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

Password Cracking Approaches The traditional approach to password guessing, or password cracking as it is called, is to develop a large dictionary of possible passwords and to try each of these against the password file. This means that each password must be hashed using each available salt value and then compared to stored hash values. If no match is found, then the cracking program tries variations on all the words in its dictionary of likely passwords. Such variations include backwards spelling of words, additional numbers or special characters, or sequence of characters,

An alternative is to trade off space for time by precomputing potential hash values. In this approach the attacker generates a large dictionary of possible passwords. For each password, the attacker generates the hash values associated with each possible salt value. The result is a mammoth table of hash values known as a **rainbow table**. For example, [OECH03] showed that using 1.4 GB of data, he could crack 99.9% of all alphanumeric Windows password hashes in 13.8 seconds. This approach can be countered by using a sufficiently large salt value and a sufficiently large hash length. Both the FreeBSD and OpenBSD approaches should be secure from this attack for the foreseeable future.

User Password Choices

Even the stupendous guessing rates referenced in the preceding section do not yet make it feasible for an attacker to use a dumb brute-force technique of trying all possible combinations of characters to discover a password. Instead, password crackers rely on the fact that some people choose easily guessable passwords.

Some users, when permitted to choose their own password, pick one that is absurdly short. One study at Purdue University [SPAF92a] observed password change choices on 54 machines, representing approximately 7000 user accounts. Almost 3% of the passwords were three characters or fewer in length. An attacker could begin the attack by exhaustively testing all possible passwords of length 3 or

fewer. A simple remedy is for the system to reject any password choice of fewer than, say, six characters or even to require that all passwords be exactly eight characters in length. Most users would not complain about such a restriction.

Password length is only part of the problem. Many people, when permitted to choose their own password, pick a password that is guessable, such as their own name, their street name, a common dictionary word, and so forth. This makes the job of password cracking straightforward. The cracker simply has to test the password file against lists of likely passwords. Because many people use guessable passwords, such a strategy should succeed on virtually all systems.

One demonstration of the effectiveness of guessing is reported in [KLEI90]. From a variety of sources, the author collected UNIX password files, containing nearly 14,000 encrypted passwords. The result, which the author rightly characterizes as frightening, is shown in Table 11.3. In all, nearly one-fourth of the passwords were guessed. The following strategy was used:

1. Try the user's name, initials, account name, and other relevant personal information. In all, 130 different permutations for each user were tried.
2. Try words from various dictionaries. The author compiled a dictionary of over 60,000 words, including the online dictionary on the system itself, and various other lists as shown.
3. Try various permutations on the words from step 2. This included making the first letter uppercase or a control character, making the entire word uppercase, reversing the word, changing the letter "o" to the digit "zero," and so on. These permutations added another 1 million words to the list.
4. Try various capitalization permutations on the words from step 2 that were not considered in step 3. This added almost 2 million additional words to the list.

Thus, the test involved in the neighborhood of 3 million words. Using the fastest Thinking Machines implementation listed earlier, the time to encrypt all these words for all possible salt values is under an hour. Keep in mind that such a thorough search could produce a success rate of about 25%, whereas even a single hit may be enough to gain a wide range of privileges on a system.

Access Control One way to thwart a password attack is to deny the opponent access to the password file. If the encrypted password portion of the file is accessible only by a privileged user, then the opponent cannot read it without already knowing the password of a privileged user. [SPAF92a] points out several flaws in this strategy:

- Many systems, including most UNIX systems, are susceptible to unanticipated break-ins. Once an attacker has gained access by some means, he or she may wish to obtain a collection of passwords in order to use different accounts for different logon sessions to decrease the risk of detection. Or a user with an account may desire another user's account to access privileged data or to sabotage the system.
- An accident of protection might render the password file readable, thus compromising all the accounts.

Table 11.3 Passwords Cracked from a Sample Set of 13,797 Accounts [KLEI90]

Type of Password	Search Size	Number of Matches	Percentage of Passwords Matched	Cost/Benefit Ratio[a]
User/account name	130	368	2.7%	2.830
Character sequences	866	22	0.2%	0.025
Numbers	427	9	0.1%	0.021
Chinese	392	56	0.4%	0.143
Place names	628	82	0.6%	0.131
Common names	2239	548	4.0%	0.245
Female names	4280	161	1.2%	0.038
Male names	2866	140	1.0%	0.049
Uncommon names	4955	130	0.9%	0.026
Myths & legends	1246	66	0.5%	0.053
Shakespearean	473	11	0.1%	0.023
Sports terms	238	32	0.2%	0.134
Science fiction	691	59	0.4%	0.085
Movies and actors	99	12	0.1%	0.121
Cartoons	92	9	0.1%	0.098
Famous people	290	55	0.4%	0.190
Phrases and patterns	933	253	1.8%	0.271
Surnames	33	9	0.1%	0.273
Biology	58	1	0.0%	0.017
System dictionary	19683	1027	7.4%	0.052
Machine names	9018	132	1.0%	0.015
Mnemonics	14	2	0.0%	0.143
King James bible	7525	83	0.6%	0.011
Miscellaneous words	3212	54	0.4%	0.017
Yiddish words	56	0	0.0%	0.000
Asteroids	2407	19	0.1%	0.007
Total	62727	3340	24.2%	0.053

[a]Computed as the number of matches divided by the search size. The more words that needed to be tested for a match, the lower the cost/benefit ratio.

- Some of the users have accounts on other machines in other protection domains, and they use the same password. Thus, if the passwords could be read by anyone on one machine, a machine in another location might be compromised.

Thus, a more effective strategy would be to force users to select passwords that are difficult to guess.

Password Selection Strategies

The lesson from the two experiments just described ([SPAF92a], [KLEI90]) is that, left to their own devices, many users choose a password that is too short or too easy to guess. At the other extreme, if users are assigned passwords consisting of eight randomly selected printable characters, password cracking is effectively impossible. But it would be almost as impossible for most users to remember their passwords. Fortunately, even if we limit the password universe to strings of characters that are reasonably memorable, the size of the universe is still too large to permit practical cracking. Our goal, then, is to eliminate guessable passwords while allowing the user to select a password that is memorable. Four basic techniques are in use:

- User education
- Computer-generated passwords
- Reactive password checking
- Proactive password checking

Users can be told the importance of using hard-to-guess passwords and can be provided with guidelines for selecting strong passwords. This **user education** strategy is unlikely to succeed at most installations, particularly where there is a large user population or a lot of turnover. Many users will simply ignore the guidelines. Others may not be good judges of what is a strong password. For example, many users (mistakenly) believe that reversing a word or capitalizing the last letter makes a password unguessable.

Computer-generated passwords also have problems. If the passwords are quite random in nature, users will not be able to remember them. Even if the password is pronounceable, the user may have difficulty remembering it and so be tempted to write it down. In general, computer-generated password schemes have a history of poor acceptance by users. FIPS PUB 181 defines one of the best-designed automated password generators. The standard includes not only a description of the approach but also a complete listing of the C source code of the algorithm. The algorithm generates words by forming pronounceable syllables and concatenating them to form a word. A random number generator produces a random stream of characters used to construct the syllables and words.

A **reactive password checking** strategy is one in which the system periodically runs its own password cracker to find guessable passwords. The system cancels any passwords that are guessed and notifies the user. This tactic has a number of drawbacks. First, it is resource intensive if the job is done right. Because a determined opponent who is able to steal a password file can devote full CPU time to the task for hours or even days, an effective reactive password checker is at a distinct disadvantage. Furthermore, any existing passwords remain vulnerable until the reactive password checker finds them.

The most promising approach to improved password security is a **proactive password checker**. In this scheme, a user is allowed to select his or her own password. However, at the time of selection, the system checks to see if the password is allowable and, if not, rejects it. Such checkers are based on the philosophy that, with sufficient guidance from the system, users can select memorable passwords from a fairly large password space that are not likely to be guessed in a dictionary attack.

The trick with a proactive password checker is to strike a balance between user acceptability and strength. If the system rejects too many passwords, users will complain that it is too hard to select a password. If the system uses some simple algorithm to define what is acceptable, this provides guidance to password crackers to refine their guessing technique. In the remainder of this subsection, we look at possible approaches to proactive password checking.

The first approach is a simple system for rule enforcement. For example, the following rules could be enforced:

- All passwords must be at least eight characters long.
- In the first eight characters, the passwords must include at least one each of uppercase, lowercase, numeric digits, and punctuation marks.

These rules could be coupled with advice to the user. Although this approach is superior to simply educating users, it may not be sufficient to thwart password crackers. This scheme alerts crackers as to which passwords *not* to try but may still make it possible to do password cracking.

Another possible procedure is simply to compile a large dictionary of possible "bad" passwords. When a user selects a password, the system checks to make sure that it is not on the disapproved list. There are two problems with this approach:

- **Space:** The dictionary must be very large to be effective. For example, the dictionary used in the Purdue study [SPAF92a] occupies more than 30 megabytes of storage.
- **Time:** The time required to search a large dictionary may itself be large. In addition, to check for likely permutations of dictionary words, either those words most be included in the dictionary, making it truly huge, or each search must also involve considerable processing.

Bloom Filter

A technique [SPAF92a, SPAF92b] for developing an effective and efficient proactive password checker that is based on rejecting words on a list has been implemented on a number of systems, including Linux. It is based on the use of a Bloom filter [BLOO70]. To begin, we explain the operation of the Bloom filter. A Bloom filter of order k consists of a set of k independent hash functions $H_1(x), H_2(x), \ldots, H_k(x)$, where each function maps a password into a hash value in the range 0 to $N - 1$. That is,

$$H_i(\mathrm{X}_j) = y \qquad 1 \leq i \leq k; \qquad 1 \leq j \leq D; \qquad 0 \leq y \leq N - 1$$

where

X_j = jth word in password dictionary
D = number of words in password dictionary

The following procedure is then applied to the dictionary:

1. A hash table of N bits is defined, with all bits initially set to 0.

2. For each password, its k hash values are calculated, and the corresponding bits in the hash table are set to 1. Thus, if $H_i(X_j) = 67$ for some (i, j), then the sixty-seventh bit of the hash table is set to 1; if the bit already has the value 1, it remains at 1.

When a new password is presented to the checker, its k hash values are calculated. If all the corresponding bits of the hash table are equal to 1, then the password is rejected. All passwords in the dictionary will be rejected. But there will also be some "false positives" (i.e., passwords that are not in the dictionary but that produce a match in the hash table). To see this, consider a scheme with two hash functions. Suppose that the passwords *undertaker* and *hulkhogan* are in the dictionary, but xG%#jj98 is not. Further suppose that

$$H_1(\text{undertaker}) = 25 \qquad H_1(\text{hulkhogan}) = 83 \qquad H_1(\text{xG\%\#jj98}) = 665$$
$$H_2(\text{undertaker}) = 998 \qquad H_2(\text{hulkhogan}) = 665 \qquad H_2(\text{xG\%\#jj98}) = 998$$

If the password xG%#jj98 is presented to the system, it will be rejected even though it is not in the dictionary. If there are too many such false positives, it will be difficult for users to select passwords. Therefore, we would like to design the hash scheme to minimize false positives. It can be shown that the probability of a false positive can be approximated by:

$$P \approx (1 - e^{kD/N})^k = (1 - e^{k/R})^k$$

or, equivalently,

$$R \approx \frac{-k}{\ln(1 - P^{1/k})}$$

where

k = number of hash functions
N = number of bits in hash table
D = number of words in dictionary
R = N/D, ratio of hash table size (bits) to dictionary size (words)

Figure 11.7 plots P as a function of R for various values of k. Suppose we have a dictionary of 1 million words and we wish to have a 0.01 probability of rejecting a password not in the dictionary. If we choose six hash functions, the required ratio is $R = 9.6$. Therefore, we need a hash table of 9.6×10^6 bits or about 1.2 MBytes of storage. In contrast, storage of the entire dictionary would require on the order of 8 MBytes. Thus, we achieve a compression of almost a factor of 7. Furthermore, password checking involves the straightforward calculation of six hash functions and is independent of the size of the dictionary, whereas with the use of the full dictionary, there is substantial searching.[1]

[1]The Bloom filter involves the use of probabilistic techniques. There is a small probability that some passwords not in the dictionary will be rejected. It is often the case in designing algorithms that the use of probabilistic techniques results in a less time-consuming or less complex solution, or both.

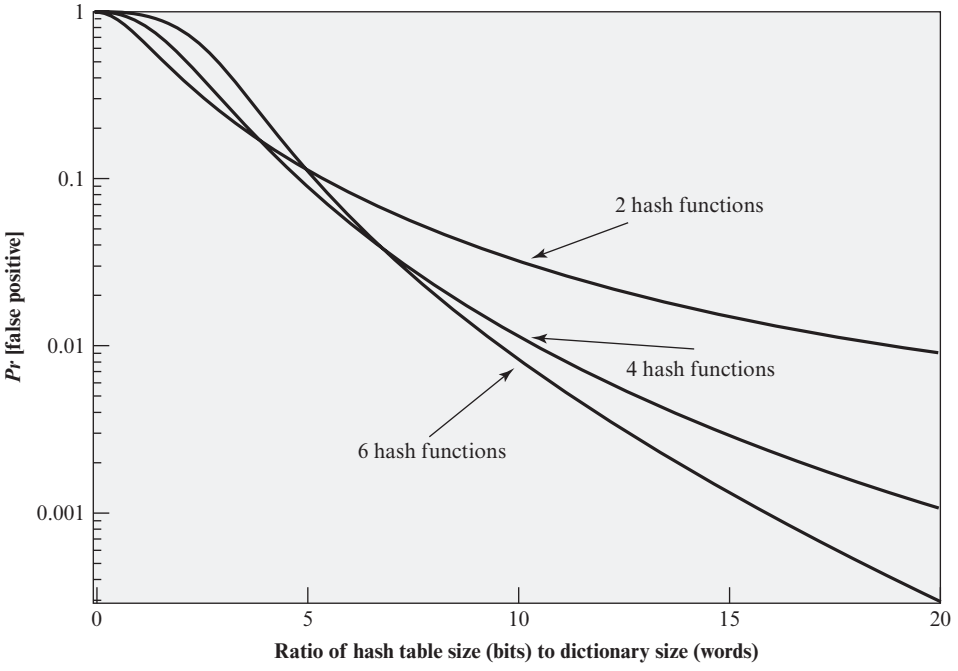


Figure 11.7 Performance of Bloom Filter

11.4 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

audit record	intruder	rainbow table
base-rate fallacy	intrusion detection	rule-based intrusion detection
bloom filter	intrusion detection exchange format	salt value
distributed intrusion detection	password	signature detection
honeypot		statistical anomaly detection

Review Questions

11.1 List and briefly define three classes of intruders.

11.2 Give examples of intrusion.

11.3 List the direct approaches that can be implemented to counter insider attacks.

11.4 Explain how statistical anomaly detection and rule-based intrusion detection are used to detect different types of intruders.

11.5 List the tests that can be performed to determine if a user's current activity is statistically anomalous or whether it is within acceptable parameters.

11.6 What is the base- rate fallacy?

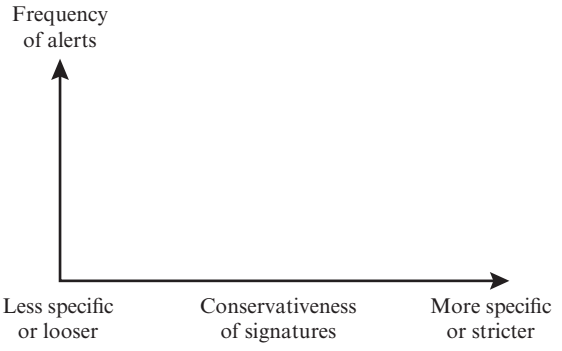
11.7 List the possible locations where a honeypot can be deployed.

11.8 Briefly explain the purposes that a salt serves in the context of UNIX password management.

11.9 Discuss the threats to the UNIX password scheme.

Problems

11.1 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.



11.2 The overlapping area of the two probability density functions of Figure 11.1 represents the region in which there is the potential for false positives and false negatives. Further, Figure 11.1 is an idealized and not necessarily representative depiction of the relative shapes of the two density functions. Suppose there is 1 actual intrusion for every 1000 authorized users, and the overlapping area covers 1% of the authorized users and 50% of the intruders.

a. Sketch such a set of density functions and argue that this is not an unreasonable depiction.

b. Observe, that the overlap region equally covers authorized users and intruders. Does it always mean there is equal probability that events in this region are by authorized users and intruders? Justify your answer.

11.3 An example of a host-based intrusion detection tool is the tripwire program. This is a file integrity checking tool that scans files and directories on the system on a regular basis and notifies the administrator of any changes. It uses a protected database of cryptographic checksums for each file checked and compares this value with that recomputed on each file as it is scanned. It must be configured with a list of files and directories to check, and what changes, if any, are permissible to each. It can allow, for example, log files to have new entries appended, but not for existing entries to be changed. What are the advantages and disadvantages of using such a tool? Consider the problem of determining which files should only change rarely, which files may change more often and how, and which change frequently and hence cannot be checked. Hence consider the amount of work in both the configuration of the program and on the system administrator monitoring the responses generated.

11.4 A taxicab was involved in a fatal hit-and-run accident at night. Two cab companies, the Yellow and the Red, operate in the city. You are told that:

- 85% of the cabs in the city are Yellow and 15% are Red.
- A witness identified the cab as Red.

The court tested the reliability of the witness under the same circumstances that existed on the night of the accident and concluded that the witness was correct in identifying the color of the cab 90% of the time. What is the probability that the cab involved in the incident was Red rather than Yellow?

11.5 Explain the suitability or unsuitability of the following passwords:

a. anu 1998
b. 5mimf2a3c (for 5 members in my family 2 adults 3 children)
c. Coimbatore16
d. Windows
e. Olympics
f. msk@123
g. g.0987654
h. iamking

11.6 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.

11.7 Assume that passwords are selected from five-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?

11.8 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 $x_k (x_i \neq x_k)$ 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?

11.9 A phonetic password generator picks two segments randomly for each six-letter password. The form of each segment is C9VC (consonant, digit, vowel, consonant), where $V = <$a, e, i, o, u$>$ and $C \neq V$.

a. What is the total password population?
b. What is the probability of an adversary guessing a password correctly?

11.10 Assume that passwords are limited to the use of the 95 printable ASCII characters and that all passwords are 12 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?

11.11 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?

11.12 The encryption scheme used for UNIX passwords is one way; it is not possible to reverse it. Therefore, would it be accurate to say that this is, in fact, a hash code rather than an encryption of the password?

11.13 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?

11.14 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?

11.15 Consider the Bloom filter discussed in Section 11.3. Define k = number of hash functions; N = number of bits in hash table; and D = number of words in dictionary.

a. Show that the expected number of bits in the hash table that are equal to zero is expressed as

$$\phi = \left(1 - \frac{k}{N}\right)^D$$

b. Show that the probability that an input word, not in the dictionary, will be falsely accepted as being in the dictionary is

$$\mathrm{P} = (1 - \phi)^k$$

c. Show that the preceding expression can be approximated as

$$\mathrm{P} \approx (1 - \mathrm{e}^{-kD/N})^k$$

11.16 Design a file access system to allow certain users read and write access to files, depending on authorization set up by the system. The instructions should be of the format:

ReadFile(F1, User A): User A has read access to file F1
WriteFile(F2, User A): User A has write access to file F2
ExecuteFile(F3, User B): User B has execute access to file F3

Each file has a *header record,* which contains authorization privileges; that is, a list of users who can read and write. The file is to be encrypted by a key that is not shared by the users but known only to the system.