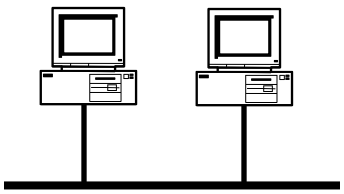
Networking Overview: "Everything" you need to know, in 50 minutes

CS 161: Computer Security

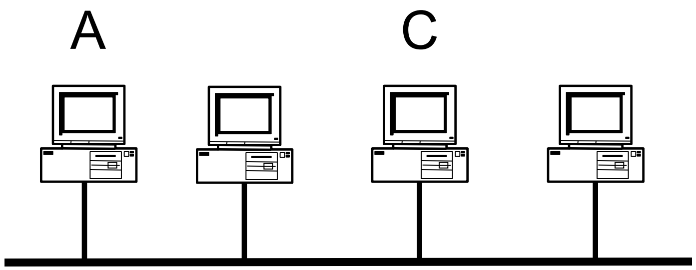
Prof. David Wagner

March 16, 2016

Local-Area Networks



point-to-point



shared

How does computer A send a message to computer C?

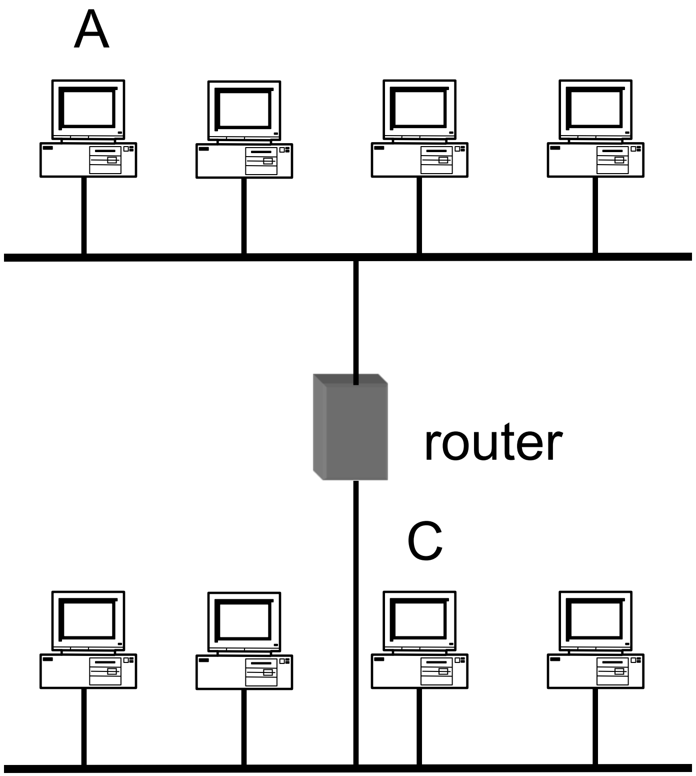
Local-Area Networks: Packets

```
From: A
To: C
Message: Hello world!
```

A	C	Hello world!

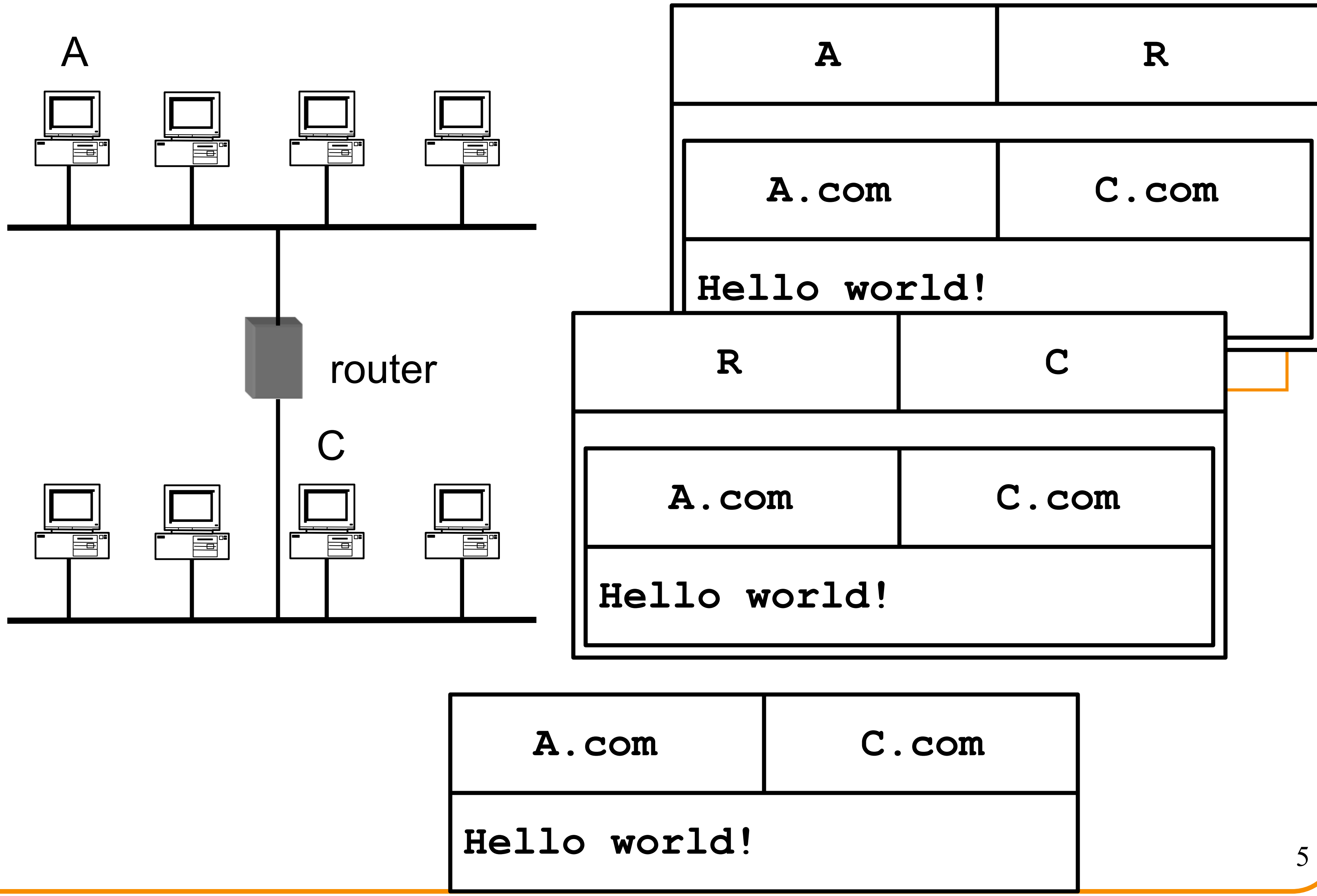
A	C
Hello world!	

Wide-Area Networks



How do we connect two LANs?

Wide-Area Networks



Key Concept #1: *Protocols*

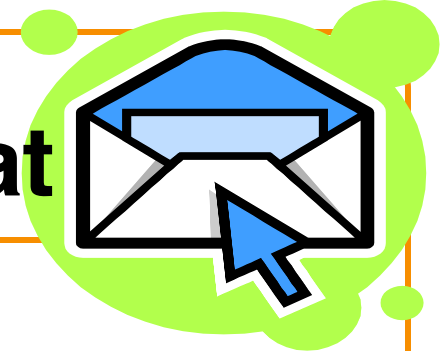
- A protocol is an agreement on how to communicate
- Includes syntax and semantics
  - How a communication is specified & structured
    - Format, order messages are sent and received
  - What a communication means
    - Actions taken when transmitting, receiving, or timer expires
- Example: making a comment 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): say “excuse me”

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

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

Self-Contained IP Packet Format



IP = Internet *Protocol*

<table>
<tr><td>4-bit Version</td><td>4-bit Header Length</td><td colspan="2">8-bit Type of Service (TOS)</td><td colspan="4">16-bit Total Length (Bytes)</td></tr>
<tr><td colspan="4">16-bit Identification</td><td>3-bit Flags</td><td colspan="3">13-bit Fragment Offset</td></tr>
<tr><td colspan="2">8-bit Time to Live (TTL)</td><td colspan="2">8-bit Protocol</td><td colspan="4">16-bit Header Checksum</td></tr>
<tr><td colspan="8">32-bit Source IP Address</td></tr>
<tr><td colspan="8">32-bit Destination IP Address</td></tr>
<tr><td colspan="8">Payload (remainder of message)
.
.
.
.
.</td></tr>
</table>

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

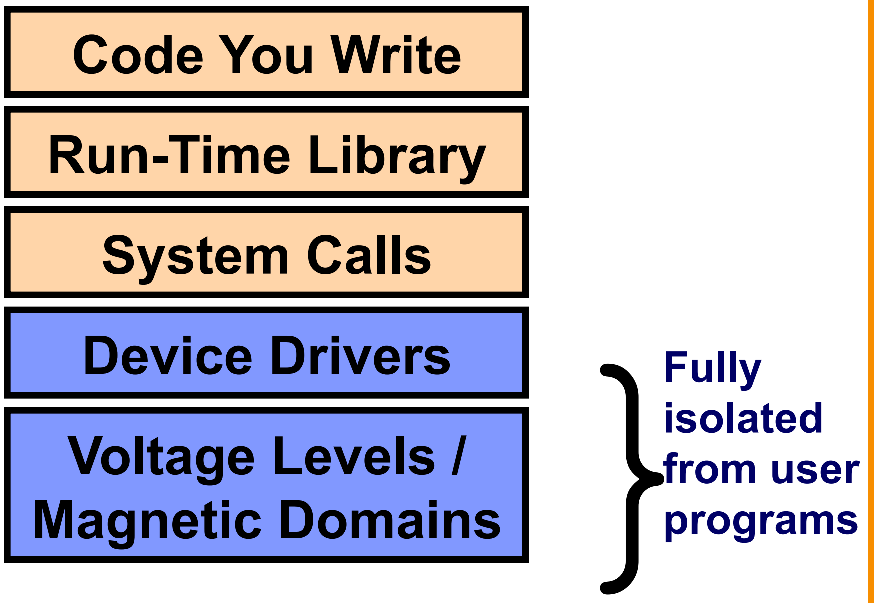
Key Concept #2: *Dumb Network*

- Original Internet design: interior nodes ("routers") have <u>no</u> 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*", not "hop-by-hop"
  - Buys simplicity & robustness at the cost of shifting complexity into end systems

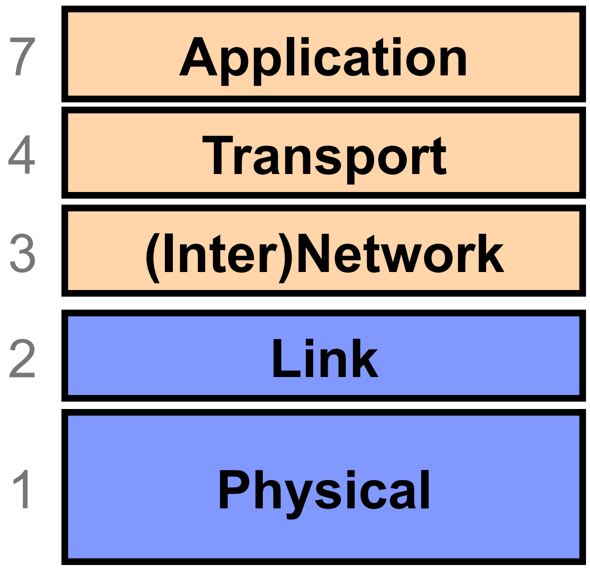
* Today's Internet is full of hacks that violate this

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



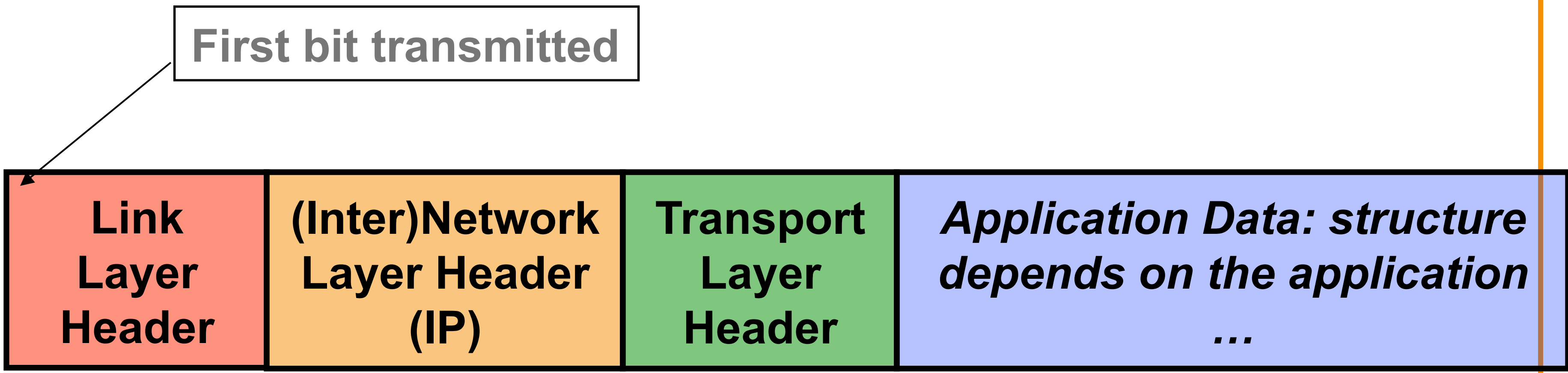
Internet Layering (“Protocol Stack”)



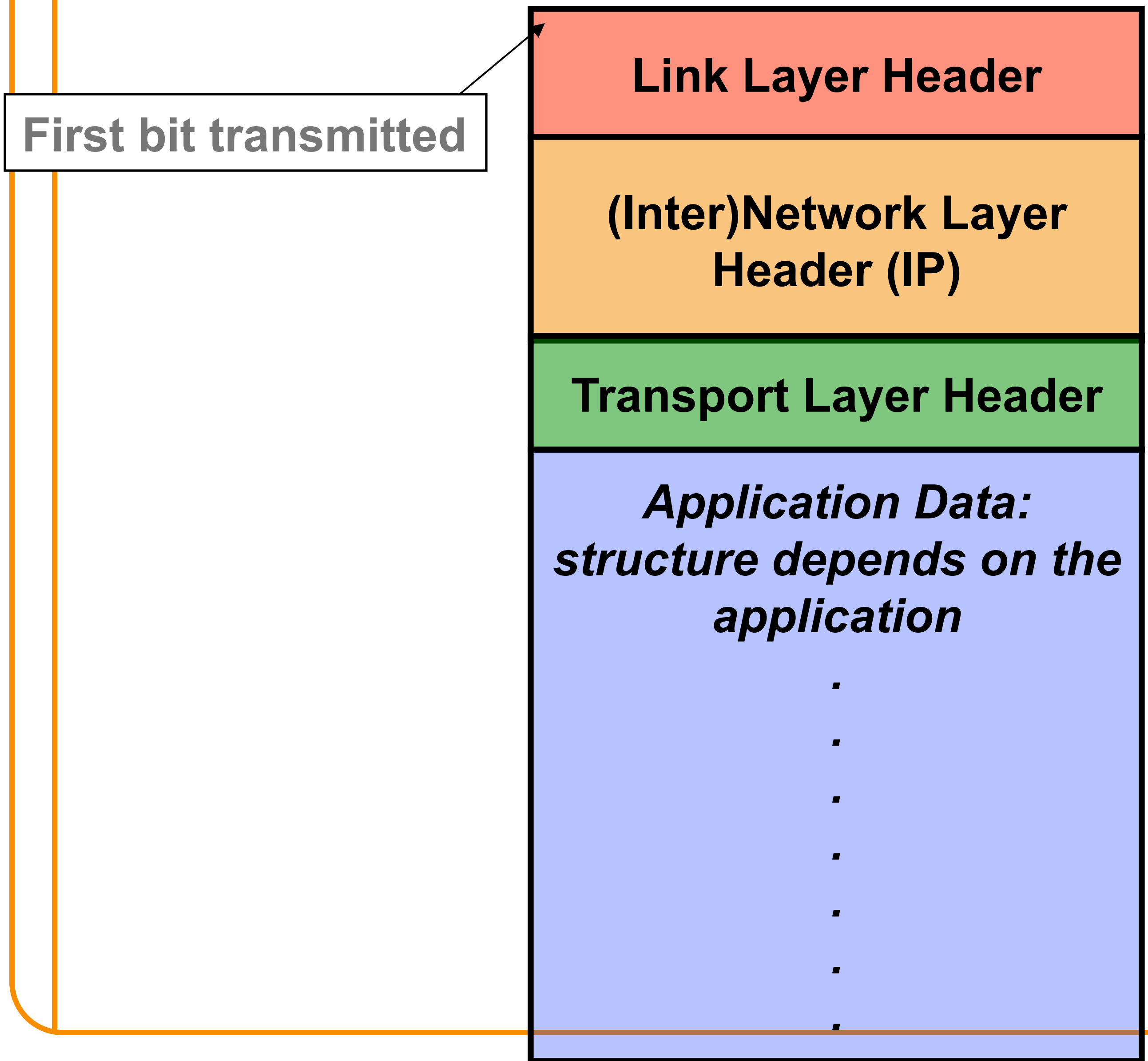
Note on a point of potential confusion: these diagrams are always drawn with lower layers **below** higher layers …

But diagrams showing the layouts of packets are often the *opposite*, with the lower layers at the **top** since their headers <u>precede</u> those for higher layers

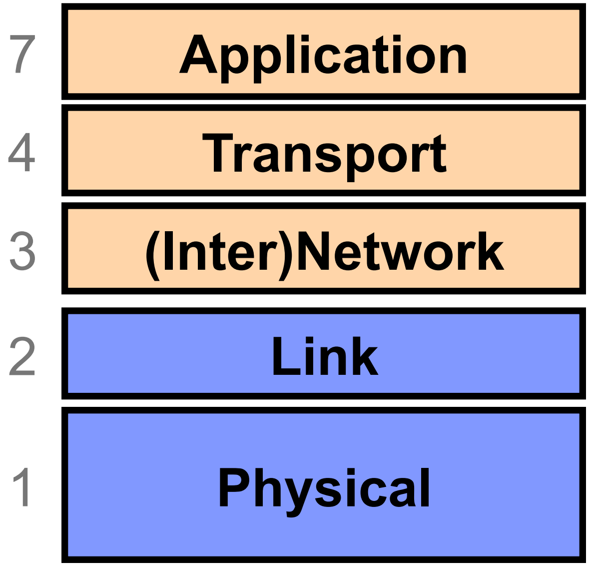
Horizontal View of a Single Packet



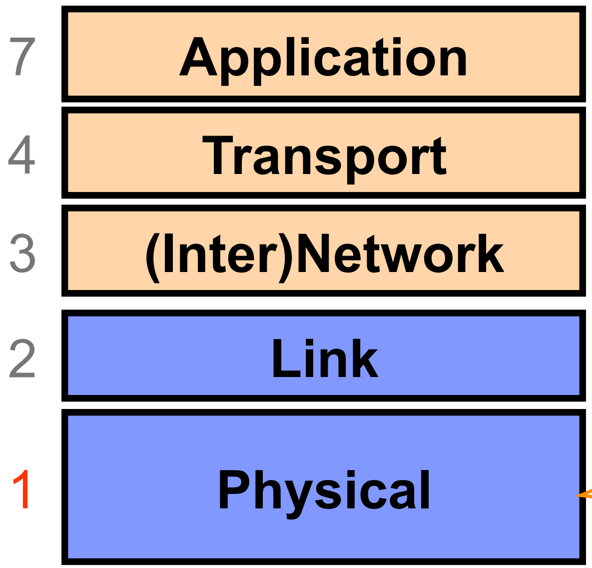
Vertical View of a Single Packet



Internet Layering ("Protocol Stack")



Layer 1: Physical Layer



Encoding bits to send them over a single **physical link**

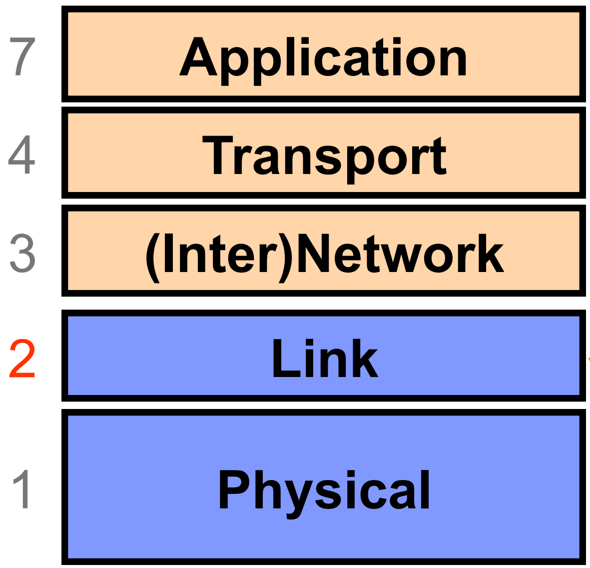
e.g. patterns of

voltage levels /

photon intensities /

RF modulation

Layer 2: Link Layer

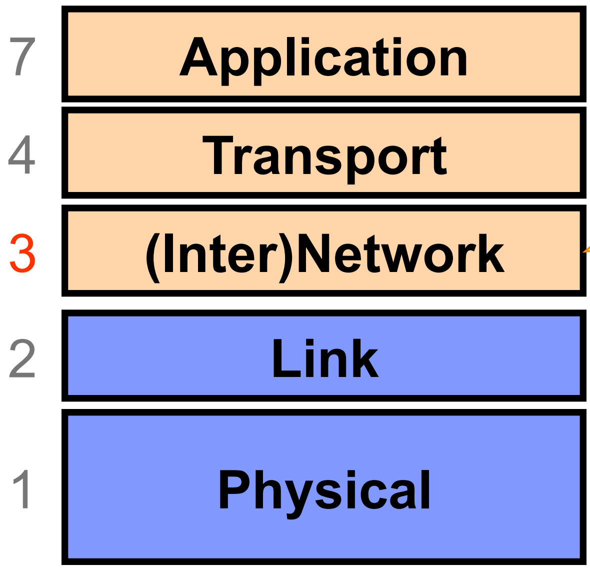


Framing and transmission of a collection of bits into individual messages sent across a single “subnetwork” (one physical technology)

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

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

Layer 3: (Inter)Network Layer *(IP)*



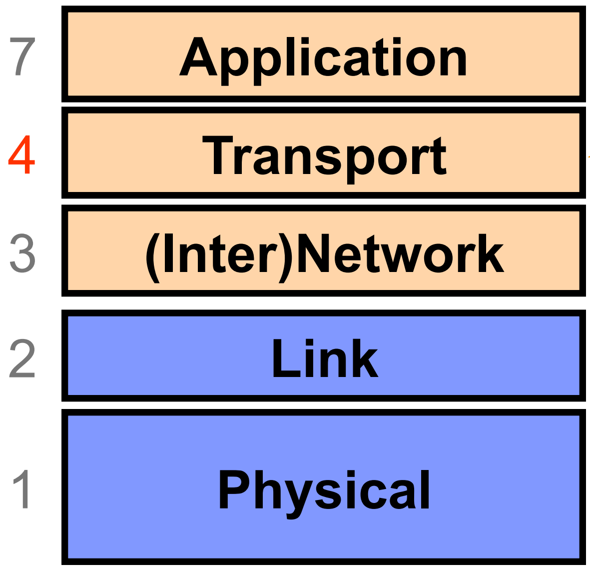
Bridges multiple "subnets" to provide *end-to-end* internet connectivity between nodes

- Provides global addressing

Works across different link technologies

Different **for each Internet "hop"**

Layer 4: Transport Layer



End-to-end communication between processes

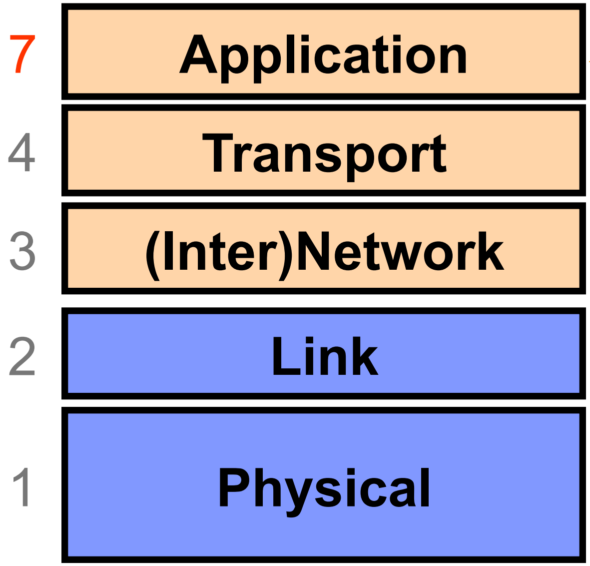
Different services provided:

TCP = reliable *byte stream*

UDP = unreliable *datagrams*

(Datagram = single packet message)

Layer 7: Application Layer



Communication of whatever you wish

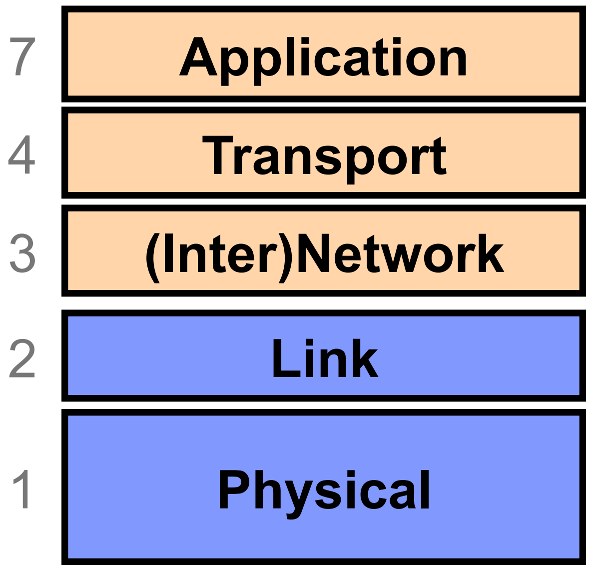
Can use whatever transport(s) is convenient

Freely structured

E.g.:

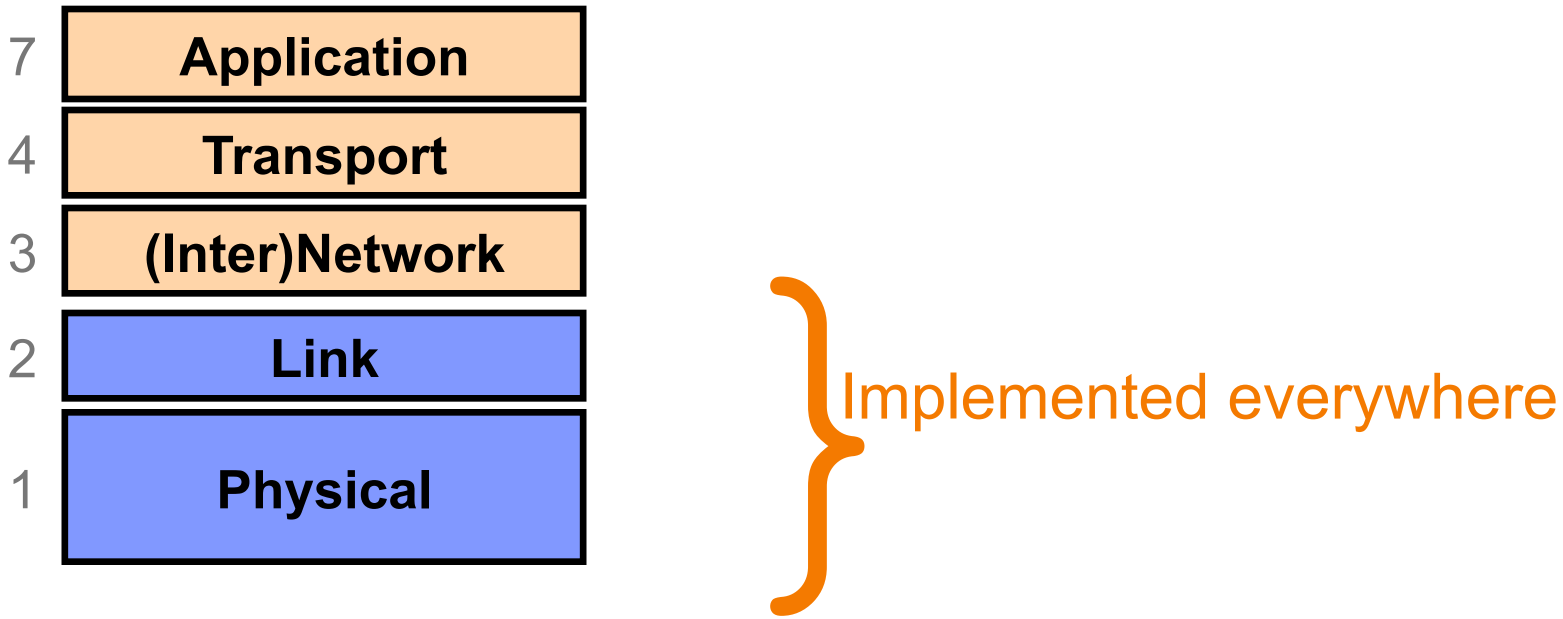
Skype, SMTP (email),
HTTP (Web), Halo, BitTorrent

Internet Layering ("Protocol Stack")



Implemented only at hosts,
not at interior routers
("dumb network")

Internet Layering ("Protocol Stack")



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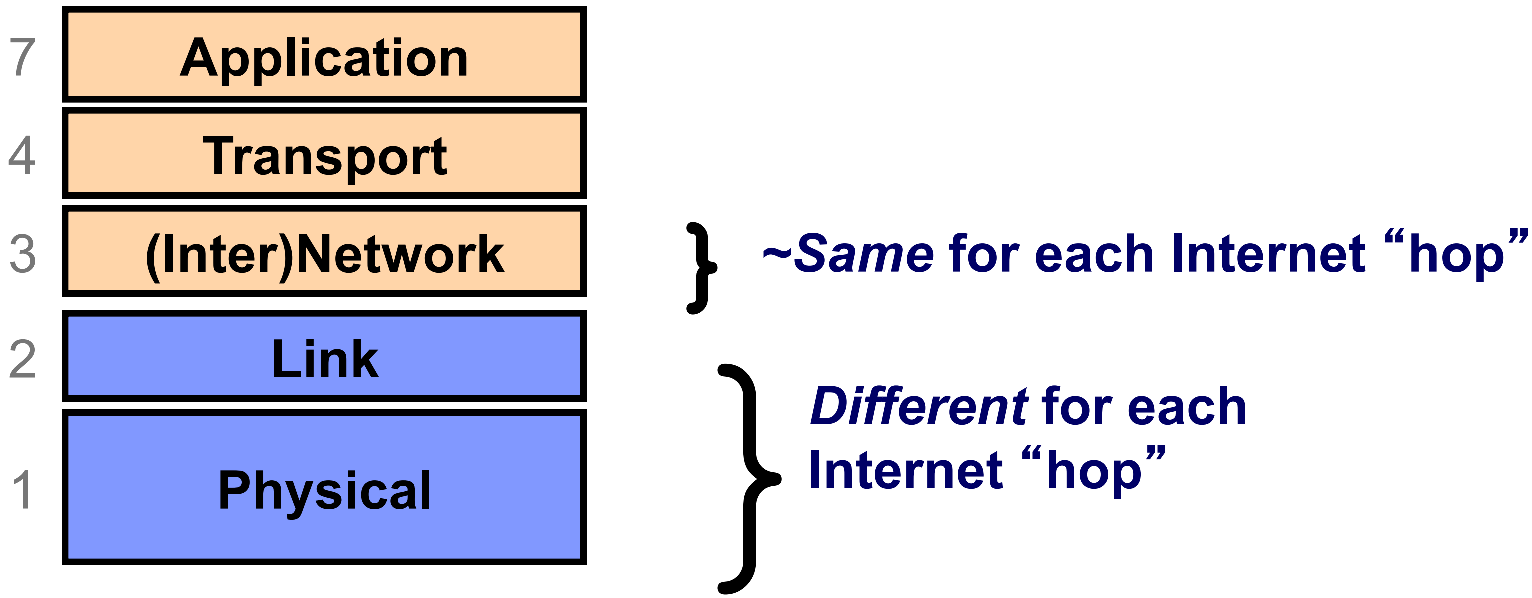
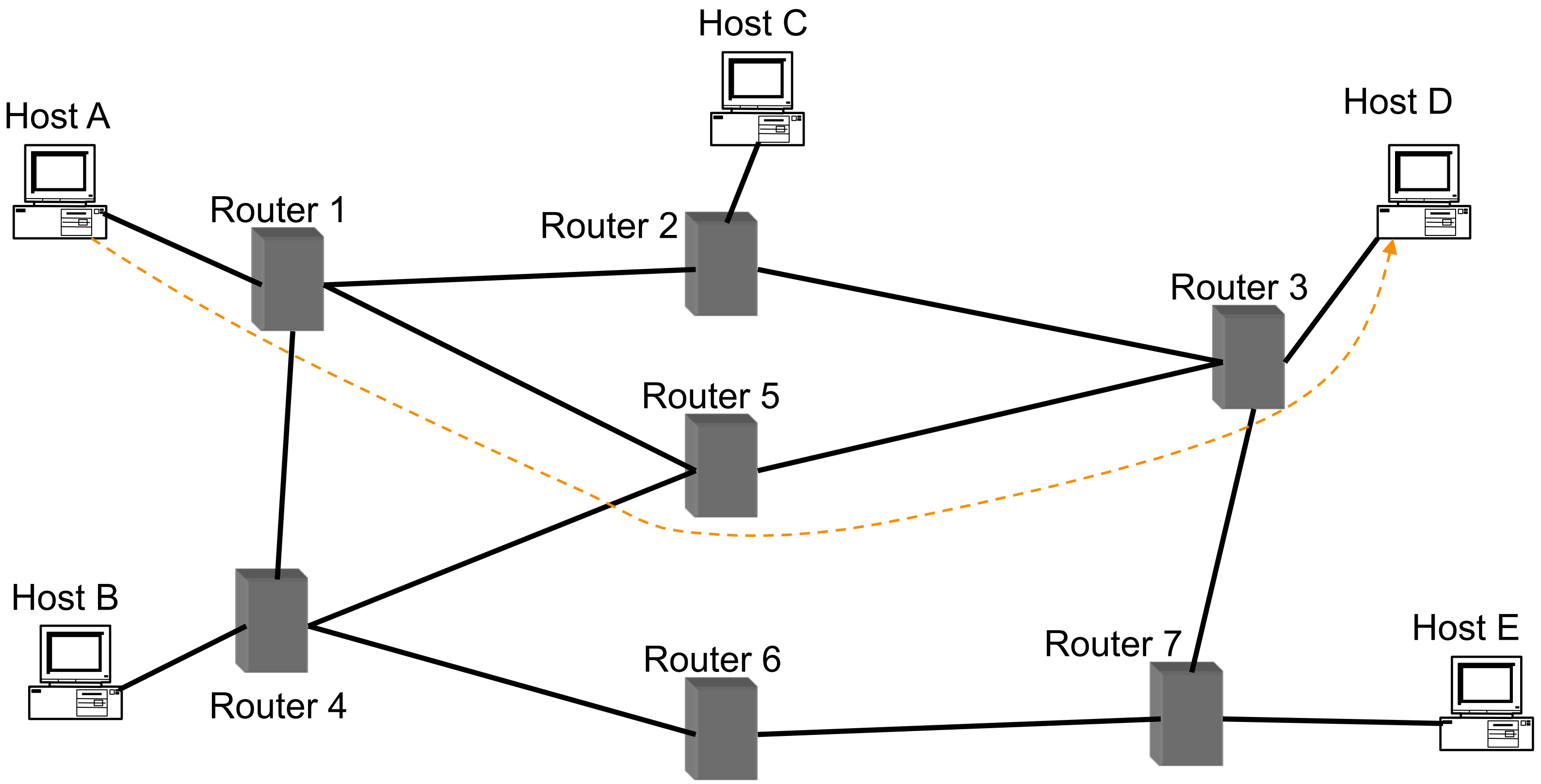


Hop-By-Hop vs. End-to-End Layers

Host A communicates with Host D



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

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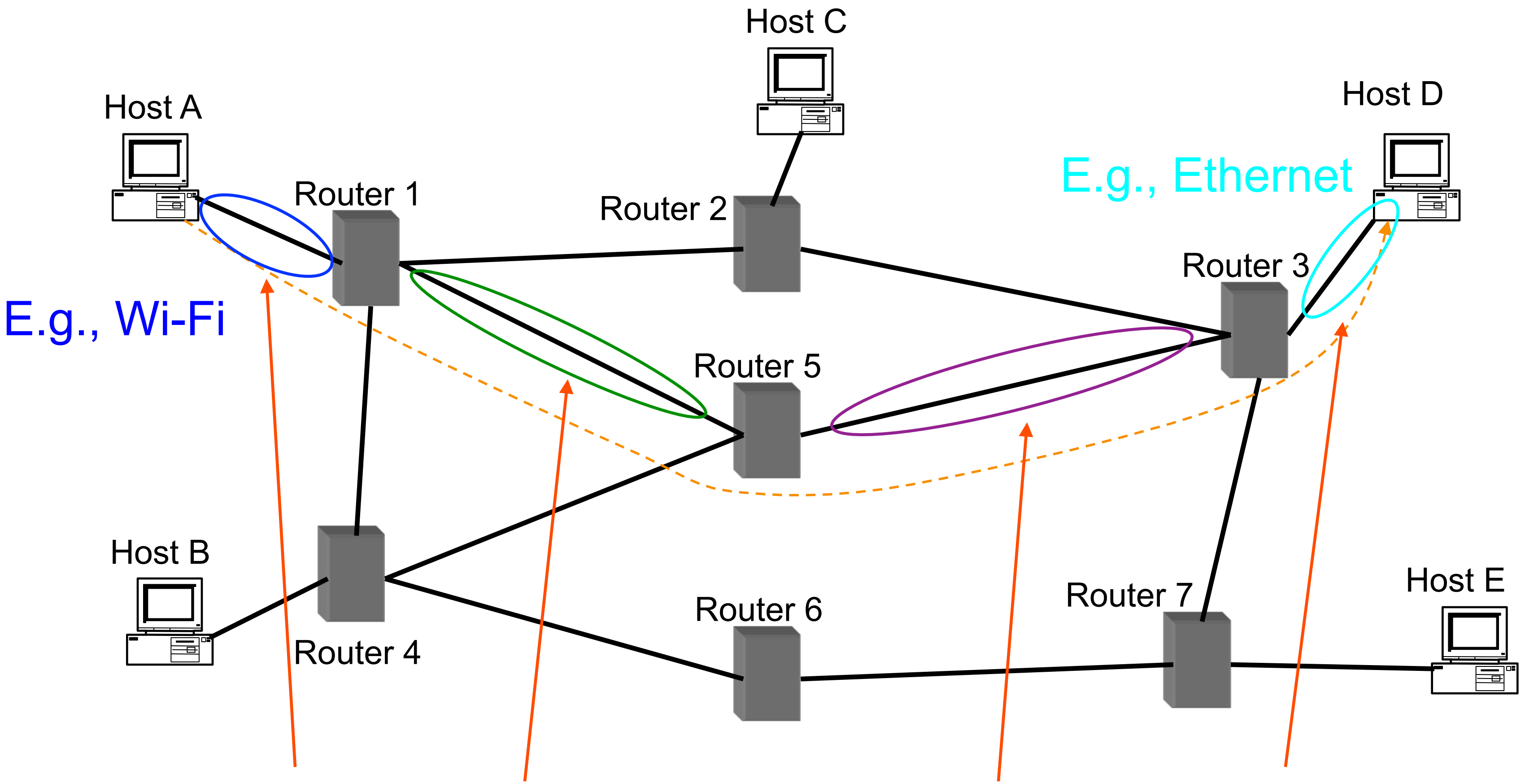
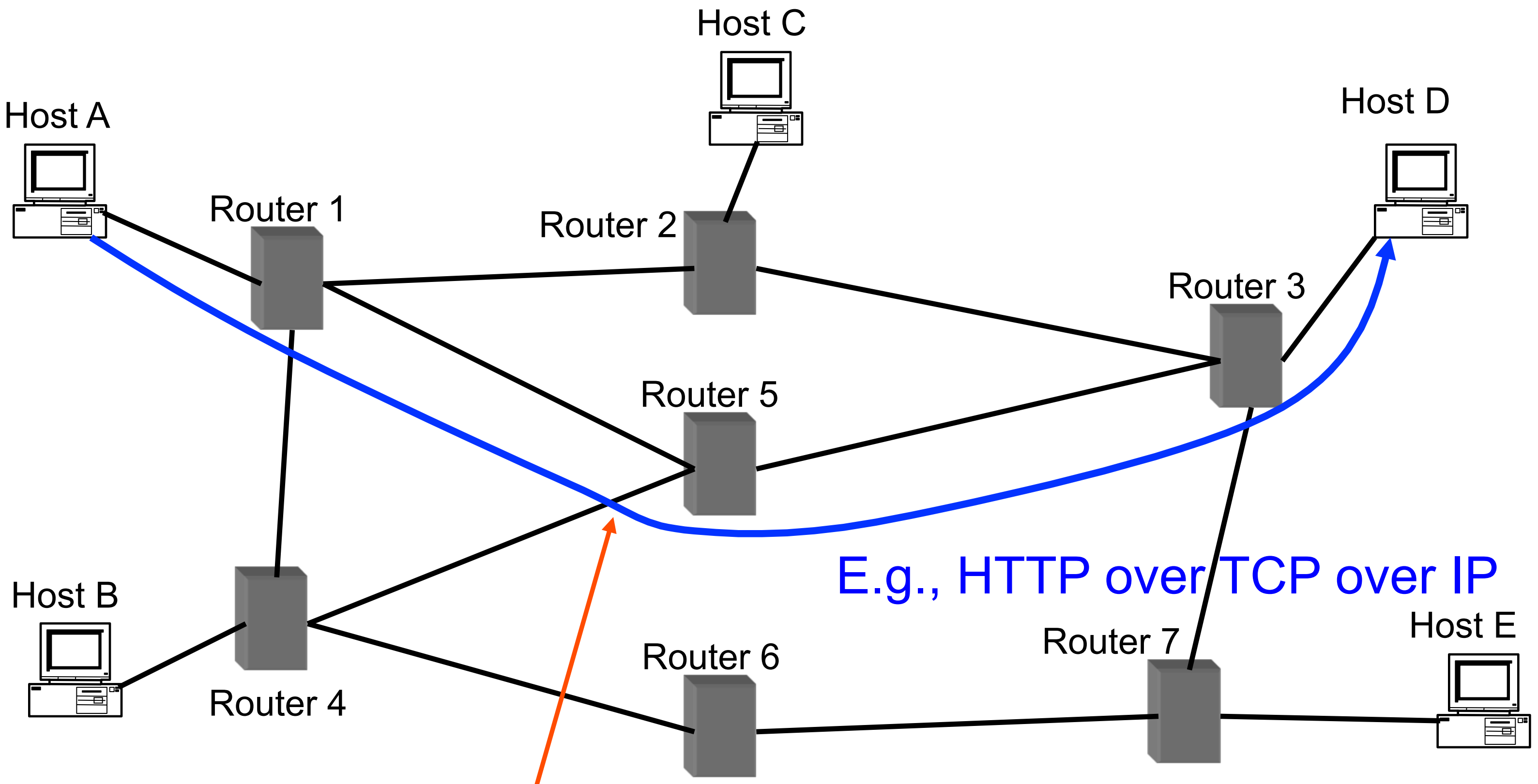


***Different* Physical & Link Layers (Layers 1 & 2)**

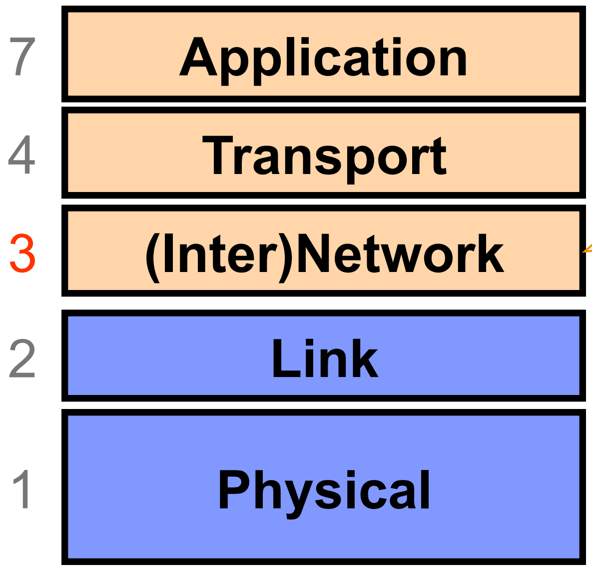
Hop-By-Hop vs. End-to-End Layers

Host A communicates with Host D



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

Layer 3: (Inter)Network Layer *(IP)*

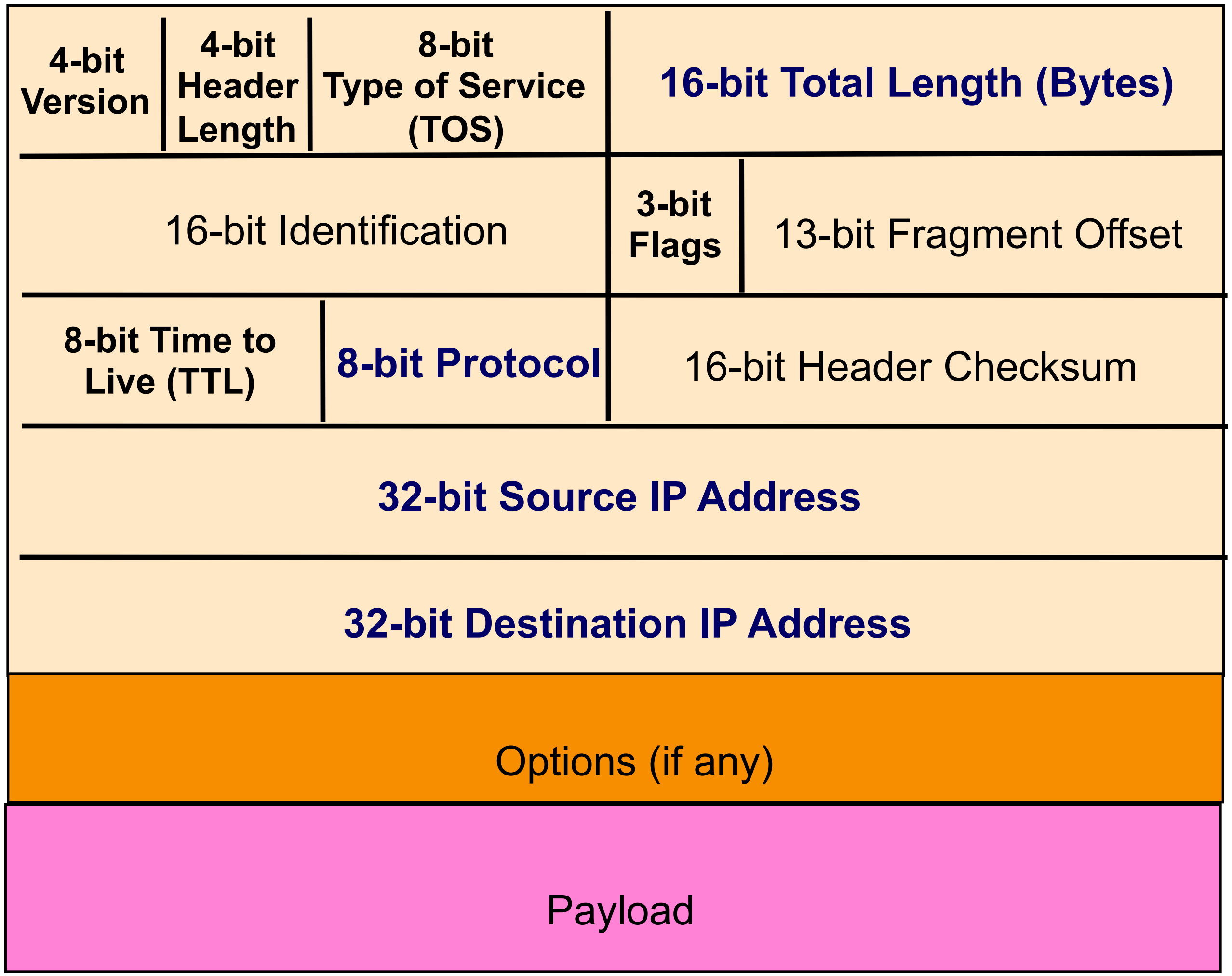


Bridges multiple "subnets" to provide *end-to-end* internet connectivity between nodes

- Provides global addressing

Works across different link technologies

IP Packet Structure



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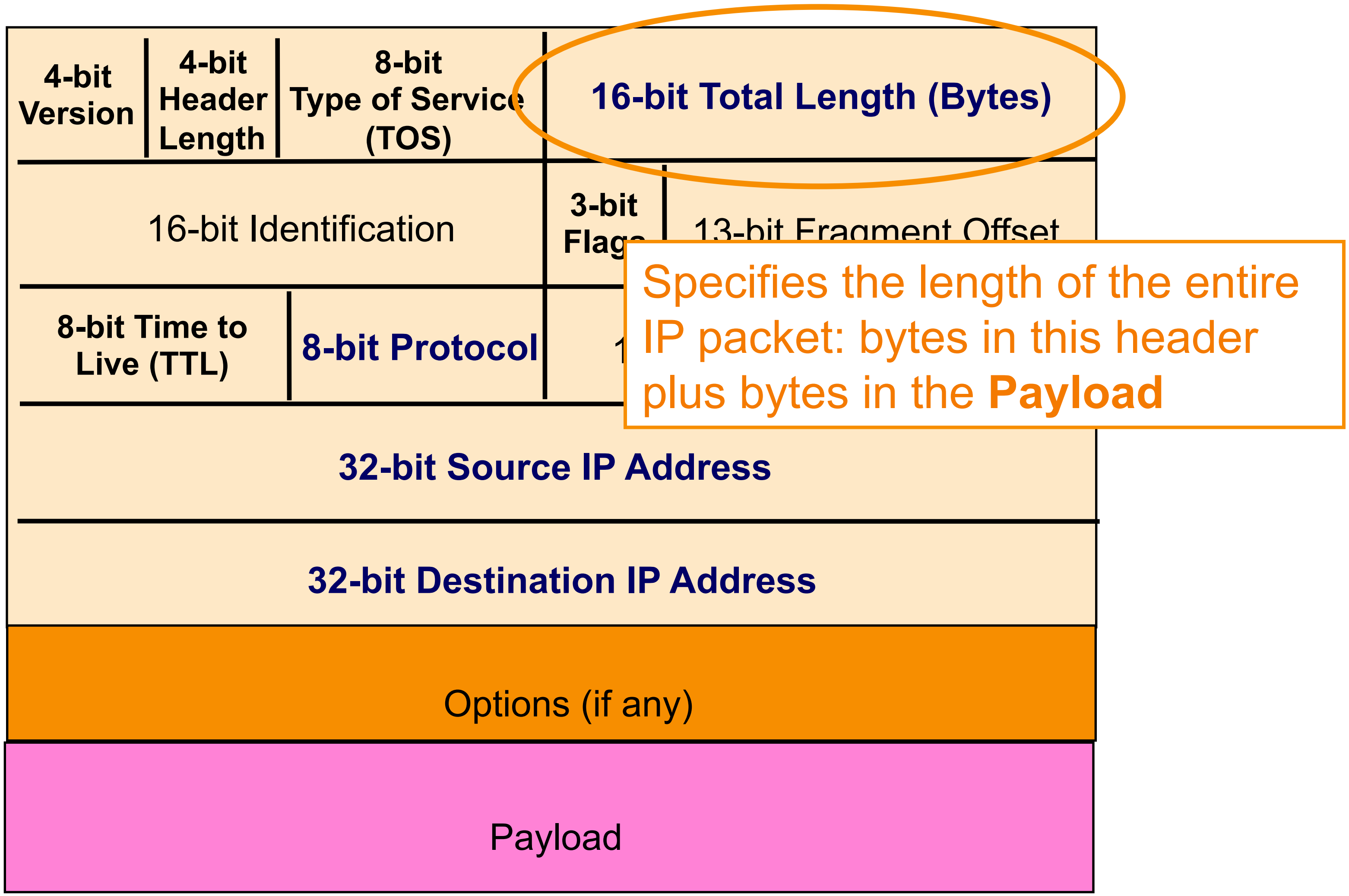

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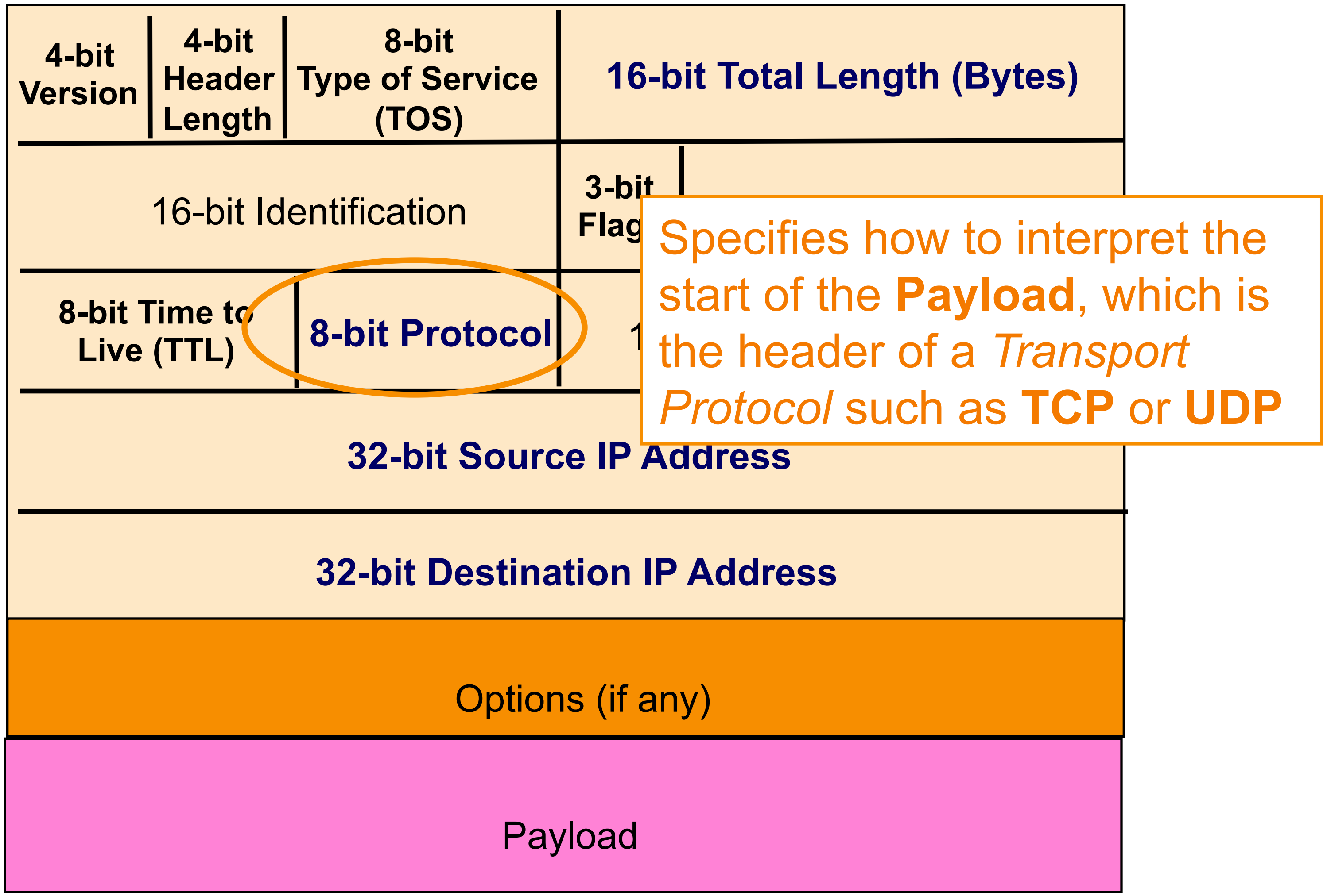

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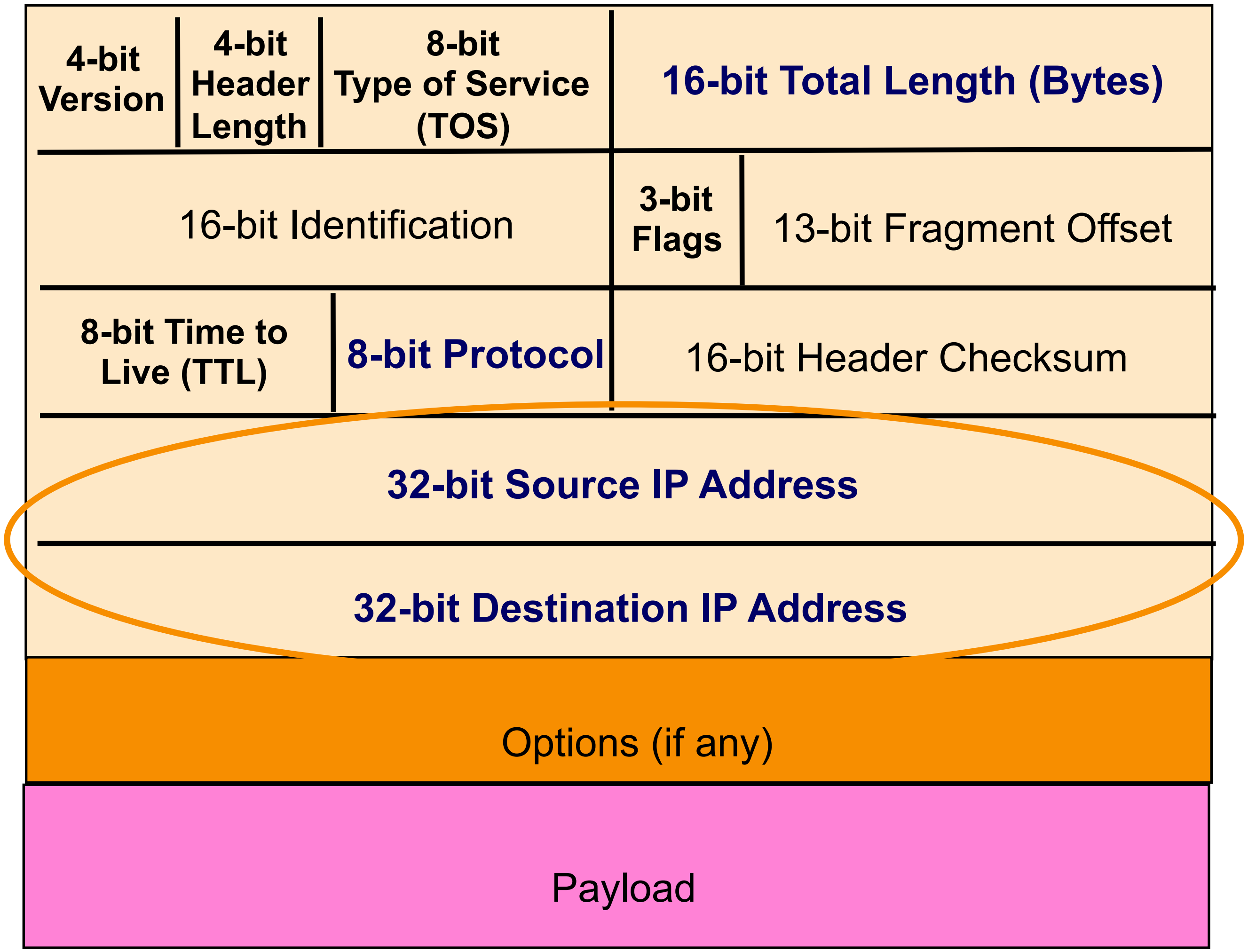
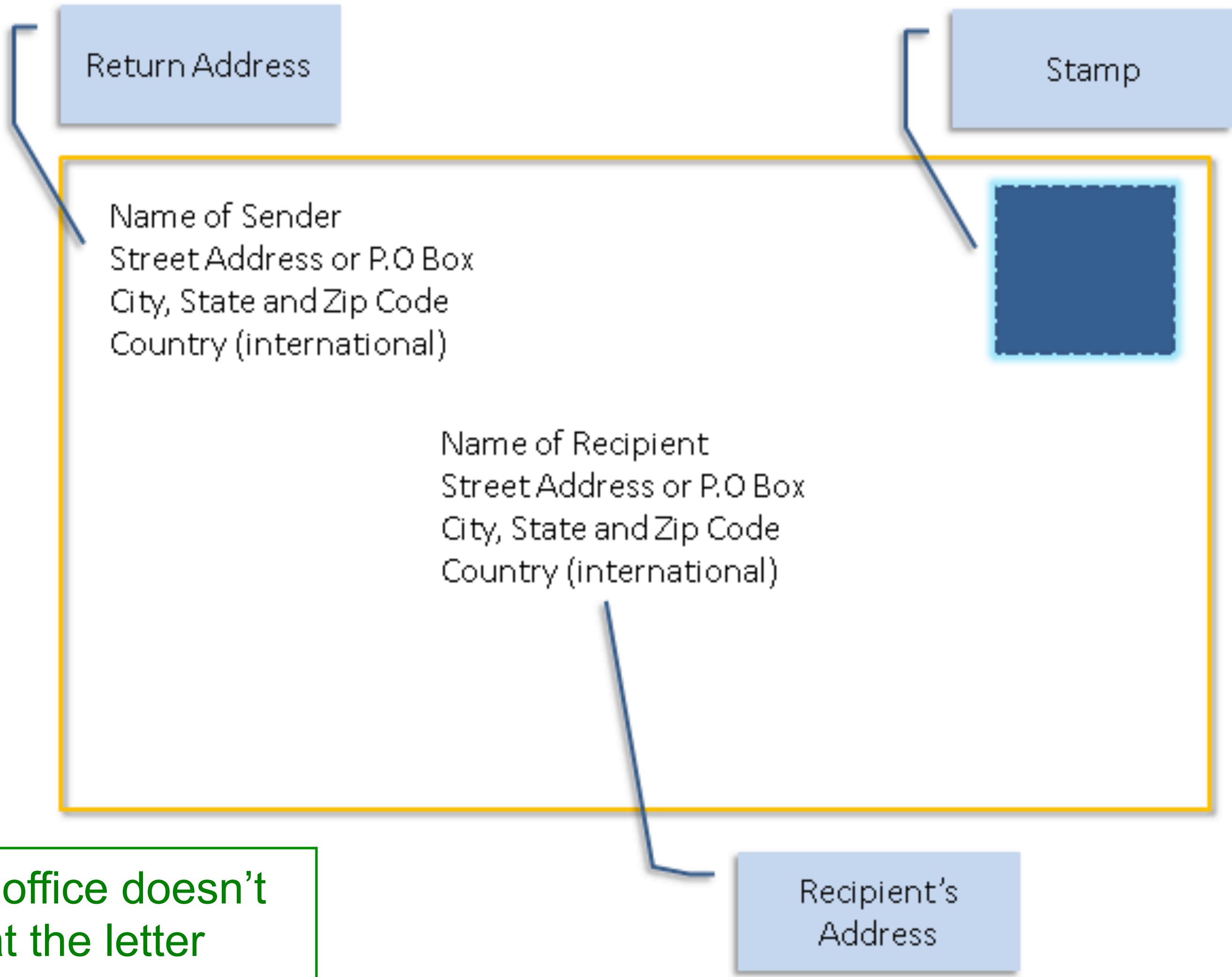


IP Packet Header (Continued)

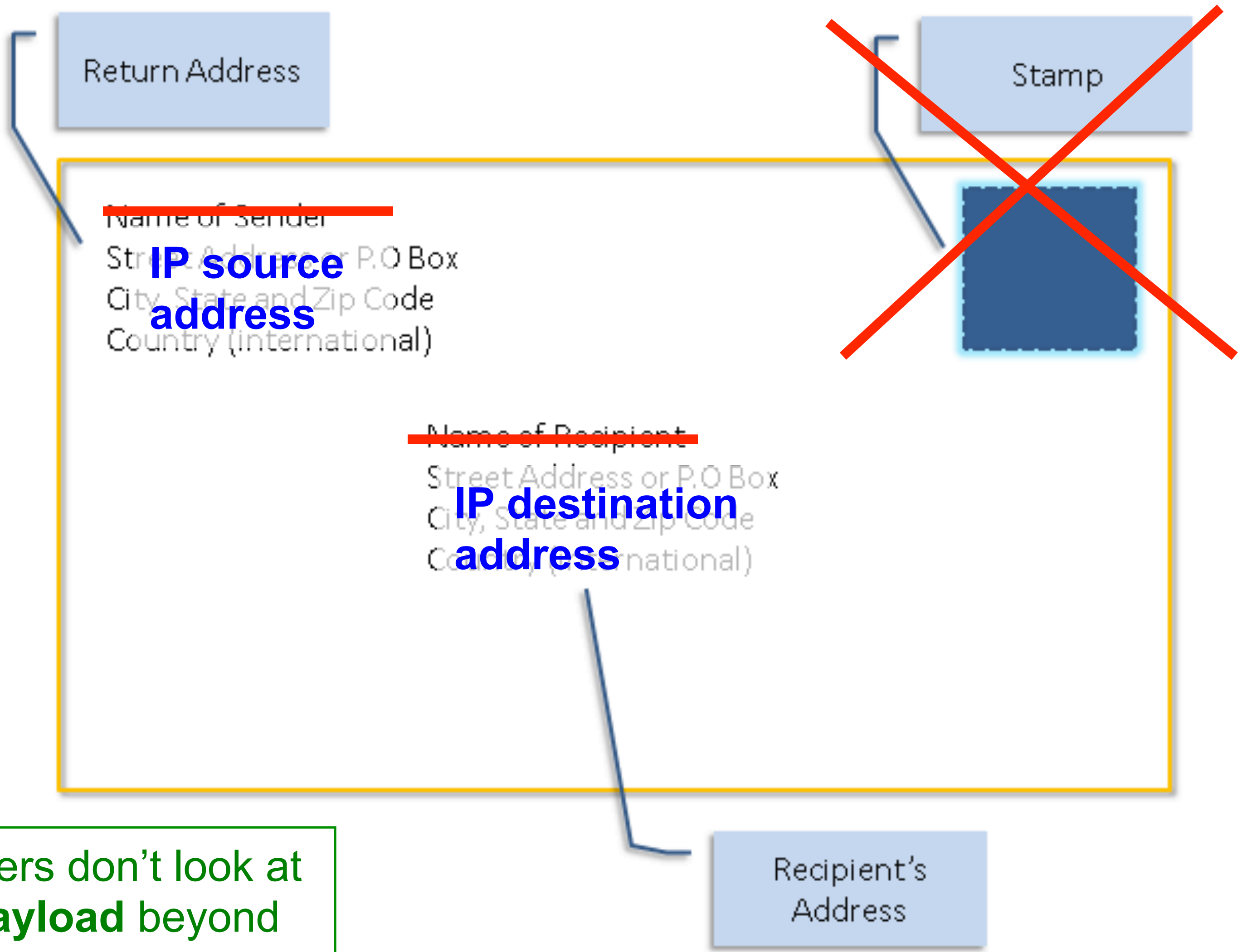
- Two IP addresses
  - Source IP address (32 bits)
  - Destination IP address (32 bits)
- Destination address
  - Unique identifier/locator for the receiving host
  - Allows each node to make forwarding decisions
- Source address
  - Unique identifier/locator for the sending host
  - Recipient can decide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

Postal Envelopes:



(Post office doesn't look at the letter inside the envelope)

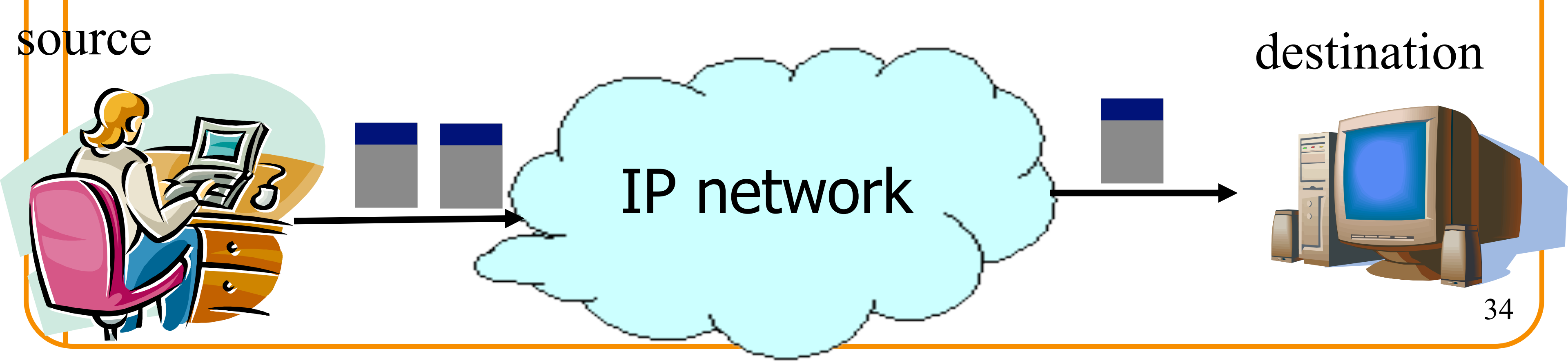
Analogy of IP to Postal Envelopes:



(Routers don't look at the **payload** beyond the IP header)

IP: "*Best Effort*" Packet Delivery

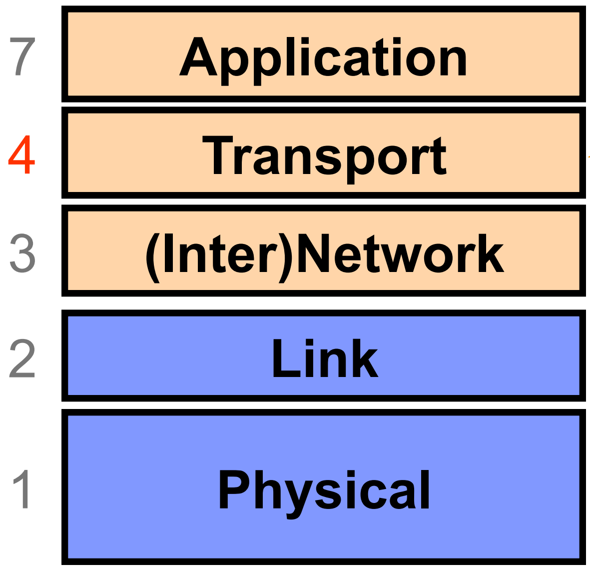
- Routers inspect destination address, locate "next hop" in forwarding table
  - Address = ~unique identifier/locator for the receiving host
- Only provides a "*I'll give it a try*" delivery service:
  - Packets may be lost
  - Packets may be corrupted
  - Packets may be delivered out of order



“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

Layer 4: Transport Layer



End-to-end communication between processes

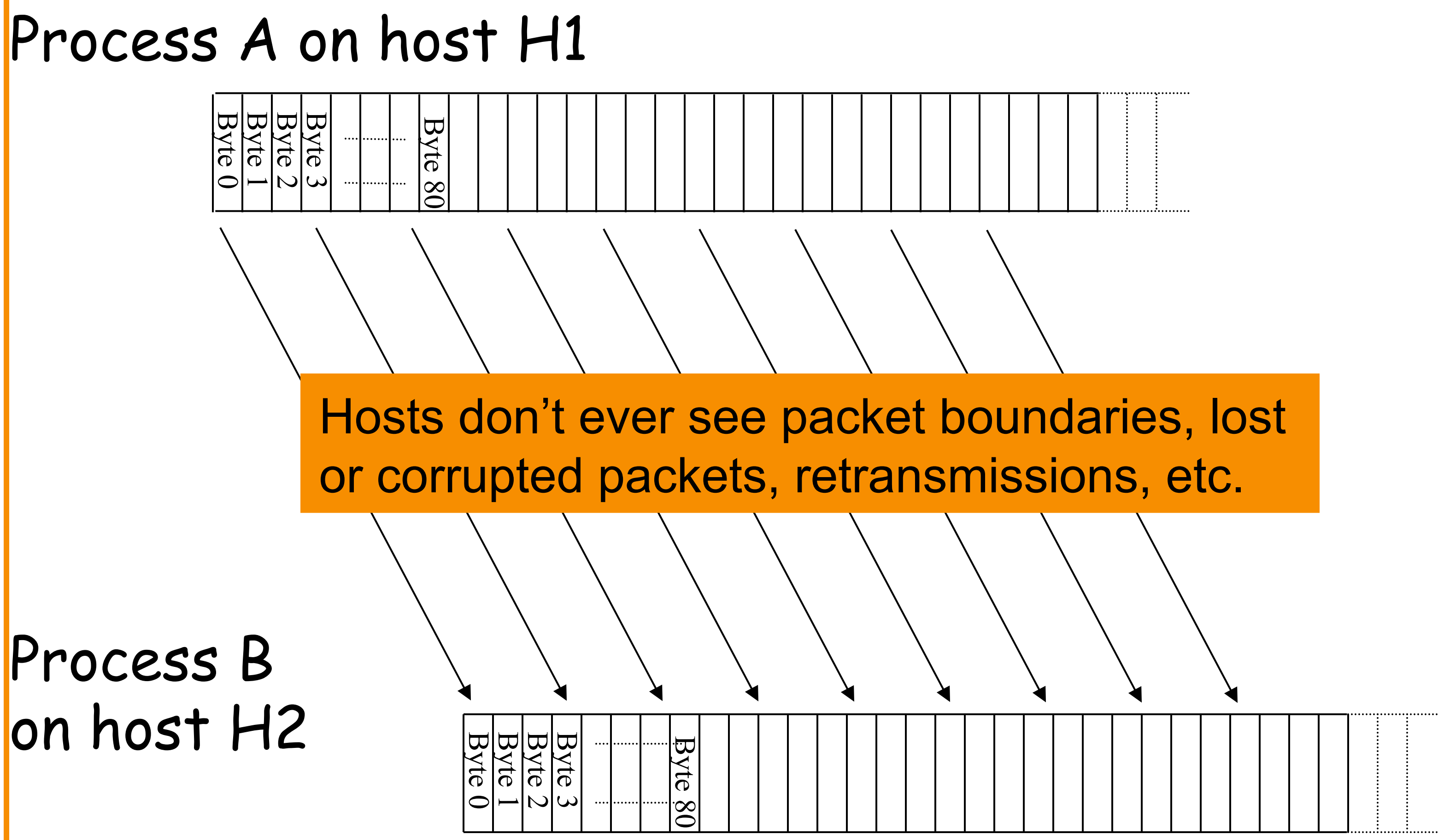
Different services provided:
TCP = reliable *byte stream*
UDP = unreliable *datagrams*

(Datagram = single packet message)

"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

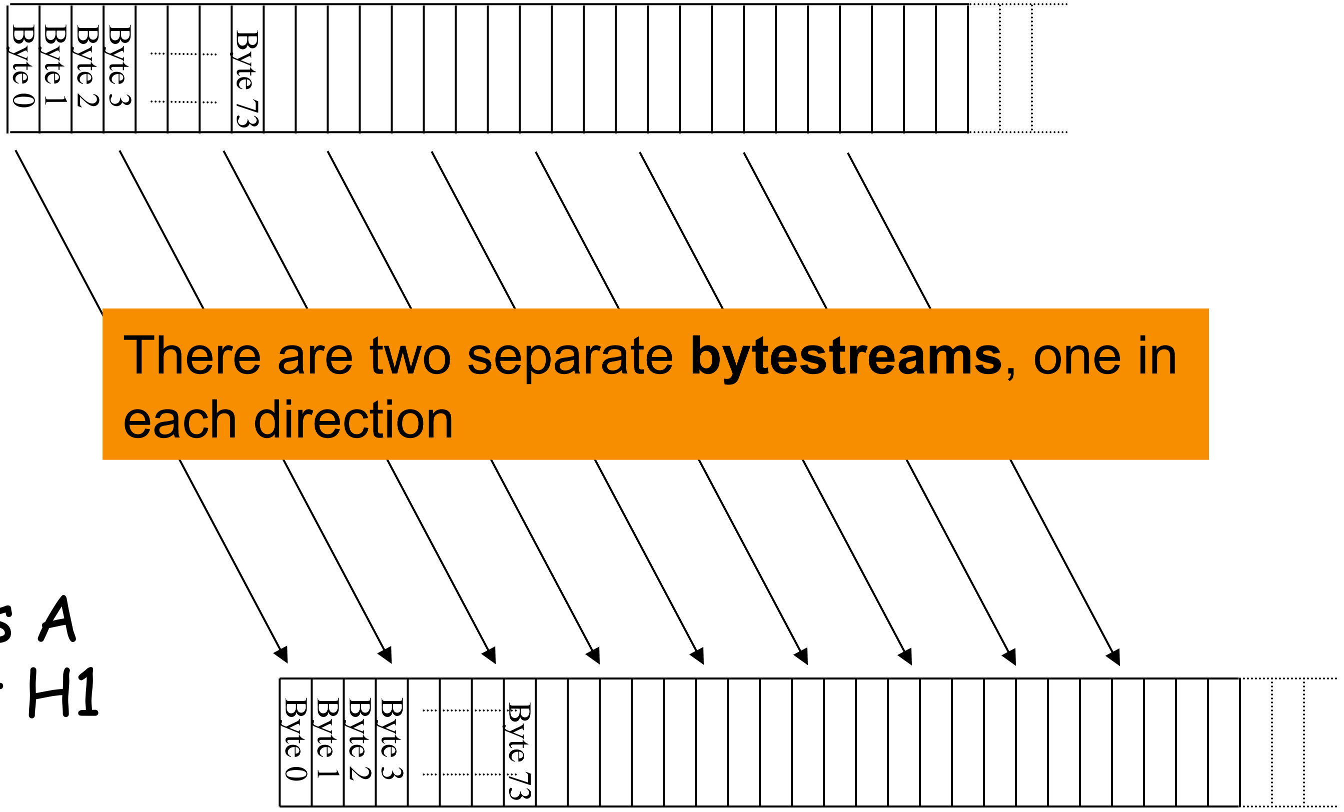
TCP "Bytestream" Service



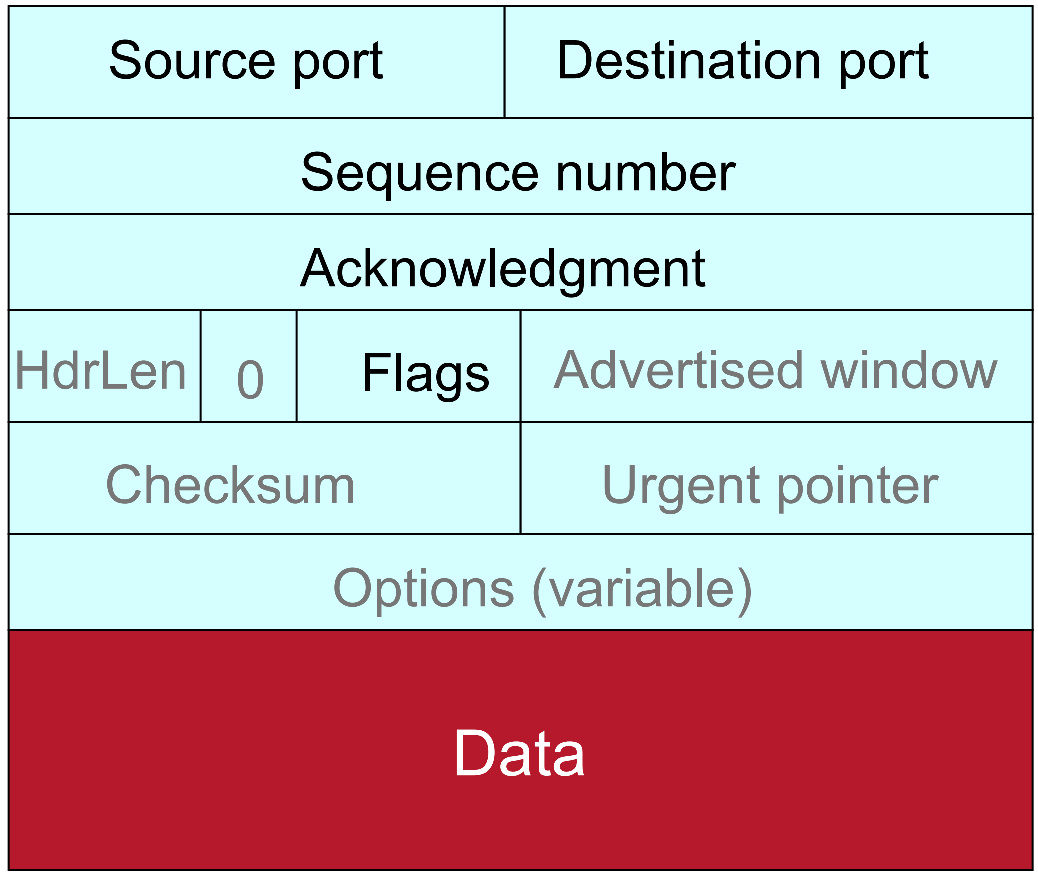
Bidirectional communication:

Process B on host H2

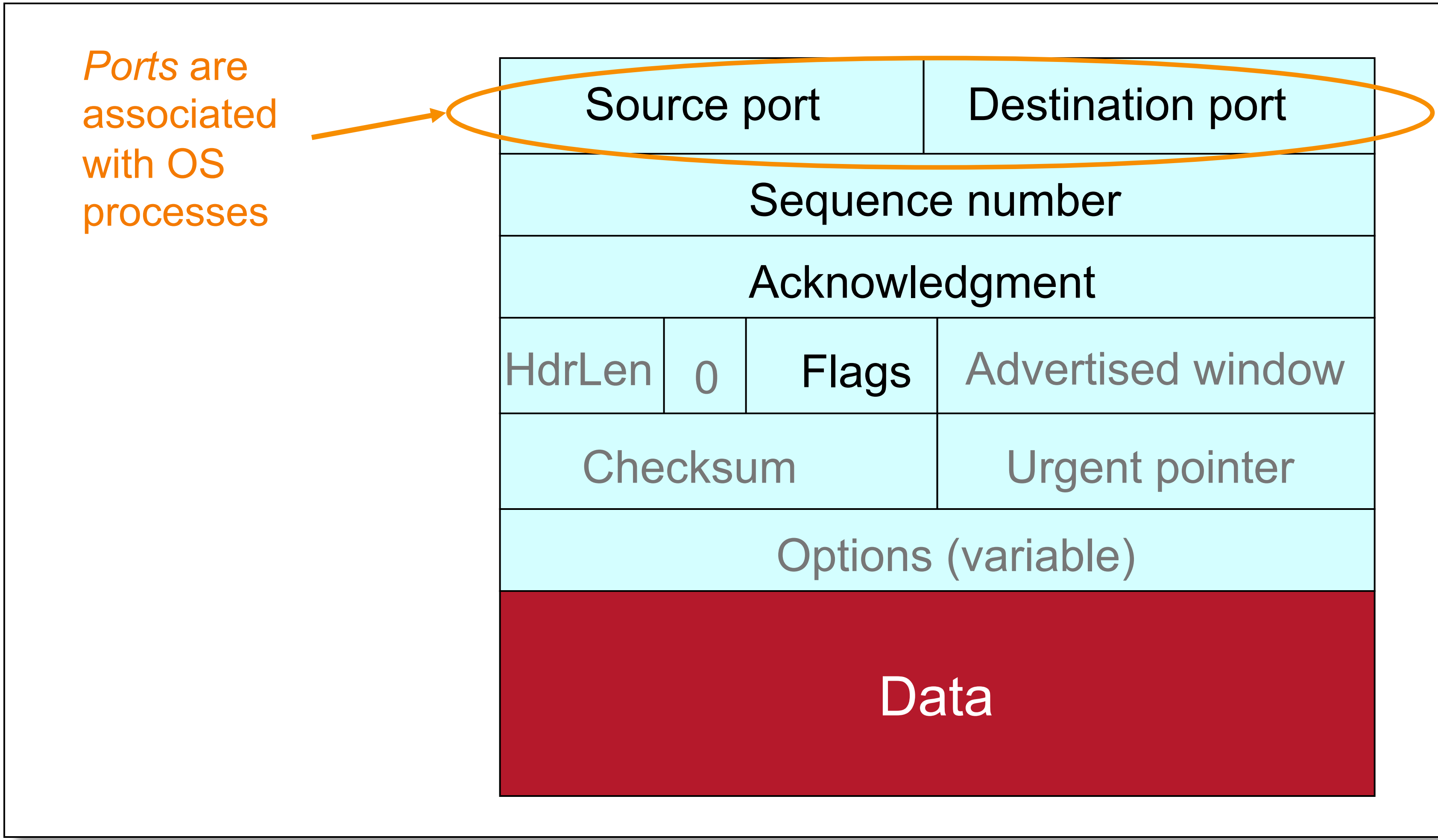
Process A
on host H1



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
Source port
Destination port
Sequence number
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HdrLen
0
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Data

TCP Header

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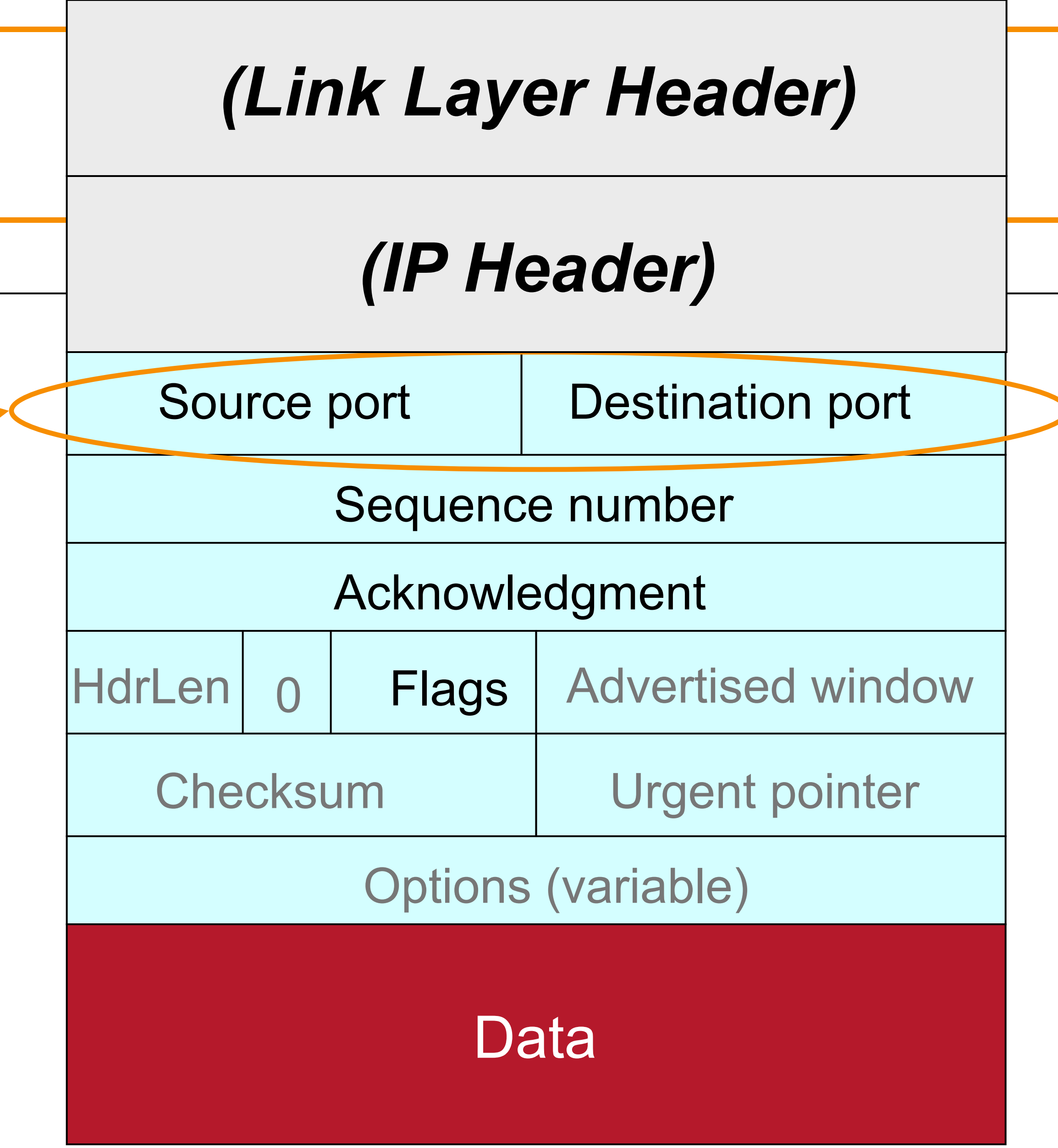
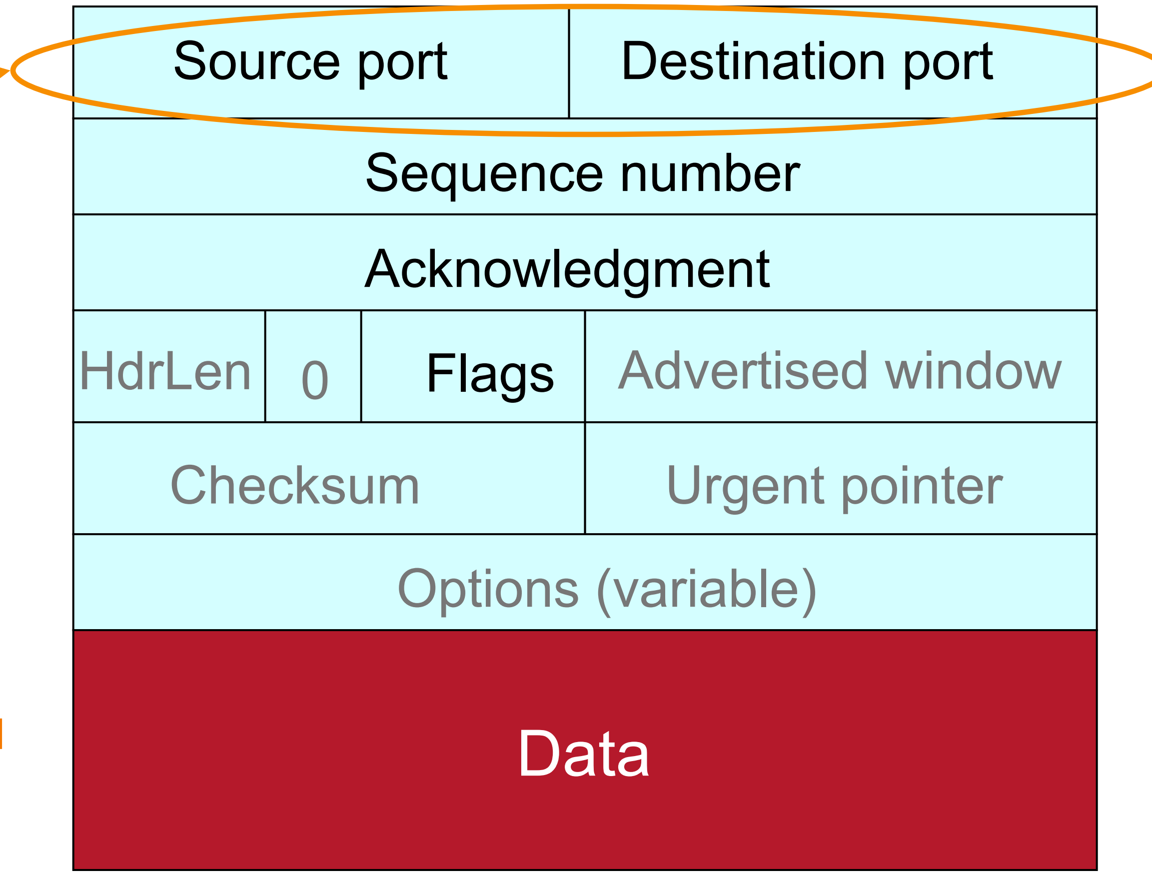


IP source & destination addresses plus TCP source and destination ports uniquely identifies a TCP connection

TCP Header

Ports are associated with OS processes

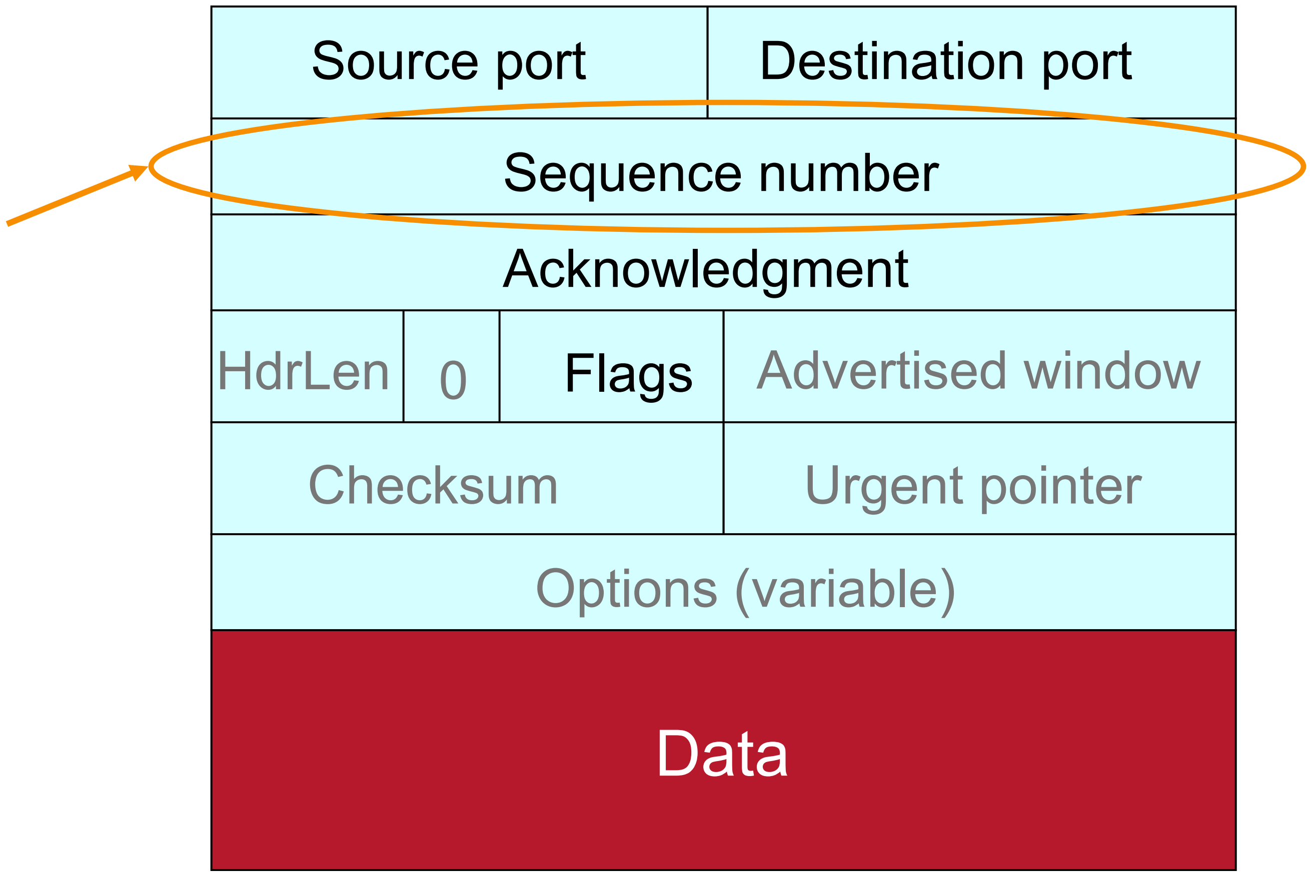


IP source & destination addresses plus TCP source and destination ports uniquely identifies a TCP connection

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



TCP Header

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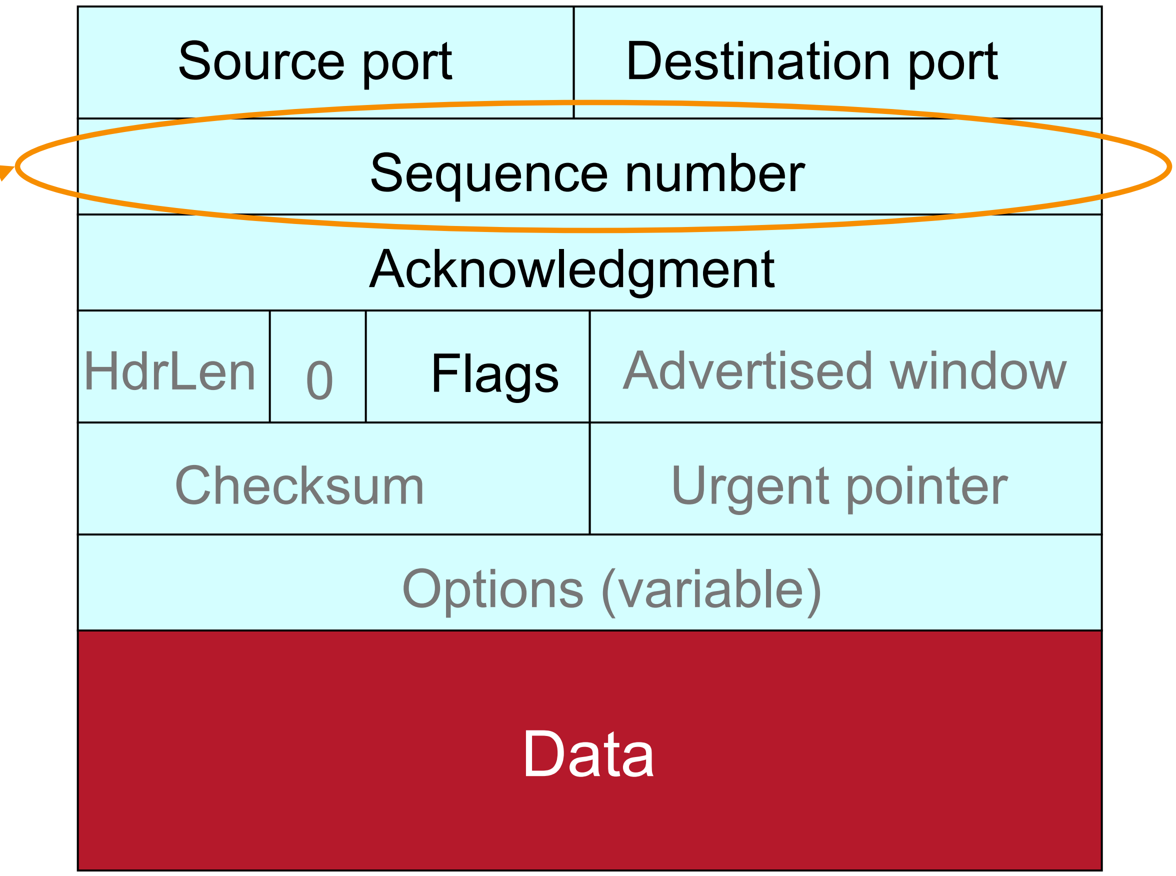

Byte streams numbered independently in each direction

TCP Header

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

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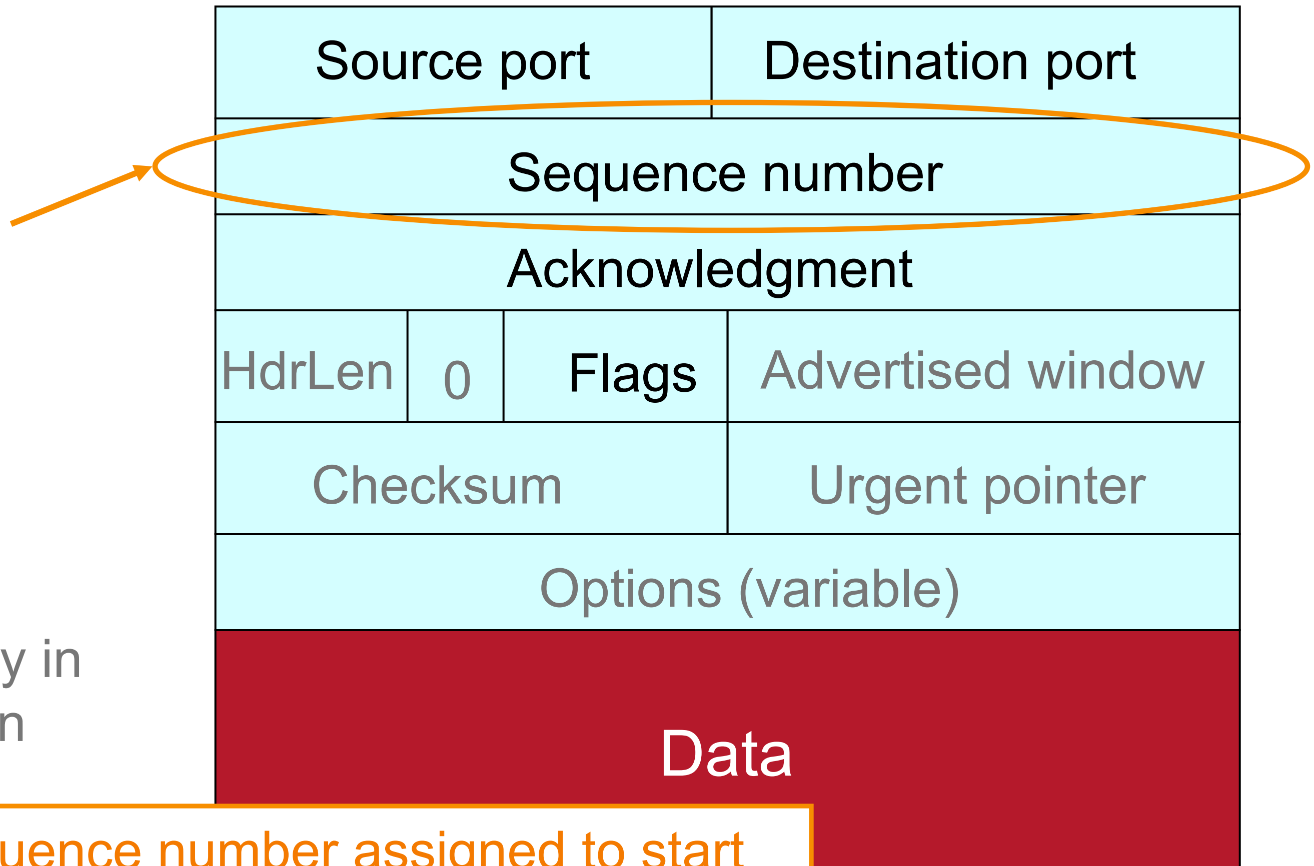
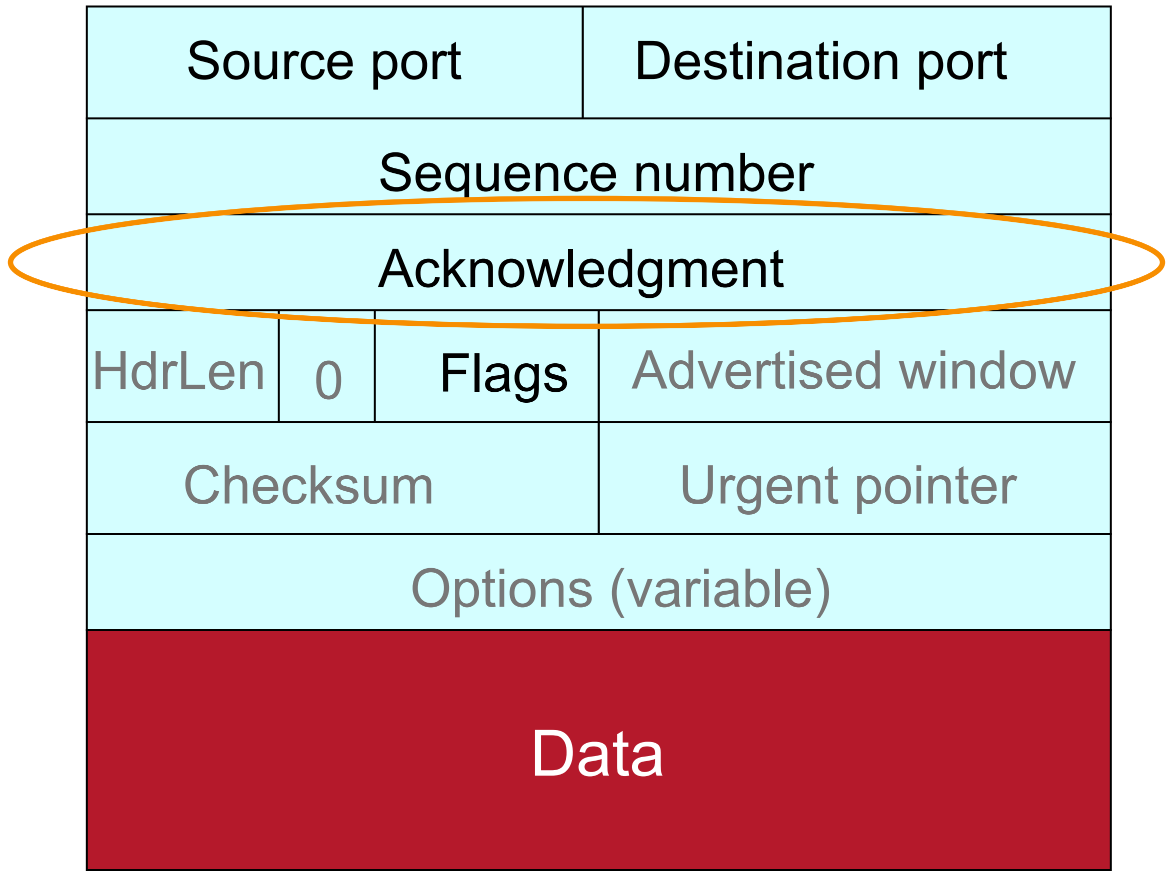


Sequence number assigned to start of byte stream is picked when connection begins; **doesn't** start at 0

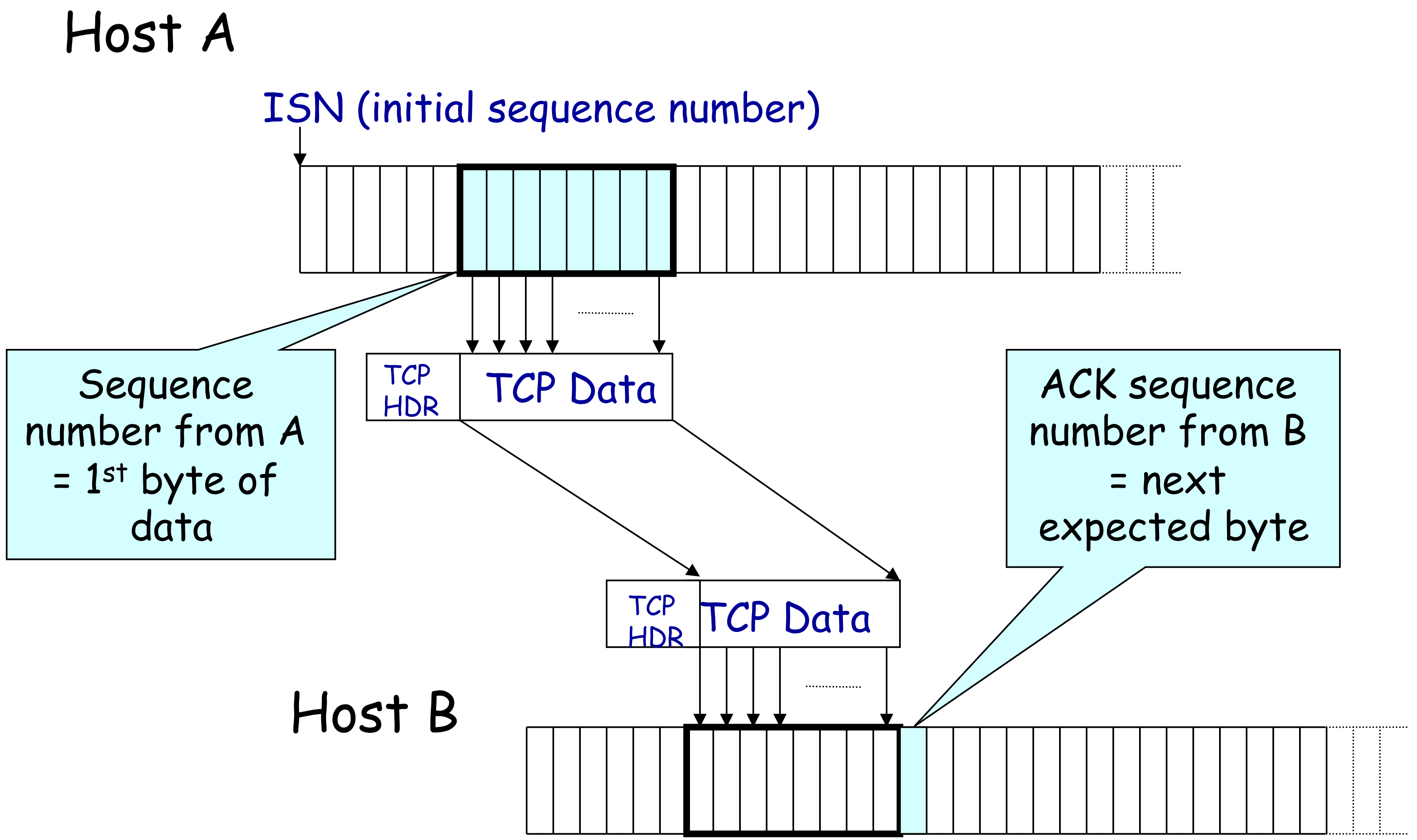
TCP Header

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

If sender sends **N** bytestream bytes starting at seq **S** then “ack” for it will be **S+N**.



Sequence Numbers

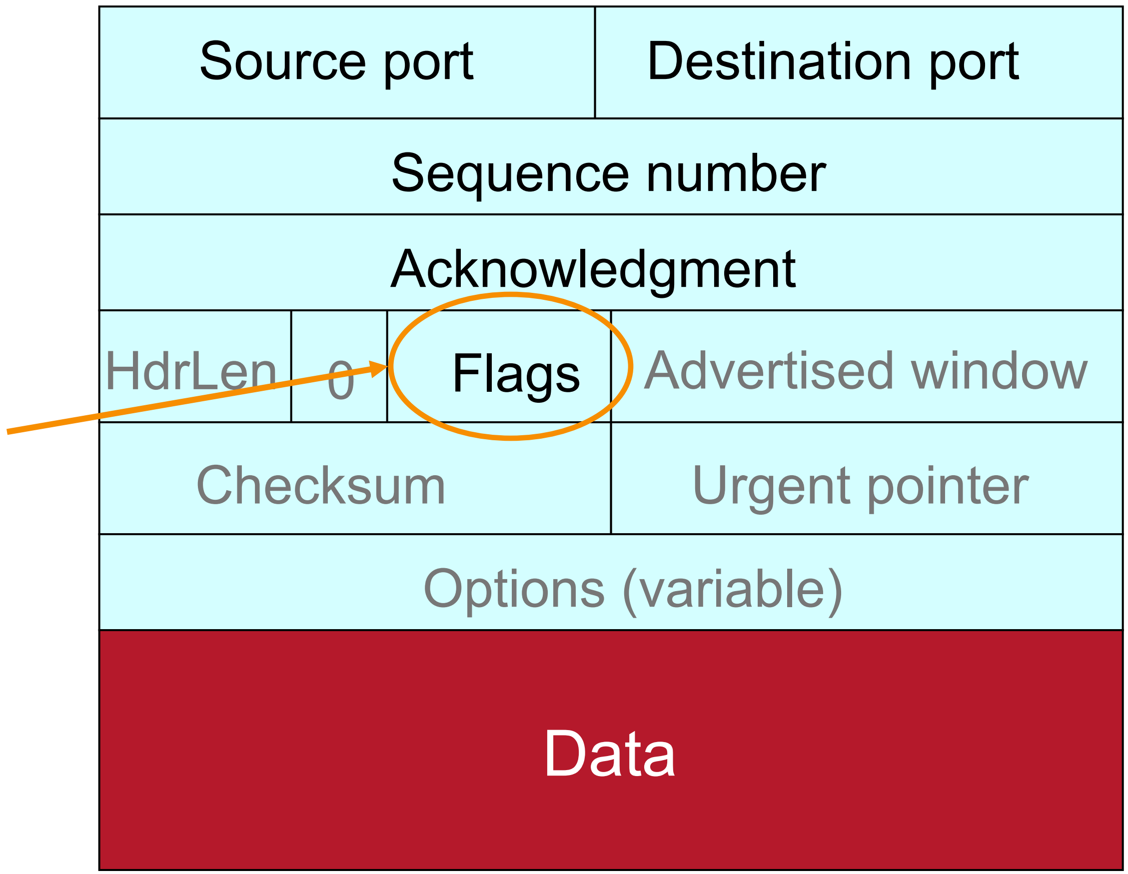


TCP Header

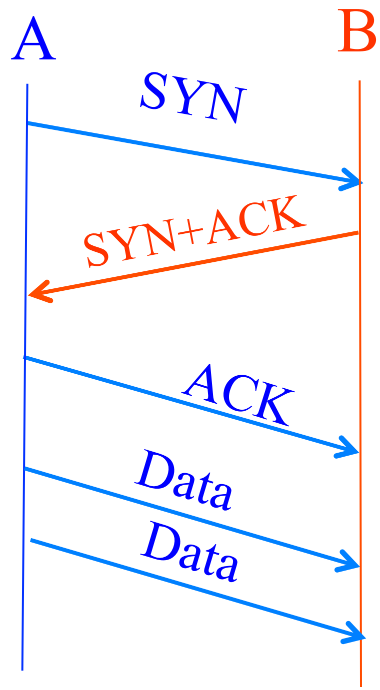
Uses include:

acknowledging data (“`ACK`”)

setting up (“`SYN`”) and closing connections (“`FIN`” and “`RST`”)



Establishing a TCP Connection

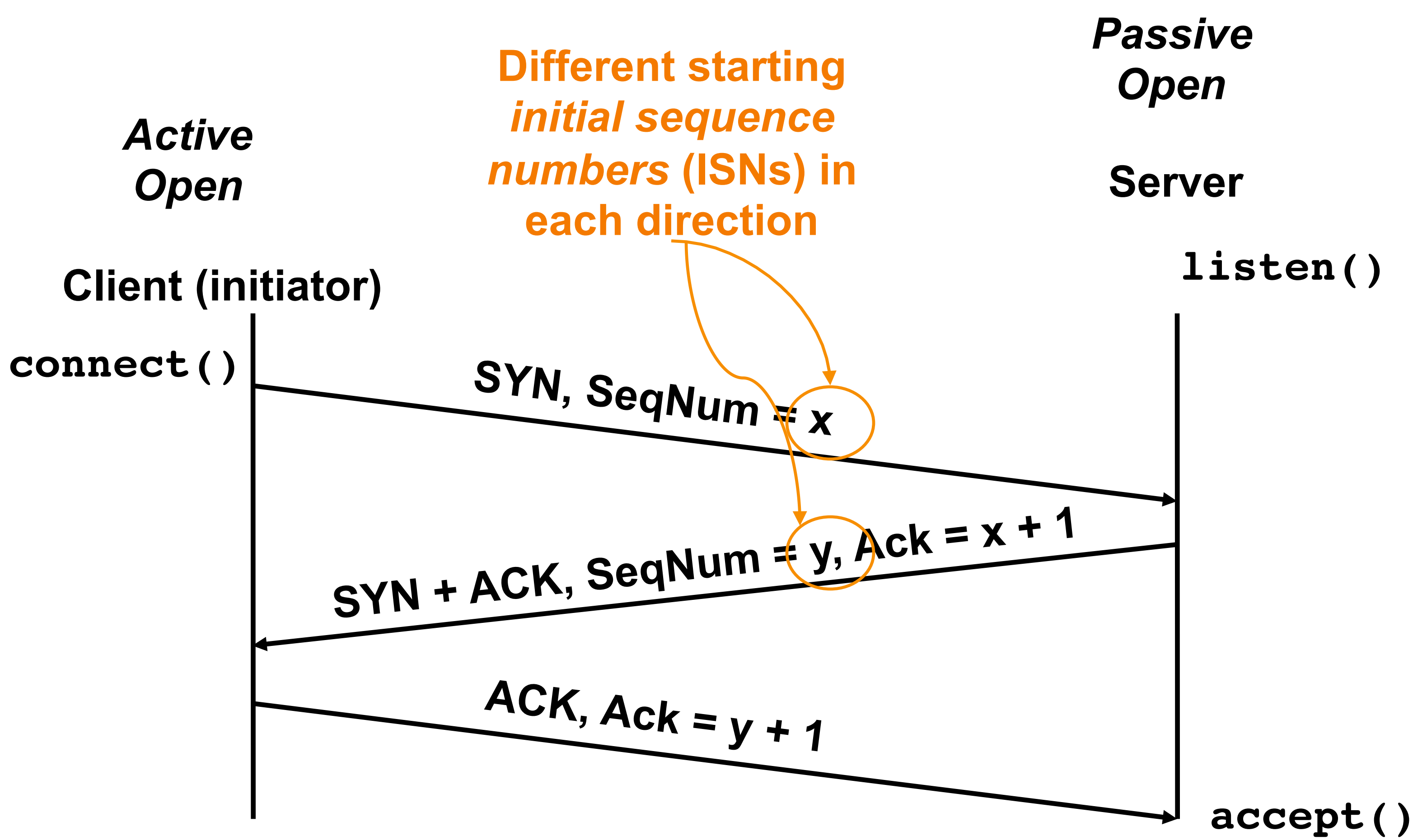


Each host tells its *Initial Sequence Number* (ISN) to the other host.

(Spec says to pick based on local clock)

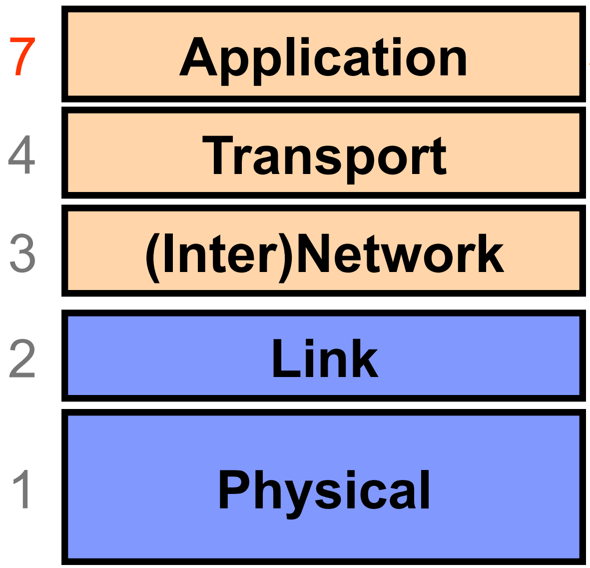
- Three-way handshake to establish connection
  - Host A sends a **SYN** (open; "synchronize sequence numbers") to host B
  - Host B returns a SYN acknowledgment (**SYN+ACK**)
  - Host A sends an **ACK** to acknowledge the SYN+ACK

Timing Diagram: 3-Way Handshaking



Extra Material

Layer 7: Application Layer



Communication of whatever you wish

Can use whatever transport(s) is convenient

Freely structured

E.g.:

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

Web (HTTP) Request

Method **Resource** **HTTP version** **Headers**

```
GET /index.html HTTP/1.1
Accept: image/gif, image/x-bitmap, image/jpeg, */*
Accept-Language: en
Connection: Keep-Alive
User-Agent: Mozilla/1.22 (compatible; MSIE 2.0; Windows 95)
Host: www.example.com
Referer: http://www.google.com?q=dingbats

```

Blank line

Data (if POST; none for GET)

GET: download data.	POST: upload data.

Web (HTTP) Response

HTTP version   Status code   Reason phrase

Headers

Data

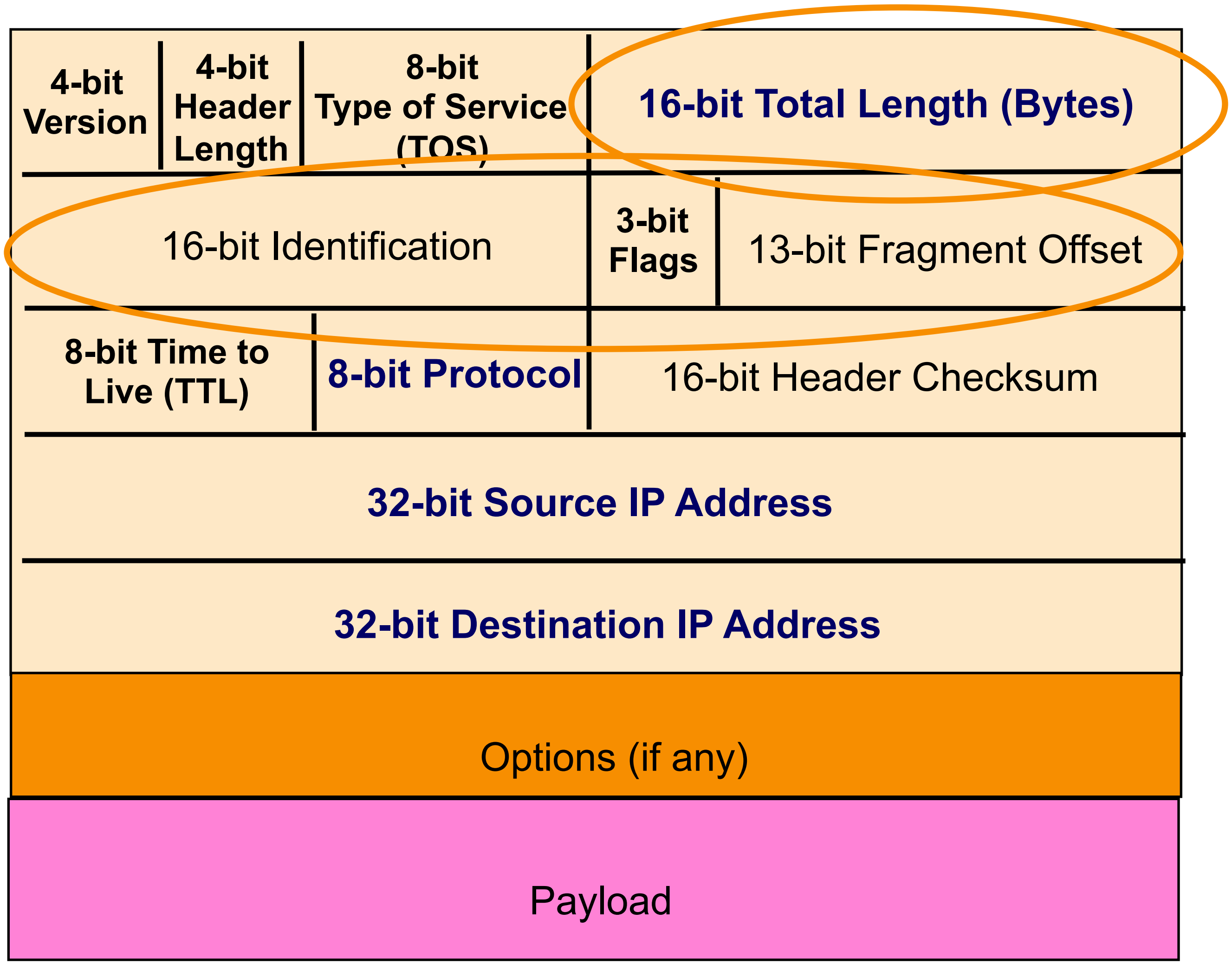
```
HTTP/1.0 200 OK
Date: Sun, 19 Apr 2009 02:20:42 GMT
Server: Microsoft-Internet-Information-Server/5.0
Connection: keep-alive
Content-Type: text/html
Last-Modified: Sat, 18 Apr 2009 17:39:05 GMT
Set-Cookie: session=44eb; path=/servlets
Content-Length: 2543

<HTML> Some data... blah, blah, blah </HTML>
```

Host Names vs. IP addresses

- Host names
  - Examples: `www.cnn.com` and `bbc.co.uk`
  - Mnemonic name appreciated by humans
  - Variable length, full alphabet of characters
  - Provide little (if any) information about location
- IP addresses
  - Examples: `64.236.16.20` and `212.58.224.131`
  - Numerical address appreciated by routers
  - Fixed length, binary number
  - Hierarchical, related to host location

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

Example: E-Mail Message Using MIME

MIME version

method used to encode data

type and subtype

encoded data

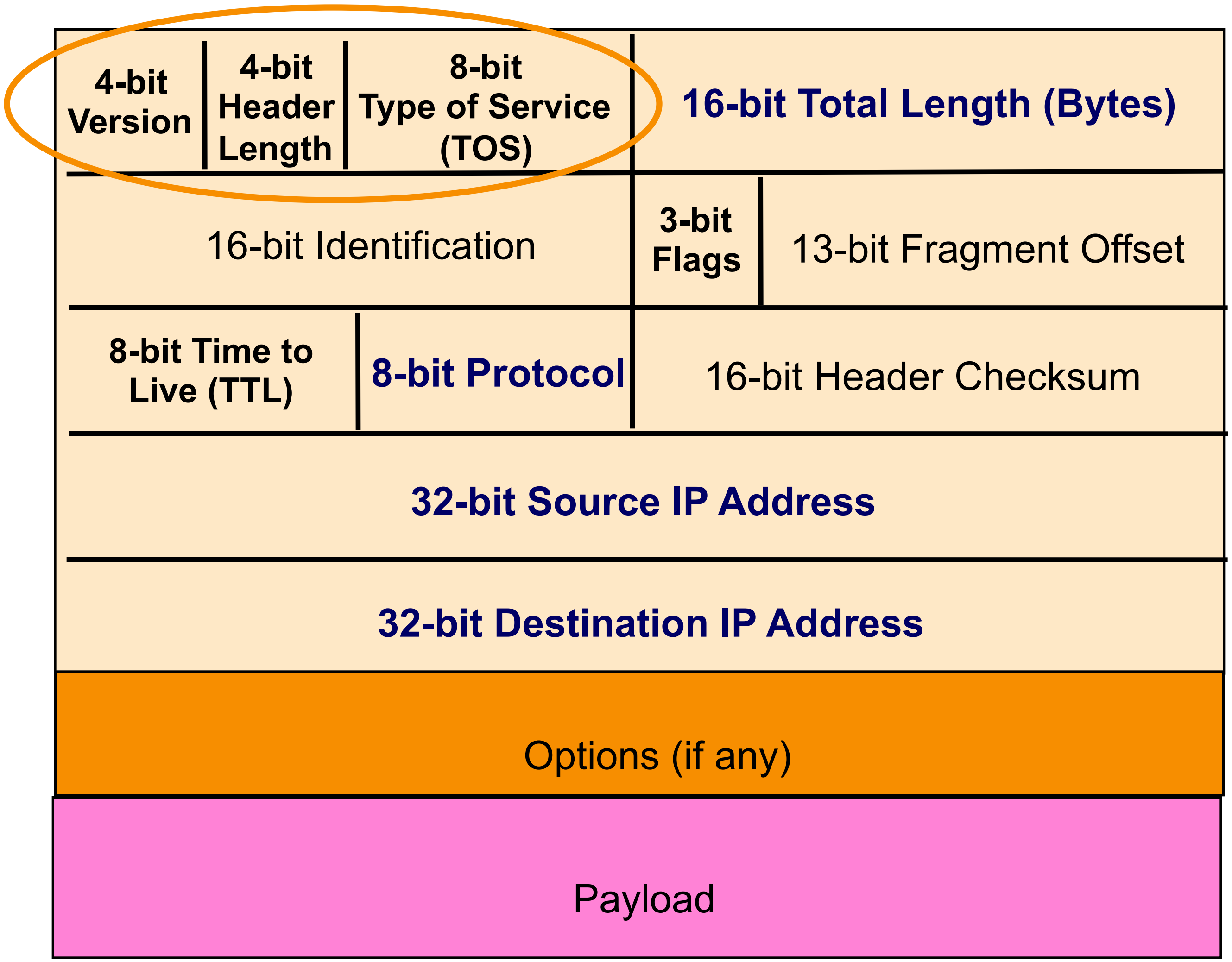
```
From: jrex@cs.princeton.edu
To: feamster@cc.gatech.edu
Subject: picture of my cat
MIME-Version: 1.0
Content-Transfer-Encoding: base64
Content-Type: image/jpeg

Base64 encoded data ….
JVBERi0xLjMNJeLjz9MNMSAwI
.........................
......base64 encoded data
```

Example With Received Header

Return-Path: <casado@cs.stanford.edu>
Received: from ribavirin.CS.Princeton.EDU (ribavirin.CS.Princeton.EDU [128.112.136.44])
by newark.CS.Princeton.EDU (8.12.11/8.12.11) with SMTP id k04M5R7Y023164
for <jrex@newark.CS.Princeton.EDU>; Wed, 4 Jan 2006 17:05:37 -0500 (EST)
Received: from bluebox.CS.Princeton.EDU ([128.112.136.38])
by ribavirin.CS.Princeton.EDU (SMSSMTP 4.1.0.19) with SMTP id M2006010417053607946
for <jrex@newark.CS.Princeton.EDU>; Wed, 04 Jan 2006 17:05:36 -0500
Received: from smtp-roam.Stanford.EDU (smtp-roam.Stanford.EDU [171.64.10.152])
by bluebox.CS.Princeton.EDU (8.12.11/8.12.11) with ESMTP id k04M5XNQ005204
for <jrex@cs.princeton.edu>; Wed, 4 Jan 2006 17:05:35 -0500 (EST)
Received: from [192.168.1.101] (adsl-69-107-78-147.dsl.pltn13.pacbell.net [69.107.78.147])
(authenticated bits=0)
by smtp-roam.Stanford.EDU (8.12.11/8.12.11) with ESMTP id k04M5W92018875
(version=TLSv1/SSLv3 cipher=DHE-RSA-AES256-SHA bits=256 verify=NOT);
Wed, 4 Jan 2006 14:05:32 -0800
Message-ID: <43BC46AF.3030306@cs.stanford.edu>
Date: Wed, 04 Jan 2006 14:05:35 -0800
From: Martin Casado <casado@cs.stanford.edu>
User-Agent: Mozilla Thunderbird 1.0 (Windows/20041206)
MIME-Version: 1.0
To: jrex@CS.Princeton.EDU
CC: Martin Casado <casado@cs.stanford.edu>
Subject: Using VNS in Class
Content-Type: text/plain; charset=ISO-8859-1; format=flowed
Content-Transfer-Encoding: 7bit

IP Packet Structure



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

Sample Email (SMTP) interaction

```
S: 220 hamburger.edu
C: HELO crepes.fr
S: 250  Hello crepes.fr, pleased to meet you
C: MAIL FROM: <alice@crepes.fr>
S: 250 alice@crepes.fr... Sender ok
C: RCPT TO: <bob@hamburger.edu>
S: 250 bob@hamburger.edu ... Recipient ok
C: DATA
S: 354 Enter mail, end with "." on a line by itself
C: From: alice@crepes.fr
C: To: hamburger-list@burger-king.com
C: Subject: Do you like ketchup?
C:
C: How about pickles?
C: .
S: 250 Message accepted for delivery
C: QUIT
S: 221 hamburger.edu closing connection
```

Email header

Email body

Lone period marks end of message