unless they had paid a royalty.

Business software vendors moved from dongles to license servers for high-value products such as the CAD software used to design everything from chips to ships. Technical support is often critical for such products, so they may be sold as a bundle of software and service. But vendors generally stopped trying to protect mass-market products using technical means, for several reasons.

- Unless you're prepared to spend money on dongle hardware to execute some of your critical code, the mechanisms in mass-market software will be defeated by people for whom it's an intellectual challenge, and unprotected code will be published anonymously.
- Protection was a nuisance. Multiple dongles get in the way or interfere with each other. Software protection techniques get in the way of backup and recovery; they also cause software from different vendors to be incompatible and in some cases unable to reside on the same machine. (The difficulty of doing this right is one reason why so many of the firms who use license management use Flexlm.)
- Many vendors preferred not to have to worry about whether the software was licensed to the user (in which case he could migrate it to a new machine) or to the machine (in which case he could sell the computer second-hand with the software installed). As both practices were common, mechanisms that made one or the other very much harder caused problems. Mechanisms that could deal with both (such as dongles and license servers) tended to be expensive.
- The arrival of computer viruses forced corporate customers to invest in software hygiene, so casual copying couldn't be condoned so easily. Within a few years, antivirus programs made life much harder for copy protection mechanisms in any case, as non-standard operating system usage tended to set off alarms.
- There was not much money to be made out of harassing personal users as they often made only casual use of the product and would throw it away rather than pay.
- A certain level of sharing was good for business. People who got a pirate copy of a tool and liked it would often buy a regular copy, or persuade their employer to buy one. In 1998 Bill Gates even said, "Although about three million computers get sold every year in China, people don't pay for the software. Someday they will, though. And as long as they're going to steal it, we want them to steal ours. They'll get sort of addicted, and then we'll somehow figure out how to collect sometime in the next decade" [737].

- Competition led to falling costs which made piracy less attractive. In the case of tools, for example, Borland shook up the industry with its launch of Turbo Pascal in 1983. Before then a typical language compiler cost about \$500 and came with such poor documentation that you had to spend a further \$50 on a book to tell you how to use it. Borland's product cost \$49.95, was technically superior to Microsoft's, and came with a manual that was just as good as a third party product. (So, like many other people, once I'd heard of it, borrowed a copy from a friend, tried it and liked it, I went out and bought it.) 'Pile it high and sell it cheap' simply proved to be a more profitable business model.

The industry then turned to the law. Software is mostly protected by copyright law; when you write software (or a book, or a tune) copyright comes into existence automatically and you have the right to sue people for damages if they make copies without your permission. The details vary by country but copyright infringement tends to be a crime only if done at commercial scale. So copyright owners can send unpleasant letters to individuals and small businesses, but actually suing them for a few dollars or pounds or euros in the small claims court is uneconomic. Against large-scale users, though, copyright enforcement can be worthwhile. In fact, when IBM separated its hardware and software businesses in 1969 – following a lawsuit from the US government which claimed that bundling software with hardware entrenched their market dominance – they took a strategic decision not to use any technical copyright enforcement mechanisms as they would be onerous to customers and not effective against clever thieves, so they'd rely on the law instead [1730].

In 1988, Microsoft led the industry in IBM's footsteps, and established trade organizations (such as the Business Software Alliance in the USA) that brought high-profile prosecutions of large companies that had been condoning widespread use of unlicensed software. This was followed up by harassing medium and even small businesses with threatening letters demanding details of the company's policy on enforcing copyright – basically demanding they sign up for an approved software audit schemes or risk a raid by an enforcement squad.

The industry discovered that the law not only provides tools for enforcement, but sets limits too. In 1993, a software company director in Scunthorpe, England, received a criminal conviction under Britain's Computer Misuse Act for 'making an unauthorized modification' to a system. Their customers had to enter unlock codes regularly into his software or it froze, denying access to data. But when he used this mechanism to enforce payment of a disputed invoice, the court decided he'd gone too far, and he ended up with a criminal record [443].

Thanks to the ubiquity of Office, Microsoft had by then become a tax on the corporate sector, making most of its revenue from customers with over 25,000 licenses. In addition to Office, it was selling many high-value products for network management and other tasks, so like the CAD firms it turned to license servers. Although these could still be defeated by disassembling the application code, this got harder as code became larger, and was unattractive to large firms after a few of them had been sued. Then the very idea of running on unlicensed software became crazy when Patch Tuesday arrived in 2003. With personal software, the emphasis shifted to online registration: you'd design your product to get customers to interact with your web site – whether to download the tunes, latest exchange rates or security updates. Large-scale commercial counterfeiting can then detected by monitoring product serial numbers registered online[2].

I wrote in the second edition of this book in 2008: "software-as-a-service may be the ultimate copyright protection or DRM for software (or any other content that can live online): you can't buy it, freeze the version you're running, or use it offline. You may also get to control all your customers' data too, giving you impressive lockin". That is precisely the model to which the software industry has converged since the early 2010s takes this to its logical conclusion. Putting some or all of the functionality in the cloud can give real advantages in terms of cost and reliability, which I will discuss in section 27.5.5. Software is then sold by subscription and the issue of copy protection goes away.

24.2.2 Free software, free culture?

In the old days, software was shared and this continued to be the case among academics and other research scientists, who evolved many communities of practice within which software was shared freely and adapted by successive contributors. This continued to support the dominant platforms of the time, which initially meant IBM. During the 1970s, for example, the UK government pushed British academics to buy ICL computers; ICL was Britain's champion, having been set up in the 1960s when the government nationalised the computer industry to 'save' it from IBM. However, we academics wanted IBM mainframes as other academics worldwide had written software that ran on their hardware, and even although most was written in high-level languages like FORTRAN, porting it was a hassle. The arrival of home computers in the 1970s and the PC in 1980 further developed communities of amateur developers who shared software.

In 1983 IBM stopped supplying the source code for its products, introducing a policy of 'object code only'. This made it a lot harder to understand the platforms and tools on which we relied and precipitated pushback on a number of fronts. Richard Stallman, an engineer at MIT, announced the GNU project to build a free operating system. Two years later he helped found the Free Software Foundation, which promoted the idea of free software as being 'free as in free speech, not as in free beer'. Free software means that users should be able to run it for any purpose, study how it works and change it, and redistribute it – including improved or modified versions. This comes in many flavours. The FSF promoted the GNU General Public License (GPL) which has the viral property that anyone adapting GPL licensed software must make their adaptation publicly available, including the source code, under the same license – a property also known as 'copyleft'. In 1988, the University of California released the Berkeley distribution of Unix under the less restrictive BSD license that simply allows anyone to use the software for any purpose.

Such licensing arrangements are necessary because otherwise an operating

[2]Once they got product registration sorted out, Microsoft found that a third of the copies of Office sold in Germany were counterfeit, and traced them to a small factory a few miles up the road from us in Cambridge. Almost all the factory's staff were unaware of the scam – they believed the company was a bona fide Microsoft supplier. They were proud of it and their sales staff used it to try to get disk duplication business from other software vendors.

system that had been written by 500 different people over 20 years would contain code that was their copyright, and so any of them could go to court to exercise their right to prevent some third party from using it. Proprietary software vendors can get the engineers they employ to assign the copyright to them, but what about projects maintained by volunteers? Open licenses help avoid thickets of conflicting claims.

There was much argument through the 1990s about their respective merits, but both approaches are in wide use. Linux was first released in 1991 under the GPL, while Berkeley Unix spawned FreeBSD and other variants which are available under the BSD license. As we noted in the chapter on Access Controls, Linux was the platform on which Android was built, while FreeBSD was evolved into OSX and iOS. Other free software licenses were developed for Apache and in other communities, and public licenses spread quickly from software to other creative activities: for example, a variant of BSD was adapted for Wikipedia.

Software and culture both involve the adaptive and cumulative contributions of many individuals. Traditional musicians sometimes compose new tunes but more often change existing ones; even new compositions draw on phrases from the existing vocabulary. DJs rip tracks from others and mash them together into new compositions. Novelists reuse old storylines and character stereotypes, while comedians recycle old jokes. The law doesn't always deal with this very well as it tends to be written by large corporate interests rather than by communities. So music companies would press musicians to write entirely new tunes with clean copyrights rather than following tradition and adapting the best tunes of the older players.

Academia is also a place where we build on each others' work, and has the further twist that we get our recognition from the number of people who use our work rather than the number of people who pay for it. Mathematicians become famous if lots of other mathematicians use their theorems in other results, and computer scientists get recognition if lots of people use our software. This creates real tensions with publishers. Indeed, starting in the 1970s, many computer scientists made both our code and our publications available freely online, using ftp servers and later, once they were invented, web pages. We tended to ignore the copyright agreements we had to sign with academic journals to get our papers published âĂŞ- or if we were careful we crossed out the 'exclusive' clause in the agreements, which at the time were paper forms that the publishers never bothered to check.

1994 saw a couple of publications with real impact. Andrew Odlyzko calculated that the U.S. government spent about \$100M a year doing mathematics (by paying professors' salaries and the stipends of grad students) and a further \$100M a year marketing mathematics (being the money that was spent in journals and conferences, plus the unpaid labour that mathematicians put in to enable the journal publishers to made their profits). If publication went fully online and all papers were available for all to read, perhaps the amount spent in actual mathematics could be increased? [**?**]. A quarter of a century and many tussles later, most government and charitable funders insist that the research they pay for is made available to all (though the journals have survived by imposing page charges on authors).

The second, and better-known, was a paper by EFF founder John Perry Barlow, who was also a lyricist for the Grateful Dead. He pointed out that as the marginal cost of copying is zero with digital technology, 'information wants to be free' (which he ascribed to Stewart Brand). Both the physical containers of ideas (books, CDs) were vanishing, as was jurisdiction, as the Internet enabled people to swap files across national boundaries. He warned against corporate legal departments trying to protect by force what could no longer be protected by practical efficiency or general social consent, and about the USA writing copyright compliance into trade treaties: "Ideally, laws ratify already developed social consensus." He called for firms to develop business models that would work with the grain of the information age. His band, the Grateful Dead, let people tape their songs from the 1970s, and became one of the biggest stadium draws. He suggested that other industries explore models of live performance and service rather than selling bundles of bits [167].

There was vigorous debate and innovation on the copyright front during the dotcom boom of the later 1990s. Quite apart from arguments about books, journals, music and films – to which we will return shortly – there was a growing realisation of the need for shared infrastructure and tools. Quite apart from the many common components of the communications infrastructure, such as BGP, DNS and SMTP, whose early implementations had often been written at taxpayer expense and published, firms often found they needed to add to the commons. For example, after Netscape made available the first popular web browser in 1994, Microsoft killed them by giving away its own browser, Internet Explorer, free with Windows, and tried to create a monopoly at the server side with a product then called Internet Information Server which it launched in 1995. Other firms who were racing to establish a presence in the growing e-commerce industry were so alarmed at the prospect of Microsoft extracting all the value that they set up Apache, which became the leading web server the following year. This may have been one of the most important pieces of software ever written, as it meant that Microsoft could not control both ends of the link in the early days of the web, so they could not turn it into something proprietary from which they could extract rent. As a result, the web remained open for many years, and it was possible for companies such as Google and Facebook to get going. (We may now have a policy struggle with them instead, but a lot of innovation happened meantime.)

Moving from the policy to the mechanics, when software engineers – or book authors or musicians – place works in the public domain, we have a wide range of conditions we may want to attach. Some writers are happy for their work to be used by anyone, so opt for a BSD-style license; others want their work to remain in the commons rather than being incorporated into closed proprietary products, so prefer the GPL; academics generally want our stuff to be used provided we're acknowledged as the creators. In 2001 Larry Lessig founded the *Creative Commons* (CC) to bring some order to this; it makes available a set of licenses which parametrise this and enable you to specify how your work may be used. For example, you can specify whether a user can share your work with others; whether commercial uses are allowed; whether they must give you proper attribution; whether they can adapt and build on it, and if so whether they have to distribute their contributions under the same license as the original. These licenses are now used widely outside of software. In fact, most of my academic papers are available under CC licenses, and my agreement with the publishers of this book specifies that I may make all the chapters available freely online 42 months after the manuscript is sent for publication. I appreciate it if you pay for the book, but I want it to be available to everybody – even if the latest versions go online after a delay.

A critical development came in 1996 with section 230 of the US Communications Decency Act (CDA). This let the online service providers off the hook on copyright law by stating that 'No provider or user of an interactive computer service shall be treated as the publisher or speaker of any information provided by another information content provider' – making firms like Google and Facebook possible, and leaving the corporate lawyers to chase individual file sharers. The service firms are supposed to take down infringing content when they're notified of it; in practice, the boundaries are hard to police, and the incentives are perverse (s230 shelters them when they run ads for counterfeiters [1770]). We'll return to this later, in this chapter and in Chapter 25.

So there are many alternative business models, both for software and for other products of human creativity. One is *freemium*: you give away a basic version of the product, and sell a premium version. (Even once this book is free online as pdfs, you'll have to pay money for a printed book.) Another to give your software away free, and make your money from selling services or from advertising. You can combine them: get customers addicted to your free product, and then sell them more storage or an ad-free experience. The success of these models in software – with the Linux industry living from consulting and Google from ads, suggested a similar approach to online content. In the second edition, I suggested that "the solution for Hollywood's problem lies in a change of business model." Since then we have Spotify and YouTube; we even have people making large incomes as Facebook influencers.

I will return to copyright policy later in section 24.5, but let's now take a quick historical tour at the world of protecting media content.

24.2.3 Books and music

In 1800, there were only 80,000 frequent readers in England; most of the books up till then were serious philosophical or theological tomes. After the invention of the novel, a mass market appeared for books, and circulating libraries sprung up to service it. The educated classes were appalled, and printers were frightened that the libraries would deprive them of sales. But the libraries so whetted people's appetite for books that the number of readers grew to 5,000,000 by 1850. Sales of books soared as people bought books they'd first borrowed from a library. The library movement turned out to have been the printers' greatest ally and helped create a whole new market for mass-market books [1662].

People have been copying music much longer than software. Paganini was so worried that people would copy his violin concertos that he distributed the scores himself to the orchestra just before rehearsals and performances, and collected them again afterwards. (As a result, many of his works were lost to posterity.)

Copyright *collecting societies* were established from the mid-19th century, starting in Paris; composers who were members would charge venues or bands a fee for performing their compositions. In many countries these have become monopolies backed by law; to perform at our university's concert hall, you have to pay the Performing Rights Society a levy. You can submit them a playlist, and if you play all your own compositions then some of the money may find its way back to you eventually. Many tunes are *orphan works* in that their composers' heirs are unknown, so the societies can either keep the money or share it among their known composers. The free culture movement and the pirate parties advocate restricting or abolishing copyright in order to erase such injustices; but while they've won a few parliamentary seats in some European countries, they always seem to be outgunned by the copyright lobbyists on the world stage (an issue to which I'll return later in section 24.5.1).

When the cassette recorder came along in the 1960's, the record industry lobbied for (and in some countries got) a tax on audiocassettes, to be distributed to copyright holders. Technical measures were also tried. The Beatles' record Sergeant Pepper contained a 20KHz spoiler tone that should in theory have combined with the 21KHz bias frequency of the tape to produce a 1KHz whistle that would spoil the sound. In practice it didn't work, as many record players didn't have the bandwidth to pick up the spoiler tone. But in practice this didn't matter. Cassettes turned out not to be a huge problem because sound quality is noticeably poorer on home equipment; people mostly used them to record music to listen to in their cars. Then, in the 1980s, the arrival of the Sony Walkman made cassettes into big business, and although there was some copying, there were huge sales of pre-recorded cassettes and the music industry cleaned up.

Audio copying became a headline concern again in the 1990s, thanks to the mp3 format for compressing audio. Previously, digital audio was protected by its size: a CD of uncompressed music can take 650Mb. However, mp3 enables people to squeeze an audio track into a few megabytes, and broadband enables files of this size to be shared easily. By 1998, some 40% of the network traffic at MIT was MP3 traffic.

The industry response was to push for technical fixes. This led to the growth of the rights-management industry. It had its origins in work on digital publishing and in the mechanisms used to protect pay-TV and DVDs, so let's take a quick look at those first.

24.2.4 Video and pay-TV

The early history of videocassettes was a replay of the history of audio cassettes. At first Hollywood was terrified, and refused to release movies for home viewing. Crude technical measures were taken to prevent copying – such as the Macrovision system which added spurious synchronization pulses to confuse the recording circuitry of domestic VCRs – which again turned out to be easy to defeat. Then Hollywood became paranoid about video rental stores, just as book publishers had been about libraries. Once more, libraries turned out to be the publiser's friend, as being able to rent videos got people to buy VCRs and whetted their desire to own their favorite movies. VCRs and videocassettes became mass-market products rather than rock stars' toys, and by 2000 sales of prerecorded cassettes make up most of the income of firms like Disney. The business model changed so that the cinema release was really just advertising for the sales of the video.

By then, many of the world's pre-teens demanded that their parents build them a collection of Disney cassettes, just like their friends had, so a videocassette pirate had to make the packaging look original. This reduced the problem to an industrial counterfeiting one. As with mass-market software before the onset of online registration, or with perfumes and Swiss watches today, enforcement involves sending out field agents to buy products, look for forgeries, trace the supply chain and bring prosecutions.

More interesting technical protection mechanisms were built into broadcast pay-TV equipment.

The advent of pay-TV, whether delivered by cable or satellite, created a need for *conditional access* mechanisms which would allow a station operator to restrict reception of a channel in various ways. If the operator had only bought the rights to screen a movie in Poland, they'd have to block German or Russian viewers within the satellite footprint from watching. Porn channel operators needed to prevent reception in countries like Ireland with strict censorship laws. Most operators also wanted to be able to charge extra for specific events such as boxing matches.

24.2.4.1 Typical system architecture

The evolution of early systems was determined largely by the hardware cost of deciphering video (for a history of set-top boxes, see [415]). The first generation of systems, available since the 1970's, were crude analog devices which used tricks such as inverting the video signal from time to time, interfering with the synchronization, and inserting spikes to confuse the TV's automatic gain control. They were easy enough to implement, but also easy to defeat; breaking them didn't involve cryptanalysis, just an oscilloscope and persistence.

The second generation of systems appeared in the late 1980's and employed a hybrid of analog and digital technologies: the broadcast was analogue, but the subscriber control was digital. These included systems such as Videocrypt and Nagravision, and typically had three components:

- a subscription management service at the station enciphered the outgoing video, embedded various *entitlement management messages* (EMMs) and *entitlement control messages* (ECMs) in it, and issues access tokens such as smartcards to subscribers;
- a *set-top box* converts the cable or satellite signal into one the TV can deal with. This includes descrambling it;
- the subscriber smartcard personalises the device and controls what programmes the set-top box is allowed to descramble. It does this by interpreting the ECMs and providing keys to the descrambling circuit in the set-top box.

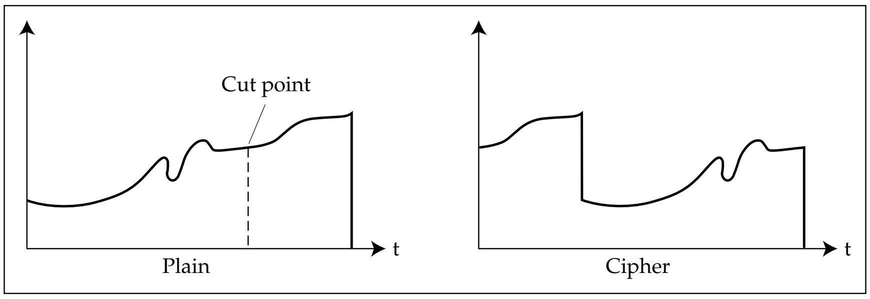


Figure 24.1: – cut-and-rotate scrambling

This architecture means that the complex, expensive processes such as bulk video scrambling could be done in a mass-produced custom chip with a long product life, while key-management functions that may need to be changed after a hack can be sold to the customer in a low-cost token that is easy to replace. If the set-top box itself had to replaced every time the system was hacked, the economics would be much less attractive[3].

The basic mechanism was that the set-top box decoded the ECMs from the input datastream and passes them to the card. The card deciphered the ECMs to get both control messages (such as "smartcard number 123356, your subscriber hasn't paid, stop working until further notice") and keys, known as *control words*, that were passed to the set-top box. The set-top box then used the control words to descramble the video and audio streams. There's a detailed description in [444].

24.2.4.2 Video scrambling techniques

Because of the limitations on the chips available at low cost in the early 1990s, hybrid systems typically scramble video by applying a transposition cipher to picture elements. A typical scheme was the *cut-and-rotate* algorithm used in Videocrypt. This scrambles one line of video at a time by cutting it at a point determined by a control byte and swapping the left and right halves (Figure 24.1):

This involved analog-to-digital conversion of the video signal, storage in a buffer, and digital-to-analog conversion after rotation – a process which could just about be shoehorned into a low-cost custom VLSI chip by 1990. However, a systemic vulnerability of such systems is that video is highly redundant, so it may be possible to reconstruct the image using 'oscilloscope and persistence' techniques, enhanced by sinple signal processing. This was first done by Markus Kuhn in 1995 and required the use of a supercomputer at the University of Erlangen to do in real time. Figure 24.2 shows a frame of enciphered video, and Figure 24.3 the same frame after processing. By 2000, it was possible to do this on a PC [1764]. If this attack had been feasible earlier, it would have given a complete break of the system, as regardless of how well the smartcard managed the keys, the video signal could be retrieved without them. Hybrid

[3]Now that set-top boxes are made in bulk for a few dollars, and the shipping costs dominate, the smartcard is often just soldered to the motherboard and the whole box is replaced if there's a hack.

systems are still used by some stations in less developed countries, together with frequent key changes to make life inconvenient for the pirates – whose problem is to distribute the keys to their customers as they crack them.

The major developed-world operators moved to digital systems in the early 2000s. These digital systems work on the same principle – a set-top box with the crypto hardware and a smartcard to hold the personal keys that in turn decipher the content keys from ECMs. However the crypto now typically uses a block cipher to protect the entire digital video stream. I'll describe the current digital video broadcast systems in the next section.

The hybrid scrambling techniques lasted (just) long enough. However, they have some interesting lessons to teach, as they were subjected to quite determined attack in the decade after 1995, so I'll go briefly through what went wrong.

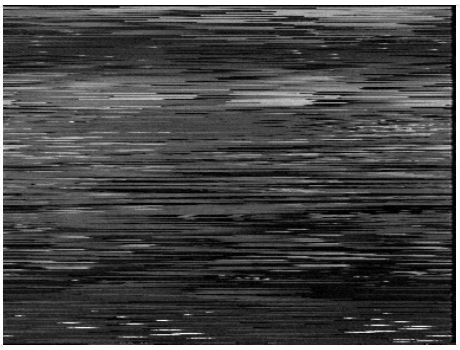


Fig 24.2 – scrambled video frame

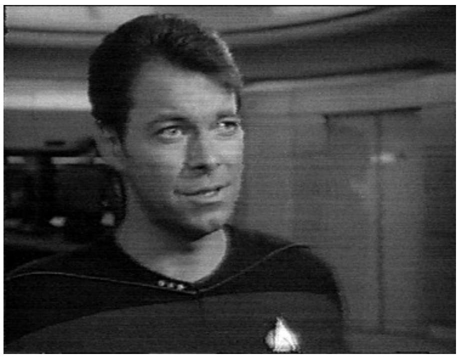


Fig 24.3 – processed video frame

24.2.4.3 Attacks on hybrid scrambling systems

Given a population of set-top boxes that will unscramble broadcast video given a stream of control words, the next problem was to see to it that only paying customers could generate the control words. In general, this could be done with allow and deny messages. But the bandwidth available was typically of the order of ten ECMs per second. So sending an allow message to each of five million subscribers would take over a week, and deny messages were mostly used instead.

The customer smartcard interprets the ECMs. If the current programme is one the subscriber is allowed to watch, then a keyed hash – essentially a message authentication code (MAC) – is computed on a series of ECMs using a master key held in the card and supplied to the set-top box as the control word:

$$CW = MAC(K; ECM_1, ECM_2, ECM_3, ECM_4)$$

So if a subscriber stops paying their subscription, their card can be inactivated by sending an ECM ordering it to stop issuing control words; and it needs access to the ECM stream in order to compute control words at all. Provided the cards can be made tamper-resistant, only compliant devices should have access to the master key K, and they should commit suicide on demand. So what could go wrong?

The first attacks were on the protocol. Since the control word sent from the smartcard is the same for every set-top box currently unscrambling the program, one person can record the stream of control words, by placing a PC between the smartcard and the set-top box, and post them online. Other people can video-record the scrambled program, and unscramble it later [1220]. Servers sprung up for this *key-log attack*, but were only a minor nuisance to the industry; not many viewers were prepared to buy or build a special adapter to connect their PC to their set-top box. Hobbyists with such equipment found other attacks including *blockers*, programs that would prevent ECMs addressed to your card from being delivered to it; this way, you could cancel your subscription without the operator being able to cancel your service [1220].

Cryptanalysis also gave some opportunities. Every half-second or so the smartcard supplies the set-top box with a new control word, and this is loaded into a keystream generator which works as follows. There are two linear feedback shift registers, of lengths 31 and 29 in the Eurocrypt system, which generate long linear sequences. Some of the bits of register 1 are used as address lines to a multiplexer, which selects a bit from register 2; this bit becomes the next bit of the keystream sequence. Each successive byte of output becomes a control byte for the scrambler (Figure 24.4).

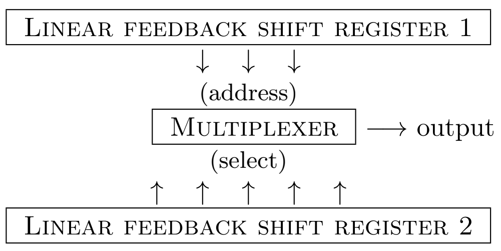

Linear feedback shift register 1
(address)
Multiplexer
output
(select)
Linear feedback shift register 2

Figure 24.4 – the multiplexer generator

The designers intended that breaking this cipher should involve guessing the key, and as this is 60 bits long a guess would take on average 2^{59} trials which is uneconomic – as it has to be done about twice a second. But it turns out that the cipher has a shortcut attack. The trick is to guess the contents of register 1, use this address information to place bits of the observed keystream in register 2, and if this causes a clash, reject the current guess for register 1. (I discovered this attack in 1985 and it's what got me interested in cryptography.) The high-order four bits or so of each control word are easy to deduce from inter-line correlations – it's the least significant bits you really have to work hard for. So you can reconstruct the latter using cryptanalysis. But this computation is still of interest to hobbyists rather than the mass market.

Perhaps the most powerful of the 'amateur' attacks exploited a master-key leakage: someone who bought a second-hand PC, looked at the hard disk out of curiosity, and managed to undelete a complete subscriber management system for one pay-TV operator, including embedded master keys. This enabled enthusiasts to write software to emulate a subscriber smartcard completely – in fact, it could even be 'improved' so it would not turn itself off when ordered to do so by an ECM.

Anyway, the commercial pirates turned to reverse engineering smartcards using microprobing techniques, and in section 18.5 I described the arms race that followed. But hardware fixes were limited to new card issues, and the operators didn't want to issue a new card more than once a year as it cost several dollars per subscriber, and the subscriptions were usually less than $20 a month. So other defensive techniques were tried too.

Litigation was one route, but it took time. A lawsuit was lost against a pirate in Ireland, which for a while became a haven from which pirates sold cards by mail order all over Europe. The industry's lobbying muscle was deployed to bring in European law to override Dublin, but this took years. By the middle of 1995, the main UK satellite TV station (Sky-TV) was losing 5% of its revenue to pirate cards, mostly sold by mail order from Dublin.

So all through the mid 1990s, pirates and the operators engaged in a war of technical countermeasures and counter-countermeasures. The operators would ship a new card, and within months the pirates would have reversed it and be offering clones for sale. The operators would buy some, analyze them, and develop tricks to cause them to fail. The problem faced by the operators was this: when all the secrets in your system can be compromised within months, how can you still fight back against the pirates without having to reissue all the cards?

The operators came up with all sorts of cunning tricks. One of their more effective ones was an ECM whose packet contents were executed as code by the smartcard; in this way, the existing card base could be upgraded on the fly and implementation differences between the genuine and pirate cards could be exploited. Any computation that would give a different answer on the two platforms – even if only as a result of an unintentional timing condition – could be fed into the MAC algorithm to make the pirate cards deliver invalid control words.

One of the systems (Eurocrypt) had an efficient revocation scheme designed in from the start, and it's worth looking at briefly. Each of the subscriber smartcards contains a subscriber key k_i, and there is a binary tree of intermediate group keys $KGij$ linking the subscriber keys to the currently active master key K_M. Each operational card knows all the group keys in the path between it and the master key, as in Figure 24.5.

In this scheme, if (say) key k_2 appears in pirate cards and has to be revoked, then the operator will send out a stream of packets that let all the other subscriber cards compute a new master key K_M. The first packet will be $\{K'_M\}_{KG12}$ which will let half the subscribers compute K'_M at once; then there will be a K'_M encrypted under an updated version of $KG11$: $\{K'_M\}_{KG'11}$; then this new group key $KG'11$ encrypted under $GK22$; and so on. The effect is that even with ten million customers the operator has to transmit less than fifty ECMs in order to do a complete key change. Of course, this isn't a complete solution: one also needs to think about how to deal with pirate cards that contain several subscriber keys, and how leaked keys can by identified without having to go to the trouble of breaking into pirate cards. But it's a useful tool in the box.

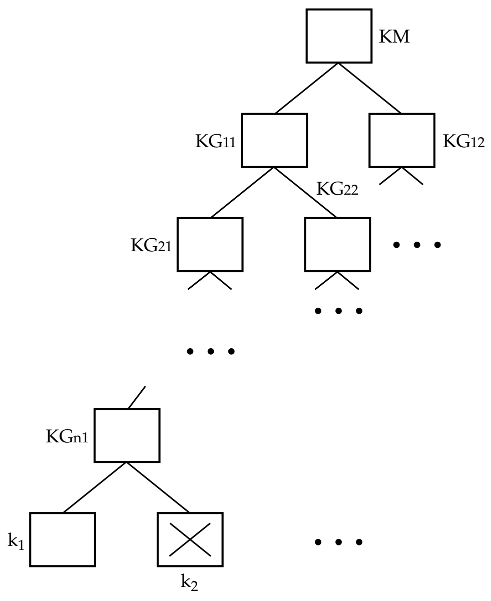


Figure 24.5: – binary revocation tree

Psychological measures were also used. For example, one cable TV station broadcast a special offer for a free T-shirt, and stopped legitimate viewers from seeing the 0800 number to call; this got them a list of the pirates' customers. Economic factors also matter here, as everywhere. Pay-TV pirates depend for their success on time-to-market as much as conventional software firms: a pirate who could produce a 99% correct forgery in three weeks would wipe out a competitor who produced a 99.9% forgery after three months. So pirates race to market just like legitimate vendors, and pirate cards have bugs too. An understanding of economics teaches that it's best to let a pirate build up a substantial user base before you pull the plug on him, as this gives him time to wipe out his competitors, and also as switching off his cards once he's established will destroy his credibility with more potential customers than an immediate response would. But if you leave him too long, he may acquire the financial and technical resources to become a persistent problem.

The pay-TV industry learned to plan in advance for security recovery, and to hide features in their products that weren't used initially but could be activated later. (The same lesson had been learned years previously by the banknote printers.)

Eventually, the smartcards were made much harder to forge by including proprietary encryption algorithms in the processor hardware. As the attacker couldn't simply read out the algorithm with a probing station but had to reverse engineer thousands of gates in the chip, they reduced to a handful the number of laboratories with the technical capability to do attacks. Many of these laboratories were drawn into the industry's orbit by consultancy deals or other kinds of sponsorship. Those who remained outside the tent were watched. Vigorous legal enforcement provided the last link in the chain. The industry hunted down the main commercial pirates and put them out of business, whether by having them jailed or by drowning them in litigation.

In the last big pay-TV piracy case in the 20th century, British pirate Chris Cary was convicted of forging Sky-TV smartcards whose design he had had reverse engineered by a company in Canada for $105,000. He sold forgeries through a front company in Ireland, where counterfeit cards were not illegal yet [1329]. So Sky TV's security consultants infiltrated a spy into his Dublin sales office, and she quietly photocopied enough documents to prove that the operation was really being run from the UK [932]. The British authorities didn't want to prosecute, so Sky brought a private prosecution and had him convicted. When the authorities put him in an open prison and he absconded, Sky's private detectives relentlessly hunted him down and caught him in New Zealand, where he'd fled using a passport in a dead person's name [827]. He then ended up in a proper jail. Sky-TV's relentless unpleasantness served as a warning to others.

24.2.4.4 DVB

Digital video broadcasting (DVB) largely operates using a set of standards that have evolved over the years since 1996 and that are controlled by the DVB Consortium, and industry group of over 250 members. The standards are many and complex, relating to IPTV and digital terrestrial TV as well as satellite TV, and to free-to-air services as well as pay-TV. DVB has been replacing analogue/hybrid systems, starting with the UK and Germany in 2003. The latest standards, DVB-T2, were promulgated by ETSI in 2009.

The protection mechanisms are complex, and some of them are covered by nondisclosure agreements, but here is a telegraphic summary. The conditional access mechanisms for DVB are similar to the hybrid system: the content encryption is digital, but the keys are generated by subscriber smartcards operating on EMMs and ECMs as before. The encryption uses the DVB Common Scrambling Algorithm, which was available only under NDA, but leaked in 2002. In 2011, an attack was found by Erik Tews, Julian Wälde and Michael Weiner, but it's barely practical as it requires an 8Tb rainbow table [1811]. The smartcards are not standardised (except at the interface level) so each broadcaster can use his favorite crypto tricks and suppliers; the piracy to date seems to have involved smartcard cloning, and there have been various lawsuits where pay-TV operators have accused each other of hacking.

Pay-TV, whether cable of satellite, peaked in 2008 with 75% of US households. What dislodged it was Netflix, and more generally the move to online subscription services based on broadband.

24.2.5 DVD

The history of DVD was both a warning of trouble to come between Hollywood and the computer industry, and an object lesson on how not to do copy protection.

The consumer electronics industry introduced the *digital video disk* (DVD), later renamed the *digital versatile disk*, in 1996. As usual, Hollywood took fright and said that unless DVD had a decent copy protection mechanism, first-class movies wouldn't be released for it. So a mechanism called the *content scrambling system* (CSS) was built in at the last minute; arguments over this held up the launch of DVD and it was designed in a rush. (The story of how the DVD standards evolved is told in Jim Taylor's standard reference [1804], which also describes most of them.)

DVD had *region coding*: disks were supposed to run only on players from some designated list of regions, to support the traditional practice of releasing a movie in the USA first, then in Europe and so on, in order to minimise the cost of producing physical film prints, and the financial loss if the film bombs. But users preferred to buy DVD players in which region coding could be turned off. So every DVD vendor wanted to have the second most insecure player on the market; they didn't want to be the firm that Hollywood was beating up on, but they wanted prospective customers to be confident that their player's region coding could be hacked.

This left CSS, which was known to be vulnerable by the time that DVD was launched [1448]. It has a keylength to 40 bits so the equipment wouldn't fall foul of US export regulations, and the design was so poor that the effective keylength was only 16 bits. A Norwegian teenager, Jon Lech Johansen, reverse engineered the algorithm and wrote decryption software for it, DeCSS. Industry lawyers got injunctions against people who put it online but these were seen as censorship, so DeCSS started appearing on websites outside the USA, on T-shirts, in songs, and in other forms of speech that traditionally enjoy constitutional protection[4]. This just got it distributed ever more widely, and made Hollywood look foolish [1095]. Their lawyers blundered on, persuading the government of Norway to prosecute Johansen. He was acquitted on appeal in 2003.

Another set of problems came from the fact that the PC is an open platform. The DVD consortium required people producing DVD player software to obfuscate their code so that it would be hard to reverse engineer. Papers duly appeared on tricks for systematic software obfuscation [139]. But this closed approach came into conflict with Linux, the open-source PC operating system that was already used by millions of people. The DVD consortium's philosophy was not consistent with making DVD drivers available to the Linux community. So as PCs with CD drives started being replaced in the shops with PCs fitted with DVD drives, the Linux user community either had to break CSS, or give up using Linux in favour of Windows. Under the circumstances, it was only a matter of time before someone figured out CSS and DeCSS appeared.

Anyway, DVD followed the usual pattern: Hollywood terrified, and refusing to release their best movies; technical measures taken to prevent copying, which quickly got broken; then litigation. I wrote in 2001: "A reasonable person might hope that once again the studios will see sense in the end, and make a lot of money from selling DVDs. There will be copying, of course, but it's not entirely trivial yet – even a DSL modem takes hours to send a 4Gb DVD movie to a friend, and PC disk space is also an issue." This came true; although some studios held out for a year or two, they all climbed on the DVD bandwagon, and by the second edition in 2008, Disney was making most of its money from DVD sales.

[4]There was a full description of CSS and how to break it in the first and second editions of this book; as DVDs are going the way of the dinosaur, I've dropped it for this edition.

There was then an attempt to market higher-density optical media, with a format war in 2007 between HD-DVD and Blu-ray, which both used shorter wavelength lasers to encode information more densely giving up to 50Gb per disk. Both used the Advanced Access Content System (AACS), which I described in the second edition of this book. However, only the Playstation 3 did a full implementation of Blu-Ray, and HD-DVD never got real traction at all. They were destroyed, as distribution media, by the growth of broadband, and as storage media by the falling cost of USB memory sticks.

24.3 DRM on general-purpose computers

Victor Shear patented self-destruct software in the 1980s and his company became InterTrust [1730]; their DigiBox system is described by Olin Sibert, David Bernstein and David Van Wie in [1675]. This enabled a DRM mechanism to reflect real-world ownership, so that I could sell you a photo and you'd be able to decrypt it once you had the receipt; what's more, you could give it to somebody else after which you'd no longer have it.

Intertrust were the most successful of a number of firms who worked in the mid-90s on ways to control the sale and distribution of digital goods over the Internet to customers with personal computers[5]. The original applications included the distribution of newspapers and articles from scientific journals [305], although it was always understood that music and video would follow once networks had enough bandwidth.

The basic problem is that a PC, being a general-purpose computer, can in principle copy any file and send it to any other computer; unlike with analogue copying, copies are perfect, so millions of copies might be made from one original. The problem is compounded by the fact that, from the viewpoint of the content vendor, the PC owner is the 'enemy'. The music industry believed that unlimited copying would destroy their business; the computer industry told them that DRM was intrinsically impossible on a general-purpose computer, so they'd better get a new business model. The music and film industries, despite being a tenth of the computer industry's size, had much more clout in Congress (a Microsoft guy complained that the average Congressman was much keener to be photographed with Madonna than with Bill), and they still controlled access to the music and video that the computer industry wanted their PCs and phones to be able to play. The result was a push for DRM.

24.3.1 Windows Media Rights Management

Windows Media Player (WMP) was an early deployment of DRM, replacing an earlier media player when Windows 98 was released. It enabled a user to play music, watch video and view photos, with features ranging from MP3 player support to synchronisation of lyrics for karaoke. It introduced *Windows Media Rights Management* (WMRM), which works as follows.

[5]The InterTrust patents were one of only four computer-related patents from the 20th century that caused a nine-figure sum to change hands, the others being the Harvard virtual memory patents, the RSA public-key patents and the Fraunhofer mp3 patents.

A store wanting to sell digital media encrypts each item using a content key and puts the encrypted files on a streaming media server linked to their web site. In order to access a media object, the customer must get hold of a license, which consists of the object identifier, the license key seed, and a set of instructions in a *rights management language* which state what they can do with it; how many times they may play it, whether they can burn it to a CD, and so on. The license is generated by a license server and encrypted using a public key generated by the customer's WMP application. License acquisition may involve registration or payment, but it may also happen silently in the background [1510].

The architecture is similar to pay-TV conditional access, in that the bulk encryption task of protecting the music or video is separated from the personalised task of key management, so the video doesn't have to be encrypted anew for each customer. And just as pay-TV smartcards can be replaced when keys are leaked or the key management mechanism compromised, so the key management functions of WMRM are performed in an 'individualized blackbox' (IBX) component of the software, which gets replaced as needed during the Windows update process.

The IBX internals have been reverse-engineered from time to time [1638]. The customer's private key is obscured by the blackbox and hidden in a file; licenses the customer has previously acquired are kept in a license store; content keys are encrypted using the customer's public key; and the protocol gets tweaked from time to time as Microsoft has to recover from hacks. I described in section 6.2.5 how in the early 2000s Microsoft, Intel and some other big players formed the Trusted Computing Group to try to build DRM properly into the PC architecture. The attempt failed for both business and technical reasons, but led to TPM chips for trusted boot, to TrustZone enclaves in Arm processors, and eventually to SGX enclaves in Intel chips.

Microsoft launched *Information Rights Management* (IRM) with Windows Server 2003, which aimed to extend DRM to general users; the idea was that access controls over a document or other digital object would be retained by its creator. So DRM wouldn't just benefit Hollywood; I could send you an email that you could only read, and never copy, and that would vanish after a month. The vision was that this would be supported by Trusted Computing mechanisms across the entire Windows ecosystem, and conveniently fortify the ecosystem against challenges from the likes of Linux or Google docs. Corporate America didn't like the lock-in, though, and Microsoft couldn't get the operating system mechanisms to work. Nowadays, it's easy to implement such distributed use controls in cloud-based systems such as Office365 or Gmail, but it's too hard to work across such ecosystems; so we've ended up not too far from where we might have been had Trusted Computing been made to work.

WMRM was then replaced in Windows 10 by PlayReady, a newer Microsoft 'media file copy prevention technology'. WMP is used at its most basic to provide a streaming media service, to support music subscription services, and geographically-linked services, such as MLB.com which makes major league baseball games available everywhere except in the team's home area – for which the rights have usually been sold to local TV stations.

24.3.2 Fairplay, html5 and other DRM systems

The Microsoft offering was fairly typical of rights-management systems. Apple's FairPlay, which was launched in the iPod and in its media player QuickTime, also has tunes encrypted under master keys. When a tune is bought the customer is sent the master key encrypted under a random session key, plus the session key encrypted under his iTunes player's RSA public key. Session keys are backed up online on Apple's servers. As with Windows, a number of programs have appeared from time to time that unlocked protected content, and Apple duly upgraded iTunes. Apple iTunes was replaced with Apple Music in 2020.

Some firms' rights-management systems were downright abusive, and a particularly extreme case arose in 2005 with Sony's XCP system. The first time a user inserted a CD with this system into a PC, it presented an end-user license agreement; if the user declined, the CD was ejected, and if they accepted it loaded and hid a rootkit that intercepted all accesses to the CD drive and prevented Sony music being played by any other media player. Microsoft classified it as malware and had it removed by Windows Defender and the Malicious Software Removal Tool [1269]. It later turned out that Sony had even included in their rootkit some software that violated the copyrights of others.

There was significant controversy in 2012–14 when the World Wide Web Consortium (W3C) was debating whether to adopted html5 which provides for a sandbox in browsers to support multimedia content with DRM, and Encrypted Media Extensions (EME) as a means for the software in the sandbox to communicate with online license managers. When they eventually went ahead in 2014, W3C chair Tim Berners-Lee was fiercely criticised for adopting a standard which excludes open-source browsers in the future. Since 2017, browsers need to license 'Widevine' DRM software from Google to support services such as Netflix. Mozilla was the last major browser to switch, after they concluded that refusing would just cause most of their users to switch browsers. In 2020, Google stopped supplying this technology to open-source browsers; thereafter all new browsers will have to be proprietary; this had been predicted by EFF during the debate in 2012–4 [558].

The other development in 2020 is Microsoft's launch of "double encryption", a kind of DRM to make regulated industries like banking happier about keeping sensitive data in the Office365 / Azure cloud: content keys are kept on the local device, but the whole thing is integrated with the Microsoft structure of access controls [422]. Whether DRM operated by Microsoft would stop an FBI agent armed with a FISA warrant getting access to data on a Microsoft cloud is an interesting question; I suppose we'll only know the answer when the next Snowden comes out.

24.3.3 Software obfuscation

As I already mentioned, early software protection mechanisms used software obscurity to hide keys and to check for the presence of machine fingerprints, dongles and license servers. Kids with disasssemblers and time on their hands tended to defeat such tricks, so where possible firms would move some critical functionality to the cloud, to trustworthy hardware, or both.

But that is not always possible, and in 2020 the critical applications include *runtime application self-protection* (RASP). As I discussed in section 12.7.4, this is a set of techniques used by some mobile app developers to protect apps on phones that may have been rooted or jailbroken by malware. It's used by Facebook to protect customers using its Android app in less developed countries where many Android phones are secondhand, out of patch support and rooted, often by local sales agents. And following a mandate from the European Central Bank, RASP is becoming mandatory for banking apps in Europe, or for authenticator apps on which they rely. In both cases the objective is to protect cryptographic keys from an attacker who roots the device. This was also the threat model for 1990s products such as Windows Media Player.

There were early attempts to write obfuscating compilers that would produce tamper-resistant software; an early Intel project is described at [139] and led to tools used in early software DVD players. These were duly broken, as I described in section 24.2.5 earlier, and led Intel to move towards Trusted Computing and eventually SGX, as I described in section 6.3.1.

Theoretical computer scientists have written many papers on obfuscation and indistinguishability; a seminal result by Boaz Barak and colleagues in 2001 suggests that we can't write obfuscating compilers with strong and sustainable protection properties [163]. But – as with other impossibility results in security such as those on malware detection – the question then arises whether even if perfect obfuscation isn't possible in theory, practical obfuscation might be good enough for some purposes.

Microsoft moved to a philosophy of security renewal: the key-management code for Windows Media Player was hidden in IBX and moved around;, so it might be in the Windows error handler one month and an obscure device driver the next. Malware writers took a similar trajectory. As I described in section 21.3.5, they often obfuscate their code by running it through a packer that contains a polymorphic header which in turn decrypts the malware body. Keys and headers are all different, making malware harder to recognise. Approaches like this can sometimes be made to work moderately well, provided the maintainers are capable and motivated. Very often, though, they aren't; naive firms buying RASP from salesy vendors should expect the worst.

The main security research conferences have tended not to accept papers on obfuscation as they see it as a tactical arms race rather than the accumulation of scientific knowledge. There is nonetheless a small research community working on obfuscation, and as of 2020 the state of the art when protecting an engine for authentication or decryption is to implement a virtual machine that has an odd instruction set, in which you implement the crypto, and then further obfuscate the virtual machine itself (custom opcodes had already been used in Sky-TV smartcards back in the 1990s). It is still a real problem though to evaluate such a scheme, or even guess how much effort it will take to break it [542]. If a RASP tester can't extract the crypto key despite trying for a fortnight, that doesn't give you any guarantee against someone who tries for a month[6]. Decompilation

[6]I bear the scars personally. Back in the 1990s, Intel paid us to spend a fortnight trying to hack a prototype DVD player binary that had been produced by Beelzebub, their internal obfuscating compiler. We only got about halfway through, and the company then boasted to its customers that 'Cambridge couldn't break this'. Jon Lech Johansen later spent a month

tools and techniques improve all the time, and many engineers spend much of our lives trying to figure out what other people's code actually does. Some people acquire a real knack for this, but they might not be working in your compliance testing lab! A lemons market is therefore to be expected.

All that said, there are some less heavyweight aspects to this. Some tools obfuscate Java bytecode as they shrink and optimise it; one such, ProGuard, is distributed as part of the Android SDK. And for entertainment, there's the International Obfuscated C Code Contest, where people have fun trying to hide functionality in plain sight.

24.3.4 Gaming, cheating, and DRM

Games were one of the first applications of all – pretty well as soon as the world's first proper computer, the EDSAC, was operational, research students were writing games for it. Computer games have been big business for decades. They drove the home-computer boom of the 1970s that in turn spawned the PC industry; games consoles have been a huge market for microprocessors and memory chips; and gaming – whether on consoles or PCs – has largely driven the development of computer graphics [1988]. Game sales in the USA surpassed movie box-office sales in 2001; and as games moved online, game firms started to sell subscriptions, not just one-off tickets [270].

When Nintendo moved console games into the home, they subsidised the consoles from later sales of software cartridges and other add-ons, so a lot of effort was put into controlling which accessories could be used, as I discuss later in section 24.6; copy-protection of game software for PCs was also a big deal. However the move to online computer games has mitigated these concerns. As a critical part of the game logic runs on a server, the client software can be given away, and the residual issue is whether players can get an unfair advantage.

There are very many ways in which gamers can cheat [1989]. Some games ban collusion, such as contract bridge, and it's hard to stop people playing on an online platform from using an entirely separate channel to cheat. In the real world, allegations of cheating are heard by a jury of experienced players, who take a view on whether the outcome was better than could have been expected in honest play. Even so, some decisions remain controversial for years: players may be lucky, and partners who've played together for years may communicate subconsciously without trying to. Online play can help as you can have online records for statistical analysis, online tournaments where many players use the same deal of cards, and new forms of play where people play with many partners rather than just one.

Other games require collusion, such as adventure games involving teams of people. As I discuss in section 8.6.8, these are currently, in 2020, the biggest market for DDoS-for-hire services. Players, who are often schoolkids, pay a few dollars for a service that will knock key members of the opposing team offline at a critical time.

The third type of cheating tactics are those that emerge from the nature

staring at the code and broke it, making us look stupid – but Intel ended up looking stupider.

of computer games. In tactical shooters, for example, success should depend on the player's tactics and shooting skill, not on the game mechanics. Yet there are always shortcomings in the game's physics model, often introduced by network latency and by the optimisations game designers use to deal with it. For example, you'd normally expect that in a shooting duel, you'd have an advantage if you have the lowest network latency, or if you move first. Yet the prediction algorithms used in many game clients cache information about nearby players, so if you leap round a corner, see your enemy and shoot, then the slower your network connection is, the longer it will take him to see you and respond. Mike Bond coined the term 'neo-tactic' to refer to players subliminally exploiting such anomalies [270]. That may not of itself be cheating, but in recent years players have started manipulating network connections deliberately to create artificial lag, whether of incoming packets to delay other players, or our outgoing ones in order to see what other players are about to do.

That brings us on to one of the classic game cheats, namely to have code of your own for automation and support. People have written a huge variety of tools, from simple routines that repeatedly click a fire button (to hack the games where the rate at which you can physically fire is a factor) through proxies that intercept the incoming network packets, identify the bad guys, examine your outgoing shots, and optimise their aim. These *aimbots* come with different levels of sophistication, from code that does all the target acquisition and shooting, to human-controlled versions that merely improve your aim. They can hook into the packet stream as proxies, into the graphics card, or even into the client code. Another variant on the same theme is the *wall hack*, where a player modifies his software to see through walls – for example, by changing the graphics software to make them translucent rather than opaque. Such hacks are possible because first-person shooters typically send out raw positional information to all players in the game, and leave it up to client software to render it according to the local physics model.

Game companies who sell first-person shooters reckon that aimbots and other client-side hacks seriously spoil other players' fun, so they use a variety of encryption, authentication and DRM mechanisms to not only reduce cheating, but also the perception of cheating – which is almost as damaging to the operator [271]. Guard software such as Punkbuster has been around since 2000, using anti-virus techniques to detect attempts to hook into game code or the drivers on which it relies. The large gaming platforms such as Steam have their own DRM mechanisms that attempt to block aimbots and other game cheats, as well as protecting their own revenue by making it harder for customers to resell games [1251]. This a constant battle, as I discussed in section above, and some techniques such as artificial lag are difficult to deal with completely. However, gaming is one of the applications in which trustworthy client software, whose protection involves DRM-like mechanisms, has become well entrenched, even though most modern games are locked to customer accounts and most of their logic now runs on a server. The server is also often fortified with analytics to detect cheating after the event, just like in a professional bridge tournament.

24.3.5 Peer-to-peer systems

From the late 1990s, peer-to-peer file-sharing became one of the main ways in which music was distributed online. Once people had CD drives on their computers and broadband connections, they could copy and share their favourite tracks. In 1999, Shawn Fanning, a 18-year-old drop-out, revolutionised the music business by creating the Napster service, which enabled people to share MP3 audio files with each other [1342]. Rather than keeping the files centrally, which would invite legal action, Napster just provided an index so that someone wanting a given track could find out who else has got it and is prepared to share or trade. It attracted tens of millions of users, but lawsuits from Hollywood closed it down in September 2002. Systems such as Gnutella and Freenet then borrowed ideas from the world of censorship-resistant systems to set up networks with no central node that could be closed down using legal attacks [427]. These were followed by other systems such as Kazaa and Bittorrent.

I was the designer of an early censorship-resistant system, the Eternity Service. The motivation came when an early anonymous remailer, `anon.penet.fi`, was used to post a message that upset the Scientologists and was closed down after they got a court order forcing its operator to disclose the linkage between users' real email addresses and the pseudonyms they used on his system [859]. The messages that were the subject of the case contained an affidavit by a former minister of their church to the effect that once members had been fully initiated they were told that the rest of the human race was suffering from false consciousness; that, in reality, Jesus was the bad guy and Lucifer was the good guy. Well, history has many examples of religions that denounced their competitors as both deluded and wicked; the Scientologists' innovation was to claim that their scriptures were their copyright, so the whistleblower's leak was a breach of copyright. They got away with this argument in a number of jurisdictions until eventually a court in the Netherlands put a stop to it by allowing an NGO there to publish the 'Fishman affidavit', as it was called.

The Eternity Service was designed to provide long-term file storage by distributing file fragments across the net, encrypted so that the people hosting them would not be able to tell which fragments they had, and so that reconstruction could only be performed via remailer mechanisms [60]. A later version of this was Publius[7], which also provided a censorship-resistant anonymous publishing mechanism [1906].

The United States Copyright Office defines peer-to-peer networks as networks where computers are linked to one another directly rather than through a central server. The absence of a server that can be closed down by court order creates an interesting problem for music industry enforcers. The two tactics on which the music industry relied were suing uploaders and technical attacks on the systems.

The music industry has filed tens of thousands of lawsuits since 2003. In many cases people agree to cease and desist and pay a small penalty rather

[7]For non-US readers: the revolutionaries Alexander Hamilton, John Jay, and James Madison used the pen name Publius when they wrote the Federalist Papers, a collection of 85 articles published in New York State newspapers in 1787–8 and which helped convince New York voters to ratify the United States constitution

than fight a case; but in October 2007 a federal jury in Duluth, MN., convicted 30-year-old Jammie Thomas of copyright infringement for sharing material on Kazaa and ordered her to pay $9,250 for each of the 24 songs involved in the case. Firms working for the music industry were uploading damaged music files to spam out systems (which will usually be legal), and it was suspected that they were also conducting denial-of-service attacks (which in many jurisdictions isn't). In September 2007, a company called Media Defender that worked for the music industry on 'file-sharing mitigation' had several thousand of its internal emails leaked, after an employee forwarded his email to Gmail and his password was compromised. The emails not only disclosed many details of the 'mitigation' tactics, but also revealed that the company worked closely with the New York Attorney General's office – potentially embarrassing in view of the industry's possibly illegal attacks on computers and invasions of privacy. It turned out that Media Defender's business model was to charge $4,000 per album per month, and $2,000 per track per month, for 'protection' that involved attacks on twelve million users of fifteen P2P networks [1455]. Peer-to-peer systems have also allegedly been attacked by Comcast, which is said to have disrupted its customers' connections by sending forged reset packets to tear down Bittorrent connections. Comcast might prefer its customers to watch TV over its cable network, so they see its ads, but the allegations raise public policy issues if true: Comcast is not a law-enforcement agency [213].

The state of play in 2020 is that some jurisdictions suffer from Torrent trolls: in Sweden, for example, there have been tens of thousands of cases attempted extortion, where lawyers demand large payments from families claiming that their kids uploaded some copyrighted material [1603]. This appears to be a function of local procedural law more than anything else; in many countries, lawyers can't be as crooked, or at least not in this particular way.

In the larger ecosystem, the big service firms are dominant and the deciding factor in copyright infringement is the notice-and-takedown regime set up under the US DMCA, and followed by similar laws elsewhere. I will discuss this further in section 24.5.

24.3.6 Managing hardware design rights

Another rights-management ecosystem is the protection of designs licensed for use in hardware. Companies like Arm earn their living by designing processors and other components that they sell to firms making custom chips, whether by designing application-specific integrated circuits (ASICs) or by using Field-Programmable Gate Arrays (FPGAs). There are several aspects to this, from using such devices to make it harder to counterfeit products, down to making it harder to infringe the design rights in the components themselves.

The most visible problem is overrun production. A camera company licenses a circuit that they integrate into a bitstream that's loaded into an FPGA, that then becomes a key component in a new camera that they have made in a factory in China. They pay for 100,000 licenses, yet 200,000 cameras arrive on the market. There are two failure modes: the camera company could have ordered the extra production and lied to the IP owner, or the Chinese factory could be cheating the camera company. In fact, they could both be cheating, each having decided to make an extra 50,000 units. Now there are technical mechanisms that the camera company could use to stop the factory cheating it, such as personalising each camera with a serial number and so on after manufacture – but these could make it harder to cheat the IP owner.

The second problem is knowing when a product contains a particular circuit. The camera company might have licensed a processor, or a filter, for one model, then built it into another cheaper model too without declaring it.

These risks cause some large IP vendors to prefer to license their best designs only to other large firms, so small startups can be disadvantages. They also depress sales of FPGAs, whose manufacturers offer mechanisms to tackle the first problem by distributing encrypted bitstreams and updates for whole chips; the second problem is harder, because chip design tools come within the trust boundary. Customers need to be able to evaluate designs, and debug designs, which is in tension with controlling dissemination. There has been some use of side-channels for forensics. Owners of semiconductor IP can buy samples of suspect goods, measure the chips' precise power consumption, electromagnetic emissions and so on, which can often reveal the presence of a given functional component. Components can even be deliberately designed to generate a suitable signal in their power trace. (Similar techniques are used by military contractors to look for hardware Trojans.)

This brings us to the question of copyright marking.

24.4 Information Hiding

Hollywood's interest in finding new mechanisms for protecting copyright came together in the mid-1990's with the military's interest in unobtrusive communications and public concerns over government efforts to control cryptography, and started to drive rapid developments in the field of *information hiding*. This largely refers to techniques for hiding data in other data, such as when a secret message is hidden in an MP3 audio file, or a program's serial number is embedded in the order in which certain instructions are executed.

Hollywood sought salvation in *copyright marks* embedded unobtrusively in digital audio, video and artwork. These include *watermarks*, copyright messages which may or may not be hidden but are hard to remove, and *fingerprints* which are hidden serial numbers. For example, when you downloaded an mp3 from Apple's iTunes music store, it contained a fingerprint embedded in the audio that identifies you. The idea was that if you then uploaded your copy to a file-sharing system, the copyright owner could sue you. (Some people believed that fingerprinting depressed sales overall because of the legal hazards it created for honest purchasers. Amazon, for example, did not mark MP3 downloads [831].)

The privacy interest is in *steganography* whose purpose is to embed a message in some cover medium in such a way that its very existence remains undetectable. The conceptual model, proposed by Gus Simmons [1683], is as follows. Alice and Bob are in jail and wish to hatch an escape plan; all their communications pass through the warden, Willie; and if Willie detects any encrypted messages, he will frustrate their plan by throwing them into solitary confinement. So they must find some way of hiding their secret messages in an innocuous covertext. As in the related field of cryptography, we assume that the mechanism in use is known to the warden, and so the security must depend solely on a secret key that Alice and Bob have somehow managed to share [1691].

There is some similarity with electronic warfare. First, if steganography is seen as a low-probability-of-intercept communication, then copyright marking is like jam-resistant communication technique: it may use much the same methods but in order to resist focused attacks it is likely to have a much lower bit rate. We can think of Willie as the pirate who tries to mangle the audio or video signal in such a way as to cause the copyright mark detector to fail. Second, techniques such as direct-sequence spread spectrum that were originally developed for electronic warfare found use in the information hiding community.

Copyright marks don't have to be hidden to be effective. Some TV stations embed their logo in a visible but unobtrusive manner in the corner of the picture, and as I noted, academic journal downloads do something similar. However, in what follows I'll concentrate on hidden copyright marks.

24.4.1 Watermarks and copy generation management

The DVD consortium became concerned that digital video or audio could be decoded to analog format and then redistributed (the so-called 'analog hole'). They set out to invent a *copy generation management system* that would work even with analog signals. The idea was that a video or music track might be unmarked, or marked 'never copy', or marked 'copy once only'; compliant players would not record a video marked 'never copy' and when recording one marked 'copy once only' would change its mark to 'never copy'. Commercially sold videos would be marked 'never copy', while TV broadcasts and similar material would be marked 'copy once only'. In this way, the DVD players available to consumers would allow unlimited copying of home videos and time-shifted viewing of TV programmes, but could not easily be abused for commercial piracy. The mechanisms depended on hiding copyright marks in the content, and are reviewed in [1134]. For each disk, choose a *ticket* X, which can be a random number, plus copy control information, plus possibly some information unique to the physical medium such as the wobble in the lead-in track. Use a one-way hash function h to compute $h(X)$ and then $h(h(X))$. Embed $h(h(X))$ in the video as a hidden copyright mark. Have compliant machines look for a watermark, and if they find one refuse to play a track unless they are supplied with $h(X)$ which they check by hashing it and comparing it with the mark. Compliant devices will only record a marked track if given X, in which case only $h(X)$ is written to the new disc. In this way, a 'copy once only' track in the original medium becomes a 'copy no more' track in the new medium. This ended up in Blu-ray, but that failed in the marketplace, as well as being a complete pain for developers to work with.

Robustness depends on many things including our old friend, the receiver operating characteristic or ROC, which sets the trade-off between false alarms and missed alarms. It's not enough for a marking mechanism to have a low missed alarm rate; it needs a low false alarm rate too [1279]. If your DVD player were to detect a 'no-copy' mark in your wedding video by mistake, then you'd have to buy a pirate player to watch it. So what sort of marks are possible, and how robust are they against forgery, spoofing and other attacks?

24.4.2 General information hiding techniques

Information hiding goes back even further than cryptology, having its roots in camouflage. Herodotus records tricks used during the wars between the Greeks and the Persians, including hiding a message in the belly of a hare carried by a hunter, tattooing it on the shaven head of a slave whose hair was then allowed to grow back, and writing it on the wooden base under the wax of a writing tablet [867]. Francis Bacon proposed a system which embedded a binary message in a book at one bit per letter by alternating between two different fonts [1468]. Until quite modern times, most writers considered hiding confidential information much more important than enciphering it [1954]. Military and intelligence organizations are keenly aware that traffic security if often more important than content confidentiality, and have used all sorts of technologies from the microdots used by spies to low-probability-of-intercept radios.

When it comes to hiding data in other data, the modern terminology of the subject is as follows [1475]. The copyright mark, or in the case of steganography, the *embedded text*, is hidden in the *cover-text* producing the *marked text* or in the case of steganography the *stego-text*. In most cases, additional secret information is used during this process; this is the *marking key* or *stego-key*, and some function of it is typically needed to recover the mark or embedded text. Here, the word 'text' can be replaced by 'audio', 'video' and so on, as appropriate.

A wide variety of embedding schemes has been proposed.

- Many people have proposed hiding mark or secret message in the least significant bits of an audio or video signal. This isn't usually a very good strategy, as the hidden data is easy to detect statistically (the least significant bits are no longer correlated with the rest of the image), and it's trivial to remove or replace. It's also severely damaged by lossy compression techniques.
- A better technique is to hide the mark at one or more locations determined by a secret key. This was first invented in classical China. The sender and receiver had copies of a paper mask with holes cut out of it at random locations. The sender would place his mask over a blank sheet of paper, write his message in the holes, then remove it and compose a cover message including the characters of the secret embedded message. This trick was reinvented in the 16th century by the Italian mathematician Cardan and is now known to cryptographers as the Cardan grille [974].
- A modern version of this hides a mark in a `.gif` format image as follows. A secret key is expanded to a keystream which selects an appropriate number of pixels. The embedded message is the parity of the color codes for these pixels. In practice even a quite large number of the pixels in an image can have their color changed to that of a similar one in the palette without any visible effects [947]. However, if all the pixels are tweaked in

this way, then again the hidden data is easy to remove by just tweaking them again. A better result is obtained if the cover image and embedding method are such that 1% of the pixels can safely be tweaked. Then, if the warden repeats the process but with a different key, a different 1% of the pixels will be tweaked and only 1% of the bits of the hidden data will be corrupted. These can then be recovered using an error-correcting code.

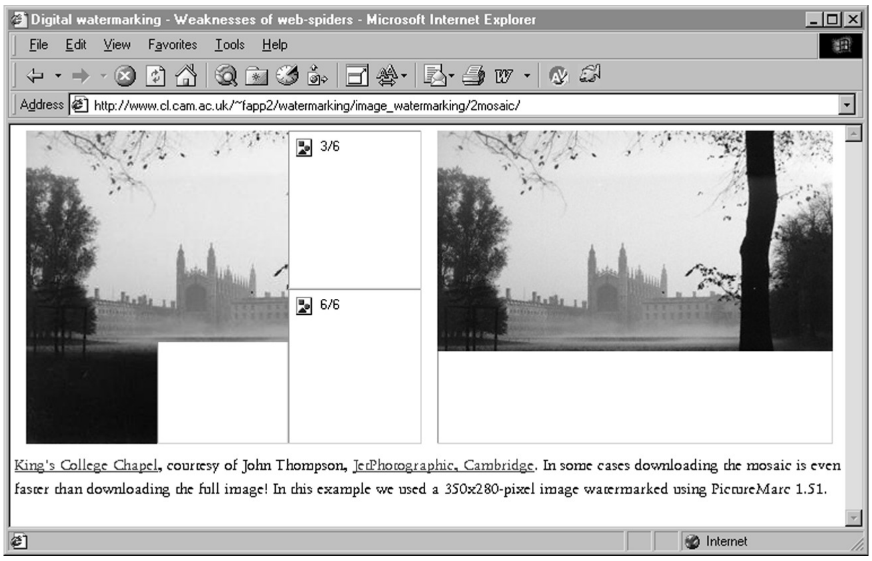
- In general, the introduction of noise or distortion – as happens with lossy compression – will introduce errors into the hidden data almost regardless of the embedding method unless some kind of error correcting code is added. A system proposed for banknote marking, Patchwork, uses a repetition code – the key selects two subsets of pixels, one of which is marked by increasing the luminosity and the other by decreasing it. This embeds a single bit; the note is either watermarked using that key, or it isn't [218, 810]. This is reminiscent of differential power analysis: the key tells you how to sort your input data into two piles, and if the key was right they're noticeably different.
- In the general case, one may want to embed more than one bit, and have the embedded data to survive very high levels of induced errors. So a common technique is to use direct-sequence spread-spectrum techniques borrowed from electronic warfare [1828]. You have a number of secret sequences, each coding a particular symbol, and you add one of them to the content to mark it.
- Spread spectrum encoding is often done in a transform space to make its effects less perceptible and more robust against common forms of compression. These techniques are also commonly used in conjunction with perceptual filtering, which emphasises the encoding in the noisiest or perceptually most significant parts of the image or music track, where it will be least obtrusive, and de-emphasises it in quiet passages of music or large expanses of color [278].
- Some schemes use the characteristics of particular media, such as a scheme for marking print media by moving text lines up or down by a three-hundredth of an inch [305], or adding extra echoes to music below the threshold of perception [218]. So far, such techniques don't seem to have become as robust, or as widely used, as generic techniques based on keyed embedding using transform spaces, spread spectrum and perceptual filtering.

Progress in copyright marking was very rapid in the late 1990s: people invented marking schemes which other people broke, until some systems were adopted in banknotes and in some tools such as Adobe's. From the mid-2000s, interest in copyright marking waned with the move to broadband, but research in steganography and steganalysis continued, merging with research in image forensics.

24.4.3 Attacks on copyright marking schemes

Throughout this book, we've seen attacks on cryptographic systems that occasionally involved cryptanalysis but more often relied on mistaken assumptions, protecting the wrong things, protocol failures and implementation bugs. And in the history of technology as a whole, inventions tend to end up being used to solve problems somewhat different from the problems the inventor was originally thinking about. Copyright marking has been no different on either count.

- In the beginning, many people tackled the problem of embedding hidden copyright messages so that ownership of a work could be proved in court. But this is a non-problem. Lawyers almost never have any difficulty in proving ownership of an exhibit; they don't rely on technical measures which might confuse a jury, but on documents such as contracts with bands and model release forms.
- As usual, many designers ignored Kerckhoffs' principle – that the security of a system should reside in the choice of key, not in the algorithm in use. But when marks are used to prove whether a particular digital object was licensed, this means disclosing them in court together with the marking keys, so it may be necessary to use multiple keys.
- As an example, color copiers sold in the US hide a *Machine Identification Code* (MIC) in the bit patterns of copies as an extra means of detecting currency forgers [1934]. Introduced by Xerox and Canon in the 1980s, apparently following a secret agreement with the government. Its existence was disclosed in a court case in the Netherlands in 2004, and the mechanism was then reverse engineered in a crowdsourced effort led by EFF. The MIC is a pattern of yellow dots 0.1mm in diameter that is barely visible to the human eye and repeated about 150 times on an A4 colour copy. There is now software to identify and remove it, so whistleblowers can sanitise sensitive documents before leaking them to the press [1552].
- Many marks simply add some noise to the signal. But if all the frames in a video carry the same mark, you can average them to get the mark and then subtract it out. Or you supply some known content to a marking system, and compare its input and output. Even if the mark is applied in a tamper-resistant process immediately after decryption, and every device adds a different mark, then if the mark consists of small signals added at discrete points in the content, an opponent can just decrypt the same ciphertext with several different devices and compare them to remove the marks.
- There have been attempts to develop a marking equivalent of public-key cryptography, so that (for example) anyone could insert a mark which only one principal could detect, or anyone could detect a mark that only one principal could have inserted. The former seems just about feasible if the mark can be inserted as the cover audio or video is being manufactured [482]. The latter seems a lot harder. First, you can't authenticate all of an image by embedding a signature in it, as then you'd be modifying it in order to prove that it has not been modified. Second, if you try to


Digital watermarking - Weaknesses of web-spiders - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Address
3/6
6/6
Internet

http://www.cl.cam.ac.uk/~fapp2/watermarking/image_watermarking/2mosaic/

King's College Chapel, courtesy of John Thompson, JetPhotographic, Cambridge. In some cases downloading the mosaic is even faster than downloading the full image! In this example we used a 350x280-pixel image watermarked using PictureMarc 1.51.

Figure 24.6: – the Mosaic attack (courtesy Jet Photographic, `www.jetphotographic.com`)

authenticate just the high-order bits or the salient features, then there are robustness issues: given a device that will detect a mark, an attacker can remove it by applying small changes to the image until the decoder cannot find it anymore [1466, 1135], then apply their own signature. So the main effort was invested in mechanisms that put a different mark in each instance of the content, as it is decrypted.

- Steganalysis techniques were developed to break most embedding schemes. For over a decade, people would propose new information hiding mechanisms at the Information Hiding Workshop, and the following year they'd be broken. The most prolific attack team was Jessica Fridrich and her students at Binghamton; her book on steganography is the starting point for serious work on the subject [706].

- The most successful marking startup – Digimarc – set up a service to track intellectual property on the web. They supplied tools to let picture owners embed invisible fingerprints, and had a bot which crawled the web looking for marked pictures and reported them to the copyright owner. There were various ways to defeat this. For example, a marked image could often be chopped up into smaller images which together look just like the original when rendered on a web page but in which a copyright mark won't be detected (Figure 24.6) [1471]. Digimarc worked for a while on monitoring broadcast streams; but over time, AI improved to the point that software can identify which song is being played directly (the pioneer, Shazam, was bought by Apple in 2017). Digimarc moved into security printing, licensing their marking technology to central banks as a counterfeit detection measure. For example, it's found in Euro banknotes, which it prevents from being scanned or copied using the latest equipment [1993]. Software packages such as Photoshop and Paintshop Pro now refuse to handle marked images. Digimarc now monitors packaging and provides labeling systems.

- The most general attacks on imperceptible copyright marking schemes involve suitably chosen distortions. Audio marks can be removed by randomly duplicating or deleting sound samples to introduce inaudible jitter; techniques used for click removal and resampling are also powerful mark removers. For images, a tool my students developed, called Stirmark, introduces the same kind of errors into an image as printing it on a high quality printer and then scanning it again with a high quality scanner. It applies a minor geometric distortion: the image is slightly stretched, sheared, shifted, and/or rotated by an unnoticeable random amount This defeated almost all the marking schemes in existence when it was developed and is now a standard benchmark for copyright mark robustness [1471].

For a fuller account of attacks on copyright marking schemes, see [706]. It's still difficult to design marking schemes that remain robust once the mark detection algorithm is known.

24.5 Policy

There was a vigorous policy debate in the 1990s and 2000s between the tech industry and many of the owners of 'intellectual property' (IP) – copyright, patents and trademarks – as the opening up of the Internet made copying easy and threatened traditional music, book and film publishers[8]. The reaction included a series of laws from copyright term extension through America's Digital Millennium Copyright Act (DMCA) to an IP Enforcement Directive in Europe, which shifted power in ways that many people in tech and elsewhere felt to be threatening. The get-out for tech was section 230 of the US Communications Decency Act of 1996 (CDA) which states that 'No provider or user of an interactive computer service shall be treated as the publisher or speaker of any information provided by another information content provider' so platforms cannot be held liable for copyright infringement by users. This favoured the growth of information service firms in the USA rather than Europe.

The US DMCA does give copyright owners the power ('Notice and Take Down') to compel ISPs to take down websites with infringing material. Although there is also a provision ('Notice and Put Back') for the subscriber to file a counter notice and have his stuff put back within 14 days unless the copyright owner files suit, in practice many ISPs will just terminate a customer's service rather than get involved in litigation. This led not just to a lot of music copying using peer-to-peer systems, but to floods of takedown requests from music industry lawyers, as well as to the push for DRM that we discussed earlier.

[8]The term 'intellectual property' is controversial. Many activists object to it as a propaganda term coined by corporate lobbyists who want people to start seeing patents and copyrights as permanent natural rights, like title to real estate or human rights, rather than as the temporary monopolies that they are.

Over half of the takedown requests to Google come from the top 16 copyright owners, with the top three generating over a billion a year – many of them to links that are not even on Google. Many complaining organisations get few or none of the links they complain about removed, as they are either not relevant or judged to be non-infringing; see Google's transparency reports for details [780]. This has real policy consequences: censoring a Chinese shop that pretends to be Nike is one thing, while censoring Black Lives Matter Peckham in response to a complaint from a white supremacist is quite another.

There are many side-effects: for example, the legal rules that allowed library lending and copying for personal use ('fair use' in the USA and 'fair dealing' in the UK) are being replaced by technical controls that don't. For example, when I applied for planning permission to extend my kitchen, I had to file four copies of a local plan; but the map software at our university library only lets you print three copies. This is quite deliberate. Legal controls are supplemented by access controls, and the legal privilege given to those access controls by the DMCA and comparable EU laws creates a new bundle of rights, described by legal scholars as 'paracopyright' [519].

In effect, copyright regulations are no longer made by lawmakers in Washington or Brussels, but by programmers working for Microsoft or Apple or Amazon. The result has been to erode the rights of copyright users. In one spectacular example, Amazon quietly removed from its customers' Kindles an edition of George Orwell's '1984' and 'Animal Farm' over which some dispute had arisen [1771]. This was a spectacular illustration of the huge gap between owning a physical copy of a book, and 'owning' an e-book – in fact you just bought a license from a vendor who wrote the license so as to give you next to no rights at all.

At the same time, copyright law suddenly became relevant to millions of people. Whereas in the past it was only a concern of specialists such as publishers, it now touches the lives of everyone who downloads music, time-shifts movies, or maintains a personal web page. As the law has failed to keep up with technology, the gap between what it permits and what people actually do has become wider. In the UK, for example, it's technically illegal to rip a CD to listen to on your phone, yet as this is one of the main reasons that people still buy CDs, the British Phonographic Industry (the trade body) graciously says it won't sue anybody. But many of the minor infringements that used to take place in private, or unsurveilled public spaces (such as singing a song in a pub), now go online (as when a phone video clip of the song gets on someone's social-network page). John Tehranian calculates that a typical law professor commits over 80 copyright infringements a day, carrying statutory penalties of over \$10m [1805]. In effect, we only tolerated copyright law because it wasn't enforced against private individuals. Technology makes enforcement possible, the consolidation of copyrights into an ever smaller number of corporate owners and collecting societies makes for a concentrated lobby, greed makes abuses happen, and the frictions increase.

The consolidation of copyrights also leads to injustice in the distribution of income. I already mentioned the problems with collecting societies, which in effect tax venues and distribute the proceeds in such a way that the rich get lots and the small fry not so much at all; this has become worse with streaming, whose payouts are a function of plays rather than users. So if my granddaughter pays £10 a month and listens to Ariana Grade four hours a day while I pay the same and listen to Kathryn Tickell two hours a week, then rather than giving them £10 each (less Apple's 30% commission), Ariana will get fourteen times what Kathryn gets [1506]. This means that most of your subscription – or at least of the money the tech firms don't take one way or another – goes to the megastars like Ariana, and Ed Sheeran and Lady Gaga.

There are also privacy concerns. In the old days, people would buy a book or a record for cash; the move to downloads means that servers run by firms such as Google, Spotify and Apple have a record of what people watch and listen to, and this can be subpoena'ed. (The move to online bookselling and then to Kindles has created similar records at Amazon.) These records are also used for marketing. A survey for the Privacy Commissioner of Canada found many examples of intrusive behavior, including e-book software profiling individuals, DoubleClick advertising in a library service, systems tracking individuals via IP addresses, and contradictions between vendors' stated privacy policies and observed behaviour – including undisclosed communications to third parties [664]. Why do copyright owners, or big tech firms claiming to act on their behalf, get away with so much? The answer lies in the dynamics of lobbying.

24.5.1 The IP lobby

The IP lobby has its modern origins in an effort by the drug company Pfizer to extend patent protection on its drugs from the USA to less developed countries like Brazil and India in the 1970s. The history is told by Peter Drahos and John Braithwaite [567]; in summary, Pfizer and the other drug companies allied themselves with the music and film industry (who wanted to cut bootlegging and copying), the luxury-goods industry (who wanted to reduce the number of cheap knock-offs), and a number of other US players (including the Business Software Alliance), and persuaded the US government to start applying pressure on other countries to bring their patent, copyright and trade-mark laws in line with America's. From the mid-1980s this was largely a matter of bullying less developed countries who wanted trade deals, but in 1995 a treaty on Trade-Related Aspects of Intellectual Property Rights (TRIPS) took effect for members of the World Trade Organisation (WTO), followed by two treaties of the World Intellectual Property Organisation (WIPO) in 1996. Essentially the USA and the EU got together and bullied holdouts like India and Brazil.

The implementation of these treaties stirred up opposition in developed countries as people began to realise how they might be affected. In the USA, the Digital Millennium Copyright Act of 1998 made it an offence to circumvent a copyright-protection mechanism, as required by WIPO, while in the European Union the Copyright Directive of 2001 had a similar effect. This was seen as enabling vendors to create closed platforms and control competition; it was also a threat by the free and open source software movement, and by security researchers – especially after the Russian researcher Dmitri Sklyarov was arrested at a US conference at the request of Adobe after his employer had sold tools circumventing password protection on pdf documents.

There were many other high-profile incidents; for example, I was on the program committee of the 2001 Information Hiding Workshop when an attempt was made by the Recording Industry Association of America (RIAA) to force the program chair to pull a paper by Ed Felten and his students describing vulnerabilities in a copyright marking scheme being touted for a digital music standard [483]. Ed then sued RIAA, in a landmark academic-freedom case [604]. The irony is that the promoters of this challenge had issued a public challenge to academics and others to break their scheme. The next case was Bunnie Huang's book "Hacking the Xbox": this described how, as an MIT student, he'd overcome the protection mechanisms in the first version of Microsoft's games console [906]. The book he wrote caused his publisher to take fright, but he found another one. The encroachment on liberties threatened by rights-management mechanisms and anti-hacking laws led to the growth of digital-rights NGOs in a number of countries (others had them already as a result of the 'Crypto Wars'; I'll discuss all this in more detail in Part III).

One turning point came in 2003–4, as the IP lobby was trying to steer a further measure through Brussels, the IP Enforcement Directive. In its original form, this would have further ratcheted up the penalties on infringers and removed the prospects for public-interest defences based on free speech or fair use. This time opponents of the measure managed to assemble a sufficiently strong coalition of opposing interests that the measure was substantially amended. This opposition led to the establishment the following year of EDRi, an NGO that promotes European digital rights, and is supported by several dozen NGOs in Europe who realised that a lobbying presence in Brussels was essential.

The IP lobby's mistake was trying to compel every country in Europe to make patent infringement a crime, rather than just a civil matter. This was intended by Big Pharma to undermine firms who make low-cost generic versions of drugs once they have come off patent. At present, drug patent holders try to prolong their patents by 'evergreening' – filing subsidiary, later patents, with often dubious derivative claims – which the generic drugmakers deal with by offering their distributors indemnities against having to pay damages. Making infringement a criminal matter would have upset these arrangements. This caused the generic drugmakers to oppose the directive vigorously, along with supermarkets, car parts dealers and consumer groups. Even the software industry started to get nervous: we pointed out to Microsoft that thousands of companies believe that Microsoft is infringing their patents, but don't have the money to go the distance in a civil court. If patent infringement became a crime, surely they would take their grievances to the police? Would Bill risk arrest on some future trip to Europe? The attempt to criminalise patent infringement collapsed when tech firms withdrew their support. A rich, powerful lobby isn't stopped by fine words, or by outrage from university professors and free-software activists. It's stopped when it comes up against another rich, powerful lobby pushing in the opposite direction.

Some copyright activists hope that once copyright expires – or assuming that lots of material can be made available under a Creative Commons license – then everything will be hunky-dory. I doubt it. The theory behind both copyright and patent was to offer creators a temporary monopoly in order to increase the supply of creations. Initially copyright was for 18 years, then 35, then 50, then the creator's lifetime plus 70 years after that. Cynics noted that whenever Mickey Mouse was in danger of going out of copyright, the US government would step in to increase the copyright term, and bully other governments to fall in line. (Other cynics noted that the copyright term for musical performance was extended from 50 years to 70 after Sir Cliff Richard let the then Prime Minister Tony Blair holiday at his mansion in Barbados.) Some lawyers would like to extend copyright term indefinitely, but that violates the social contract on which copyright is based and it also doesn't solve the problem of preservation: many publishers have failed to look after their own back catalogue properly and had to retrieve copies from national deposit collections.

Curating old bits costs money, just as curating old manuscripts does; indeed the film industry has recently discovered that archiving digital productions actually costs more than they used to pay in the old days, when they just locked away the master copies in an old salt mine. There's just an awful lot of bits generated during digital production, and copying them to new disks every few years isn't cheap. In the long term, once bitstrings belong to nobody, who will pay for their upkeep? Might we extend the existing taxpayer-funded deposit library system to digital materials? But such organisations typically fail to make much progress with digital materials for a number of reasons, from lack of understanding to being too defensive about copyright law[9]. There has been a very creditable effort by the Internet Archive, a San Francisco NGO, to preserve online material for future generations, and has had an open library project since 2006; and Google scanned many books in university libraries, eventually getting a legal settlement with authors and other interested parties following a long court case[10]. As a result, Google Books can make millions of volumes searchable, supply the full contents of books that are out of copyright; it can enable people to search copyrighted materials, and see snippets from them, as a fair use allowed under copyright law; but it was not allowed to sell electronic versions of copyright material and simply pay the authors a fixed royalty, as it had wanted to, unless it has agreements with the publishers. The latest development in 2020 is a lawsuit by book publishers (including Wiley, the publisher of this book) to stop the Internet Archive lending out electronic copies of books [973]. The copyright wars drag on, even despite the pandemic.

24.5.2 Who benefits?

As I mentioned in section 8.6.4, a turning point in the copyright wars came in 2005. In January of that year, Google's chief economist Hal Varian addressed a DRM conference in Berlin and asked who would benefit from stronger DRM. He pointed out that, in classical economic theory, a technical link between two industries would usually benefit the more concentrated industry (for example, car makers and car parts). But the platform industry was concentrated (then it was Apple, Microsoft and Sony) while the music industry was less so (four majors and many independents): so why should the music industry expect to

[9]When the British Library wanted to archive our NGO web page they wanted us to sign copyright release and indemnity forms, which we couldn't do for material from third parties or written by people who'd left or died. The only practical way forward is to just put stuff online and take it down if anyone makes a convincing objection. That's what tech firms do; legacy organisations often don't have the confidence.

[10]The Authors Guild, Inc. et al v. Google, Inc.; October 16, 2015 (2d Circuit); November 14, 2013 (SDNY)

be the winners from better DRM? Economic theory says that platform vendors should win more. The music industry scoffed, and yet by the end of that year they were hurting – by the fall of that year, they were tearfully lobbying the UK government and the European Commission to 'do something' about Apple, such as forcing it to open its FairPlay DRM scheme.

Over the next few years, Hal's prediction came true. The music majors lost their market power to firms like Apple, Amazon and Spotify, while Netflix established a dominant position in distributing video. Music downloading – with or without DRM – changed the structure and dynamics of the music industry. Bands used to rely on the majors to promote them, but now they can do that themselves by giving away their albums on their websites; they always made most of their money from performances, and now they make more than ever – just as John Perry Barlow had predicted back in 1994. In fact, smart bands now go with an indie label, as then they'll get a bigger share of the streaming and other revenues. And thanks to the pandemic, there is now a rapidly-growing new sector of online concerts, where bands perform in empty venues and stream live to their fans, cutting out both the subscription streaming services and the big firms that own the big venues [1631].

24.6 Accessory Control

One of the most important and rapidly-growing uses of cryptographic mechanisms and of rights-management technology generally since the DMCA was passed is in accessory control. The familiar example is the printer cartridge.

The practice started in 1996 with the Xerox N24 (see [1762] for the history of cartridge chips). In a typical system, if the printer senses a third-party cartridge, or a refilled cartridge, it may silently downgrade from 1200 dpi to 300 dpi, or even refuse to work at all. In 2003, expiry dates and ink usage controls were added [1173]; and modern cartridges now limit the amount of ink dispensed electronically rather than waiting for it to run out physically. The latest development is region coding: you can't use US ink cartridges in a recently UK-purchased HP printer. Other industries are adopting this technology. For example, the amount of RAM you are allowed to use in our lab oscilloscope depends on how much you paid for it.

After some grumbling, European regulators decided to put up with this, but in the USA, the matter was decided in court. The printer maker Lexmark sued SCC, which had reverse-engineered their print-cartridge crypto, alleging violation of the Digital Millennium Copyright Act. Although they won at first instance, they lost on appeal in 2004 [1123]. In a similar case, Chamberlain (who make garage door openers) sued Skylink (who made compatible openers) and also lost, losing the appeal too in 2004. This settled US law in favour of a free market for cryptologists, which was the position before the DMCA came along [1595]. A firm wanting to control its aftermarket using crypto chips is free to hire the smartest cryptographers it can find to build authentication chips that are really hard to hack, while its competitors are free to hire the smartest cryptanalysts they can find to try to reverse-engineer them.

There are now many, many more examples. Even things that never used to have electronics in them, and that don't need electronics for any purpose, have acquired chips to enforce predatory business models. There are hundreds of examples: one that came up in 2020 as I was revising this chapter is their use in water filters in GE fridges. Six months after he bought a 'smart' fridge, Jack Busch got a demand that he buy another water filter for $54.99. It turned out that the filtered water option would turn itself off unless you bought a new filter every six months, whether you needed it or not. Jack duly figured out how a hackand published it [343].

Is accessory control objectionable? The view that I took in the second edition of this book was that of standard economics: depends on how competitive the markets are. If cartridges have a high profit margin but the market for printers is competitive, competition will push down the price of printers to compensate for the high-priced cartridges [1876]. But in many other industries it might be anticompetitive; it just depends on how concentrated the industry is, and in winner-take-all platform markets it could be particularly objectionable [72].

I have since changed my mind. Competition matters, and we're seeing less of it as one industry after another adopts software in its products and becomes more like the software industry, with its tendency to monopoly that we discussed in chapter 8. For example, John Deere now fits its tractors with locks that limit repairs to authorised dealers, causing great resentment among farmers at having to pay a $230 call-out and $135 an hour for a technician to authorise a spare part [1042]. The use of cryptographic mechanisms for product tying and bundling is among the anti-competitive factors with which our policymakers are now realising they have to deal. In the case of tractors, a right-to-repair law may be one of the necessary mitigations.

Sustainability also matters, and technical tying mechanisms are often about shortening product lives, leading to unnecessary consumption. Forcing a six-monthly change of water filter cartridges as a good example; we use ours for about five years. Such mechanisms also lead to products that are fragile and difficult to maintain. Another common outcome if you buy a 'smart fridge' is that it will turn into a frosty brick a couple of years later, when the vendor stops maintaining the server that it speaks to. I will discuss this at greater length in section 28.5.

The covid pandemic has illustrated other side-effects of accessory control. Early in the lockdown, some hospitals did not have enough batteries for the respirators used by their intensive-care clinicians, now they were being used 24 x 7 rather than occasionally. The market-leading 3M respirators and the batteries that powered them had authentication chips, so the company could sell batteries for over $200 that cost $5 to make. Hospitals would happily have bought more for $200, but China had nationalised the factory the previous month, and the lawyers wouldn't let anybody do anything; 3M wouldn't release the keys to other component suppliers. The fix in this case was competition; respirators from other suppliers are cheaper and don't insist on proprietary batteries, while in Southampton, Paul Elkington and colleagues at the medical school designed their own, making the design open to everyone in the world who wants to make them [607]. Competition did indeed fix 3M, but at some cost to medical staff who didn't have enough personal protective equipment in the early months of the pandemic. The use of market control mechanisms can have implications not just for sustainability tomorrow, but for safety today.

24.7 Summary

The technical protection of digital content against unauthorised copying is a wicked problem both technically and politically. It's difficult technically because general-purpose computers can copy bitstrings at no cost, and it's difficult politically because rights-management technology has done a lot of collateral damage. That the music industry itself was one of the casualties may have been just, but doesn't solve the continuing problems. These are tied up with much broader and deeper problems of competition, consumer protection and sustainability.

Research Problems

Many of the tough problems around copyright in 2020 are policy problems rather than technical ones. If you want to do work on information hiding, that nowadays has become entangled with digital image forensics; the leaders are Jessica Fridrich and her team at Binghamton, so I'd suggest you read her books as a starting point [706]. For software obfuscation, a good starting point is the report of a 2019 Dagstuhl seminar on the subject organised by Bjorn De Sutter and colleagues [542].

Further Reading

Kahn is, as usual, good historical background reading [974]. The software copy protection techniques of 30 years ago are discussed in [809]; there's a history of the coevolution of attack and defense in pay-TV systems in [1220]. As for information hiding, there's a book by Katzenbeisser and Petitcolas [997], as well as Jessica's books I already referred to [706].

For a principled discussion of the policy issues around copyright and open culture, you might start with Larry Lessig [1110, 1111] and Pam Samuelson [1592, 1593, 1594, 1595].