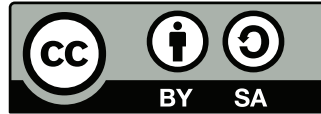


Operating Systems and Middleware: Supporting Controlled Interaction

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Chapter 11

Security

11.1 Introduction

I have addressed security issues in each preceding chapter because security is a pervasive design issue, the same way performance is. Just as one can't discuss virtual memory mechanisms or persistent storage as though performance didn't exist and then devote a later chapter solely to performance, it would have been wrong to treat security as an add-on. On the other hand, there has been such sustained attention to security from so many talented researchers that a rich, coherent body of security concepts has resulted, worthy of a chapter of its own.

Section 11.2 recapitulates and amplifies on Chapter 1's definition of security and statement of security objectives. It also lists a number of high-level security principles, many of which were illustrated in particular cases throughout the book.

Sections 11.3 and 11.4 discuss the two most well-developed areas of security technology: the authentication of user identities and the provision of access control and information-flow control to limit the authority of users. The latter topic builds on Chapter 7's introduction to protection. (Another well-developed area of security technology, cryptography, was addressed in Chapter 9.)

Section 11.5 describes viruses and worms, some of the most prevalent security threats, which fall largely outside of the scope of conventional authentication and authorization controls. Because worms often propagate by exploiting buffer-overflow vulnerabilities, I also describe this widespread form of vulnerability in the same section.

Security measures are subject to imperfection, just like all other human

endeavors. Sections 11.6 and 11.7 describe two responses to this reality: (1) assurance techniques used to assess the quality of security measures and (2) monitoring techniques used to collect information on attacks, particularly any that are not thwarted.

Finally, Section 11.8 closes the book on a practical note by providing a summary of key security best practices. Many of these have already been mentioned in earlier chapters or will be mentioned in the course of Sections 11.2–11.7. However, by bringing all of them together in one place, I hope to provide something of a checklist for your guidance. After this summary, the chapter ends with exercises, programming and exploration projects, and notes.

11.2 Security Objectives and Principles

Security is best understood as one aspect of overall system quality. Like quality in general, it refers to how well the system meets the objectives of its owner or other primary stakeholders. If you think about all the factors that can stop a system from meeting those objectives, it should be clear that quality stems from a combination of proper design, implementation, and operation. Similarly, security spans all these areas. Before examining what makes security different from other aspects of quality, I would like to pin down the definition of quality a bit more carefully.

A tempting first definition of a quality system is that it is one that is designed, implemented, and operated so as to meet the objectives of its owner. However, this definition is somewhat unrealistic because it fails to acknowledge that decisions, particularly regarding design, need to be made without complete knowledge of how they will affect the system's suitability. Therefore, I would refine the definition to say that a quality system is one that is designed, implemented, and operated to reduce to an appropriate level the risk that it will fail to meet the objectives of its owner.

A system's risk has been reduced to an appropriate level if it is preferable to accept the remaining risk than to incur the costs of further reducing the risk. This definition makes risk management sound like a straightforward economic calculation, like deciding whether to continue paying high fire-insurance premiums for an old warehouse or instead build a new, more fire-resistant warehouse. Unfortunately, the decisions regarding system development and operation are not so precisely calculable.

An insurance company has a good estimate of how likely the warehouse is to burn down; the probability a computer system will fail to meet objec-

tives is far fuzzier. In addition, the insurance company has a good estimate of how large a loss would result from the fire, denominated in dollars. In contrast, the consequences of a low-quality computer system may be difficult to predict, and in some cases may not be adequately translatable into financial terms. Consider, for example, a computer system that is essential to national security.

Nonetheless, however imperfect the risk-management approach to system quality may be, it provides the correct conceptual framework. The management goal should be to expend resources in a way that provides a commensurate reduction in risk. This requires keeping in view all three factors: cost, likelihood of failure, and consequences of failure. Moreover, all three factors may be manipulable. For example, rather than building a new warehouse, it may be preferable to reduce the amount of material stored in the warehouse, thus reducing the possible loss. Similarly, rather than making a computer system less likely to fail, it may be preferable to reduce reliance on the system so that its failure would not be so significant. That reliance may be reduced through the use of redundant computer systems as well as through the use of noncomputerized systems.

Having provided this background on quality in general, I can define system security similarly. A system is secure if it is designed, implemented, and operated so as to reduce to an appropriate level the risk that it will fail to meet the objectives of its owner, even in the face of adversaries. An *adversary* is someone with objectives so contrary to those of the owner as to strive to make the system fail.

One mildly interesting consequence of this definition is that security is irrelevant for low-quality systems, because they will fail to meet their owners' objectives even without intervention by adversaries. However, the more interesting consequence is that the risk-management approach to system quality needs to be extended to include the actions of adversaries.

A secure system need not be impervious to attack by adversaries. In fact, it need not even be especially difficult for adversaries to interfere with. Instead, what is needed is that the likelihood an adversary will choose to mount an attack, the likelihood that the attack will succeed, and the damage likely to be done to the system owner's objectives by a successful attack all combine to produce an appropriate level of risk relative to the cost of available countermeasures.

Generally, an acceptable level of risk will not be achievable if the system offers no resistance to attack. However, at some point further reduction in the system's vulnerability will be a less appropriate risk-management approach than reducing the threats the system faces and the consequences

of a successful attack.

Some of these risk-management actions may be nontechnical. For example, if the organization can avoid creating disgruntled employees, its systems will not face such severe threats, independent of how vulnerable they are. As another example, a company might choose to accept the cost of repeated data entry rather than store its customers' credit-card numbers online. Doing so will both reduce threats (because adversaries will have less motivation to break into the system) and reduce the consequences of successful attacks (because the company will lose less customer goodwill).

However, it would be wrong to equate technical efforts with only the reduction of vulnerabilities and assume that all efforts to reduce threats or the consequences of failure are nontechnical in nature. In fact, one of the most active technical areas today is the monitoring of systems' operation; I discuss this in Section 11.7. This monitoring does nothing to reduce a system's inherent vulnerability. However, it both deters adversaries (especially adversaries internal to the organization), thereby reducing threats, and allows rapid-response incident-handling teams to quickly and efficiently get systems operational again after attacks, thereby reducing losses.

So, what might the owner's objectives be that an adversary could seek to thwart? There is no end to the specific objectives an owner might have. However, there are four broad classes of objectives that commonly arise in discussions of security:

- The owner may wish to maintain the *confidentiality* of information stored in the computer system. That is, the information should not be disclosed to any person who has not been authorized to receive it.
- The owner may wish to maintain the *integrity* of information stored in the computer system. That is, the information should not be modified or deleted by any person who has not been authorized to do so.
- The owner may wish to preserve the *availability* of the services provided by the computer system. That is, persons authorized to use the system should be able to do so without interference from adversaries. The adversaries should not be able to cause a *denial of service*.
- The owner may wish to ensure *accountability*. That is, it should be possible to determine how users have chosen to exercise their authority, so that they can be held responsible for the discretionary choices they made within the limits set by the security controls.

All four of these objectives have a common prerequisite, user *authentication*. That is, the system must verify that each user is correctly identified. Without reliable user identities, there is no way the system can enforce a restriction on which users can retrieve or modify information and no way it can keep records of who has done what. Even availability relies on authentication, because without a way to determine whether a user is a bona fide system administrator, there is no way to control the use of commands that shut the system down.

To increase the chance that these objectives are achieved, system designers have found it useful to have a guiding set of principles. These are more specific than the overall risk-management perspective sketched earlier, but less specific than individual technical measures. Most of these principles came to prominence in a 1975 paper by Saltzer and Schroeder, though they date back yet further. The following list largely echoes Saltzer and Schroeder's:

Economy of mechanism: Simple designs that consistently use a small number of general mechanisms are more likely to be secure. An example would be Chapter 5's point that a general-purpose transaction-processing infrastructure is more likely to be secure than individual ad hoc mechanisms for atomicity.

Fail-safe (and fail-noisy) defaults: A security system should be designed to withhold access by default. If anything goes wrong in the granting of authority, the result will be too little authority, rather than too much. This makes the problem more likely to be fixed, because legitimate users will complain. An example from Chapter 7 is Microsoft's mechanism for resolving conflicts between ACL entries. That mechanism governs the case when one entry says to allow a permission and another says to deny it. The kernel itself is not fail-safe, because it gives precedence to whichever entry is listed first. However, the higher-level API used by the GUI is fail-safe, because it always gives precedence to denying permission.

Complete mediation: Ideally, every access should be checked for authority. Processes should not be allowed to continue accessing a resource just because authority was checked at some earlier point. An example from Chapter 7 is the change IBM made in deriving the AS/400 design from the System/38. The original design used ACLs to decide whether to grant capabilities, but then allowed the capabilities to be retained and used without any further reference to the ACLs. The

revised design causes the ACLs' record of authorization to be checked more consistently.

Open design: The only secret parts of the security mechanism should be cryptographic keys and passwords. The design should be inspected by as many parties as possible to increase the chance of a weakness coming to light. An example would be Chapter 9's description of openly standardized cryptographic algorithms. In particular, that chapter mentioned that the MD5 algorithm was found to be weak. I would not have been able to give you that warning without the public scrutiny MD5 has received.

Separation of privilege: No one individual should be authorized to carry out any particularly sensitive task. Instead, the system should be designed so that two authorized users need to collaborate. Among other benefits, this defends against the corruption of persons in positions of authority.

Least privilege: Each process should operate with only the authority it needs so that even if an adversary makes something go wrong in the process's execution, there will be many kinds of damage it can't do. In Chapter 4, I described a case where adversaries exploited a Time Of Check To Time Of Use (TOCTTOU) vulnerability to trick a mail delivery program into writing into sensitive files. I highlighted the failure to use proper synchronization, resulting in the vulnerable race condition. However, I could equally well point to that mail program as a failure to honor the principle of least privilege. The mail program needed authority only to write in each user's mail file, not authority to write in all files whatsoever. Because UNIX provided no easy way to grant it just the requisite authority, it was given way too much, and hence its vulnerability was rendered far more dangerous.

Psychological acceptability: All security mechanisms must have sufficiently well-designed user interfaces that they will be used correctly. An example is the graphical user interface Microsoft Windows provides for ACLs, as shown in Chapter 7. As I pointed out there, the user interface design includes such features as hiding unnecessary complexity.

Work factor: Just as you reason about the cost and benefit of security countermeasures, you should reason about your adversaries' cost/benefit trade-offs. You should make sure that breaking into your systems

takes more time and trouble than it is worth. An example would be the discussion of cryptographic key length in Chapter 9. Keys are not completely secure, in that they can be figured out with sufficient trial and error. However, the usual key lengths are such that adversaries will not have the resources necessary to find the keys in this way.

Compromise recording: If the system's security is breached, information about the breach should be recorded in a tamper-proof fashion. This allows an appropriate technical and legal response to be mounted. An important example of this principle, described in Chapter 9, is the use of network intrusion detection systems.

Defense in depth: An adversary should need to penetrate multiple independent defenses to be able to compromise a system's functioning. For example, Chapter 9 suggested the use of multiple firewalls, such as hardware firewalls at the organizational and workgroup perimeters and a software firewall on each desktop machine.

Alignment of authority and control: The same person should control what a process will do and supply the authorization credentials for the process's action. In Chapter 7, I described the risk of Trojan horse programs, which combine their executors' authority with their authors' control, and setuid programs, which may combine their executors' control with their authors' authority. Many network server programs have problems similar to setuid programs, in that they allow anonymous individuals elsewhere on the Internet some degree of control over their actions while using a local user's authority.

Physical security: The system's owner should control physical access to computer equipment and unencrypted data. An example from Chapter 8 is that disk drives must be protected from physical theft. Otherwise, confidentiality cannot be ensured. As another example, I once visited an organization that was in the business of printing and mailing out lots of checks to individuals. Much to my shock, their computer room was wide open. Here the threat is to integrity rather than confidentiality. An adversary could exploit physical access to change the list of recipients for the checks—an attractive proposition.

Before leaving this section of generalities and diving into technical specifics, I want to return to the topic of adversaries. Adversaries can be outside your organization, but they can also be inside. Either way, they may exploit technical vulnerabilities, misuse authority they have been granted, or engage in

social engineering, that is, tricking others who may have greater authority into cooperating. For this reason, I generally use the word adversary rather than such alternative terms as intruder and cracker. The word *intruder* implies an external adversary, and *cracker* implies one who uses technical means. The largest danger is that if you use one of these terms, you may blind yourself to significant threats. For example, protecting your organization's network perimeter may be a fine defense against intruders—but not against all adversaries.

Occasionally I will call an adversary an intruder or cracker, when appropriate. However, I will never call one a hacker, contrary to what has become common usage. Decades before crackers co-opted the word, it meant someone who had a deep, creative relationship with systems. Many of the technologies taken for granted today were developed by people who described themselves as hackers. Today, I would no longer dare call such a person a hacker outside a knowledgeable circle of old-timers, for fear of being misunderstood. However, just because I no longer use the word in its traditional sense does not mean I would use it for crackers.

11.3 User Authentication

You are probably most familiar with user authentication in a very basic form: logging into a computer system using a password at the start of a session of usage. This authentication mechanism suffers from several potentially serious weaknesses:

- Because the authentication takes place only at the beginning of the session, the computer system at best knows who was seated at the keyboard then. No attempt is made to notice whether you have walked away and someone else has taken your place.
- Because you identify yourself using something intangible (your knowledge of a password), there is nothing to discourage you from sharing it with someone else. You wouldn't need to give up your own knowledge to let someone else also have it.
- Similarly, someone can steal the password without depriving you of it, and hence without drawing attention to themselves. As an example, if you have written the password down, the adversary can copy it yet leave you your copy.

- Because the same password is used each time you log in, anyone who observes you using it can then reuse it. This is true whether they physically observe your typing (known as *shoulder surfing*) or use technical means to capture the password, either with covert software on the computer where you are typing (a *keylogger*) or with a network packet capture program (a *sniffer*). The use of network encryption prevents sniffing but not the other techniques.
- Either the password is easy for you to remember, in which case it is also probably easy for an adversary to guess, or you wrote it down, thereby exposing it.

In addition, there are several other pitfalls that, though not unavoidable, are common in actual password systems:

- If you type in your password without the computer system having first authenticated itself to you, then you could fall prey to a *spoofing* attack, in which the adversary sets up a fake system to capture passwords and then presents them to the real system.
- If the system checks your password by comparing it with a copy it has stored, then any exposure of its storage would reveal your password and probably many others.
- If you have to choose your own passwords for many different systems and are like most people, you will use the same password for several different systems. This means any weakness in the security of one system, such as the use of stored passwords, will spread to the others.

With such a long list of weaknesses, you can be sure that security specialists have devised other means of authentication. I will discuss those in Section 11.3.4. Nonetheless, I would first like to explain how you can make the best of password authentication because it is still widely used. I will start with the most avoidable weaknesses, which are those listed most recently: spoofing, storing passwords, and choosing the same passwords for several systems.

11.3.1 Password Capture Using Spoofing and Phishing

One form of spoofing attack is to write a program that puts the correct image on the screen to look like a logged-out system prompting for username and password. Thus, when someone comes up to the computer and

sees what looks like a login screen, they will enter their information, only to have it recorded by the program. The program can avoid detection by displaying a realistic error message and then logging itself out, returning to the genuine login window. To defend against this version of a spoofing attack, there needs to be something the genuine login window can do to authenticate itself to users that no other program could do. Microsoft Windows can be configured to take this approach by requiring users to press the CTRL+ALT+DEL key combination at the start of a login. The reason Microsoft chose this combination is that Windows allows programmers to draw anything at all to the screen and to respond to any other key combination, but not that one particular key combination. Thus, so long as Windows is running, you can be sure that CTRL+ALT+DEL is being responded to by Windows itself, not by a spoofing program. The one hitch is that a spoofer could have installed software that runs without Windows. To defend against that, you would need to use physical security, which is important for other reasons anyhow.

Another style of spoofing has become more problematic lately. A web site may be set up to look like a password-protected site, but really be in the business of capturing the passwords. Users can be directed to the fake site using sophisticated network manipulations, but more commonly they are simply tricked into accessing it using a misleading email message, a technique known as *phishing*. One important countermeasure in this case is user education. Users need to be much less credulous of emails they receive.

However, there is also a technical dimension to the problem of web spoofing. As described in Chapter 10, the SSL protocol used for encrypted web communication allows your browser to verify the identity of the web server by using a public-key certificate. Spoofing is made much less likely if you type your password in only to web pages that have authenticated themselves in this way. Unfortunately, some web site designers are conditioning users to ignore this principle. These web sites use non-SSL connections to display the form into which users type their passwords. The form then submits the information back using SSL. The designers probably think all is well, because the actual password transmission is SSL-encrypted. However, unless the user looks at the HTML source of the web form, there is no way to be sure where the password will be sent. To protect against spoofing, the login form itself should be sent using SSL. That way, the user will have seen the server's authentication before typing the password.

11.3.2 Checking Passwords Without Storing Them

To avoid storing passwords, a system should use a cryptographic hash function, such as the SHA-1 function described in Chapter 9. Recall that these functions are designed not to be easily invertible and in practice to essentially never have two inputs produce the same output. Therefore, the system can feed a newly chosen password through the hash function and store the hash value. When a user tries to log in, the system feeds the proffered password through the same hash function and compares the resulting value with the stored hash code, as shown in Figure 11.1. If the two hash codes are equal, then for all practical purposes the system can be sure the correct password was entered. However, if the stored hash values are disclosed, no one can recover the passwords from them other than by trial and error. One cost to user convenience is that the system cannot support a function to “remind me of my password,” only one to “assign me a new password.” In most settings, that is a reasonable price to pay.

11.3.3 Passwords for Multiple, Independent Systems

In principle, you can easily avoid the problems stemming from using the same password on multiple systems. You just need to train yourself not to pick the same password for shopping on Sleazy Sam’s Super Saver Site as you use to guard your employer’s confidential records. In practice, however, picking a new password for every system would lead to an unmemorable array of different passwords. Even one password for each general category of system may be difficult. Therefore, an active area of development today is *password wallet* systems, which store a range of passwords under the protection of one master password. The stored passwords constitute a security vulnerability; this vulnerability is hopefully not so severe as the alternatives.

Another technique that can help users cope with multiple systems also makes use of a master password but does not use it to protect storage of individual passwords. Instead, the individual passwords are generated algorithmically from the master password and the sites’ names. As an advantage compared with a password wallet, nothing at all needs to be stored on the client machines. As a disadvantage, there is no easy way to change the master password.

11.3.4 Two-Factor Authentication

Even if a system is designed and operated so as to avoid the pitfalls of spoofing, password storage, and password reuse, if it relies on password-controlled

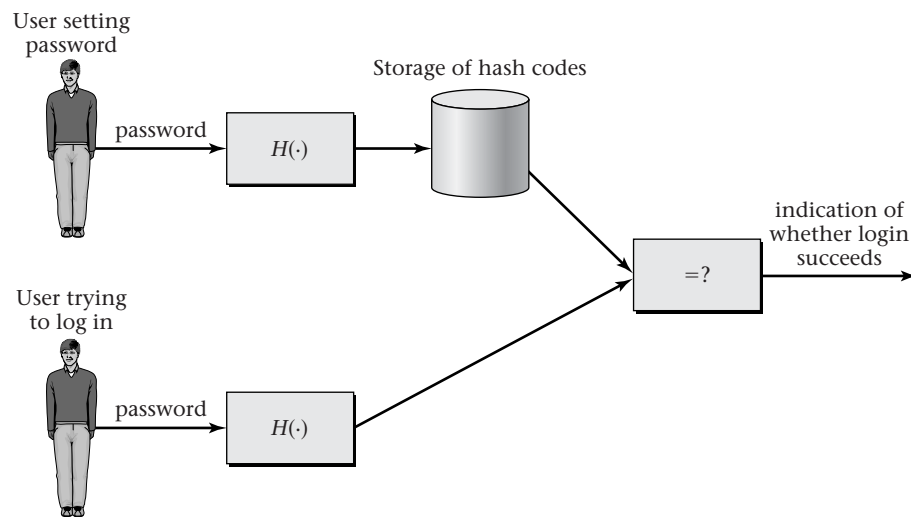


Figure 11.1: The system stores a cryptographic hash of the password when it is set, and compares that with the hash of the attempted password. Because the hash function is collision-resistant, equal hashes mean the password was almost surely correct. Because the hash function is difficult to invert, disclosure of the stored hash codes would not reveal the passwords.

login as its sole authentication method, it will still possess the more fundamental vulnerabilities listed earlier. Some of those can be overcome with sufficient user education or mitigated in other ways. For example, a system can be designed so as to issue passwords (or pass phrases) that are random, and hence difficult to guess, but are constructed out of real syllables or words so as to be easily memorizable—an example of psychological acceptability. To avoid problems with users walking away, a system can demand reentry of the password before any particularly sensitive operation or after any sufficiently long period of inactivity. All these countermeasures to password threats are valuable but still leave something to be desired. Thus, I will turn now to other authentication methods.

Rather than relying on something the authorized user knows (a password), an authentication mechanism can rely on something the user physically possesses, such as a card or small plug-in device. These physical devices are generically called *tokens*. The big problem with tokens is that they can be lost or stolen. Therefore, they are normally combined with passwords to provide *two-factor authentication*, that is, authentication that combines two different sources of information. Another way to achieve two-factor authentication is by combining either a password or a token with *biometric authentication*, that is, the recognition of some physical attribute of the user, such as a fingerprint or retinal pattern.

The most familiar two-factor authentication system is that used for bank automated teller machines (ATMs), in which you insert or swipe a card and also type in a four-digit personal identification number (PIN), which is essentially a short password. Cards that use only magnetic stripes (as opposed to integrated circuits) are rather weak tokens, because they carry fixed information rather than engaging in a cryptographic authentication protocol and because they are easily copied. However, in the ATM application, they provide sufficient security that they continue to be used in the US. In part, this stems from other aspects of the system design, such as a limit on how much money a customer can withdraw in a day.

One important difference between biometric authentication and other techniques is that it is inextricably tied with actual human identity. A password-protected or token-protected account can be issued to a person known only by a pseudonym, and it will never be possible to ascertain the true identity of the user. By contrast, even if a biometric authentication user is initially enrolled without presenting any proof of true identity (such as a passport), the user's identity could later be deduced from matching the fingerprint (or other biometric) with other records. This is both an advantage and a disadvantage. Where the highest standards of accountability

are necessary, it can be advantageous. However, it also cuts into personal privacy. For many purposes, pseudonymity is desirable, so that people can dissociate some portion of their life from another unrelated, perhaps earlier, portion.

When a user logs in using biometric authentication, some physical device scans the user's fingerprint or other attribute and then transmits a digitally coded version of the scan to a computer for checking. If an attacker can capture the digital version and later replay it, the system's security will be breached, just as would be the case if a password were captured and replayed. One crucial difference, however, is that a user can be issued a new password but not a new fingerprint. Therefore, the design of any biometric authentication system needs to be particularly resistant to such replay attacks.

Biometrics can be used for *identification* as well as *authentication*. That is, a user's physical attributes can play the role of a username (selecting a specific user) as well as of a password (providing evidence that the selected user is actually present). However, biometric identification is a harder problem than biometric authentication, as it requires searching an entire database of biometric information, rather than only the information for a specific user. This broader search space increases the chance for error. Therefore, the most reliable systems still require the user to enter some other identifier, such as a textual username.

11.4 Access and Information-Flow Controls

In Chapter 7, I briefly made the distinction between Discretionary Access Control (DAC), in which the creator or other "owner" of an object can determine access rights to it, and Mandatory Access Control (MAC), in which organizational policy directly governs the access rights. In that chapter, I then went into some depth on capabilities and access control lists (ACLs), which are the two mechanisms commonly used to implement DAC. Therefore, I will now focus on MAC in order to round out the picture.

The most well-developed MAC policies and mechanisms are geared to protecting the confidentiality of information in national security systems, where formal policies regarding the flow of information predated the introduction of computer systems. My discussion in this section will be based on the policies of the United States government, as is much of the published literature. The general principles, however, apply equally well to other similar systems of information classification and user clearance. In particular,

after discussing government classification systems, I will briefly remark on a currently popular application to commercial web servers. The goal there is to limit the damage if an attacker achieves control over the web server.

The United States military sponsored research, particularly in the early 1970s, with the goal of allowing a single computer system to be shared by principals operating on data of varying sensitivity and running programs written by authors who are not fully trusted. This sort of system is known as a *Multi-Level Security (MLS)* system. In this context, the technical security mechanism must enforce *information-flow control* rather than only *access control*. That is, the system must protect sensitive information from indirect disclosure rather than only from direct access by unauthorized principals.

To appreciate the need for information-flow control in an MLS system, consider the simplest possible system: one handling information of two different levels of sensitivity. Suppose objects containing high-level information are labeled H and those containing low-level (less sensitive) information are labeled L . There are some principals, those with H clearance, who may read and modify all objects. There are others, with L clearance, who may only read L objects. So far, access control would suffice, granting each class of principals access to specific objects. Now consider one further requirement: an untrusted program run by an H principal must not be allowed to copy data out of an H object and into an L object where an L principal could retrieve it. Ideally, the program must also not leak the information any other way, though as you will see, this is a challenging requirement. I can summarize the requirements by saying that information initially contained in an H object must not flow to an L principal, even through means other than the L user accessing the object.

Real MLS systems handle more than two categories of information. The information is categorized in two ways. First, there is an overall *classification level*, indicating the degree to which disclosure could damage national security. In the United States, four classification levels are used: unclassified, confidential, secret, and top secret. (Technically, unclassified is not a classification level. However, it is handled like a level below the lowest true classification level, which is confidential.) Second, there are *compartments*, which indicate topics, such as nuclear weapons or international terrorism. A principal may be cleared for access to data all the way up to top secret classification, but be limited to a specific compartment, such as nuclear weapons only.

Each object is labeled with exactly one classification level but can be labeled with any set of compartments because (for example) a document might concern the acquisition of nuclear weapons by international terrorists.

Figure 11.2 shows how each of the two kinds of labels forms a partially ordered set, and Figure 11.3 shows how combining them results in another partially ordered set, known mathematically as their Cartesian product.

In a partial order, two elements may be ordered relative to one another, with $x < y$ or $y < x$, or they may be unordered. For example, $\{I\}$ and $\{H\}$ are unordered, because neither is a subset of the other. In security applications, a principal with clearance p is allowed to view information with label i only if $p \geq i$, a condition known as p dominating i in the partial order. This rules out disclosing information to principals with too low a clearance level, but also to those who aren't cleared for all the necessary compartments.

Whenever an untrusted subject (that is, a process running an untrusted program) has read from an object with label l_1 and then modifies an object with label l_2 , an unauthorized information flow may result unless $l_2 \geq l_1$. That is, information is only allowed to flow into an object whose consumers could all have directly accessed the source information. Strictly speaking, the information flow results not from the modification of an l_2 object *after* accessing the l_1 object, but rather from the modification of an l_2 object *based on* the earlier access to the l_1 object. However, it is extremely difficult to test whether an earlier access has had some influence on a later modification. In particular, the earlier access can have a subtle influence on whether the later modification occurs, as well as an overt influence on the nature of that possible later modification. Therefore, practical MLS systems generally take the simpler, more conservative approach of forbidding any subject from modifying an object that does not dominate all previously accessed objects in the security label partial order.

The best-known information-flow control policy is known as the *Bell-LaPadula model*, after the two MITRE Corporation researchers who developed it in the early 1970s.¹ The key idea of the Bell-LaPadula model is to associate with each subject a current level chosen by the principal running the subject process. The current level must be dominated by the principal's security clearance, but can be lower in the partial order if the principal chooses. This flexibility to run at a lower current level allows a principal to run subjects that modify low-level objects and other subjects that read from high-level objects, but not to have any one subject do both. These restrictions are enforced by two rules, each based on a formal property from

¹LaPadula's name was spelled La Padula on the original publications and therefore is cited that way in the end-of-chapter notes and the bibliography. However, in this section I will use the spelling LaPadula for consistency with most published descriptions, as well as with LaPadula's own current spelling of his name.

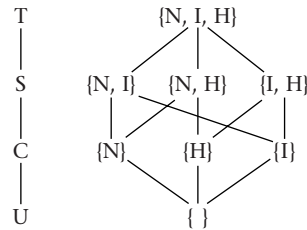


Figure 11.2: The classification levels top secret (T), secret (S), confidential (C), and unclassified (U) form a total order, as shown on the left. Sets of compartments, on the other hand, form only a partial order, namely the subset order in which one set of compartments is below another if it has a subset of the other's compartments. This is illustrated on the right with three hypothetical compartments: nuclear weapons (N), international terrorism (I), and human intelligence (H). Someone cleared for $\{I, H\}$, for example, could read documents labeled with $\{I, H\}$, $\{I\}$, $\{H\}$, or $\{\}$.

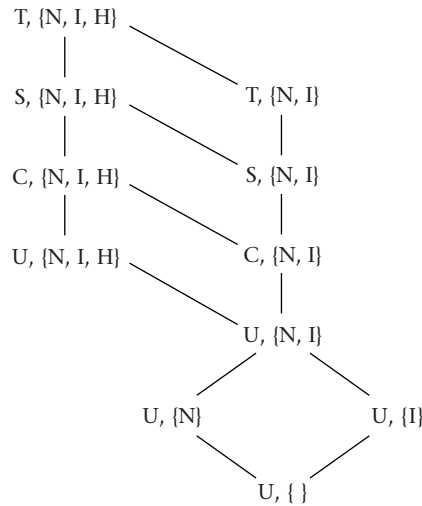


Figure 11.3: Forming the Cartesian product of the two partial orders from Figure 11.2 results in a 32-element partial order, each element of which pairs one of the four classification levels (T, S, C, or U) with one of the eight sets of compartments (ranging from $\{N, I, H\}$ down to $\{\}$). Of those 32 elements, only 11 are shown here in order not to clutter the diagram. What you should note in the diagram is the definition of ordering in the Cartesian product: a pair $(level_1, compartments_1)$ dominates $(level_2, compartments_2)$ only if both $level_1 \geq level_2$ and $compartments_1 \supseteq compartments_2$.

Bell and LaPadula's mathematical model, as follows:

- A subject running with current level c may read only from objects with level r such that c dominates r , that is, $c \geq r$. This corresponds to Bell and LaPadula's *simple security property*.
- A subject running with current level c may only modify an object with level m only if m dominates c , that is, $m \geq c$. This can be derived from Bell and LaPadula's **-property* (pronounced *star-property*), which prevents untrusted programs from transferring information into inappropriate objects.

In order for these two rules to effectively regulate information flow, the Bell-LaPadula model also includes tight restrictions on how a subject may change current levels. In practical systems, the current level is selected when a principal logs in and then is left unchanged until the principal logs out.

You can gain some appreciation for the role of untrusted subjects in the Bell-LaPadula model by considering that a principal may be simultaneously logged in at two adjacent terminals, one set to a high current level (as high as the principal is allowed) and the other set to a low current level (unclassified, with no compartments). The human principal may display highly sensitive material on one terminal and type it into an unclassified file on the other. However, no untrusted subject (that is, no process running an untrusted program) may do the same information transfer. The idea is that the human principal is granted a high-level clearance only upon providing evidence of trustworthiness. Moreover, the principal can be monitored to detect suspicious meetings, an excess of cash, and other signs of corruption. The author of the untrusted program, on the other hand, is beyond reach of monitoring, and the group of low-clearance principals who could be reading the leaked data is too large to monitor.

Mandatory Access Control of the Bell-LaPadula variety can also be combined with Discretionary Access Control using a mechanism such as access control lists. In fact, Bell and LaPadula themselves recommended this. The underlying security principle is *Need-To-Know*; that is, the possessor of sensitive information ought not to disclose it to all principals of appropriately high clearance level, but rather only to those with a specific need to know. Compartments provide a crude approximation to the Need-To-Know principle, but many people cleared for a particular compartment will not have a need to know any one specific document within that compartment. Therefore, it is wise to give the owner of an object the ability to further restrict access to it using an ACL. However, unlike in a pure DAC system, the ACL

restrictions serve only to further refine the access limits set by the simple security and *-properties. An otherwise cleared subject may be denied access for lack of an appropriate ACL entry. However, adding an ACL entry cannot grant access to a subject running at an inappropriate current level.

Even with the Bell-LaPadula simple security and *-properties, an untrusted subject may not be completely stopped from leaking sensitive information. Rather than leaking the information through a file, network connection, or other legitimate storage or communication object, the subject could disclose the sensitive information by way of a *covert channel*. A covert channel is a mechanism not intended to be used for communication, but which can be manipulated by one subject and observed by another, thus achieving communication. An example would be if a subject with access to highly sensitive information varied the demands it placed on the CPU or disk based on the sensitive information, and another subject, run at a lower clearance level, was able to detect the changes in system utilization. Complete protection against covert channels is impractical, but if processes' resource utilization is tightly controlled, the risk can be reduced.

Moving outside the area of military classification levels, one currently popular MAC system is *Security-enhanced Linux* (*SELinux*), a version of the Linux kernel. This system is quite flexible and can enforce a wide variety of rules regarding which objects each subject can read and write. Objects are tagged with type labels, which are a generalization of classification levels and compartments. Subjects are assigned to domains, which are a generalization of clearance levels. One popular configuration tags the files containing web pages with a specific label and assigns the Apache web server to a domain that is allowed to read those files but not to write them nor to read any other files. That way, even if an attacker can exploit some bug in the web server to obtain control over it and make it execute arbitrary code, it cannot leak confidential information or damage the system's integrity. This is an example of the principle of least privilege.

11.5 Viruses and Worms

As the Bell-LaPadula model and SELinux illustrate, security mechanisms need to limit the actions not only of users, but also of programs. Limiting programs' actions is important because they may be under the control of untrusted programmers as well as because they may have exploitable bugs that allow them to be misused. In this section, I will address two particular kinds of adversarial programs, or *malware*, that pose especially widespread

security threats. The common feature of viruses and worms, which distinguish these two kinds of malware from garden-variety Trojan horses, is that one of the actions they are programmed to take is to propagate themselves to other systems. Thus, an adversary can effectively attack all the computers on the Internet, not by directly connecting to each one, but rather by attacking only a few initial systems and programming each attacked system to similarly attack others. Through their sheer ubiquitousness, viruses and worms constitute significant threats.

Both worms and viruses strive to replicate themselves. The difference is in how they do this. A *virus* acts by modifying some existing program, which the adversary hopes will be copied to other systems and executed on them. The modified program will then run the inserted viral code as well as the original legitimate code. The viral code will further propagate itself to other programs on the infected system as well as carrying out any other actions it has been programmed to perform. A *worm*, on the other hand, does not modify existing programs. Instead, it directly contacts a target system and exploits some security vulnerability in order to transfer a copy of itself and start the copy running. Again, the worm can also be programmed to take other actions beyond mere propagation. Even propagation alone can be a significant problem if carried out as fast as possible, because the rapid propagation of worm copies can constitute a denial-of-service attack.

Viruses were a greater problem in the days when the major communication channel between personal computers was hand-carried diskettes. As the Internet has become dominant, worms have become the more common form of self-propagating malware. However, because of the earlier prominence of viruses, many people inaccurately use the word virus to refer to worms.

Any network-accessible vulnerability that a human intruder could exploit can in principle be exploited by a worm in order to propagate. Historically, for example, worms have used password guessing. Also, as mentioned in Chapter 7, email worms are common today; these worms arrive as email attachments and are run by unwary users. However, the most serious means of worm propagation has come to be the exploitation of buffer-overflow vulnerabilities. Therefore, I will explain this common chink in systems' defenses.

Most programs read input into a contiguous block of virtual memory, known as a buffer. The first byte of input goes into the first byte of the buffer, the second into the second, and so forth. Often, the program allocates a fixed-size buffer rather than allocating progressively larger ones as more and more input arrives. In this case, the programmer must test the amount of input against the size of the buffer and take some defensive action if an unreasonably large amount of input is presented, which would other-

wise overflow the buffer. Unfortunately, programmers perennially omit this checking. Therefore, adversaries are perennially able to find programs that, when presented with unusually large inputs, try to write the input data into addresses beyond the end of the buffer. This is particularly problematic for network server programs, which can be provided input by an adversary elsewhere on the Internet.

The consequences of a buffer overflow depend heavily on the programming language implementation, operating system, and computer architecture. In modern languages such as Java, any attempt to write past the end of an array is detected. Often, the detected error will cause the attacked server program to crash. In some cases, this is victory enough for an adversary. However, it is minor compared with the damage an adversary can do when exploiting a buffer overflow in a program written using more primitive technology, such as typical implementations of the programming language C. In those settings, the extra input data may be written to addresses beyond the end of the buffer, overwriting other data assigned to those later addresses.

One possible tactic an adversary could use is to look for a server program in which a buffer is followed by some particularly sensitive variable, such as a Boolean flag indicating whether a password has been successfully checked yet. However, buffer-overflow exploits typically take a different approach, which allows the adversary to inject entirely new instructions for the process to execute, which it ordinarily would not even contain. In this way, the server process can be made to take any action whatsoever, within the limits of the authority it has been granted. This an extreme example of misalignment between authority and control.

To understand how a buffer overflow can lead to the execution of arbitrary code, you need to consider some facts about typical runtime stacks, which are described in Appendix A. Often, program variables such as buffers are allocated their space within the stack. The stack also typically contains the return address for each procedure invocation, that is, the address of the instruction that should be executed next when the procedure invocation returns. If the stack grows downward in virtual memory, expanding from higher addresses down into lower ones, then the return address will follow the buffer, as shown in Figure 11.4(a).

In this circumstance, which arises on many popular architectures, a buffer overflow not only can overwrite data values, as shown in Figure 11.4(b), but also can overwrite the return address, as shown in Figure 11.4(c). This form of buffer overflow is commonly called *smashing the stack*. When the current procedure invocation completes, the overwritten return address

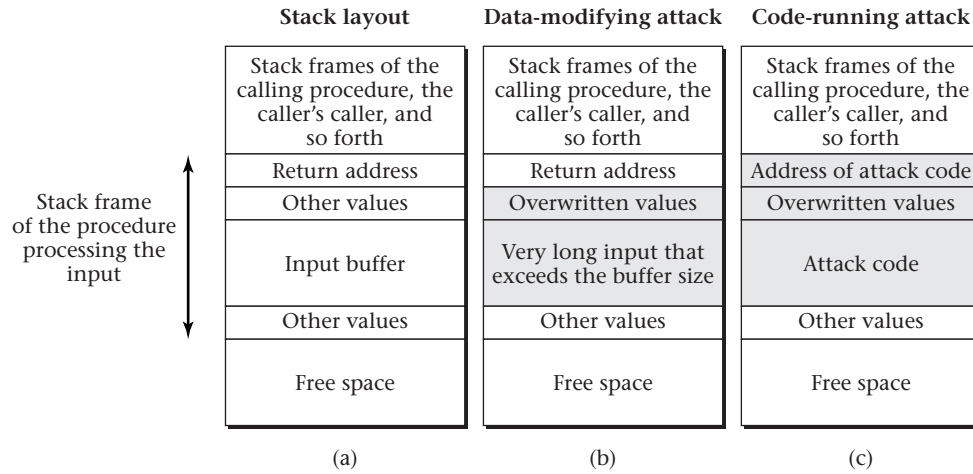


Figure 11.4: If input (shown in grey) is allowed to overflow the amount of memory allocated on the stack for an input buffer, it can overwrite other data values, as shown in part (b), or the return address, as shown in part (c). In the latter case, the modified return address can point to attack code included in the oversized input.

causes the processor to jump to an adversary-specified instruction address. On its own, this would allow the adversary only to choose which existing code to execute. However, when taken together with one other factor, it provides the means to execute code provided by the adversary.

Many architectures and operating systems provide virtual memory mechanisms that allow each page of virtual memory to be independently read-protected or write-protected, but that do not allow a distinction between reading data and fetching instructions. In this circumstance, the pages holding the stack, which need to be readable for data, can also contain executable code—even though extremely few programs legitimately write instructions into the stack and then jump to them.

An adversary can exploit this situation by writing a large input that not only overflows the buffer and overwrites the return address, but also contains the bytes constituting the adversary's choice of machine language instructions. These machine language instructions are labeled as attack code in Figure 11.4(c). The overwritten return address is used to jump into the buffer itself, thereby executing the provided instructions.

Because these exploits are so prevalent, there has been considerable interest recently in modifying virtual memory mechanisms so as to allow stack

space to be readable (and writable) but not executable. Other than techniques such as this for preventing malware from entering, the major countermeasure has been the use of antivirus scanning programs, which commonly scan for worms as well. These programs look for distinctive patterns of bytes, known as *signatures*, found in known viruses and worms. As such, scanners need to be frequently updated with signatures for newly emerging threats.

11.6 Security Assurance

Organizations directly influence their systems' security through the manner in which the systems are installed and operated, as well as through the design of components developed in-house. However, the organizations also exercise more indirect control by choosing to procure security-critical components from vendors that demonstrate that the components are suited to the organizations' needs. In this section, I will explain how this kind of security assurance is provided by vendors and interpreted by consumers. The component in question may be an operating system, middleware system, or a network device such as a firewall or intrusion detection system, among others. In the security assurance field, any of these may be referred to as a *Target of Evaluation (TOE)*, because the assurance derives from an independent evaluation of how well the TOE satisfies stated security requirements.

The assurance of security-related products is governed by an international standard called the *Common Criteria*, because it was developed to harmonize previously independent national standards. The Common Criteria are also sometimes known by their International Standards Organization number, ISO 15408. The Common Criteria define a process in which a vendor contracts with a qualified independent assessor to evaluate how well a product meets a set of security requirements known as a *Security Target (ST)*.

Each ST is an individual requirements document specific to the particular product under evaluation, that is, specific to the TOE. However, because consumers can more easily compare products whose STs share a common basis, the STs are built in a modular fashion from common groups of requirements. A published group of requirements, intended to be used as the basis for multiple STs, is called a *Protection Profile (PP)*.

Just as STs are built from standard PPs, each PP is assembled by choosing from a standard menu of potential requirements. Extra custom require-

ments can be added at either stage, but the bulk of any ST's requirements will come from the standard list by way of one of the standard PPs. Thus, consumers are in a better position to learn their way around the landscape of potential requirements. This is critical, because a product certified by an independent assessor to meet its ST is worthless if that ST does not contain requirements appropriate to a particular consumer's needs.

The requirements contained in PPs and STs fall into two general categories: functional requirements and assurance requirements. An example of a functional requirement would be a mandate for a spoofing-resistant login method. (Microsoft Windows would satisfy this requirement, using CTRL+ALT+DEL.) An example of an assurance requirement would be a mandate that detailed design documents, testing reports, and samples of security-critical code be reviewed by outside evaluators.

The assurance requirements are summarized by a numerical *Evaluation Assurance Level* (*EAL*), in the range from EAL1 to EAL7. For example, an ST based on EAL4 will contain moderately rigorous demands regarding the evidence that the system actually meets its functional requirements, but none that go beyond ordinary good development practices outside the security field. At EAL5 and above, specific security-oriented assurance practices need to be incorporated into the development process, including progressively increasing use of semiformal and formal methods. Figure 11.5 gives a brief rubric for each EAL, taken from the Common Criteria documentation.

Although each EAL includes a whole package of sophisticated assurance requirements, the EALs can be easily understood in a comparative way: a higher-numbered EAL is stricter. This makes it tempting to focus on the EALs. However, you need to remember that an EAL, even a very strict one,

EAL	Rubric
EAL1	functionally tested
EAL2	structurally tested
EAL3	methodically tested and checked
EAL4	methodically designed, tested, and reviewed
EAL5	semiformally designed and tested
EAL6	semiformally verified design and tested
EAL7	formally verified design and tested

Figure 11.5: This table shows brief rubrics for the Common Criteria Evaluation Assurance Levels; expanded descriptions are available in the Common Criteria documentation.

tells only how thorough a job the vendor has done of demonstrating that the TOE meets the functional requirements that are in the ST. It tells nothing about how demanding those functional requirements are. More importantly, the EAL tell nothing about how well matched the requirements are to your needs.

As an example, Microsoft contracted for a Common Criteria evaluation of one particular version of Windows, relative to an ST that included the assumption that the only network connections would be to equally secure systems under the same management and that all authorized users would be cooperative rather than adversarial. Thus, it gave no indication how well the system would fare if confronted with serious adversaries, either within the user population or out on the Internet. These issues arise from the functional requirements in the ST, completely independent of the EAL. Figure 11.6 shows the relevant language from Microsoft's ST.

The weakness of these small excerpts from one particular ST may leave you wondering about the value of the Common Criteria process. The lesson you should take away is not that the Common Criteria process is worthless, but rather that it relies upon educated consumers. To benefit from the process, you need to understand its vocabulary, such as what the difference is between an EAL and an ST.

11.7 Security Monitoring

System operators have at least three reasons to monitor for attacks, both successful and unsuccessful:

- By gaining a better understanding of adversaries' behavior, you can develop better countermeasures.
- By putting adversaries on notice that you may gather enough evidence to allow successful prosecution or other punishment, you may deter attacks. This tends to work better against adversaries within your organization than against adversaries on the other side of the Internet. You should coordinate in advance with legal counsel on appropriate policies and notices.
- By quickly detecting a successful attack, you can limit the damage, and by obtaining accurate information about the extent of the damage, you can avoid overly conservative responses, such as reinstalling software on uncompromised systems. Overly conservative responses not only

- Any other systems with which the TOE communicates are assumed to be under the same management control and operate under the same security policy constraints. The TOE is applicable to networked or distributed environments only if the entire network operates under the same constraints and resides within a single management domain. There are no security requirements that address the need to trust external systems or the communications links to such systems.
- Authorized users possess the necessary authorization to access at least some of the information management [sic] by the TOE and are expected to act in a cooperating manner in a benign environment.

Figure 11.6: These excerpts are from the Windows 2000 Security Target, ST Version 2.0, 18 October 2002, prepared for Microsoft Corporation by Science Applications International Corporation.

take time and money, they also require system downtime. Thus, an overly conservative response magnifies the damage done by an attack.

For all these reasons, security professionals have been very active in developing monitoring techniques. I already mentioned one in Chapter 9, namely network intrusion detection systems (IDSes). Others that I will summarize here include robust logging facilities, integrity checking software, and honeypots.

Intrusion detection systems are perhaps best thought of as anomaly detectors for network traffic. Many IDSes can be configured to spot anomalous traffic even if it results from an adversary internal to your network, rather than an intruder. Thus, the name IDS is somewhat misleading. An IDS may look for specific attack signatures or may respond to deviations from past patterns of activity. For example, if a normally quiet desktop machine starts spewing out UDP datagrams at the maximum rate the network can carry (as it would if infected with the SQL Slammer worm), even an IDS that had no signature for the specific worm ought to raise a warning about the sudden traffic.

Other anomalous events may be detected internal to a particular system, rather than in network traffic. For example, an operating system may be programmed to note repeated failed attempts to log in as the system admin-

istrator, which could constitute a particularly dangerous password-guessing attack, worthy of notice even if unsuccessful. These sorts of anomalies are routinely logged by systems into a chronological event log, which can be used to reconstruct a break-in after the fact as well as serving as a source to drive real-time alerts. The biggest technical challenge is that a successful attack may give the adversary the necessary access privileges to clean up the log, covering traces of the attack. High-security systems therefore use append-only logging devices. Log entries can also be sent over the network to a centralized, heavily-protected logging server.

Another non-network monitoring approach is to periodically check the integrity of a system's configuration, such as whether any of the system programs have been modified. Successful attackers will frequently modify programs or configuration files so as to give themselves a *back door*, that is, a second way in to use even if the initial vulnerability is fixed. Thus, a periodic check may turn up signs of a successful break-in since the previous check, even if the break-in was sufficiently stealthy to otherwise go unnoticed.

In addition to periodic checks, the same integrity checking can be done after any break-in that comes to notice through other means. Without integrity checking, a system administrator has little choice but to treat the whole system as compromised, scrub it clean, and reinstall from scratch. Thus, integrity checking not only allows successful attacks to be detected, it also guides the mounting of an appropriate response.

An example integrity monitoring system is *Tripwire*. The basic principle of operation is that a cryptographic hash of each critical file is computed and stored in a tamper-resistant database, such as on a CD that is writable only once. The Tripwire program itself is also stored in tamper-resistant form. To check the system, the known-good copy of Tripwire recomputes the cryptographic hashes and compares them with the stored copies.

The integrity checking needs to be done with a tamper-resistant program because attackers frequently install modified versions of system programs that hide the corruption. For example, the attacker may install a version of `ps` that hides the attacker's processes and a version of `ls` that shows the `ps` and `ls` programs as though they were unmodified. This kind of camouflage is commonly called a *root kit*.

The final form of security monitoring I will mention is the use of honeypots. A *honeypot* is a decoy system used specifically to monitor adversaries. It is configured to appear as realistic as possible but is not used for any genuinely valuable purpose other than monitoring. It is subject to extreme but clandestine monitoring, so as to fully record adversaries' behavior but not tip them off. Because no legitimate user will ever have reason to connect to

the honeypot, the monitoring can be comprehensive—no anomaly detection filtering is needed to distinguish legitimate traffic from attack traffic.

By letting an adversary take over the system, rather than immediately repelling the attack, you can learn more about the attack techniques beyond the initial connection and thus learn more about vulnerabilities you need to repair on other systems, as well as other countermeasures you need to take. However, because the adversary is allowed to take over the honeypot, it must be thoroughly firewalled against outbound attacks so that you don't provide the means to launch attacks on further systems. Humans should also monitor the honeypot continuously and be ready to intervene. These considerations help explain why honeypots, although quite in vogue, are best left to large organizations with experienced security professionals. Smaller organizations can still benefit because honeypots largely provide epidemiological evidence about what worms are circulating, which can serve the whole Internet community.

11.8 Key Security Best Practices

Appropriate security practices depend on many factors, including whether you are defending your home computer or an employer's high-value system and whether you are engaging in custom application-software development or only procuring, installing, configuring, and operating existing systems. However, I will attempt a unified list of best practices with the understanding that some may be more applicable than others to any one context:

- Consult others. Everybody, even home users, should at least read the the website of the SANS (SysAdmin, Audit, Network, Security) Institute, <http://www.sans.org>. Organizations should also hire reputable consultants, as well as engage in conversations with legal counsel, those responsible for noncomputer security, and the human resources department.
- Adopt a holistic risk-management perspective. Consider how much you have to lose and how much an adversary has to gain, as well as how likely an adversary is to be caught and punished. Are any of these factors more manipulable than the inherent vulnerability of your system?
- Deploy firewalls and make sure they are correctly configured. The best approach combines hardware firewalls guarding organizational

and workgroup perimeters with software firewalls guarding individual machines. Even a home can use this approach, often with a NAT router serving as the hardware firewall.

- Deploy anti-virus software. An organization should have server-based software that scans all incoming email so as not to be at risk should an individual client machine fail to scan. However, the individual client machines should also have protection for defense in depth and in particular to guard against infections that sneak past the network perimeter by being carried in on a portable computer or storage device.
- Keep all your software up to date. This includes not only system software such as the operating system, but also any application software that may be exposed to data from the network. Today, that includes nearly everything.
- Deploy an IDS, integrity checking software such as Tripwire, and a robust logging platform. These steps are not very practical for typical home users yet.
- Assume all network communications are vulnerable; use end-to-end encryption rather than relying on the security of network infrastructure. The same principle applies if storage media are physically shipped between locations.
- Use two-factor user authentication, as described in Section 11.3.4.
- Maintain physical security over computer equipment and be vigilant of service personnel or others with extraordinary physical access.
- Do what you can to stay on good terms with employees and to part from them cleanly. When hiring for particularly sensitive positions, such as system administrators, candidly disclose that you will be checking background and do so. Establish realistic expectations that do not encourage people to work nights or weekends when no one else is around. Have employees cross-train one another and take vacations.
- Establish and clearly communicate policies on acceptable use and on monitoring.
- Beware of any security-relevant phone calls and emails that you do not originate, as well as of storage media that arrive by mail or courier. A “vendor” with a critical patch you need to install could be a con

artist. The same is true of a law-enforcement agent or a member of your organization's upper management; being cooperative should not preclude taking a minute to politely confirm identity and authority.

- Examine closely any case where the user whose authority is exercised by a process is not the same as the user who controls the process's actions:
 - If at all possible, never run a program from an untrusted source. Failing that, run it with the least possible authority and the greatest possible monitoring.
 - If you need to write a `setuid` program, check very carefully what it does with all user input. Might any buffer overflow? Might any input be interpolated into a shell command or otherwise allowed to exert control? Did a programmer insert an intentional “trapdoor,” whereby a particular input can trigger the program to bypass normal security controls? Are there any TOCTTOU races? Also, have the program owned by a special-purpose user account that is granted only the necessary authority. More generally, review the principles listed in Section 11.2.
 - Examine any program that communicates over the network according to the exact same standards as a `setuid` program.

Exercises

11.1 To keep certain individuals from flying on commercial airliners, a list is maintained that airlines must check before issuing a boarding pass. The pass may be issued over the web, as well as at the airport. The pass must be presented to a human at the airport along with an identifying document. The human, who uses no computer technology, checks that the name on the pass matches that on the identifying document and that the photo on the identifying document matches the appearance of the person presenting it. This check is done at the perimeter of the secured portion of the airport as an admission condition. You may assume that identifying documents are hard to forge and that getting past the perimeter control without going through the check is difficult.

- (a) How could an adversary get admitted to the secure area despite being on the no-fly list?

- (b) Is the vulnerability you identified in part (a) one that could be explained by inattention to any of the security principles listed in Section 11.2?
 - (c) Can you design a countermeasure to deter the exploitation of the vulnerability you identified? Would the use of additional computer technology help you do so without sacrificing desirable properties of the current system?
- 11.2 An organization's checks are preprinted with a statement that checks for \$100 or more require a handwritten signature, whereas smaller checks are valid with a printed signature. How is this explainable in terms of the general principles of security enumerated in Section 11.2?
- 11.3 Section 11.2 contains a long list of general security principles. For each of the following audiences, suppose you had time to explain only a few of the principles. Which few would you explain? Why?
- (a) software developers designing and programming new systems
 - (b) information technology staff who will be purchasing, configuring, and administering systems
 - (c) the Chief Information Officer, who is the executive supervising both of the above groups
- 11.4 Another weakness of password security is that there is always an administrator to whom a user can turn upon forgetting a password. That administrator has the ability to reset the password. This person may be gulled by a con artist (who tells a pitiful tale of woe) into resetting a password without first authenticating the user in some alternate manner, for example, by using a photograph on an ID card.
- (a) What is the name for the general category of threat of which this is an example?
 - (b) Even if the human customer-service staff can't be stopped from resetting passwords like this, the system can be programmed to print out a letter acknowledging the password change, which is mailed by ordinary postal mail to the registered address of the user. Why would this enhance security, even though it wouldn't prevent the adversary from obtaining access?
- 11.5 What is two-factor authentication? Give an example.

- 11.6 Why should a blank web form to be filled in with a password be downloaded to the browser via SSL, rather than using SSL only to send the filled-in form back to the server?
- 11.7 Draw the following partially ordered sets:
- (a) One based on the subset ordering for sets of compartments, as in Figure 11.2 on page 489, but using only the N and I compartments.
 - (b) The full Cartesian product of your answer from part (a) and the total ordering of $\{T, S, C, U\}$. Unlike Figure 11.3 on page 489, no elements should be left out.
- 11.8 Figure 11.7 shows the full 32-element Cartesian product of the 4-element and 8-element partial orders shown in Figure 11.2 on page 489. However, the elements are not labeled with their security classification levels and sets of compartments; instead, they are shown just as circles. What should the labels be for the eight circles shown in black? (Note that this diagram is arranged differently than the 11-element excerpt in Figure 11.3 on page 489. Do not expect to find those 11 elements in the same positions here.)
- 11.9 Using the Bell-LaPadula model, with the compartments $\{N, I, H\}$ and classification levels $\{T, S, C, U\}$, which of the following statements are true?
- (a) A subject with current level C and compartments N and H may read from an object with level C and compartments N and H.
 - (b) A subject with current level C and compartments N and H may read from an object with level C and compartment N.

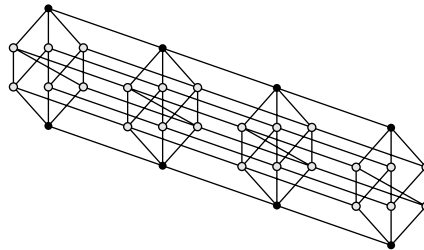


Figure 11.7: This is an unlabeled version of the Cartesian product of the partial orders shown in Figure 11.2 on page 489.

- (c) A subject with current level C and compartments N and H may read from an object with level C and compartments N, I, and H.
 - (d) A subject with current level C and compartments N and H may read from an object with level C and compartments N and I.
 - (e) A subject with current level C and compartments N and H may read from an object with level S and compartments N and H.
 - (f) A subject with current level C and compartments N and H may read from an object with level S and compartment N.
 - (g) A subject with current level C and compartments N and H may read from an object with level S and compartments N, I, and H.
 - (h) A subject with current level C and compartments N and H may read from an object with level U and no compartments.
 - (i) A subject with current level C and compartments N and H may write into an object with level C and compartments N and H.
 - (j) A subject with current level C and compartments N and H may write into an object with level C and compartment N.
 - (k) A subject with current level C and compartments N and H may write into an object with level C and compartments N, I, and H.
 - (l) A subject with current level C and compartments N and H may write into an object with level C and compartments N and I.
 - (m) A subject with current level C and compartments N and H may write into an object with level S and compartments N and H.
 - (n) A subject with current level C and compartments N and H may write into an object with level S and compartment N.
 - (o) A subject with current level C and compartments N and H may write into an object with level S and compartments N, I, and H.
 - (p) A subject with current level C and compartments N and H may write into an object with level U and no compartments.
- 11.10 In the Bell-LaPadula model, under what conditions may a subject read from an object and then modify the object to contain new information that is derived from the old?
- 11.11 Why, in the Bell-LaPadula model, is it important that a principal can run a subject at a current security level below the one the principal is cleared for?

- 11.12 In the Bell-LaPadula model, a subject running at a high current level may read from an object that is labeled with a lower level. In a system with readers-writers locks, this could block a subject running at a lower level from writing the object. Explain why this could compromise the design goals of the Bell-LaPadula model.
- 11.13 Viruses have historically been a problem primarily on systems designed with little regard for the principle of least privilege. Explain why this would be expected. Keep in mind the distinction between viruses and worms.
- 11.14 A Common Criteria assessment includes inspection not only of the system design and code, but also of documentation intended for system administrators and users. Why is this relevant?
- 11.15 Explain the difference in the Common Criteria between a PP, an ST, and an EAL.
- 11.16 Is a system certified at a high EAL necessarily more secure than one certified at a low EAL? Explain.
- 11.17 Distinguish honeypots from IDSes.
- 11.18 Why should the code of network server programs be audited for correct processing of received input in the same way a setuid program's processing of user input is audited?
- 11.19 Section 11.3 points out that password-based user authentication is vulnerable to a user walking away and being replaced at the keyboard by an adversary. Section 11.3.4 indicates that this vulnerability can be mitigated, but not eliminated, by demanding reentry of the password at appropriate moments.
 - (a) Explain how the vulnerability might be more thoroughly mitigated using an appropriately designed token.
 - (b) Explain how the vulnerability might be eliminated using biometric authentication.

Programming Projects

- 11.1 Write a program that runs all strings of six or fewer lowercase letters through a library implementation of SHA-1. Report how long

your program takes, with enough details of the hardware and software context that someone could approximately replicate your result.

Consider the system shown in Figure 11.1 on page 484 in which the hash function can be SHA-1. The point of this system is to increase an adversary's work factor if the stored value is disclosed. Based on your experiment, you should have some indication how much the work factor increases by, given an assumption that users pick passwords of the sort your program checked. Under what sorts of circumstances would this increase in work factor be sufficient?

- 11.2 On a Linux system, you can read cryptographically-strong random bytes from `/dev/random` and can generally read a list of words (one per line) from a file such as `/usr/share/dict/words`. Other systems are likely to have similar information available. Write a program that randomly chooses four words, each of which is four letters long, and prints them out with hyphens between them to serve as a passphrase. For example, you might get the output `mean-chef-pour-pubs`. On the Linux distribution on my computer, there are 2236 four-letter words. How many four-word passphrases can be formed from them? How long would a random string of lowercase letters need to be to have a comparable number of possibilities? Which seems to be more memorable?

Exploration Projects

- 11.1 User authentication systems are successfully attacked all the time, usually without generating much publicity. However, when the user in question is a celebrity, the newspapers sit up and take notice. Write a summary of a user-authentication failure involving Paris Hilton in February of 2005. Your sources should include at least the article that month by Brian McWilliams in *MacDev Center* as well as the article by Brian Krebs in the May 19, 2005, issue of *The Washington Post*; both articles are cited in the end-of-chapter notes. As these articles contain contradictory information, presumably they should be taken with a grain of salt. Nonetheless, are there any lessons you can draw, both for designers of authentication systems and for users?
- 11.2 The website <http://www.sans.org> contains a list of top-twenty vulnerabilities. Look at the information given on how to remedy each

problem. How many of these correspond to the best practices listed in this chapter?

- 11.3 Research and write a paper about the role that Trojan horses reportedly played in a 2004 unauthorized access to Cisco Systems and in a 2005 unauthorized access to LexisNexis's Seisint unit. In the first, the Trojan horse was reportedly a version of the `ssh` program, whereas in the second, the Trojan horse reportedly masqueraded as a display of nude photos of a teenage girl. Setting that difference aside, what commonality and what other differences can you find in the way the two attacks worked? What more general lessons for computer system security can be gained from these two incidents?
- 11.4 Most UNIX and Linux systems include a program called `sudo`. Read the documentation for it on your system or on the web at <http://www.sudo.ws>. Write a description of how this program's design reflects several of the principles explained in this chapter.
- 11.5 Check the web sites of a variety of banks to see whether they have login forms available through http (non-SSL) URLs, rather than only https (SSL-encrypted) ones. Document your findings using screen captures.
- 11.6 Find several commercially available biometric systems. For each one, indicate whether it provides identification or only authentication.
- 11.7 What is address space layout randomization and how does it help deter stack smashing attacks?
- 11.8 Bradley Manning has been charged with disclosing a large volume of classified information to WikiLeaks. Write a paper that uses publicly available information about this case to illustrate general security principles.

Notes

The single most important source of practical information about security is <http://www.sans.org>. There are also a number of good books on practical security matters, such as those by Garfinkel, Spafford, and Schwartz [60]; Cheswick, Bellovin, and Rubin [33]; and Northcutt et al. [109]. For a broad treatment of security, Anderson's book [6] is highly regarded.

Saltzer and Schroeder presented most of Section 11.2's general security principles in their 1975 tutorial paper [125]. That paper also described capabilities and access control lists, along the lines of Chapter 7's presentation.

Because one important class of security threats involves tricking legitimate users into cooperating with an adversary, Stajano and Wilson have analyzed the methods that con artists use [136, 135].

One example of a system that generates multiple passwords from a single master password was described by Ross et al. [121].

The Bell-LaPadula model was described by Bell and La Padula in a series of MITRE Corporation technical reports in the early 1970s. Their best summary is in a later "unified exposition," which was also published only as a technical report [14]. A more sophisticated, but less influential, information-flow model was published by Dorothy Denning [43]. Both of these and other formal models were surveyed by Landwehr [94]. The problem of covert channels was described by Lampson [92]. Another important survey of the state of security research in the highly-productive 1970s was published by Dorothy and Peter Denning [44].

I mentioned that although most buffer-overflow attacks overwrite return addresses, an attacker could instead arrange to overwrite some security-critical variable, such as a Boolean flag used to control access. Chen et al. [32] showed that such attacks are in fact realistic, even if not currently popular. As defenses are put in place against current-generation stack-smashing attacks, these alternate forms of attack are likely to gain in popularity.

Information about the Common Criteria is available from <http://www.commoncriteriaportal.org>. A good overview is in the introductory document [141]. The specific ST that I use for illustration is the one for Windows 2000 [127]. It was also used by Shapiro to make similar points about the importance of functional requirements [131].

Exploration Project 11.1 mentions a user authentication failure involving Paris Hilton. Many published accounts at the time included some information about the attack; the one specifically mentioned in the project assignment is by McWilliams [103]. Information about the attack seems to have shifted over time; the project assignment also mentions an article a few months later by Krebs [90].

