Firewalls

CS 161: Computer Security

Prof. David Wagner

March 7, 2013

Controlling Networks … On The Cheap

- Motivation: How do you harden a set of systems against external attack?
  - *Key Observation:*
    - *The more network services your machines run, the greater the risk*
  - Due to larger attack surface
- One approach: on each system, turn off unnecessary network services
  - But you have to know ***all*** the services that are running
  - And sometimes some trusted remote users still require access

Controlling Networks … On The Cheap

- Motivation: How do you harden a set of systems against external attack?
  - *Key Observation:*
    - *The more network services your machines run, the greater the risk*
  - Due to larger attack surface
- One approach: on each system, turn off unnecessary network services
  - But you have to know ***all*** the services that are running
  - And sometimes some trusted remote users still require access
- Plus key question of scaling
  - What happens when you have to secure 100s/1000s of systems?
  - Which may have different OSs, hardware & users …
  - Which may in fact not all even be identified …

Taming Management Complexity

- Possibly more scalable defense: Reduce risk by blocking *in the network* outsiders from having unwanted access your network services
  - Interpose a **firewall** the traffic to/from the outside must traverse
  - Chokepoint can cover thousands of hosts
    - Where in everyday experience do we see such chokepoints?

Selecting a Security Policy

- Firewall enforces an (access control) policy:
  - *Who is allowed to talk to whom, accessing what service?*
- Distinguish between inbound & outbound connections
  - Inbound: attempts by external users to connect to services on internal machines
  - Outbound: internal users to external services
  - Why? Because fits with a common ***threat model***. There are thousands of internal users (and we've vetted them). There are billions of outsiders.
- Conceptually simple *access control policy*:
  - Permit inside users to connect to any service
  - External users restricted:
    - Permit connections to services meant to be externally visible
    - Deny connections to services not meant for external access

How To Treat Traffic Not Mentioned in Policy?

- **Default Allow**: start off permitting external access to services
  - Shut them off as problems recognized

How To Treat Traffic Not Mentioned in Policy?

- **Default Allow**: start off permitting external access to services
  - Shut them off as problems recognized
- **Default Deny**: start off permitting just a few known, well-secured services
  - Add more when users complain (and mgt. approves)

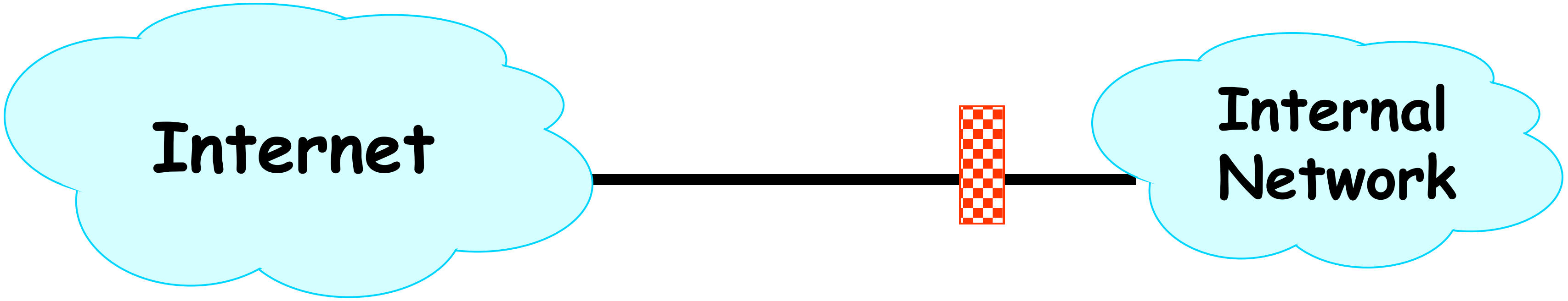
How To Treat Traffic Not Mentioned in Policy?

- **Default Allow**: start off permitting external access to services
  - Shut them off as problems recognized
- **Default Deny**: ✓ rt off permitting just a few known, well-secured services
  - Add more when users complain (and mgt. approves)
- Pros & Cons?
  - Flexibility vs. conservative design
  - Flaws in Default Deny get noticed more quickly / less painfully

In general, use Default Deny

Stateful Packet Filter

- Stateful packet filter is a router that checks each packet against security rules and decides to forward or drop it
  - Firewall keeps track of all connections (inbound/outbound)
  - Each rule specifies which connections are allowed/denied (*access control policy*)
  - A packet is forwarded if it is part of an allowed connection



Example Rule

```
allow tcp connection 4.5.5.4:* -> 3.1.1.2:80
```

- Firewall should **permit** TCP connection that's:
  - Initiated by host with Internet address `4.5.5.4` **and**
  - Connecting to port `80` of host with IP address `3.1.1.2`
- Firewall should permit any packet associated with this connection

- Thus, firewall keeps a table of (allowed) active connections. When firewall sees a packet, it checks whether it is part of one of those active connections. If yes, forward it; if no, drop it.

Example Rule

```
allow tcp connection *:*/in -> 3.1.1.2:80/out
```

- Firewall should **permit** TCP connection that's:
  - Initiated by host with any internal host **and**
  - Connecting to port `80` of host with IP address `3.1.1.2` on external Internet
- Firewall should permit any packet associated with this connection

- The `/in` indicates the network interface.

Example Ruleset

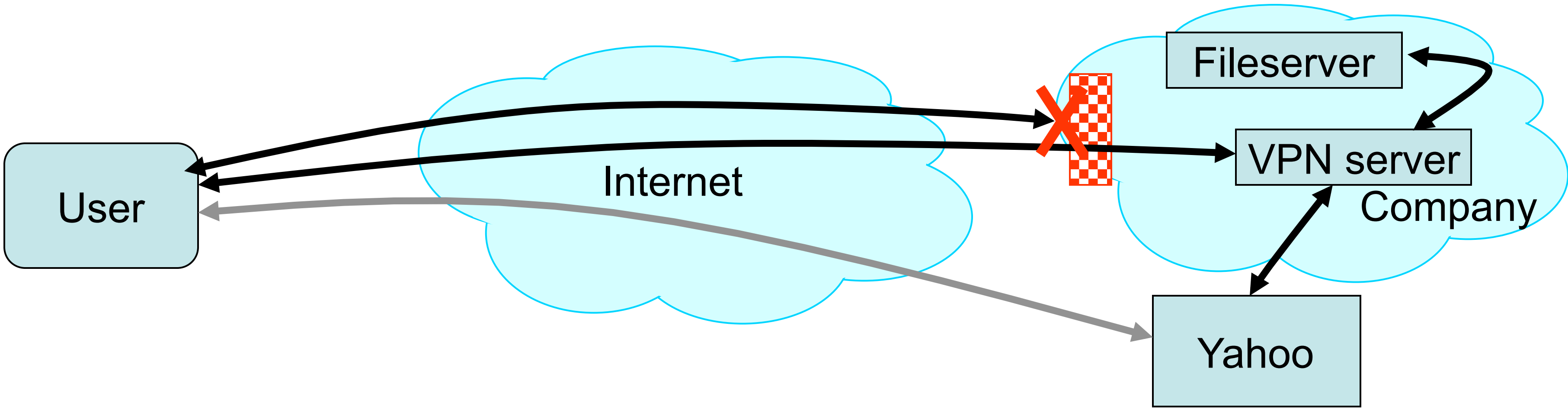
```
allow tcp connection *:*/in -> *:*/out
allow tcp connection *:*/out -> 1.2.2.3:80/in
```

- Firewall should permit outbound TCP connections (i.e., those that are initiated by internal hosts)
- Firewall should permit inbound TCP connection to our public webserver at IP address 1.2.2.3

Other Kinds of Firewalls

- Stateless packet filter
  - No state in the packet filter. Rules specify whether to drop packet, without history.
  - Problem: requires hacks to handle TCP connections (e.g., an inbound packet is OK if it is associated with a TCP connection initiated by an inside host to an outside host).
- Application-level firewall
  - Firewall acts as a proxy. TCP connection from client to firewall, which then makes a second TCP connection from firewall to server.
  - Only modest benefits over stateful packet filter.

Secure External Access to Inside Machines



- Often need to provide secure remote access to a network protected by a firewall
  - Remote access, telecommuting, branch offices, …
- Create secure channel (*Virtual Private Network*, or **VPN**) to tunnel traffic from outside host/network to inside network
  - Provides Authentication, Confidentiality, Integrity
  - However, also raises *perimeter issues*

    (Try it yourself at http://www.net.berkeley.edu/vpn/)

Why Have Firewalls Been Successful?

- *Central control – easy administration and update*
  - Single point of control: update one config to change security policies
  - Potentially allows rapid response
- *Easy to deploy – transparent to end users*
  - Easy incremental/total deployment to protect 1000's
- *Addresses an important problem*
  - Security vulnerabilities in network services are rampant
  - Easier to use firewall than to directly secure code …

Firewall Disadvantages?

Discussion question:

What are the limitations of firewalls?
Why have firewalls become less effective over time?

Discuss with a partner.

Firewall Disadvantages?

- *Functionality loss – less connectivity, less risk*
  - May reduce network's usefulness
  - Some applications don't work with firewalls
    - Two peer-to-peer users behind different firewalls
- *The malicious insider problem*
  - Assume insiders are trusted
    - Malicious insider (or anyone gaining control of internal machine) can wreak havoc
- Firewalls establish a *security perimeter*
  - Like *Eskimo Pies*: "hard crunchy exterior, soft creamy center"
  - Threat from travelers with laptops, cell phones, …

Takeaways on Firewalls

- Firewalls: Reference monitors and access control all over again, but at the network level
- Attack surface reduction
- Centralized control

Detecting Attacks

CS 161: Computer Security

Prof. David Wagner

March 7, 2013

Approaches to Security

- Prevent, Detect and respond, Deter, Tolerate
- Detection might enable…
  - Recovery: if I know my machine is infected, I can recover (nuke it from orbit and re-install)
  - Risk management: if I can measure prevalence of different attacks, I can prioritize spending on different defenses wisely
  - Deterrence: if I can detect the attack *and* attribute the source, maybe we can punish/prosecute the attacker – deterring others in the future
- If we can detect an attack, why not just block it when you detect it?
  - False alarms: detector might occasionally make false positives, and it'd be costly to block legitimate activity
  - After-the-fact response: might be easier to detect attack later than to detect attack in real time

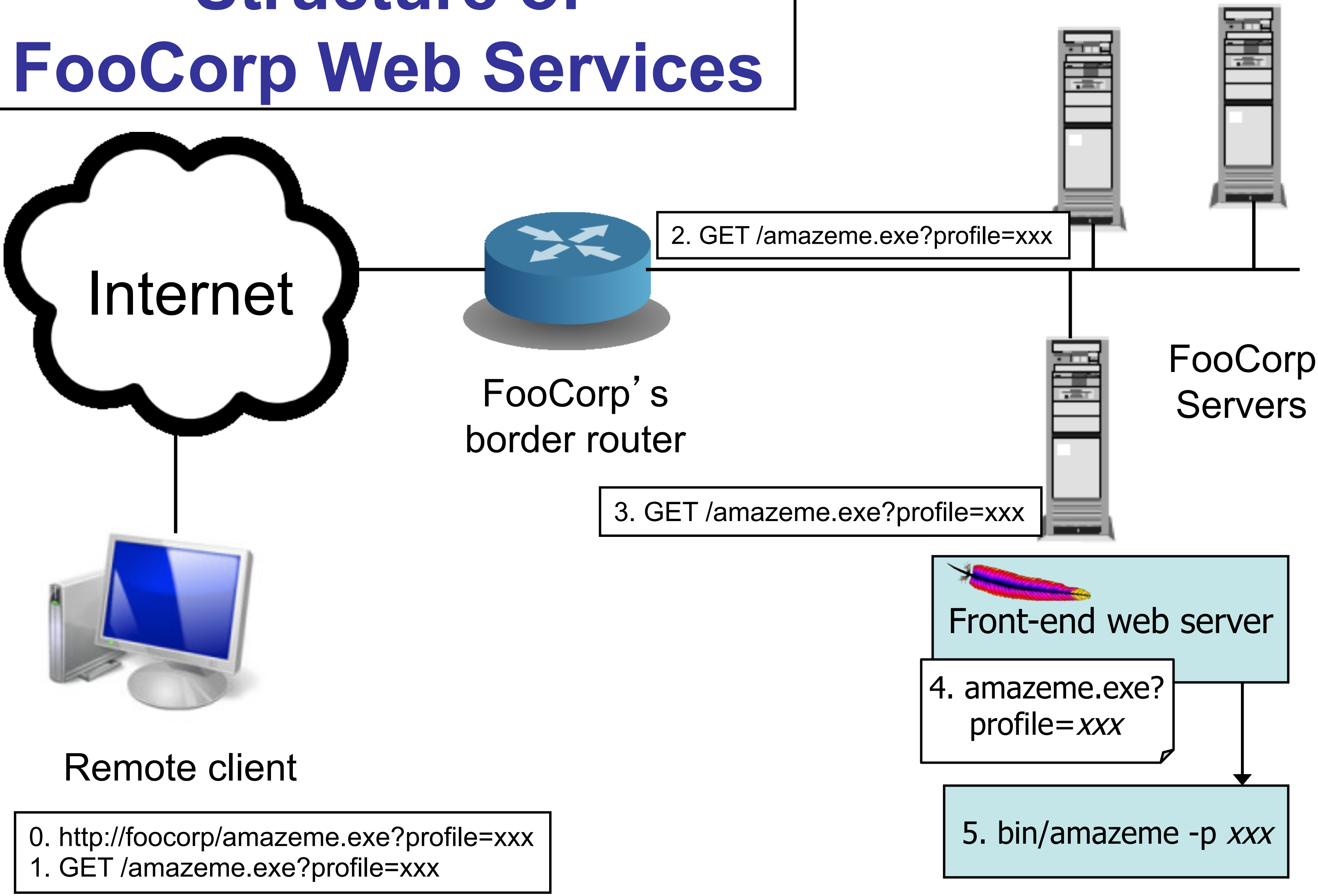
The Problem of Detecting Attacks

- Given a choice, we'd like our systems to be airtight-secure
- But often we don't have that choice
  - #1 reason why not: **cost** (in different dimensions)
- A (messy) alternative: detect misuse rather than build a system that can't be misused
  - Upon detection: clean up damage, maybe block incipient "*intrusion*"
  - Note: can be prudent for us to do this even if we think system is solid – defense in depth
  - Note: "misuse" might be about policy rather than security
    - Example: your own employees shouldn't be using file-sharing apps
- Problem space:
  - *Lacks principles*
  - Has many dimensions (where to monitor, how to look for problems, how much accuracy required, what can attackers due to elude us)
  - Is messy and in practice also very useful

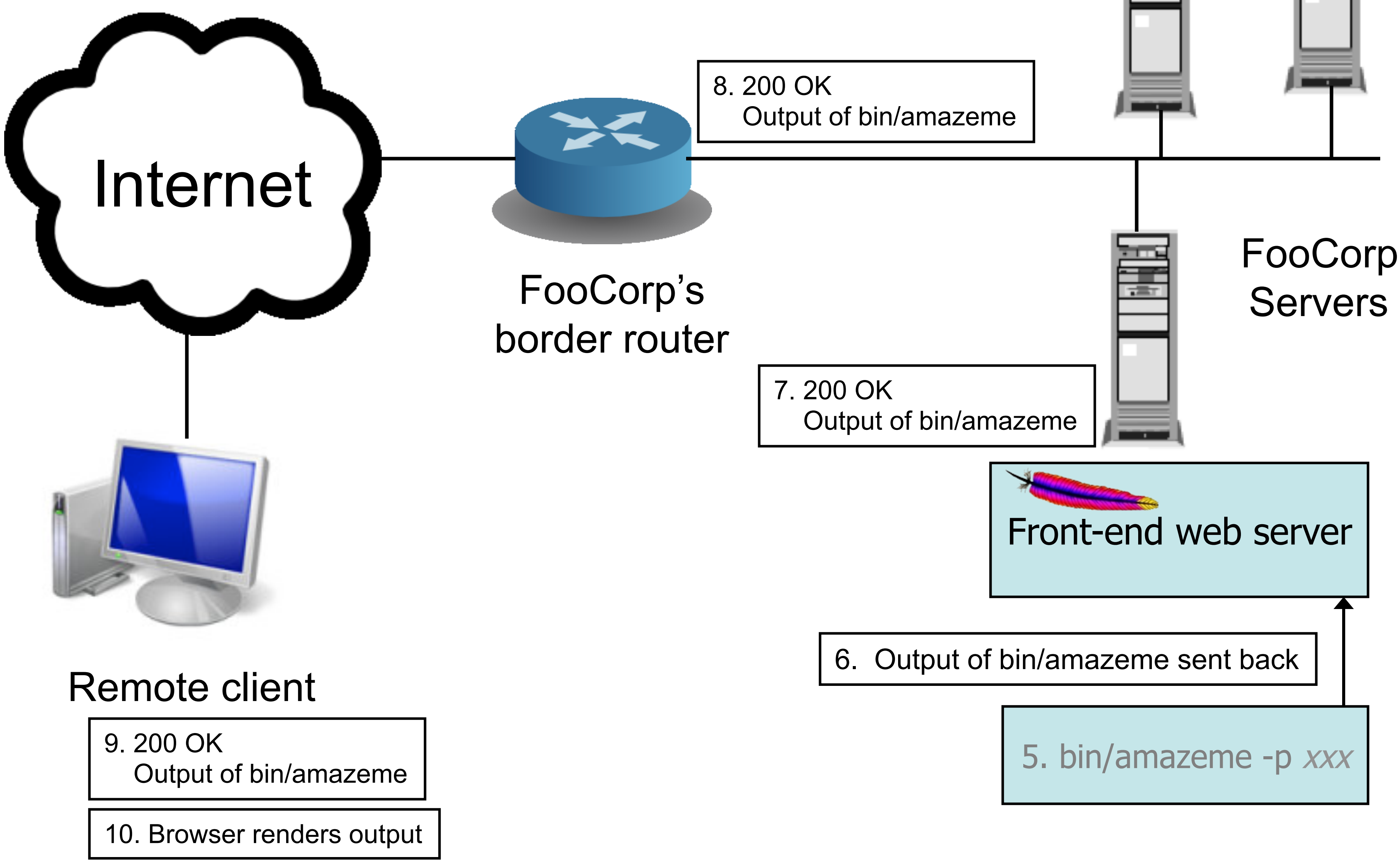
Example Scenario

- Suppose you've been hired to provide computer security for FooCorp. They offer web-based services via backend programs invoked via URLs:
  - http://foocorp.com/amazeme.exe?profile=info/luser.txt
  - Script makes sure that "profile" argument is a relative filename

Structure of FooCorp Web Services



Structure of FooCorp Web Services



Example Scenario

- Suppose you've been hired to provide computer security for FooCorp. They offer web-based services via backend programs invoked via URLs:
  - http://foocorp.com/amazeme.exe?profile=info/luser.txt
  - Script makes sure that "profile" argument is a relative filename
- Due to installed base issues, you can't alter backend components like `amazeme.exe`
- One of the zillion of attacks you're worried about is information leakage via *directory traversal*:
  - E.g. GET /amazeme.exe?profile=../../../../../etc/passwd

Problem with accessing the AmazeMe Foocorp service

Error parsing profile: ../../../../../etc/passwd
Can't find foreground/background color preferences in:

---

root:fo8bXK3L6xI:0:0:Administrator:/:/bin/sh
flash:pR.33HwJa2c:51:51:Flash User:/flash:/bin/false
nobody:*:99:99:Nobody:/:
jluser:lT9q23cjwVs:500:503:Jerome L. User:/home/jlusr:/bin/tcsh
hefalump:bKKdz92sk1b:501:503:Mr. Hef:/home/hef:/bin/bash
backdoor:9aBz331dDe1:0:0:Emergency Access:/:/bin/sh
ncsd:$1GnYOsA552:505:505:NSCD Daemon:/ncsd:/sbin/nologin

Please correct the profile entries and resubmit.

Thank you for using FooCorp.

Helpful error message returns contents of profile that appeared mis-formed, revealing the raw password file

Example Scenario

- Suppose you've been hired to provide computer security for FooCorp. They offer web-based services via backend programs invoked via URLs:
  - http://foocorp.com/amazeme.exe?profile=info/luser.txt
  - Script makes sure that "profile" argument is a relative filename
- Due to installed base issues, you can't alter backend components like `amazeme.exe`
- One of the zillion of attacks you're worried about is information leakage via *directory traversal*:
  - E.g. GET /amazeme.exe?profile=../../../../../etc/passwd
- What different approaches could detect this attack?

Extra Materials

Subverting Firewalls

- Along with possible bugs, packet filters have a fundamentally limited semantic model
  - They lack a full understanding of the meaning of the traffic they carry
    - In part because operate only at layers 3 & 4; not 7
- How can a local user who wants to get around their site's firewall exploit this?
  - (**Note**: we're not talking about how an external attacker can escape a firewall's restrictions)
- One method of subversion: **abuse ports**
  - Who says that e.g. port 22/tcp = SSH?
    - Why couldn't it be say Skype or BitTorrent?
    - Just requires that client & server agree on app protocol

Hiding on Other Ports

- Method #1: use port allocated to another service
  (how can this be detected?)
- Method #2: **tunneling**
  - Encapsulate one protocol inside another
  - Receiver of "outer" protocol *decapsulates* interior tunneled protocol to recover it
  - Pretty much <u>any</u> protocol can be tunneled over another (with enough effort)
- E.g., tunneling IP over SMTP
  - Just need a way to code an IP datagram as an email message (either mail body or just headers)

Example: Tunneling IP over Email

From: doesnt-matter@bogus.com
To: my-buddy@tunnel-decapsulators.R.us
Subject: Here's my IP datagram

IP-header-version: 4
IP-header-len: 5
IP-ID: 11234
IP-src: 1.2.3.4
IP-dst: 5.6.7.8
IP-payload: 0xa144bf2c0102…

This operator of this email server has chosen to *cooperate* with the email sender to help them tunnel

Remote email server receives this legal email, **builds** an IP packet corresponding to description in email body …
… and **injects** it into the network

How can a firewall detect this??

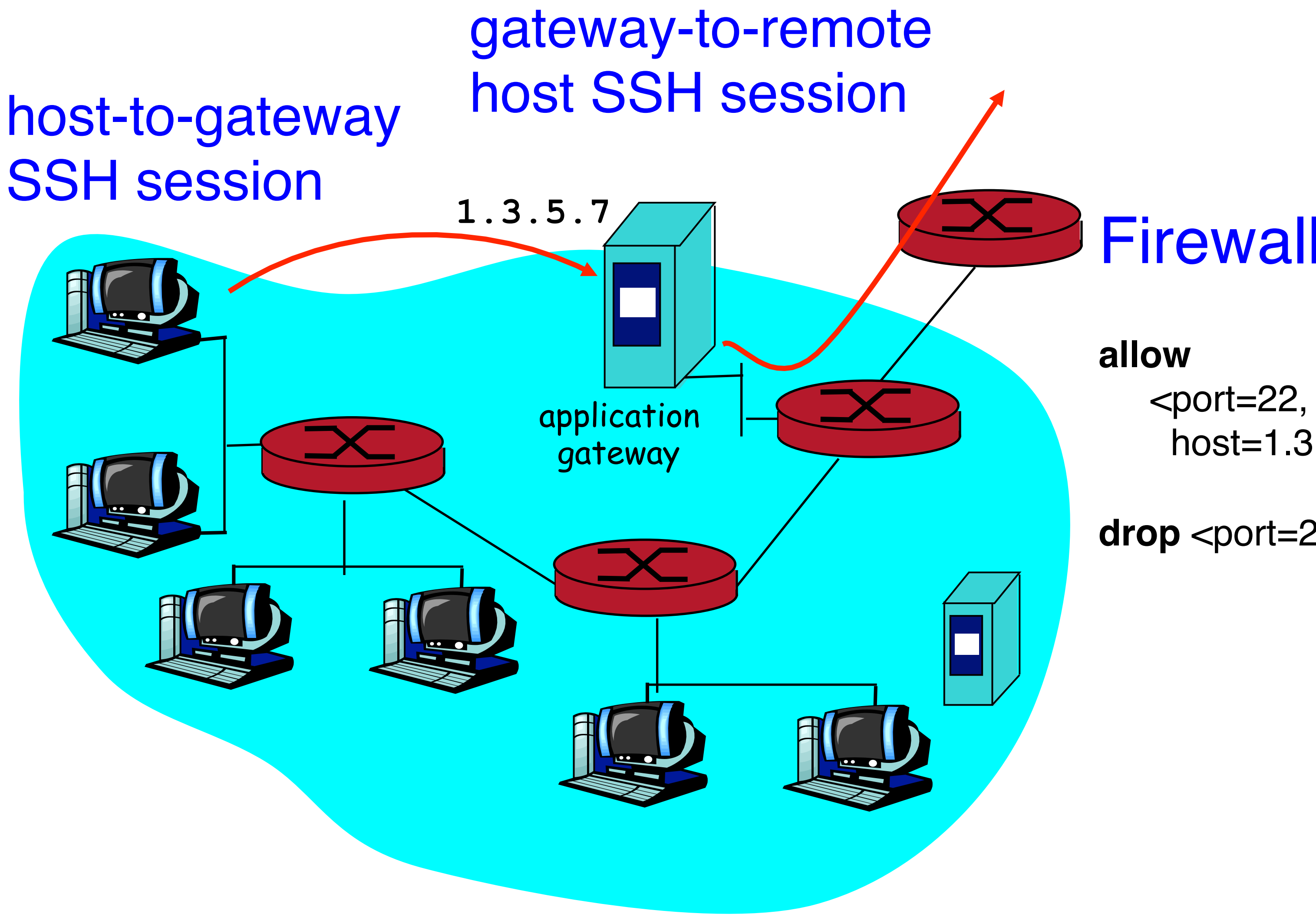
Tunneling, cont.

- E.g., IP-over-ICMP:
  - Embed IP datagram as the payload of a “ping” packet
- E.g., Skype-over-HTTP:
  - Encode Skype messages in URL of requests and header fields of replies
- Note #1: to tunnel, the sender and receiver must both cooperate (so it’s not useful for initial attacks)
- Note #2: tunneling has many legitimate uses too
  - E.g., Virtual Private Networks (VPNs)
    - Make a remote machine look like it’s local to its home network
    - Tunnel encrypts traffic for privacy & to prevent meddling

Application-level Firewall

- Can more directly control applications by requiring them to go through a proxy for external access
  - Proxy doesn't simply forward, but acts as an application-level middleman
- Example: SSH gateway
  - Require all SSH in/out of site to go through gateway
  - Gateway logs authentication, inspects decrypted text
  - Site's firewall configured to *prohibit any other* SSH access

SSH Gateway Example



allow
<port=22,
host=1.3.5.7>

drop <port=22>

Application-level Firewall

- Can more directly control applications by requiring them to go through a proxy for external access
  - Proxy doesn’t simply forward, but acts as an application-level middleman
- Example: SSH gateway
  - Require all SSH in/out of site to go through gateway
  - Gateway logs authentication, inspects decrypted text
  - Site’s firewall configured to prohibit any other SSH access
- Provides a powerful degree of monitoring/control
- Costs?
  - Need to run extra server(s) per app (possible *bottleneck*)
  - Each server requires careful hardening

FW Disadvantages, con't

- *"Malicious" applications*
  - Previous properties combine in a very nasty way: app protocol blocked by users' firewalls
- What to do?
  - Tunnel app's connections over HTTP or SMTP
  - Web is killer app, so most firewalls allow it
  - Now firewall can't distinguish real/app traffic
  - Insiders trusted ⇒ their apps trusted ⇒ firewall can't protect against malicious apps
  - More and more traffic goes over port 25/80/…
    - Firewalls have less visibility into traffic
    - Firewalls become less effective

Security Principle: *Reference Monitors*

- Firewalls embody useful principles that are applicable elsewhere in computer security
  - Optimized for enforcing particular kind of *access control policy*
  - Chokepoint notion makes enforcement possible
- A key conceptual approach to access control: *reference monitor*
  - Examines every request to access a controlled resource (an *object*) and determines whether to allow request

Reference Monitor Security Properties

- *Always invoked*
  - *Complete mediation* property: all security-relevant operations must be mediated by RM
  - RM should be invoked on every operation controlled by access control policy
- *Tamper-resistant*
  - Maintain RM integrity (no code/state tampering)
- *Verifiable*
  - Can verify RM operation (correctly enforces desired access control policy)
    - Requires extremely **simple** RM
    - We find we can't verify correctness for systems with any appreciable degree of complexity

Considering Firewalls as Reference Monitors

- Always invoked?
  - Place Packet Filter as an *in-path* element on chokepoint link for all internal-external communications
  - Packets only forwarded across link if firewall explicitly decides to do so after inspection

Potential Problems?

- What if a user hooks up an unsecured wireless access point to their internal machine?
- Anyone who drives by with wireless-enabled laptop can gain access to internal network
  - Bypasses packet filter!

- To use a firewall safely, must ensure we've covered all links between internal and external networks with firewalls
  - Set of links known as the ***security perimeter***

RM Property: *Tamper-Resistant*

- Will this hold?

- Do not allow management access to firewall other than from specific hosts
  - I.e., firewall itself needs firewalling
- Protect firewall's physical security
- Must also secure storage & propagation of configuration data

RM Property: *Verifiable*

- Will this hold?
- Current practice:
  - Packet filter software too complex for feasible systematic verification …
  - … and rulesets with 1,000s (!) of rules
- Result:
  - *Bugs* that allowed attackers to defeat intended security policy by sending unexpected packets that packet filter doesn't handle as desired

Stateless Packet Filters

- Basic kind of firewall: *stateless packet filter*
  - Router with list of *access control rules*
  - Router checks each received packet against security rules to decide to forward or drop it
  - Each rule specifies which packets it applies to based on a packet's header fields (stateless)
    - Specify source and destination IP addresses, port numbers, and protocol names, or wild cards
    - Each rule specifies the *action* for matching packets: **ALLOW** or **DROP** (aka DENY)

    <ACTION> <PROTO> <SRC:PORT> -> <DST:PORT>
  - First listed rule has *precedence*

Examples of Packet Filter Rules

```
allow tcp 4.5.5.4:1025 -> 3.1.1.2:80
```

- States that the firewall should **permit** any TCP packet that's:
  - from Internet address `4.5.5.4` **and**
  - using a source port of `1025` **and**
  - destined to port `80` of Internet address `3.1.1.2`

```
deny tcp 4.5.5.4:* -> 3.1.1.2:80
```

- States that the firewall should **drop** any TCP packet like the above, regardless of source port

Examples of Packet Filter Rules

```
deny tcp 4.5.5.4:* -> 3.1.1.2:80
allow tcp 4.5.5.4:1025 -> 3.1.1.2:80
```

- *In this order*, the rules won't allow *any* TCP packets from `4.5.5.4` to port `80` of `3.1.1.2`

```
allow tcp 4.5.5.4:1025 -> 3.1.1.2:80
deny tcp 4.5.5.4:* -> 3.1.1.2:80
```

- *In this order*, the rules allow TCP packets from `4.5.5.4` to port `80` of `3.1.1.2` ***only*** if they come from source port `1025`

Expressing Policy with *Rulesets*

- Goal: prevent *external access* to Windows SMB (TCP port 445)
  - Except for one special external host, `8.4.4.1`
- Ruleset:

```
allow tcp 8.4.4.1:* -> *:445
drop  tcp *:* -> *:445
allow  *   *:* -> *:*
```

- Problems?
  - No notion of inbound vs outbound connections
    - Drops outbound SMB connections from inside users
  - (This is a *default-allow* policy!)

Expressing Policy with Rulesets

- Want to allow:
  - Inbound mail connections to our mail server (`1.2.3.4:25`)
  - All outbound connections from our network, `1.2.3.0/24`
    - `1.2.3/24` = "any address for which the top 24 bits match `1.2.3.0`"
    - So it ranges from `1.2.3.0, 1.2.3.1, …, 1.2.3.255`
  - Nothing else
- Consider this ruleset:

```
allow tcp *:* -> 1.2.3.4:25
allow tcp 1.2.3.0/24:* -> *:*
drop   *  *:* -> *:*
```

- This policy doesn't work …
  - TCP connections are *bidirectional*
  - 3-way handshake: client sends `SYN`, receives `SYN+ACK`, sends `ACK`
    - Followed by either/both sides sending DATA (w/ `ACK` bit set)

Problem: Outbound Connections Fail

```
1.allow tcp *:* -> 1.2.3.4:25
2.allow tcp 1.2.3.0/24:* -> *:*
3.drop    *   *:* -> *:*
```

- Inside host opens TCP connection to port 80 on external machine:
  - Initial SYN packet passed through by rule 2
  - SYN+ACK packet coming back is dropped
    - *Fails* rule 1 (not destined for port 25)
    - *Fails* rule 2 (source not inside host)
    - Matches rule 3 $\Rightarrow$ **DROP**

Problem: Outbound Connections Fail

```
1.allow tcp *:* -> 1.2.3.4:25
2.allow tcp 1.2.3.0/24:* -> *:*
3.drop   *   *:* -> *:*
```

- Fix?
  - In general, we need to distinguish between 2 kinds of inbound packets
    - Allow inbound packets *associated with* an outbound connection
    - Restrict inbound packets *associated with* an inbound connection
  - How do we tell them apart?
    - Approach #1: remember previous outbound connections
      - Requires **state** :-(
    - Approach #2: leverage details of how TCP works …

Inbound vs. Outbound Connections

- Key TCP feature: ACK bit set on all packets except first
  - **Plus**: TCP receiver disregards packets with ACK set if they don't belong to an existing connection
- Solution ruleset:

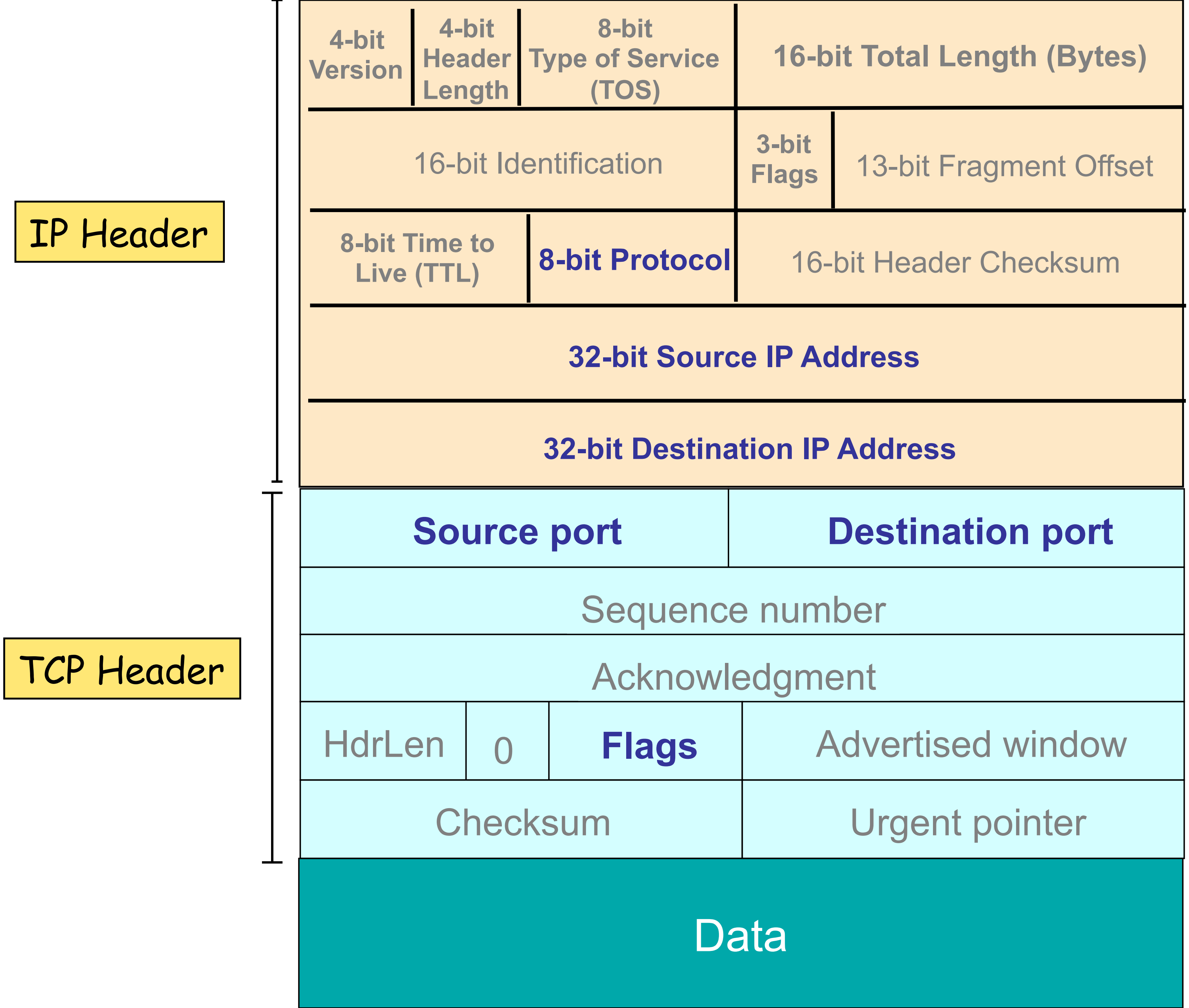
```
1.allow tcp *:* -> 1.2.3.4:25
2.allow tcp 1.2.3.0/24:* -> *:*
3.allow tcp *:* -> 1.2.3.0/24:* only if ACK bit set
4.drop   *  *:* -> *:*
```

  - Rules 1 and 2 allow traffic in either direction for inbound connections to port 25 on machine `1.2.3.4`
  - Rules 2 and 3 allow outbound connections to any port

How This Ruleset Protects

```
1.allow tcp *:* -> 1.2.3.4:25
2.allow tcp 1.2.3.0/24:* -> *:*
3.allow tcp *:* -> 1.2.3.0/24:* only if ACK bit set
4.drop   *   *:* -> *:*
```

- Suppose external attacker tries to exploit vulnerability in SMB (TCP port 445):
  = Attempts to open an inbound TCP connection to internal SMB server
- Attempt #1: Sends SYN packet to server
  - Packet lacks ACK bit ⇒ no match to Rules 1-3, dropped by Rule 4
- Attempt #2: Sends SYN+ACK packet to server
  - Firewall permits the packet due to Rule 3
  - But then **dropped** by server's TCP stack (since ACK bit set, but isn't part of existing connection)



IP Header
4-bit Version
4-bit Header Length
8-bit Type of Service (TOS)
16-bit Total Length (Bytes)
16-bit Identification
3-bit Flags
13-bit Fragment Offset
8-bit Time to Live (TTL)
8-bit Protocol
16-bit Header Checksum
32-bit Source IP Address
32-bit Destination IP Address
TCP Header
Source port
Destination port
Sequence number
Acknowledgment
HdrLen
0
Flags
Advertised window
Checksum
Urgent pointer
Data