Network Control

CS 161: Computer Security

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Network Control: Firewalls

- 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 that **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 1000s of hosts
    - Where in everyday experience do we see such chokepoints?

Selecting a Security Policy

- Effectiveness of firewall relies on deciding what policy it should implement:
  - 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***
- 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

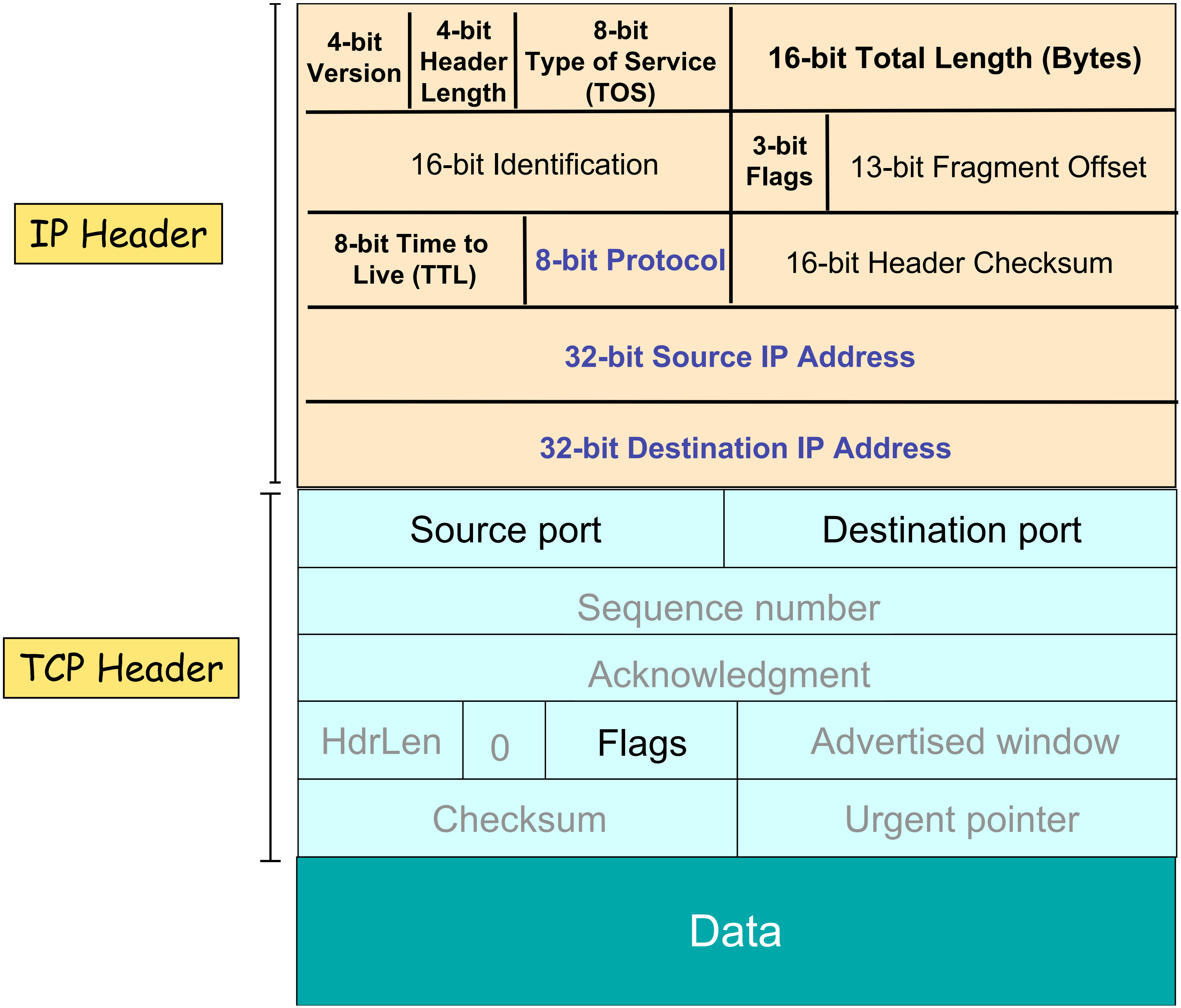
How To Treat Traffic Not Mentioned in Policy?

- **Default Allow**: start off permitting external access to services
  - Shut them off as problems recognized
- **Default Deny**: start 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
- (Which do you think UCB uses?)
  - Default Allow: institute's **mission** thrives on flexibility

In general, use Default Deny

Packet Filters

- Most basic kind of firewall is a *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


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

Packet Filters

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  - 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> -> <DEST: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, con't

- 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 ⇒ 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
      - takes **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)

5 Minute Break

Questions Before We Proceed?

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 1000s (!) of rules
- Result:
  - *Bugs* that allowed attackers to defeat intended security policy by sending unexpected packets that packet filter doesn't handle as desired

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 an attacker exploit this?
- 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 proto

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…

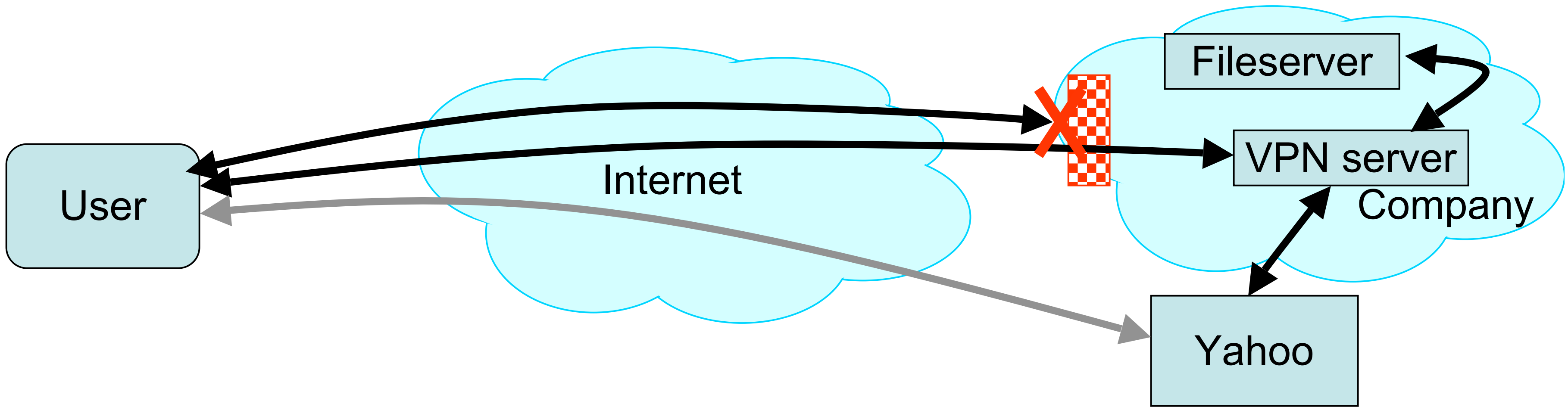
Program receives this legal email and **builds** an IP packet corresponding to description in email body …
… **injects** it into the network

How can a firewall detect this??

Tunneling, con't

- E.g., IP-over-ICMP:
  - Embed IP datagram as the payload of a "ping" packet
- E.g., Skype-over-HTTP:
  - Encode Skype message in URL of requests and header fields of replies
- Note #1: to tunnel, the sender and receiver must both cooperate
- Note #2: tunneling has many legitimate uses too
  - E.g., *overlay* networks that forward packets along paths different from what direct routing would pick
  - 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

Secure External Access to Inside Machines



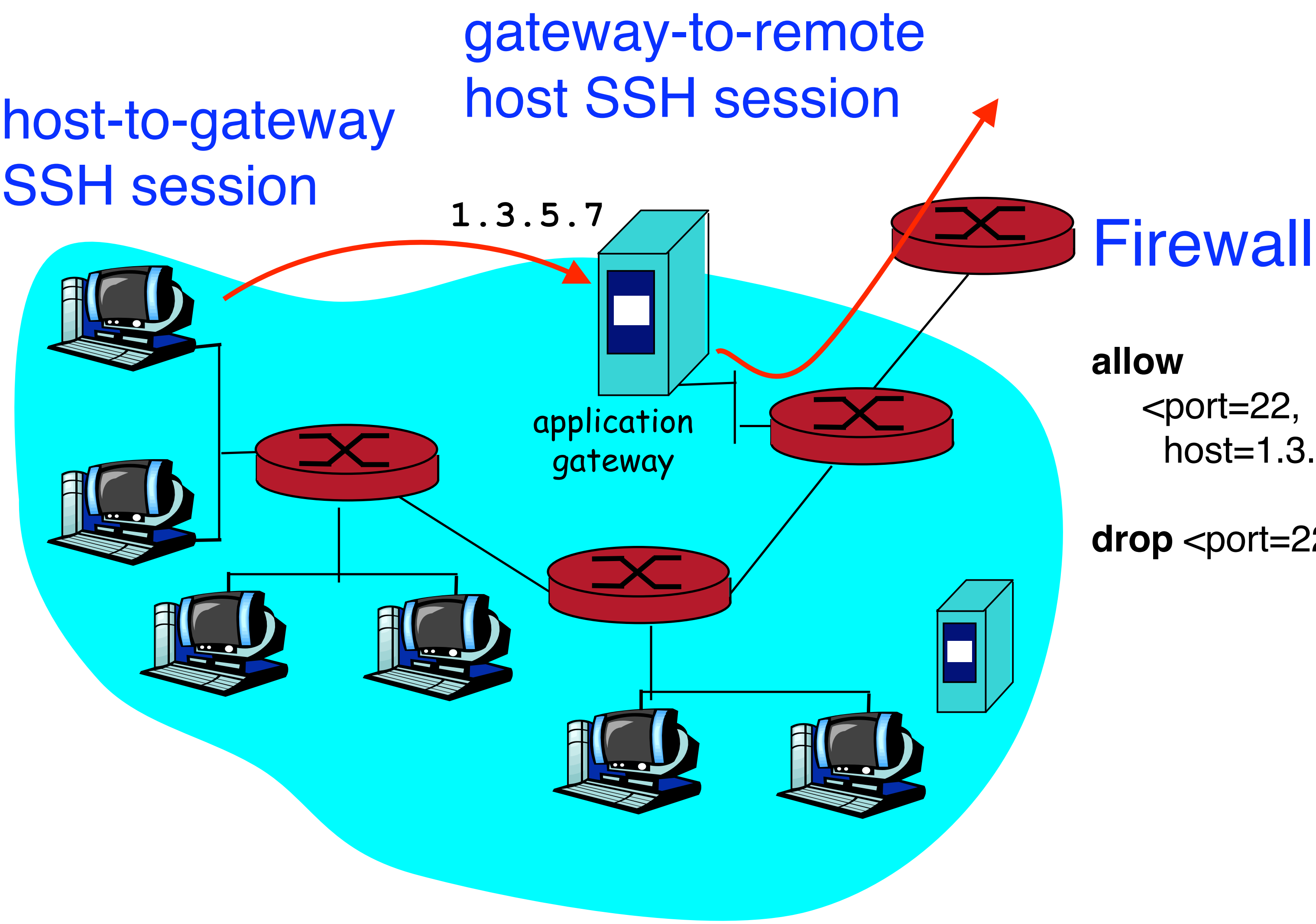
- Often need to provide secure remote access to a network protected by a firewall
  - Remote access, telecommuting, branch offices, …
- Create secure channel (*Virtual Private Network*, or VPN) to tunnel traffic from outside host/network to inside network
  - Provides Authentication, Confidentiality,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

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

Application Proxies

- 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 Proxies

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  - 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

Experience with Firewalls

- Firewalls have been very widely used
  - Success story: R&D to industry tech transfer
    - First paper published at 1990 conference
    - Checkpoint firewall vendor founded in 1993, largest fw market share, >$500M/yr revenue
- Why do They Work Well?
  - *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 1,000's
  - *Addresses an important problem*
    - Security vulnerabilities in network services are rampant
    - Easier to use firewall than to directly secure code …

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
    - Defeats physical and network security
  - Firewalls establish *security perimeter*
    - Like *Eskimo Pies*: "hard crunchy exterior, soft creamy center"
    - Threat from travelers with laptop …

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 $\Rightarrow$ their apps trusted $\Rightarrow$ 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

Other Kinds of Firewalls

- Packet filters are quite crude firewalls
  - Network level using TCP, UDP, and IP headers
- Alternative: examine data field contents
  - Application-layer firewalls (application firewalls)
    - Can enforce more restrictive security policies and transform data on the fly
- For more information on firewalls, read:
  - Cheswick, Bellovin, and Rubin: *Firewalls and Internet Security: Repelling the Wily Hacker*.