CSE 127: Introduction to Security

Lecture 11: Network Defenses

Deian Stefan

UCSD

Winter 2020

Material from Nadia Heninger, Stefan Savage, David Wagner, and Zakir Durumeric

Defending Networks

- Motivation: How do you harden a set of systems against external attack?
  - The more network services your machines run, the greater the risk (i.e., the attack surface is larger)

Defending Networks

- Motivation: How do you harden a set of systems against external attack?
    - The more network services your machines run, the greater the risk (i.e., the attack surface is larger)
- One approach: Turn off unnecessary network services on each system
    - Requires knowing all the services that are running

Defending Networks

- Motivation: How do you harden a set of systems against external attack?
  - The more network services your machines run, the greater the risk (i.e., the attack surface is larger)
- One approach: Turn off unnecessary network services on each system
  - Requires knowing all the services that are running
- How does this approach scale?
  - What happens when you have hundreds or thousands of systems?
  - Systems may have different OSes, hardware, and users
  - May not even be known

Network Perimeter Defense

- Idea: Network defenses on “outside” of organization (e.g. between org and Internet)
  - Assumption?
- Typical elements:
  - Firewalls
  - Network Address Translation
  - Application Proxies
  - Network Intrusion Detection/Prevention Systems (NIDS/NIPS)

Firewalls

- Problem: Protecting or isolating one part of the network from other parts
    - In particular: Protect your network from global Internet
- Need to filter or otherwise limit network traffic
    - How to configure this information?
- Questions:
    - What information do you use to filter?
    - Where do you do the filtering?

Kinds of Firewalls

- Personal firewalls
    - Run at the end hosts
    - e.g. Norton, Windows, etc.
    - Benefit: has more application/user-specific information

Kinds of Firewalls

- Personal firewalls
  - Run at the end hosts
  - e.g. Norton, Windows, etc.
  - Benefit: has more application/user-specific information
- Network firewalls
  - Intercept and evaluate communications from many hosts

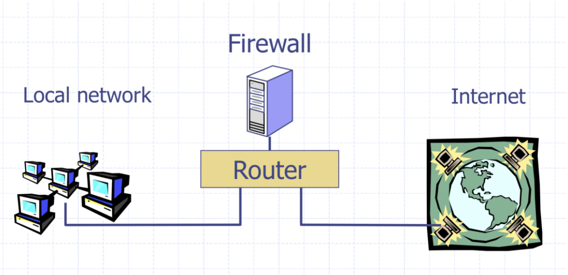
Kinds of Firewalls

- Personal firewalls
  - Run at the end hosts
  - e.g. Norton, Windows, etc.
  - Benefit: has more application/user-specific information
- Network firewalls
  - Intercept and evaluate communications from many hosts
- Filter-based
  - Operates by filtering on packet headers

Kinds of Firewalls

- Personal firewalls
  - Run at the end hosts
  - e.g. Norton, Windows, etc.
  - Benefit: has more application/user-specific information
- Network firewalls
  - Intercept and evaluate communications from many hosts
- Filter-based
  - Operates by filtering on packet headers
- Proxy-based
  - Operates at the level of the application
  - e.g. HTTP web proxy

Network Firewalls



- Filters protect against “bad” communications.
- Protect services offered internally from outside access.
- Provide outside services to hosts located inside.

Access Control Policies

- A firewall enforces an access control policy
    - Who is talking to whom and accessing what service?

- Distinguish between inbound and outbound connections
    - Inbound: Attempts by external users to connect to services on internal machines
    - Outbound: Internal users to external services

Access Control Policies

- A firewall enforces an access control policy
  - Who is talking to whom and accessing what service?

- Distinguish between inbound and outbound connections
  - Inbound: Attempts by external users to connect to services on internal machines
  - Outbound: Internal users to external services

- Conceptually simple access control policy:
  - Permit users inside to connect to any service
  - External users are restricted
    - Permit connections to services meant to be externally visible
    - Deny connections to services not meant for external access

Access Control Policies

How to treat traffic not mentioned in policy?

Default allow

- Permit all services, shut off for specific problems

Access Control Policies

How to treat traffic not mentioned in policy?

Default allow

- Permit all services, shut off for specific problems

Default deny

- Permit only a few well-known services, add more as users complain

Access Control Policies

How to treat traffic not mentioned in policy?

Default allow

- Permit all services, shut off for specific problems

Default deny

- Permit only a few well-known services, add more as users complain

In general, default deny is safer.

- Conservative design
- Flaws in default deny get noticed more quickly.

Example Firewall Policy

- Configure: Only allow SSH.

```
# ufw default deny
# ufw allow from 100.64.0.0/24
# ufw allow ssh
```

- Status: Only allow SSH.

```
# ufw status
Status: active

To                         Action      From
--                         ------      ----
22                         ALLOW       Anywhere
Anywhere                   ALLOW       100.64.0.0/24
22 (v6)                    ALLOW       Anywhere (v6)
```

Packet Filtering Firewalls

- Define list of access-control rules
- Check every packet against rules and forward or drop
- Packet-filtering firewalls can take advantage of the following information from network and transport layer headers:
    - Source IP
    - Destination IP
    - Source Port
    - Destination Port
    - Flags (e.g. ACK)

Ports

Recall: Ports used to distinguish applications and services on a machine.

- Low-numbered ports (1–1023) are often reserved for server listening.
- High-numbered ports are often assigned for client requests.

IANA port numbering:

- Less well-known services may use user or registered ports (1024–49151)
- Short-lived connections may use ephemeral/dynamic ports (49152–65535)

- Port 7 (UDP,TCP): echo server
- Port 13 (UDP,TCP): daytime
- Port 20 (TCP): FTP data
- Port 21 (TCP): FTP control
- Port 22 (TCP): SSH
- Port 25 (TCP): SMTP (mail)
- Port 80 (TCP): HTTP
- Port 123 (UDP): NTP
- Port 143 (TCP): IMAP
- Port 2049 (UDP): NFS
- Port 6000 to 6xxx (TCP): X11

Example packet filtering rules

- Block incoming DNS (port 53) except known trusted servers
- Block incoming HTTP (port 80) except to whitelisted hosts
- Block forged internal addresses

Example packet filtering rules

- Block incoming DNS (port 53) except known trusted servers
- Block incoming HTTP (port 80) except to whitelisted hosts
- Block forged internal addresses

Limitations:

- A stateless packet filter can’t distinguish packets associated with a connection from those that are not.

Some firewalls keep state about open TCP connections.

- Allows conditional filtering rules of the form “if internal machine has established the TCP connection, permit inbound reply packets”.

Circumventing simple firewall rules

Idea 1: Send traffic on a port usually allocated for another service.

Circumventing simple firewall rules

Idea 1: Send traffic on a port usually allocated for another service.

Idea 2: Tunneling

- Encapsulate one protocol inside another
- Recipient of outer protocol decapsulates to recover inner protocol
- Examples:
    - iodine IP over DNS
    - ssh tunnel
    - VPN (Virtual Private Network)

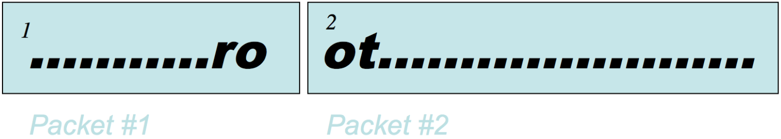
Stateful Packet Filtering Example

Suppose you want to allow inbound connections to a FTP server, but block any attempts to log in as “root”.

- How would you do this?
- What state do you need to keep?

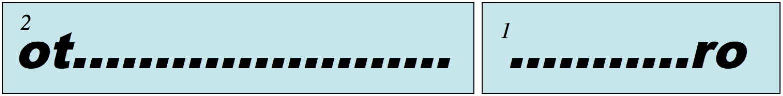
Stateful Packet Filtering is Hard

- Sender might be malicious and try to sneak through firewall
- “root” might span packet boundaries



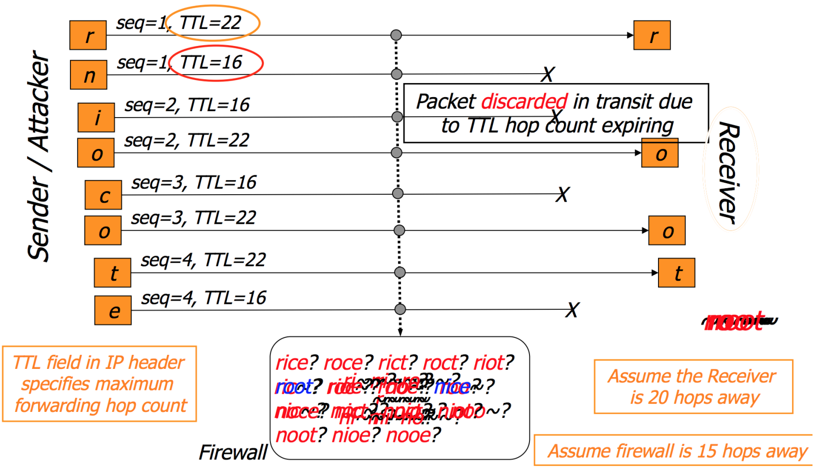
Stateful Packet Filtering is Hard

- Sender might be malicious and try to sneak through firewall
- Packets might be reordered



Stateful Packet Filtering is Hard

- TTL evasion



Packet discarded in transit due to TTL hop count expiring

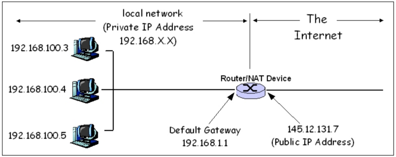
TTL field in IP header specifies maximum forwarding hop count

Assume the Receiver is 20 hops away

Assume firewall is 15 hops away

Network Address Translation (NAT)

- Idea: IP addresses do not need to be globally unique
- NATs map between two different address spaces.
- Most home routers are NATs and firewalls.



Private Subnets

10.0.0.0–10.255.255.255
172.16.0.0–172.31.255.255
192.168.0.0–192.168.255.255

Typical NAT Behavior

- NAT maintains a table of the form:
  `<client IP> <client port> <NAT ID>`
- Outoing packets (on non-NAT port):
  - Look for client IP address, client port in mapping table
  - If found, replace client port with previously allocated NAT ID (same size as port number)
  - If not found, allocate a new NAT ID and replace source port with NAT ID
  - Replace source address with NAT address
- Incoming packets (on NAT port)
  - Look up destination port as NAT ID in port mapping table
  - If found, replace destination address and port with client entries from the mapping table
  - If not found, the packet should be rejected
- Table entries expire after 2–3 minutes of no activity to allow them to be garbage collected

NAT Pros and Cons

- Benefits
  - Only allows connections to the outside that are established from inside.
    - Hosts from outside can only contact internal hosts that appear in the mapping table, and they’re only added when they establish the connection.
  - Don’t need as large an external address space
    - i.e. 10 machines can share 1 IP address

- Costs
  - Rewriting IP addresses isn’t so easy.
    - IP addresses may appear in the content of the packet in some protocols like FTP.
  - Breaks some protocols
    - e.g. some streaming protocols have client invoke server and then server opens a new connection to the client

Application Proxies

Idea: Control apps by requiring them to pass through proxy

- Proxy is application-level man-in-the-middle
- Enforce policy for specific protocols:
  - SMTP: Scan for viruses, reject spam
  - SSH: Log authentication, inspect encrypted text
  - HTTP: Block forbidden URLs

Be careful on enterprise networks. Companies inspect outbound traffic, will install root certificates on employee workstations to monitor TLS traffic.

⚠ WARNING!

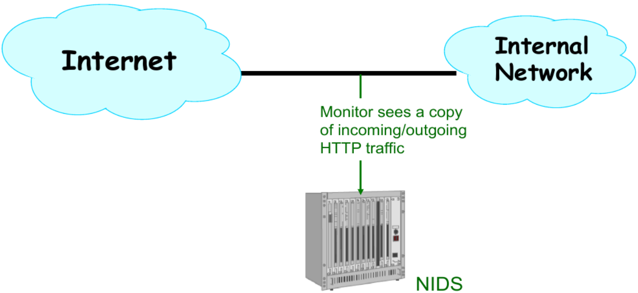
THIS TYPE OF FILE CAN HARM YOUR COMPUTER!
ARE YOU SURE YOU WANT TO DOWNLOAD:

HTTP://65.222.202.53/~TILDE/PUB/CIA-BIN/ETC/INIT.DLL?FILE=__AUTOEXEC.BAT.MY%20OSX%20DOCUMENTS—INSTALL.EXE.RAR.INI.TAR.DOÇX.PHPHPHP.XHTML.TML.XTL.TXXT.0DAY.HACK.ERS_(1995)_BLURAY_CAM-XVID.EXE.TAR.[SCR].LISP.MSI.LNK.ZDA.GNN.WRBT.OBJ.O.H.SWF.DPKG.APP.ZIP.TAR.TAR.CO.GZ.A.OUT.EXE

XKCD

Network Intrusion Detection Systems (NIDS)

- Idea: Passively monitor network traffic for signs of attack (e.g., look for `/etc/passwd`)



Network Intrusion Detection Systems (NIDS)

- NIDS has a table of all active connections, and maintains state for each
  - E.g., has it seen partial match of `/etc/passwd`

- What do you do when you see a new packet not associated with any known connection?

Network Intrusion Detection Systems (NIDS)

- NIDS has a table of all active connections, and maintains state for each
  - E.g., has it seen partial match of `/etc/passwd`
- What do you do when you see a new packet not associated with any known connection?
  - Create a new connection: when NIDS starts, it doesn't know what connections might be existing

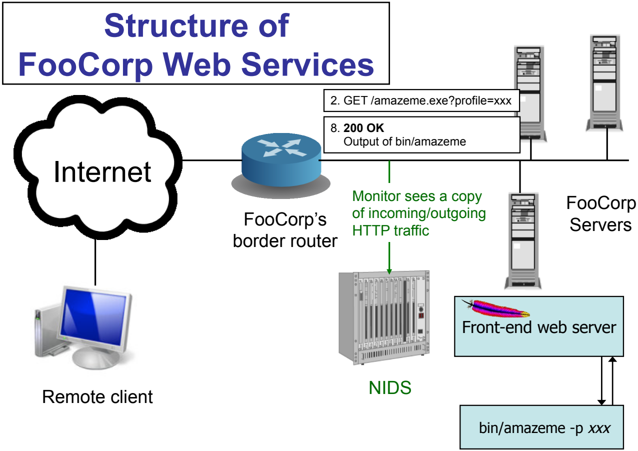
Network Intrusion Detection Systems (NIDS)

- NIDS has a table of all active connections, and maintains state for each
  - E.g., has it seen partial match of `/etc/passwd`

- What do you do when you see a new packet not associated with any known connection?
  - Create a new connection: when NIDS starts, it doesn’t know what connections might be existing

- Where should you do the detection?
  - Network, host, or both?

Approach #1: Network-based Detection



Structure of FooCorp Web Services
Internet
2. GET /amazeme.exe?profile=xxx
8. **200 OK** Output of bin/amazeme
FooCorp's border router
Monitor sees a copy of incoming/outgoing HTTP traffic
FooCorp Servers
NIDS
Remote client
Front-end web server
bin/amazeme -p *xxx*

- Look at network traffic, scanning HTTP requests
  - E.g., look for `/etc/password` or `../../`

Network-based Detection Pros and Cons

Benefits

- Don’t need to *modify* or *trust* end systems
- Cover many systems with single monitor
- Centralized management

Network-based Detection Pros and Cons

Benefits

- Don’t need to *modify* or *trust* end systems
- Cover many systems with single monitor
- Centralized management

Issues

- Expensive: 10Gbps link $\approx$ 1M packets/second $\approx$ ns/packet

Network-based Detection Pros and Cons

Benefits

- Don’t need to *modify* or *trust* end systems
- Cover many systems with single monitor
- Centralized management

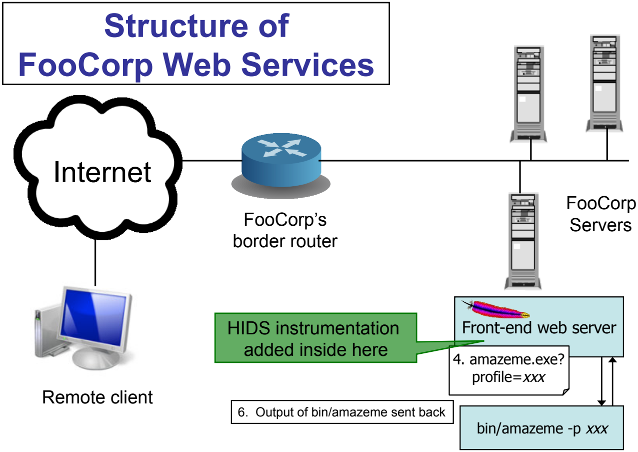
Issues

- Expensive: 10Gbps link $\approx$ 1M packets/second $\approx$ ns/packet
- Vulnerable to evasion attacks
    - Some evasions reflect incomplete analysis
        - E.g., hex escape or `..///.///..////`
        - In principle, can deal with these with implementation care
    - Some are due to imperfect observability
        - E.g., what if what NIDS sees doesn’t exactly match what arrives at destination?

Understanding the Downsides

- Does `/etc/passwd` exist on all systems? Do you include rules for all OSes?
- Are all requests with `../../` *necessarily* bad?
  - False positives: Sometimes seen in legit requests
- Do you handle all encodings and semantic meaning?
  - Evasion: Abusing URL encodings (`%2e%2e%2f%2e%2e%2f`)
  - Evasion: Abusing UNIX semantics (`..///.///..////`)
- What if the traffic is encrypted (HTTPS)?
  - Need access to session key or decrypted text
  - Why might you not want to give the NIDS your TLS keys?

Approach #2: Host-based Detection



- Instrument web server, scan arguments sent to back-end programs (and outbound requests)
    - E.g., look for `/etc/password` or `../../`

Host-based Detection Pros and Cons

Benefits

- The semantic gap is smaller, have understanding of URLs (and thus `%2e%2e%2f%2e%2e%2f`)
- Don’t need to intercept HTTPS

Host-based Detection Pros and Cons

Benefits

- The semantic gap is smaller, have understanding of URLs (and thus `%2e%2e%2f%2e%2e%2f`)
- Don’t need to intercept HTTPS

Issues

- Expensive: Add code to each server
- Still have to consider e.g., UNIX filename semantics `..///.///..////`
- Still have to consider other sensitive files, databases, etc.

Host-based Detection Pros and Cons

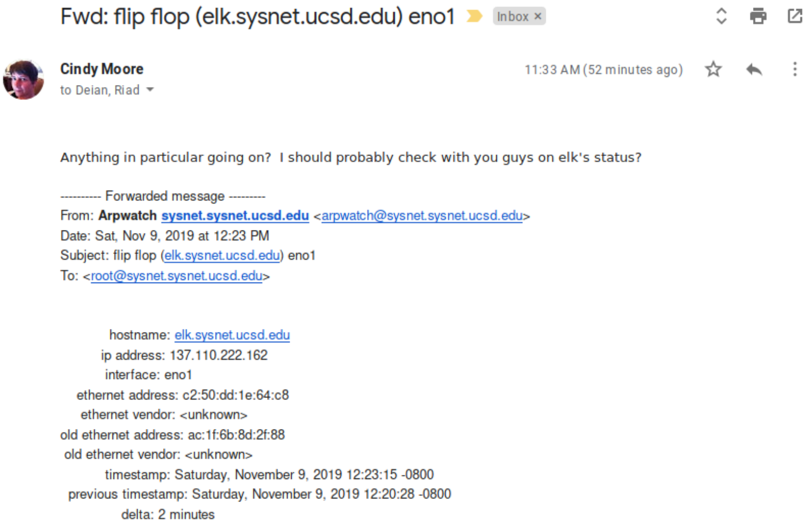
Benefits

- The semantic gap is smaller, have understanding of URLs (and thus `%2e%2e%2f%2e%2e%2f`)
- Don’t need to intercept HTTPS

Issues

- Expensive: Add code to each server
- Still have to consider e.g., UNIX filename semantics `..///.///..////`
- Still have to consider other sensitive files, databases, etc.
- Only (kind of) helps with web server attacks; what do you do about other end systesm?

Example: arpwatch



Fwd: flip flop (elk.sysnet.ucsd.edu) eno1

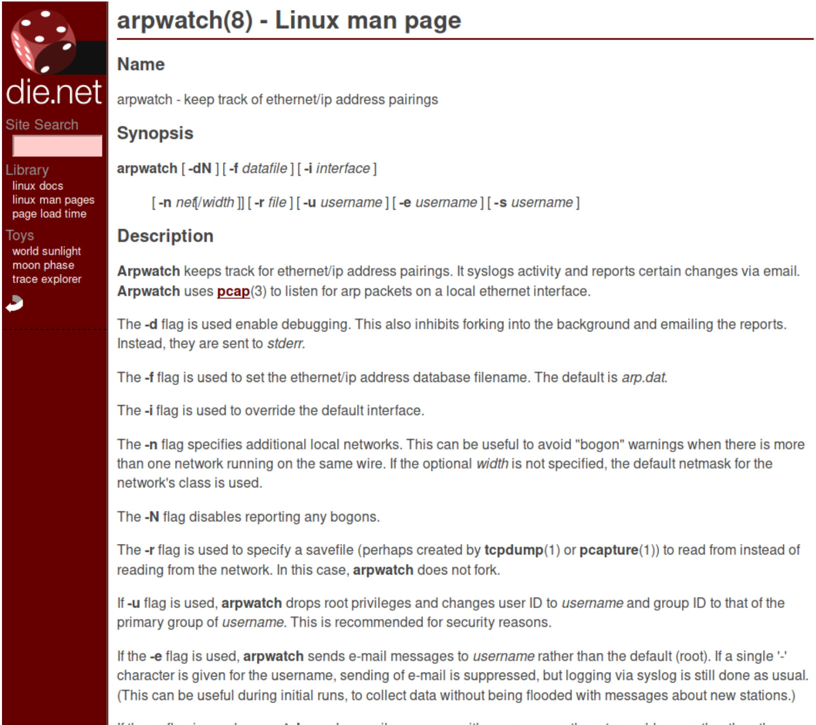
Cindy Moore
to Deian, Riad

11:33 AM (52 minutes ago)

Anything in particular going on? I should probably check with you guys on elk's status?

---------- Forwarded message ---------
From: **Arpwatch sysnet.sysnet.ucsd.edu** <arpwatch@sysnet.sysnet.ucsd.edu>
Date: Sat, Nov 9, 2019 at 12:23 PM
Subject: flip flop (elk.sysnet.ucsd.edu) eno1
To: <root@sysnet.sysnet.ucsd.edu>

```
            hostname: elk.sysnet.ucsd.edu
          ip address: 137.110.222.162
           interface: eno1
    ethernet address: c2:50:dd:1e:64:c8
     ethernet vendor: <unknown>
old ethernet address: ac:1f:6b:8d:2f:88
 old ethernet vendor: <unknown>
           timestamp: Saturday, November 9, 2019 12:23:15 -0800
  previous timestamp: Saturday, November 9, 2019 12:20:28 -0800
               delta: 2 minutes
```



die.net

Site Search

Library
linux docs
linux man pages
page load time

Toys
world sunlight
moon phase
trace explorer

arpwatch(8) - Linux man page

Name

arpwatch - keep track of ethernet/ip address pairings

Synopsis

arpwatch [**-dN**] [**-f** *datafile*] [**-i** *interface*]

[**-n** *net*[/*width*]] [**-r** *file*] [**-u** *username*] [**-e** *username*] [**-s** *username*]

Description

Arpwatch keeps track for ethernet/ip address pairings. It syslogs activity and reports certain changes via email. **Arpwatch** uses **pcap**(3) to listen for arp packets on a local ethernet interface.

The **-d** flag is used enable debugging. This also inhibits forking into the background and emailing the reports. Instead, they are sent to *stderr*.

The **-f** flag is used to set the ethernet/ip address database filename. The default is *arp.dat*.

The **-i** flag is used to override the default interface.

The **-n** flag specifies additional local networks. This can be useful to avoid "bogon" warnings when there is more than one network running on the same wire. If the optional *width* is not specified, the default netmask for the network's class is used.

The **-N** flag disables reporting any bogons.

The **-r** flag is used to specify a savefile (perhaps created by **tcpdump**(1) or **pcapture**(1)) to read from instead of reading from the network. In this case, **arpwatch** does not fork.

If **-u** flag is used, **arpwatch** drops root privileges and changes user ID to *username* and group ID to that of the primary group of *username*. This is recommended for security reasons.

If the **-e** flag is used, **arpwatch** sends e-mail messages to *username* rather than the default (root). If a single '-' character is given for the username, sending of e-mail is suppressed, but logging via syslog is still done as usual. (This can be useful during initial runs, to collect data without being flooded with messages about new stations.)

Approach #3: Log analysis

- Log analysis: run scripts to analyze system log files (e.g., every night, hour, etc.)

Benefits

- Cheap: Servers already have logging facilities
- No escaping issues (logging done by server)

Approach #3: Log analysis

- Log analysis: run scripts to analyze system log files (e.g., every night, hour, etc.)

Benefits

- Cheap: Servers already have logging facilities
- No escaping issues (logging done by server)

Issues

- Reactive: detection delayed, can’t block attacks

Approach #3: Log analysis

- Log analysis: run scripts to analyze system log files (e.g., every night, hour, etc.)

Benefits

- Cheap: Servers already have logging facilities
- No escaping issues (logging done by server)

Issues

- Reactive: detection delayed, can’t block attacks
- Still need to worry about UNIX filename semantics

Approach #3: Log analysis

- Log analysis: run scripts to analyze system log files (e.g., every night, hour, etc.)

Benefits

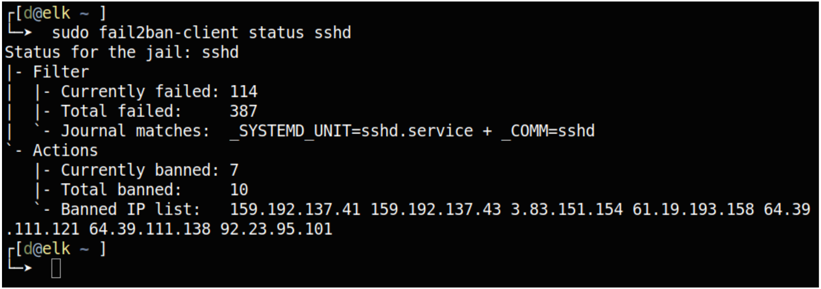
- Cheap: Servers already have logging facilities
- No escaping issues (logging done by server)

Issues

- Reactive: detection delayed, can't block attacks
- Still need to worry about UNIX filename semantics
- Malware may be able to modify logs

Example: fail2ban

***Fail2ban** scans log files (e.g. `/var/log/apache/error_log`) and bans IPs that show the malicious signs – too many password failures, seeking for exploits, etc. Generally Fail2Ban is then used to update firewall rules to reject the IP addresses for a specified amount of time, although any arbitrary other **action** (e.g. sending an email) could also be configured. Out of the box Fail2Ban comes with **filters** for various services (apache, courier, ssh, etc).*



```
┌[d@elk ~ ]
└→  sudo fail2ban-client status sshd
Status for the jail: sshd
|- Filter
|  |- Currently failed: 114
|  |- Total failed:     387
|  `- Journal matches:  _SYSTEMD_UNIT=sshd.service + _COMM=sshd
`- Actions
   |- Currently banned: 7
   |- Total banned:     10
   `- Banned IP list:   159.192.137.41 159.192.137.43 3.83.151.154 61.19.193.158 64.39
.111.121 64.39.111.138 92.23.95.101
┌[d@elk ~ ]
└→  
```

But this has its own issues

- Filters are complicated regular expressions
- Can accidentally block self
- Can be tricked into blocking others

```
# !!! WARNING !!!
#   Since UDP is connection-less protocol, spoofing of IP and imitation
#   of illegal actions is way too simple.  Thus enabling of this filter
#   might provide an easy way for implementing a DoS against a chosen
#   victim. See
#    http://nion.modprobe.de/blog/archives/690-fail2ban-+-dns-fail.html
#   Please DO NOT USE this jail unless you know what you are doing.
#
# IMPORTANT: see filter.d/named-refused for instructions to enable logging
# This jail blocks UDP traffic for DNS requests.
# [named-refused-udp]
#
# filter   = named-refused
# port     = domain,953
# protocol = udp
# logpath  = /var/log/named/security.log

# IMPORTANT: see filter.d/named-refused for instructions to enable logging
# This jail blocks TCP traffic for DNS requests.
```

Detection Accuracy

- Two types of detector errors:
  - False positives (FPs): alerting about a non-problem
  - False negatives (FNs): failing to alert about a real problem
- Detector accuracy is often addressed in terms of rates:
  - Let I be the event of an instance of intrusive behavior
  - Let A be the event of detector generating an alarm
  - We then define: FP rate $= P[A|\neg I]$ and FN rate $= P[\neg A|I]$
- Can we build a perfect detector?

Detection Tradeoffs

- The art of a good detector is achieving **effective balance** between FP and FN rate.
  - Is low FP rate more better than low FN rate?
  - Is an FP rate of 0.1% and FN rate of 2% good?

Detection Tradeoffs

- The art of a good detector is achieving **effective balance** between FP and FN rate.
  - Is low FP rate more better than low FN rate?
  - Is an FP rate of 0.1% and FN rate of 2% good?
- It depends…
  - on cost of each type of error (e.g., FPs can waste an engineer's time; FN might lead to huge clean up fee)
  - on rate at which attacks occur (e.g., your laptop vs. Google's servers)

Vulnerability Scanning

Idea: Rather than detect attacks, launch them yourself.

- Probe internal systems with a range of attacks
- Patch/fix/block any that succeed.
- Pros:
  - Accurate: If your scanning tool is good, it finds real problems
  - Proactive: Can prevent future misuse
  - Intelligence: Can ignore IDS alarms you know can’t succeed
- Issues:

Vulnerability Scanning

Idea: Rather than detect attacks, launch them yourself.

- Probe internal systems with a range of attacks
- Patch/fix/block any that succeed.
- Pros:
  - Accurate: If your scanning tool is good, it finds real problems
  - Proactive: Can prevent future misuse
  - Intelligence: Can ignore IDS alarms you know can’t succeed
- Issues:
  - Can take a lot of work
  - Not helpful for systems you can’t modify
  - Dangerous for disruptive attacks

Vulnerability Scanning

Idea: Rather than detect attacks, launch them yourself.

- Probe internal systems with a range of attacks
- Patch/fix/block any that succeed.
- Pros:
  - Accurate: If your scanning tool is good, it finds real problems
  - Proactive: Can prevent future misuse
  - Intelligence: Can ignore IDS alarms you know can’t succeed
- Issues:
  - Can take a lot of work
  - Not helpful for systems you can’t modify
  - Dangerous for disruptive attacks
- In practice, this approach is prudent and widely used.
- Good complement to running an IDS

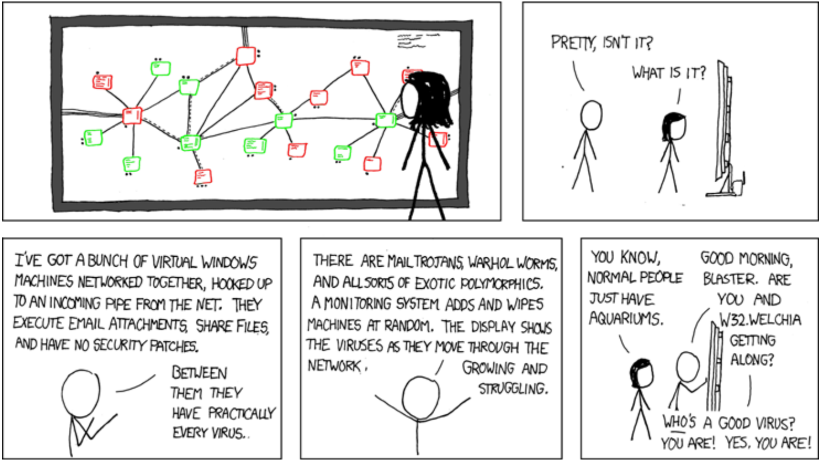
Honeypots

Idea: Deploy a sacrificial system that has no operational purpose

- Designed to lure attackers
- Any access is by definition not authorized, and is either an intruder or a mistake
- Provides opportunity to:
    - Identify intruders
    - Study what they're up to
    - Divert them from legitimate targets

Honeypots

Honeypots for automated attacks easier than building a convincing environment for dedicated attackers.


PRETTY, ISN'T IT?
WHAT IS IT?
I'VE GOT A BUNCH OF VIRTUAL WINDOWS MACHINES NETWORKED TOGETHER, HOOKED UP TO AN INCOMING PIPE FROM THE NET. THEY EXECUTE EMAIL ATTACHMENTS, SHARE FILES, AND HAVE NO SECURITY PATCHES.
BETWEEN THEM THEY HAVE PRACTICALLY EVERY VIRUS.
THERE ARE MAIL TROJANS, WARHOL WORMS, AND ALL SORTS OF EXOTIC POLYMORPHICS. A MONITORING SYSTEM ADDS AND WIPES MACHINES AT RANDOM. THE DISPLAY SHOWS THE VIRUSES AS THEY MOVE THROUGH THE NETWORK,
GROWING AND STRUGGLING.
YOU KNOW, NORMAL PEOPLE JUST HAVE AQUARIUMS.
GOOD MORNING, BLASTER. ARE YOU AND W32.WELCHIA GETTING ALONG?
WHO'S A GOOD VIRUS? YOU ARE! YES, YOU ARE!

XKCD