Chapter 6

Access Control

Microsoft could have incorporated e↵ective security measures as standard, but good sense prevailed. Security systems have a nasty habit of backﬁring and there is no doubt they would cause

enormous problems.

– RICK MAYBURY

Optimisation consists of taking something that works and replacing it with something that almost works

but is cheaper.

– ROGER NEEDHAM

# Introduction

I ﬁrst learned to program on an IBM mainframe whose input was punched cards and whose output was a printer. You queued up with a deck of cards, ran the job, and went away with printout. All security was physical. Then along came machines that would run more than one program at once, and the *protection problem* of preventing one program from interfering with another. You don’t want a virus to steal the passwords from your browser, or patch a banking application so as to steal your money. And many reliability problems stem from applications misunderstanding each other, or ﬁghting with each other. But it’s tricky to separate applications when the customer wants them to share data. It would make phishing much harder if your email client and browser ran on separate machines, so you were unable to just click on URLs in emails, but that would make life too hard.

From the 1970s, access control became the centre of gravity of computer security. It’s where security engineering meets computer science. Its function is to control which principals (persons, processes, machines, . . .) have access to which resources in the system – which ﬁles they can read, which programs they can execute, how they share data with other principals, and so on. It’s become horrendously complex. If you start out by leaﬁng through the 7000-plus pages of Arm’s architecture reference manual or the equally complex arrangements for

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Windows at the O/S level, your ﬁrst reaction might be ‘I wish I’d studied music instead!’ In this chapter I try to help you make sense of it all.

Access control works at a number of di↵erent levels, including at least:

1. Access controls at the application level may express a very rich, domain- speciﬁc security policy. The call centre sta↵ in a bank are typically not allowed to see your account details until you have answered a couple of security questions; this not only stops outsiders impersonating you, but also stops the bank sta↵ looking up the accounts of celebrities, or their neighbours. Some transactions might also require approval from a super- visor. And that’s nothing compared with the complexity of the access controls on a modern social networking site, which will have a thicket of rules about who can see, copy, and search what data from whom, and privacy options that users can set to modify these rules.
2. The applications may be written on top of middleware, such as a web browser, a bank’s bookkeeping system or a social network’s database man- agement system. These enforce a number of protection properties. For example, bookkeeping systems ensure that a transaction that debits one account must credit another, with the debits and credits balancing so that money cannot be created or destroyed; they must also allow the system’s state to be reconstructed later.
3. As the operating system constructs resources such as ﬁles and commu- nications ports from lower level components, it has to provide ways to control access to them. Your Android phone treats apps written by di↵er- ent companies as di↵erent users and protects their data from each other. The same happens when a shared server separates the VMs, containers or other resources belonging to di↵erent users.
4. Finally, the operating system relies on hardware protection provided by the processor and its associated memory-management hardware, which control which memory addresses a given process or thread can access.

As we work up from the hardware through the operating system and middle- ware to the application layer, the controls become progressively more complex and less reliable. And we ﬁnd the same access-control functions being imple- mented at multiple layers. For example, the separation between di↵erent phone apps that is provided by Android is mirrored in your browser which separates

web page material according to the domain name it came from (though this separation is often less thorough). And the access controls built at the appli- cation layer or the middleware layer may largely duplicate access controls in the underlying operating system or hardware. It can get very messy, and to make sense of it we need to understand the underlying principles, the common architectures, and how they have evolved.

I will start o↵ by discussing operating-system protection mechanisms that support the isolation of multiple processes. These came ﬁrst historically – being invented along with the ﬁrst time-sharing systems in the 1960s – and they re- main the foundation on which many higher-layer mechanisms are built, as well as inspiring similar mechanisms at higher layers. They are often described as

*discretionary access control* (DAC) mechanisms, which leave protection to the machine operator, or *mandatory access control* (MAC) mechanisms which are typically under the control of the vendor and protect the operating system itself from being modiﬁed by malware. I’ll give an introduction to software attacks and techniques for defending against them – MAC, ASLR, sandboxing, virtuali- sation and what can be done with hardware. Modern hardware not only provides CPU support for virtualisation and capabilities, but also hardware support such as TPM chips for trusted boot to stop malware being persistent. These help us tackle the toxic legacy of the old single-user PC operating systems such as DOS and Win95/98 which let any process modify any data, and constrain the many applications that won’t run unless you trick them into thinking that they are running with administrator privileges.

# Operating system access controls

The access controls provided with an operating system typically authenticate principals using a mechanism such as passwords or ﬁngerprints in the case of phones, or passwords or security protocols in the case of servers, then authorise access to ﬁles, communications ports and other system resources.

Access controls can often be modeled as a matrix of access permissions, with columns for ﬁles and rows for users. We’ll write r for permission to read, w for permission to write, x for permission to execute a program, and - for no access at all, as shown in Figure 6.1.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Operating  System | Accounts  Program | Accounting  Data | Audit  Trail |
| Sam Alice  Bob | rwx x  rx | rwx x  r | rw rw  r | r  –  r |

Fig. 6.1 – naive access control matrix

In this simpliﬁed example, Sam is the system administrator and has universal access (except to the audit trail, which even he should only be able to read). Alice, the manager, needs to execute the operating system and application, but only through the approved interfaces – she mustn’t have the ability to tamper with them. She also needs to read and write the data. Bob, the auditor, can read everything.

This is often enough, but in the speciﬁc case of a bookkeeping system it’s not quite what we need. We want to ensure that transactions are well-formed

– that each debit is balanced by credits somewhere else – so we don’t want Alice to have uninhibited write access to the account ﬁle. We would also rather that Sam didn’t have this access. So we would prefer that write access to the accounting data ﬁle be possible only via the accounting program. The access permissions might now look like in Figure 6.2:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| User | Operating  System | Accounts  Program | Accounting  Data | Audit  Trail |
| Sam | rwx | rwx | r | r |
| Alice | rx | x | – | – |
| Accounts program | rx | rx | rw | w |
| Bob | rx | r | r | r |

Fig. 6.2 – access control matrix for bookkeeping

Another way of expressing a policy of this type would be with *access triples* of *(user, program, ﬁle)*. In the general case, our concern isn’t with a program so much as a *protection domain* which is a set of processes or threads that share access to the same resources.

Access control matrices (whether in two or three dimensions) can be used to implement protection mechanisms as well as just model them. But they don’t scale well: a bank with 50,000 sta↵ and 300 applications would have a matrix of 15,000,000 entries, which might not only impose a performance overhead but also be vulnerable to administrators’ mistakes. We will need a better way of storing and managing this information, and the two main options are to compress the users and to compress the rights. With the ﬁrst, we can use groups or roles to manage large sets of users simultaneously, while with the second we may store the access control matrix either by columns (access control lists) or rows (capabilities, also known as ‘tickets’ to protocol engineers and ‘permissions’ on mobile phones) [1639, 2020].

## Groups and Roles

When we look at large organisations, we usually ﬁnd that most sta↵ ﬁt into one of a small number of categories. A bank might have 40 or 50: teller, call centre operator, loan oﬃcer and so on. Only a few dozen people (security manager, chief foreign exchange dealer, ...) will need personally customised access rights.

So we need to design a set of groups, or functional roles, to which sta↵ can be assigned. Some vendors (such as Microsoft) use the words *group* and *role* almost interchangeably, but a more careful deﬁnition is that a group is a list of principals, while a role is a ﬁxed set of access permissions that one or more principals may assume for a period of time. The classic example of a role is the oﬃcer of the watch on a ship. There is exactly one watchkeeper at any one time, and there is a formal procedure whereby one oﬃcer relieves another when the watch changes. In most government and business applications, it’s the role that matters rather than the individual.

Groups and roles can be combined. *The oﬃcers of the watch of all ships currently at sea* is a group of roles. In banking, the manager of the Cambridge branch might have their privileges expressed by membership of the group *man- ager* and assumption of the role *acting manager of Cambridge branch*. The group *manager* might express a rank in the organisation (and perhaps even a salary band) while the role *acting manager* might include an assistant accoun- tant standing in while the manager, deputy manager, and branch accountant are all o↵ sick.

Whether we need to be careful about this distinction is a matter for the application. In a warship, even an ordinary seaman may stand watch if everyone more senior has been killed. In a bank, we might have a policy that “transfers over $10m must be approved by two sta↵, one with rank at least manager and one with rank at least assistant accountant”. If the branch manager is sick, then the assistant accountant acting as manager might have to get the regional head oﬃce to provide the second signature on a large transfer.

## Access control lists

The traditional way to simplify the management of access rights is to store the access control matrix a column at a time, along with the resource to which the column refers. This is called an *access control list* or ACL (pronounced ‘ackle’). In the ﬁrst of our above examples, the ACL for ﬁle 3 (the account ﬁle) might look as shown here in Figure 6.3.

|  |  |
| --- | --- |
| User | Accounting  Data |
| Sam Alice  Bob | rw rw  r |

Fig. 6.3 – access control list (ACL)

ACLs have a number of advantages and disadvantages as a means of man- aging security state. They are a natural choice in environments where users manage their own ﬁle security, and became widespread in Unix systems from the 1970s. They are the basic access control mechanism in Unix-based systems such as Linux and Apple’s macOS, as well as in derivatives such as Android and iOS. The access controls in Windows were also based on ACLs, but have become more complex over time. Where access control policy is set centrally, ACLs are suited to environments where protection is data-oriented; they are less suited where the user population is large and constantly changing, or where users want to be able to delegate their authority to run a particular program to another user for some set period of time. ACLs are simple to implement, but are not eﬃcient for security checking at runtime, as the typical operating system knows

which user is running a particular program, rather than what ﬁles it has been

authorized to access since it was invoked. The operating system must either check the ACL at each ﬁle access, or keep track of the active access rights in some other way.

Finally, distributing the access rules into ACLs makes it tedious to ﬁnd all the ﬁles to which a user has access. Verifying that no ﬁles have been left world- readable or even world-writable could involve checking ACLs on millions of user ﬁles; this is a real issue for large complex ﬁrms. Although you can write a script to check whether any ﬁle on a server has ACLs that breach a security policy, you can be tripped up by technology changes; the move to containers has led to many corporate data exposures as admins forgot to check the containers’ ACLs too. (The containers themselves are often dreadful as it’s a new technology being sold by dozens of clueless startups.) And revoking the access of an employee

who has just been ﬁred will usually have to be done by cancelling their password or authentication token.

Let’s look at an important example of ACLs – their implementation in Unix (plus its derivatives Android, MacOS and iOS).

## Unix operating system security

In traditional Unix systems, ﬁles are not allowed to have arbitrary access control lists, but simply rwx attributes that allow the ﬁle to be read, written and exe- cuted. The access control list as normally displayed has a ﬂag to show whether the ﬁle is a directory, then ﬂags r, w and x for owner, group and world respec- tively; it then has the owner’s name and the group name. A directory with all ﬂags set would have the ACL:

drwxrwxrwx Alice Accounts

In our ﬁrst example in Figure 6.1, the ACL of ﬁle 3 would be:

-rw-r----- Alice Accounts

This records that the ﬁle is simply a ﬁle rather than a directory; that the ﬁle owner can read and write it; that group members (including Bob) can read it but not write it; that non-group members have no access at all; that the ﬁle owner is Alice; and that the group is Accounts.

The program that gets control when the machine is booted (the operating system kernel) runs as the supervisor, and has unrestricted access to the whole machine. All other programs run as users and have their access mediated by the supervisor. Access decisions are made on the basis of the userid associated with the program. However if this is zero (root), then the access control decision is ‘yes’. So root can do what it likes – access any ﬁle, become any user, or whatever. What’s more, there are certain things that only root can do, such as starting certain communication processes. The root userid is typically made available to the system administrator in systems with discretionary access control.

This means that the system administrator can do anything, so we have dif- ﬁculty implementing an audit trail as a ﬁle that they cannot modify. In our example, Sam could tinker with the accounts, and have diﬃculty defending himself if he were falsely accused of tinkering; what’s more, a hacker who man-

aged to become the administrator could remove all evidence of his intrusion. The traditional, and still the most common, way to protect logs against root compromise is to keep them separate. In the old days that meant sending the system log to a printer in a locked room; nowadays, it means sending it to an- other machine, or even to a third-party service. Increasingly, it may also involve mandatory access control, as we discuss later.

Second, ACLs only contain the names of users, not of programs; so there is no straightforward way to implement access triples of (user, program, ﬁle). Instead, Unix provides an indirect method: the *set-user-id* (suid) ﬁle attribute. The owner of a program can mark the ﬁle representing that program as suid, which enables it to run with the privilege of its owner rather than the privilege of the user who has invoked it. So in order to achieve the functionality needed by our second example above, we could create a user ‘account-package’ to own

ﬁle 2 (the accounts package), make the ﬁle suid and place it in a directory to which Alice has access. This special user can then be given the access that the accounts program needs.

But when you take an access control problem that has three dimensions – (user, program, data) – and implement it using two-dimensional mechanisms, the outcome is much less intuitive than triples and people are liable to make mistakes. Programmers are often lazy or facing tight deadlines; so they just make the application suid root, so it can do anything. This practice leads to some shocking security holes. The responsibility for making access control decisions is moved from the operating system environment to the application program, and most programmers are insuﬃciently experienced to check every- thing they should. (It’s hard to know what to check, as the person invoking a suid root program controls its environment and could manipulate this in unexpected ways.)

Third, ACLs are not very good at expressing mutable state. Suppose we want a transaction to be authorised by a manager and an accountant before it’s acted on; we can either do this at the application level (say, by having queues of transactions awaiting a second signature) or by doing something fancy with suid. Managing stateful access rules is diﬃcult; they can complicate the

revocation of users who have just been ﬁred, as it can be hard to track down the ﬁles they’ve opened, and stu↵ can get stuck.

Fourth, the Unix ACL only names one user. If a resource will be used by more than one of them, and you want to do access control at the OS level, you have a couple of options. With older systems you had to use groups; newer systems implement the Posix system of extended ACLs, which may contain any number of named user and named group entities. In theory, the ACL and

suid mechanisms can often be used to achieve the desired e↵ect. In practice, programmers are often in too much of a hurry to ﬁgure out how to do this, and security interfaces are usually way too ﬁddly to use. So people design their code to require much more privilege than it strictly ought to have, as that seems to be the only way to get the job done.

## Capabilities

The next way to manage the access control matrix is to store it by rows. These are called *capabilities*, and in our example in Figure 6.1 above, Bob’s capabilities would be as in Figure 6.4 here:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| User | Operating  System | Accounts  Program | Accounting  Data | Audit  Trail |
| Bob | rx | r | r | r |

Fig. 6.4 – a capability

The strengths and weaknesses of capabilities are roughly the opposite of ACLs. Runtime security checking is more eﬃcient, and we can delegate a right without much diﬃculty: Bob could create a certiﬁcate saying ‘Here is my capa- bility and I hereby delegate to David the right to read ﬁle 4 from 9am to 1pm,

signed Bob’. On the other hand, changing a ﬁle’s status becomes more tricky as it can be hard to ﬁnd out which users have access. This can be tiresome when we have to investigate an incident or prepare evidence. In fact, scalable systems end up using de-facto capabilities internally, as instant system-wide re- vocation is just too expensive; in Unix, ﬁle descriptors are really capabilities, and continue to grant access for some time even after ACL permissions or even ﬁle owners change. In a distributed Unix, access may persist for the lifetime of Kerberos tickets.

Could we do away with ACLs entirely then? People built experimental ma- chines in the 1970s that used capabilities throughout [2020]; the ﬁrst commercial product was the Plessey System 250, a telephone-switch controller [1575]. The IBM AS/400 series systems brought capability-based protection to the main- stream computing market in 1988, and enjoyed some commercial success. The public key certiﬁcates used in cryptography are in e↵ect capabilities, and became mainstream from the mid-1990s. Capabilities have started to supplement ACLs in operating systems, including more recent versions of Windows, FreeBSD and iOS, as I will describe later.

In some applications, they can be the natural way to express security policy. For example, a hospital may have access rules like ‘a nurse shall have access to all the patients who are on his or her ward, or who have been there in the last 90 days’. In early systems based on traditional ACLs, each access control decision required a reference to administrative systems to ﬁnd out which nurses and which patients were on which ward, when – but this made both the HR system and the patient administration system safety-critical, which hammered reliability. Matters were ﬁxed by giving nurses ID cards with certiﬁcates that

entitle them to access the ﬁles associated with a number of wards or hospital

departments [535, 536]. If you can make the trust relationships in systems mirror the trust relationships in that part of the world you’re trying to automate, you should. Working with the grain can bring advantages at all levels in the stack, making things more usable, supporting safer defaults, cutting errors, reducing engineering e↵ort and saving money too.

## DAC and MAC

In the old days, anyone with physical access to a computer controlled all of it: you could load whatever software you liked, inspect everything in memory or on disk and change anything you wanted to. This is the model behind *discretionary access control* (DAC): you start your computer in supervisor mode and then, as the administrator, you can make less-privileged accounts available for less- trusted tasks – such as running apps written by companies you don’t entirely trust, or giving remote logon access to others. But this can make things hard to manage at scale, and in the 1970s the US military started a huge computer-

security research program whose goal was to protect classiﬁed information: to ensure that a ﬁle marked ‘Top Secret’ would never be made available to a user with only a ‘Secret’ clearance, regardless of the actions of any ordinary user or even of the supervisor. In such a *multilevel secure* (MLS) system, the sysadmin

is no longer the boss: ultimate control rests with a remote government authority that sets security policy. The mechanisms started to be described as *mandatory*

*access control* (MAC). The supervisor, or root access if you will, is under remote control. This drove development of technology for mandatory access control – a fascinating story, which I tell in Part 2 of the book.

From the 1980s, safety engineers also worked on the idea of *safety integrity levels*; roughly, that a more dependable system must not rely on a less depend- able one. They started to realise they needed something similar to multilevel security, but for safety. Military system people also came to realise that the tamper-resistance of the protection mechanisms themselves was of central im- portance. In the 1990s, as computers and networks became fast enough to handle audio and video, the creative industries lobbied for *digital rights man- agement* (DRM) in the hope of preventing people undermining their business models by sharing music and video. This is also a form of mandatory access control – stopping a subscriber sharing a song with a non-subscriber is in many ways like stopping a Top Secret user sharing an intelligence report with a Secret user.

In the early 2000s, these ideas came together as a number of operating-system vendors started to incorporate ideas and mechanisms from the MAC research programme into their products. The catalyst was an initiative by Microsoft and Intel to introduce cryptography into the PC platform to support DRM. Intel believed the business market for PCs was saturated, so growth would come from home sales where, they believed, DRM would be a requirement. Microsoft started with DRM and then realised that o↵ering rights management for documents too might be a way of locking customers tightly into Windows and Oﬃce. They set up an industry alliance, now called the Trusted Computing Group, to introduce cryptography and MAC mechanisms into the PC platform. To do this, the operating system had to be made tamper-resistant, and this is achieved by means of a separate processor, the Trusted Platform Module (TPM), basically a smartcard chip mounted on the PC motherboard to support trusted boot and hard disk encryption. The TPM monitors the boot process, and at each stage a hash of everything loaded so far is needed to retrieve the key needed to decrypt the next stage. The real supervisor on the system is now no longer you, the machine owner – it’s the operating-system vendor.

MAC, based on TPMs and trusted boot, was used in Windows 6 (Vista) from 2006 as a defence against persistent malware1. The TPM standards and architecture were adapted by other operating-system vendors and device OEMs, and there is now even a project for an open-source TPM chip, OpenTitan, based on Google’s product. However the main purpose of such a design, whether its own design is open or closed, is to lock a hardware device to using speciﬁc software.

1Microsoft had had more ambitious plans; its project Palladium would have provided a new, more trusted world for rights-management apps, alongside the normal one for legacy software. They launched Information Rights Management – DRM for documents – in 2003 but corporates didn’t buy it, seeing it as a lock-in play. A two-world implementation turned out to be too complex for Vista and after two separate development e↵orts it was was abandoned; but the vision persisted from 2004 in Arm’s TrustZone, which I discuss below.

## Apple’s macOS

Apple’s macOS operating system (formerly called OS/X or Mac OS X) is based on the FreeBSD version of Unix running on top of the Mach kernel. The BSD layer provides memory protection; applications cannot access system memory (or each others’) unless running with advanced permissions. This means, for example, that you can kill a wedged application using the ‘Force Quit’ command without having to reboot the system. On top of this Unix core are a number of graphics components, including OpenGL, Quartz, Quicktime and Carbon, while at the surface the Aqua user interface provides an elegant and coherent view to the user.

At the ﬁle system level, macOS is almost a standard Unix. The default installation has the root account disabled, but users who may administer the system are in a group ‘wheel’ that allows them to su to root. If you are such a user, you can install programs (you are asked for the root password when you do so). Since version 10.5 (Leopard), it has been based on TrustedBSD, a variant of BSD that incorporates mandatory access control mechanisms, which are used to protect core system components against tampering by malware.

## iOS

Since 2008, Apple has led the smartphone revolution with the iPhone, which (along with other devices like the iPad) uses the iOS operating system – which is now (in 2020) the second-most popular. iOS is based on Unix; Apple took the Mach kernel from CMU and fused it with the FreeBSD version of Unix, making a number of changes for performance and robustness. For example, in vanilla Unix a ﬁlename can have multiple pathnames that lead to an inode

representing a ﬁle object, which is what the operating system sees; in iOS, this

has been simpliﬁed so that ﬁles have unique pathnames, which in turn are the subject of the ﬁle-level access controls. Again, there is a MAC component, where mechanisms from Domain and Type Enforcement (DTE) are used to tamper- proof core system components (we’ll discuss DTE in more detail in chapter 9).

Apple introduced this because they were worried that apps would brick the iPhone, leading to warranty claims.

Apps also have *permissions*, which are capabilities; they request a capability to access device services such as the mobile network, the phone, SMSes, the camera, and the ﬁrst time the app attempts to use such a service. This is granted if the user consents2. The many device services open up possible side-

channel attacks; for example, an app that’s denied access to the keyboard could deduce keypresses using the accelerometer and gyro. We’ll discuss side channels in Part 2, in the chapter on that subject.

The Apple ecosystem is closed in the sense that an iPhone will only run apps

2The trust-on-ﬁrst-use model goes back to the 1990s with the Java standard J2ME, popu- larised by Symbian, and the Resurrecting Duckling model from about the same time. J2ME also supported trust-on-install and more besides. When Apple and Android came along, they initially made di↵erent choices. In each case, having an app store was a key innovation; Nokia failed to realise that this was important to get a two-sided market going. The app store does some of the access control by deciding what apps can run. This is hard power in Apple’s case, and soft power in Android’s; we’ll discuss this in the chapter on phones.

that Apple has signed3. This enables the company to extract a share of app revenue, and also to screen apps for malware or other undesirable behaviour, such as the exploitation of side channels to defeat access controls.

The iPhone 5S introduced a ﬁngerprint biometric and payments, adding a *secure enclave* (SE) to the A7 processor to give them separate protection. Apple decided to trust neither iOS nor TrustZone with such sensitive data, since vulnerabilities give transient access until they’re patched. Its engineers also worried that an unpatchable exploit might be found in the ROM (this eventually happened, with Checkm8). While iOS has access to the system partition, the user’s personal data are encrypted, with the keys managed by the SE. Key management is bootstrapped by a unique 256-bit AES key burned into fusible links on the system-on-chip. when the device is powered up, the user has ten tries to enter a passcode; only then are ﬁle keys derived from the

master key and made available4. When the device is locked, some keys are still

usable so that iOS can work out who sent an incoming message and notify you; the price of this convenience is that forensic equipment can get some access to user data. The SE also manages upgrades and prevents rollbacks. Such public information as there is can be found in the iOS Security white paper [128].

The security of mobile devices is a rather complex issue, involving not just access controls and tamper resistance, but the whole ecosystem – from the provision of SIM cards through the operation of app stores to the culture of how people use devices, how businesses try to manipulate them and how government agencies spy on them. I will discuss this in detail in the chapter on phones in Part 2.

## Android

Android is the world’s most widely used operating system, with 2.5 billion active Android devices in May 2019, according to Google’s ﬁgures. Android is based on Linux; apps from di↵erent vendors run under di↵erent userids. The Linux mechanisms control access at the ﬁle level, preventing one app from reading another’s data and exhausting shared resources such as memory and CPU. As in iOS, apps have *permissions*, which are in e↵ect capabilities: they grant access to device services such as SMSes, the camera and the address book.

Apps come in signed packages, as .apk ﬁles, and while iOS apps are signed by Apple, the veriﬁcation keys for Android come in self-signed certiﬁcates and function as the developer’s name. This supports integrity of updates while

maintaining an open ecosystem. Each package contains a manifest that demands a set of permissions, and users have to approve the ‘dangerous’ ones – roughly, those that can spend money or compromise personal data. In early versions of Android, the user would have to approve the lot on installation or not run the app. But experience showed that most users would just click on anything to get through the installation process, and you found even ﬂashlight apps demanding access to your address book, as they could sell it for money. So Android 6 moved

3There are a few exceptions: corporates can get signing keys for internal apps, but these can be blacklisted if abused.

4I’ll discuss fusible links in the chapter on tamper resistance, and iPhone PIN retry defeats in the chapter on surveillance and privacy.

to the Apple model of trust on ﬁrst use; apps compiled for earlier versions still demand capabilities on installation.

Since Android 5, SELinux has been used to harden the operating system with mandatory access controls, so as not only to protect core system functions from attack but also to separate processes strongly and log violations. SELinux was developed by the NSA to support MAC in government systems; we’ll discuss it further in chapter 9. The philosophy is actions require the consent of three parties: the user, the developer and the platform.

As with iOS (and indeed Windows), the security of Android is a matter of the whole ecosystem, not just of the access control mechanisms. The new phone ecosystem is suﬃciently di↵erent from the old PC ecosystem, but inherits enough of the characteristics of the old wireline phone system, that it merits a separate discussion in the chapter on Phones in Part II. We’ll consider other aspects in the chapters on Side Channels and Surveillance.

## Windows

The current version of Windows (Windows 10) appears to be the third-most popular operating system, having achieved a billion monthly active devices in March 2020 (until 2016, Windows was the leader). Windows has a scarily com- plex access control system, and a quick canter through its evolution may make it easier to understand what’s going on.

Early versions of Windows had no access control. A break came with Win- dows 4 (NT), which was very much like Unix, and was inspired by it, but with some extensions. First, rather than just *read*, *write* and *execute* there were sep- arate attributes for *take ownership*, *change permissions* and *delete*, to support more ﬂexible delegation. These attributes apply to groups as well as users, and

group permissions allow you to achieve much the same e↵ect as suid programs

in Unix. Attributes are not simply on or o↵, as in Unix, but have multiple values: you can set *AccessDenied*, *AccessAllowed* or *SystemAudit*. These are parsed in that order: if an AccessDenied is encountered in an ACL for the relevant user or group, then no access is permitted regardless of any conﬂicting AccessAllowed ﬂags. The richer syntax lets you arrange matters so that ev- eryday conﬁguration tasks, such as installing printers, don’t have to require full administrator privileges.

Second, users and resources can be partitioned into domains with distinct administrators, and trust can be inherited between domains in one direction or both. In a typical large company, you might put all the users into a personnel domain administered by HR, while assets such as servers and printers may be in resource domains under departmental control; individual workstations may even be administered by their users. Things can be arranged so that the departmental resource domains trust the user domain, but not vice versa – so a hacked or careless departmental administrator can’t do too much external damage. The individual workstations would in turn trust the department (but not vice versa) so that users can perform tasks that require local privilege (such as installing software packages). Limiting the damage a hacked administrator can do still needs careful organisation. The data structure used to manage all this, and hide

the ACL details from the user interface, is called the *Registry*. Its core used to be the *Active Directory* which managed remote authentication – using either a Kerberos variant or TLS, encapsulated behind the *Security Support Provider Interface* (SSPI) which enables administrators to plug in other authentication services. Active Directory is essentially a database that organises users, groups, machines, and organisational units within a domain in a hierarchical namespace. It lurked behind Exchange, but is now being phased out as Microsoft becomes a cloud-based company and moves its users to Oﬃce365.

Windows has added capabilities in two ways which can override or comple- ment ACLs. First, users or groups can be either allowed or denied access by means of proﬁles. Security policy is set by groups rather than for the system as a whole; group policy overrides individual proﬁles, and can be associated with sites, domains or organisational units, so it can start to tackle complex

problems. Policies can be created using standard tools or custom coded.

The second way in which capabilities insinuate their way into Windows is that in many applications, people use TLS for authentication, and TLS certiﬁ- cates provide another, capability-oriented, layer of access control outside the purview of the Active Directory.

I already mentioned that Windows Vista introduced trusted boot to make the operating system itself tamper-resistant, in the sense that it always boots into a known state, limiting the persistence of malware. It added three further protection mechanisms to get away from the previous default of all software running as root. First, the kernel was closed o↵ to developers; second, the graphics subsystem and most drivers were removed from the kernel; and third, *User Account Control* (UAC) replaced the default administrator privilege with user defaults instead. Previously, so many routine tasks needed administrative privilege that many enterprises made all their users administrators, which made it diﬃcult to contain malware; and many developers wrote their software on the assumption that it would have access to everything (for a hall of shame, see [?]). According to Microsoft engineers, this was a major reason for Windows’ lack of robustness: applications monkey with system resources in incompatible ways. So they added an Application Information Service that launches applications which require elevated privilege and uses virtualisation to contain them: if they modify the registry, for example, they don’t modify the ‘real’ registry but simply the version of it that they can see.

Since Vista, the desktop acts as the parent process for later user processes, so even administrators browse the web as normal users, and malware they down- load can’t overwrite system ﬁles unless given later authorisation. When a task requires admin privilege, the user gets an *elevation prompt* asking them for an admin password. (Apple’s macOS is similar although the details under the hood di↵er somewhat.) As admin users are often tricked into installing malicious soft- ware, Vista added mandatory access controls in the form of ﬁle integrity levels. The basic idea is that low-integrity processes (such as code you download from

the Internet) should not be able to modify high-integrity data (such as system ﬁles) in the absence of some trusted process (such as veriﬁcation of a signature by Microsoft on the code in question).

In 2012, Windows 8 added *dynamic access control* which lets you control

user access by context, such as their work PC versus their home PC and their phone; this is done via account attributes in Active Directory, which appear as claims about a user, or in Kerberos tickets as claims about a domain. In 2016, Windows 8.1 added a cleaner abstraction with *principals*, which can be a user, computer, process or thread running in a security context or a group to which such a principal belongs, and *security identiﬁers* (SIDs) which represent such principals. When a user signs in, they get tickets with the SIDs to which they belong. Windows 8.1 also prepared for the move to cloud computing by adding *Microsoft accounts* (formerly LiveID), whereby a user signs in to a Microsoft cloud service rather than to a local server. Where credentials are stored locally, it protects them using virtualisation. Finally, Windows 10 added a number of features to support the move to cloud computing with a diversity of client devices, ranging from certiﬁcate pinning (which we’ll discuss in the chapter on Network Security) to the abolition of the old secure attention sequence ctrl- alt-del (which is hard to do on touch-screen devices and which users didn’t understand anyway).

To sum up, Windows evolved to provide a richer and more ﬂexible set of access control tools than any system previously sold in mass markets. It was driven by corporate customers who need to manage tens of thousands of sta↵ performing hundreds of di↵erent job roles across hundreds of di↵erent sites, pro- viding internal controls to limit the damage that can be done by small numbers of dishonest sta↵ or infected machines. (How such controls are actually designed will be our topic in the chapter on Banking and Bookkeeping.) The driver for this development was the fact that Microsoft made over half of its revenue from ﬁrms that licensed more than 25,000 seats; but the cost of the ﬂexibility that corporate customers demanded is complexity. Setting up access control for a big Windows shop is a highly skilled job.

## Middleware

Doing access control at the level of ﬁles and programs was ﬁne in the early days of computing, when these were the resources that mattered. Since the 1980s, growing scale and complexity has led to access control being done at other levels instead of (or as well as) at the operating system level. For example, bookkeeping systems often run on top of a database product such as Oracle, which looks to the operating system as one large ﬁle. So most of the access control has to be done in the database; all the operating system supplies may be an authenticated ID for each user who logs on. And since the 1990s, a lot of the work at the client end has been done by the web browser.

* + - 1. Database access controls

Before people started using websites for shopping, database security was largely a back-room concern. But enterprises now have critical databases to handle inventory, dispatch and e-commerce, fronted by web servers that pass transac- tions to the databases directly. These databases now contain much of the data that matter to our lives – bank accounts, vehicle registrations and employment records – and failures sometimes expose them to random online users.

Database products, such as Oracle, DB2 and MySQL, have their own access control mechanisms, which are modelled on operating-system mechanisms, with privileges typically available for both users and objects (so the mechanisms are a mixture of access control lists and capabilities). However, the typical database access control architecture is comparable in complexity with Windows; modern databases are intrinsically complex, as are the things they support – typically business processes involving higher levels of abstraction than ﬁles or domains. There may be access controls aimed at preventing any user learning too much about too many customers; these tend to be stateful, and may deal with possible statistical inference rather than simple yes-no access rules. I devote a whole chapter in Part 2 to exploring the topic of Inference Control.

Ease of administration is often a bottleneck. In companies I’ve advised, the operating-system and database access controls have been managed by di↵erent departments, which don’t talk to each other; and often IT departments have to put in crude hacks to make the various access control systems seem to work as one, but which open up serious holes.

Some products let developers bypass operating-system controls. For exam- ple, Oracle has both operating system accounts (whose users must be authen- ticated externally by the platform) and database accounts (whose users are authenticated directly by the Oracle software). It is often convenient to use the latter, to save the e↵ort of synchronising with what other departments are doing. In many installations, the database is accessible directly from the out- side; and even where it’s shielded by a web service front-end, this often contains loopholes that let SQL code be inserted into the database.

Database security failures can thus cause problems directly. The Slammer worm in 2003 propagated itself using a stack-overﬂow exploit against Microsoft SQL Server 2000 and created large amounts of traﬃc as compromised machines sent ﬂoods of attack packets to random IP addresses.

Just as Windows is tricky to conﬁgure securely, because it’s so complicated, the same goes for the typical database system. If you ever have to lock one down

– or even just understand what’s going on – you had better read a specialist textbook, such as [1174], or get in an expert.

* + - 1. Browsers

The web browser is another middleware platform on which we rely for access control and whose complexity often lets us down. The main access control rule is the *same-origin policy* whereby JavaScript or other active content on a web page is only allowed to communicate with the IP address that it originally came from; such code is run in a *sandbox* to prevent it altering the host system, as I’ll describe in the next section. But many things can go wrong.

In previous editions of this book, we considered web security to be a matter of how the servers were conﬁgured, and whether this led to cross-site vulnerabil- ities. For example a malicious website can include links or form buttons aimed at creating a particular side-e↵ect:

https://mybank.com/transfer.cgi?amount=10000USD&recipient=thief

The idea is that if a user clicks on this who is logged into mybank.com, there may be a risk that the transaction will be executed, as there’s a valid session cookie. So payment websites deploy countermeasures such as using short-lived sessions and an anti-CSRF token (an invisible MAC of the session cookie), and checking the Referer: header. There are also issues around web authentication mechanisms; I described OAuth brieﬂy in section 4.7.4. If you design web pages for a living you had better understand the mechanics of all this in rather more detail (see for example [119]); but many developers don’t take enough care. For example, as I write in 2020, Amazon Alexa has just turned out to have a misconﬁgured policy on cross-origin resource sharing, which meant that anyone who compromised another Amazon subdomain could replace the skills on a target Alexa with malicious ones [1481].

By now there’s a realisation that we should probably have treated browsers as access control devices all along. After all, the browser is the place on your laptop were you run code written by people you don’t want to trust and who will occasionally be malicious; as we discussed earlier, mobile-phone operating systems run di↵erent apps as di↵erent users to give even more robust protection. Even in the absence of malice, you don’t want to have to reboot your browser if it hangs because of a script in one of the tabs. (Chrome tries to ensure this by running each tab in a separate operating-system process.)

Bugs in browsers are exploited in *drive-by download* attacks, where visiting an attack web page can infect your machine, and even without this the modern web environment is extremely diﬃcult to control. Many web pages are full of trackers and other bad things, supplied by multiple ad networks and data brokers, which make a mockery of the intent behind the same-origin policy. Malicious actors can even use web services to launder origin: for example, the attacker makes a mash-up of the target site plus some evil scripts of his own, and then gets the victim to view it through a proxy such as Google Translate [1854]. A prudent person will go to their bank website by typing in the URL directly, or using a bookmark; unfortunately, the marketing industry trains everyone to click on links in emails.

## Sandboxing

The late 1990s saw the emergence of yet another type of access control: the software *sandbox*, introduced by Sun with its Java programming language. The model is that a user wants to run some code that she has downloaded as an applet, but is concerned that the applet might do something nasty, such as stealing her address book and mailing it o↵ to a marketing company, or just hogging the CPU and running down the battery.

The designers of Java tackled this problem by providing a ‘sandbox’ – a restricted environment in which the code has no access to the local hard disk (or at most only temporary access to a restricted directory), and is only allowed to communicate with the host it came from (the *same-origin policy*). This is enforced by having the code executed by an interpreter – the Java Virtual Machine (JVM) – with only limited access rights [783]. This idea was adapted to JavaScript, the main scripting language used in web pages, though it’s actually a di↵erent language; and other active content too. A version of Java is also used

on smartcards so they can support applets written by di↵erent ﬁrms.

## Virtualisation

Virtualisation is what powers cloud computing; it enables a single machine to emulate a number of machines independently, so that you can rent a *virtual ma- chine* (VM) in a data centre for a few tens of dollars a month rather than having to pay maybe a hundred for a whole server. Virtualisation was invented in the 1960s by IBM [496]; a single machine could be partitioned using VM/370 into multiple virtual machines. Initially this was about enabling a new mainframe to run legacy apps from several old machine architectures; it soon became normal for a company that bought two computers to use one for its production environ- ment and the other as a series of logically separate machines for development, testing, and minor applications. It’s not enough to run a virtual machine mon- itor (VMM) on top of a host operating system, and then run other operating systems on top; you have to deal with sensitive instructions that reveal proces- sor state such as absolute addresses and the processor clock. Working VMMs appeared for Intel platforms with VMware ESX Server in 2003 and (especially) Xen in 2003, which accounted for resource usage well enough to enable AWS and the cloud computing revolution. Things can be done more cleanly with processor support, which Intel has provided since 2006 with VT-x, and whose details I’ll discuss below. VM security claims rest to some extent on the argu- ment that a VMM hypervisor’s code can be much smaller than an operating system and thus easier to code-review and secure; whether there are actually fewer vulnerabilities is of course an empirical question [1575].

At the client end, virtualisation allows people to run a guest operating system on top of a host (for example, Windows on top of macOS), which o↵ers not just ﬂexibility but the prospect of better containment. For example, an employee might have two copies of Windows running on their laptop – a locked-down version with the oﬃce environment, and another for use at home. Samsung o↵ers Knox, which creates a virtual machine on a mobile phone that an employer can lock down and manage remotely, while the user enjoys a normal Android as well on the same device.

But using virtualisation to separate security domains on clients is harder than it looks. People need to share data between multiple VMs and if they use ad-hoc mechanisms, such as USB sticks and webmail accounts, this undermines the separation. Safe data sharing is far from trivial. For example, Bromium5 o↵ers VMs tailored to speciﬁc apps on corporate PCs, so you have one VM for Oﬃce, one for Acrobat reader, one for your browser and so on. This enables ﬁrms to work reasonably securely with old, unsupported software. So how do you download an Oﬃce document? Well, the browser exports the ﬁle from its VM to the host hard disc, marking it ‘untrusted’, so when the user tries to open it they’re given a new VM which holds that document plus Oﬃce and nothing else. When they then email this untrusted document, there’s an Outlook plugin that stops it being rendered in the ‘sent mail’ pane. Things get even more messy with network services integrated into apps; the rules on what sites can access which cookies are complicated, and it’s hard to deal with single signon and workﬂows

5Now owned by HP

that cross multiple domains. The clipboard also needs a lot more rules to control it. Many of the rules change from time to time, and are heuristics rather than hard, veriﬁable access logic. In short, using VMs for separation at the client requires deep integration with the OS and apps if it’s to appear transparent to the user, and there are plenty of tradeo↵s made between security and usability. In e↵ect, you’re retroﬁtting virtualisation on to an existing OS and apps that were not built for it.

*Containers* have been the hot new topic in the late 2010s. They evolved as a lightweight alternative to virtualisation in cloud computing and are often confused with it, especially by the marketing people. My deﬁnition is that while a VM has a complete operating system, insulated from the hardware by a hy- pervisor, a container is an isolated guest process that shares a kernel with other containers. Container implementations separate groups of processes by virtu- alising a subset of operating-system mechanisms, including process identiﬁers, interprocess communication, and namespaces; they also use techniques such as sandboxing and system call ﬁltering. The business incentive is to minimise the guests’ size, their interaction complexity and the costs of managing them, so they are deployed along with orchestration tools. Like any other new technol- ogy, there are many startups with more enthusiasm than experience. A 2019 survey by Jerry Gamblin disclosed that of the top 1000 containers available to developers on Docker Hub, 194 were setting up blank root passwords [743]. If you’re going to use cloud systems, you need to pay serious attention to your choice of tools, and also learn yet another set of access control mechanisms – those o↵ered by the service provider, such as the Amazon AWS Identity and Access Management (IAM). This adds another layer of complexity, which people

can get wrong. For example, in 2019 a security ﬁrm providing biometric iden- tiﬁcation services to banks and the police left its entire database unprotected;

two researchers found it using Elasticsearch and discovered millions of people’s photos, ﬁngerprints, passwords and security clearance levels on a database that they could not only read but write [1864].

But even if you tie down a cloud system properly, there are hardware limits on what the separation mechanisms can achieve. In 2018, two classes of powerful side-channel attacks were published: Meltdown and Spectre, which I discuss in the following section and at greater length in the chapter on side channels. Those banks that use containers to deploy payment processing rely, at least implicitly, on their containers being diﬃcult to target in a cloud the size of Amazon’s or Google’s. For a comprehensive survey of the evolution of virtualisation and containers, see Randal [1575].

# Hardware Protection

Most access control systems set out not just to control what users can do, but to limit what programs can do as well. In many systems, users can either write programs, or download and install them, and these programs may be buggy or even malicious.

Preventing one process from interfering with another is the *protection prob- lem*. The *conﬁnement problem* is that of preventing programs communicating

outward other than through authorized channels. There are several ﬂavours of each. The goal may be to prevent active interference, such as memory over- writing, or to stop one process reading another’s memory directly. This is what commercial operating systems set out to do. Military systems may also try to protect *metadata* – data about other data, or subjects, or processes – so that, for example, a user can’t ﬁnd out what other users are logged on to the system or what processes they’re running.

Unless one uses sandboxing techniques (which are too restrictive for general programming environments), solving the protection problem on a single proces- sor means, at the very least, having a mechanism that will stop one program from overwriting another’s code or data. There may be areas of memory that are shared to allow interprocess communication; but programs must be protected from accidental or deliberate modiﬁcation, and must have access to memory that is similarly protected.

This usually means that hardware access control must be integrated with the processor’s memory management functions. A classic mechanism is *segment addressing*. Memory is addressed by two registers, a segment register that points to a segment of memory, and an address register that points to a location within that segment. The segment registers are controlled by the operating system, often by a component of it called the *reference monitor* which links the access control mechanisms with the hardware.

The implementation has become more complex as processors themselves have. Early IBM mainframes had a two-state CPU: the machine was either in authorized state or it was not. In the latter case, the program was restricted to a memory segment allocated by the operating system; in the former, it could write to segment registers at will. An authorized program was one that was loaded from an authorized library.

Any desired access control policy can be implemented on top of this, given suitable authorized libraries, but this is not always eﬃcient; and system security depended on keeping bad code (whether malicious or buggy) out of the autho- rized libraries. So later processors o↵ered more complex hardware mechanisms. Multics, an operating system developed at MIT in the 1960s and which inspired Unix, introduced *rings of protection* which express di↵ering levels of privilege: ring 0 programs had complete access to disk, supervisor states ran in ring 2, and user code at various less privileged levels [1684]. Many of its features have been adopted in more recent processors.

There are a number of general problems with interfacing hardware and soft- ware security mechanisms. For example, it often happens that a less privileged process such as application code needs to invoke a more privileged process (e.g. a device driver). The mechanisms for doing this need to be designed with care, or security bugs can be expected. Also, performance may depend quite drasti- cally on whether routines at di↵erent privilege levels are called by reference or by value [1684].

## Intel processors

The Intel 8088/8086 processors used in early PCs had no distinction between system and user mode, and thus any running program controlled the whole machine6. The 80286 added protected segment addressing and rings, so for the ﬁrst time a PC could run proper operating systems. The 80386 had built-in virtual memory, and large enough memory segments (4 Gb) that they could be ignored and the machine treated as a 32-bit ﬂat address machine. The 486 and Pentium series chips added more performance (caches, out of order execution and additional instructions such as MMX).

The rings of protection are supported by a number of mechanisms. The current privilege level can only be changed by a process in ring 0 (the ker- nel). Procedures cannot access objects in lower-level rings directly but there are *gates* that allow execution of code at a di↵erent privilege level and manage the supporting infrastructure, such as multiple stack segments.

From 2006, Intel added hardware support for x86 virtualisation, known as Intel VT, which helped drive the adoption of cloud computing. Some pro- cessor architectures such as S/370 and PowerPC are easy to virtualise, and the theoretical requirements for this had been established in 1974 by Gerald Popek and Robert Goldberg [1532]; they include that all sensitive instructions that expose raw processor state be privileged instructions. The native Intel instruction set, however, has sensitive user-mode instructions, requiring messy workarounds such as application code rewriting and patches to hosted operat- ing systems. Adding VMM support in hardware means that you can run an operating system in ring 0 as it was designed; the VMM has its own copy of the memory architecture underneath. You still have to trap sensitive opcodes, but system calls don’t automatically require VMM intervention, you can run

unmodiﬁed operating systems, things go faster and systems are generally more

robust. Modern Intel CPUs now have nine rings: ring 0–3 for normal code, under which is a further set of ring 0–3 VMM root mode for the hypervisor, and at the bottom is *system management mode* (SMM) for the BIOS. In practice, the four levels that are used are SMM, ring 0 of VMX root mode, the normal ring 0 for the operating system, and ring 3 above that for applications.

In 2015, Intel released Software Guard eXtensions (SGX), which lets trusted code run in an *enclave* – an encrypted section of the memory – while the rest of the code is executed as usual. The company had worked on such architectures in the early years of the Trusted Computing initiative, but let things slide until it needed an enclave architecture to compete with TrustZone, which I discuss in the next section. The encryption is performed by a Memory Encryption En- gine (MEE), while SGX also introduces new instructions and memory-access checks to ensure non-enclave processes cannot access enclave memory (not even root processes). SGX has been promoted for DRM and securing cloud VMs, particularly those containing crypto keys, credentials or sensitive personal in- formation; this is under threat from Spectre and similar attacks, which I discuss in detail in the chapter on side channels. Since SGX’s security perimeter is the CPU, its software is encrypted in main memory, which imposes real penalties

6They had been developed on a crash programme to save market share following the advent of RISC processors and the market failure of the iAPX432.

in both time and space. Another drawback used to be that SGX code had to be signed by Intel. The company has now delegated signing (so bad people can get code signed) and from SGXv2 will open up the root of trust to others. So people are experimenting with SGX malware, which can remain undetectable by anti-virus software. As SGX apps cannot issue syscalls, it had been hoped that enclave malware couldn’t do much harm, yet Michael Schwarz, Samuel Weiser and Daniel Gruss have now worked out how to mount stealthy return-oriented programming (ROP) attacks from an enclave on a host app; they argue that the problem is a lack of clarity about what enclaves are supposed to do, and that any reasonable threat model must include untrusted enclaves [1688]. This

simple point may force a rethink of enclave architectures; Intel says ‘In the future, Intel’s control-ﬂow enforcement technology (CET) should help address this threat inside SGX’7. As for what comes next, AMD released full system memory encryption in 2016, and Intel announced a competitor. This aimed to

deal with cold-boot and DMA attacks, and protect code against an untrusted hypervisor; it might also lift space and performance limits on next-generation enclaves. However, Jan Werner and colleagues found multiple inference and data-injection attacks on AMD’s o↵ering when it’s used in a virtual environ- ment. [2010]. There’s clearly some way to go.

As well as the access-control vulnerabilities, there are crypto issues, which I’ll discuss in the chapter on Advanced Cryptographic Engineering.

## Arm processors

The Arm is the processor core most commonly used in phones, tablets and IoT devices; billions have been used in mobile phones alone, with a high-end device having several dozen Arm cores of various sizes in its chipset. The original Arm

(which stood for *Acorn Risc Machine*) was the ﬁrst commercial RISC design; it was released in 1985, just before MIPS. In 1991, Arm became a separate ﬁrm which, unlike Intel, does not own or operate any fabs: it licenses a range of processor cores, which chip designers include in their products. Early cores had a 32-bit datapath and contained ﬁfteen registers, of which seven were shadowed by banked registers for system processes to cut the cost of switching context on

interrupt. There are multiple supervisor modes, dealing with fast and normal interrupts, the system mode entered on reset, and various kinds of exception handling. The core initially contained no memory management, so Arm-based designs could have their hardware protection extensively customized; there are now variants with *memory protection units* (MPUs), and others with *memory management units* (MMUs) that handle virtual memory as well.

In 2011, Arm launched version 8, which supports 64-bit processing and en- ables multiple 32-bit operating systems to be virtualised. Hypervisor support added yet another supervisor mode. The cores come in all sizes, from large 64-bit superscalar processors with pipelines over a dozen stages deep, to tiny ones for cheap embedded devices.

TrustZone is a security extension that supports the ‘two worlds’ model men-

7The best defence against ROP attacks in 2019 appears to be Apple’s mechanism, in the iPhone X3 and later, for signing pointers with a key that’s kept in a register; this stops ROP attacks as the attacker can’t guess the signatures.

tioned above; it was made available to mobile phone makers in 2004 [44]. Phones were the ‘killer app’ for enclaves as operators wanted to lock subsidised phones and regulators wanted to make the baseband software that controls the RF functions tamper-resistant [1239]. TrustZone supports an open world for a nor- mal operating system and general-purpose applications, plus a closed enclave to handle sensitive operations such as cryptography and critical I/O (in a mo- bile phone, this can include the SIM card and the ﬁngerprint reader). Whether the processor is in a secure or non-secure state is orthogonal to whether it’s in user mode or a supervisor mode (though it must choose between secure and hy- pervisor mode). The closed world hosts a single *trusted execution environment* (TEE) with separate stacks, a simpliﬁed operating system, and typically runs only trusted code signed by the OEM – although Samsung’s Knox, which sets out to provide ‘home’ and ‘work’ environments on your mobile phone, allows regular rich apps to execute in the secure environment.

Although TrustZone was released in 2004, it was kept closed until 2015; OEMs used it to protect their own interests and didn’t open it up to app devel- opers, except occasionally under NDA. As with Intel SGX, there appears to be no way yet to deal with malicious enclave apps, which might come bundled as DRM with gaming apps or be mandated by authoritarian states; and, as with Intel SGX, enclave apps created with TrustZone can raise issues of transparency and control, which can spill over into auditability, privacy and much else. Again, company insiders mutter ‘wait and see’; no doubt we shall.

Arm’s latest o↵ering is CHERI8 which adds ﬁne-grained capability support to Arm CPUs. At present, browsers such as Chrome put tabs in di↵erent pro- cesses, so that one webpage can’t slow down the other tabs if its scripts run slowly. It would be great if each object in each web page could be sandboxed

separately, but this isn’t possible because of the large cost, in terms of CPU cycles, of each inter-process context switch. CHERI enables a process spawning a subthread to allocate it read and write accesses to speciﬁc ranges of memory, so that multiple sandboxes can run in the same process. This was announced as a product in 2018 and we expect to see ﬁrst silicon in 2021. The long-term promise of this technology is that, if it were used thoroughly in operating sys- tems such as Windows, Android and iOS, it would have prevented most of the zero-day exploits of recent years. Incorporating a new protection technology at scale costs real money, just like the switch from 32-bit to 64-bit CPUs, but it could save the cost of lots of patches.

# What Goes Wrong

Popular operating systems such as Android, Linux and Windows are very large and complex, with their features tested daily by billions of users under very diverse circumstances. Many bugs are found, some of which give rise to vulner- abilities, which have a typical lifecycle. After discovery, a bug is reported to a CERT or to the vendor; a patch is shipped; the patch is reverse-engineered, and an exploit may be produced; and people who did not apply the patch in time

8Full disclosure: this was developed by a team of my colleagues at Cambridge and else- where, led by Robert Watson.

may ﬁnd that their machines have been compromised. In a minority of cases, the vulnerability is exploited at once rather than reported – called a *zero-day* exploit as attacks happen from day zero of the vulnerability’s known existence. The economics, and the ecology, of the vulnerability lifecycle are the subject of intensive study by security economists; I’ll discuss this in Part III.

The traditional goal of an attacker was to get a normal account on the system and then become the system administrator, so they could take over the system completely. The ﬁrst step might have involved guessing, or social-engineering, a password, and then using an operating-system bug to escalate from user to root [1129].

The user/root distinction became less important in the twenty-ﬁrst century for two reasons. First, Windows PCs were the most common online devices (until 2017 when Android overtook them) so they were the most common attack targets; and as they ran many applications as administrator, any application that could be compromised gave administrator access. Second, attackers come in two basic types: targeted attackers, who want to spy on a speciﬁc individual and whose goal is typically to acquire access to that person’s accounts; and scale attackers, whose goal is typically to compromise large numbers of PCs, which they can organise into a botnet in order to make money. This, too, doesn’t require administrator access. Even if your mail client does not run as administrator, it can still be useful to a spammer who takes control.

However, botnet herders do prefer to install *rootkits* which, as their name suggests, run as root; they are also known as *remote access trojans* or RATs. The user/root distinction does still matter in business environments, where you do not want such a kit installed as an *advanced persistent threat* by a hostile intelligence agency, or corporate espionage ﬁrm, or by a crime gang doing re- connaissance to set you up for a large fraud.

A separate distinction is whether an exploit is *wormable* – whether it can be used to spread malware quickly online from one machine to another without human intervention. The Morris worm was the ﬁrst large-scale case of this, and there have been many since. I mentioned Wannacry and NotPetya in chapter 2; these used a vulnerability developed by the NSA and then leaked to other state actors. Operating system vendors react quickly to wormable exploits, typically releasing out-of-sequence patches, because of the scale of the damage they can do. The most troublesome wormable exploits at the time of writing are variants of Mirai, a worm used to take over IoT devices that use known root passwords. This appeared in October 2016 to exploit CCTV cameras, and hundreds of versions have been produced since, adapted to take over di↵erent vulnerable devices and recruit them into botnets. Wormable exploits often use root access but don’t have to; it is suﬃcient that the exploit be capable of automatic onward

transmission9.

In any case, the basic types of technical attack have not changed hugely in a generation and I’ll now consider them brieﬂy.

9In rare cases even human transmission can make malware spread quickly: an example was the ILoveYou worm which spread itself in 2000 via an email with that subject line, which caused enough people to open it, running a script that caused it to be sent to everyone in the new victim’s address book.

## Smashing the stack

The classic software exploit is the memory overwriting attack, colloquially known as ‘smashing the stack’, as used by the Morris worm in 1988; this infected so many Unix machines that it disrupted the Internet and brought malware force- fully to the attention of the mass media [1806]. Attacks involving violations of memory safety accounted for well over half the exploits against operating systems in the late 1990s and early 2000s [487] but the proportion has been dropping slowly since then.

Programmers are often careless about checking the size of arguments, so an attacker who passes a long argument to a program may ﬁnd that some of it gets treated as code rather than data. The classic example, used in the Morris worm, was a vulnerability in the Unix finger command. A common implementation of this would accept an argument of any length, although only 256 bytes had been allocated for this argument by the program. When an attacker used the command with a longer argument, the trailing bytes of the argument ended up overwriting the stack and being executed by the system.

The usual exploit technique was to arrange for the trailing bytes of the argument to have a *landing pad* – a long space of *no-operation* (NOP) commands, or other register commands that didn’t change the control ﬂow, and whose task was to catch the processor if it executed any of them. The landing pad delivered the processor to the attack code which will do something like creating a shell with administrative privilege directly (see Figure 6.5).

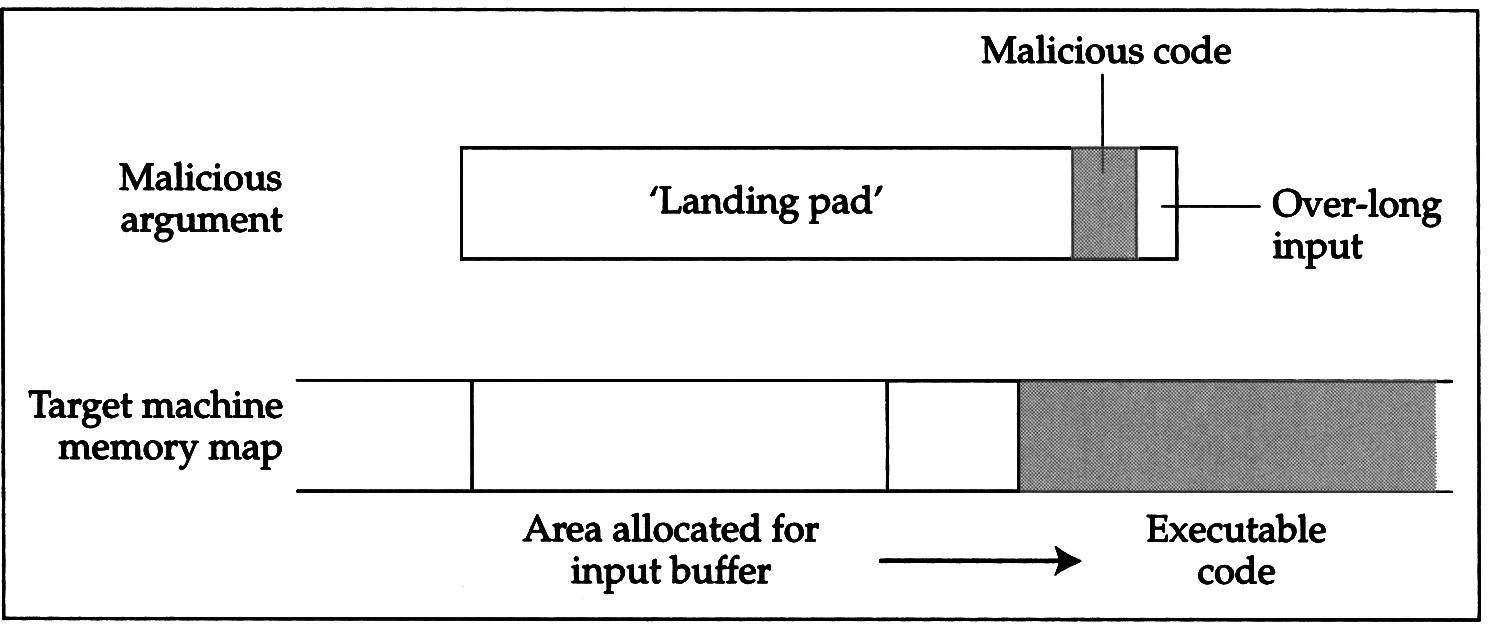


Figure 6.5: – stack smashing attack

Stack-overwriting attacks were around long before 1988. Most of the early 1960s time-sharing systems su↵ered from this vulnerability, and ﬁxed it [804]. Penetration testing in the early ’70s showed that one of the most frequently- used attack strategies was still “unexpected parameters” [1165]. Intel’s 80286 processor introduced explicit parameter checking instructions – verify read, ver- ify write, and verify length – in 1982, but they were avoided by most software designers to prevent architecture dependencies. Stack overwriting attacks have been found against all sorts of programmable devices – even against things like smartcards and hardware security modules, whose designers really should have known better.

## Other technical attacks

Many vulnerabilities are variations on the same general theme, in that they occur when data in grammar A is interpreted as being code in grammar B. A stack overﬂow is when data are accepted as input (e.g. a URL) and end up being executed as machine code. These are failures of *type safety*. In fact, a stack overﬂow can be seen either as a memory safety failure or as a failure to sanitise user input, but there are purer examples of each type.

The *use after free* type of safety failure is now the most common cause of remote execution vulnerabilities and has provided a lot of attacks on browsers in recent years. It can happen when a chunk of memory is freed and then still used, perhaps because of confusion over which part of a program is responsible for freeing it. If a malicious chunk is now allocated, it may end up taking its place on the heap, and when an old innocuous function is called a new, malicious function may be invoked instead. There are many other variants on the memory

safety theme; bu↵er overﬂows can be induced by improper string termination, passing an inadequately sized bu↵er to a path manipulation function, and many other subtle errors. See Gary McGraw’s book *‘Software Security* [1266] for a taxonomy.

*SQL injection attacks* are the most common attack based on failure to sani- tise input, and arise when a careless web developer passes user input to a back- end database without checking to see whether it contains SQL code. The game is often given away by error messages, from which a capable and motivated user may infer enough to mount an attack. There are similar command-injection problems a✏icting other languages used by web developers, such as PHP. The usual remedy is to treat all user input as suspicious and validate it. But this

can be harder than it looks, as it’s diﬃcult to anticipate all possible attacks and the ﬁlters written for one shell may fail to be aware of extensions present in another. Where possible, one should only act on user input in a safe context, by designing such attacks out; where it’s necessary to blacklist speciﬁc exploits, the mechanism needs to be competently maintained.

Once such type-safety and input-sanitisation attacks are dealt with, *race conditions* are probably next. These occur when a transaction is carried out in two or more stages, where access rights are veriﬁed at the ﬁrst stage and something sensitive is done at the second. If someone can alter the state in between the two stages, this can lead to an attack. A classic example arose in early versions of Unix, where the command to create a directory, ‘mkdir’, used to work in two steps: the storage was allocated, and then ownership was transferred to the user. Since these steps were separate, a user could initiate a ‘mkdir’ in background, and if this completed only the ﬁrst step before being suspended, a second process could be used to replace the newly created directory

with a link to the password ﬁle. Then the original process would resume, and change ownership of the password ﬁle to the user.

A more modern example arises with the wrappers used in containers to intercept system calls made by applications to the operating system, parse them, and modify them if need be. These wrappers execute in the kernel’s address space, inspect the enter and exit state on all system calls, and encapsulate only security logic. They generally assume that system calls are atomic, but modern

operating system kernels are highly concurrent. System calls are not atomic with respect to each other; there are many possibilities for two system calls to race each other for access to shared memory, which gives rise to *time-of-check-to- time-of-use* (TOCTTOU) attacks. An early (2007) example calls a path whose name spills over a page boundary by one byte, causing the kernel to sleep while the page is fetched; it then replaces the path in memory [1992]. There have been others since, and as more processors ship in each CPU chip as time passes, and containers become an ever more common way of deploying applications, this sort of attack may become more and more of a problem. Some operating systems have features speciﬁcally to deal with concurrency attacks, but this ﬁeld

is still in ﬂux.

A di↵erent type of timing attack can come from backup and recovery sys- tems. It’s convenient if you can let users recover their own ﬁles, rather than having to call a sysadmin – but how do you protect information assets from a

time traveller? People can reacquire access rights that were revoked, and play even more subtle tricks.

One attack that has attracted a lot of research e↵ort recently is *return- oriented programming* (ROP) [1708]. Many modern systems try to prevent type safety attacks by *data execution prevention* – marking memory as either code or data, a measure that goes back to the Burroughs 5000; and if all the code is signed, surely you’d think that unauthorised code cannot be executed? Wrong! An attacker can look for *gadgets* – sequences of instructions with some use- ful e↵ect, ending in a return. By collecting enough gadgets, it’s possible to assemble a machine that’s Turing powerful, and implement our attack code as a chain of ROP gadgets. Then all one has to do is seize control of the call stack. This evolved from the *return-to-libc attack* which uses the common shared library libc to provide well-understood gadgets; many variants have been de- veloped since, including an attack that enables malware in an SGX enclave to mount stealthy attacks on host apps [1688]. The latest attack variant, *block- oriented programming* (BOP), can often generate attacks automatically from crashes discovered by program fuzzing, defeating current control-ﬂow integrity controls [964]. This coevolution of attack and defence will no doubt continue.

Finally there are *side channels*. The most recent major innovation in attack technology targets CPU pipeline behaviour. In early 2018, two game-changing attacks pioneered the genre: *Meltdown*, which exploits side-channels created by out-of-order execution on Intel processors [1172], and *Spectre*, which exploits speculative execution on Intel, AMD and Arm processors [1068]. The basic idea is that large modern CPUs’ pipelines are so long and complex that they look ahead and anticipate the next dozen instructions, even if these are instructions that the current process wouldn’t be allowed to execute (imagine the access check is two instructions in the future and the read operation it will forbid is two instructions after that). The path not taken can still load information into a cache and thus leak information in the form of delays. With some cunning, one process can arrange things to read the memory of another. I will discuss Spectre and Meltdown in more detail in the chapter on side channels in the second part of this book. Although mitigations have been published, further attacks of the same general kind keep on being discovered, and it may take several years and a new generation of processors before they are brought entirely under control.

It all reminds me of the saying by Roger Needham at the head of this chapter. Optimisation consists of replacing something that works with something that almost works, but is cheaper; and modern CPUs are so heavily optimised that we’re bound to see more variants on the Spectre theme. Such attacks limit the protection that can be o↵ered not just by containers and VMs, but also by enclave mechanisms such as TrustZone and SGX. In particular, they may stop careful ﬁrms from entrusting high-value cryptographic keys to enclaves and prolong the service life of old-fashioned hardware cryptography.

## User interface failures

A common way to attack a fortress is to trick the guards into helping you, and operating systems are no exception. One of the earliest attacks was the *Trojan Horse*, a program the administrator is invited to run but which contains a nasty surprise. People would write games that checked whether the player was the system administrator, and if so would create another administrator account with a known password. A variant was to write a program with the same name as a common system utility, such as the ls command which lists all the ﬁles in a Unix directory, and design it to abuse the administrator privilege (if any) before invoking the genuine utility. You then complain to the administrator that something’s wrong with the directory. When they enter the directory and type ls to see what’s there, the damage is done. This is an example of the *confused deputy* problem: if A does some task on behalf of B, and its authority comes from both A and B, and A’s authority exceeds B, things can go wrong. The ﬁx in this particular case was simple: an administrator’s ‘PATH’ variable (the list of directories to be searched for a suitably-named program when a command is invoked) should not contain ‘.’ (the symbol for the current directory). Modern Unix versions ship with this as a default. But it’s still an example of how you have to get lots of little details right for access control to be robust, and these details aren’t always obvious in advance.

Perhaps the most serious example of user interface failure, in terms of the number of systems historically attacked, consists of two facts: ﬁrst, Windows is forever popping up conﬁrmation dialogues, which trained people to click boxes away to get their work done; and second, that until 2006 a user needed to be the administrator to install anything. The idea was that restricting software in-

stallation to admins enabled Microsoft’s big corporate customers, such as banks and government departments, to lock down their systems so that sta↵ couldn’t run games or other unauthorised software. But in most environments, ordinary people need to install software to get their work done. So hundreds of millions of people had administrator privileges who shouldn’t have needed them, and installed malicious code when a website simply popped up a box telling them to do something. This was compounded by the many application developers who insisted that their code run as root, either out of laziness or because they wanted to collect data that they really shouldn’t have had. Windows Vista started to move away from this, but a malware ecosystem is now well established in the PC world, and one is starting to take root in the Android ecosystem as businesses pressure people to install apps rather than using websites, and the apps demand access to all sorts of data and services that they really shouldn’t have. We’ll

discuss this later in the chapter on phones.

## Remedies

Software security is not all doom and gloom; things got substantially better during the 2000s. At the turn of the century, 90% of vulnerabilties were bu↵er overﬂows; by the time the second edition of this book came out in 2008, it was just under half, and now it’s even less. Several things made a di↵erence.

* + - 1. The ﬁrst consists of speciﬁc defences. *Stack canaries* are a random num- ber inserted by the compiler next to the return address on the stack. If the stack is overwritten, then with high probability the canary will change [487]. *Data execution prevention* (DEP) marks all memory as ei- ther data or code, and prevents the former being executed; it appeared in 2003 with Windows XP. *Address space layout randomisation* (ASLR) arrived at the same time; by making the memory layout di↵erent in each instance of a system, it makes it harder for an attacker to predict target addresses. This is particularly important now that there are toolkits to do ROP attacks, which bypass DEP. *Control ﬂow integrity* mechanisms involve analysing the possible control-ﬂow graph at compile time and en-

forcing this at runtime by validating indirect control-ﬂow transfers; this

appeared in 2005 and was incorporated in various products over the follow- ing decade [348]. However the analysis is not precise, and block-oriented programming attacks are among the tricks that have evolved to exploit the gaps [964].

* + - 1. The second consists of better general-purpose tools. Static-analysis pro- grams such as Coverity can ﬁnd large numbers of potential software bugs and highlight ways in which code deviates from best practice; if used from the start of a project, they can make a big di↵erence. (If added later, they can throw up thousands of alerts that are a pain to deal with.) The rad- ical solution is to use a better language; my colleagues increasingly write systems code in Rust rather than in C or C++10.
      2. The third is better training. In 2002, Microsoft announced a security ini- tiative that involved every programmer being trained in how to write se- cure code. (The book they produced for this, *‘Writing Secure Code’* [927], is still worth a read.) Other companies followed suit.
      3. The latest approach is DevSecOps, which I discuss in Part 3. Agile de- velopment methodology is extended to allow very rapid deployment of patches and response to incidents; it may enable the e↵ort put into de- sign, coding and testing to be aimed at the most urgent problems.

Architecture matters; having clean interfaces that evolve in a controlled way, under the eagle eye of someone experienced who has a long-term stake in the security of the product, can make a huge di↵erence. Programs should only have

10Rust emerged from Mozilla research in 2010 and has been used to redevelop Firefox; it’s been voted the favourite language in the Stack Overﬂow annual survey from 2016–2019.

as much privilege as they need: the *principle of least privilege* [1639]. Software should also be designed so that the default conﬁguration, and in general, the easiest way of doing something, should be safe. Sound architecture is critical in achieving safe defaults and using least privilege. However, many systems are shipped with dangerous defaults and messy code, exposing all sorts of interfaces to attacks like SQL injection that just shouldn’t happen. These involve failures of incentives, personal and corporate, as well as inadequate education and the poor usability of security tools.

## Environmental creep

Many security failures result when environmental change undermines a security model. Mechanisms that worked adequately in an initial environment often fail in a wider one.

Access control mechanisms are no exception. Unix, for example, was origi- nally designed as a ‘single user Multics’ (hence the name). It then became an operating system to be used by a number of skilled and trustworthy people in a laboratory who were sharing a single machine. In this environment the function of the security mechanisms is mostly to contain mistakes; to prevent one user’s typing errors or program crashes from deleting or overwriting another user’s ﬁles. The original security mechanisms were quite adequate for this purpose.

But Unix security became a classic ‘success disaster’. Over the 50 years since Ken Thomson started work on it at Bell Labs in 1969, Unix was repeat- edly extended without proper consideration being given to how the protection mechanisms also needed to be extended. The Berkeley versions assumed an extension from a single machine to a network of machines that were all on one LAN and all under one management. The Internet mechanisms (telnet, ftp, DNS, SMTP) were originally written for mainframes on a secure network. Mainframes were autonomous, the network was outside the security protocols, and there was no transfer of authorisation. So remote authentication, which the Berkeley model really needed, was simply not supported. The Sun extensions

such as NFS added to the party, assuming a single ﬁrm with multiple trusted LANs. We’ve had to retroﬁt protocols like Kerberos, TLS and SSH as duct tape to hold the world together. The arrival of billions of phones, which communicate sometimes by wiﬁ and sometimes by a mobile network, and which run apps from millions of authors (most of them selﬁsh, some of them actively malicious), has left security engineers running ever faster to catch up.

Mixing many di↵erent models of computation together has been a factor in the present chaos. Some of their initial assumptions still apply partially, but none of them apply globally any more. The Internet now has billions of phones, billions of IoT devices, maybe a billion PCs, and millions of organisations whose managers not only fail to cooperate but may be in conﬂict. There are companies that compete; political groups that despise each other, and nation states that are at war with each other. Users, instead of being trustworthy but occasionally incompetent, are now largely unskilled – but some are both capable and hostile. Code used to be simply buggy – but now there is a lot of malicious code out there. Attacks on communications used to be the purview of intelligence agencies

– now they can be done by youngsters who’ve downloaded attack tools from the

net and launched them without any real idea of how they work.

# Summary

Access control mechanisms operate at a number of levels in a system, from the hardware up through the operating system and middleware like browsers to the applications. Higher-level mechanisms can be more expressive, but also tend to be more vulnerable to attack for a variety of reasons ranging from intrinsic complexity to implementer skill.

The main function of access control is to limit the damage that can be done by particular groups, users, and programs whether through error or malice. The most widely ﬁelded examples are Android and Windows at the client end and Linux at the server end; they have a common lineage and many architectural similarities. The basic mechanisms (and their problems) are pervasive. Most at- tacks involve the opportunistic exploitation of bugs; products that are complex, widely used, or both are particularly likely to have vulnerabilities found and turned into exploits. Many techniques have been developed to push back on the number of implementation errors, to make it less likely that the resulting bugs give rise to vulnerabilties, and harder to turn the vulnerabilities into exploits; but the overall dependability of large software systems improves only slowly.

# Research Problems

Most of the issues in access control were identiﬁed by the 1960s or early 1970s and were worked out on experimental systems such as Multics [1684] and the CAP [2020]. Much of the research in access control systems since then has involved reworking the basic themes in new contexts, such as mobile phones.

Recent threads of research include enclaves, and the CHERI mechanisms for adding ﬁner-grained access control. Another question is: how will developers use such tools e↵ectively?

In the second edition I predicted that ‘a useful research topic for the next few years will be how to engineer access control mechanisms that are not just robust but also usable – by both programmers and end users.’ Recent work by Yasemin Acar and others has picked that up and developed it into one of the most rapidly-growing ﬁelds of security research [11]. Many if not most technical security failures are due at least in part to the poor usability of the protection mechanisms that developers are expected to use. I already mention in the chapter on cryptography how crypto APIs often induce people to use really unsafe defaults, such as encrypting long messages with ECB mode; access control is just as bad, as anyone coming cold to the access control mechanisms in a Windows system or either an Intel or Arm CPU will ﬁnd.

As a teaser, here’s a new problem. Can we extend what we know about access control at the technical level – whether hardware, OS or app – to the organisational level? In the 20th century, there were a number of security poli- cies proposed, from Bell-LaPadula to Clark-Wilson, which we discuss at greater

length in Part 2. Is it time to revisit this for a world of deep outsourcing and virtual organisations, now that we have interesting technical analogues?

# Further Reading

There’s a history of virtualisation and containers by Allison Randal at [1575]; a discussion of how mandatory access controls were adapted to operating systems such as OS X and iOS by Robert Watson in [1993]; and a reference book for Java security written by its architect Li Gong [783]. The Cloud Native Secu- rity Foundation is trying to move people towards better open-source practices around containers and other technologies for deploying and managing cloud- native software. Going back a bit, the classic descriptions of Unix security are by Fred Grampp and Robert Morris in 1984 [805] and by Simson Garﬁnkel and

Eugene Spa↵ord in 1996 [753], while the classic on Internet security by Bill

Cheswick and Steve Bellovin [221] gives many examples of network attacks on Unix systems.

Carl Landwehr gives a useful reference to many of the ﬂaws found in oper- ating systems in the 1960s through the 1980s [1129]. One of the earliest reports on the subject (and indeed on computer security in general) is by Willis Ware in 1970 [1986]; Butler Lampson’s seminal paper on the conﬁnement problem appeared in 1970s [1125] and three years later, another inﬂuential early paper was written by Jerry Saltzer and Mike Schroeder [1639]. The textbook we get

our students to read on access control issues is Dieter Gollmann’s *‘Computer Security’* [779]. The standard reference on Intel’s SGX and indeed its CPU security architecture is by Victor Costan and Srini Devadas [479].

The ﬁeld of software security is fast-moving; the attacks change signiﬁcantly (at least in their details) from one year to the next. The classic starting point is Gary McGraw’s 2006 book [1266]. Since then we’ve had ROP attacks, Spectre and much else; a short but useful update is Matthias Payer’s *Software Secu- rity* [1504]. But to really keep up, it’s not enough to just read textbooks; you need to follow security conferences such as Usenix and CCS as well as the se- curity blogs such as Bruce Schneier, Brian Krebs and – dare I say it – our own lightbluetouchpaper.org. The most detail on the current attacks is proba- bly in Google’s Project Zero blog; see for example their analysis of attacks on iPhones found in the wild for an insight into what’s involved in hacking modern operating systems with mandatory access control components [204].