CHAPTER 15

Computer Security Techniques

This chapter introduces common measures used to counter the security threats discussed in Chapter 14.

15.1 AUTHENTICATION

In most computer security contexts, user authentication is the fundamental building block and the primary line of defense. User authentication is the basis for most types of access control and for user accountability. RFC 2828 defines user authentication as follows:

> The process of verifying an identity claimed by or for a system entity. An authentication process consists of two steps:
>
> - **Identification step:** Presenting an identifier to the security system. (Identifiers should be assigned carefully, because authenticated identities are the basis for other security services, such as access control service.)
> - **Verification step:** Presenting or generating authentication information that corroborates the binding between the entity and the identifier.

For example, user Alice Toklas could have the user identifier ABTOKLAS. This information needs to be stored on any server or computer system that Alice wishes to use and could be known to system administrators and other users. A typical item of authentication information associated with this user ID is a password, which is kept secret (known only to Alice and to the system). If no one is able to obtain or guess Alice's password, then the combination of Alice's user ID and password enables administrators to set up Alice's access permissions and audit her activity. Because Alice's ID is not secret, system users can send her e-mail, but because her password is secret, no one can pretend to be Alice.

In essence, identification is the means by which a user provides a claimed identity to the system; user authentication is the means of establishing the validity of the claim. Note that user authentication is distinct from message authentication. As defined in Chapter 2, message authentication is a procedure that allows communicating parties to verify that the contents of a received message have not been altered and that the source is authentic. This chapter is concerned solely with user authentication.

Means of Authentication

There are four general means of authenticating a user's identity, which can be used alone or in combination:

- **Something the individual knows:** Examples includes a password, a personal identification number (PIN), or answers to a prearranged set of questions.
- **Something the individual possesses:** Examples include electronic keycards, smart cards, and physical keys. This type of authenticator is referred to as a *token*.

- **Something the individual is (static biometrics):** Examples include recognition by fingerprint, retina, and face.
- **Something the individual does (dynamic biometrics):** Examples include recognition by voice pattern, handwriting characteristics, and typing rhythm.

All of these methods, properly implemented and used, can provide secure user authentication. However, each method has problems. An adversary may be able to guess or steal a password. Similarly, an adversary may be able to forge or steal a token. A user may forget a password or lose a token. Further, there is a significant administrative overhead for managing password and token information on systems and securing such information on systems. With respect to biometric authenticators, there are a variety of problems, including dealing with false positives and false negatives, user acceptance, cost, and convenience.

Password-Based Authentication

A widely used line of defense against intruders is the password system. Virtually all multiuser systems, network-based servers, Web-based e-commerce sites, and other similar services require that a user provide not only a name or identifier (ID) but also a password. The system compares the password to a previously stored password for that user ID, maintained in a system password file. The password serves to authenticate the ID of the individual logging on to the system. In turn, the ID provides security in the following ways:

- The ID determines whether the user is authorized to gain access to a system. In some systems, only those who already have an ID filed on the system are allowed to gain access.
- The ID determines the privileges accorded to the user. A few users may have supervisory or "superuser" status that enables them to read files and perform functions that are especially protected by the operating system. Some systems have guest or anonymous accounts, and users of these accounts have more limited privileges than others.
- The ID is used in what is referred to as discretionary access control. For example, by listing the IDs of the other users, a user may grant permission to them to read files owned by that user.

The Use of Hashed Passwords

A widely used password security technique is the use of hashed passwords and a salt value. This scheme is found on virtually all UNIX variants as well as on a number of other operating systems. The following procedure is employed (Figure 15.1a). To load a new password into the system, the user selects or is assigned a password. This password is combined with a fixed-length **salt value** [MORR79]. In older implementations, this value is related to the time at which the password is assigned to the user. Newer implementations use a pseudorandom or random number. The password and salt serve as inputs to a hashing algorithm to produce a fixed-length hash code. The hash algorithm is designed to be slow to execute to thwart attacks. The hashed password is then stored, together with a plaintext copy of the salt, in the password file for the corresponding user ID. The hashed-password method has been shown to be secure against a variety of cryptanalytic attacks [WAGN00].

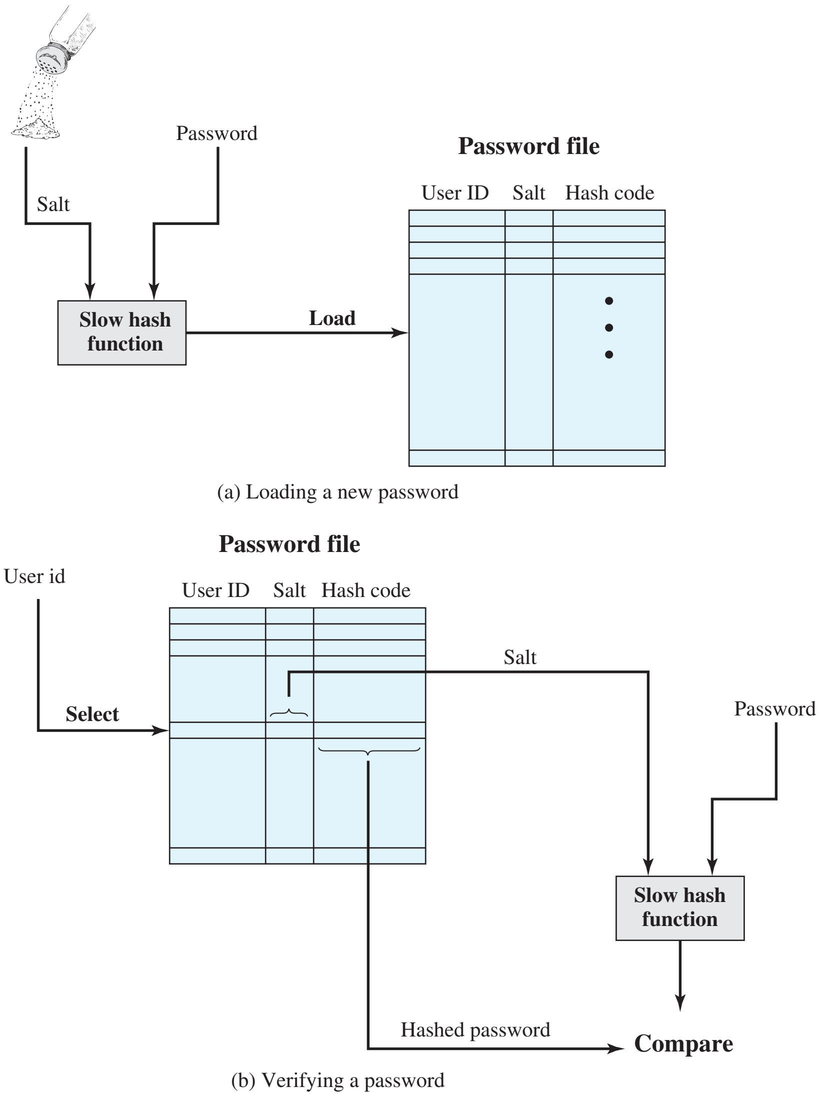


Figure 15.1 **UNIX Password Scheme**

When a user attempts to log on to a UNIX system, the user provides an ID and a password (Figure 15.1b). The operating system uses the ID to index into the password file and retrieve the plaintext salt and the encrypted password. The salt and user-supplied password are used as input to the encryption routine. If the result matches the stored value, the password is accepted.

The salt serves three purposes:

- It prevents duplicate passwords from being visible in the password file. Even if two users choose the same password, those passwords will be assigned different salt values. Hence, the hashed passwords of the two users will differ.

- It greatly increases the difficulty of offline dictionary attacks. For a salt of length b bits, the number of possible passwords is increased by a factor of 2^b, increasing the difficulty of guessing a password in a dictionary attack.
- It becomes nearly impossible to find out whether a person with passwords on two or more systems has used the same password on all of them.

To see the second point, consider the way that an offline dictionary attack would work. The attacker obtains a copy of the password file. Suppose first that the salt is not used. The attacker's goal is to guess a single password. To that end, the attacker submits a large number of likely passwords to the hashing function. If any of the guesses matches one of the hashes in the file, then the attacker has found a password that is in the file. But faced with the UNIX scheme, the attacker must take each guess and submit it to the hash function once for each salt value in the dictionary file, multiplying the number of guesses that must be checked.

There are two threats to the UNIX password scheme. First, a user can gain access on a machine using a guest account or by some other means and then run a password guessing program, called a password cracker, on that machine. The attacker should be able to check many thousands of possible passwords with little resource consumption. In addition, if an opponent is able to obtain a copy of the password file, then a cracker program can be run on another machine at leisure. This enables the opponent to run through millions of possible passwords in a reasonable period.

UNIX Implementations Since the original development of UNIX, most implementations have relied on the following password scheme. Each user selects a password of up to eight printable characters in length. This is converted into a 56-bit value (using 7-bit ASCII) that serves as the key input to an encryption routine. The hash routine, known as crypt(3), is based on DES. A 12-bit salt value is used. The modified DES algorithm is executed with a data input consisting of a 64-bit block of zeros. The output of the algorithm then serves as input for a second encryption. This process is repeated for a total of 25 encryptions. The resulting 64-bit output is then translated into an 11-character sequence. The modification of the DES algorithm converts it into a one-way hash function. The crypt(3) routine is designed to discourage guessing attacks. Software implementations of DES are slow compared to hardware versions, and the use of 25 iterations multiplies the time required by 25.

This particular implementation is now considered woefully inadequate. For example, [PERR03] reports the results of a dictionary attack using a supercomputer. The attack was able to process over 50 million password guesses in about 80 minutes. Further, the results showed that for about $10,000 anyone should be able to do the same in a few months using one uniprocessor machine. Despite its known weaknesses, this UNIX scheme is still often required for compatibility with existing account management software or in multivendor environments.

There are other, much stronger, hash/salt schemes available for UNIX. The recommended hash function for many UNIX systems, including Linux, Solaris, and FreeBSD, is based on the MD5 secure hash algorithm (which is similar to, but not as secure as SHA-1).[1] The MD5 crypt routine uses a salt of up to 48 bits and effectively

[1]See Appendix F for a discussion of secure hash algorithms.

has no limitations on password length. It produces a 128-bit hash value. It is also far slower than crypt(3). To achieve the slowdown, MD5 crypt uses an inner loop with 1000 iterations.

Probably the most secure version of the UNIX hash/salt scheme was developed for OpenBSD, another widely used open source UNIX. This scheme, reported in [PROV99], uses a hash function based on the Blowfish symmetric block cipher. The hash function, called Bcrypt, is quite slow to execute. Bcrypt allows passwords of up to 55 characters in length and requires a random salt value of 128 bits, to produce a 192-bit hash value. Bcrypt also includes a cost variable; an increase in the cost variable causes a corresponding increase in the time required to perform a Bcyrpt hash. The cost assigned to a new password is configurable, so that administrators can assign a higher cost to privileged users.

Token-Based Authentication

Objects that a user possesses for the purpose of user authentication are called tokens. In this subsection, we examine two types of tokens that are widely used; these are cards that have the appearance and size of bank cards.

Memory Cards Memory cards can store but not process data. The most common such card is the bank card with a magnetic stripe on the back. A magnetic stripe can store only a simple security code, which can be read (and unfortunately reprogrammed) by an inexpensive card reader. There are also memory cards that include an internal electronic memory.

Memory cards can be used alone for physical access, such as a hotel room. For computer user authentication, such cards are typically used with some form of password or personal identification number (PIN). A typical application is an automatic teller machine (ATM).

The memory card, when combined with a PIN or password, provides significantly greater security than a password alone. An adversary must gain physical possession of the card (or be able to duplicate it) plus must gain knowledge of the PIN. Among the potential drawbacks are the following [NIST95]:

- **Requires special reader:** This increases the cost of using the token and creates the requirement to maintain the security of the reader's hardware and software.
- **Token loss:** A lost token temporarily prevents its owner from gaining system access. Thus there is an administrative cost in replacing the lost token. In addition, if the token is found, stolen, or forged, then an adversary now need only determine the PIN to gain unauthorized access.
- **User dissatisfaction:** Although users may have no difficulty in accepting the use of a memory card for ATM access, its use for computer access may be deemed inconvenient.

Smart Cards A wide variety of devices qualify as smart tokens. These can be categorized along three dimensions that are not mutually exclusive:

- **Physical characteristics:** Smart tokens include an embedded microprocessor. A smart token that looks like a bank card is called a smart card. Other smart tokens can look like calculators, keys, or other small portable objects.

- **Interface:** Manual interfaces include a keypad and display for human/token interaction. Smart tokens with an electronic interface communicate with a compatible reader/writer.
- **Authentication protocol:** The purpose of a smart token is to provide a means for user authentication. We can classify the authentication protocols used with smart tokens into three categories:
  - **Static:** With a static protocol, the user authenticates himself or herself to the token and then the token authenticates the user to the computer. The latter half of this protocol is similar to the operation of a memory token.
  - **Dynamic password generator:** In this case, the token generates a unique password periodically (e.g., every minute). This password is then entered into the computer system for authentication, either manually by the user or electronically via the token. The token and the computer system must be initialized and kept synchronized so that the computer knows the password that is current for this token.
  - **Challenge-response:** In this case, the computer system generates a challenge, such as a random string of numbers. The smart token generates a response based on the challenge. For example, public-key cryptography could be used and the token could encrypt the challenge string with the token's private key.

For user authentication to computer, the most important category of smart token is the smart card, which has the appearance of a credit card, has an electronic interface, and may use any of the type of protocols just described. The remainder of this section discusses smart cards.

A smart card contains within it an entire microprocessor, including processor, memory, and I/O ports. Some versions incorporate a special co-processing circuit for cryptographic operation to speed the task of encoding and decoding messages or generating digital signatures to validate the information transferred. In some cards, the I/O ports are directly accessible by a compatible reader by means of exposed electrical contacts. Other cards rely instead on an embedded antenna for wireless communication with the reader.

Biometric Authentication

A biometric authentication system attempts to authenticate an individual based on his or her unique physical characteristics. These include static characteristics, such as fingerprints, hand geometry, facial characteristics, and retinal and iris patterns; and dynamic characteristics, such as voiceprint and signature. In essence, biometrics is based on pattern recognition. Compared to passwords and tokens, biometric authentication is both technically complex and expensive. While it is used in a number of specific applications, biometrics has yet to mature as a standard tool for user authentication to computer systems.

A number of different types of physical characteristics are either in use or under study for user authentication. The most common are the following:

- **Facial characteristics:** Facial characteristics are the most common means of human-to-human identification; thus it is natural to consider them for identification by computer. The most common approach is to define characteristics based on relative location and shape of key facial features, such as eyes, eyebrows, nose, lips, and chin shape. An alternative approach is to use an infrared camera to produce a face thermogram that correlates with the underlying vascular system in the human face.

- **Fingerprints:** Fingerprints have been used as a means of identification for centuries, and the process has been systematized and automated particularly for law enforcement purposes. A fingerprint is the pattern of ridges and furrows on the surface of the fingertip. Fingerprints are believed to be unique across the entire human population. In practice, automated fingerprint recognition and matching system extract a number of features from the fingerprint for storage as a numerical surrogate for the full fingerprint pattern.
- **Hand geometry:** Hand geometry systems identify features of the hand, including shape, and lengths and widths of fingers.
- **Retinal pattern:** The pattern formed by veins beneath the retinal surface is unique and therefore suitable for identification. A retinal biometric system obtains a digital image of the retinal pattern by projecting a low-intensity beam of visual or infrared light into the eye.
- **Iris:** Another unique physical characteristic is the detailed structure of the iris.
- **Signature:** Each individual has a unique style of handwriting, and this is reflected especially in the signature, which is typically a frequently written sequence. However, multiple signature samples from a single individual will not be identical. This complicates the task of developing a computer representation of the signature that can be matched to future samples.
- **Voice:** Whereas the signature style of an individual reflects not only the unique physical attributes of the writer but also the writing habit that has developed, voice patterns are more closely tied to the physical and anatomical characteristics of the speaker. Nevertheless, there is still a variation from sample to sample over time from the same speaker, complicating the biometric recognition task.

Figure 15.2 gives a rough indication of the relative cost and accuracy of these biometric measures. The concept of accuracy does not apply to user authentication schemes using smart cards or passwords. For example, if a user enters a password, it

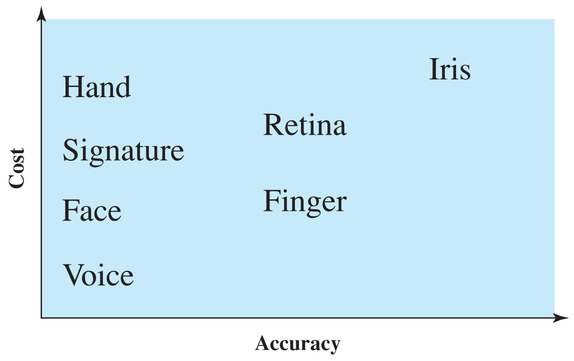


Figure 15.2 Cost versus Accuracy of Various Biometric Characteristics in User Authentication Schemes

either matches exactly the password expected for that user or not. In the case of biometric parameters, the system instead must determine how closely a presented biometric characteristic matches a stored characteristic. Before elaborating on the concept of biometric accuracy, we need to have a general idea of how biometric systems work.

15.2 ACCESS CONTROL

An access control policy dictates what types of access are permitted, under what circumstances, and by whom. Access control policies are generally grouped into the following categories:

- **Discretionary access control (DAC):** Controls access based on the identity of the requestor and on access rules (authorizations) stating what requestors are (or are not) allowed to do. This policy is termed *discretionary* because an entity might have access rights that permit the entity, by its own volition, to enable another entity to access some resource.
- **Mandatory access control (MAC):** Controls access based on comparing security labels (which indicate how sensitive or critical system resources are) with security clearances (which indicate system entities are eligible to access certain resources). This policy is termed *mandatory* because an entity that has clearance to access a resource may not, just by its own volition, enable another entity to access that resource.
- **Role-based access control (RBAC):** Controls access based on the roles that users have within the system and on rules stating what accesses are allowed to users in given roles.

DAC is the traditional method of implementing access control. This method was introduced in Chapter 12; we provide more detail in this section. MAC is a concept that evolved out of requirements for military information security and is beyond the scope of this book. RBAC has become increasingly popular and is introduced later in this section.

These three policies are not mutually exclusive (Figure 15.3). An access control mechanism can employ two or even all three of these policies to cover different classes of system resources.

Discretionary Access Control[2]

This section introduces a general model for DAC developed by Lampson, Graham, and Denning [LAMP71, GRAH72, DENN71]. The model assumes a set of subjects, a set of objects, and a set of rules that govern the access of subjects to objects. Let us define the protection state of a system to be the set of information, at a given point in time, that specifies the access rights for each subject with respect to each object. We can identify three requirements: representing the protection state, enforcing access rights, and allowing subjects to alter the protection state in certain ways. The model addresses all three requirements, giving a general, logical description of a DAC system.

[2]Before continuing, the reader should review Section 12.7 and the discussion of UNIX file access control in Section 12.8.

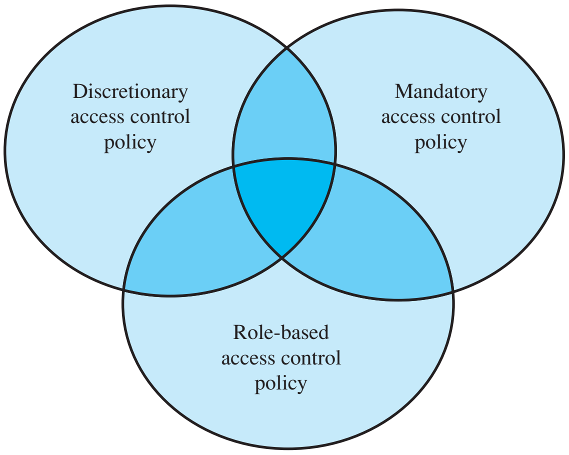

Discretionary access control policy
Mandatory access control policy
Role-based access control policy

Figure 15.3 Access Control Policies

To represent the protection state, we extend the universe of objects in the access control matrix to include the following:

- **Processes:** Access rights include the ability to delete a process, stop (block), and wake up a process.
- **Devices:** Access rights include the ability to read/write the device, to control its operation (e.g., a disk seek), and to block/unblock the device for use.
- **Memory locations or regions:** Access rights include the ability to read/write certain locations of regions of memory that are protected so that the default is that access is not allowed.
- **Subjects:** Access rights with respect to a subject have to do with the ability to grant or delete access rights of that subject to other objects, as explained subsequently.

Figure 15.4 is an example (compare Figure 12.13a). For an access control matrix A, each entry $A[S, X]$ contains strings, called access attributes, that specify the access

		Objects								
		Subjects			Files		Processes		Disk drives	
		S_1	S_2	S_3	F_1	F_2	P_1	P_2	D_1	D_2
	S_1	control	owner	owner control	read *	read owner	wakeup	wakeup	seek	owner
Subjects	S_2		control		write *	execute			owner	seek *
	S_3			control		write	stop			

* = copy flag set

Figure 15.4 Extended Access Control Matrix

rights of subject S to object X. For example, in Figure 15.4, S_1 may read file F_2, because 'read' appears in $A[S_1, F_1]$.

From a logical or functional point of view, a separate access control module is associated with each type of object (Figure 15.5). The module evaluates each request by a subject to access an object to determine if the access right exists. An access attempt triggers the following steps:

1. A subject S_0 issues a request of type α for object X.
2. The request causes the system (the operating system or an access control interface module of some sort) to generate a message of the form (S_0, α, X) to the controller for X.

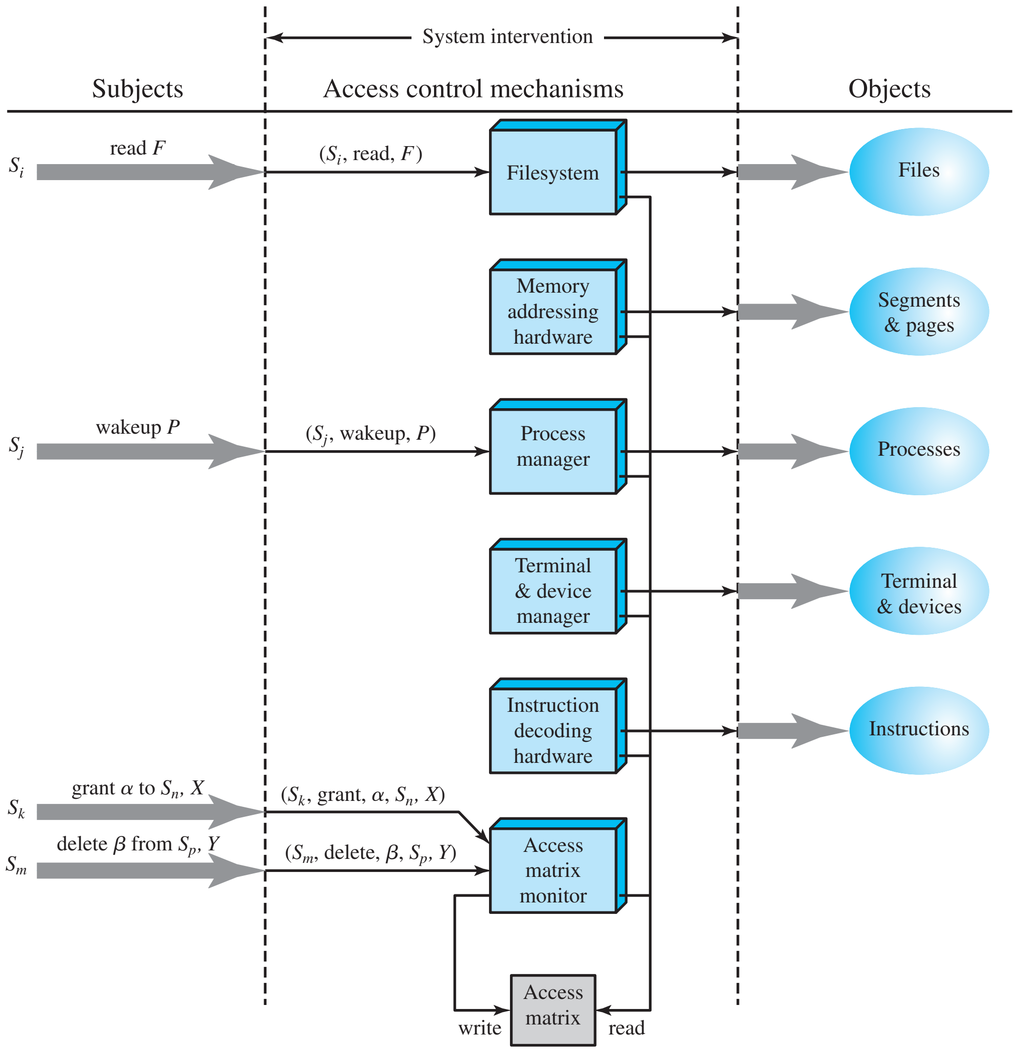


Figure 15.5 **An Organization of the Access Control Function**

Table 15.1 Access Control System Commands

Rule	Command (by S_0)	Authorization	Operation
R1	**transfer** $\left\{\begin{matrix}\alpha^*\\ \alpha\end{matrix}\right\}$ **to** S, X	'α^*' in $A[S_0, X]$	store $\left\{\begin{matrix}\alpha^*\\ \alpha\end{matrix}\right\}$ in $A[S, X]$
R2	**grant** $\left\{\begin{matrix}\alpha^*\\ \alpha\end{matrix}\right\}$ **to** S, X	'owner' in $A[S_0, X]$	store $\left\{\begin{matrix}\alpha^*\\ \alpha\end{matrix}\right\}$ in $A[S, X]$
R3	**delete** α **from** S, X	'control' in $A[S_0, S]$ or 'owner' in $A[S_0, X]$	delete α from $A[S, X]$
R4	$w \leftarrow$ **read** S, X	'control' in $A[S_0, S]$ or ' owner' in $A[S_0, X]$	copy $A[S, X]$ into w
R5	**create object** X	None	add column for X to A; store 'owner' in $A[S_0, X]$
R6	**destroy object** X	'owner' in $A[S_0, X]$	delete column for X from A
R7	**create subject** S	none	add row for S to A; execute **create object** S; store 'control' in $A[S, S]$
R8	**destroy subject** S	'owner' in $A[S_0, S]$	delete row for S from A; execute **destroy object** S

3. The controller interrogates the access matrix A to determine if α is in $A[S_0, X]$. If so, the access is allowed; if not, the access is denied and a protection violation occurs. The violation should trigger a warning and appropriate action.

Figure 15.5 suggests that every access by a subject to an object is mediated by the controller for that object, and that the controller's decision is based on the current contents of the matrix. In addition, certain subjects have the authority to make specific changes to the access matrix. A request to modify the access matrix is treated as an access to the matrix, with the individual entries in the matrix treated as objects. Such accesses are mediated by an access matrix controller, which controls updates to the matrix.

The model also includes a set of rules that govern modifications to the access matrix, shown in Table 15.1. For this purpose, we introduce the access rights 'owner' and 'control' and the concept of a copy flag, explained in the subsequent paragraphs.

The first three rules deal with transferring, granting, and deleting access rights. Suppose that the entry α^* exists in $A[S_0, X]$. This means that S_0 has access right α to subject X and, because of the presence of the copy flag, can transfer this right, with or without copy flag, to another subject. Rule R1 expresses this capability. A subject would transfer the access right without the copy flag if there were a concern that the new subject would maliciously transfer the right to another subject that should not have that access right. For example, S_1 may place 'read' or 'read *' in any matrix entry in the F_1 column. Rule R2 states that if S_0 is designated as the owner of object X, then S_0 can grant an access right to that object for any other subject. Rule 2 states that S_0 can add any access right to $A[S, X]$ for any S, if S_0 has 'owner' access to x. Rule R3 permits S_0 to delete any access right from any matrix entry in a row for which S_0 controls the subject and for any matrix entry in a column for which S_0 owns the object. Rule R4 permits a subject to read that portion of the matrix that it owns or controls.

The remaining rules in Table 15.1 govern the creation and deletion of subjects and objects. Rule R5 states that any subject can create a new object, which it owns, and can then grant and delete access to the object. Under rule R6, the owner of an object can destroy the object, resulting in the deletion of the corresponding column of the access matrix. Rule R7 enables any subject to create a new subject; the creator owns the new subject and the new subject has control access to itself. Rule R8 permits the owner of a subject to delete the row and column (if there are subject columns) of the access matrix designated by that subject.

The set of rules in Table 15.1 is an example of the rule set that could be defined for an access control system. The following are examples of additional or alternative rules that could be included. A transfer-only right could be defined, which results in the transferred right being added to the target subject and deleted from the transferring subject. The number of owners of an object or a subject could be limited to one by not allowing the copy flag to accompany the owner right.

The ability of one subject to create another subject and to have 'owner' access right to that subject can be used to define a hierarchy of subjects. For example, in Figure 15.4, S_1 owns S_2 and S_3, so that S_2 and S_3 are subordinate to S_1. By the rules of Table 15.1, S_1 can grant and delete to S_2 access rights that S_1 already has. Thus, a subject can create another subject with a subset of its own access rights. This might be useful, for example, if a subject is invoking an application that is not fully trusted, and does not want that application to be able to transfer access rights to other subjects.

Role-Based Access Control

Traditional DAC systems define the access rights of individual users and groups of users. In contrast, RBAC is based on the roles that users assume in a system rather than the user's identity. Typically, RBAC models define a role as a job function within an organization. RBAC systems assign access rights to roles instead of individual users. In turn, users are assigned to different roles, either statically or dynamically, according to their responsibilities.

RBAC now enjoys widespread commercial use and remains an area of active research. The National Institute of Standards and Technology (NIST) has issued a standard, *Security Requirements for Cryptographic Modules* (FIPS PUB 140-2, May 25, 2001), that requires support for access control and administration through roles.

The relationship of users to roles is many to many, as is the relationship of roles to resources, or system objects (Figure 15.6). The set of users changes, in some environments frequently, and the assignment of a user to one or more roles may also be dynamic. The set of roles in the system in most environments is likely to be static, with only occasional additions or deletions. Each role will have specific access rights to one or more resources. The set of resources and the specific access rights associated with a particular role are also likely to change infrequently.

We can use the access matrix representation to depict the key elements of an RBAC system in simple terms, as shown in Figure 15.7. The upper matrix relates individual users to roles. Typically there are many more users than roles. Each matrix entry is either blank or marked, the latter indicating that this user is assigned to this role. Note that a single user may be assigned multiple roles (more than one mark in a row) and that multiple users may be assigned to a single role (more than one mark in a column). The lower matrix has the same structure as the DAC access control matrix,

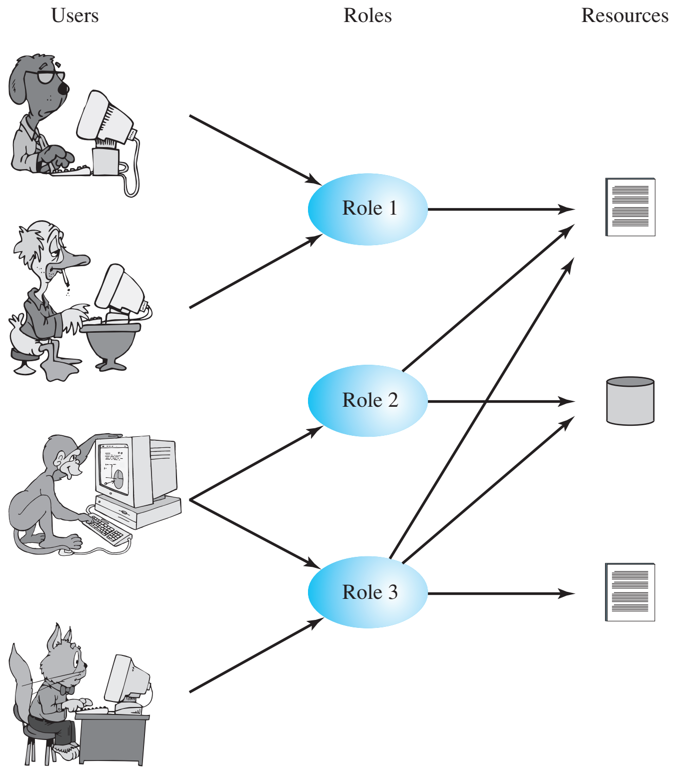


Figure 15.6 **Users, Roles, and Resources**

with roles as subjects. Typically, there are few roles and many objects or resources. In this matrix the entries are the specific access rights enjoyed by the roles. Note that a role can be treated as an object, allowing the definition of role hierarchies.

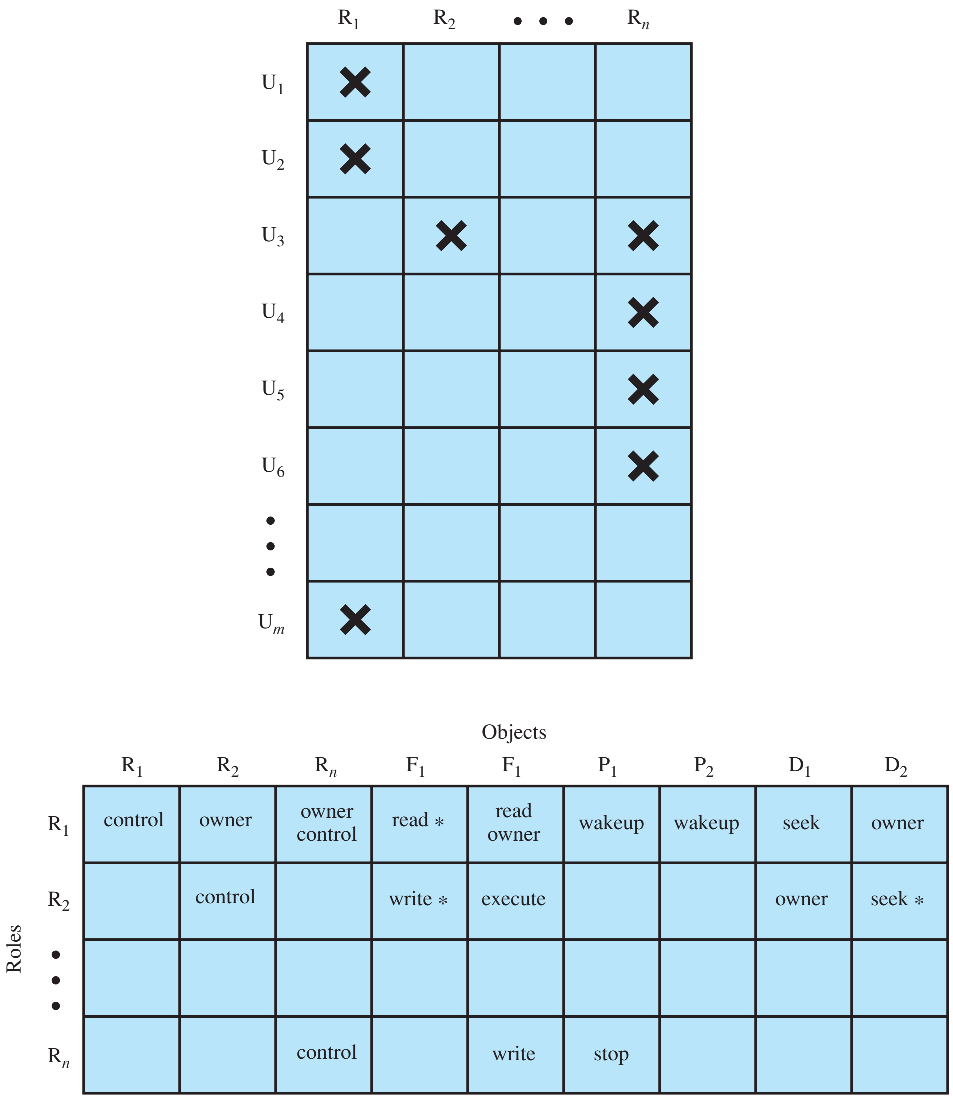
RBAC lends itself to an effective implementation of the principle of least privilege. That is, each role should contain the minimum set of access rights needed for that role. A user is assigned to a role that enables him or her to perform only what is required for that role. Multiple users assigned to the same role enjoy the same minimal set of access rights.

15.3 INTRUSION DETECTION

The following definitions from RFC 2828 (Internet Security Glossary) are relevant to our discussion:

Security intrusion: A security event, or a combination of multiple security events, that constitutes a security incident in which an intruder gains, or attempts to gain, access to a system (or system resource) without having authorization to do so.

Intrusion detection: A security service that monitors and analyzes system events for the purpose of finding, and providing real-time or near real- time warning of, attempts to access system resources in an unauthorized manner.



	R_1	R_2	• • •	R_n
U_1	✕			
U_2	✕			
U_3		✕		✕
U_4				✕
U_5				✕
U_6				✕
⋮				
U_m	✕			

Objects

Roles	R_1	R_2	R_n	F_1	F_1	P_1	P_2	D_1	D_2
R_1	control	owner	owner control	read *	read owner	wakeup	wakeup	seek	owner
R_2		control		write *	execute			owner	seek *
⋮									
R_n			control		write	stop			

Figure 15.7 Access Control Matrix Representation of RBAC

IDSs can be classified as follows:

- **Host-based IDS:** Monitors the characteristics of a single host and the events occurring within that host for suspicious activity
- **Network-based IDS:** Monitors network traffic for particular network segments or devices and analyzes network, transport, and application protocols to identify suspicious activity

An IDS comprises three logical components:

- **Sensors:** Sensors are responsible for collecting data. The input for a sensor may be any part of a system that could contain evidence of an intrusion. Types of input to a sensor include network packets, log files, and system call traces. Sensors collect and forward this information to the analyzer.

- **Analyzers:** Analyzers receive input from one or more sensors or from other analyzers. The analyzer is responsible for determining if an intrusion has occurred. The output of this component is an indication that an intrusion has occurred. The output may include evidence supporting the conclusion that an intrusion occurred. The analyzer may provide guidance about what actions to take as a result of the intrusion.
- **User interface:** The user interface to an IDS enables a user to view output from the system or control the behavior of the system. In some systems, the user interface may equate to a manager, director, or console component.

Basic Principles

Authentication facilities, access control facilities, and firewalls all play a role in countering intrusions. Another line of defense is intrusion detection, and this has been the focus of much research in recent years. This interest is motivated by a number of considerations, including the following:

1. If an intrusion is detected quickly enough, the intruder can be identified and ejected from the system before any damage is done or any data are compromised. Even if the detection is not sufficiently timely to preempt the intruder, the sooner that the intrusion is detected, the less the amount of damage and the more quickly that recovery can be achieved.
2. An effective IDS can serve as a deterrent, thus acting to prevent intrusions.
3. Intrusion detection enables the collection of information about intrusion techniques that can be used to strengthen intrusion prevention measures.

Intrusion detection is based on the assumption that the behavior of the intruder differs from that of a legitimate user in ways that can be quantified. Of course, we cannot expect that there will be a crisp, exact distinction between an attack by an intruder and the normal use of resources by an authorized user. Rather, we must expect that there will be some overlap.

Figure 15.8 suggests, in abstract terms, the nature of the task confronting the designer of an IDS. Although the typical behavior of an intruder differs from the typical behavior of an authorized user, there is an overlap in these behaviors. Thus, a loose interpretation of intruder behavior, which will catch more intruders, will also lead to a number of **false positives**, or authorized users identified as intruders. On the other hand, an attempt to limit false positives by a tight interpretation of intruder behavior will lead to an increase in **false negatives**, or intruders not identified as intruders. Thus, there is an element of compromise and art in the practice of intrusion detection.

In Anderson's study [ANDE80], it was postulated that one could, with reasonable confidence, distinguish between a masquerader and a legitimate user. Patterns of legitimate user behavior can be established by observing past history, and significant deviation from such patterns can be detected. Anderson suggests that the task of detecting a misfeasor (legitimate user performing in an unauthorized fashion) is more difficult, in that the distinction between abnormal and normal behavior may

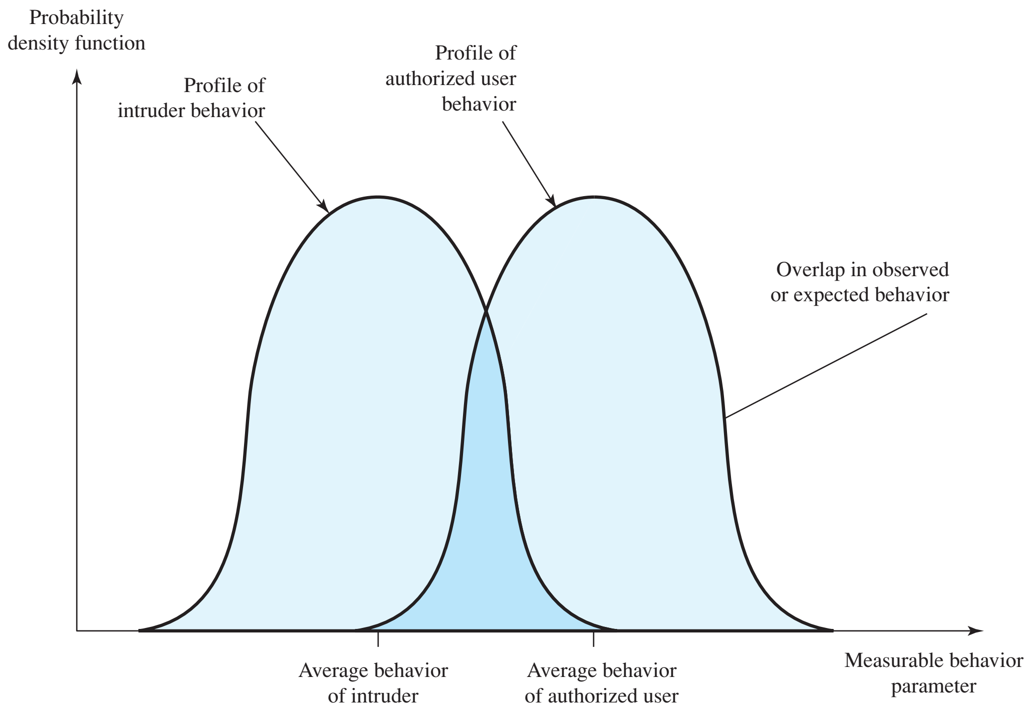


Figure 15.8 Profiles of Behavior of Intruders and Authorized Users

be small. Anderson concluded that such violations would be undetectable solely through the search for anomalous behavior. However, misfeasor behavior might nevertheless be detectable by intelligent definition of the class of conditions that suggest unauthorized use. Finally, the detection of the clandestine user was felt to be beyond the scope of purely automated techniques. These observations, which were made in 1980, remain true today.

For the remainder of this section, we concentrate on host-based intrusion detection.

Host-Based Intrusion Dectection Techniques

Host-based IDSs add a specialized layer of security software to vulnerable or sensitive systems; examples include database servers and administrative systems. The host-based IDS monitors activity on the system in a variety of ways to detect suspicious behavior. In some cases, an IDS can halt an attack before any damage is done, but its primary purpose is to detect intrusions, log suspicious events, and send alerts.

The primary benefit of a host-based IDS is that it can detect both external and internal intrusions, something that is not possible either with network-based IDSs or firewalls.

Host-based IDSs follow one of two general approaches to intrusion detection:

1. **Anomaly detection:** Involves the collection of data relating to the behavior of legitimate users over a period of time. Then statistical tests are applied to

observed behavior to determine with a high level of confidence whether that behavior is not legitimate user behavior. The following are two approaches to statistical anomaly detection:

   a. *Threshold detection:* This approach involves defining thresholds, independent of user, for the frequency of occurrence of various events.
   b. *Profile based:* A profile of the activity of each user is developed and used to detect changes in the behavior of individual accounts.

2. **Signature detection:** Involves an attempt to define a set of rules or attack patterns that can be used to decide that a given behavior is that of an intruder.

In essence, anomaly approaches attempt to define normal, or expected, behavior, whereas signature-based approaches attempt to define proper behavior.

In terms of the types of attackers listed earlier, anomaly detection is effective against masqueraders, who are unlikely to mimic the behavior patterns of the accounts they appropriate. On the other hand, such techniques may be unable to deal with misfeasors. For such attacks, signature-based approaches may be able to recognize events and sequences that, in context, reveal penetration. In practice, a system may employ a combination of both approaches to be effective against a broad range of attacks.

Audit Records

A fundamental tool for intrusion detection is the audit record. Some record of ongoing activity by users must be maintained as input to an IDS. Basically, two plans are used:

- **Native audit records:** Virtually all multiuser operating systems include accounting software that collects information on user activity. The advantage of using this information is that no additional collection software is needed. The disadvantage is that the native audit records may not contain the needed information or may not contain it in a convenient form.
- **Detection-specific audit records:** A collection facility can be implemented that generates audit records containing only that information required by the IDS. One advantage of such an approach is that it could be made vendor independent and ported to a variety of systems. The disadvantage is the extra overhead involved in having, in effect, two accounting packages running on a machine.

A good example of detection-specific audit records is one developed by Dorothy Denning [DENN87]. Each audit record contains the following fields:

- **Subject:** Initiators of actions. A subject is typically a terminal user but might also be a process acting on behalf of users or groups of users. All activity arises through commands issued by subjects. Subjects may be grouped into different access classes, and these classes may overlap.
- **Action:** Operation performed by the subject on or with an object; for example, login, read, perform I/O, execute.
- **Object:** Receptors of actions. Examples include files, programs, messages, records, terminals, printers, and user- or program-created structures. When a subject is the recipient of an action, such as electronic mail, then that subject is

considered an object. Objects may be grouped by type. Object granularity may vary by object type and by environment. For example, database actions may be audited for the database as a whole or at the record level.

- **Exception-Condition:** Denotes which, if any, exception condition is raised on return.
- **Resource-Usage:** A list of quantitative elements in which each element gives the amount used of some resource (e.g., number of lines printed or displayed, number of records read or written, processor time, I/O units used, session elapsed time).
- **Time-Stamp:** Unique time-and-date stamp identifying when the action took place.

Most user operations are made up of a number of elementary actions. For example, a file copy involves the execution of the user command, which includes doing access validation and setting up the copy, plus the read from one file, plus the write to another file. Consider the command

COPY GAME.EXE TO <Library>GAME.EXE

issued by Smith to copy an executable file GAME from the current directory to the <Library> directory. The following audit records may be generated:

Smith	execute	<Library>COPY.EXE	0	CPU = 00002	11058721678
Smith	read	<Smith>GAME.EXE	0	RECORDS = 0	11058721679
Smith	execute	<Library>COPY.EXE	write-viol	RECORDS = 0	11058721680

In this case, the copy is aborted because Smith does not have write permission to <Library>.

The decomposition of a user operation into elementary actions has three advantages:

1. Because objects are the protectable entities in a system, the use of elementary actions enables an audit of all behavior affecting an object. Thus, the system can detect attempted subversions of access controls (by noting an abnormality in the number of exception conditions returned) and can detect successful subversions by noting an abnormality in the set of objects accessible to the subject.
2. Single-object, single-action audit records simplify the model and the implementation.
3. Because of the simple, uniform structure of the detection-specific audit records, it may be relatively easy to obtain this information or at least part of it by a straightforward mapping from existing native audit records to the detection-specific audit records.

15.4 MALWARE DEFENSE

Antivirus Approaches

The ideal solution to the threat of viruses is prevention: Do not allow a virus to get into the system in the first place. This goal is, in general, impossible to achieve, although prevention can reduce the number of successful viral attacks. The next best approach is to be able to do the following:

- **Detection:** Once the infection has occurred, determine that it has occurred and locate the virus.
- **Identification:** Once detection has been achieved, identify the specific virus that has infected a program.
- **Removal:** Once the specific virus has been identified, remove all traces of the virus from the infected program and restore it to its original state. Remove the virus from all infected systems so that the disease cannot spread further.

If detection succeeds but either identification or removal is not possible, then the alternative is to discard the infected program and reload a clean backup version.

Advances in virus and antivirus technology go hand in hand. Early viruses were relatively simple code fragments and could be identified and purged with relatively simple antivirus software packages. As the virus arms race has evolved, both viruses and, necessarily, antivirus software have grown more complex and sophisticated. Increasingly sophisticated antivirus approaches and products continue to appear. In this subsection, we highlight two of the most important.

Generic Decryption Generic decryption (GD) technology enables the antivirus program to easily detect even the most complex polymorphic viruses while maintaining fast scanning speeds [NACH97]. Recall that when a file containing a polymorphic virus is executed, the virus must decrypt itself to activate. In order to detect such a structure, executable files are run through a GD scanner, which contains the following elements:

- **CPU emulator:** A software-based virtual computer. Instructions in an executable file are interpreted by the emulator rather than executed on the underlying processor. The emulator includes software versions of all registers and other processor hardware, so that the underlying processor is unaffected by programs interpreted on the emulator.
- **Virus signature scanner:** A module that scans the target code looking for known virus signatures.
- **Emulation control module:** Controls the execution of the target code.

At the start of each simulation, the emulator begins interpreting instructions in the target code, one at a time. Thus, if the code includes a decryption routine that decrypts and hence exposes the virus, that code is interpreted. In effect, the virus does the work for the antivirus program by exposing the virus. Periodically, the control module interrupts interpretation to scan the target code for virus signatures.

During interpretation, the target code can cause no damage to the actual personal computer environment, because it is being interpreted in a completely controlled environment.

The most difficult design issue with a GD scanner is to determine how long to run each interpretation. Typically, virus elements are activated soon after a program begins executing, but this need not be the case. The longer the scanner emulates a particular program, the more likely it is to catch any hidden viruses. However, the antivirus program can take up only a limited amount of time and resources before users complain of degraded system performance.

Digital Immune System The digital immune system is a comprehensive approach to virus protection developed by IBM [KEPH97a, KEPH97b, WHIT99] and subsequently refined by Symantec [SYMA01]. The motivation for this development has been the rising threat of Internet-based virus propagation. We first say a few words about this threat and then summarize IBM's approach.

Traditionally, the virus threat was characterized by the relatively slow spread of new viruses and new mutations. Antivirus software was typically updated on a monthly basis, and this was sufficient to control the problem. Also traditionally, the Internet played a comparatively small role in the spread of viruses. But as [CHES97] points out, two major trends in Internet technology have had an increasing impact on the rate of virus propagation in recent years:

- **Integrated mail systems:** Systems such as Lotus Notes and Microsoft Outlook make it very simple to send anything to anyone and to work with objects that are received.
- **Mobile-program systems:** Capabilities such as Java and ActiveX allow programs to move on their own from one system to another.

In response to the threat posed by these Internet-based capabilities, IBM has developed a prototype digital immune system. This system expands on the use of program emulation discussed in the preceding subsection and provides a general-purpose emulation and virus-detection system. The objective of this system is to provide rapid response time so that viruses can be stamped out almost as soon as they are introduced. When a new virus enters an organization, the immune system automatically captures it, analyzes it, adds detection and shielding for it, removes it, and passes information about that virus to systems running IBM AntiVirus so that it can be detected before it is allowed to run elsewhere.

Figure 15.9 illustrates the typical steps in digital immune system operation:

1. A monitoring program on each PC uses a variety of heuristics based on system behavior, suspicious changes to programs, or family signature to infer that a virus may be present. The monitoring program forwards a copy of any program thought to be infected to an administrative machine within the organization.
2. The administrative machine encrypts the sample and sends it to a central virus analysis machine.
3. This machine creates an environment in which the infected program can be safely run for analysis. Techniques used for this purpose include emulation, or the

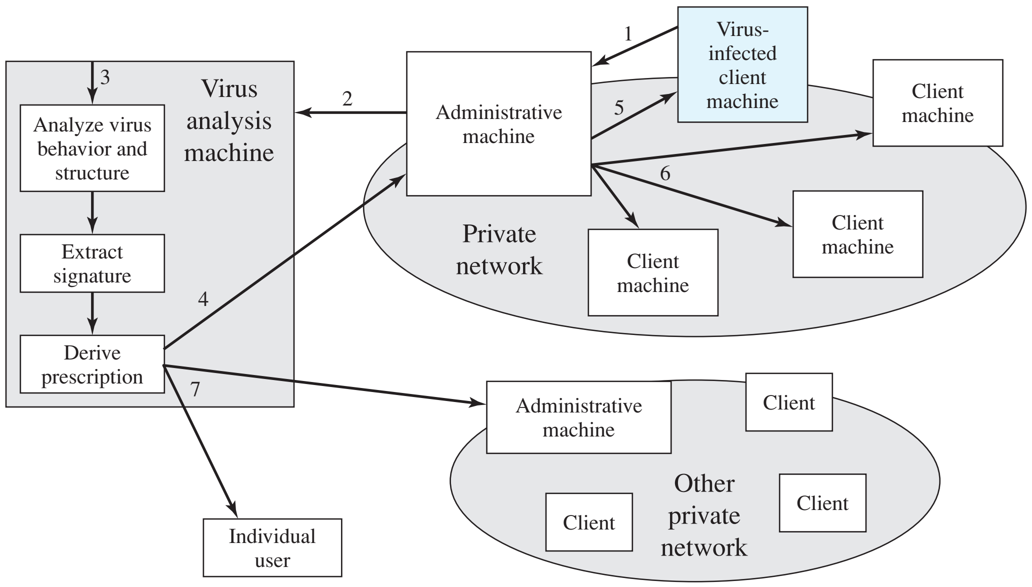


Figure 15.9 **Digital Immune System**

creation of a protected environment within which the suspect program can be executed and monitored. The virus analysis machine then produces a prescription for identifying and removing the virus.

4. The resulting prescription is sent back to the administrative machine.
5. The administrative machine forwards the prescription to the infected client.
6. The prescription is also forwarded to other clients in the organization.
7. Subscribers around the world receive regular antivirus updates that protect them from the new virus.

The success of the digital immune system depends on the ability of the virus analysis machine to detect new and innovative virus strains. By constantly analyzing and monitoring the viruses found in the wild, it should be possible to continually update the digital immune software to keep up with the threat.

Behavior-Blocking Software Unlike heuristics or fingerprint-based scanners, behavior blocking software integrates with the operating system of a host computer and monitors program behavior in real time for malicious actions [CONR02, NACH02]. The behavior-blocking software then blocks potentially malicious actions before they have a chance to affect the system. Monitored behaviors can include

- Attempts to open, view, delete, and/or modify files;
- Attempts to format disk drives and other unrecoverable disk operations;
- Modifications to the logic of executable files or macros;
- Modification of critical system settings, such as start-up settings;

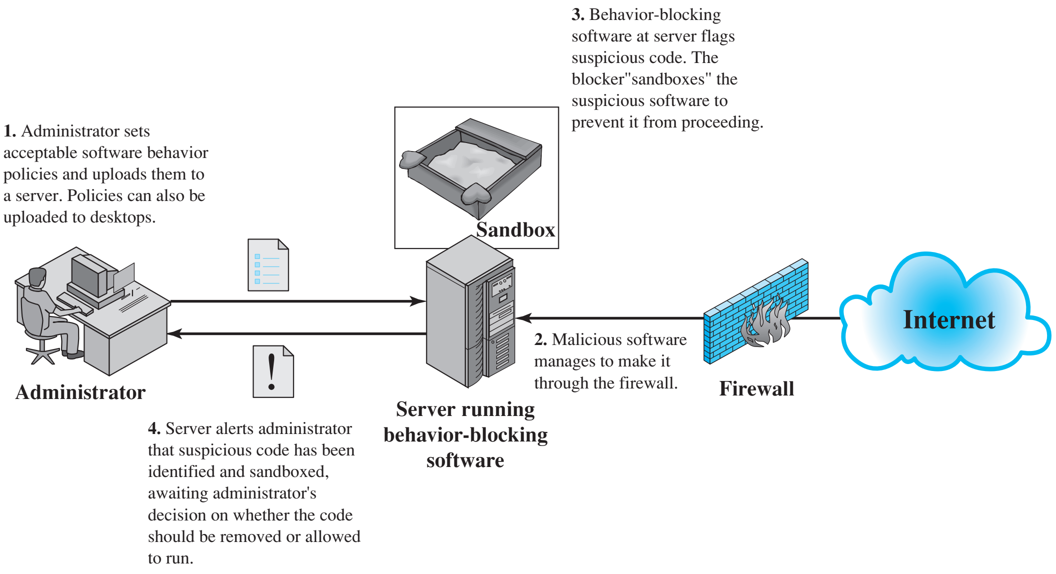

3. Behavior-blocking software at server flags suspicious code. The blocker"sandboxes" the suspicious software to prevent it from proceeding.
1. Administrator sets acceptable software behavior policies and uploads them to a server. Policies can also be uploaded to desktops.
Sandbox
Internet
2. Malicious software manages to make it through the firewall.
Administrator
Firewall
Server running behavior-blocking software
4. Server alerts administrator that suspicious code has been identified and sandboxed, awaiting administrator's decision on whether the code should be removed or allowed to run.

Figure 15.10 **Behavior-Blocking Software Operation**

- Scripting of e-mail and instant messaging clients to send executable content; and
- Initiation of network communications.

Figure 15.10 illustrates the operation of a behavior blocker. Behavior-blocking software runs on server and desktop computers and is instructed through policies set by the network administrator to let benign actions take place but to intercede when unauthorized or suspicious actions occur. The module blocks any suspicious software from executing. A blocker isolates the code in a sandbox, which restricts the code's access to various OS resources and applications. The blocker then sends an alert.

Because a behavior blocker can block suspicious software in real time, it has an advantage over such established antivirus detection techniques as fingerprinting or heuristics. While there are literally trillions of different ways to obfuscate and rearrange the instructions of a virus or worm, many of which will evade detection by a fingerprint scanner or heuristic, eventually malicious code must make a well-defined request to the operating system. Given that the behavior blocker can intercept all such requests, it can identify and block malicious actions regardless of how obfuscated the program logic appears to be.

Behavior blocking alone has limitations. Because the malicious code must run on the target machine before all its behaviors can be identified, it can cause harm before it has been detected and blocked. For example, a new virus might shuffle a number of seemingly unimportant files around the hard drive before infecting a single file and being blocked. Even though the actual infection was blocked, the user may be unable to locate his or her files, causing a loss to productivity or possibly worse.

Worm Countermeasures

There is considerable overlap in techniques for dealing with viruses and worms. Once a worm is resident on a machine, antivirus software can be used to detect it. In addition, because worm propagation generates considerable network activity, network activity and usage monitoring can form the basis of a worm defense.

To begin, let us consider the requirements for an effective worm countermeasure scheme:

- **Generality:** The approach taken should be able to handle a wide variety of worm attacks, including polymorphic worms.
- **Timeliness:** The approach should respond quickly so as to limit the number infected systems and the number of generated transmissions from infected systems.
- **Resiliency:** The approach should be resistant to evasion techniques employed by attackers to evade worm countermeasures.
- **Minimal denial-of-service costs:** The approach should result in minimal reduction in capacity or service due to the actions of the countermeasure software. That is, in an attempt to contain worm propagation, the countermeasure should not significantly disrupt normal operation.
- **Transparency:** The countermeasure software and devices should not require modification to existing (legacy) OSs, application software, and hardware.
- **Global and local coverage:** The approach should be able to deal with attack sources both from outside and inside the enterprise network.

No existing worm countermeasure scheme appears to satisfy all these requirements. Thus, administrators typically need to use multiple approaches in defending against worm attacks.

Following [JHI07], we list six classes of worm defense:

A. **Signature-based worm scan filtering:** This type of approach generates a worm signature, which is then used to prevent worm scans from entering/leaving a network/host. Typically, this approach involves identifying suspicious flows and generating a worm signature. This approach is vulnerable to the use of polymorphic worms: Either the detection software misses the worm or, if it is sufficiently sophisticated to deal with polymorphic worms, the scheme may take a long time to react. [NEWS05] is an example of this approach.

B. **Filter-based worm containment:** This approach is similar to class A but focuses on worm content rather than a scan signature. The filter checks a message to determine if it contains worm code. An example is Vigilante [COST05], which relies on collaborative worm detection at end hosts. This approach can be quite effective but requires efficient detection algorithms and rapid alert dissemination.

C. **Payload-classification-based worm containment:** These network-based techniques examine packets to see if they contain a worm. Various anomaly detection techniques can be used, but care is needed to avoid high levels of false positives or negatives. An example of this approach is reported in [CHIN05], which looks for exploit code in network flows. This approach does not generate signatures based on byte patterns but rather looks for control and data flow structures that suggest an exploit.

D. **Threshold random walk (TRW) scan detection:** TRW exploits randomness in picking destinations to connect to as a way of detecting if a scanner is in operation [JUNG04]. TRW is suitable for deployment in high-speed, low-cost network devices. It is effective against the common behavior seen in worm scans.

E. **Rate limiting:** This class limits the rate of scanlike traffic from an infected host. Various strategies can be used, including limiting the number of new machines a host can connect to in a window of time, detecting a high connection failure rate, and limiting the number of unique IP addresses a host can scan in a window of time. [CHEN04] is an example. This class of countermeasures may introduce longer delays for normal traffic. This class is also not suited for slow, stealthy worms that spread slowly to avoid detection based on activity level.

F. **Rate halting:** This approach immediately blocks outgoing traffic when a threshold is exceeded either in outgoing connection rate or diversity of connection attempts [JHI07]. The approach must include measures to quickly unblock mistakenly blocked hosts in a transparent way. Rate halting can integrate with a signature- or filter-based approach so that once a signature or filter is generated, every blocked host can be unblocked. Rate halting appears to offer a very effective countermeasure. As with rate limiting, rate halting techniques are not suitable for slow, stealthy worms.

Bot Countermeasures

A number of the countermeasures discussed in this chapter make sense against bots, including IDSs and digital immune systems. Once bots are activated and an attack is underway, these countermeasures can be used to detect the attack. But the primary objective is to try to detect and disable the botnet during its construction phase.

Rootkit Countermeasures

Rootkits can be extraordinarily difficult to detect and neutralize, particularly so for kernel-level rootkits. Many of the administrative tools that could be used to detect a rootkit or its traces can be compromised by the rootkit precisely so that it is undetectable.

Countering rootkits requires a variety of network- and computer-level security tools. Both network-based and host-based intrusion detection systems can look for the code signatures of known rootkit attacks in incoming traffic. Host-based antivirus software can also be used to recognize the known signatures.

Of course, there are always new rootkits and modified versions of existing rootkits that display novel signatures. For these cases, a system needs to look for behaviors that could indicate the presence of a rootkit, such as the interception of system calls or a keylogger interacting with a keyboard driver. Such behavior detection is far from straightforward. For example, antivirus software typically intercepts system calls.

Another approach is to do some sort of file integrity check. An example of this is RootkitRevealer, a freeware package from SysInternals. The package compares the results of a system scan using APIs with the actual view of storage using instructions that do not go through an API. Because a rootkit conceals itself by modifying the view of storage seen by administrator calls, RootkitRevealer catches the discrepancy.

If a kernel-level rootkit is detected, by any means, the only secure and reliable way to recover is to do an entire new OS install on the infected machine.

15.5 DEALING WITH BUFFER OVERFLOW ATTACKS[3]

Finding and exploiting a stack buffer overflow is not difficult. The large number of exploits over the previous couple of decades clearly illustrates this. There is consequently a need to defend systems against such attacks by either preventing them, or at least detecting and aborting such attacks. This section discusses possible approaches to implementing such protections. These can be broadly classified into two categories:

- Compile-time defenses, which aim to harden programs to resist attacks in new programs
- Run-time defenses, which aim to detect and abort attacks in existing programs

While suitable defenses have been known for a couple of decades, the very large existing base of vulnerable software and systems hinders their deployment; hence the interest in run-time defenses, which can be deployed in operating systems and updates and can provide some protection for existing vulnerable programs. Most of these techniques are mentioned in [LHEE03].

Compile-Time Defenses

Compile-time defenses aim to prevent or detect buffer overflows by instrumenting programs when they are compiled. The possibilities for doing this range from choosing a high-level language that does not permit buffer overflows, to encouraging safe coding standards, using safe standard libraries, or including additional code to detect corruption of the stack frame.

Choice of Programming Language One possibility is a to write the program using a modern high-level programming language, one that has a strong notion of variable type and what constitutes permissible operations on them. Such languages are not vulnerable to buffer overflow attacks, because their compilers include additional code to enforce range checks automatically, removing the need for the programmer to explicitly code them. The flexibility and safety provided by these languages does come at a cost in resource use, both at compile time and also in additional code that must executed at runtime to impose checks such as that on buffer limits. These disadvantages are much less significant than they used to be, due to the rapid increase in processor performance. Increasingly programs are being written in these languages and hence should be immune to buffer overflows in their code (though if they use existing system libraries or run-time execution environments written in less safe languages, they may still be vulnerable). The distance from the underlying machine language and architecture also means that access to some instructions and hardware resources is lost. This limits their usefulness in writing code, such as device drivers, that must interact with such resources. For these reasons, there is still likely to be at least some code written in less safe languages such as C.

[3]The material in this section was developed by Lawrre Brown of the Australian Defence Force Academy.

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Safe Coding Techniques If languages such as C are being used, programmers need to be aware that their ability to manipulate pointer addresses and access memory directly comes at a cost. C was designed as a systems programming language, running on systems that were vastly smaller and more constrained than we now use. This meant that C's designers placed much more emphasis on space efficiency and performance considerations than on type safety. They assumed that programmers would exercise due care in writing code using these languages and take responsibility for ensuring the safe use of all data structures and variables.

Unfortunately, as several decades of experience has shown, this has not been the case. This may be seen in large legacy body of potentially unsafe code in the UNIX and Linux operating systems and applications, some of which are potentially vulnerable to buffer overflows.

In order to harden these systems, the programmer needs to inspect the code and rewrite any unsafe coding constructs in a safe manner. Given the rapid uptake of buffer overflow exploits, this process has begun in some cases. A good example is the OpenBSD project, which produces a free, multiplatform 4.4BSD-based UNIX-like operating system. Among other technology changes, programmers have undertaken an extensive audit of the existing code base, including the operating system, standard libraries, and common utilities. This has resulted in what is widely regarded as one of the safest operating systems in widespread use. The OpenBSD project claims as of mid-2006 that there has only been one remote hole discovered in the default install in more than eight years. This is a clearly enviable record. Microsoft have also undertaken a major project in reviewing their code base, partly in response to continuing bad publicity over the number of vulnerabilities, including many buffer overflow issues, that have been found in their operating systems and applications code. This has clearly been a difficult process, though they claim that their new Vista operating system will benefit greatly from this process.

Language Extensions and Use of Safe Libraries Given the problems that can occur in C with unsafe array and pointer references, there have been a number of proposals to augment compilers to automatically insert range checks on such references. While this is fairly easy for statically allocated arrays, handling dynamically allocated memory is more problematic, because the size information is not available at compile time. Handling this requires an extension to the semantics of a pointer to include bounds information and the use of library routines to ensure that these values are set correctly. Several such approaches are listed in [LHEE03]. However, there is generally a performance penalty with the use of such techniques that may or may not be acceptable. These techniques also require all programs and libraries that require these safety features to be recompiled with the modified compiler. While this can be feasible for a new release of an operating system and its associated utilities, there will still likely be problems with third-party applications.

A common concern with C comes from the use of unsafe standard library routines, especially some of the string manipulation routines. One approach to improving the safety of systems has been to replace these with safer variants. This can include the provision of new functions, such as `strlcpy()` in the BSD family of systems, including OpenBSD. Using these requires rewriting the source to conform to the new safer semantics. Alternatively, it involves replacement of the standard string library with a safer variant. Libsafe is a well-known example of this. It implements the standard semantics but includes additional checks to ensure that the copy operations do not extend beyond the local variable space in the stack frame. So while it cannot prevent corruption of adjacent local variables, it can prevent any modification of the old stack frame and return address values, and thus prevent the classic stack buffer overflow types of attack we examined previously. This library is implemented as a dynamic library, arranged to load before the existing standard libraries, and can thus provide protection for existing programs without requiring them to be recompiled, provided they dynamically access the standard library routines (as most programs do). The modified library code has been found to typically be at least as efficient as the standard libraries, and thus its use is an easy way of protecting existing programs against some forms of buffer overflow attacks.

Stack Protection Mechanisms An effective method for protecting programs against classic stack overflow attacks is to instrument the function entry and exit code to setup and then check its stack frame for any evidence of corruption. If any modification is found, the program is aborted rather than allowing the attack to proceed. There are several approaches to providing this protection, which we discuss next.

Stackguard is one of the best known protection mechanisms. It is a GCC compiler extension that inserts additional function entry and exit code. The added function entry code writes a **canary**[4] value below the old frame pointer address, before the allocation of space for local variables. The added function exit code checks that the canary value has not changed before continuing with the usual function exit operations of restoring the old frame pointer and transferring control back to the return address. Any attempt at a classic stack buffer overflow would have to alter this value in order to change the old frame pointer and return addresses, and would thus be detected, resulting in the program being aborted. For this defense to function successfully, it is critical that the canary value be unpredictable and should be different on different systems. If this were not the case, the attacker would simply ensure the shellcode included the correct canary value in the required location. Typically, a random value is chosen as the canary value on process creation and saved as part of the processes state. The code added to the function entry and exit then use this value.

There are some issues with using this approach. First, it requires that all programs needing protection be recompiled. Second, because the structure of the stack frame has changed, it can cause problems with programs, such as debuggers, which analyze stack frames. However, the canary technique has been used to recompile an entire Linux distribution and provide it with a high level of resistance to stack over-

[4]Named after the miner's canary used to detect poisonous air in a mine and thus warn the miners in time for them to escape.

flow attacks. Similar functionality is available for Windows programs by compiling them using Microsoft's /GS Visual C++ compiler option.

Run-Time Defenses

As has been noted, most of the compile-time approaches require recompilation of existing programs. Hence there is interest in run-time defenses that can be deployed as operating systems updates to provide some protection for existing vulnerable programs. These defenses involve changes to the memory management of the virtual address space of processes. These changes act to either alter the properties of regions of memory, or to make predicting the location of targeted buffers sufficiently difficult to thwart many types of attacks.

Executable Address Space Protection Many of the buffer overflow attacks involve copying machine code into the targeted buffer and then transferring execution to it. A possible defense is to block the execution of code on the stack, on the assumption that executable code should only be found elsewhere in the processes address space.

To support this feature efficiently requires support from the processor's memory management unit (MMU) to tag pages of virtual memory as being nonexecutable. Some processors, such as the SPARC used by Solaris, have had support for this for some time. Enabling its use in Solaris requires a simple kernel parameter change. Other processors, such as the x86 family, have not had this support until recently, with the relatively recent addition of the **no-execute** bit in its MMU. Extensions have been made available to Linux, BSD, and other UNIX-style systems to support the use of this feature. Some indeed are also capable of protecting the heap as well as the stack, which is also is the target of attacks. Support for enabling no-execute protection is also included in recent Windows systems.

Making the stack (and heap) nonexecutable provides a high degree of protection against many types of buffer overflow attacks for existing programs; hence the inclusion of this practice is standard in a number of recent operating systems releases. However, one issue is support for programs that do need to place executable code on the stack. This can occur, for example, in just-in-time compilers, such as is used in the Java Runtime system. Executable code on the stack is also used to implement nested functions in C (a GCC extension) and also Linux signal handlers. Special provisions are needed to support these requirements. Nonetheless, this is regarded as one of the best methods for protecting existing programs and hardening systems against some attacks.

Address Space Randomization Another run-time technique that can be used to thwart attacks involves manipulation of the location of key data structures in a processes address space. In particular, recall that in order to implement the classic stack overflow attack, the attacker needs to be able to predict the approximate location of the targeted buffer. The attacker uses this predicted address to determine a suitable return address to use in the attack to transfer control to the shellcode. One technique to greatly increase the difficulty of this prediction is to change the address

WINDOWS/LINUX COMPARISON—SECURITY

Windows	Linux
A kernel object, called a token, is used to define the security boundaries in the system. Most processes share the token created when a user logs on	Processes have an identify determined by simple integers representing user and group-ids
Tokens include authenticated identities (both local and remote) of individuals and groups, as well as specific privileges	Users can be authenticated locally or remotely
Objects (in the general kernel object sense of Windows) are protected by access control lists (ACLs) which grant and deny access to particular users and groups. The ACLs are maintained in Security Descriptors which are preserved on disk in the most common Windows file system, NTFS	Objects are represented as files and use the permissions in the inode to say what basic operations can be performed by users, groups, and others While normal Linux security is based on the simple model of UNIX, a more sophisticated version is available, SELinux, developed by the National Security Agency of the United States government

at which the stack is located in a random manner for each process. The range of addresses available on modern processors is large (32 bits), and most programs only need a small fraction of that. Therefore, moving the stack memory region around by a megabyte or so has minimal impact on most programs but makes predicting the targeted buffer's address almost impossible.

Another target of attack is the location of standard library routines. In an attempt to bypass protections such as nonexecutable stacks, some buffer overflow variants exploit existing code in standard libraries. These are typically loaded at the same address by the same program. To counter this form of attack, we can use a security extension that randomizes the order of loading standard libraries by a program and their virtual memory address locations. This makes the address of any specific function sufficiently unpredictable as to render the chance of a given attack correctly predicting its address very low.

The OpenBSD system includes versions of these extensions in its technological support for a secure system.

Guard Pages A final runtime technique that can be used places **guard pages** between critical regions of memory in a processes address space. Again, this exploits the fact that a process has much more virtual memory available than it typically needs. Gaps are placed between the ranges of addresses used for each of the components of the address space. These gaps, or guard pages, are flagged in the MMU as illegal addresses, and any attempt to access them results in the process being aborted. This can prevent buffer overflow attacks, typically of global data, which attempt to overwrite adjacent regions in the processes address space.

A further extension places guard pages between stack frames or between different allocations on the heap. This can provide further protection against stack and heap over flow attacks, but at cost in execution time supporting the large number of page mappings necessary.

15.6 WINDOWS VISTA SECURITY

A good example of the access control concepts we have been discussing is the Windows access control facility, which exploits object-oriented concepts to provide a powerful and flexible access control capability.

Windows provides a uniform access control facility that applies to processes, threads, files, semaphores, windows, and other objects. Access control is governed by two entities: an access token associated with each process and a security descriptor associated with each object for which interprocess access is possible.

Access Control Scheme

When a user logs on to an Windows system, Windows uses a name/password scheme to authenticate the user. If the logon is accepted, a process is created for the user and an access token is associated with that process object. The access token, whose details are described later, include a security ID (SID), which is the identifier by which this user is known to the system for purposes of security. If the initial user process spawns a new process, the new process object inherits the same access token.

The access token serves two purposes:

1. It keeps all necessary security information together to speed access validation. When any process associated with a user attempts access, the security subsystem can make use of the token associated with that process to determine the user's access privileges.
2. It allows each process to modify its security characteristics in limited ways without affecting other processes running on behalf of the user.

The chief significance of the second point has to do with privileges that may be associated with a user. The access token indicates which privileges a user may have. Generally, the token is initialized with each of these privileges in a disabled state. Subsequently, if one of the user's processes needs to perform a privileged operation, the process may enable the appropriate privilege and attempt access. It would be undesirable to share the same token among all a user's processes, because in that case enabling a privilege for one process enables it for all of them.

Associated with each object for which interprocess access is possible is a security descriptor. The chief component of the security descriptor is an access control list that specifies access rights for various users and user groups for this object. When a process attempts to access this object , the SID of the process is matched against the access control list of the object to determine if access will be allowed or denied.

When an application opens a reference to a securable object, Windows verifies that the object's security descriptor grants the application's user access. If the check succeeds, Windows caches the resulting granted access rights.

An important aspect of Windows security is the concept of impersonation, which simplifies the use of security in a client/server environment. If client and server talk through a RPC connection, the server can temporarily assume the

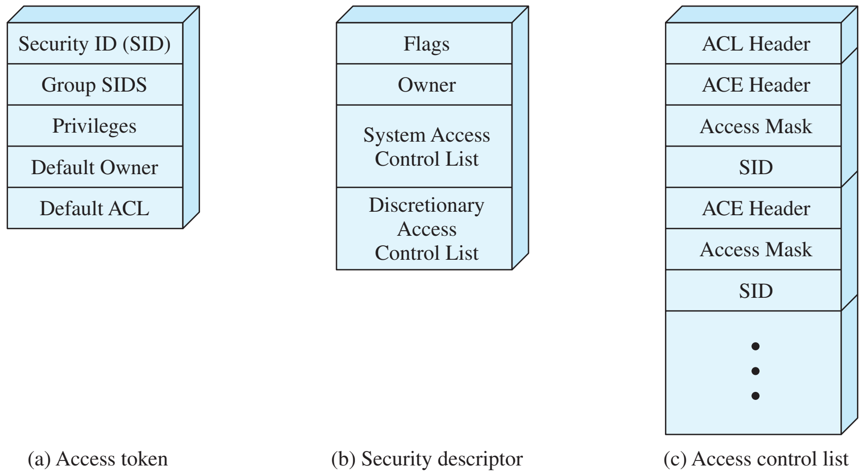


Figure 15.11 **Windows Security Structures**

identity of the client so that it can evaluate a request for access relative to that client's rights. After the access, the server reverts to its own identity.

Access Token

Figure 15.11a shows the general structure of an access token, which includes the following parameters:

- **Security ID:** Identifies a user uniquely across all of the machines on the network. This generally corresponds to a user's logon name.
- **Group SIDs:** A list of the groups to which this user belongs. A group is simply a set of user IDs that are identified as a group for purposes of access control. Each group has a unique group SID. Access to an object can be defined on the basis of group SIDs, individual SIDs, or a combination. There is also a SID which reflects the process integrity level (low, medium, high, or system).
- **Privileges:** A list of security-sensitive system services that this user may call. An example is create token. Another example is the set backup privilege; users with this privilege are allowed to use a backup tool to back up files that they normally would not be able to read.
- **Default Owner:** If this process creates another object, this field specifies who is the owner of the new object. Generally, the owner of the new process is the same as the owner of the spawning process. However, a user may specify that the default owner of any processes spawned by this process is a group SID to which this user belongs.
- **Default ACL:** This is an initial list of protections applied to the objects that the user creates. The user may subsequently alter the ACL for any object that it owns or that one of its groups owns.

Security Descriptors

Figure 15.11b shows the general structure of a security descriptor, which includes the following parameters:

- **Flags:** Defines the type and contents of a security descriptor. The flags indicate whether or not the SACL and DACL are present, whether or not they were placed on the object by a defaulting mechanism, and whether the pointers in the descriptor use absolute or relative addressing. Relative descriptors are required for objects that are transmitted over a network, such as information transmitted in a RPC.
- **Owner:** The owner of the object can generally perform any action on the security descriptor. The owner can be an individual or a group SID. The owner has the authority to change the contents of the DACL.
- **System Access Control List (SACL):** Specifies what kinds of operations on the object should generate audit messages. An application must have the corresponding privilege in its access token to read or write the SACL of any object. This is to prevent unauthorized applications from reading SACLs (thereby learning what not to do to avoid generating audits) or writing them (to generate many audits to cause an illicit operation to go unnoticed). The SACL also specifies the object integrity level. Processes cannot modify an object unless the process integrity level meets or exceeds the level on the object.
- **Discretionary Access Control List (DACL):** Determines which users and groups can access this object for which operations. It consists of a list of access control entries (ACEs).

When an object is created, the creating process can assign as owner its own SID or any group SID in its access token. The creating process cannot assign an owner that is not in the current access token. Subsequently, any process that has been granted the right to change the owner of an object may do so, but again with the same restriction. The reason for the restriction is to prevent a user from covering his tracks after attempting some unauthorized action.

Let us look in more detail at the structure of access control lists, because these are at the heart of the Windows access control facility (Figure 15.11c). Each list consists of an overall header and a variable number of access control entries. Each entry specifies an individual or group SID and an access mask that defines the rights to be granted to this SID. When a process attempts to access an object, the object manager in the Windows Executive reads the SID and group SIDs from the access token and including the integrity level SID. If the access requested includes modifying the object, the integrity level is checked against the object integrity level in the SACL. If that test passes, the object manager then scans down the object's DACL. If a match is found (that is, if an ACE is found with a SID that matches one of the SIDs from the access token), then the process can have the access rights specified by the access mask in that ACE. This also may including denying access, in which case the access request fails.

Figure 15.12 shows the contents of the access mask. The least significant 16 bits specify access rights that apply to a particular type of object. For example, bit 0 for a file object is `File_Read_Data` access and bit 0 for an event object is `Event_Query_Status` access.

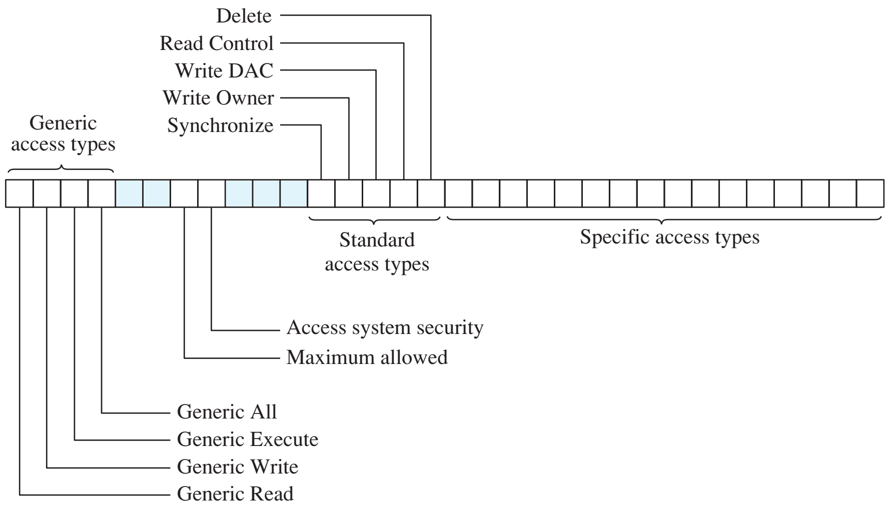


Figure 15.12 Access Mask

The most significant 16 bits of the mask contains bits that apply to all types of objects. Five of these are referred to as standard access types:

- **Synchronize:** Gives permission to synchronize execution with some event associated with this object. In particular, this object can be used in a wait function.
- **Write_owner:** Allows a program to modify the owner of the object. This is useful because the owner of an object can always change the protection on the object (the owner may not be denied Write DAC access).
- **Write_DAC:** Allows the application to modify the DACL and hence the protection on this object.
- **Read_control:** Allows the application to query the owner and DACL fields of the security descriptor of this object.
- **Delete:** Allows the application to delete this object.

The high-order half of the access mask also contains the four generic access types. These bits provide a convenient way to set specific access types in a number of different object types. For example, suppose an application wishes to create several types of objects and ensure that users have read access to the objects, even though read has a somewhat different meaning for each object type. To protect each object of each type without the generic access bits, the application would have to construct a different ACE for each type of object and be careful to pass the correct ACE when creating each object. It is more convenient to create a single ACE that expresses the generic concept allow read, simply apply this ACE to each object that is created, and have the right thing happen. That is the purpose of the generic access bits, which are

- Generic_all: Allow all access
- Generic_execute: Allow execution if executable
- Generic_write: Allow write access
- Generic_read: Allow read only access

The generic bits also affect the standard access types. For example, for a file object, the Generic_Read bit maps to the standard bits Read_Control and Synchronize and to the object-specific bits File_Read_Data, File_Read_Attributes, and File_Read_EA. Placing an ACE on a file object that grants some SID Generic_Read grants those five access rights as if they had been specified individually in the access mask.

The remaining two bits in the access mask have special meanings. The Access_System_Security bit allows modifying audit and alarm control for this object. However, not only must this bit be set in the ACE for a SID, but the access token for the process with that SID must have the corresponding privilege enabled.

Finally, the Maximum_Allowed bit is not really an access bit, but a bit that modifies Windows 's algorithm for scanning the DACL for this SID. Normally, Windows will scan through the DACL until it reaches an ACE that specifically grants (bit set) or denies (bit not set) the access requested by the requesting process or until it reaches the end of the DACL, in which latter case access is denied. The Maximum_Allowed bit allows the object's owner to define a set of access rights that is the maximum that will be allowed to a given user. With this in mind, suppose that an application does not know all of the operations that it is going to be asked to perform on an object during a session. There are three options for requesting access:

1. Attempt to open the object for all possible accesses. The disadvantage of this approach is that the access may be denied even though the application may have all of the access rights actually required for this session.
2. Only open the object when a specific access is requested, and open a new handle to the object for each different type of request. This is generally the preferred method because it will not unnecessarily deny access, nor will it allow more access than necessary. However, it imposes additional overhead.
3. Attempt to open the object for as much access as the object will allow this SID. The advantage is that the user will not be artificially denied access, but the application may have more access than it needs. This latter situation may mask bugs in the application.

An important feature of Windows security is that applications can make use of the Windows security framework for user-defined objects. For example, a database server might create it own security descriptors and attach them to portions of a database. In addition to normal read/write access constraints, the server could secure database-specific operations, such as scrolling within a result set or performing a join. It would be the server's responsibility to define the meaning of special rights and perform access checks. But the checks would occur in a standard context, using systemwide user/group accounts and audit logs. The extensible security model should prove useful to implementers of foreign files systems.

15.7 RECOMMENDED READING AND WEB SITES

The topics in this chapter are covered in more detail in [STAL08].

[OGOR03] is the paper to read for an authoritative survey of user authentication. [BURR04] is also a worthwhile survey. [SAND94] is an excellent overview of access control. [SAND96] is a comprehensive overview of RBAC. [SAUN01] compares RBAC and DAC. [SCAR07] is a detailed and worthwhile treatment of intrusion detection. Two short but useful survey articles on the subject are [KENT00] and [MCHU00]. [NING04] surveys recent advances in intrusion detection techniques. Good overview articles on antivirus approaches and malware defense generally are [CASS01], [FORR97], [KEPH97], and [NACH97]. [LHEE03] surveys a range of alternative buffer overflow techniques, including a number not mentioned in this chapter, along with possible defensive techniques. The original published description of buffer overflow attacks is given in [LEVY96]. [KUPE05] is a good overview.

BURR04 Burr, W.; Dodson, D.; and Polk, W. *Electronic Authentication Guideline.* Gaithersburg, MD: National Institute of Standards and Technology, Special Publication 800-63, September 2004.

CASS01 Cass, S. "Anatomy of Malice." *IEEE Spectrum*, November 2001.

FORR97 Forrest, S.; Hofmeyr, S.; and Somayaji, A. "Computer Immunology." *Communications of the ACM*, October 1997.

KENT00 Kent, S. "On the Trail of Intrusions into Information Systems." *IEEE Spectrum*, December 2000.

KEPH97 Kephart, J.; Sorkin, G.; Chess, D.; and White, S. "Fighting Computer Viruses." *Scientific American*, November 1997.

KUPE05 Kuperman, B., et al. "Detection and Prevention of Stack Buffer Overflow Attacks." *Communications of the ACM*, November 2005.

LEVY96 Levy, E., "Smashing the stack for Fun and Profit." *Phrack Magazine*, file 14, Issue 49, November 1996.

LHEE03 Lhee, K., and Chapin, S., "Buffer Overflow and Format String Overflow Vulnerabilities." *Software—Practice and Experience*, Volume 33, 2003.

MCHU00 McHugh, J.; Christie, A.; and Allen, J. "The Role of Intrusion Detection Systems." *IEEE Software*, September/October 2000.

NACH97 Nachenberg, C. "Computer Virus-Antivirus Coevolution." *Communications of the ACM*, January 1997.

NING04 Ning, P., et al. "Techniques and Tools for Analyzing Intrusion Alerts." *ACM Transactions on Information and System Security*, May 2004.

OGOR03 O'Gorman, L. "Comparing Passwords, Tokens and Biometrics for User Authentication." *Proceedings of the IEEE*, December 2003.

SAND94 Sandhu, R., and Samarati, P. "Access Control: Principles and Practice." *IEEE Communications Magazine*, February 1996.

SAND96 Sandhu, R., et al. "Role-Based Access Control Models." *Computer*, September 1994.

SAUN01 Saunders, G.; Hitchens, M.; and Varadharajan, V. "Role-Based Access Control and the Access Control Matrix." *Operating Systems Review*, October 2001.

SCAR07 Scarfone, K., and Mell, P. *Guide to Intrusion Detection and Prevention Systems.* NIST Special Publication SP 800-94, February 2007.

STAL08 Stallings, W., and Brown L. *Computer Security: Principles and Practice.* Upper Saddle River, NJ: Prentice Hall, 2008.

Recommended Web sites:

- **Password usage and generation:** NIST documents on this topic
- **Biometrics Consortium:** Government-sponsored site for the research, testing, and evaluation of biometric technology
- **NIST RBAC site:** Includes numerous documents, standards, and software on RBAC
- **STAT Project:** A research and open source project that focuses on signature-based intrusion detection tools for hosts, applications, and networks
- **Snort:** Web site for Snort, an open source network intrusion prevention and detection system
- **AntiVirus Online:** IBM's site on virus information
- **VirusList:** Site maintained by commercial antivirus software provider; good collection of useful information

15.8 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

access control	discretionary access control (DAC)	malware
antivirus	hashed passwords	memory cards
audit records	host-based IDS	role-based access control (RBAC)
authentication	intrusion detection	rootkit
bot	intrusion detections system (IDS)	smart cards
buffer overflow		worm
digital immune system		

Review Questions

15.1 In general terms, what are four means of authenticating a user's identity?

15.2 Explain the purpose of the salt in Figure 15.1.

15.3 Explain the difference between a simple memory card and a smart card.

15.4 List and briefly describe the principal physical characteristics used for biometric identification.

15.5 Briefly describe the difference between DAC and RBAC.

15.6 Explain the difference between anomaly intrusion detection and signature intrusion detection.

15.7 What is a digital immune system?

15.8 How does behavior-blocking software work?

15.9 Describe some worm countermeasures.

15.10 What types of programming languages are vulnerable to buffer overflows?

15.11 What are the two broad categories of defenses against buffer overflows?

15.12 List and briefly describe some of the defenses against buffer overflows that can be used when compiling new programs.

15.13 List and briefly describe some of the defenses against buffer overflows that can be implemented when running existing, vulnerable programs.

Problems

15.1 Explain the suitability or unsuitability of the following passwords:

a. YK 334
b. mfmitm (for "my favorite movie is tender mercies")
c. Natalie1
d. Washington
e. Aristotle
f. tv9stove
g. 12345678
h. dribgib

15.2 An early attempt to force users to use less predictable passwords involved computer-supplied passwords. The passwords were eight characters long and were taken from the character set consisting of lowercase letters and digits. They were generated by a pseudorandom number generator with 2^{15} possible starting values. Using the technology of the time, the time required to search through all character strings of length 8 from a 36-character alphabet was 112 years. Unfortunately, this is not a true reflection of the actual security of the system. Explain the problem.

15.3 Assume that passwords are selected from four-character combinations of 26 alphabetic characters. Assume that an adversary is able to attempt passwords at a rate of one per second.

a. Assuming no feedback to the adversary until each attempt has been completed, what is the expected time to discover the correct password?
b. Assuming feedback to the adversary flagging an error as each incorrect character is entered, what is the expected time to discover the correct password?

15.4 Assume that source elements of length k are mapped in some uniform fashion into a target elements of length p. If each digit can take on one of r values, then the number of source elements is r^k and the number of target elements is the smaller number r^p. A particular source element x_i is mapped to a particular target element y_j.

a. What is the probability that the correct source element can be selected by an adversary on one try?
b. What is the probability that a different source element x_k $(x_i\ x_k)$ that results in the same target element, y_j, could be produced by an adversary?
c. What is the probability that the correct target element can be produced by an adversary on one try?

15.5 Assume that passwords are limited to the use of the 95 printable ASCII characters and that all passwords are 10 characters in length. Assume a password cracker with an encryption rate of 6.4 million encryptions per second. How long will it take to test exhaustively all possible passwords on a UNIX system?

15.6 Because of the known risks of the UNIX password system, the SunOS-4.0 documentation recommends that the password file be removed and replaced with a publicly readable file called /etc/publickey. An entry in the file for user A consists of a user's identifier ID_A, the user's public key, PU_a, and the corresponding private key PR_a. This private key is encrypted using DES with a key derived from the user's login password P_a. When A logs in, the system decrypts $E(P_a, PR_a)$ to obtain PR_a.

a. The system then verifies that P_a was correctly supplied. How?
b. How can an opponent attack this system?

15.7 It was stated that the inclusion of the salt in the UNIX password scheme increases the difficulty of guessing by a factor of 4096. But the salt is stored in plaintext in the same entry as the corresponding ciphertext password. Therefore, those two characters are known to the attacker and need not be guessed. Why is it asserted that the salt increases security?

15.8 Assuming that you have successfully answered the preceding problem and understand the significance of the salt, here is another question. Wouldn't it be possible to thwart completely all password crackers by dramatically increasing the salt size to, say, 24 or 48 bits?

15.9 For the DAC model discussed in Section 4.3, an alternative representation of the protection state is a directed graph. Each subject and each object in the protection state is represented by a node (a single node is used for an entity that is both subject and object). A directed line from a subject to an object indicates an access right, and the label on the link defines the access right.
a. Draw a directed graph that corresponds to the access matrix of Figure 12.13a.
b. Draw a directed graph that corresponds to the access matrix of Figure 15.4.
c. Is there a one-to-one correspondence between the directed graph representation and the access matrix representation? Explain.

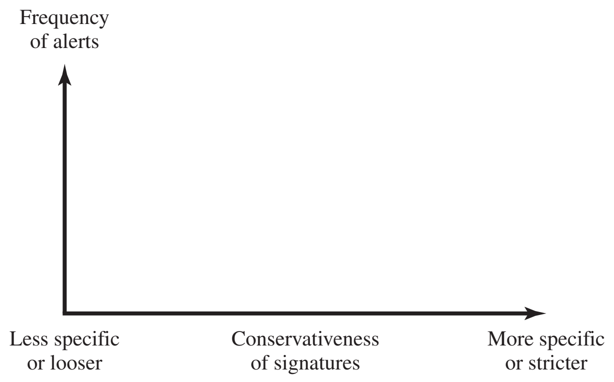
15.10 UNIX treats file directories in the same fashion as files; that is, both are defined by the same type of data structure, called an inode. As with files, directories include a 9-bit protection string. If care is not taken, this can create access control problems. For example, consider a file with protection mode 644 (octal) contained in a directory with protection mode 730. How might the file be compromised in this case?

15.11 In the traditional UNIX file access model, UNIX systems provide a default setting for newly created files and directories, which the owner may later change. The default is typically full access for the owner combined with one of the following: no access for group and other, read/execute access for group and none for other, or read/execute access for both group and other. Briefly discuss the advantages and disadvantages of each of these cases, including an example of a type of organization where each would be appropriate.

15.12 Consider user accounts on a system with a Web server configured to provide access to user Web areas. In general, this scheme uses a standard directory name, such as `public_html`, in a user's home directory. This acts as the user's Web area if it exists. However, to allow the Web server to access the pages in this directory, it must have at least search (execute) access to the user's home directory, read/execute access to the Web directory, and read access to any Web pages in it. Consider the interaction of this requirement with the cases you discussed for the preceding problem. What consequences does this requirement have? Note that a Web server typically executes as a special user, and in a group that is not shared with most users on the system. Are there some circumstances when running such a Web service is simply not appropriate? Explain.

15.13 Assume a system with N job positions. For job position i, the number of individual users in that position is U_i and the number of permissions required for the job position is P_i.
a. For a traditional DAC scheme, how many relationships between users and permissions must be defined?
b. For a RBAC scheme, how many relationships between users and permissions must be defined?

15.14 In the context of an IDS, we define a false positive to be an alarm generated by an IDS in which the IDS alerts to a condition that is actually benign. A false negative occurs when an IDS fails to generate an alarm when an alert-worthy condition is in effect. Using the following diagram, depict two curves that roughly indicate false positives and false negatives, respectively.



15.15 Rewrite the function shown in Figure 7.13a so that it is no longer vulnerable to a stack buffer overflow.