Attack Class: Address Spoofing

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Abstract

We present an analysis of a class of attacks we call address spoofing. With the recent publicity surrounding an instance of such an attack, we have written up a presentation we gave nine months before the attack; we include an analysis of the recent attack. First, we present some fundamentals behind network communication and routing. Next we discuss the class of attacks we call address spoofing. We then give a real-world example of an attack in this class. Finally, we address some of the questions related to these attacks.

1 Introduction

Last year we began analyzing known vulnerabilities and attacks for the purpose of modelling them. We believe a sufficiently complete model will allow us to both predict new instances of general attack classes and build generic schemes for detecting exploitations of general vulnerability classes. This paper discusses one vulnerability/attack class we call address spoofing.

Many of today's network services use host names or addresses for both identification and authentication. A system using such a service composes a message and sends the message to the service on a remote system. The service on the remote system allows or disallows the request solely on the sender's address included in the request. For example, a remote login may be allowed without formal authentication (e.g., no password is required) if that remote login is coming from a "trusted" host. Table 1 describes some of the services using the senders address for authentication. Many higher level network services (e.g., network back-ups) are built on these vulnerable services thereby inheriting or extending their risks.

Unfortunately, addresses were not designed to provide authentication, and an adversary can take advantage of this fact by forging an artificial request. This paper explores how, why, and under what conditions an adversary can exploit services using address-based authentication. Following a discussion of the problem in the most general sense, we present a specific example of such an attack. Finally, we will conclude by answering some of the questions surrounding this problem.

2 Background Fundamentals

In order to more fully understand why and how address spoofing can be performed, we first cover some of the basics of communication and routing. These basic properties will be used to characterize an adversary's capabilities and strategies.

2.1 Connectionless vs. Connection-oriented Communication

As mentioned in the previous section, an adversary exploits the services of interest by forging a message; however, before we can define what a "message" is, we must examine some of the fundamentals of network communication.

Communication across a network falls into two broad categories: connectionless and connection-oriented communication. In connectionless

Service	Explanation
r* commands	remote login, remote shell, remote copy, etc.; host address can provide authentication by .rhosts and hosts.equiv files.
mountd	file system mounting; host address is used to allow access and access rights. Host access is usually specified in a file called something like /etc/exports.
TCP/UDP wrappers	wrappers around network services; wrappers are often used to deny access except to a few hosts to network services. IP access/restriction can be set in specific configuration files.
firewalls	IP firewalls are used to restrict access into a network to certain services and certain IP addresses. IP access/restrictions can be set in configuration files.

Table 1

communication, typically supplied by a protocol layer such as UDP, no state information about previously exchanged information is kept. If a process wants to send a message to another process which is already waiting, the first process simply constructs the message and gives it to the connectionless protocol layer (e.g., UDP) to deliver. Because no state information is kept, the underlying protocol being used does NOT guarantee that messages will arrive at their destination or even if they will arrive in the order that they were sent. However, this lack of state also makes connectionless protocols such as UDP very efficient and therefore desirable for many network services.

Processes requiring more robust communication, at the cost of some efficiency, use connection-oriented communication; the TCP layer provides such services. Connection-oriented communication "guarantees" that information will both arrive and arrive in order at the destination process, or if delivery could not be made, at least the sending process will be notified. Connection-oriented communication goes through three phases: connection set-up, data exchange, and connection tear-down. Under TCP, the set-up and tear-down process are performed by three way handshakes; the set-up handshake is described below.

The connection set-up is a three way handshake during which each host tells the other its beginning sequence number and acknowledges the beginning sequence number of the other host (see Fig. 1). The connection is NOT considered established until both hosts have acknowledged the other host's sequence number. Once the connection is established, the sequence numbers will be used to guarantee in-order delivery of data. In the first packet exchange in figure 1, Host A (Alice) notifies Host B (Bob) that she wants to establish a connection and provides her starting sequence number X. In the second packet exchange, Bob sends his starting sequence number, Y, and acknowledges that he has received Alice's starting number (it is incremented by one). In the final exchange, Alice acknowledges that she has received Bob's starting sequence number (once again, incrementing Y by one). At this point, the connection is established and data can be exchanged.

An important feature to note is that Bob's sequence number, Y, must be used in the third part of the handshake - Alice's second packet. If Alice is not able to demonstrate to Bob that she knows his sequence number, Bob will terminate the connection before it is fully established.

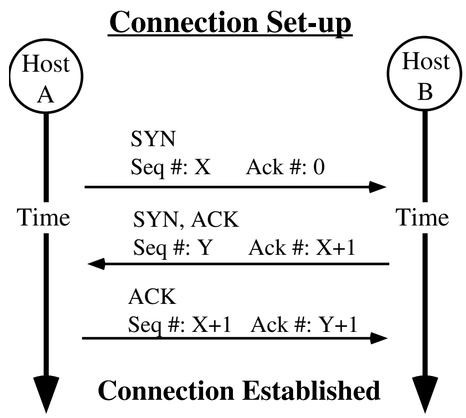

Figure 1

2.2 Routing

Routing, under the internet protocol suite, is almost magical. A host wanting to send a packet to a remote host somewhere else on the internetwork need only place the packet on the network, and the packet will be automatically routed through the network until it reaches its destination. Neither the sending nor receiving host need to know about the underlying architecture of the internetwork (hence, we often refer to an internetwork as a cloud). What is even more interesting for our needs is that, for the most part, during a packet's travels across the internetwork, only the destination address of the packet is examined. Therefore, the source address can be anything, including a non-existent host, and the internetwork will still deliver the message.

In Figure 2, our adversary E (Eve) wants to send a message to B (Bob) pretending to be A (Alice). Fortunately for Eve, she only needs to construct the packet and place it on the internet. The cloud will properly route the packet to Bob, and he will be unable to tell that it was not Alice who sent it. Once again, this feature will be important when we describe the potential attacks.

3 The Attack

We are now prepared to present the address spoofing attack class. In this section we will explain exactly what we consider is an attack, explain the restriction in the attack, and provide the strategy for an adversary.

3.1 Definition

Our model includes three players, Host A (Alice), Host B (Bob), and the adversary, Host E (Eve). Bob explicitly grants Alice special privileges. This granting of privileges is performed by listing Alice's name (or address) in special configuration files (e.g., .rhosts). Thus, Alice is able to get Bob to perform certain actions, actions he will not perform for just anybody, simply because she is who she says she is. Eve's goal is the following: **To get Bob to perform a specific action that he would perform for Alice but not Eve.**

3.2 Restrictions

We must concern ourselves with two

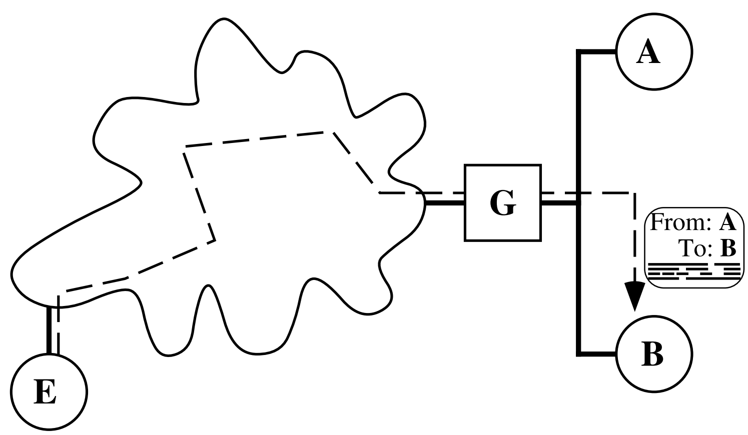

Figure 2

major issues: (1) the placements of Alice, Bob, and Eve and (2) the nature of the communication used to get Bob to perform the desired actions.

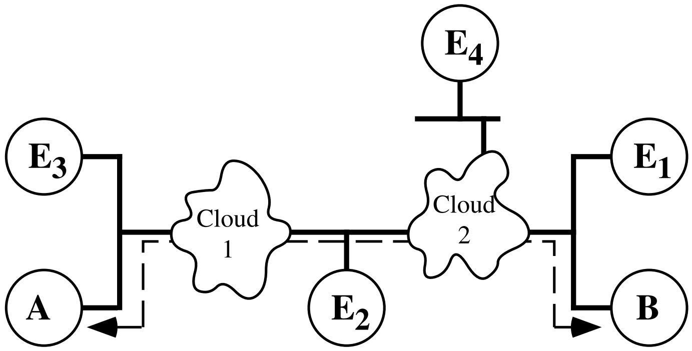

Figure 3

3.2.1 Architecture

The placement of the three players can be described as the model's architecture. The most basic architecture has Alice and Bob on the same network as in figure 2. In this scenario, either Eve is also on the same network or she is outside the network. However, for the purpose of this presentation we will examine the more general architecture where Alice and Bob are on separate networks. In this scenario, Eve's location relative to Alice and Bob can be described by one of the following four categories: (1) on the same network as Bob, (2) somewhere on the path between Alice and Bob, (3) on the same network as Alice, or (4) not on either of Alice or Bob's network and not in the path of the data (see figure 3) Each of Eve's four positions will dictate different strategies used by Eve and different defensive/detection strategies used by Alice or Bob.

Please note that the simpler architecture, where Alice and Bob are on the same network, is really a special case of our more general architecture depicted in figure 3. Namely, E_1 and E_3 collapse into one case, E_4 remains as is, and E_2 is eliminated.

3.2.2 Communication Nature

Here we are concerned with how Alice and Bob normally communicate. For if Eve is to get Bob to perform some action by making him believe Alice is requesting it, Eve's communication with Bob must be indistinguishable from Alice's communication with Bob (at least from Bob's perspective). We divide communication into two broad categories we call orders and dialogues. In order communication, Alice sends a single message to Bob. Bob may reply, but he we assume he has already carried out the order before replying. A popular form of order communication is the remote procedure call (RPC) over UDP.

In dialogue communication, Alice and Bob exchange several messages prior to Bob carrying out any request. If the dialogue does not make sense from Bob's perspective, Bob will not carry out the requested action (indeed, Bob may stop the dialogue before he even receives the request). Any communication over TCP must be considered a dialogue because as we showed earlier, several messages (packets) must be exchanged to set up a TCP/IP connection. Furthermore, Bob will be replying to Alice (not to Eve, who is pretending to be Alice). If Alice receives Bob's replies, she may tell Bob that she isn't talking to him, at which point Bob will terminate the dialogue. Eve may need to keep the dialogue going for some time, so she will need to prevent Alice from alerting Bob.

The nature of the communication, order or dialogue, used to get Bob to perform the desired action will dictate Eve's strategy.

3.3 Strategy

For Eve to complete her goal, she must achieve two main subgoals: establish a forged communication with Bob and prevent Alice from alerting Bob until it is too late. we examine each of these goals and their challenges in the following section.

For Eve to transmit a forged packet to Bob, she must simply construct the packet and place it on the network. The routing software in the network will deliver the packet for Eve. If the communication is order-based in which only a single packet is needed (e.g., a remote procedure call over UDP), then Eve has completed her communication subgoal. However, if communication is dialogue-based, Eve will need to send multiple packets to Bob, the contents of which will depend on replies that Bob makes (e.g., Bob's sequence number under TCP). If Eve is in positions E_1, E_2, or E_3, she is able to observe Bob's responses thereby allowing her to send meaningful subsequent packets to Bob. If Eve is in position E_4, she can still observe Bob's responses if she is able to modify the reply path from Bob to Alice. This can easily be done through source routing in IP networks. Modifying router settings are also an option to Eve. Finally, even if Eve is in position E_4 and is unable to direct Bob's traffic to Alice through Eve's own network, if Eve can predict Bob's responses (e.g., what Bob's sequence number will be), she can still carry on the communication with Bob. Predicting sequence numbers is discussed in [Morris 85] and [Bellovin 89] and was used in the recently publicized IP spoofing attack.

Eve's second major goal is to prevent Alice from interfering with the attack. Eve can achieve this goal in many ways; we will discuss three: (1) prevent the packets from reaching Alice (or Alice's packets from reaching Bob), (2) take away Alice's ability to respond, and (3) completing the communication before Alice's alerts can reach Bob.. The first approach requires Eve to modify the routing behavior of the network. If Eve is a node in the routing path (e.g., she is a router or has used source routing to make the route flow through her), she simply doesn't forward the packets to Alice. Even if Eve is not on the path between Alice and Bob, she could modify the routing information in one of the routers in the path to misroute Alice's packets. Eve could also wait for the internetwork between Alice and Bob to fail and launch her attack then.

The second approach, taking away Alice's ability to respond, can be much simpler for Eve to implement. Eve can (1) cause Alice to crash (not terribly difficult), (2) wait for Alice to go down for other reasons (e.g., maintenance), or (3) block the TCP/IP part of Alice's operating system so that it cannot process Bob's packets. This latter approach, perhaps the most graceful, was used in the recently publicized IP spoofing attack.

The third approach, completing the communication (at which time Bob has completed the action) before Alice can alert Bob, is trivial in the order-based communication (e.g., RPC). Bob will have completed any operation prior to sending any messages to Alice; therefore, by the time Alice is aware that something it wrong, she is too late. For dialogue-based communication, the solution is more difficult, because Bob will be sending data to Alice before Bob completes the requested operation. However, if the communication between Eve and Bob is much faster than between Alice and Bob, Eve could complete the attack in time.

3.4 Attack Summary

For Eve to achieve her goal of getting Bob to perform an action for Eve when he thinks he is doing it for Alice, Eve must (1) get the forged message to Bob, (2) if necessary carry on a dialogue with Bob, and (3) prevent Alice from interfering with the communication. Internetwork routing will usually take care of the first subgoal for Eve. The last two goals may be achieved in a number of ways; our suggested approaches were by no means complete.

4 An Example Attack

Having mapped out a general plan for Eve to exploit access control which is based on IP addresses or names, we now examine a particular instance of such an attack. The attack, launched this past Christmas, has gained the attention of the popular press, the usenet, and CERT. The attack can be mapped directly onto the general plan we discussed back in March of 1994. The only novel step in this attack was the way in which the attackers prevented the equivalent of Alice (in this case a server to an X-client (Bob)) from responding to Bob's replies. Namely, the attackers filled up Alice's internal TCP/IP structures preventing that layer from responding (by sending a

Players **E** adversary
A server
B X-client

Steps **1** Prevent Alice From Responding
2 Probe for sequence number prediction
3 Forge communication

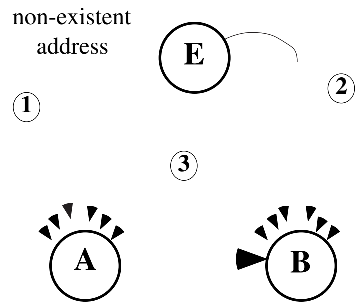

Figure 4

reset, RST) in response to Bob's messages. This approach provides a number of additional benefits; however, we will not discuss them at this time.

This particular attack involved a server (Alice) and an X-client (Bob) (see Figure 4). Eve was in position E_4. That is, she was unable to observe the messages passing between Alice and Bob.

Step 1: "Wedge" Alice's OS such that it cannot process Bob's replies. This is performed by sending multiple connection requests to the rlogin port (port 513) from a non-existent host. Alice responds to each request (the second part of the TCP handshake), but since the originating host does not exist, the third part of the handshake never comes. Alice is left with several partially opened connection, each filling up space in her internal data structures. Alice is only able to support up to eight of these partial connections before internal tables fill up and she stops responding.

Please note that had Eve listed her own IP address in the forged, artificial requests, her own TCP/IP software would have sent a reset command, RST, following Alice's reply. The RST would have freed Alice's data structures. Therefore, Eve had to use an artificial address as the sender of the request—one that would never reply to Alice's responses.

Step 2: Predict what Bob's sequence number will be. The attackers approach is essentially the same as those described in [Morris 85] and [Bellovin 89]. Eve sent 20 connection attempts to Bob's remote shell server; the starting sequence number for each connection request incremented by a predictable value of 128,000. Eve used her own address in the forged, artificial request to make sure the replies, with Bob's initial sequence numbers, were visible to her.

Bob did not suffer the same fate as Alice, namely halting after a number of connection requests, because Eve canceled each request with a reset command (RST) freeing the internal structures. Eve's own TCP/IP software probably took care of this for her.

Step 3: Have a dialogue with Bob pretending to be Alice (which is still in a confused state). In this particular case, the dialogue was a TCP/IP connection to the remote shell server. Although Eve could not see Bob's replies, she accurately predicted that Bob's starting sequence number would be 2,024,384,000—exactly 128,000 more than the last requested shell connection in step 2. Eve's requested action: place a "+ +" in the /.rhosts file (a shell command such as "`echo + + >> /.rhosts`" was sent). Bob, believing the connection was from Alice, carried out the request.

At this stage, the goal we set forth for Eve has been completed. She was able to get Bob (the X-client) to perform an action (place a "+ +" in /.rhosts) for her; something only Alice could legitimately do. Following this attack, the adversary easily logged into Bob via rlogin. In fact, at this point anyone from anywhere could rlogin to Bob.

5 Popular questions

Couldn't this attack be simply stopped by configuring routers (or firewalls) to not forward an obviously

forged packets? This is true in limited circumstances. For example, if the gateway G in figure 2 did not forward the packet which states that it is from A onto A's network, then the forgery in figure 2 could not take place. However, this is only a partial solution. If hosts A and B (Alice and Bob) are not on the same network already, this approach cannot work. Furthermore, even if Alice and Bob are on the same network, this cannot prevent attacks coming from Eve if she is on the same network already. In short, this solution is limited in scope. A solution should not be dependent on the network architecture.

Couldn't we simply write a more secure algorithm for choosing initial sequence numbers? If by "secure" you mean a less predictable starting sequence number, the answer is again true, but only in limited circumstances. This would work if, as in the case in figure 3, the adversary Eve is in position E_4 and unable to alter routing information to get the traffic to flow through her. However, if Eve is in positions E_1, E_2, or E_3 or if Eve is in position E_4 and can use source router or other means to alter routing, a more random initial sequence number would still not work. Eve is still able to observe what Bob's sequence number is.

What other extensions to this attack might exist? While numerous possibilities exist, perhaps the one which concerns us the most is the placing of a forged request into an already existing TCP/IP connection. This would immediately nullify the security provided by most of today's one-time password schemes. In fact, we have already heard rumors of such attacks already existing. Just as the Internet community was declaring the end of the reusable password, we may be witnessing the end of the password concept itself. The idea of a single authentication at the beginning of a connection may soon be history.

What solutions are there? The only effective solution from the network is to use cryptography to authenticate the origin of each packet using data secret to the originator. This way, if Eve wants to spoof Bob by imitating a packet from Alice, Eve won't know the secret information needed to construct the fake packet. Note that Eve can get around this if the sequence numbers are not random by recording messages between Alice and Bob, and when Bob repeats a sequence number, Eve can replay Alice's end of the previous conversation. We leave discussion of the usefulness of this attack, as well as countermeasures, for another time.

A second, more effective solution is for applications to regard the network as inherently untrustworthy, and require application-level authentication (and security mechanisms) to validate claims. These mechanisms should assume any data from the network is bogus, unless the peer application has secured the data before putting it on the network. In this way, applications need not wait for ubiquitous network security services before enhancing their own security.

6 Summary

We have described a class of attacks we have called address spoofing. The reason this class exists rests squarely on the fact that systems and application developers have chosen to use a property which was not designed to provide security, namely the sender's IP address, as a means of authentication. We have outlined where and how this vulnerability can be exploited, and we described a real instance of such an attack. Finally, we hope to have convinced you that the solution is not with "fixing" parts of the protocols (addresses and sequence numbers) which are not broken, but with getting systems and application developers to build their security on properties developed with the purpose of providing security in the first place.

References

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