Network Security I: Overview

April 13, 2015

Lecture by: Kevin Chen

Slides credit: Vern Paxson, Dawn Song

network security

Today's Lecture

- Networking overview + security issues

Keep in mind, networking is:

- Complex topic with many facets
  - We will omit concepts/details that are not very security-relevant
  - We'll mainly look at IP, TCP, DNS and DHCP
- Networking is full of abstractions
  - Goal is for you to develop apt *mental models* / analogies
  - ASK questions when things are unclear
    - (but we may skip if not ultimately relevant for security, or postpone if question itself is directly about security)

Networking Overview

Key Concept #1: *Protocols*

- A protocol is an agreement on how to communicate
- Includes syntax and semantics
  - How a communication is specified & structured
    - Format, order messages are sent and received
  - What a communication means
    - Actions taken when transmitting, receiving, or timer expires
- E.g.: asking a question in lecture?
  1. Raise your hand.
  2. Wait to be called on.
  3. Or: wait for speaker to **pause** and vocalize
  4. If unrecognized (after timeout): vocalize w/ “excuse me”

Example: IP Packet *Header*

<table>
<tr><td>4-bit Version</td><td>4-bit Header Length</td><td>8-bit Type of Service (TOS)</td><td colspan="2">16-bit Total Length (Bytes)</td></tr>
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<tr><td colspan="5">Payload</td></tr>
</table>

Header is like a letter envelope: contains all info needed for delivery

IP = Internet Protocol

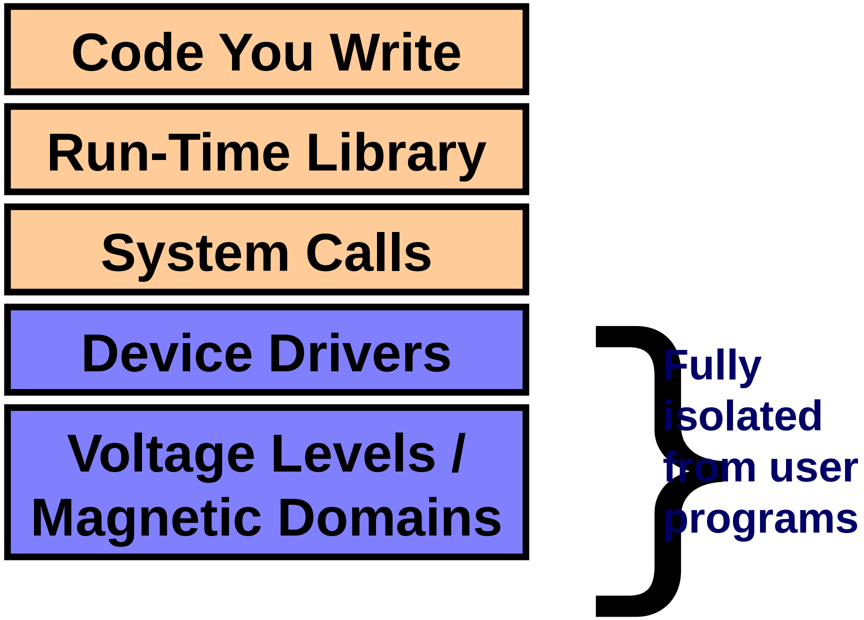
Key Concept #2: *Dumb Network*

- Original Internet design: interior nodes ("routers") have no knowledge* of ongoing connections going through them
- **Not**: how you picture the telephone system works
  - Which internally tracks all of the active voice calls
- Instead: the postal system!
  - Each Internet message ("packet") self-contained
  - Interior "routers" look at destination address to forward
  - If you want smarts, build it "end-to-end"
  - Buys simplicity & robustness at the cost of shifting complexity into end systems

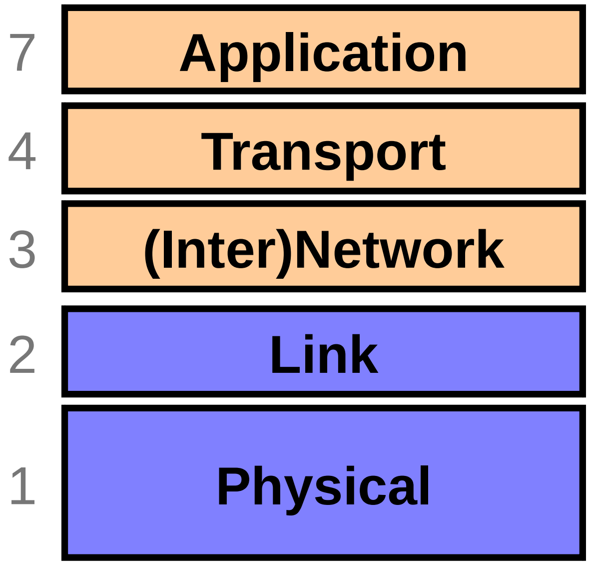
* Today's Internet is full of hacks that violate this

Key Concept #3: *Layering*

- Internet design is strongly partitioned into layers
  - Each layer relies on services provided by next layer below …
  - … and provides services to layer above it
- Analogy:
  - Consider structure of an application you've written and the "services" each layer relies on / provides



Internet Layering (“Protocol Stack”)



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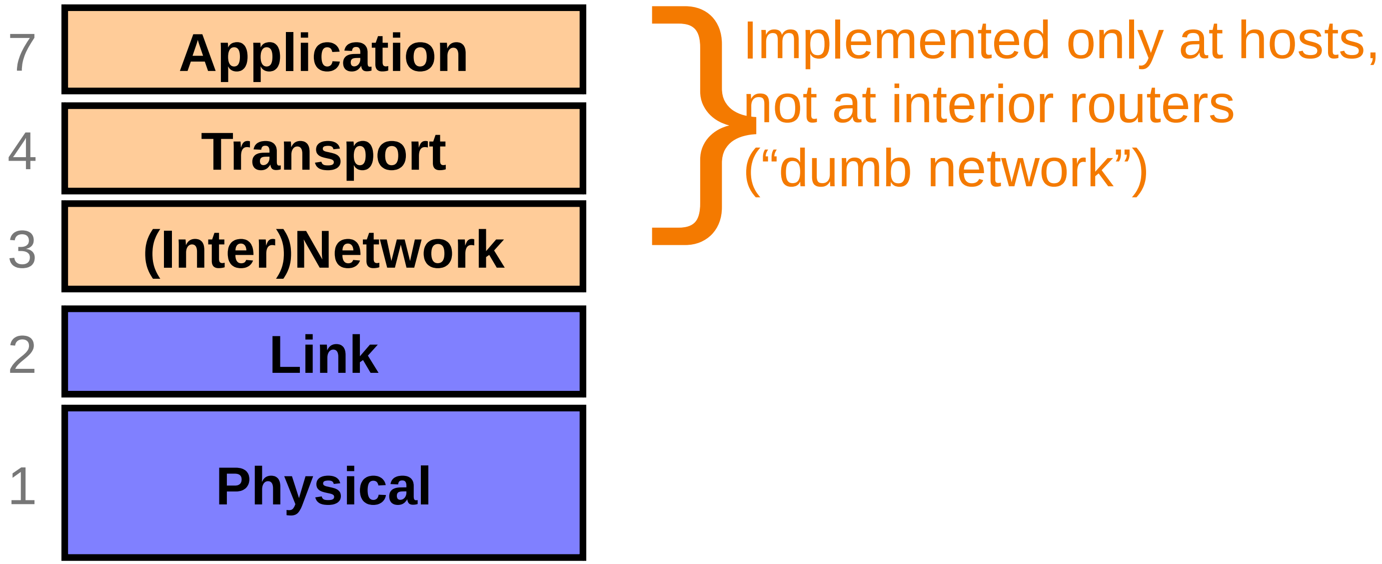

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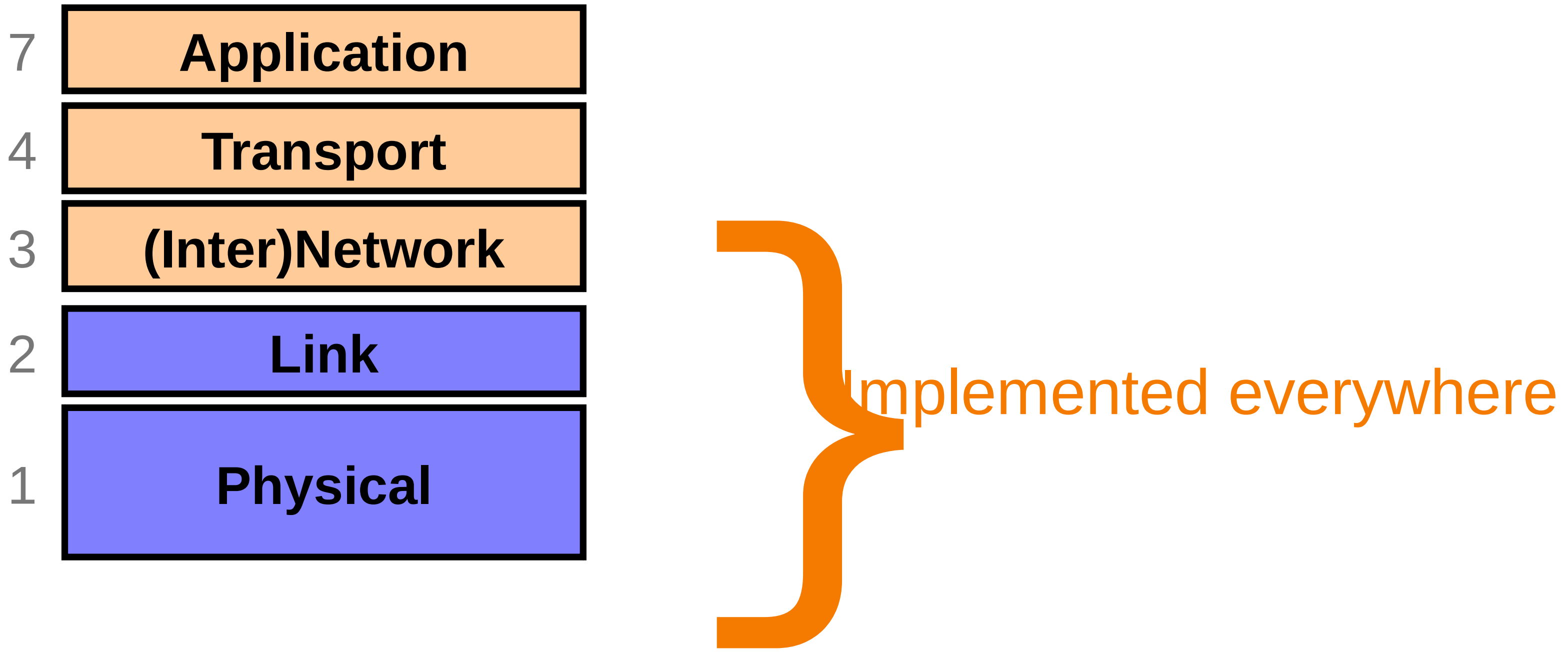

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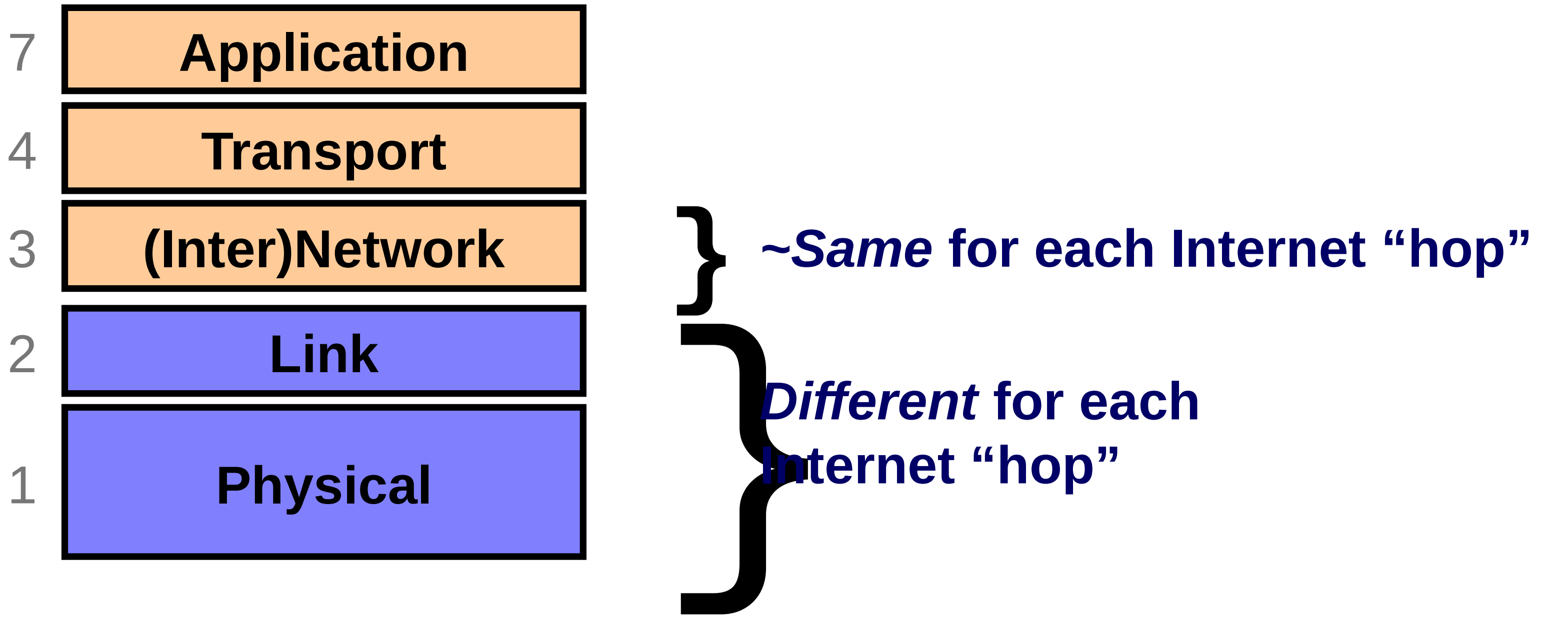
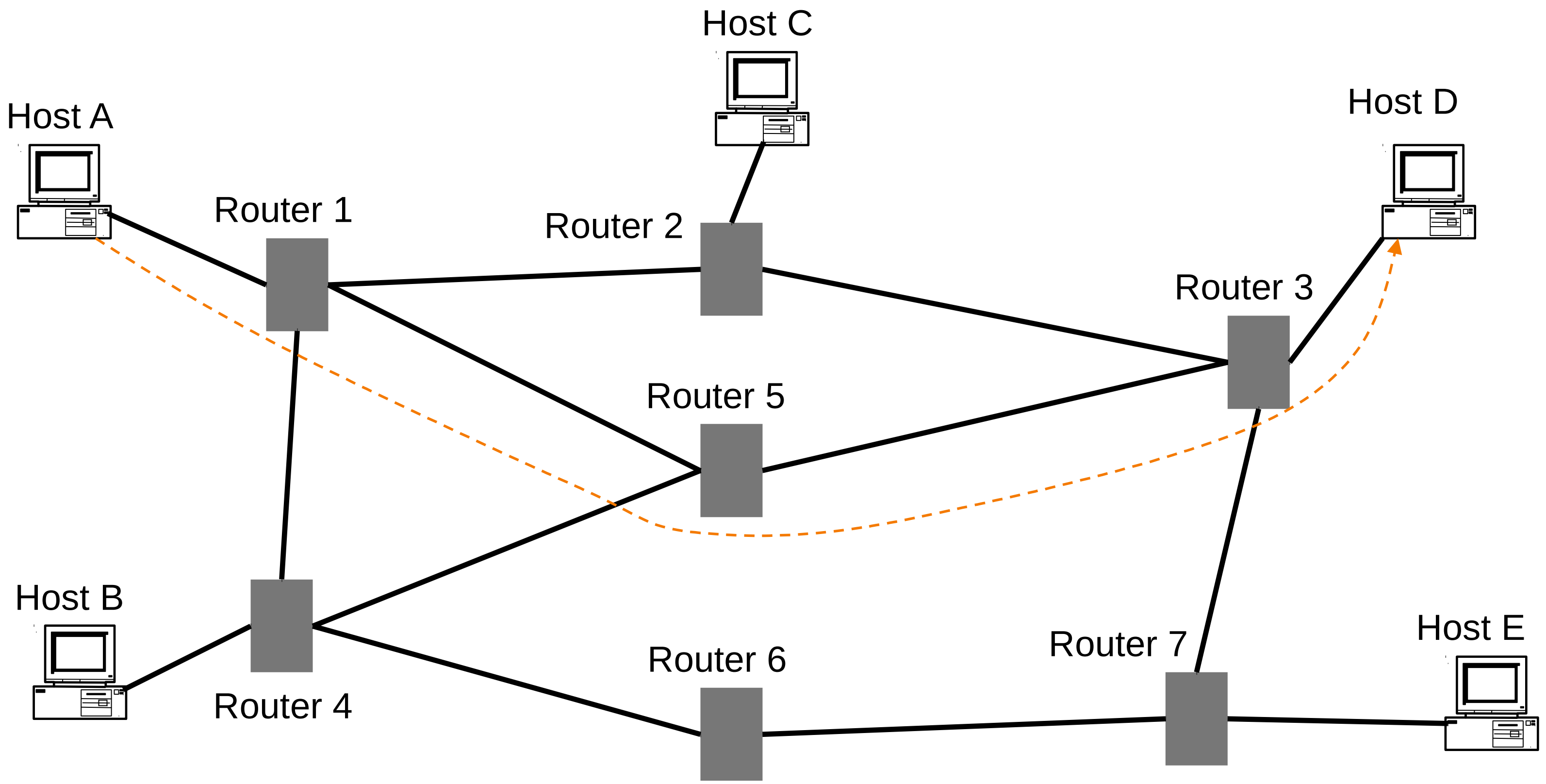


Hop-By-Hop vs. End-to-End Layers

Host A communicates with Host D



Hop-By-Hop vs. End-to-End Layers

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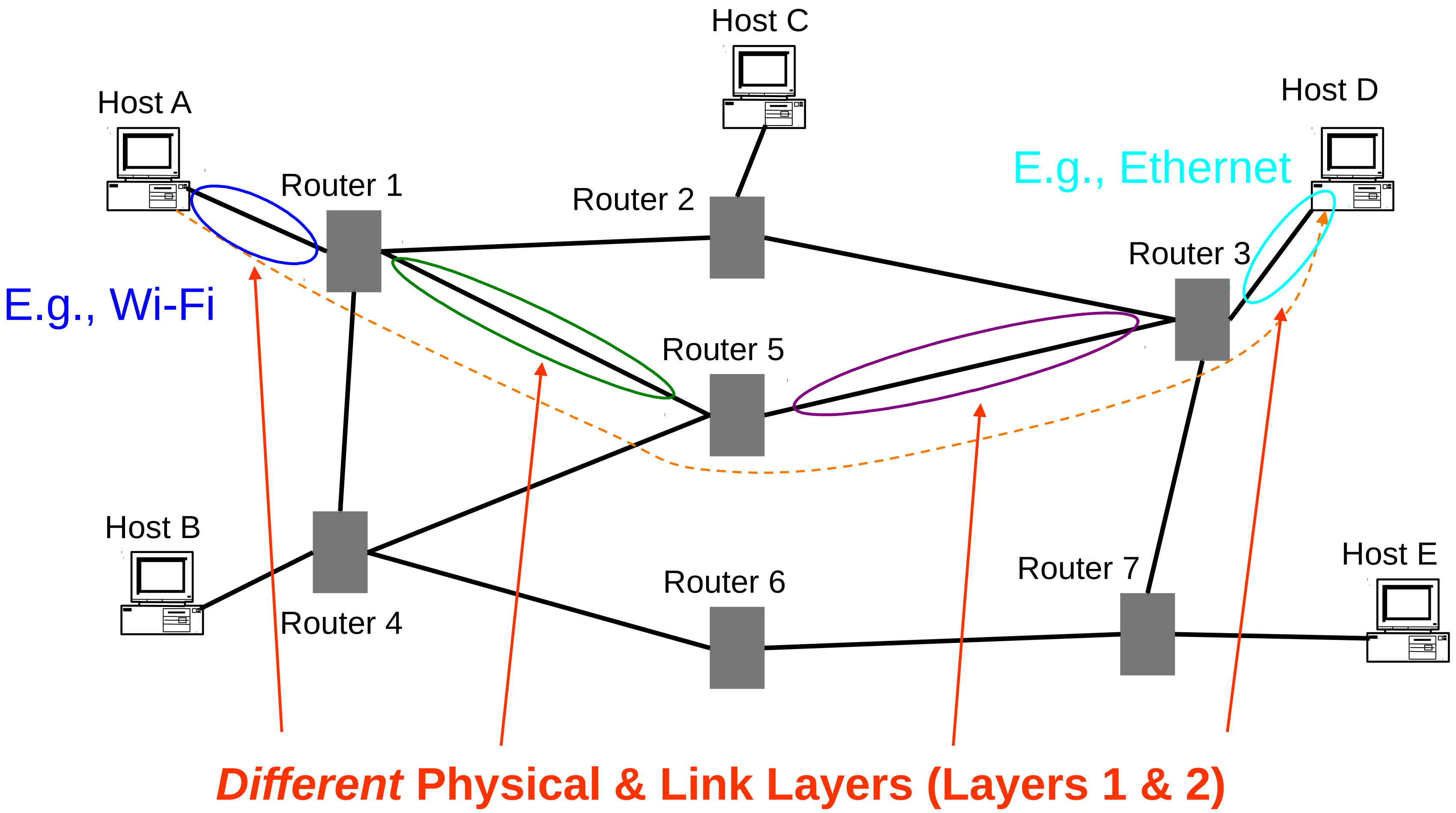

Hop-By-Hop vs. End-to-End Layers

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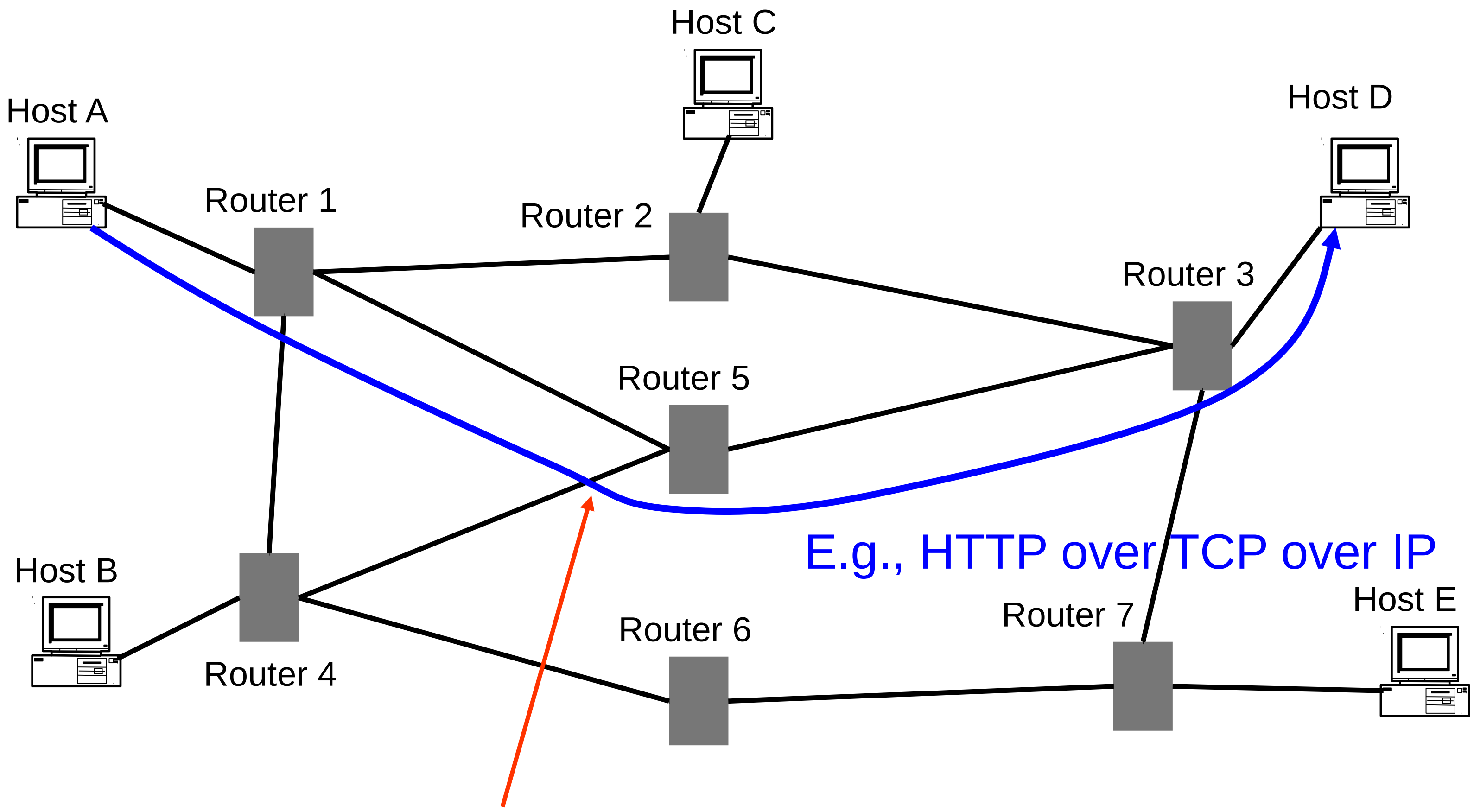


Same Network / Transport / Application Layers (3/4/7)
(Routers **ignore** Transport & Application layers)

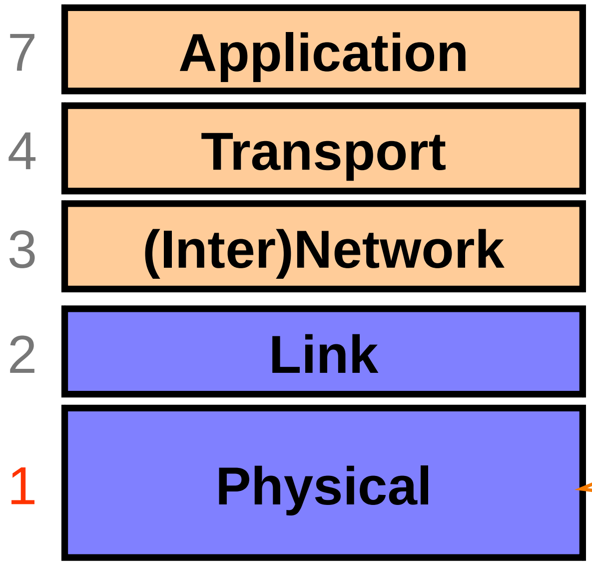
Security Issues

Review: General Security Goals: CIA

- Confidentiality:
  - No one can read our data / communication unless we want them to
- Integrity
  - No one can manipulate our data / processing / communication unless we want them to
- Availability
  - We can access our data / conduct our processing / use our communication capabilities when we want to
- Also: no additional traffic other than ours ...

Layer 1,2

Layer 1: Physical Layer

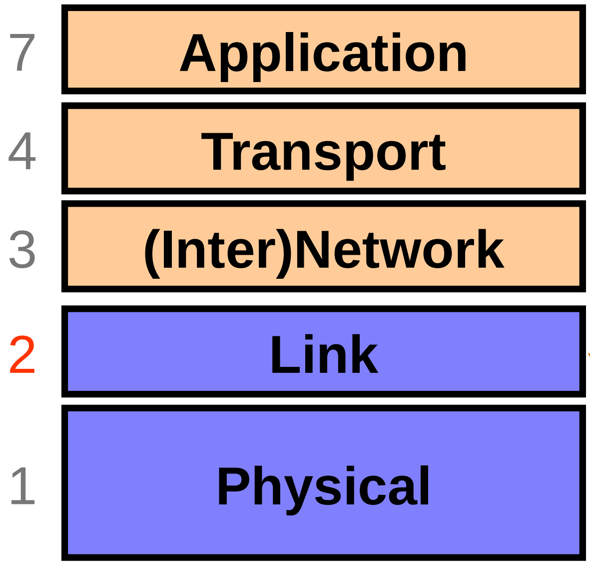


Encoding bits to send them over a <u>single</u> **physical link**

e.g. patterns of

voltage levels /
photon intensities /
RF modulation

Layer 2: Link Layer



Framing and transmission of a collection of bits into individual messages sent across a single "subnetwork" (one physical technology)

Might involve multiple *physical links* (e.g., modern Ethernet)

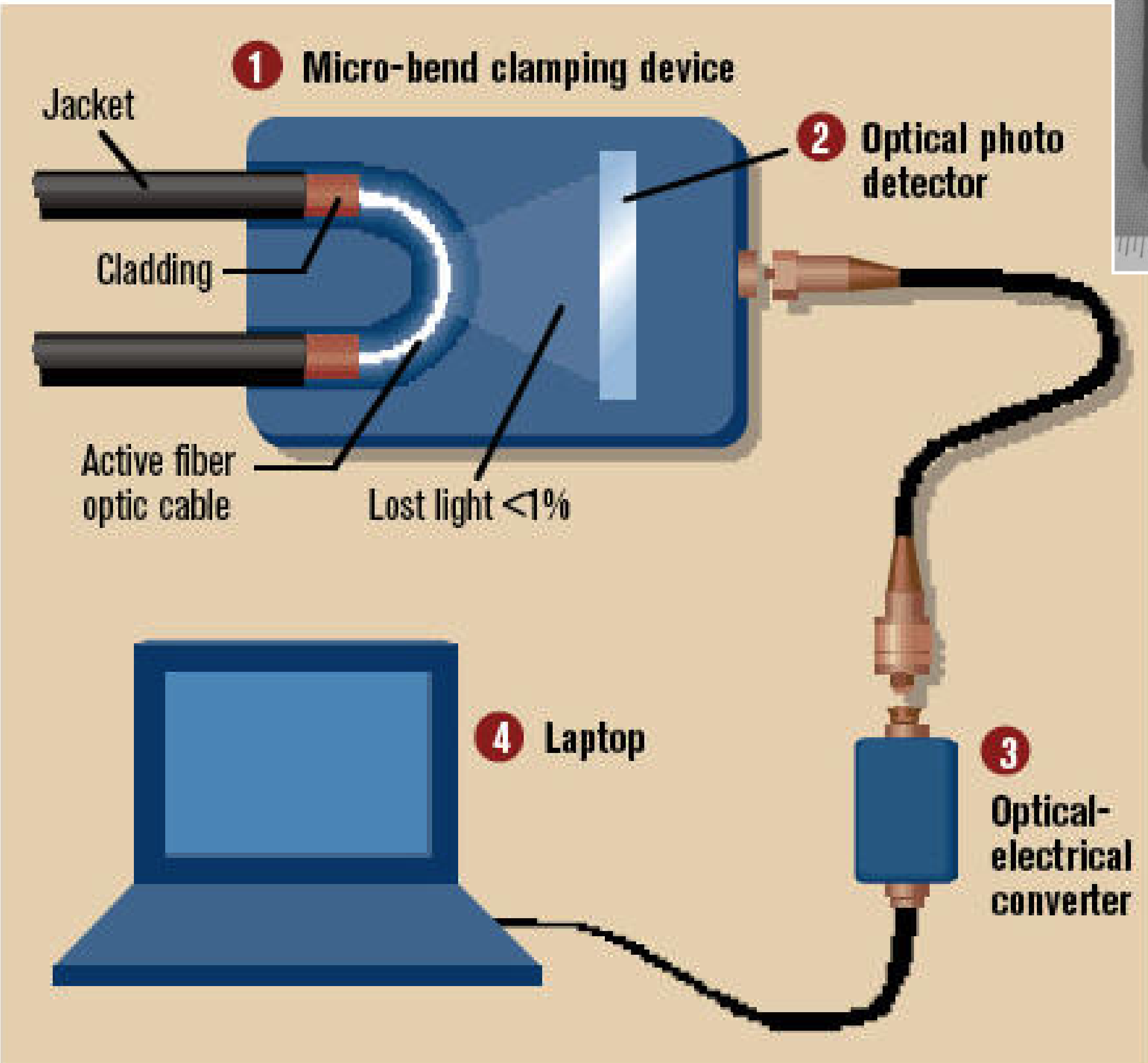
Often technology supports broadcast transmission (**every** "node" connected to subnet receives)

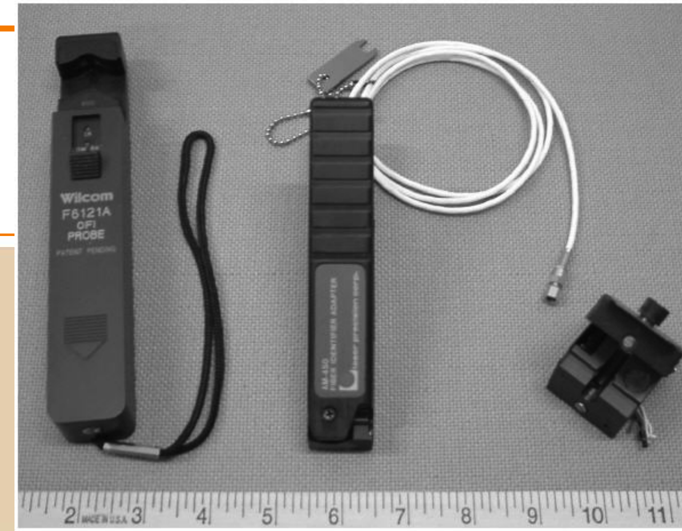
Layer 1,2 Threats

Physical/Link-Layer Threats: *Eavesdropping*

- For subnets using broadcast technologies (e.g., WiFi, some types of Ethernet), get it for "free"
  - Each attached system 's NIC (= Network Interface Card) can capture any communication on the subnet
  - Some handy tools for doing so
    - Wireshark (GUI for displaying 800+ protocols)
    - tcpdump / windump (low-level ASCII printout)
- For any technology, routers (and internal "switches") can look at / export traffic they forward
- You can also "tap" a link
  - Insert a device to mirror physical signal
  - Or: just steal it!

Stealing Photons





Operation Ivy Bells

By Matthew Carle
Military.com

The Regulus guided missile submarine, USS Halibut (SSN 587) which carried out Operation Ivy Bells.

At the beginning of the 1970's, divers from the specially-equipped submarine, USS Halibut (SSN 587), left their decompression chamber to start a bold and dangerous mission, code named "Ivy Bells".

In an effort to alter the balance of Cold War, these men scoured the ocean floor for a five-inch diameter cable carry secret Soviet communications between military bases.

The divers found the cable and installed a 20-foot long listening device on the cable. designed to attach to the cable without piercing the casing, the device recorded all communications that occurred. If the cable malfunctioned and the Soviets raised it for repair, the bug, by design, would fall to the bottom of the ocean. Each month Navy divers retrieved the recordings and installed a new set of tapes.

Upon their return to the United States, intelligence agents from the NSA analyzed the recordings and tried to decipher any encrypted information. The Soviets apparently were confident in the security of their communications lines, as a surprising amount of sensitive information traveled through the lines without encryption.

prison. The original tap that was discovered by the Soviets is now on exhibit at the KGB museum in Moscow.

Physical/Link-Layer Threats: *Disruption*

- With physical access to a subnetwork, attacker can
  - Overwhelm its signaling
    - E.g., jam WiFi's RF
  - Send messages that violate the Layer-2 protocol's rules
    - E.g., send messages > maximum allowed size, sever timing synchronization, ignore fairness rules
- Routers & switches can simply "drop" traffic
- There's also the heavy-handed approach …

Sabotage attacks knock out phone service

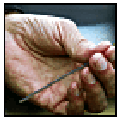
Nanette Asimov, Ryan Kim,Kevin Fagan, Chronicle Staff Writers
Friday, April 10, 2009

PRINT E-MAIL SHARE COMMENTS (477) FONT | SIZE: – +

(04-10) 04:00 PDT SAN JOSE --

Police are hunting for vandals who chopped fiber-optic cables and killed landlines, cell phones and Internet service for tens of thousands of people in Santa Clara, Santa Cruz and San Benito counties on Thursday.

IMAGES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MORE NEWS

- Toyota seeks damage control, in public and private 02.09.10
- Snow shuts down federal government, life goes on 02.09.10
- Iran boosts nuclear enrichment, drawing warnings 02.09.10

The sabotage essentially froze operations in parts of the three counties at hospitals, stores, banks and police and fire departments that rely on 911 calls, computerized medical records, ATMs and credit and debit cards.

The full extent of the havoc might not be known for days, emergency officials said as they finished repairing the damage late Thursday.

Whatever the final toll, one thing is certain: Whoeve did this is in a world of trouble if he, she or they get caught.

"I pity the individuals who have done this," said San Jose Police Chief Rob Davis.

Ten fiber-optic cables carrying were cut at four locations in the predawn darkness. Residential and business customers quickly found that telephone service was perhaps more laced into their everyday needs than they thought. Suddenly they couldn't draw out money, send text messages, check e-mail or Web sites, call anyone for help, or eve check on friends or relatives down the road.

Several people had to be driven to hospitals because they were unable to summon ambulances. Many businesses lapsed into idleness for hours, without the ability to contact associates or customers.

More than 50,000 landline customers lost service - some were residential, others were business lines that needed the connections for ATMs, Internet and bank card transactions. One line alone could affect hundreds of users.

UPDATE LOOK Vancouver's Venues Shine Up

NEWS | LOCAL BEAT

$250K Reward Out for Vandals Who Cut AT&T Lines

Local emergency declared during outage

By LORI PREUITT

Updated 2:12 PM PST, Fri, Apr 10, 2009

PRINT EMAIL SHARE BUZZ UP! TWITTER FACEBOOK

AT&T is now offering a $250,000 reward for information leading to the arrest of whoever is responsible for severing lines fiber optic cables in San Jose tha left much of the area without phone or cell service Thursday.

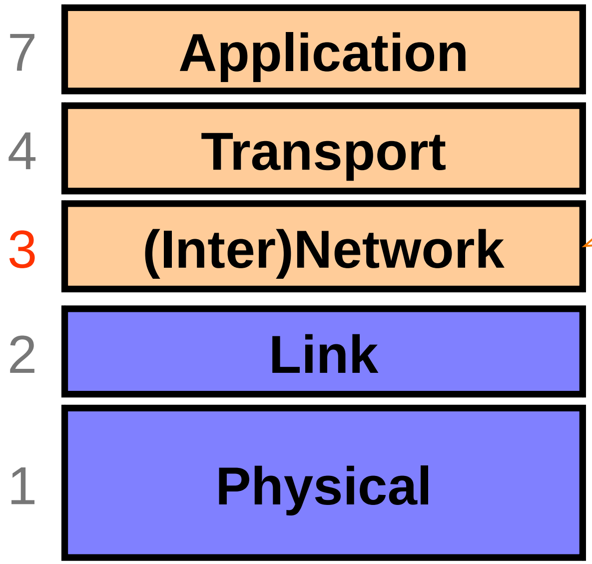
John Britton of AT&T said the reward is the largest ever offered by the company.

Physical/Link-Layer Threats: *Spoofing*

- With physical access to a subnetwork, attacker can create any message they like
  - Termed *spoofing*
- May require root/administrator access to have full freedom
- Particularly powerful when combined with *eavesdropping*
  - Because attacker can understand exact state of victim's communication and craft their spoofed traffic to match it
  - Spoofing w/o eavesdropping = *blind spoofing*

Layer 3: The Network Layer

Layer 3: (Inter)Network Layer

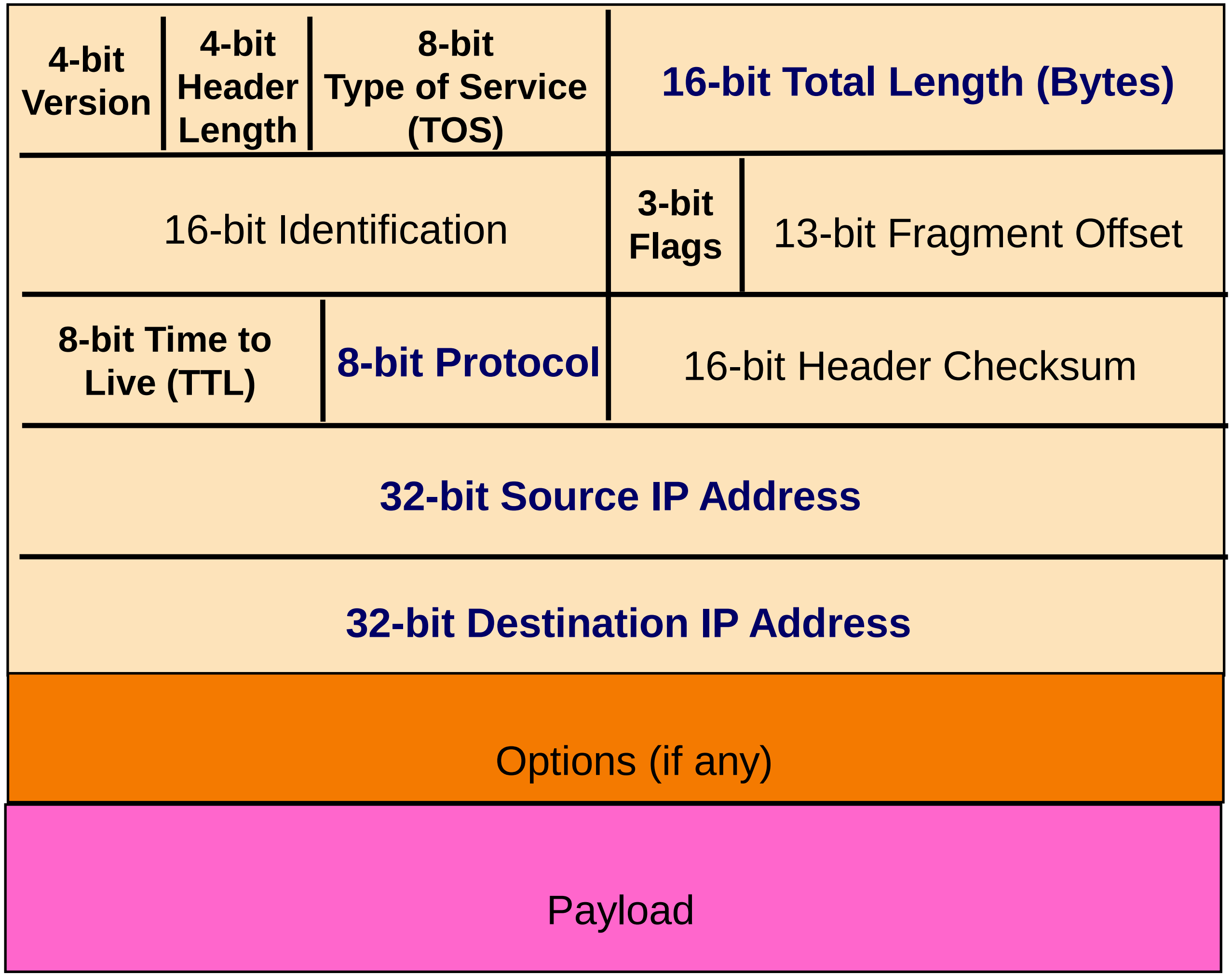


Bridges multiple "subnets" to provide *end-to-end* internet connectivity between nodes

- Provides global addressing

Works across different link technologies

IP Packet Structure



IP Packet Structure

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<tr><td colspan="5">Options (if any)</td></tr>
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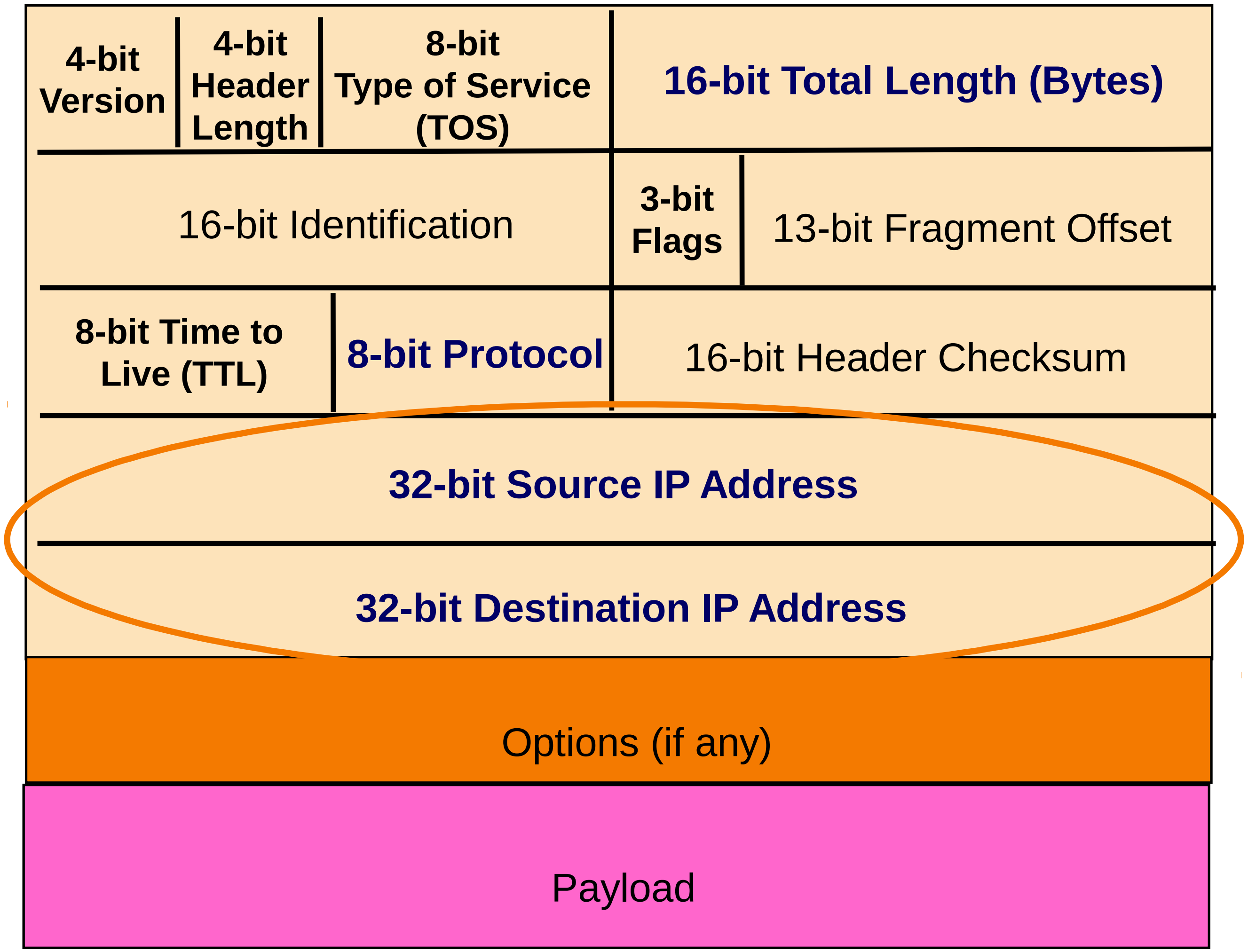
</table>

IP Packet Header Fields

- Version number (4 bits)
  - Indicates the version of the IP protocol
  - Necessary to know what other fields to expect
  - Typically "4" (for IPv4), and sometimes "6" (for IPv6)
- Header length (4 bits)
  - Number of 32-bit words in the header
  - Typically "5" (for a 20-byte IPv4 header)
  - Can be more when IP options are used
- Type-of-Service (8 bits)
  - Allow packets to be treated differently based on needs
  - E.g., low delay for audio, high bandwidth for bulk transfer

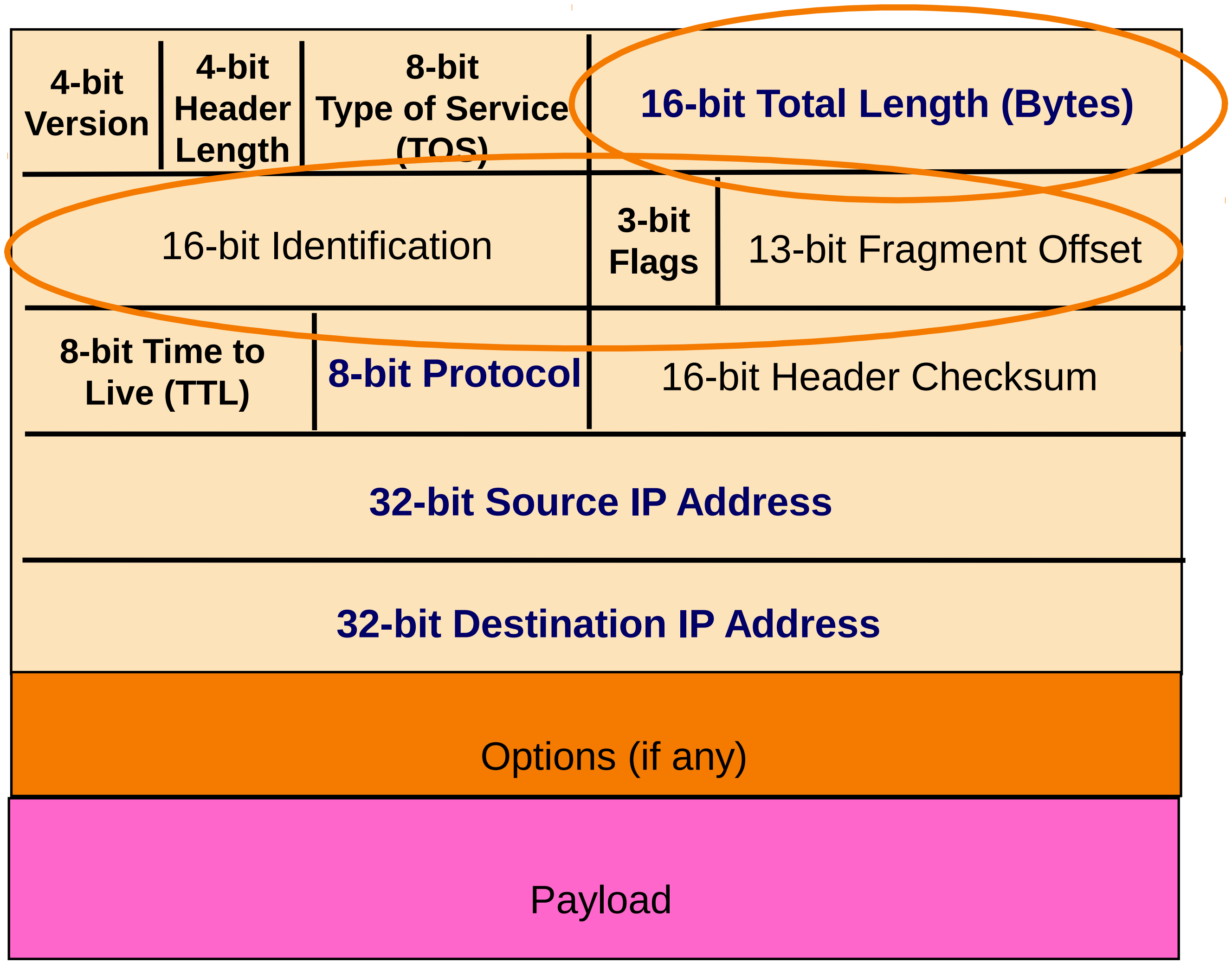
IP Packet Structure



IP Packet Header (Continued)

- Two IP addresses
  - Source IP address (32 bits)
  - Destination IP address (32 bits)
- Destination address
  - Unique identifier/locator for the receiving host
  - Allows each node to make forwarding decisions
- Source address
  - Unique identifier/locator for the sending host
  - Recipient can decide whether to accept packet
  - Enables recipient to send a reply back to source

IP Packet Structure

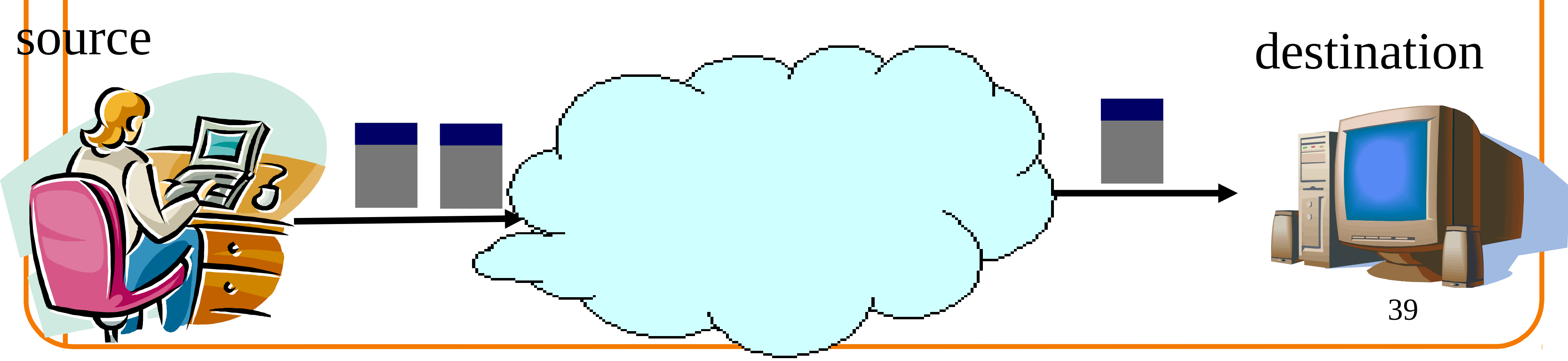


IP Packet Header Fields (Continued)

- Total length (16 bits)
  - Number of bytes in the packet
  - Maximum size is 65,535 bytes (2^{16} -1)
  - … though underlying links may impose smaller limits
- Fragmentation: when forwarding a packet, an Internet router can split it into multiple pieces ("fragments") if too big for next hop link
- End host reassembles to recover original packet
- Fragmentation information (32 bits)
  - Packet identifier, flags, and fragment offset
  - Supports dividing a large IP packet into fragments
  - … in case a link cannot handle a large IP packet

IP: "*Best Effort* " Packet Delivery

- Routers inspect destination address, locate "next hop" in forwarding table
  - Address = ~unique identifier/locator for the receiving host
- Only provides a "*I'll give it a try*" delivery service:
  - Packets may be lost
  - Packets may be corrupted
  - Packets may be delivered out of order



Layer 3 Threats

Network-Layer Threats (mainly IP)

- Major:
  - Can set arbitrary source address
    - "*Spoofing*" - receiver has no idea who you are
    - Could be *blind*, or could be coupled w/ *sniffing*
  - Can set arbitrary destination address
    - Enables "*scanning*" - brute force searching for hosts
- Lesser: **(FYI; don't worry about unless later explicitly covered)**
  - Identification field leaks information
  - Time To Live allows discovery of topology
  - IP "options" can reroute traffic

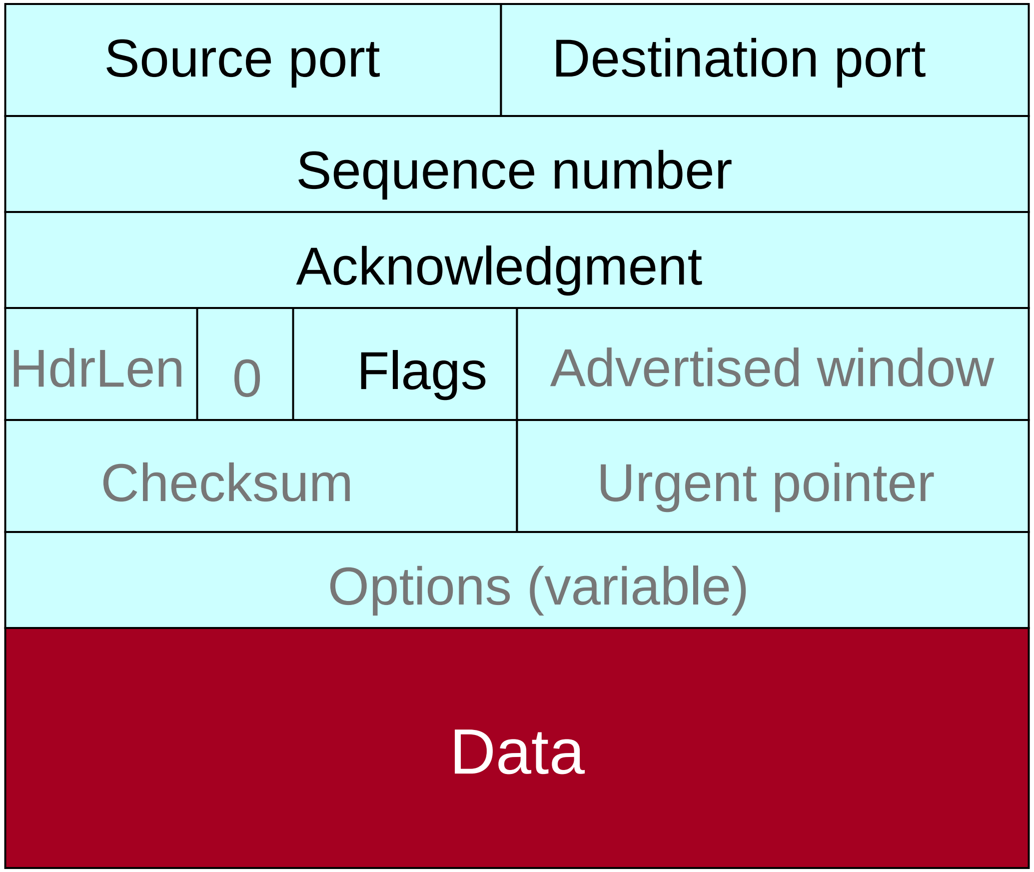
Other: ARP Poisoning Attacks

Layer 4: The Transport Layer

IP's "Best Effort" is Lame! What to do?

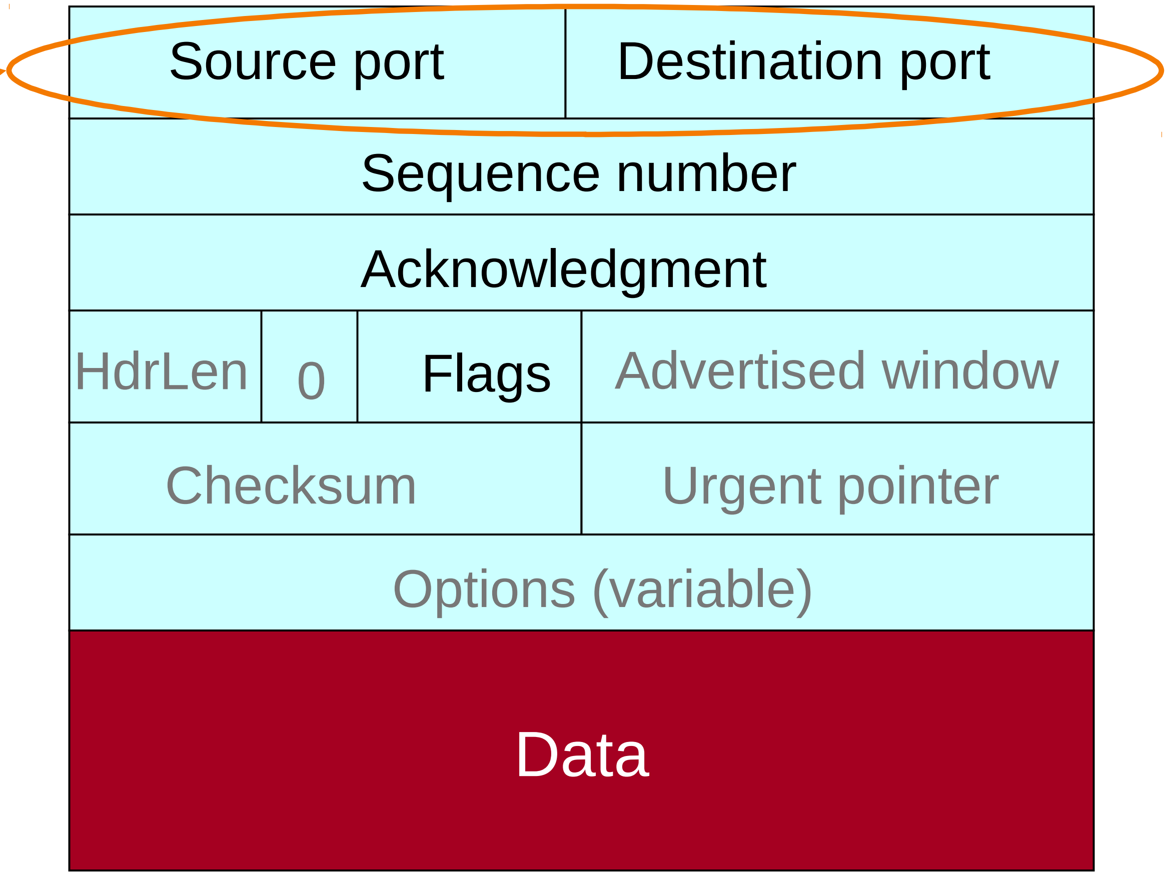
- It's the job of our Transport (layer 4) protocols to build services our apps need out of IP's modest layer-3 service
- #1 workhorse: TCP (Transmission Control Protocol)
- Service provided by TCP:
  - Connection oriented (explicit set-up / tear-down)
    - End hosts (processes) can have multiple concurrent long-lived communication
  - **Reliable**, in-order, byte-stream delivery
    - Robust detection & retransmission of lost data
  - Congestion control
    - Dynamic adaptation to network path's capacity

TCP Header


Source port
Destination port
Sequence number
Acknowledgment
HdrLen
0
Flags
Advertised window
Checksum
Urgent pointer
Options (variable)
Data

TCP Header

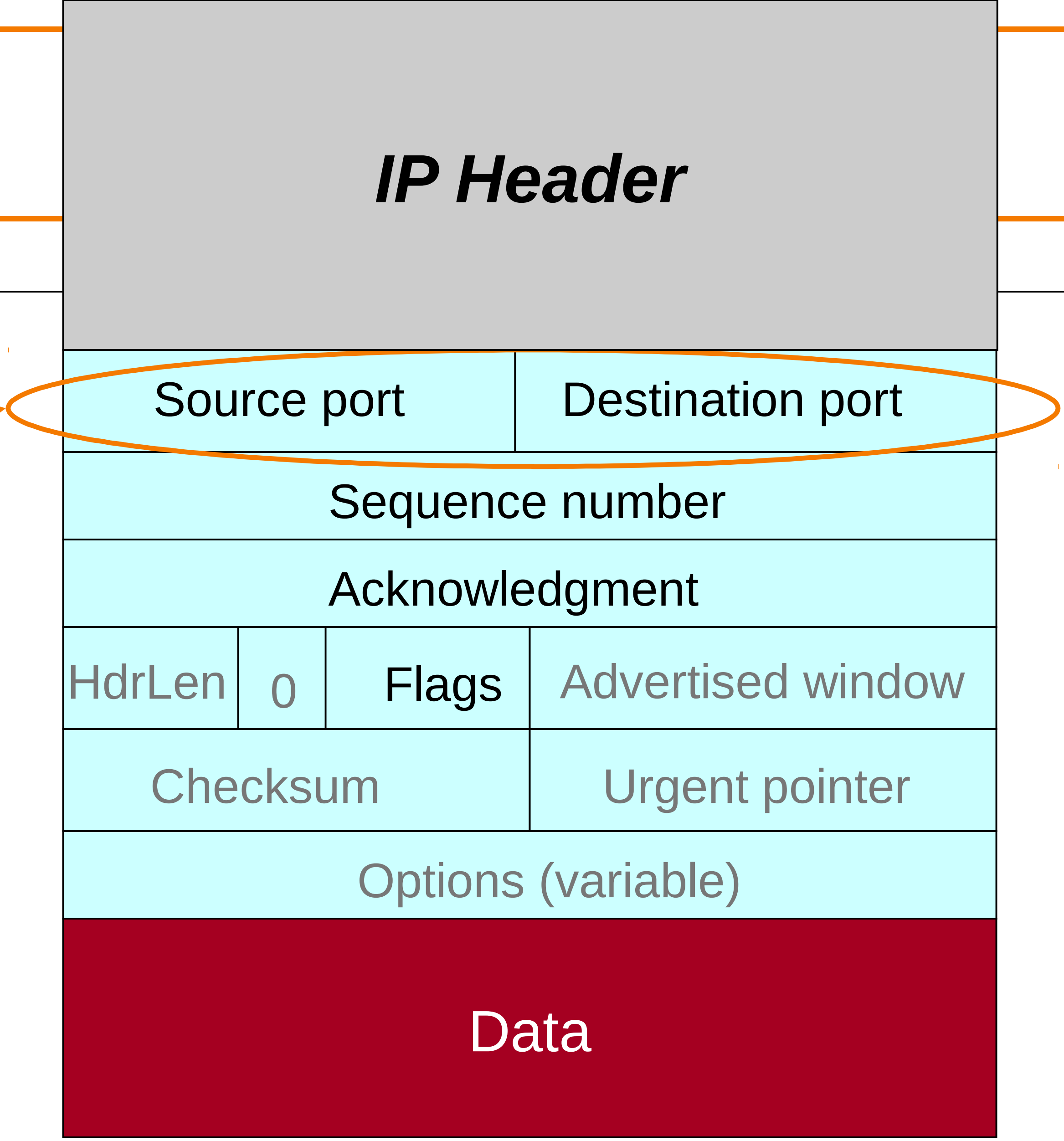
Ports are associated with OS processes



TCP Header

Ports are associated with OS processes

IP source & destination addresses plus TCP source and destination ports uniquely identifies a TCP connection



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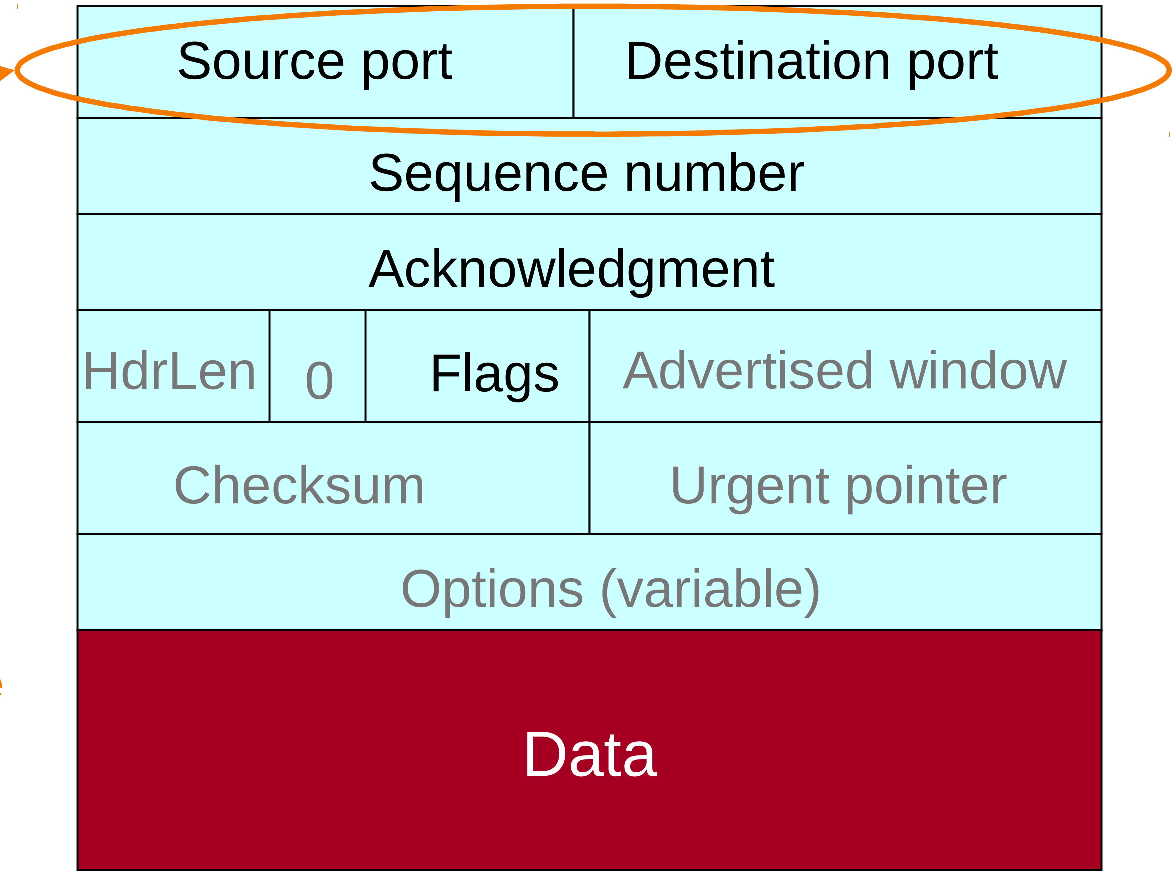
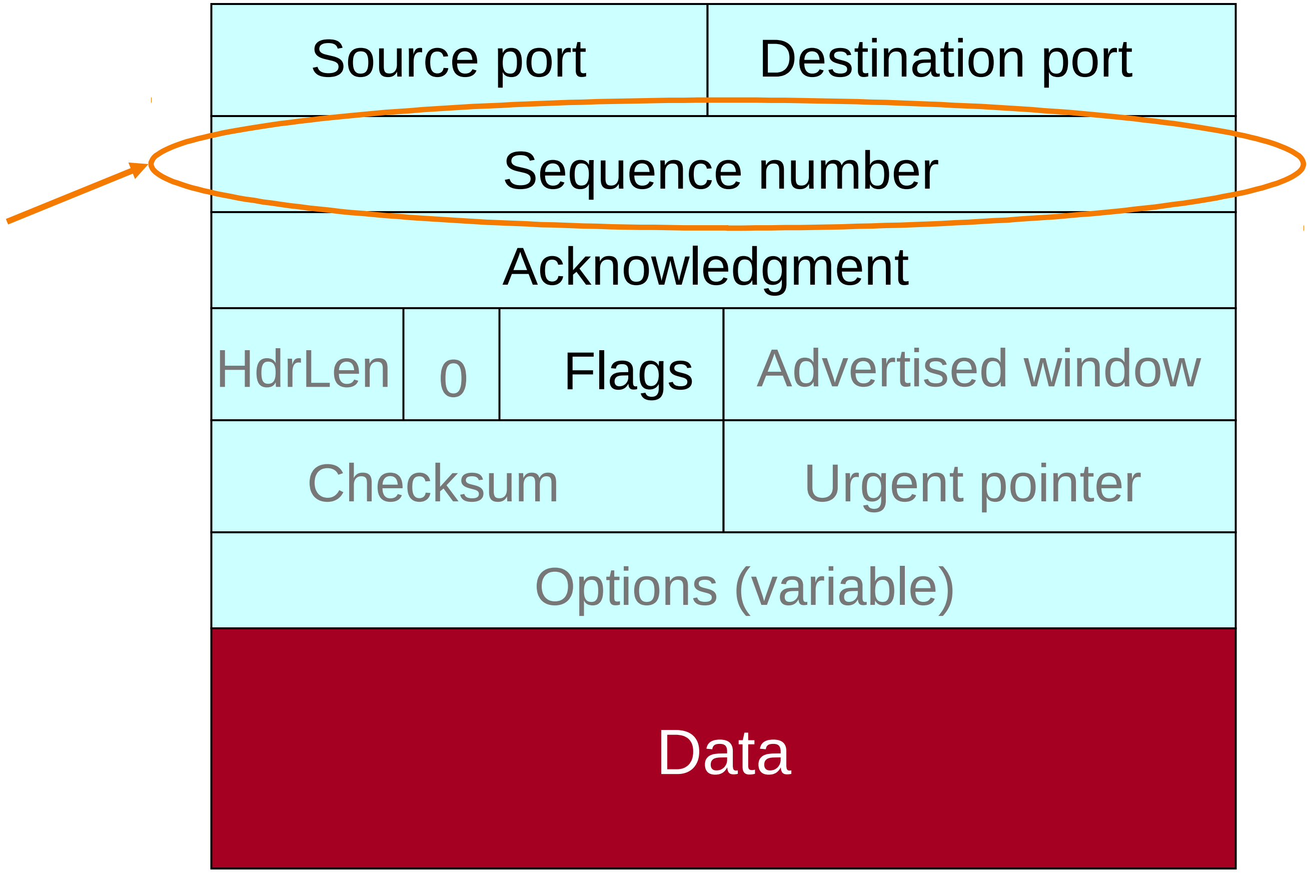


IP source & destination addresses plus TCP source and destination ports uniquely identifies a TCP connection

Some port numbers are “well known” / reserved e.g. port 80 = HTTP

TCP Header

Starting sequence number (byte offset) of data carried in this packet



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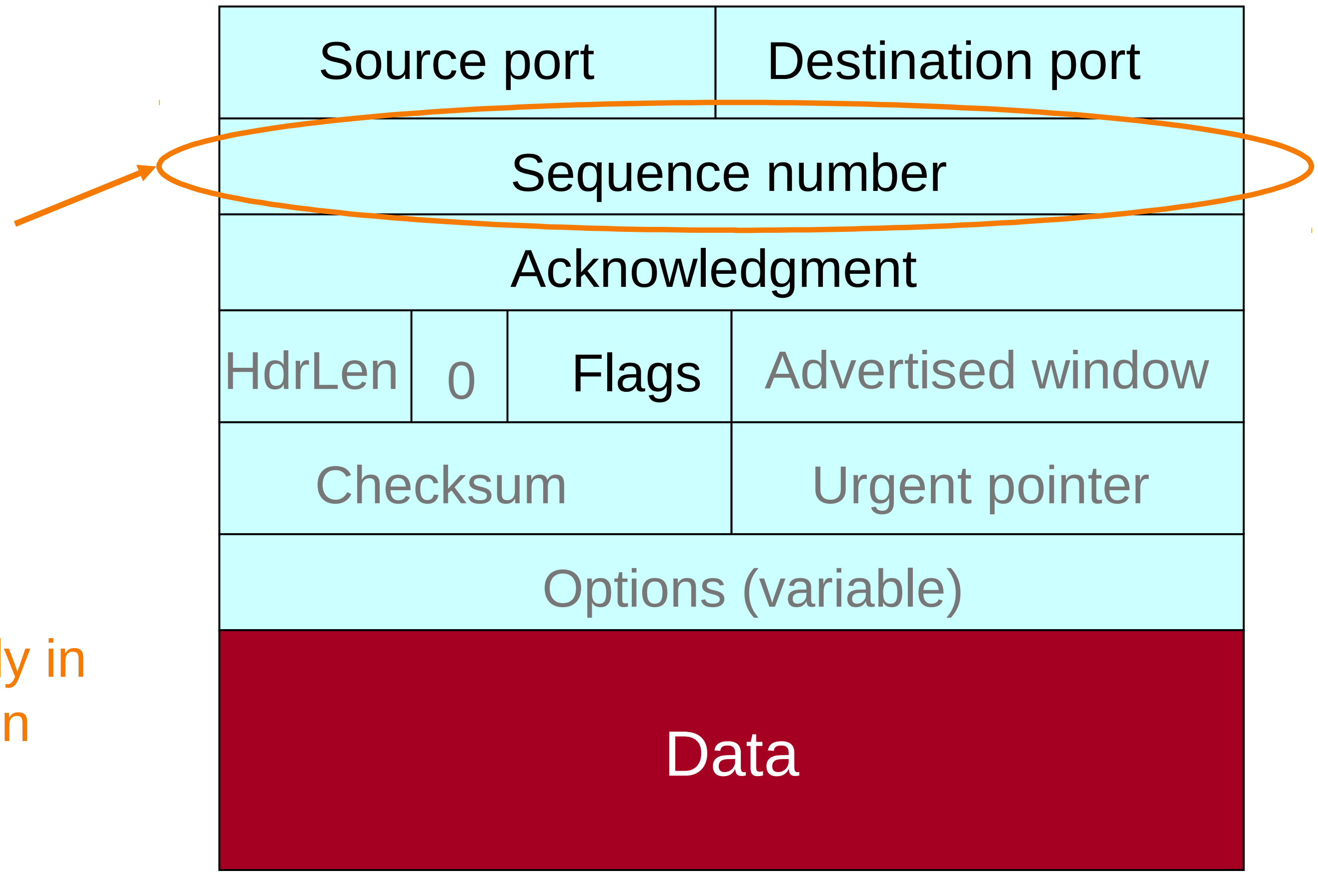
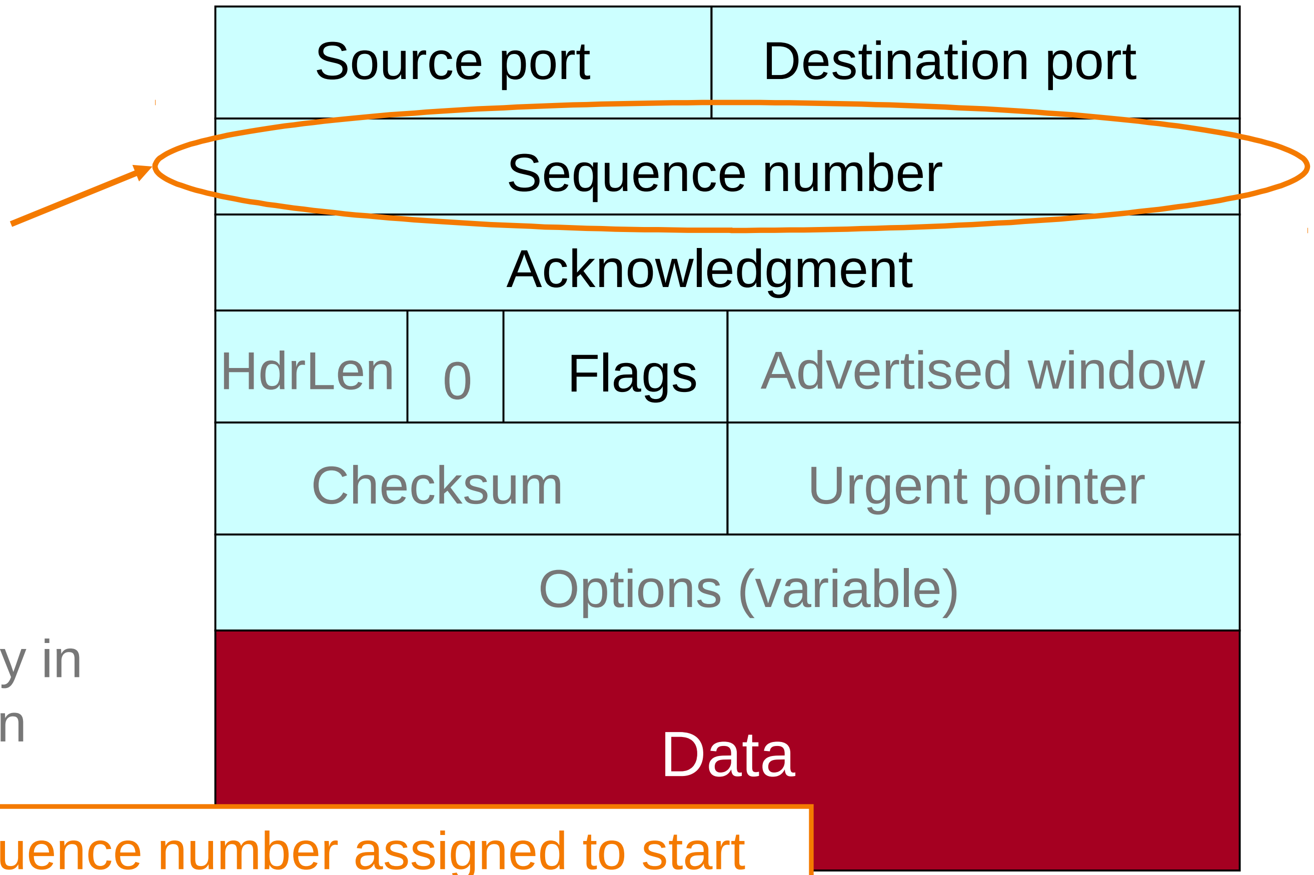


Byte stream numbered independently in each direction

TCP Header

Starting sequence number (byte offset) of data carried in this packet



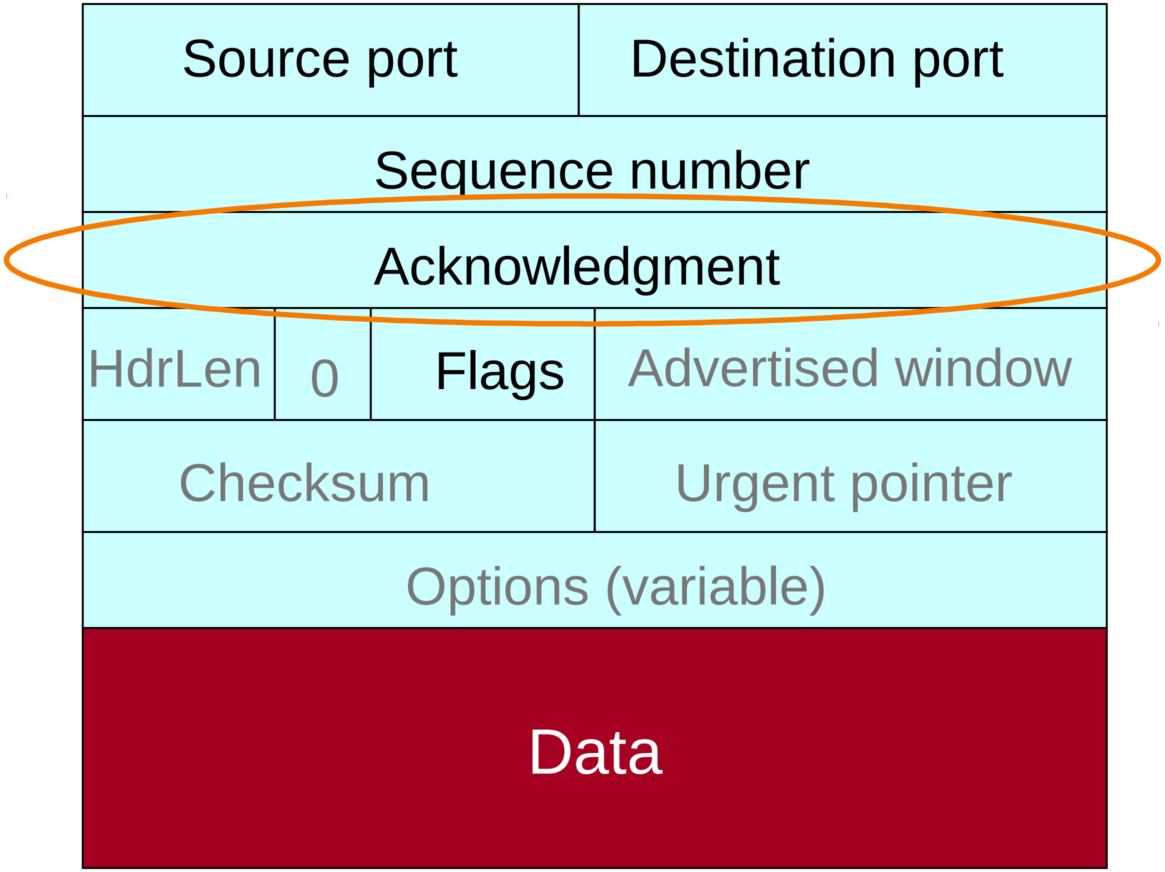
Byte stream numbered independently in each direction

Sequence number assigned to start of byte stream is picked when connection begins; **doesn't** start at 0

TCP Header

Acknowledgment gives seq # **just beyond** highest seq. received **in order**.

If sender sends **N** in-order bytes starting at seq **S** then ack for it will be **S+N**.

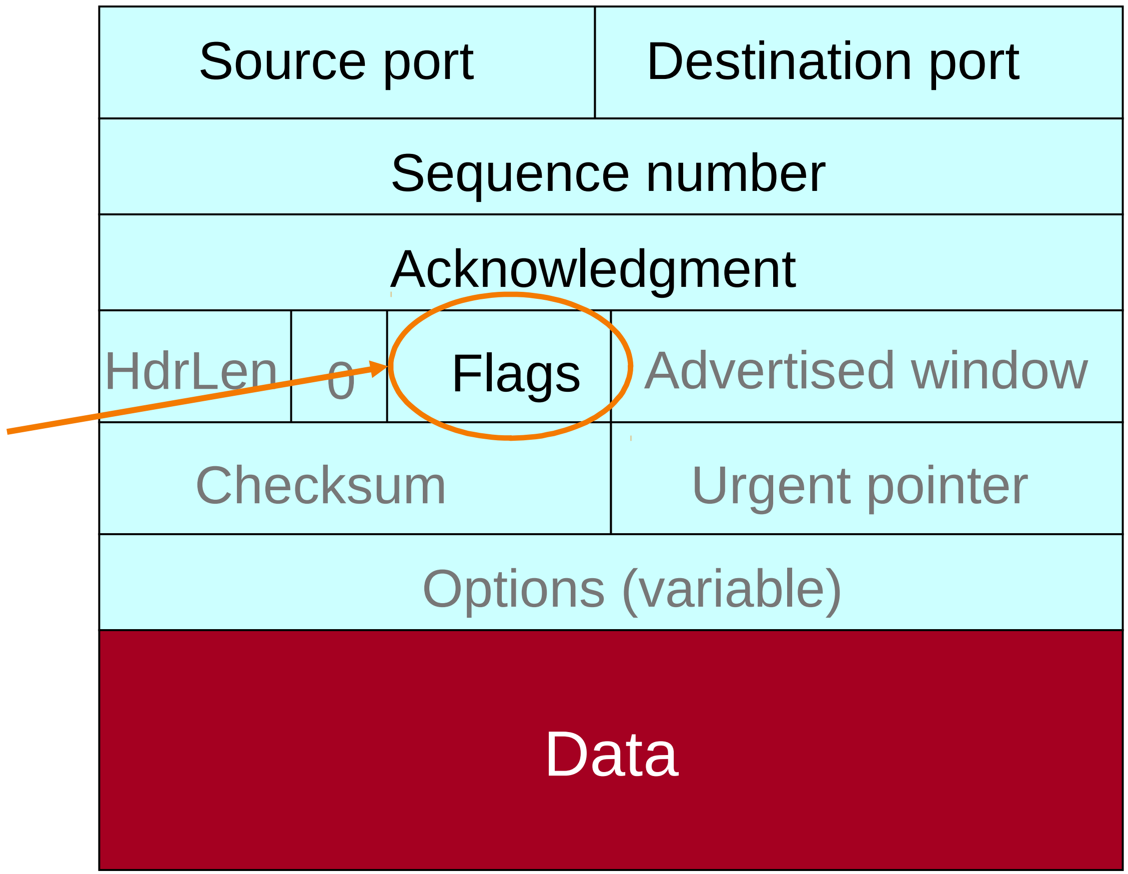


TCP Header

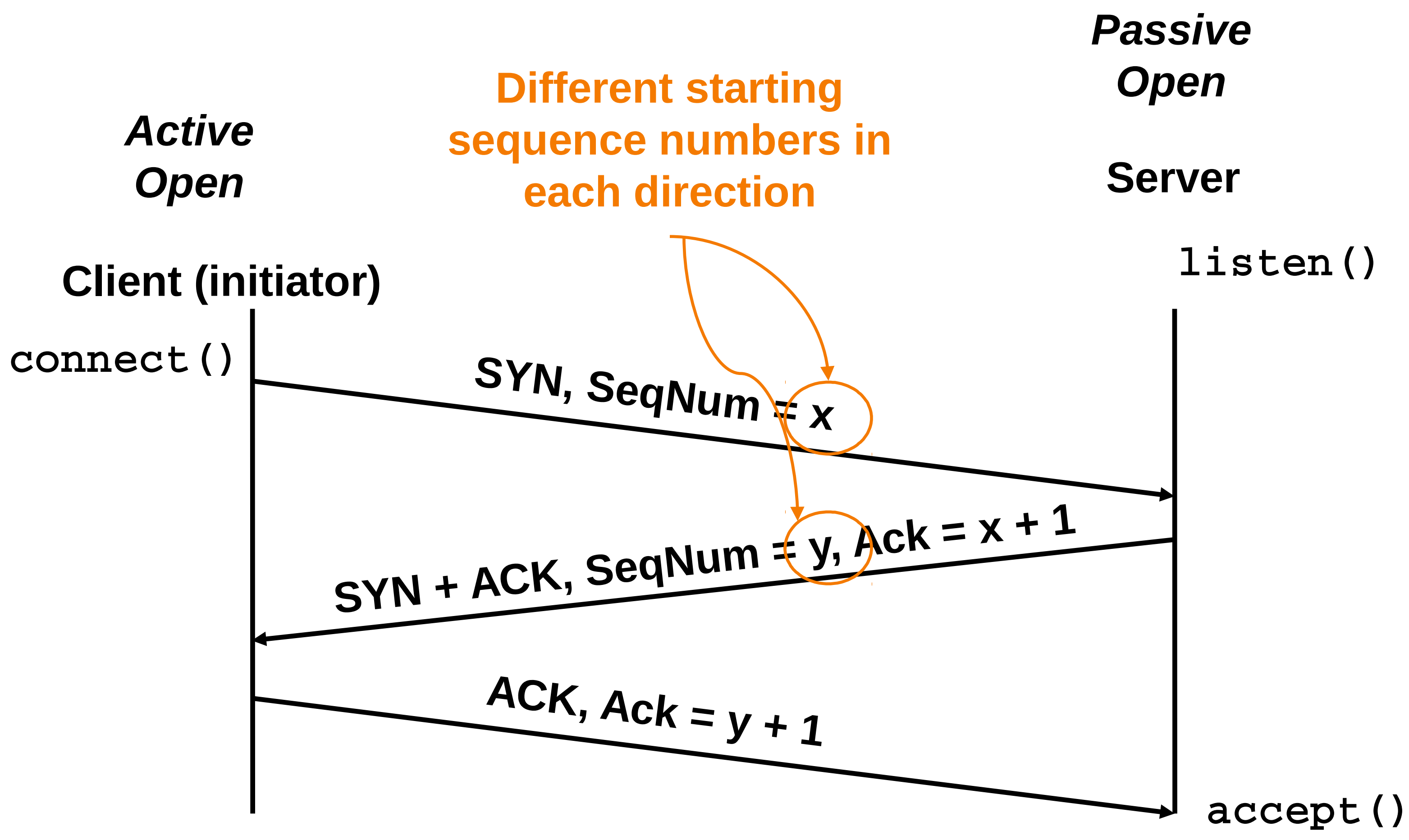
Uses include:

acknowledging data ("**ACK**")

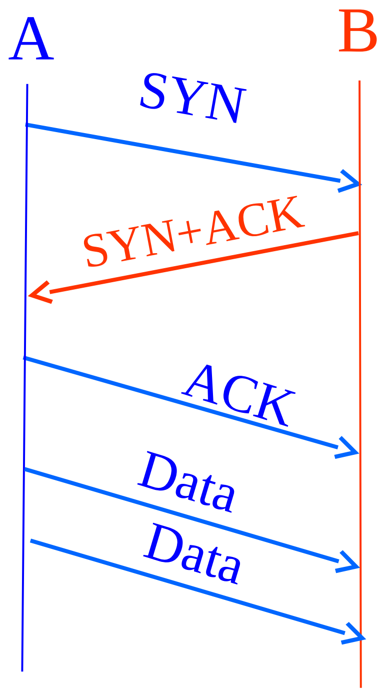
setting up ("**SYN**") and closing connections ("**FIN**" and "**RST**")



Timing Diagram: 3-Way Handshaking



Establishing a TCP Connection

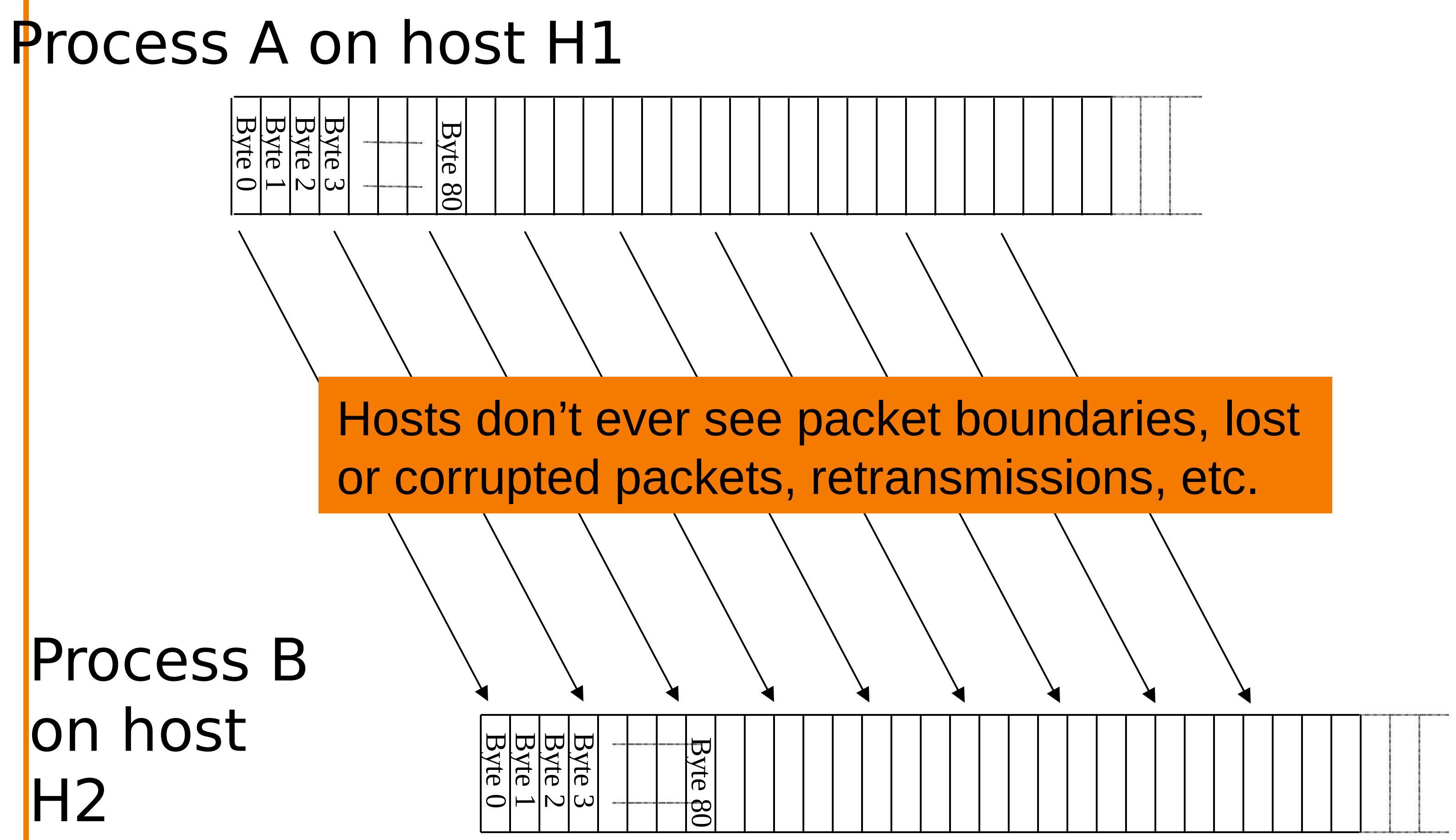


Each host tells its *Initial Sequence Number* (ISN) to the other host.

(Spec says to pick based on local clock)

- Three-way handshake to establish connection
  - Host A sends a **SYN** (open; “synchronize sequence numbers”) to host B
  - Host B returns a SYN acknowledgment (**SYN+ACK**)
  - Host A sends an **ACK** to acknowledge the SYN+ACK

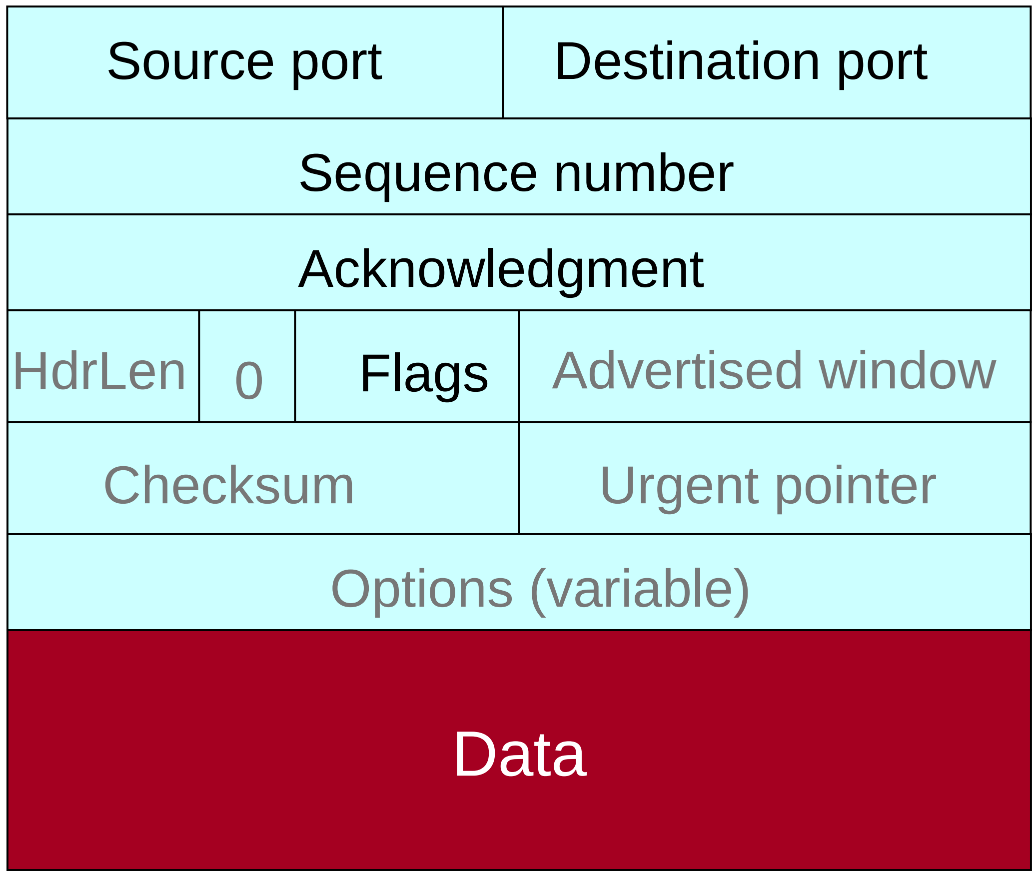
TCP “Bytestream” Service



Issues with TCP

TCP Threat: Disruption

- Normally, TCP finishes ("closes") a connection by each side sending a `FIN` control message
  - Reliably delivered, since other side must <u>ack</u>
- But: if a TCP endpoint finds unable to continue (process dies; info from other "peer" is inconsistent), it abruptly terminates by sending a **`RST`** control message
  - Unilateral
  - Takes effect immediately (no ack needed)
  - Only accepted by peer if has correct* sequence number


Source port
Destination port
Sequence number
Acknowledgment
HdrLen
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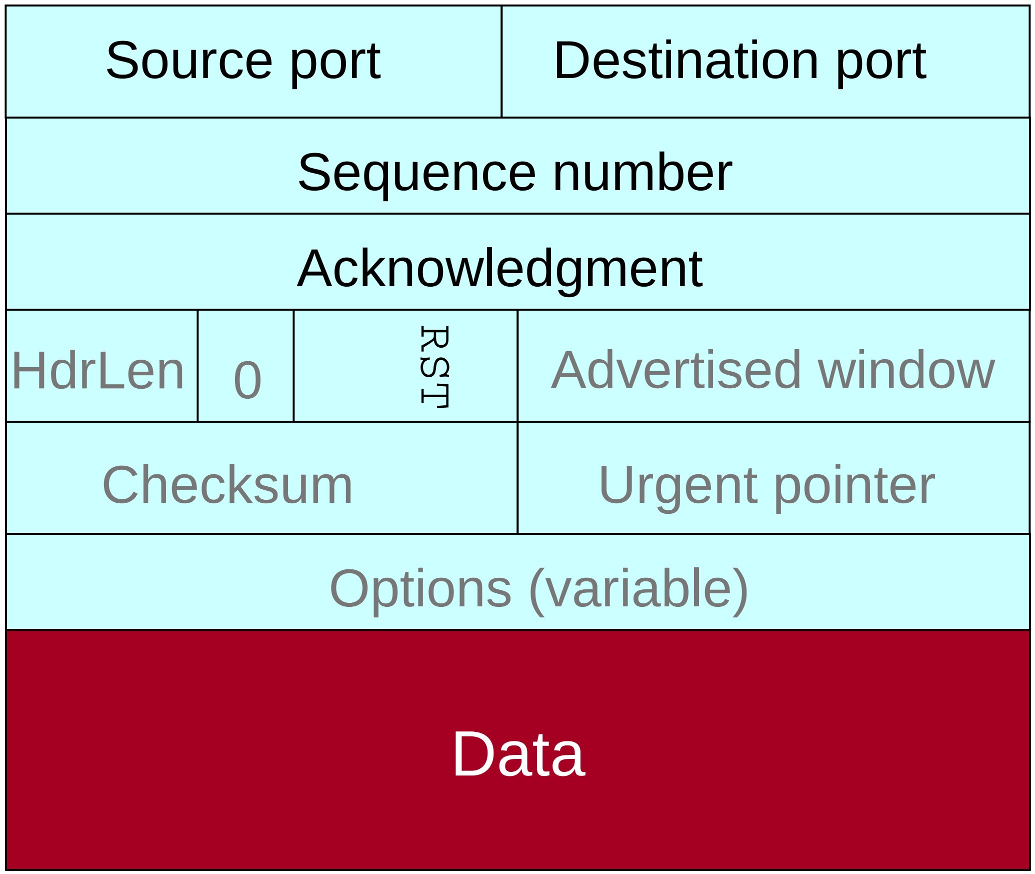
Flags
Advertised window
Checksum
Urgent pointer
Options (variable)
Data


Source port
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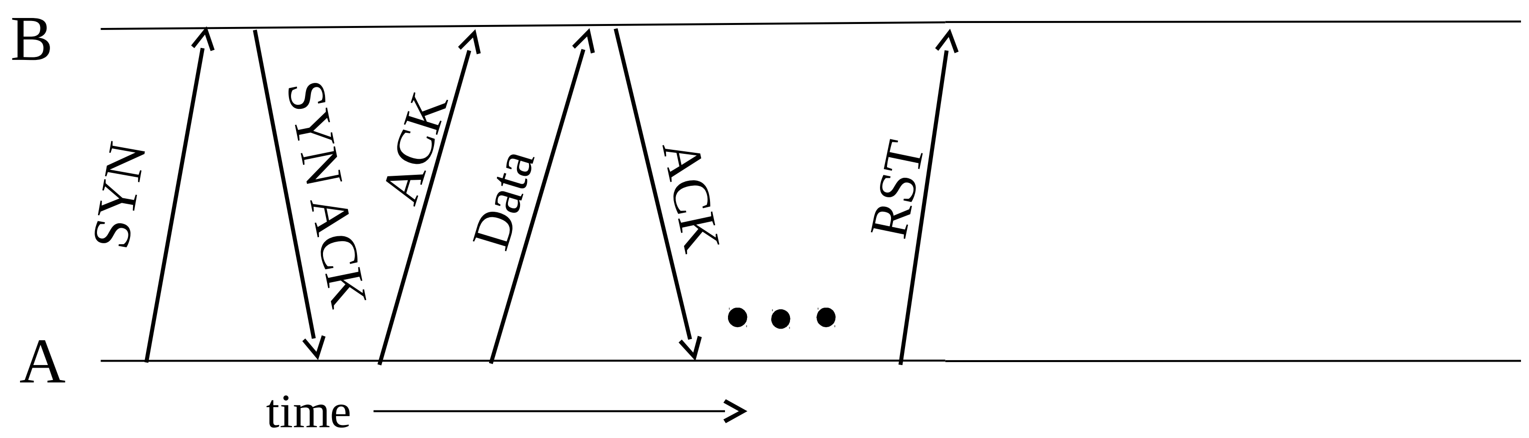
Data

Abrupt Termination



- A sends a TCP packet with RESET (**RST**) flag to B
  - E.g., because app. process on A crashed
- Assuming that the sequence numbers in the **RST** fit with what B expects, That's It:
  - B's user-level process receives: `ECONNRESET`
  - No further communication on connection is possible

TCP Threat: Disruption

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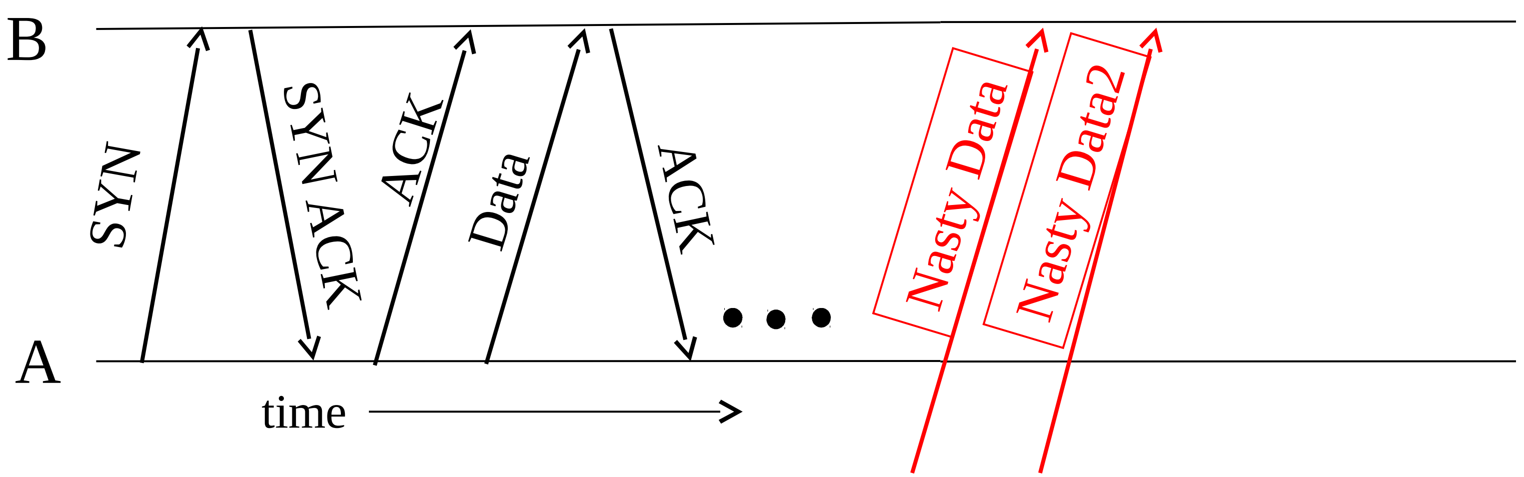
- So: if attacker knows ports & sequence numbers, can disrupt any TCP connection

TCP Threat: Injection



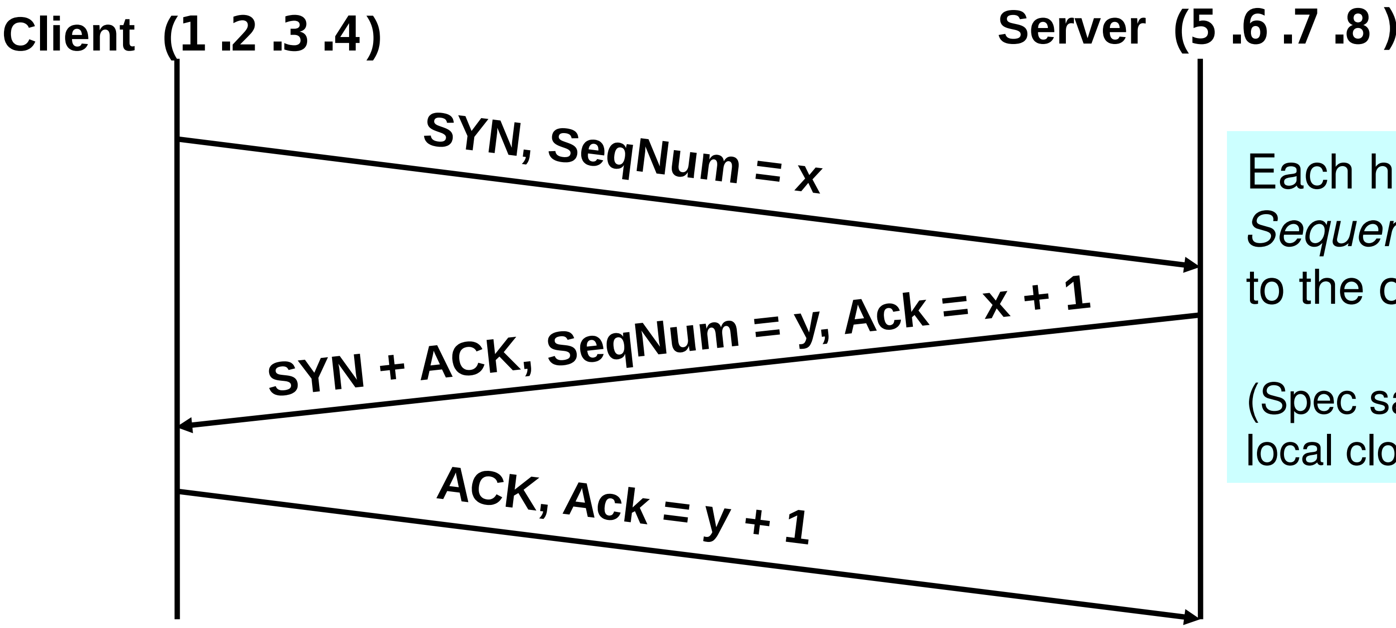
- What about inserting data rather than disrupting a connection?
  - Again, all that's required is attacker knows correct ports, seq. numbers
  - Receiver B is *none the wiser!*
- Termed TCP connection hijacking (or "*session hijacking*")
  - General means to take over an already-established connection!
- We are toast if an attacker can see our TCP traffic!
  - Because then they immediately know the port & sequence numbers

TCP Threat: Blind Spoofing

- Is it possible for an attacker to inject into a TCP connection even if they can't see our traffic?
- YES: if somehow they can guess the port and sequence numbers
- Let's look at a related attack where the goal of the attacker is to create a fake connection, rather than inject into a real one
  - Why?
  - Perhaps to leverage a server's trust of a given client as identified by its IP address
  - Perhaps to frame a given client so the attacker's actions during the connections can't be traced back to the attacker

TCP Threat: Blind Spoofing

- TCP connection establishment:

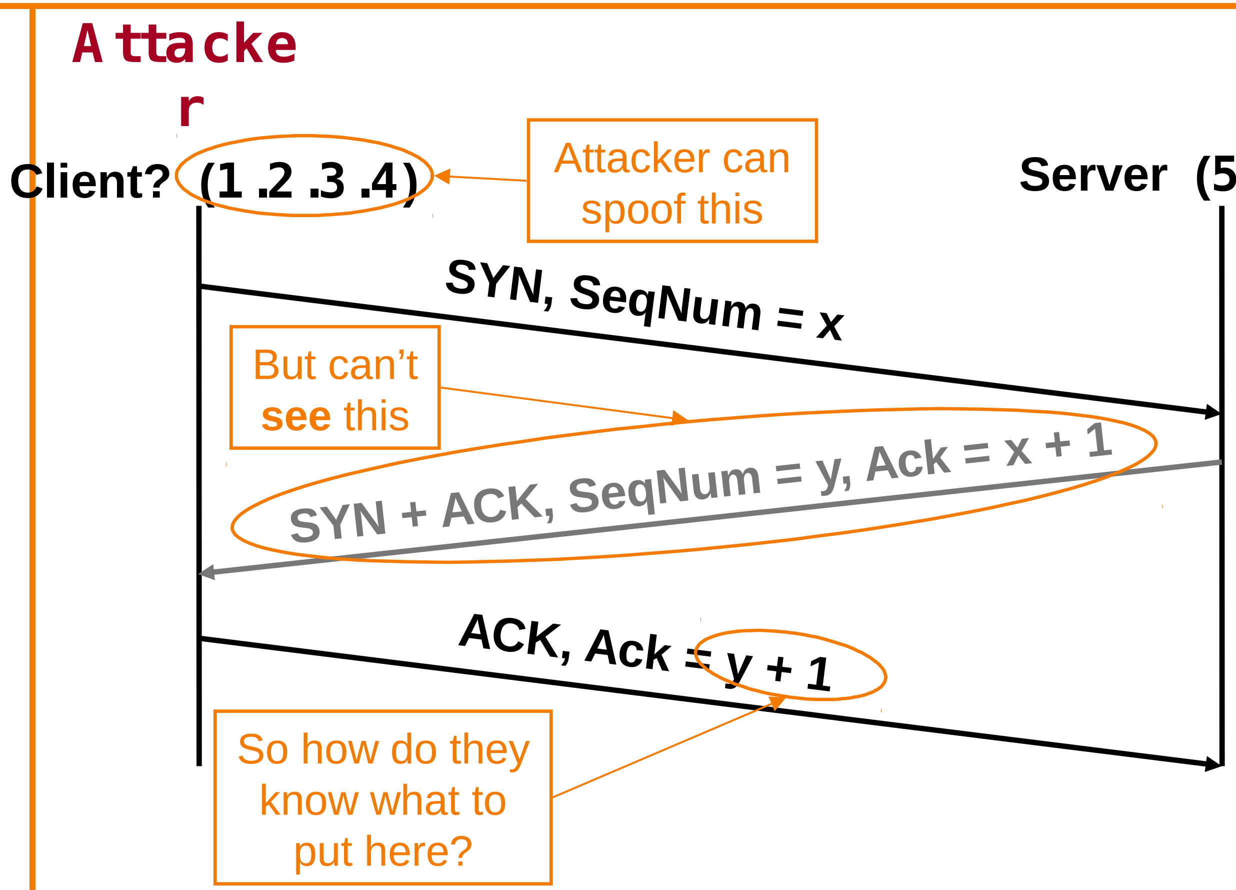


Each host tells its *Initial Sequence Number* (ISN) to the other host.

(Spec says to pick based on local clock)

- How can an attacker create an *apparent but fake* connection from 1.2.3.4 to 5.6.7.8?

Blind Spoofing: Attacker's Viewpoint



Each host tells its *Initial Sequence Number* (ISN) to the other host.

(Spec says to pick based on local clock)

Hmm, any way for the attacker to know ***this?***

How Do We Fix This?

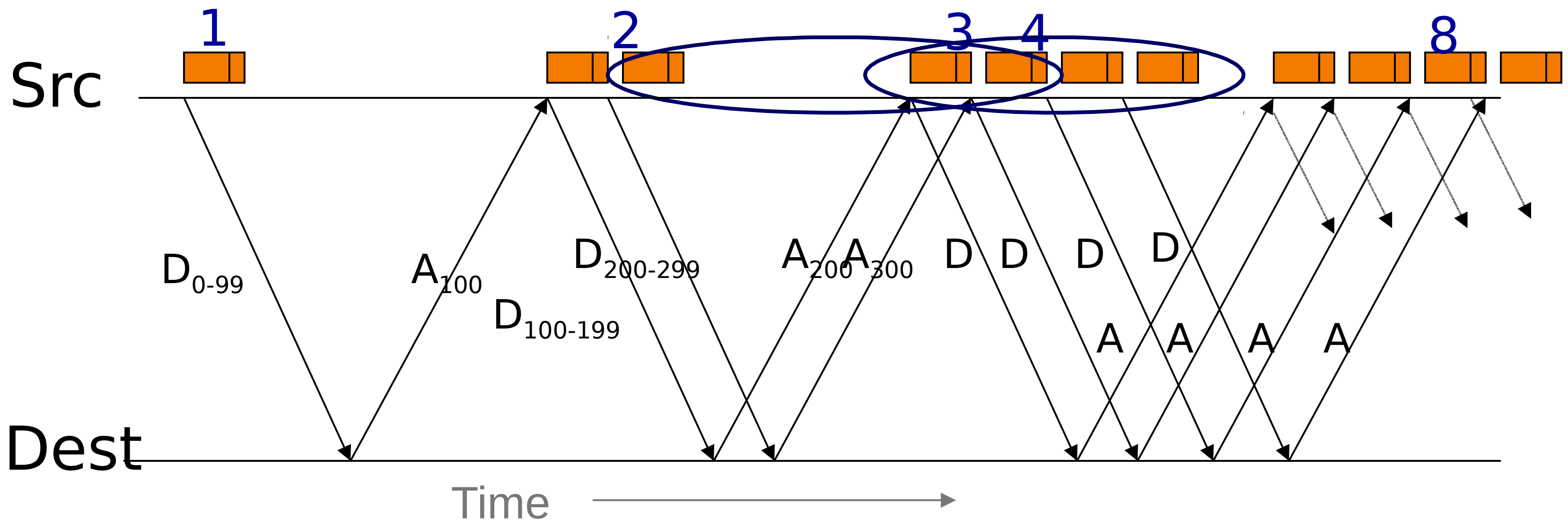
Use A *Random* ISN

Sure - make a non-spoofed connection *first*, and see what server used for ISN y then!

TCP's Rate Management

Unless there's loss, TCP doubles data in flight every "round-trip". All TCPs expected to obey ("fairness").

Mechanism: for each arriving ack for new data, increase allowed data by 1 maximum-sized packet

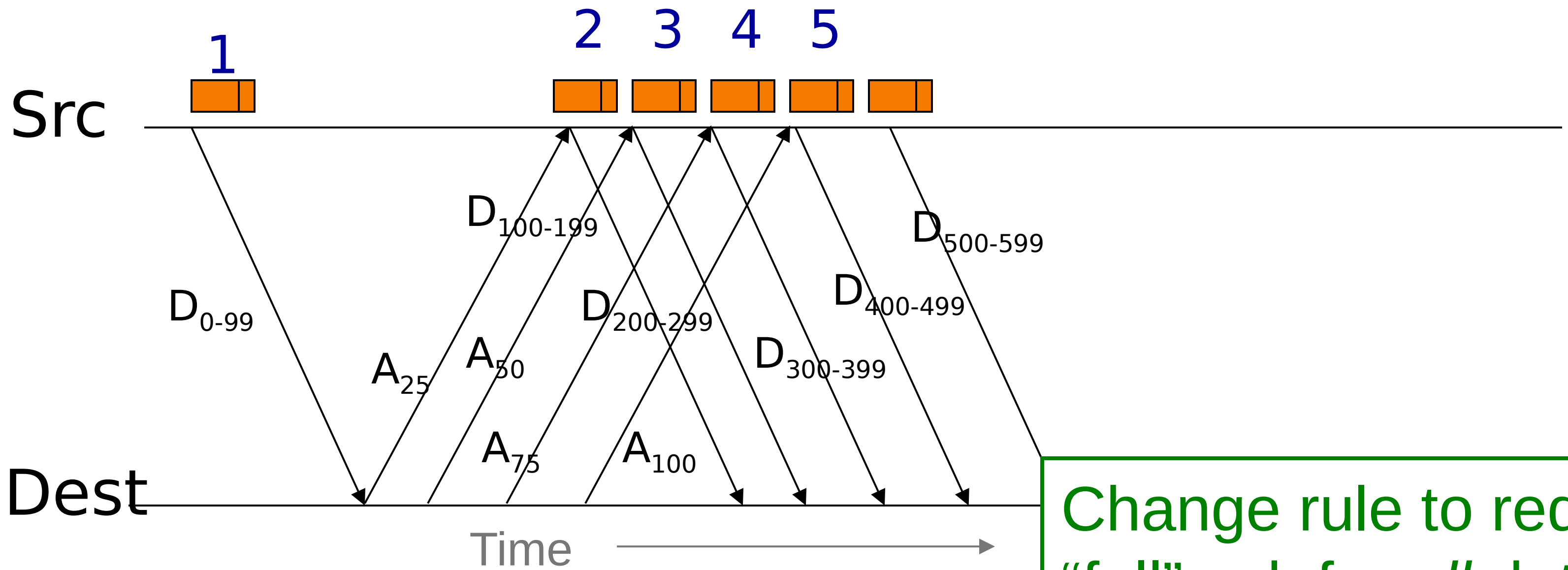


E.g., suppose maximum-sized packet = 100 bytes

Protocol Cheating

How can the destination (receiver) get data to come to them faster than normally allowed?

ACK-Splitting: each ack, even though **partial**, increases allowed data by one maximum-sized packet



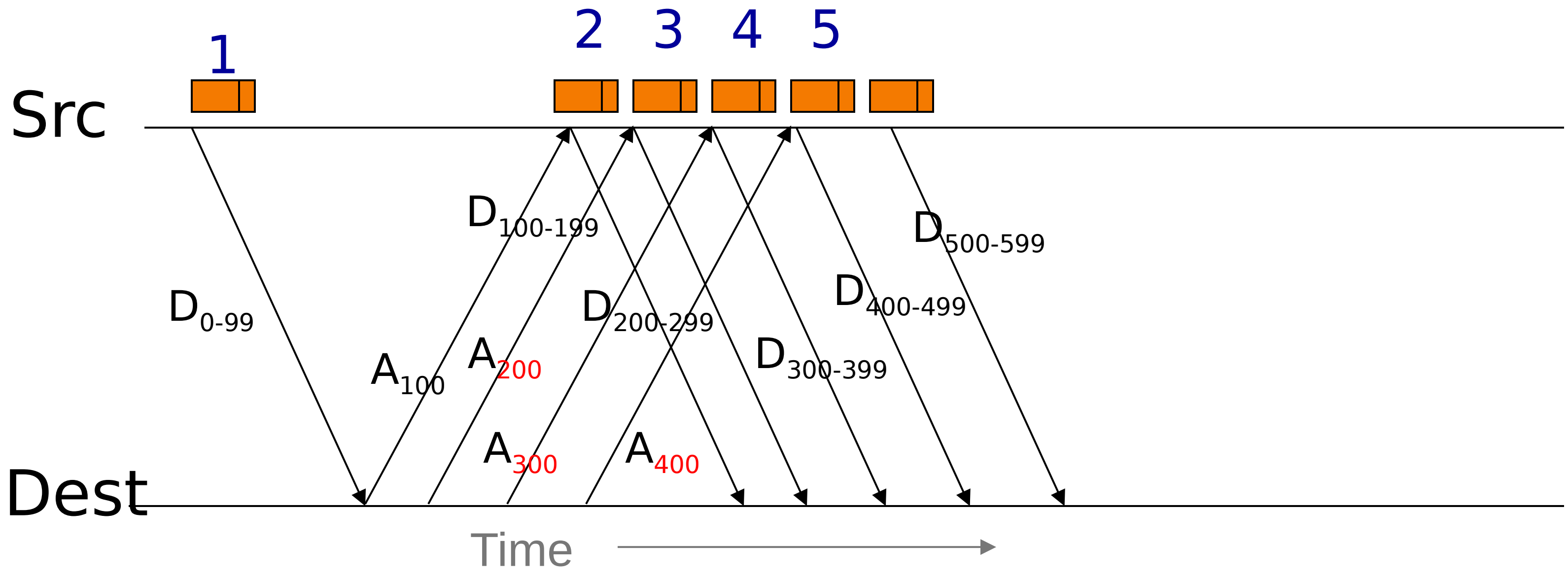
How do we defend against this?

Change rule to require "full" ack for *all* data sent in a packet

Protocol Cheating

How can the destination (receiver) *still* get data to come to them faster than normally allowed?

Opportunistic ack'ing: acknowledge data not yet seen!



How do we defend against *this*?

Keeping Receivers Honest

- Approach #1: if you receive an ack for data you haven't sent, kill the connection
  - Works only if receiver acks too far ahead
- Approach #2: follow the "round trip time" (RTT) and if ack arrives too quickly, kill the connection
  - Flaky: RTT can vary a lot, so you might kill innocent connections
- Approach #3: make the receiver prove they received the data

  Note: a *protocol* change

  - Add a **nonce** ("random" marker) & require receiver to include it in ack. Kill connections w/ incorrect nonces
    - (nonce could be function computed over payload, so sender doesn't explicitly transmit, only implicitly)

Summary of TCP Security Issues

- An attacker who can observe your TCP connection can manipulate it:
  - Forcefully **terminate** by forging a RST packet
  - **Inject** (*spoof*) data into either direction by forging data packets
  - Works because they can include in their spoofed traffic the correct sequence numbers (both directions) and TCP ports
  - *Remains a major threat today*

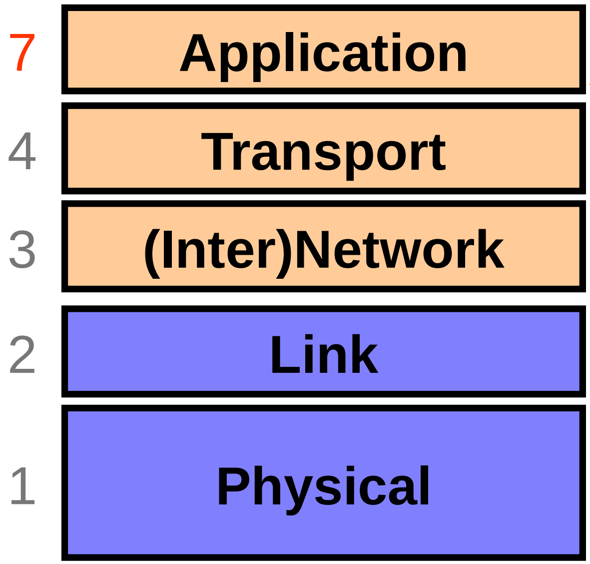
Summary of TCP Security Issues

- An attacker who can observe your TCP connection can manipulate it:
  - Forcefully **terminate** by forging a RST packet
  - **Inject** (*spoof*) data into either direction by forging data packets
  - Works because they can include in their spoofed traffic the correct sequence numbers (both directions) and TCP ports
  - *Remains a major threat today*
- An attacker who can predict the ISN chosen by a server can "blind spoof" a connection to the server
  - Makes it appear that host `ABC` has connected, and has sent data of the attacker's choosing, when in fact it hasn't
  - *Undermines any security based on trusting `ABC`'s IP address*
  - Allows attacker to "frame" `ABC` or otherwise avoid detection
  - **Fixed** today by choosing **random** ISNs

TCP Security Issues, con't

- TCP limits the rate at which senders transmit:
  - TCP relies on endpoints behaving properly to achieve "fairness" in how network capacity is used
  - Protocol lacks a mechanism to prevent cheating
  - Senders can cheat by just not abiding by the limits
    - Remains a significant vulnerability: essentially nothing today prevents
- Receivers can manipulate honest senders into sending too fast because senders trust that receivers are honest
  - To a degree, sender can validate (e.g., partial acks)
  - A **nonce** can force receiver to only act on data they've seen
  - Such rate manipulation remains a vulnerability today
- General observation: tension between ease/power of protocols that assume everyone follows vs. violating
  - Security problems persist due to difficulties of retrofitting …
  - … coupled with **investment in installed base**

Layer 7: Application Layer



Communication of whatever you wish

Can use whatever transport(s) is convenient

Freely structured

E.g.: DNS, DHCP (Next Lecture)

- Skype, SMTP (email), HTTP (Web), Halo, BitTorrent