Network Control: Firewalls

CS 161: Computer Security

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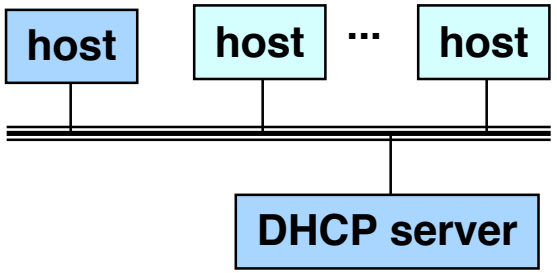
February 14, 2013

Game Plan

- Network Attacks:
  - DHCP: protocol for *bootstrapping* Internet access
- Firewalls: Controlling networks
  - (on the cheap!)
- Users/applications subverting (sneaking around) firewalls
  - (as time permits)

Internet Bootstrapping: DHCP

- New host doesn't have an IP address yet
  - So, host doesn't know what source address to use
- Host doesn't know *who to ask* for an IP address
  - So, host doesn't know what destination address to use
- Solution: *shout* to "**discover**" server that can help
  - Broadcast a server-discovery message (layer 2)
  - Server(s) sends a reply offering an address



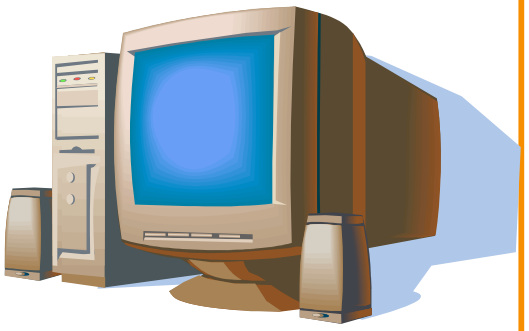
DHCP = Dynamic Host Configuration Protocol

Dynamic Host Configuration Protocol

new client

DHCP discover (broadcast)

DHCP offer



DHCP server

"**offer**" message includes IP address, DNS server, "gateway router", and how long client can have these ("lease" time)

DNS server = system used by client to map hostnames like `gmail.com` to IP addresses like `74.125.224.149`

Gateway router = router that client uses as the first hop for all of its Internet traffic to remote hosts

Dynamic Host Configuration Protocol

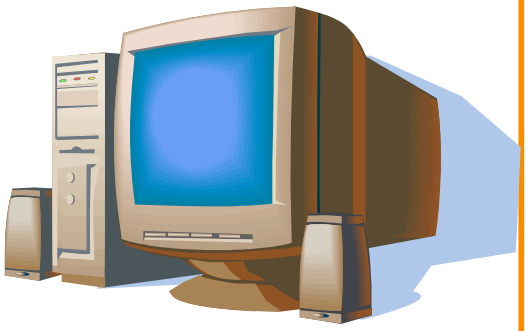
new client

DHCP discover (broadcast)

DHCP offer

DHCP request (broadcast)

DHCP ACK



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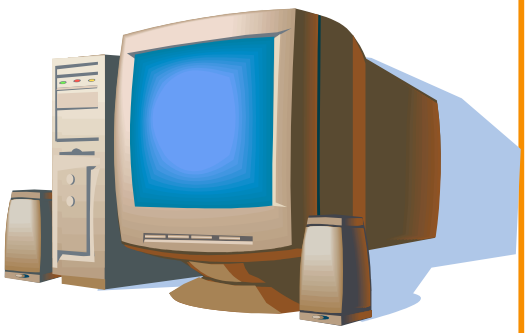

DHCP server

"**offer**" message includes IP address, DNS server, "gateway router", and how long client can have these ("lease" time)

Threats?

Dynamic Host Configuration Protocol

new client

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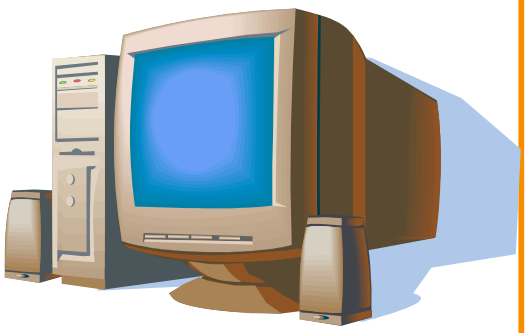

DHCP server

DHCP offer

DHCP request (broadcast)

DHCP ACK

Local attacker on same subnet can **hear** new host's DHCP request

"**offer**" message includes IP address, DNS server, "gateway router", and how long client can have these ("lease" time)

Dynamic Host Configuration Protocol

new client

DHCP discover (broadcast)

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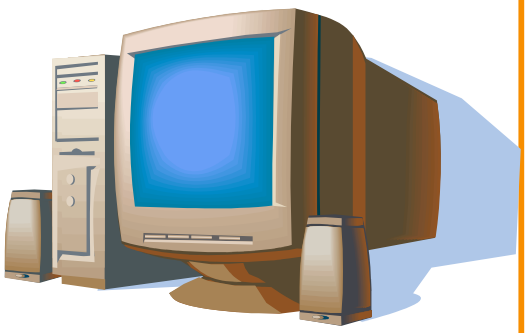


DHCP server

"**offer**" message includes IP address, DNS server, "gateway router", and how long client can have these ("lease" time)

Attacker can **race** the actual server; if attacker wins, replaces DNS server and/or gateway router

DHCP Threats

- Substitute a fake DNS server
  - Redirect any of a host's lookups to a machine of attacker's choice (e.g., `gmail.com` = `6.6.6.6`)
- Substitute a fake gateway router
  - Intercept all of a host's off-subnet traffic
    - (even if not preceded by a DNS lookup)
  - Relay contents back and forth between host and remote server
    - Modify however attacker chooses
  - This is one type of invisible ***Man In The Middle*** (MITM)
    - Victim host generally has no way of knowing it's happening! :-(
    - (Can't necessarily alarm on peculiarity of receiving multiple DHCP replies, since that can happen benignly)
- How can we fix this? ***Hard***

Summary: DHCP Security Issues

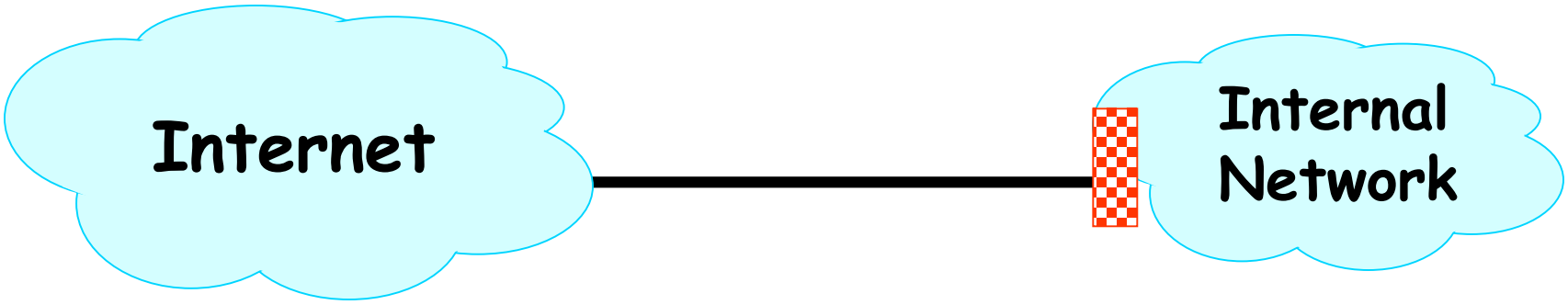
- DHCP threats highlight:
  - Broadcast protocols inherently at risk of **local** attacker spoofing
    - Attacker knows exactly when to try it …
    - … and can see the victim's messages
  - When initializing, systems are particularly vulnerable because they can *lack a trusted foundation* to build upon
  - Tension between wiring in trust vs. flexibility and convenience
  - MITM attacks **insidious** because no indicators they're occurring

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 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

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

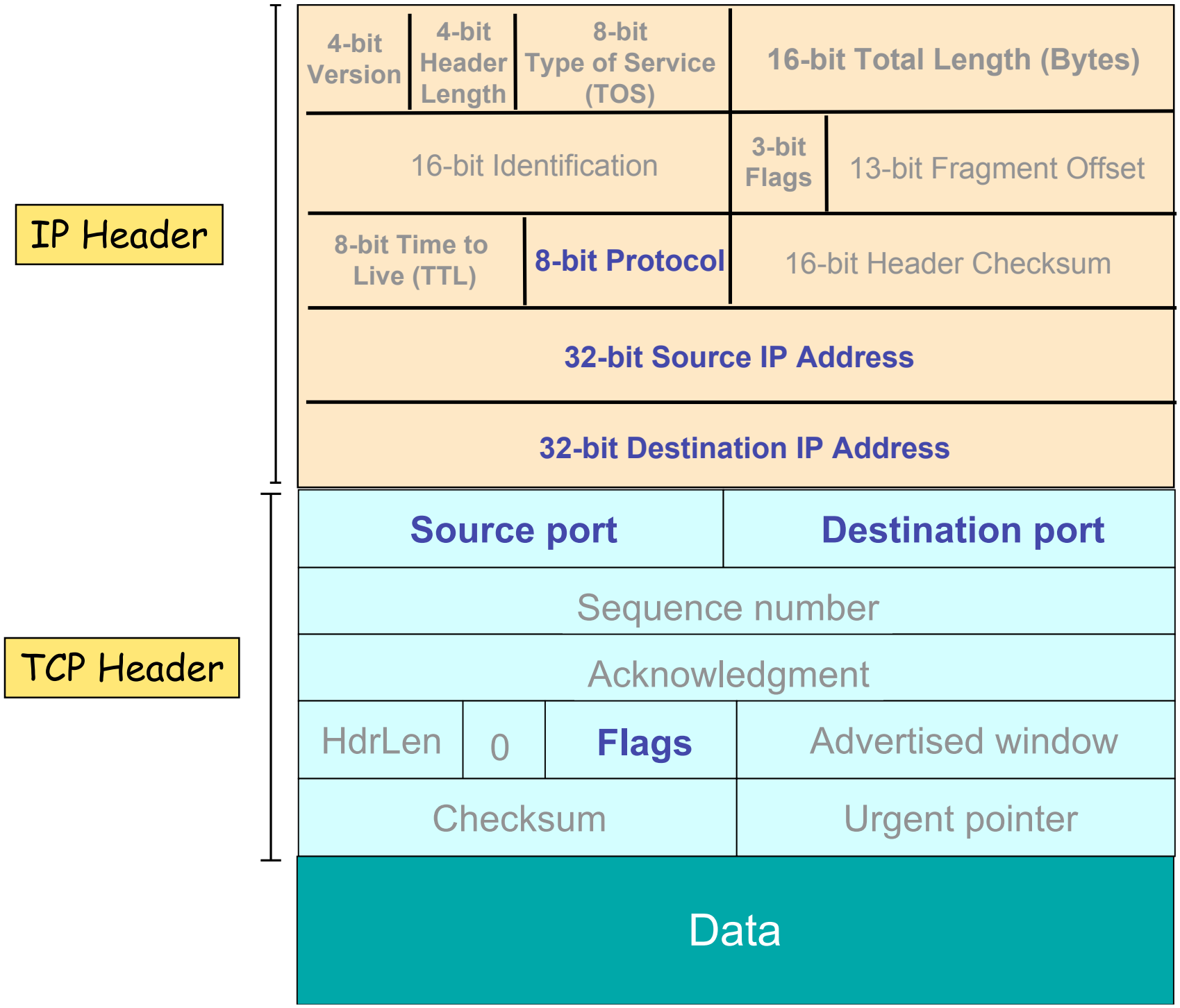
How To Treat Traffic Not Mentioned in Policy?

- **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

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 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`

5 Minute Break

Questions Before We Proceed?

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
      - 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)

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 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 any 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

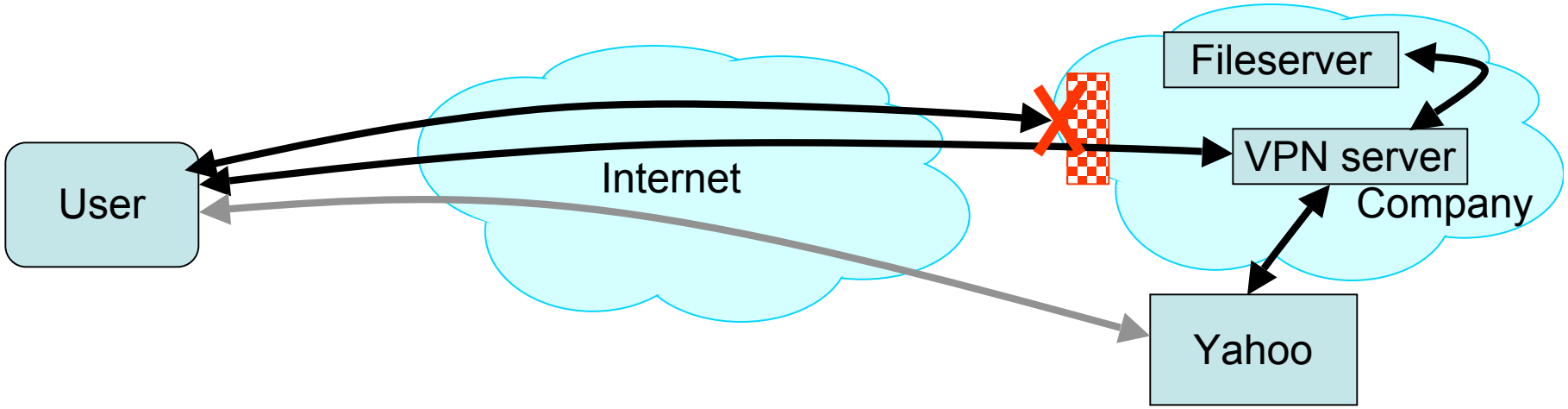
Remote email server receives this legal email, **builds** an IP packet corresponding to description in email body …
… and **injects** it into the network

How can a firewall detect this??

Tunneling, con't

- 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

Secure External Access to Inside Machines



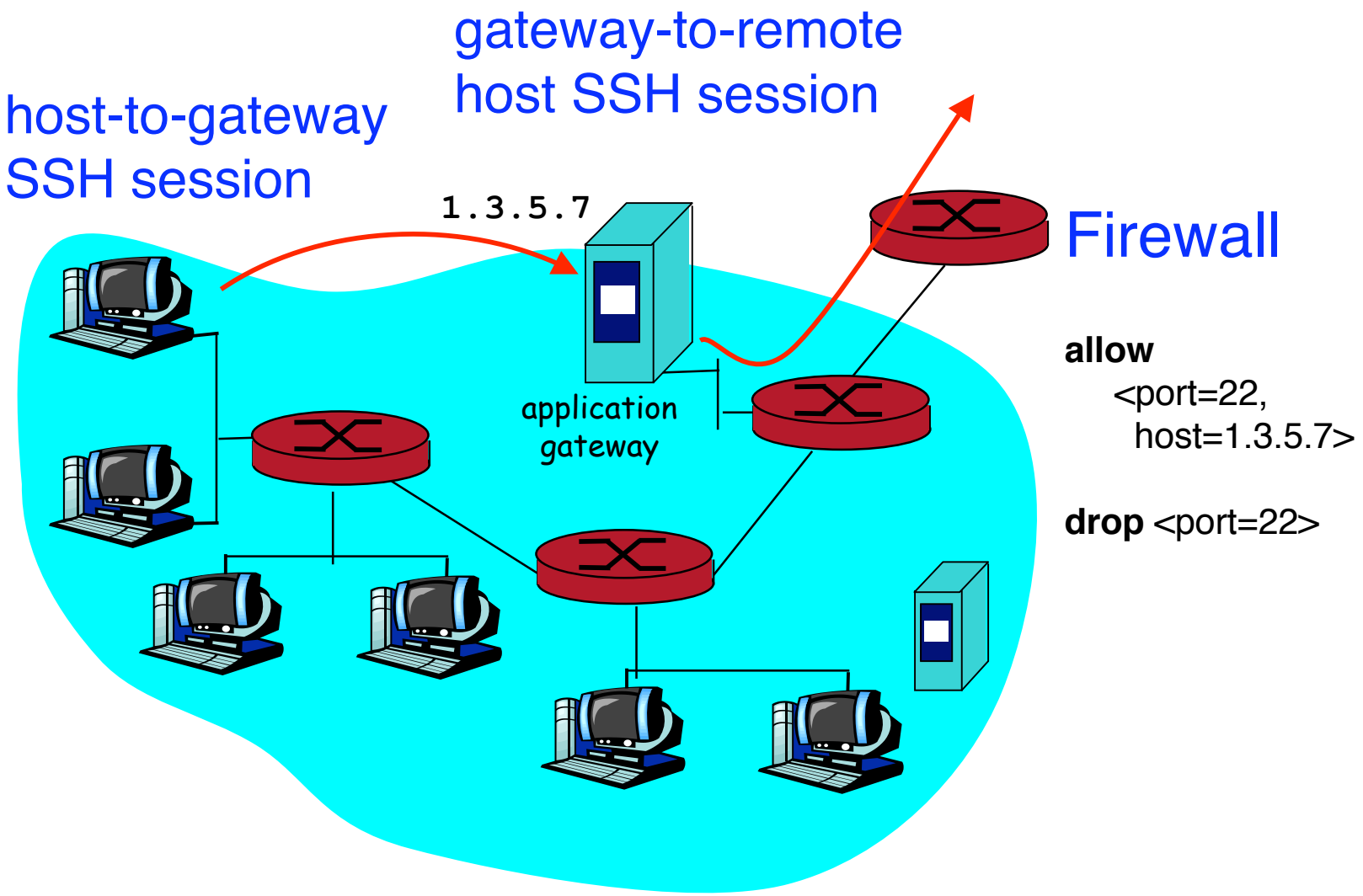
- Often need to provide secure remote access to a network protected by a firewall
  - Remote access, telecommuting, branch offices, …
- Create secure channel (*Virtual Private Network*, or **VPN**) to tunnel traffic from outside host/network to inside network
  - Provides Authentication, Confidentiality,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



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- 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

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 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
- Firewalls establish a *security perimeter*
  - Like *Eskimo Pies*: "hard crunchy exterior, soft creamy center"
  - Threat from travelers with laptops, cell phones, …