EECS 489
Computer Networks

Fall 2021

Mosharaf Chowdhury

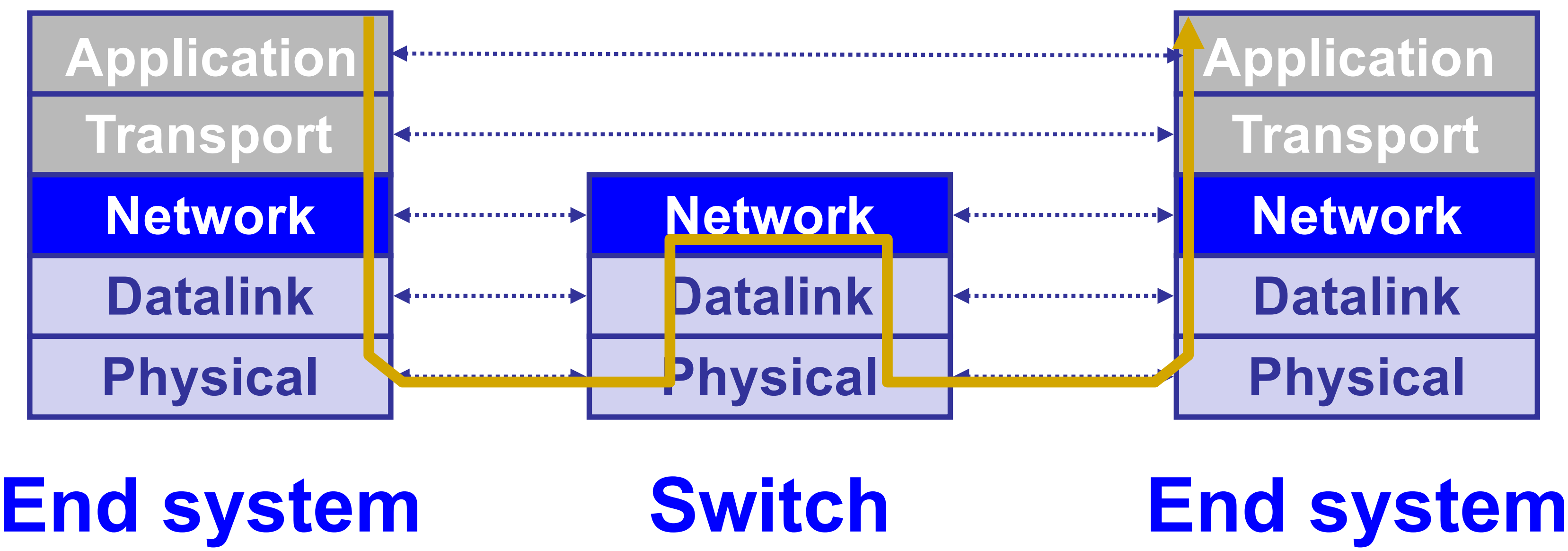
Material with thanks to Aditya Akella, Sugih Jamin, Philip Levis, Sylvia Ratnasamy, Peter Steenkiste, and many other colleagues.

Agenda

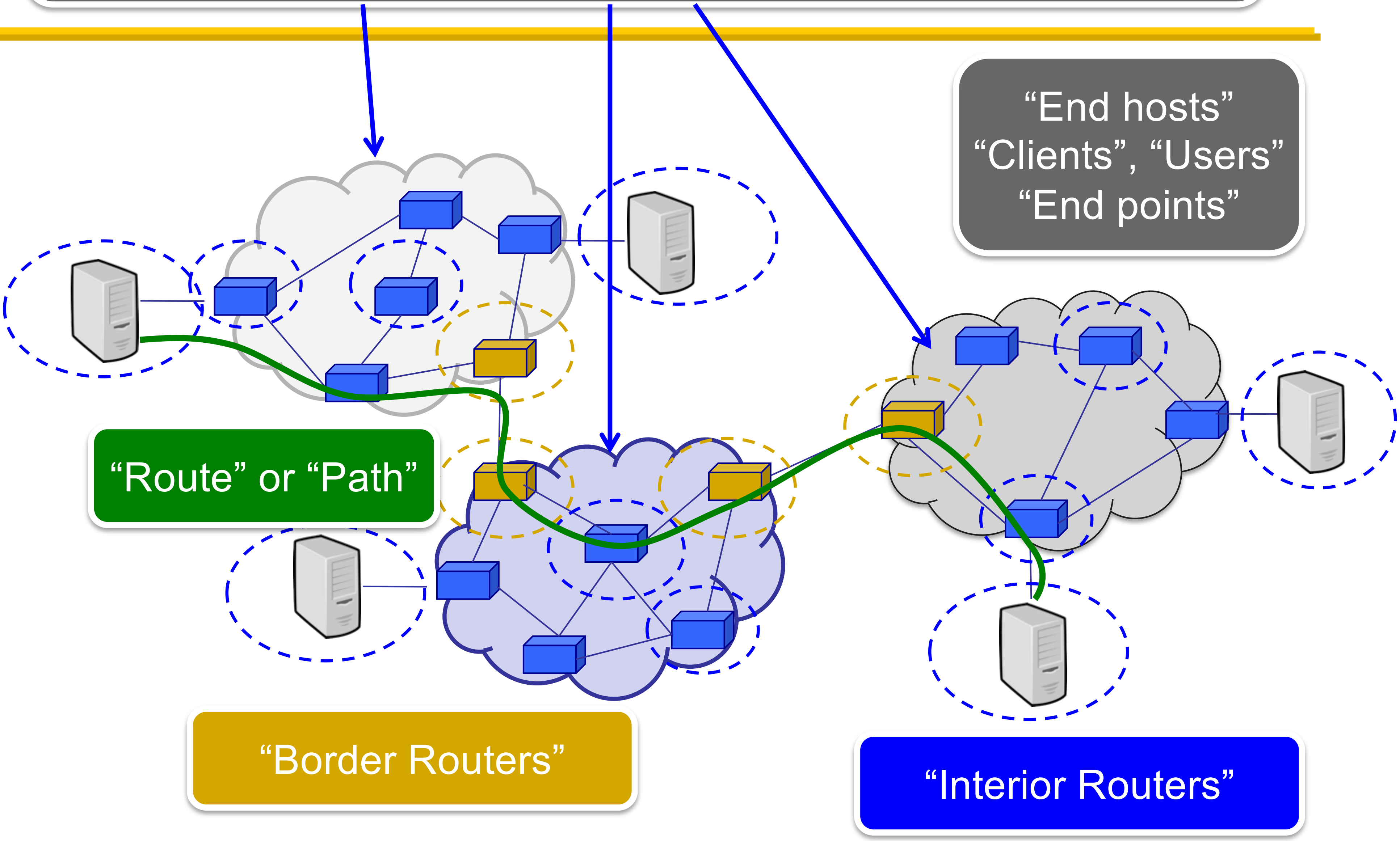
- Network layer basics
- The Internet Protocol (IP)

Network layer

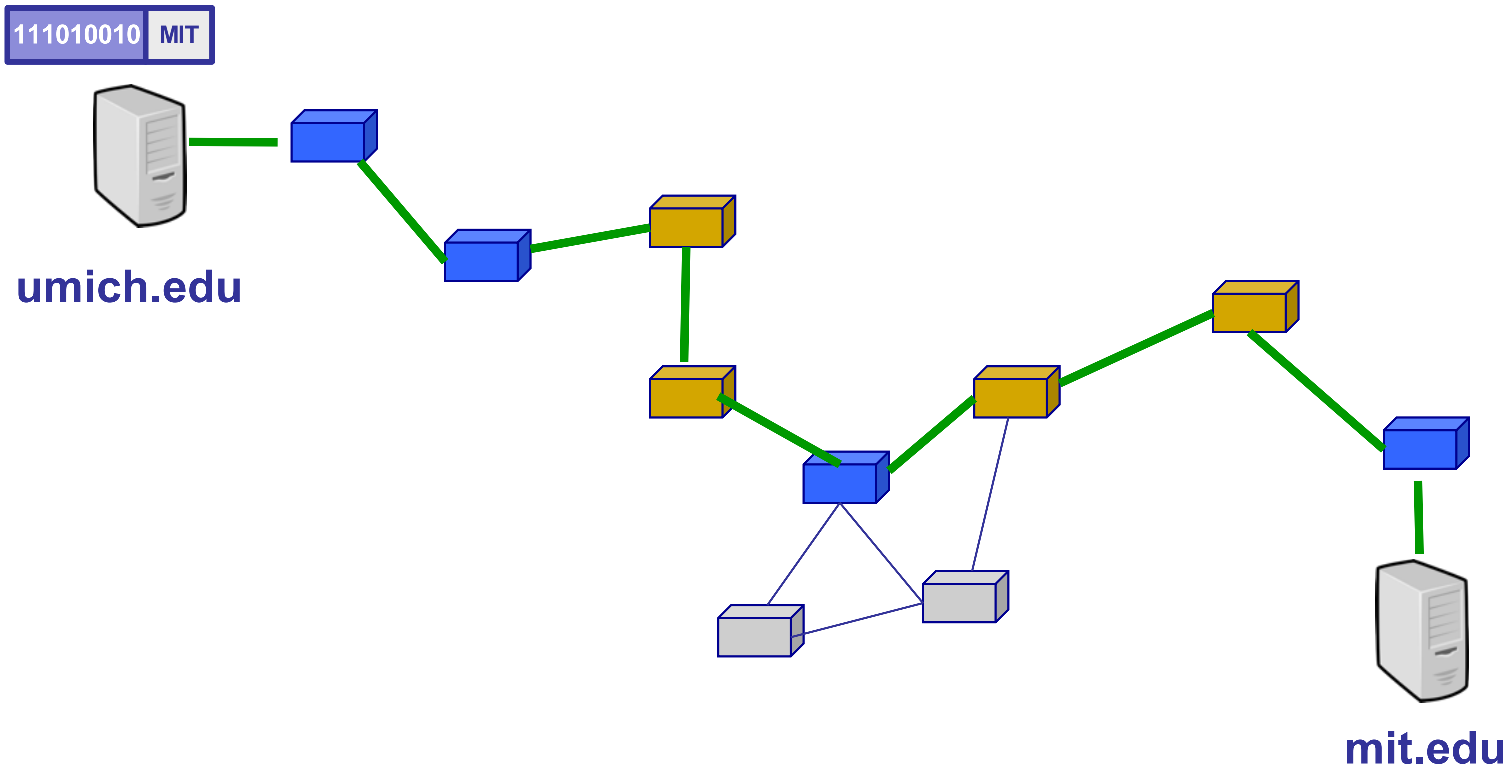
- Present everywhere
- Performs addressing, forwarding, and routing, among other tasks



“Autonomous System (AS)” or “Domain”
Region of a network under a single administrative entity



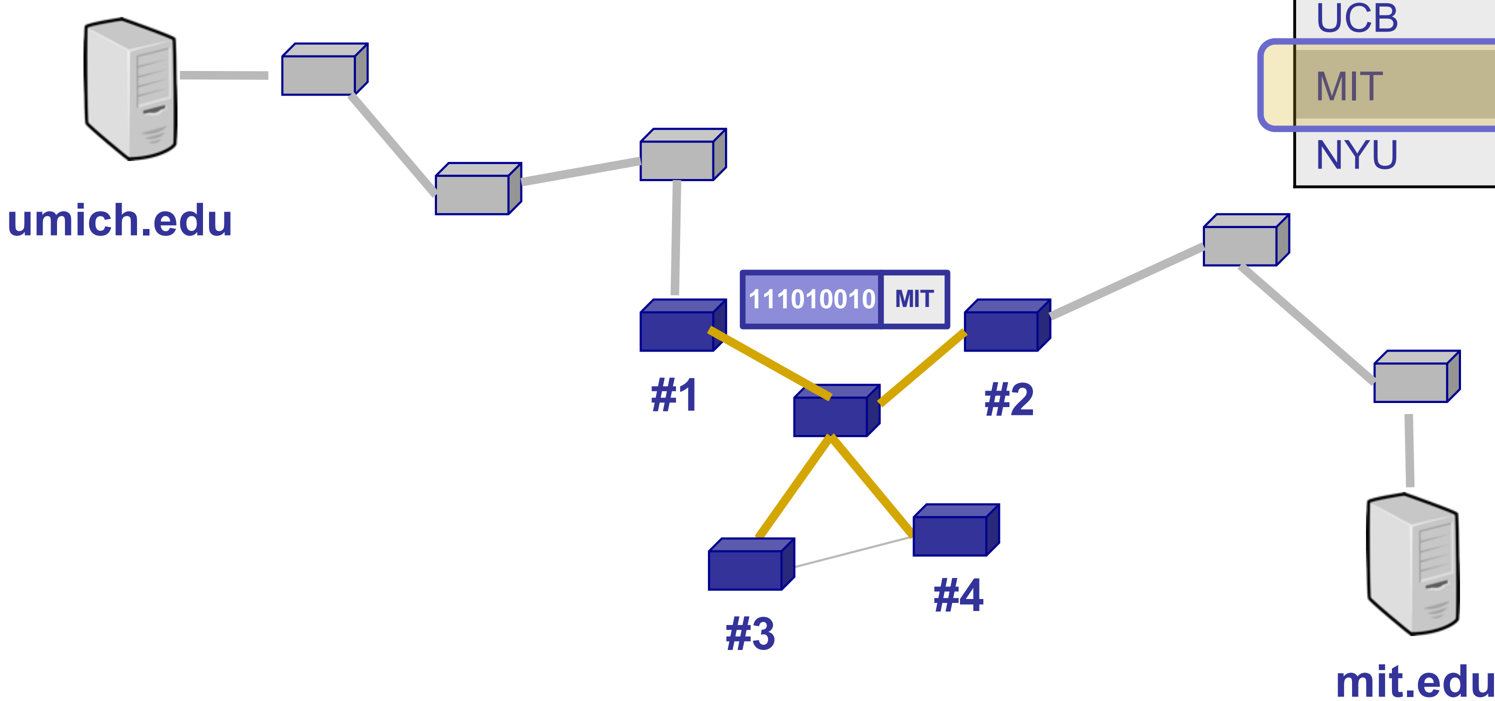
Forwarding



Forwarding

Forwarding Table

Destination	Next Hop
UMICH	1
UCB	3
MIT	2
NYU	4



Forwarding

- Directing a packet to the correct interface so that it progresses to its destination
  - Local
- How?
  - Read address from packet header
  - Search forwarding table

Routing

- Setting up network-wide *forwarding tables* to enable end-to-end communication
  - Global
- How?
  - Using different routing protocols

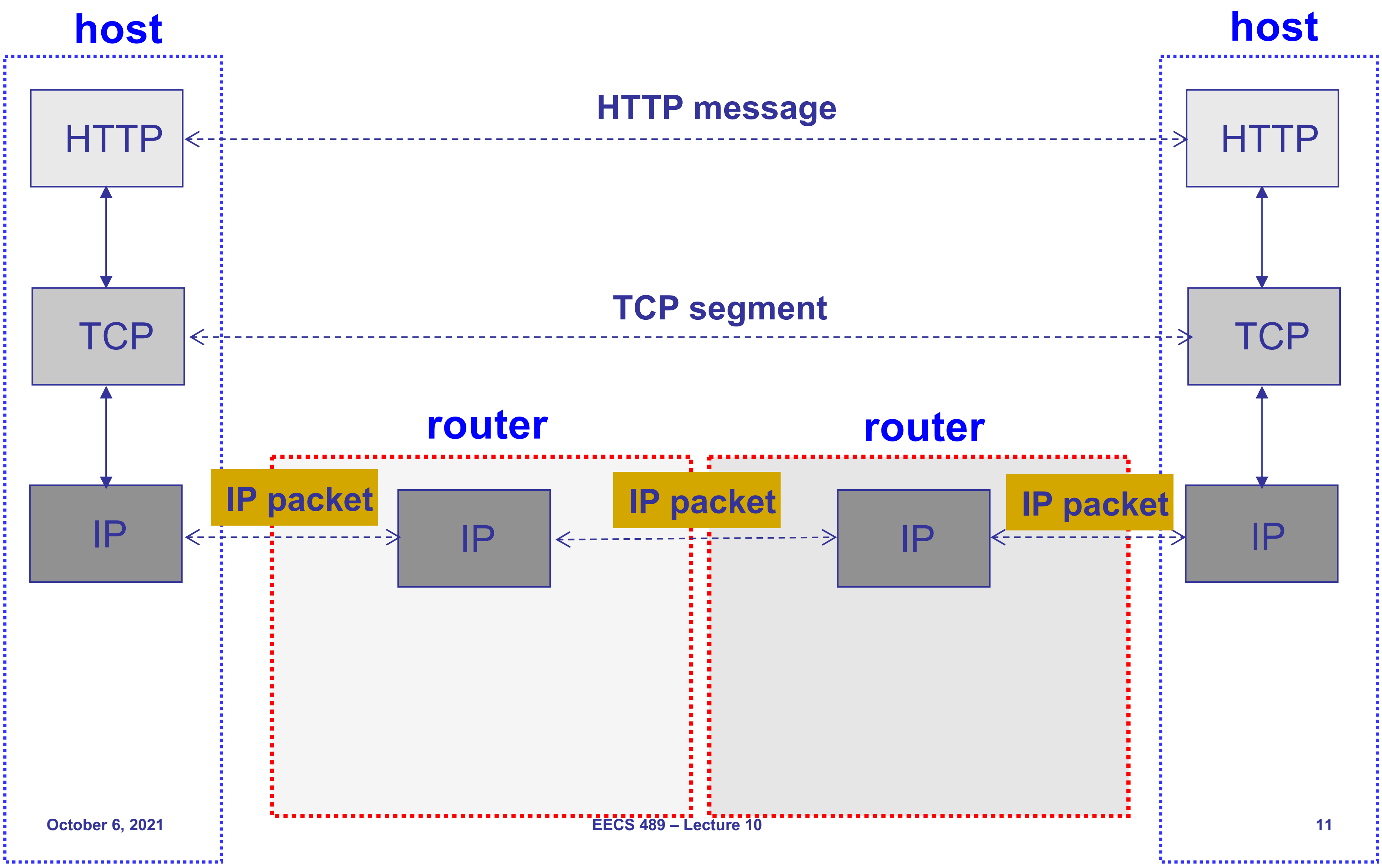
Forwarding vs. routing

- Forwarding: "data plane"
  - Directing one data packet
  - Each router using local routing state
- Routing: "control plane"
  - Computing the forwarding tables that guide packets
  - Jointly computed by routers using a distributed algorithm

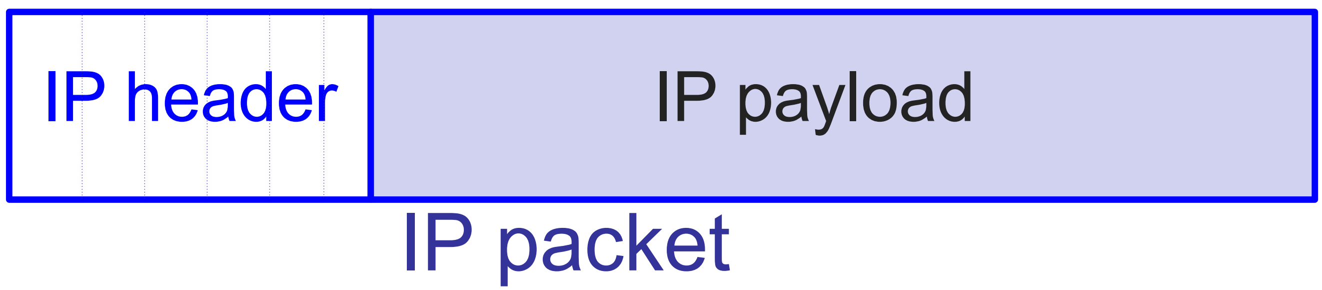
- Very different timescales!

THE IP LAYER

Lecture 2: Layer encapsulation



Recall: IP packet



- IP packet contains a header and payload
  - Payload is opaque to the network
  - Header is what we care about
  - First end-to-end layer (going bottom-up)

Designing the IP header

- Think of the IP header as an interface
  - Between the source and destination end-systems
  - Between the source and network (routers)
- Designing an interface
  - What task(s) are we trying to accomplish?
  - What information is needed to do it?
- Header reflects information needed for basic tasks

What are these tasks? (in network)

- Parse packet
- Carry packet to the destination
- Deal with problems along the way
  - Loops
  - Corruption
  - Packet too large
- Accommodate evolution
- Specify any special handling

What information do we need?

- Parse packet
- Carry packet to the destination
- Deal with problems along the way
  - Loops
  - Corruption
  - Packet too large
- Accommodate evolution
- Specify any special handling

What information do we need?

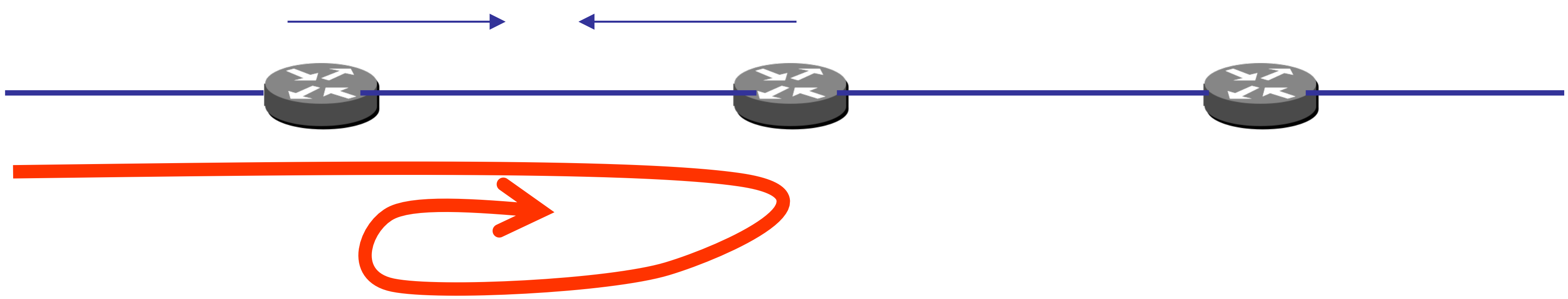
- Parse packet
  - IP version number (4 bits), packet length (16 bits)
- Carry packet to the destination
  - Destination's IP address (32 bits)
- Deal with problems along the way
  - Loops:
  - Corruption:
  - Packet too large:

What information do we need?

- Parse packet
  - IP version number (4 bits), packet length (16 bits)
- Carry packet to the destination
  - Destination's IP address (32 bits)
- Deal with problems along the way
  - Loops: TTL (8 bits)
  - Corruption: checksum (16 bits)
  - Packet too large: fragmentation fields (32 bits)

Preventing loops (TTL)

- Forwarding loops cause packets to cycle for a long time
  - Left unchecked would accumulate to consume all capacity



- Time-to-Live (TTL) Field (8 bits)
  - Decremented at each hop; packet discarded if 0
    - "Time exceeded" message is sent to the source

Header corruption (Checksum)

- Checksum (16 bits)
  - Particular form of checksum over packet header
- If not correct, router discards packets
  - So it doesn't act on bogus information
- Checksum recalculated at every router
  - Why?

Fragmentation

- Every link has a “Maximum Transmission Unit” (MTU)
  - Largest number of bits it can carry as one unit
- A router can split a packet into multiple “fragments” if the packet size exceeds the link’s MTU
- Must reassemble to recover original packet
- Will return to fragmentation later today…

What information do we need?

- Parse packet
  - IP version number (4 bits), packet length (16 bits)
- Carry packet to the destination
  - Destination's IP address (32 bits)
- Deal with problems along the way
  - TTL (8 bits), checksum (16 bits), frag. (32 bits)
- Accommodate evolution
  - Version number (4 bits) (+ fields for special handling)
- Specify any special handling

Special handling

- "Type of Service" (8 bits)
  - Allow packets to be treated differently based on needs
    - e.g., indicate priority, congestion notification
  - Has been redefined several times
  - Now called "Differentiated Services Code Point (DSCP)"

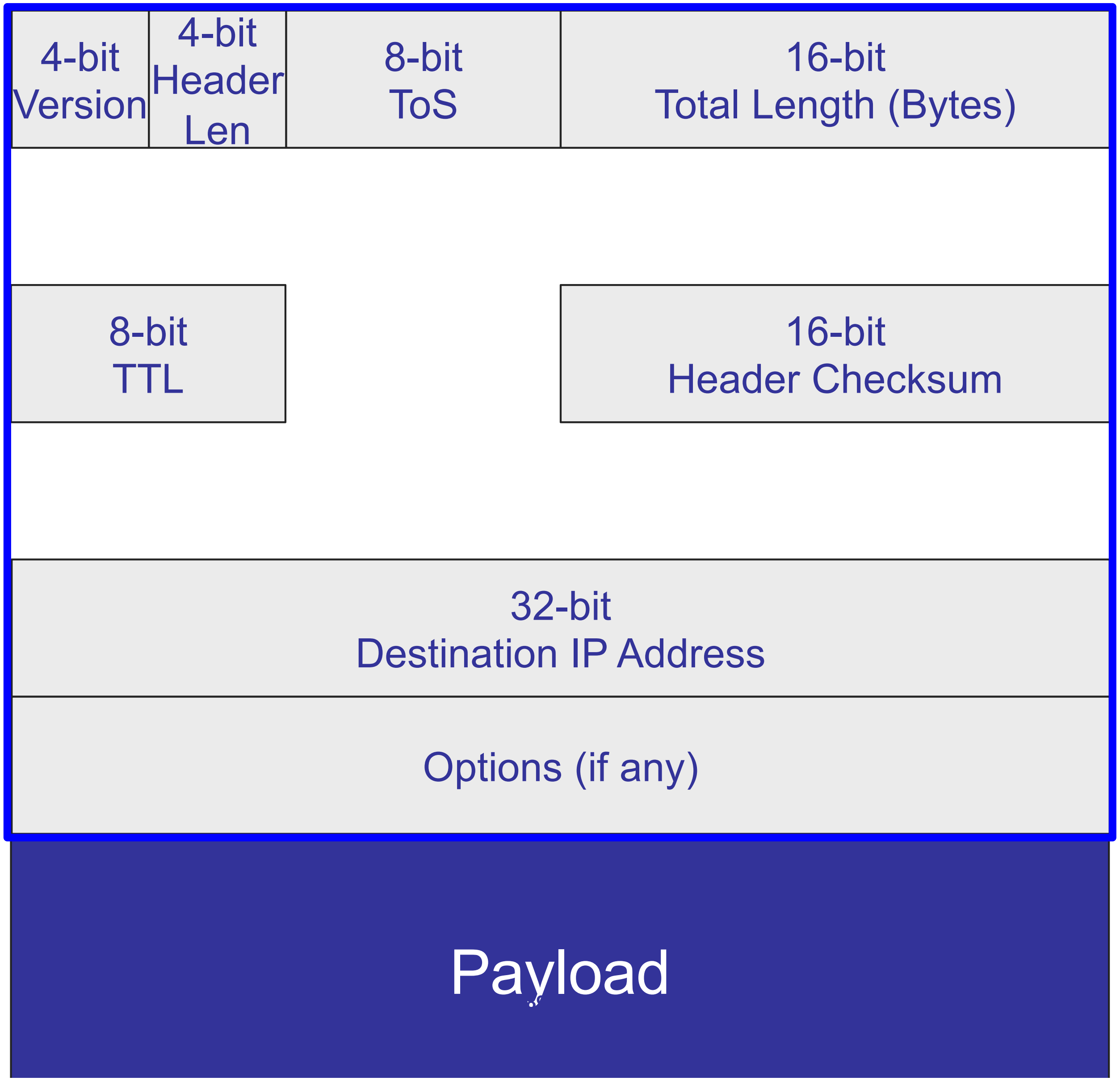
Options

- Optional directives to the network
  - Not used very often
  - 16 bits of metadata + option-specific data
- Examples of options
  - Record Route
  - Strict Source Route
  - Loose Source Route
  - Timestamp

What information do we need?

- Parse packet
  - IP version number (4 bits), packet length (16 bits)
- Carry packet to the destination
  - Destination's IP address (32 bits)
- Deal with problems along the way
  - TTL (8 bits), checksum (16 bits), frag. (32 bits)
- Accommodate evolution
  - Version number (4 bits) (+ fields for special handling)
- Specify any special handling
  - ToS (8 bits), Options (variable length)

IP packet structure



Parse packet

- 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

IP packet structure

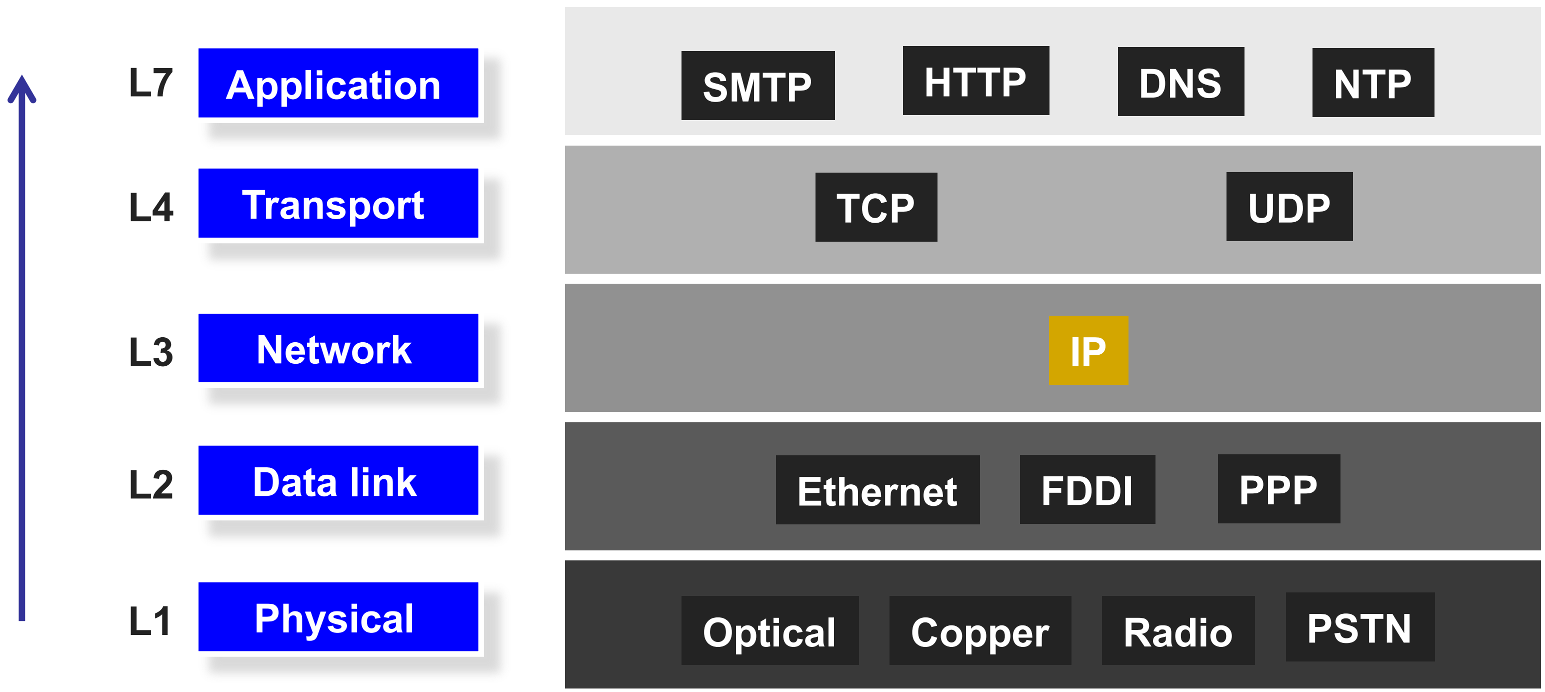
4-bit Version	4-bit Header Len	8-bit ToS	16-bit Total Length (Bytes)
For Fragmentation			
8-bit TTL			16-bit Header Checksum
32-bit Destination IP Address			
Options (if any)			

Tasks at the destination end-system

- Tell destination what to do with the received packet
- Get responses to the packet back to the source

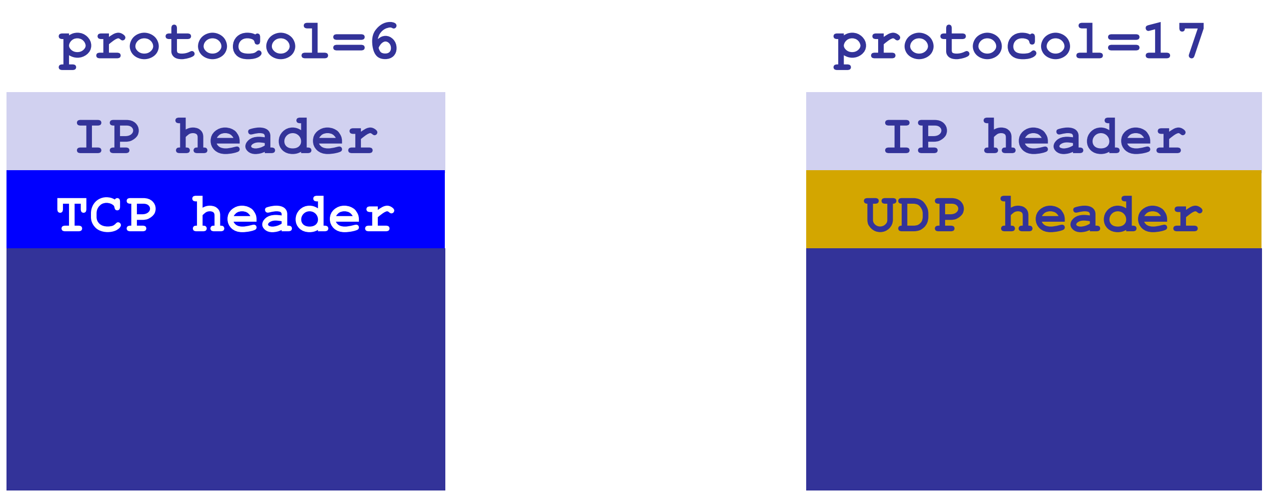
Telling end-host how to handle packet

- Protocol (8 bits)
  - Identifies the higher-level protocol
  - Important for de-multiplexing at receiving host



Telling end-host how to handle packet

- Protocol (8 bits)
  - Identifies the higher-level protocol
  - Important for de-multiplexing at receiving host
- Most common examples
  - E.g., “6” for the Transmission Control Protocol (TCP)
  - E.g., “17” for the User Datagram Protocol (UDP)



Tasks at the destination end-system

- Tell destination what to do with the received packet
  - Transport layer protocol (8 bits)
- Get responses to the packet back to the source
  - Source IP address (32 bits)

IP packet structure

<table>
<tr><td>4-bit
Version</td><td>4-bit
Header
Len</td><td>8-bit
ToS</td><td>16-bit
Total Length (Bytes)</td></tr>
<tr><td colspan="4">For Fragmentation</td></tr>
<tr><td colspan="2">8-bit
TTL</td><td>8-bit
Protocol</td><td>16-bit
Header Checksum</td></tr>
<tr><td colspan="4">32-bit
Source IP Address</td></tr>
<tr><td colspan="4">32-bit
Destination IP Address</td></tr>
<tr><td colspan="4">Options (if any)</td></tr>
</table>

5-MINUTE BREAK!

Announcements

- Sign up for your Midterm slot at https://forms.gle/uh88HWE2dDh9ZMLm6

DEALING WITH FRAGMENTATION

A closer look at fragmentation

- Every link has a "Maximum Transmission Unit" (MTU)
  - Largest number of bits it can carry as one unit
- A router can split a packet into multiple "fragments" if the packet size exceeds the link's MTU
- Must reassemble to recover original packet

Example of fragmentation

- A 4000 byte packet crosses a link w/ MTU=1500B

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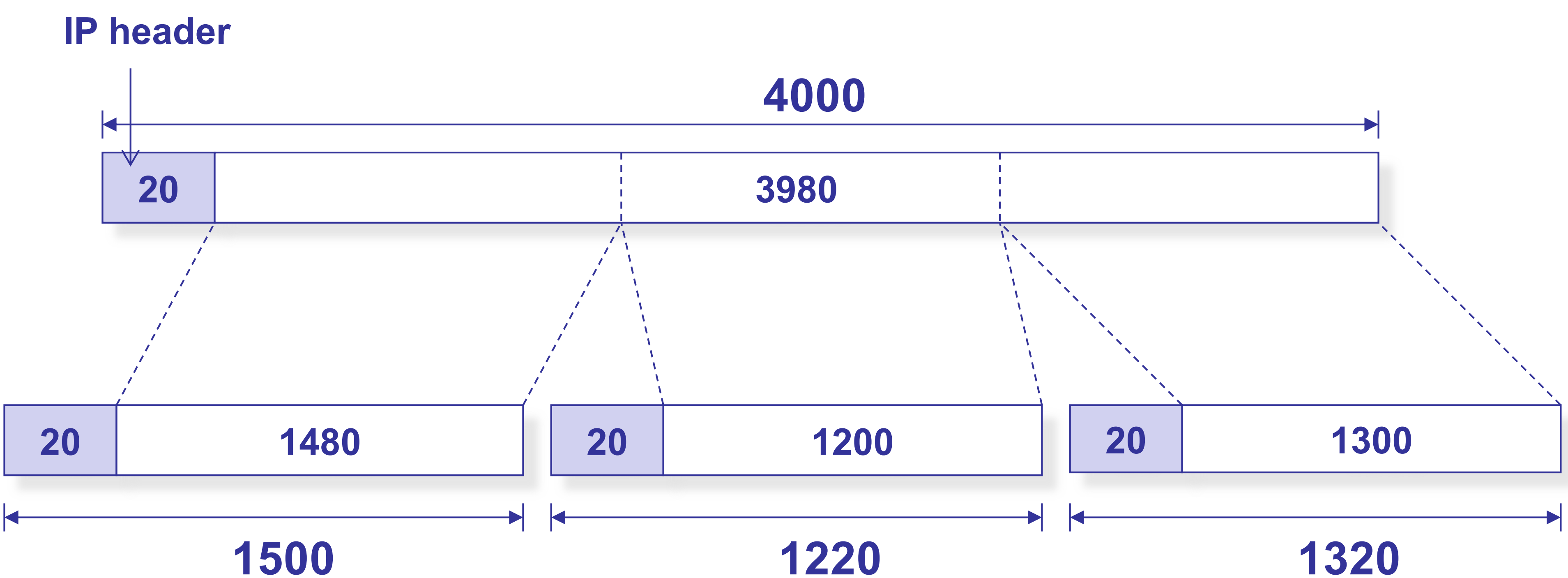
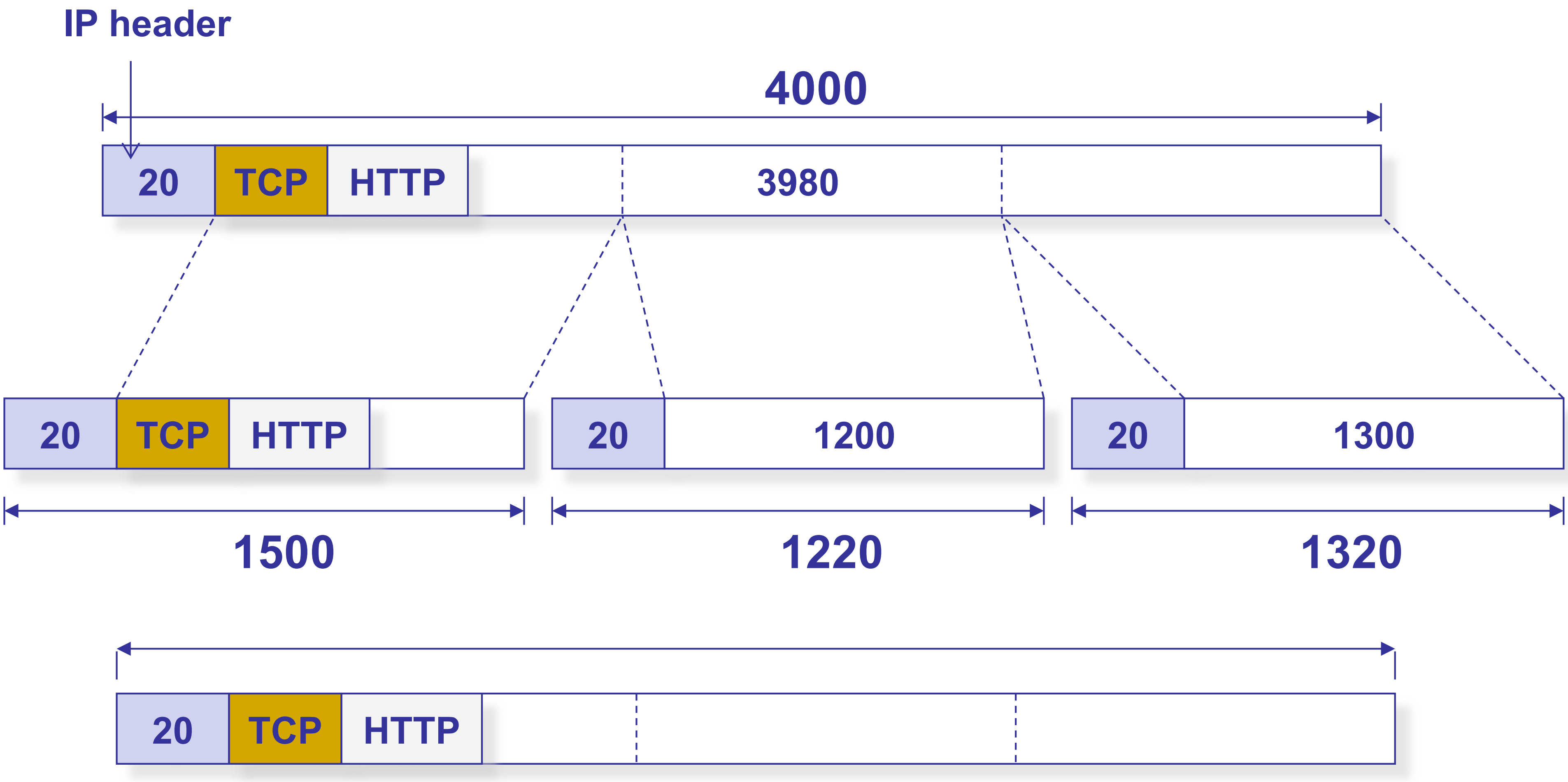


Why reassemble?



Must reassemble before sending packet to higher layers!

A few considerations

- Where to reassemble?
- Fragments can get lost
- Fragments can follow different paths
- Fragments can get fragmented again

Where should reassembly occur?

- Classic case of E2E principle
- At next-hop router imposes burden on network
  - Complicated reassembly algorithm
  - Must hold onto fragments/state
- Any other router may not work
  - Fragments may take different paths
- Little benefit, large cost for network reassembly
- Hence, reassembly is done at the destination

Reassembly: What fields?

- Need a way to identify fragments of the packet
  - Introduce an identifier
- Fragments can get lost
  - Need some form of sequence number or offset
- Sequence numbers / offset
  - How do I know when I have them all? (need max seq# / flag)
  - What if a fragment gets re-fragmented?

IPv4's fragmentation fields

- Identifier: which fragments belong together
- Flags:
  - Reserved: ignore
  - DF: don't fragment
    - May trigger error message back to sender
  - MF: more fragments coming
- Offset: portion of original payload this fragment contains
  - In 8-byte units

IP packet structure

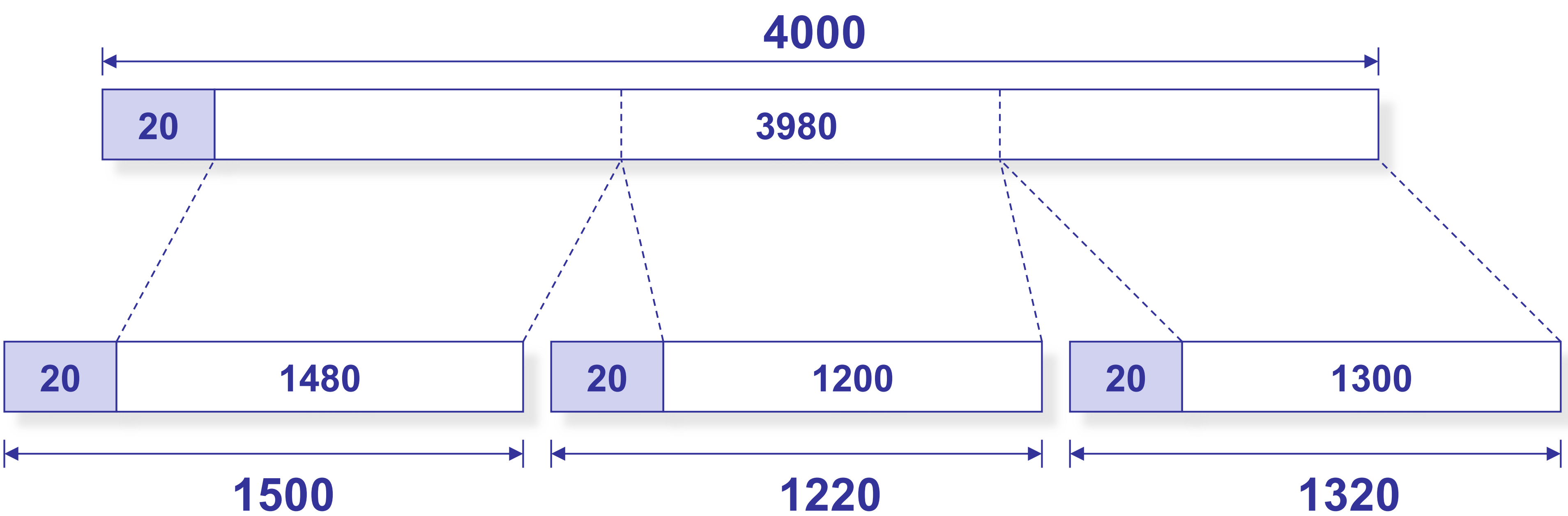
<table>
<tr><td colspan="1">4-bit
Version</td><td colspan="1">4-bit
Header
Len</td><td colspan="2">8-bit
ToS</td><td colspan="4">16-bit
Total Length (Bytes)</td></tr>
<tr><td colspan="8">For Fragmentation</td></tr>
<tr><td colspan="2">8-bit
TTL</td><td colspan="2">8-bit
Protocol</td><td colspan="4">16-bit
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">Options (if any)</td></tr>
</table>

Why this works

- Fragment without MF set (last fragment)
  - Tells host which are the last bits in original payload
- All other fragments fill in holes
- Can tell when holes are filled, regardless of order
  - Use offset field
- Q: why use a byte-offset for fragments rather than numbering each fragment?
  - Allows further fragmentation of fragments

Example of fragmentation (contd.)

- Packet split into 3 pieces
- Example:



Example of fragmentation, contd.

- 4000 byte packet from host 1.2.3.4 to 5.6.7.8 traverses a link with MTU 1,500 bytes

Version **4**	Header Len **5**	ToS **0**		Total Length (Bytes) **4000**
Identification **56273**			R/D/M **0/0/0**	Fragment Offset **0**
TTL **127**		Protocol **6**	Header Checksum **44019**	
Source IP Address **1.2.3.4**				
Destination IP Address **5.6.7.8**				

(3980 more bytes of payload here)

Example of fragmentation, contd.

- Datagram split into 3 pieces. Possible first piece:

Version 4	Header Len 5	ToS 0	Total Length (Bytes) 1500	
Identification 56273			R/D/M 0/0/1	Fragment Offset 0
TTL 127		Protocol 6	Header Checksum xxx	
Source IP Address 1.2.3.4				
Destination IP Address 5.6.7.8				

Example of fragmentation, contd.

- Possible second piece: Frag#1 covered 1480bytes

Version **4**	Header Len **5**	ToS **0**	Total Length (Bytes) **1220**	
Identification **56273**		R/D/M **0/0/1**	Fragment Offset **185** (185 * 8 = 1480)	
TTL **127**	Protocol **6**	Header Checksum **yyy**		
Source IP Address **1.2.3.4**				
Destination IP Address **5.6.7.8**				

Example of fragmentation, contd.

- Possible third piece: 1480+1200 = 2680

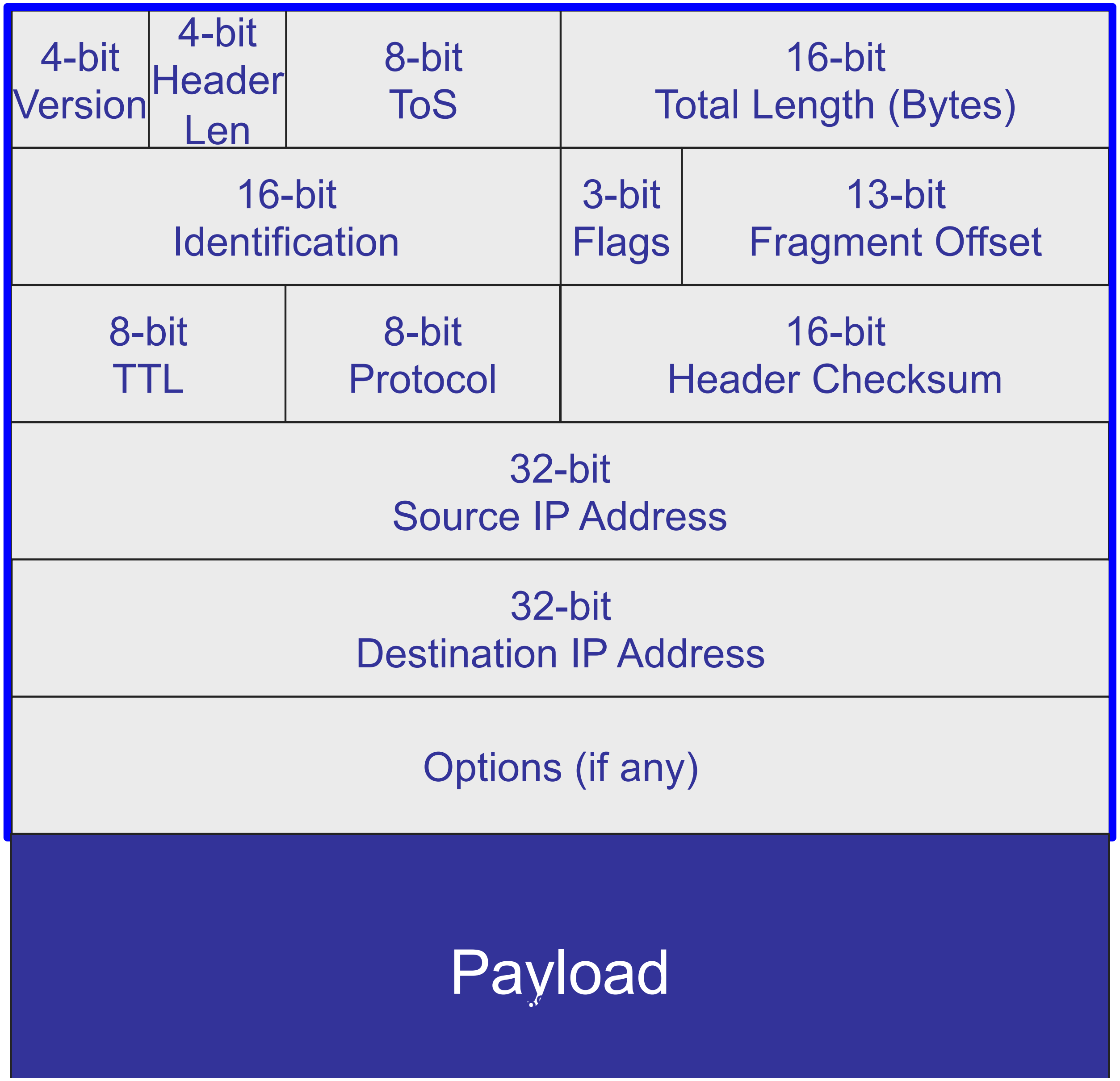
Version **4**	Header Len **5**	ToS **0**	Total Length (Bytes) **1320**	
Identification **56273**			R/D/M **0/0/0**	Fragment Offset **335** (335 * 8 = 2680)
TTL **127**		Protocol **6**	Header Checksum **zzz**	
Source IP Address **1.2.3.4**				
Destination IP Address **5.6.7.8**				

A QUICK LOOK INTO IPV6

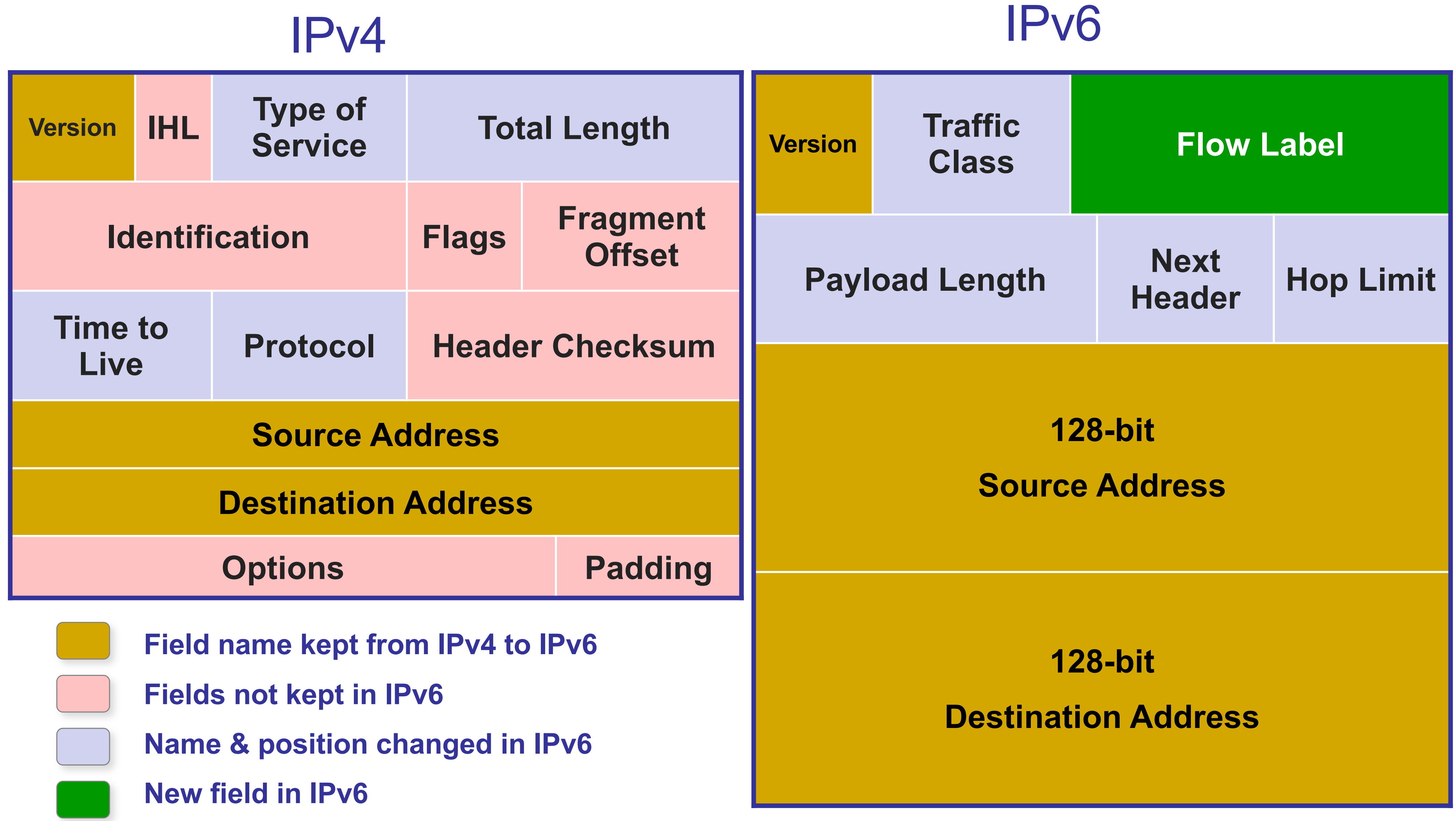
IPv6

- Motivated (prematurely) by address exhaustion
  - Addresses four times as big (128-bit)
- Focused on simplifying IP
  - Got rid of all fields that were not absolutely necessary
- Result is an elegant, if unambitious, protocol

What “clean up” would you do?



IPv4 and IPv6 header comparison



Summary of changes

- Eliminated fragmentation (why?)
- Eliminated checksum (why?)
- New options mechanism (why?)
- Eliminated header length (why?)
- Expanded addresses
- Added Flow Label

Philosophy of changes

- Don’t deal with problems: leave to ends
  - Eliminated fragmentation and checksum
  - Why retain TTL?
- Simplify handling:
  - New options mechanism (uses next header)
  - Eliminated header length
    - »Why couldn’t IPv4 do this?
- Provide general flow label for packet
  - Not tied to semantics
  - Provides great flexibility

Summary

- Network layer can be divided into data plane and control plane
  - Data plane deals with “how?”
  - Control plane deals with “what?”
- IP is simple yet nuanced