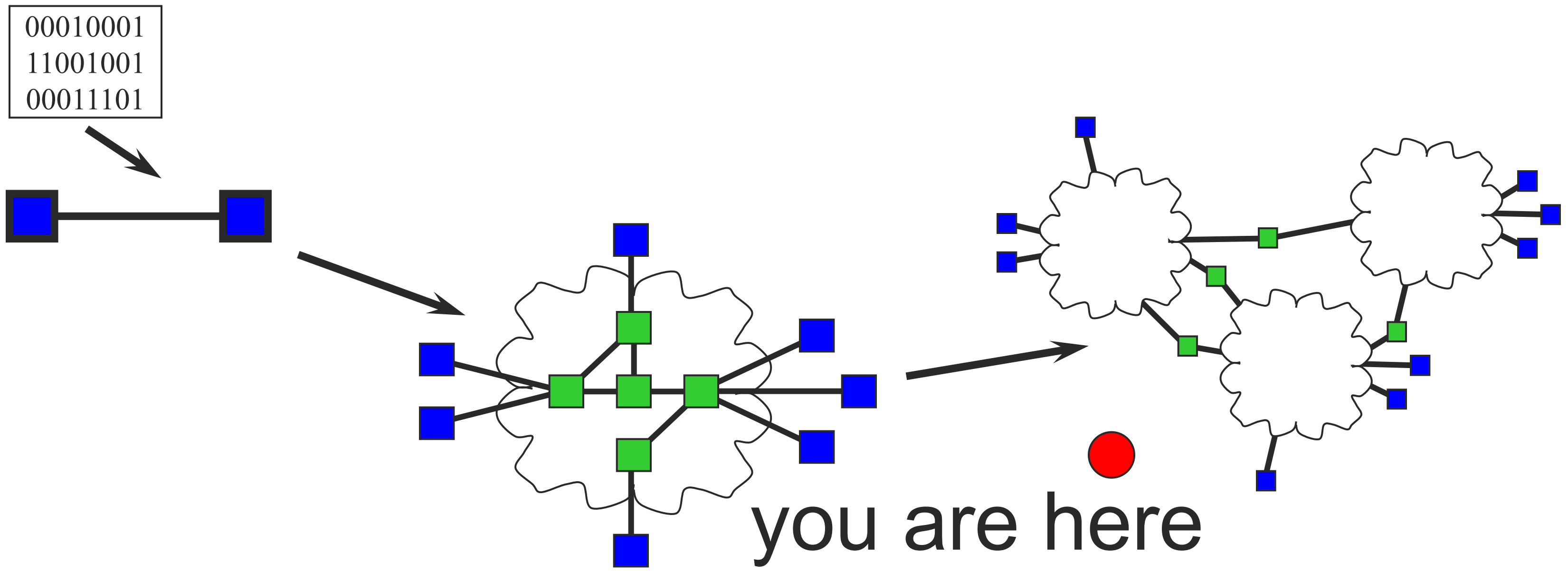
Internetworking Chapter 4

The Big Picture

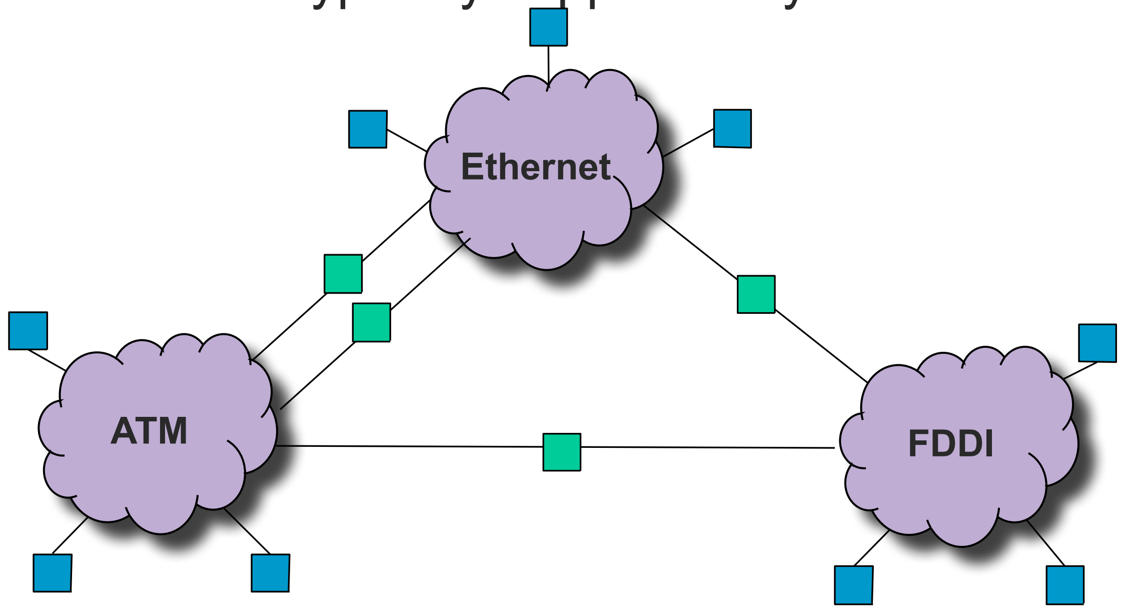


Internetworking

- Dealing with heterogeneity issues
  - Defining a service model
  - Defining a global namespace
  - Structuring the namespace to simplify forwarding
  - Building forwarding information (routing)
  - Translating between global and local (physical) names
  - Hiding variations in frame size limits
- Dealing with global scale
- Moving forward with IP

Basics of Internetworking

- What is an internetwork
  - Illusion of a single (direct link) network
  - Built on a set of distributed heterogeneous networks
  - Abstraction typically supported by software



Basics of Internetworking

- What is an internetwork
  - Illusion of a single (direct link) network
  - Built on a set of distributed heterogeneous networks
  - Abstraction typically supported by software
- Properties
  - Supports heterogeneity
    - Hardware, OS, network type, and topology independent
  - Scales to global connectivity
- The Internet is the specific global internetwork that grew out of ARPANET

What is the Internet?

- A pretty important example of an internetwork!
- It’s big and complex
  - 53,277 ASs, over 2,000,000 routers, 1,048,766,623 hosts
    - Last I checked …
  - Rich array of systems and protocols

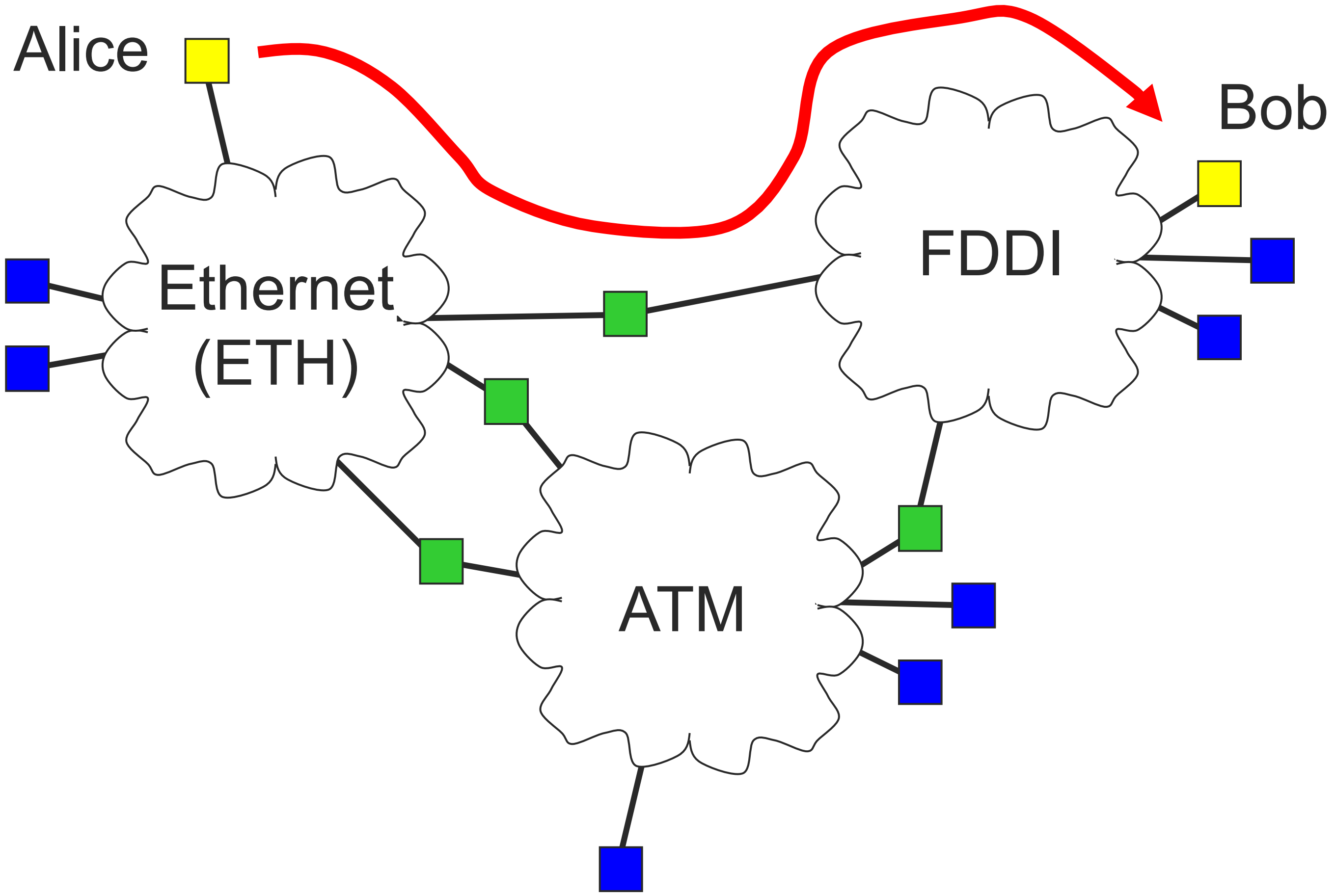
What is the Internet?

- How does it work?
  - ISPs compete for business, hide private information, end-hosts misbehave, complex failure modes, cross-dependencies and oscillations
- Yet everyone must cooperate to ensure reachability
  - Relies on complex interactions across multiple systems and protocols

Internetworking challenges

- Heterogeneity
  - Application service
  - Underlying networking technology
    - physical layer, frame sizes, reliability or not, …
  - Network routing / forwarding protocols
  - Intended use
- Global scale
  - All of humanity and more …
- Distributed control
  - Different parties own different parts of the net
  - Different and conflicting goals for how network is used

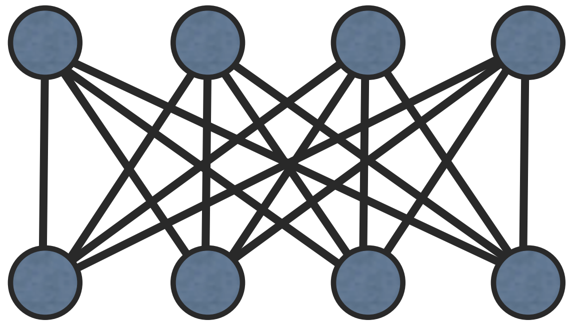
Message Transmission



Handling heterogeneity badly

Hosts

Networking protocols

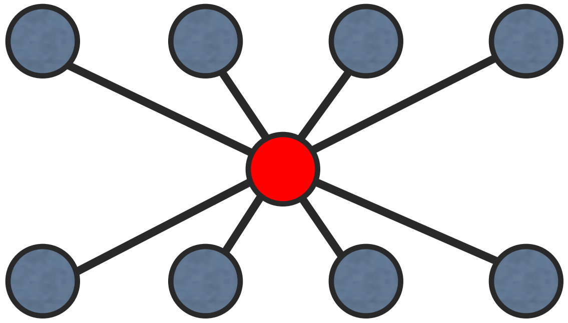


n entities: n^2 interactions!

Handling heterogeneity well

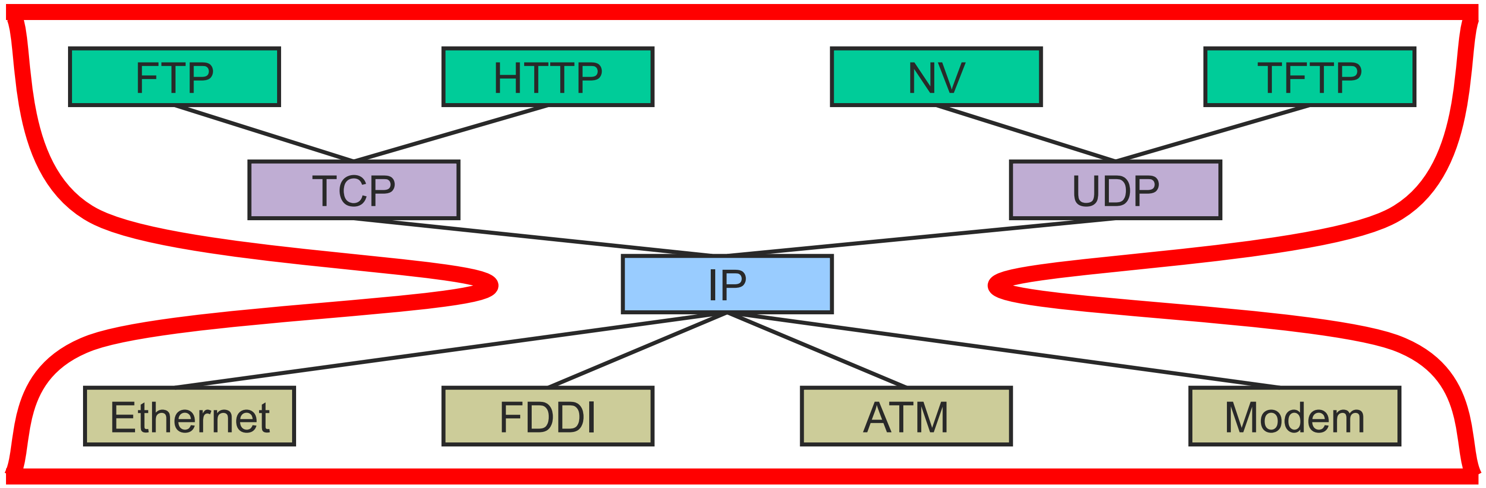
Hosts

Networking protocols



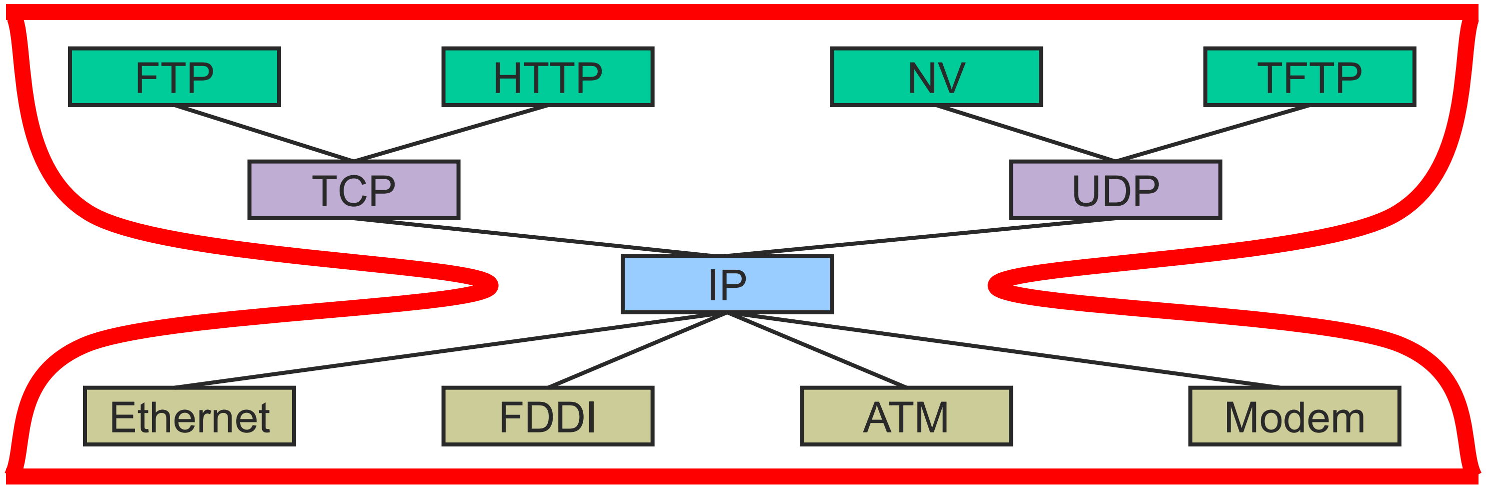
Handling heterogeneity well

- Network-level protocol for the Internet
- Operates on all hosts and routers
  - Routers are nodes connecting distinct networks to the Internet



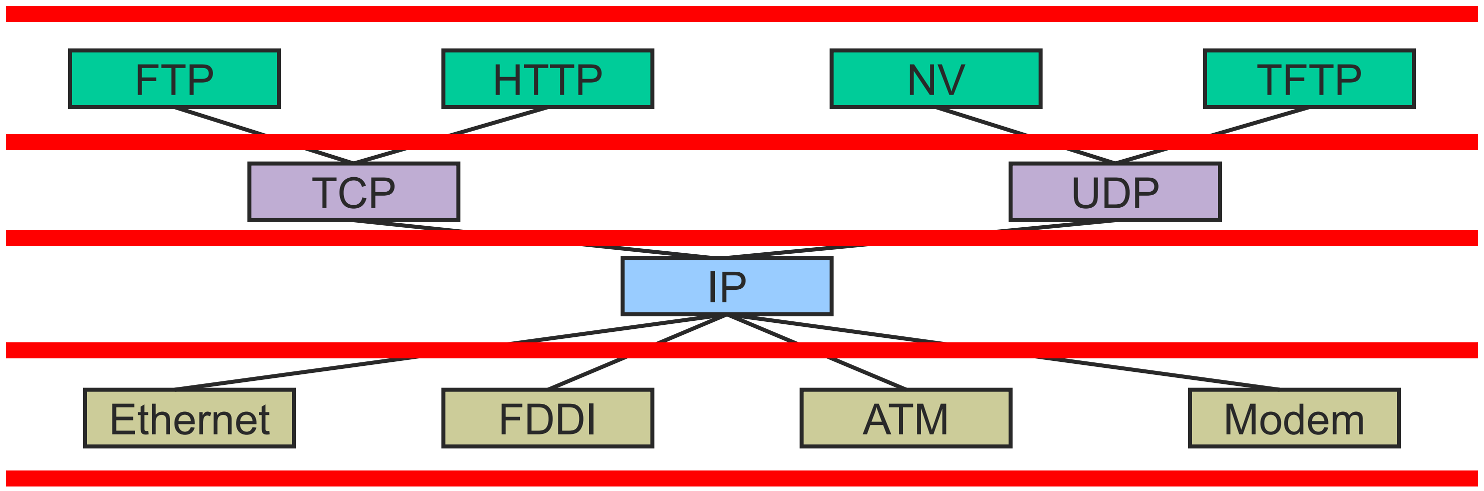
Architectural principle #1: Modularity

- IP's "narrow waist"
  - Single simple unifying protocol
  - Many heterogeneous uses above
  - Many heterogeneous implementations below

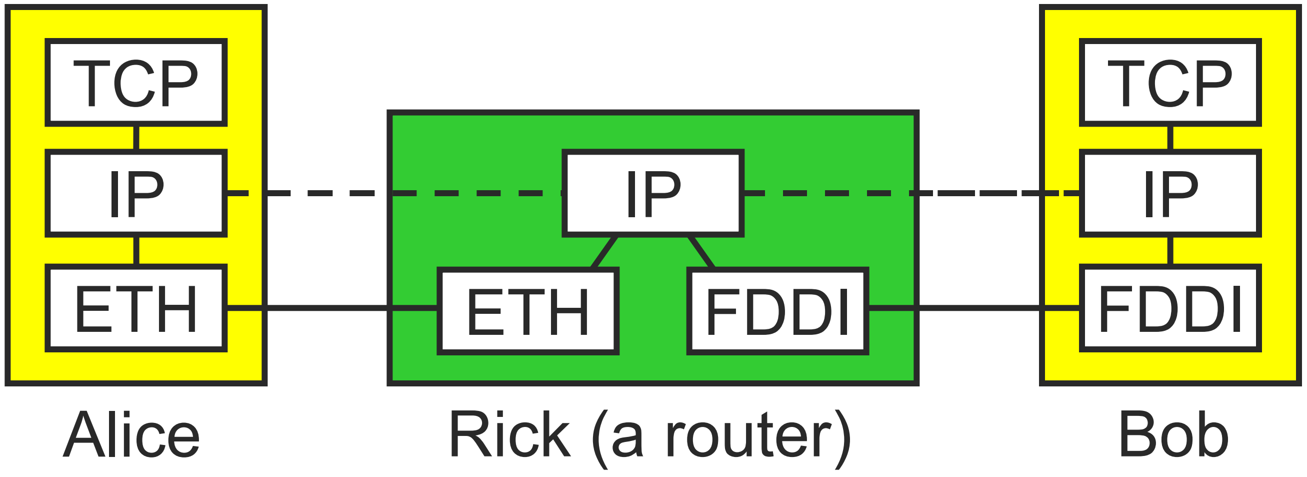


Architectural principle #1: Modularity

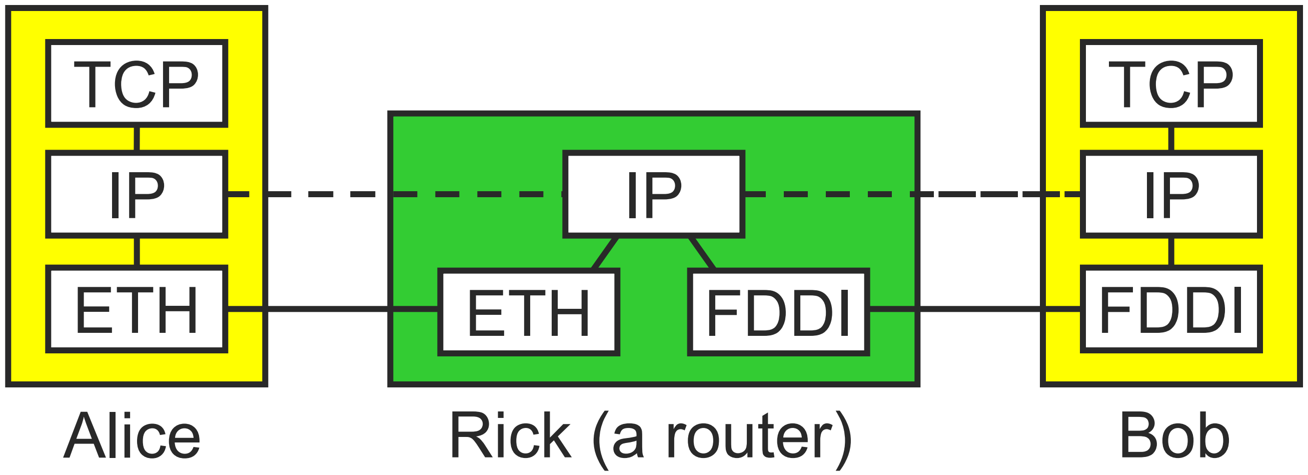
- Narrow waist: a special kind of layering
  - Protocols separated into layers
  - Each layer has well-defined interface and service model
  - Layer n needs only to talk to layers n+1 and n-1 (ideal case)



Layering



Message Transmission



1. Alice/application finds Bob's IP address, sends packet
2. Alice/IP forwards packet to Rick
3. Alice/IP looks up Rick's Ethernet address and sends
4. Rick/IP forwards packet to Bob
5. Rick/IP looks up Bob's FDDI address and sends

Internet Protocol Service Model

- Service provided to transport layer (TCP, UDP)
  - Global name space
  - Host-to-host connectivity (connectionless)
  - Best-effort packet delivery
- Not in IP service model
  - Delivery guarantees on bandwidth, delay or loss
- Delivery failure modes
  - Packet delayed for a very long time
  - Packet loss
  - Packet delivered more than once
  - Packets delivered out of order

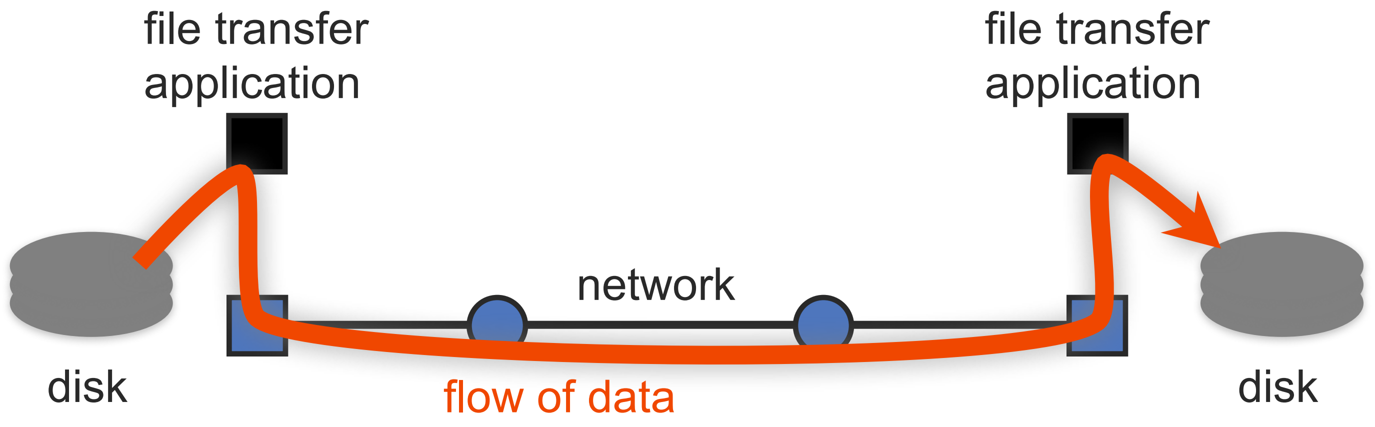
Architectural principle #2: End-to-end Principle

If a function can completely and correctly be implemented only with the knowledge and help of the application standing at the endpoints of the communication system, then providing that function as a feature of the communication system itself is not possible.

[Saltzer, Reed, Clark, 1984]

Example: file transfer

- Suppose the link layer is reliable. Does that ensure reliable file transfer?
- Suppose the network layer is reliable. Does that ensure reliable file transfer?



E2E Principle: Interpretation

- If function can only be fully implemented at endpoints of communication, then...
  - End-to-end implementation
    - Correct
    - Simplifies, generalizes lower layers
  - In-network implementation
    - Insufficient
    - May help – or hurt – performance. Examples?
- Be wary to sacrifice generality for performance!

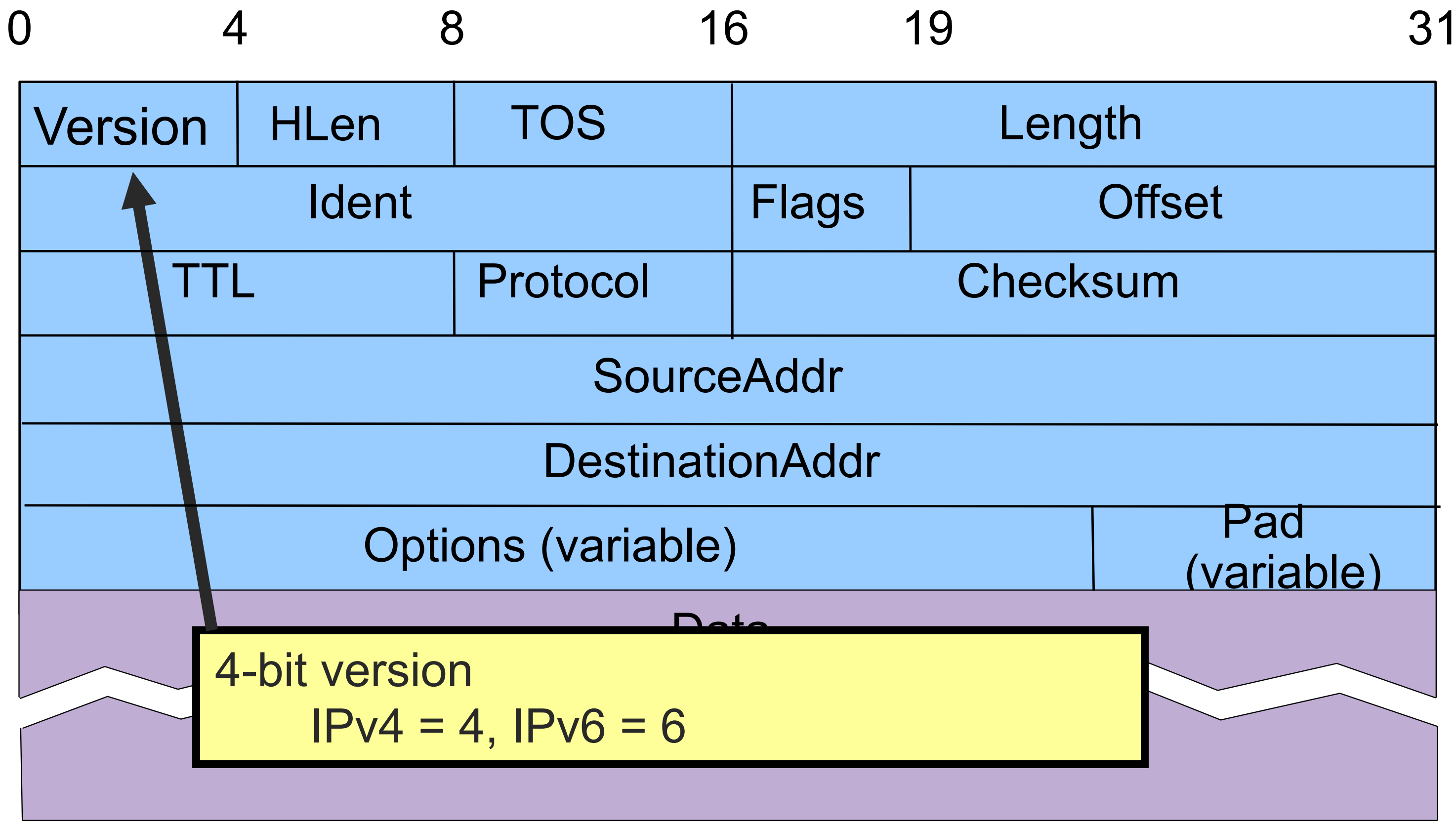
E2E Principle and IP

- Implications
  - No need for reliability in network
  - No need to be connection-oriented (virtual circuits): datagram packet switching enough
- Benefits
  - Easy to implement IP on top of many different underlying network technologies below IP layer
  - Lightweight yet sufficient platform for many applications on top of the IP layer

Designing IP: What do we need to know?

- Addresses: source and destination of datagram
- Framing: datagram length
- Dealing with problems
  - Integrity: is the header what it's supposed to be?
  - Loop avoidance: make sure packets don't endlessly circulate
  - Fragmentation: what if the datagram is too large?
- Options and extensibility
  - Ways to give more specific information to routers
  - Ways to extend the protocol with new features

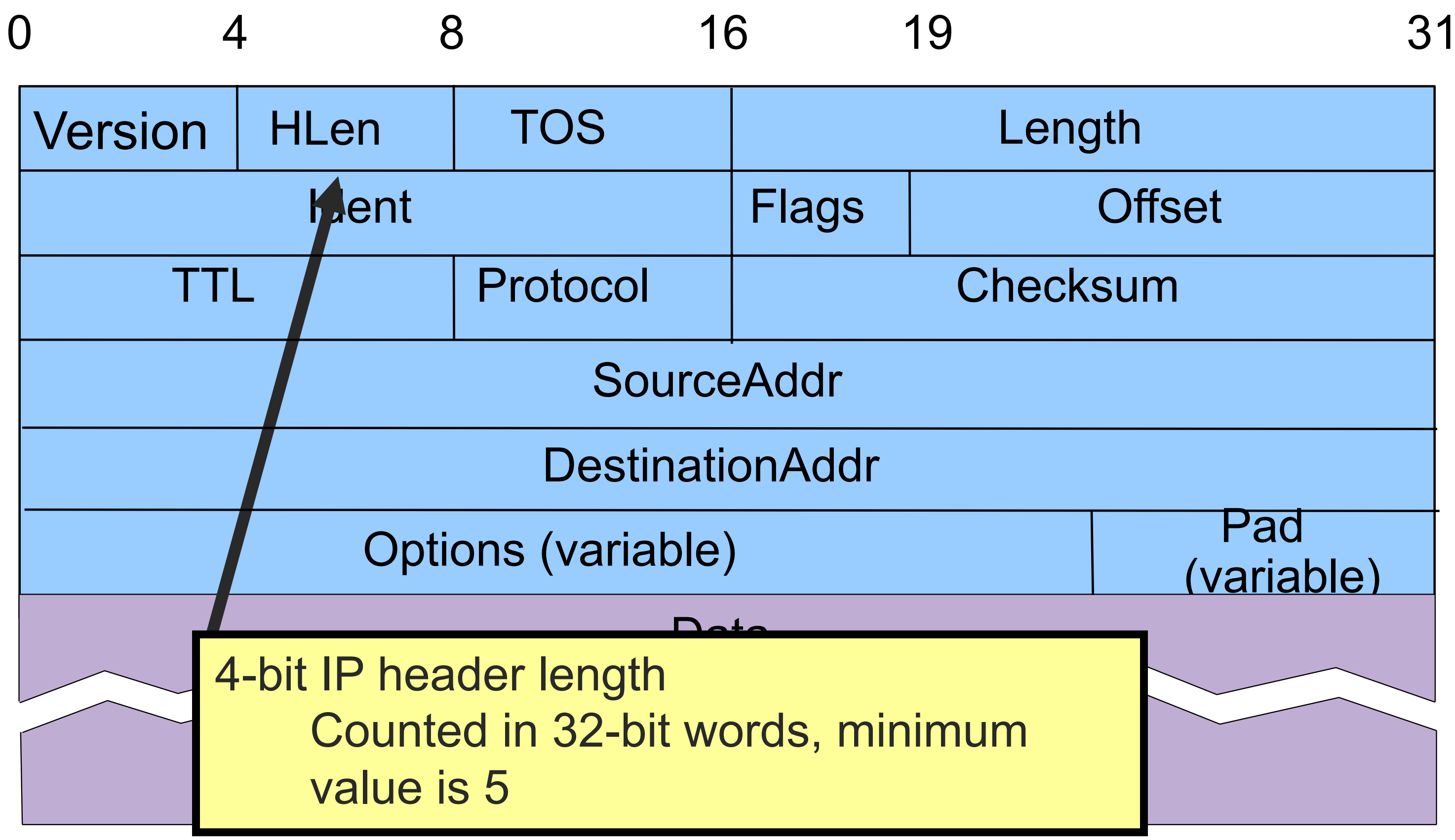
IP Packet Format



4-bit version

IPv4 = 4, IPv6 = 6

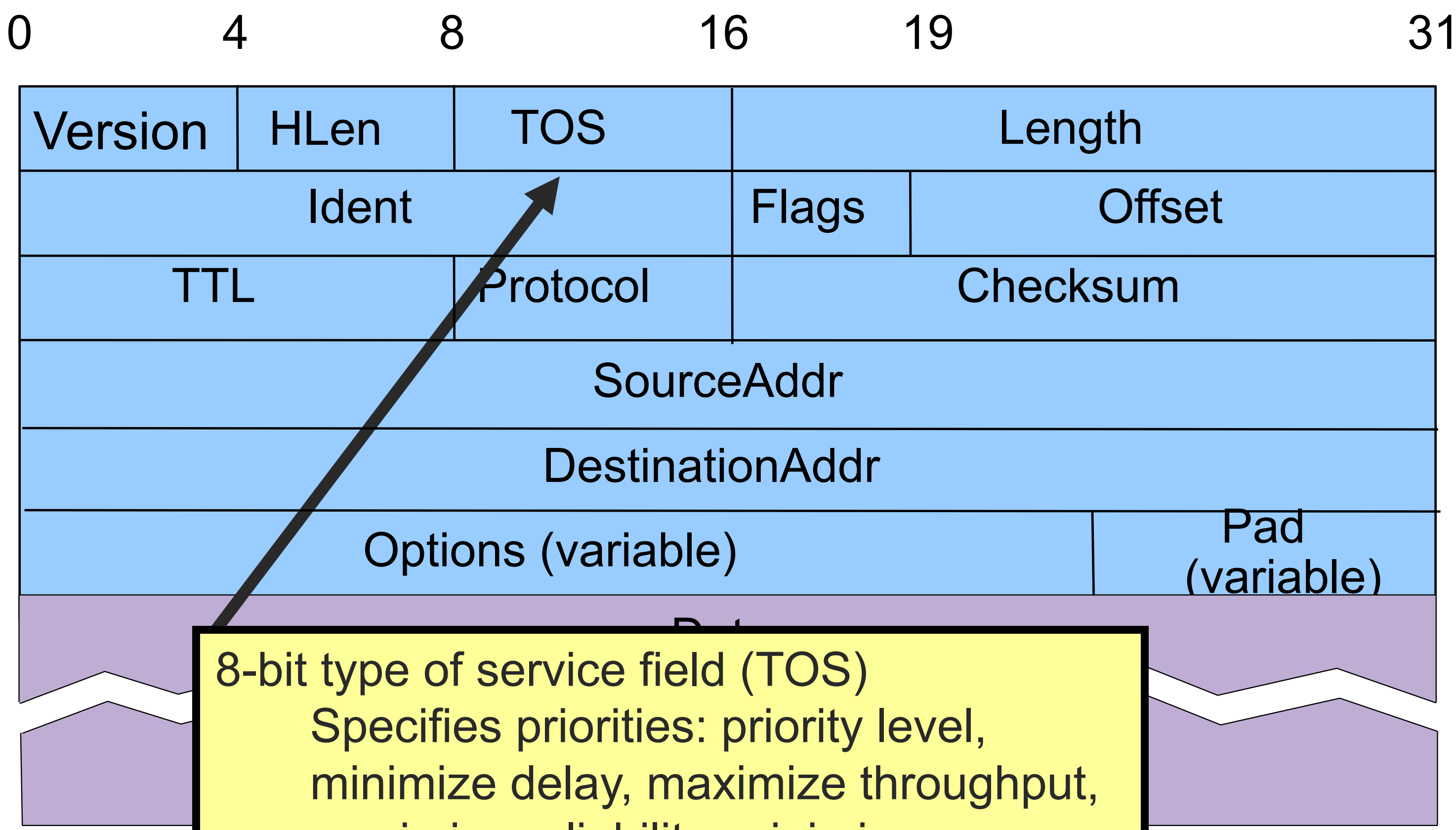
IP Packet Format



4-bit IP header length

Counted in 32-bit words, minimum value is 5

IP Packet Format

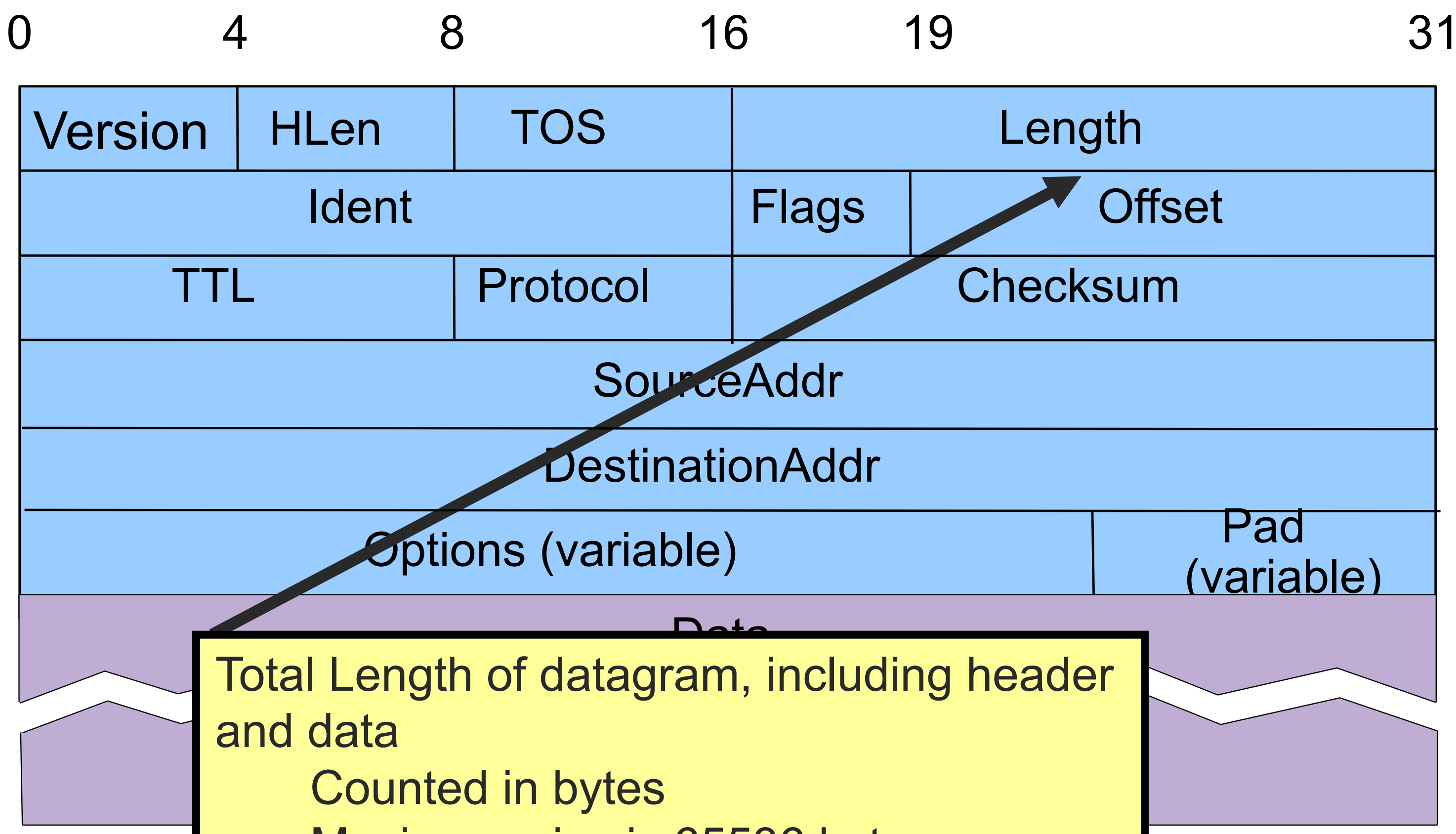


8-bit type of service field (TOS)

Specifies priorities: priority level, minimize delay, maximize throughput, maximize reliability, minimize monetary cost, etc

Mostly unused

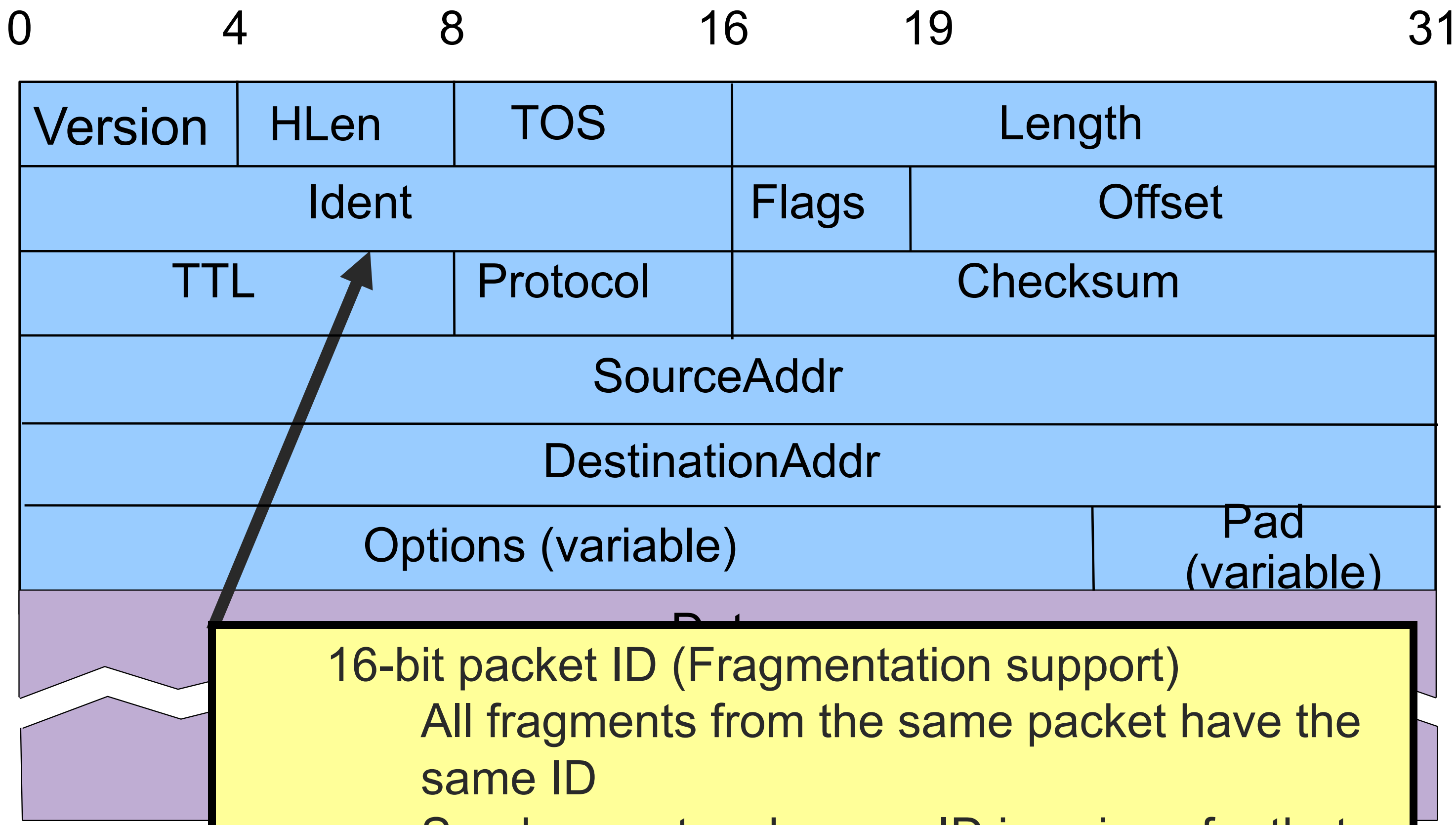
IP Packet Format



Total Length of datagram, including header and data

- Counted in bytes
- Maximum size is 65536 bytes

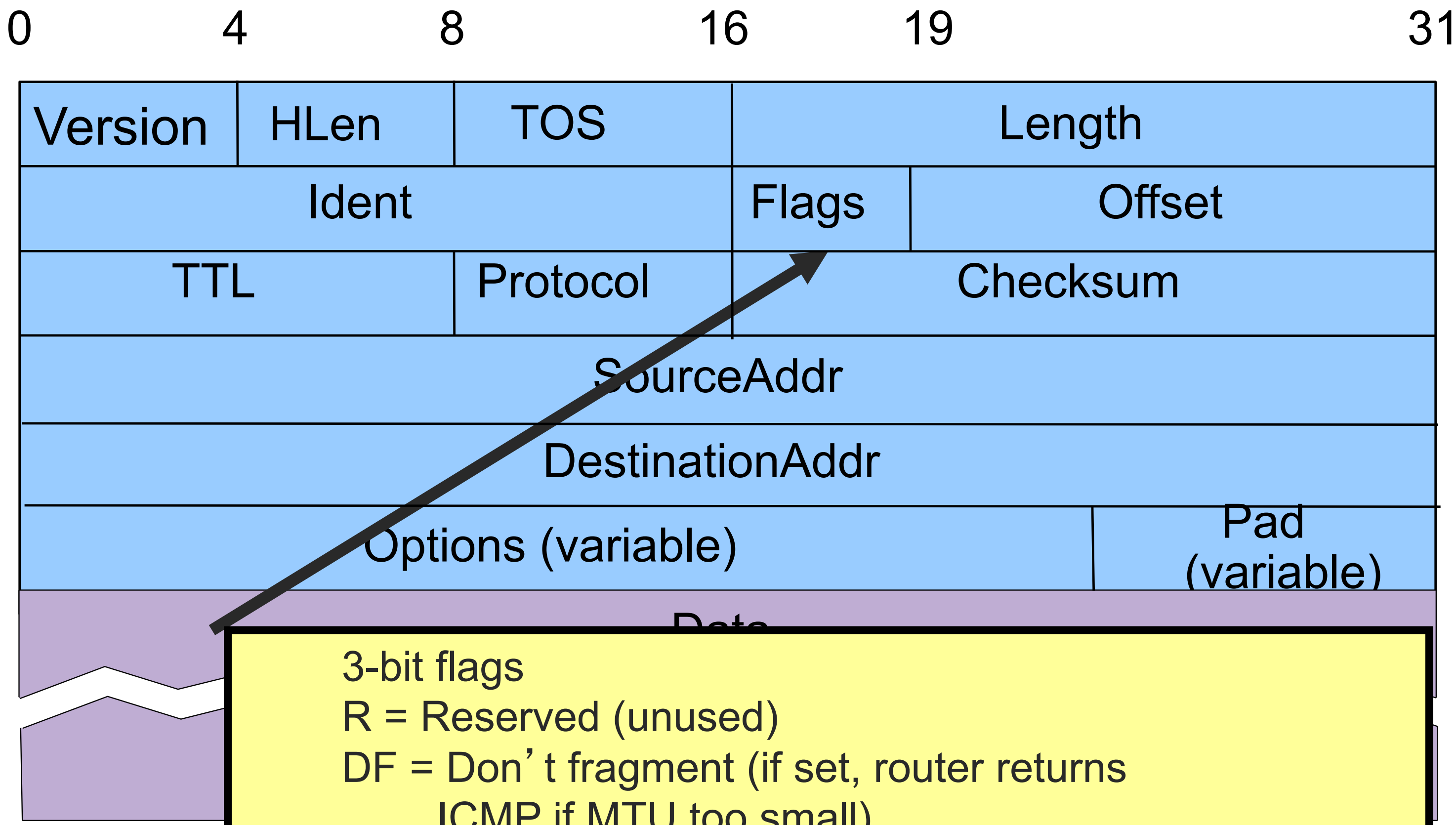
IP Packet Format



16-bit packet ID (Fragmentation support)

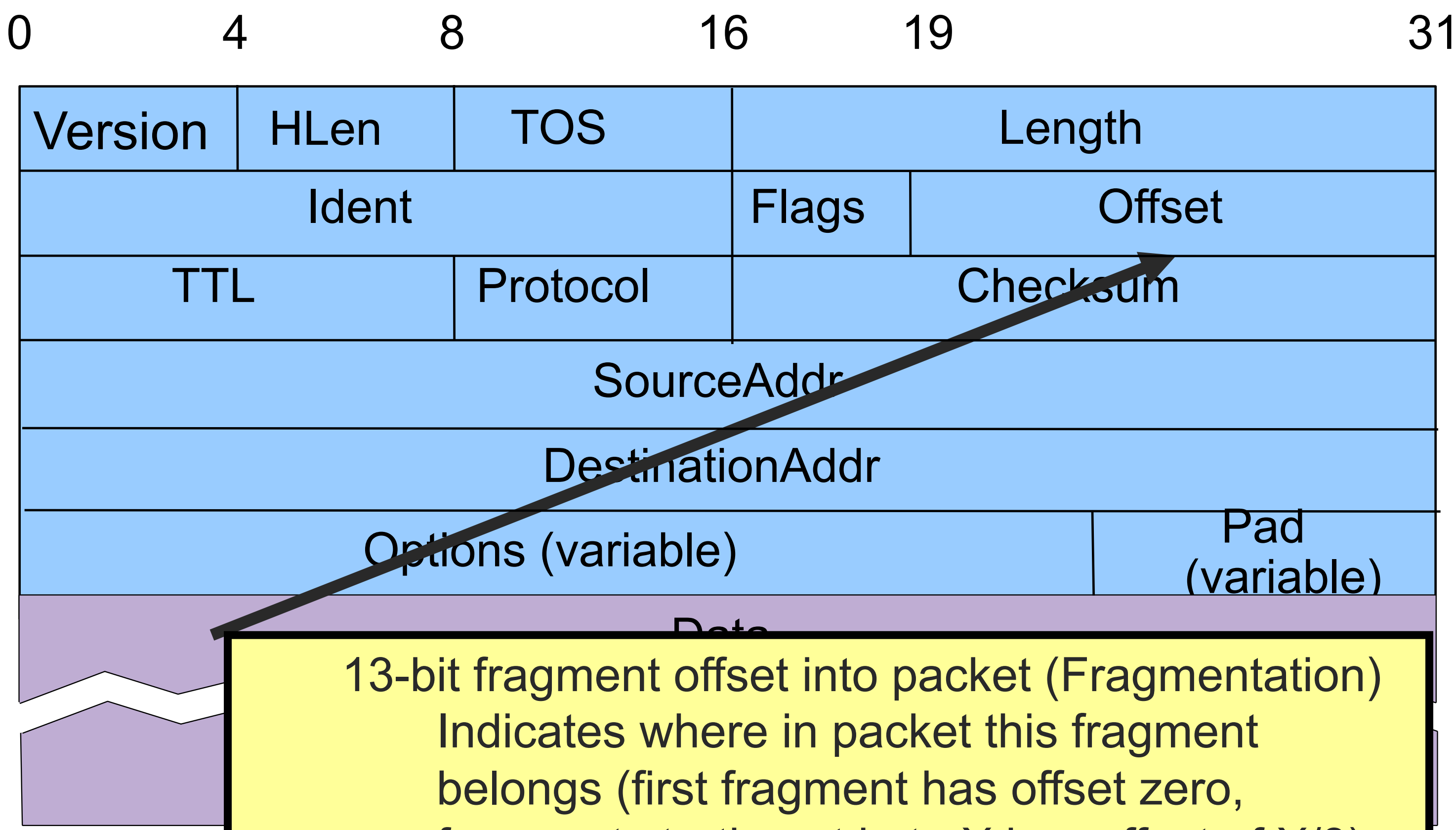
- All fragments from the same packet have the same ID
- Sender must make sure ID is unique for that (src,dest) pair, for the time the datagram will be active in the Internet

IP Packet Format



3-bit flags
R = Reserved (unused)
DF = Don't fragment (if set, router returns ICMP if MTU too small)
MF = More fragments (1 indicates datagram has additional fragments on the way, 0 indicates this is the last fragment)

IP Packet Format

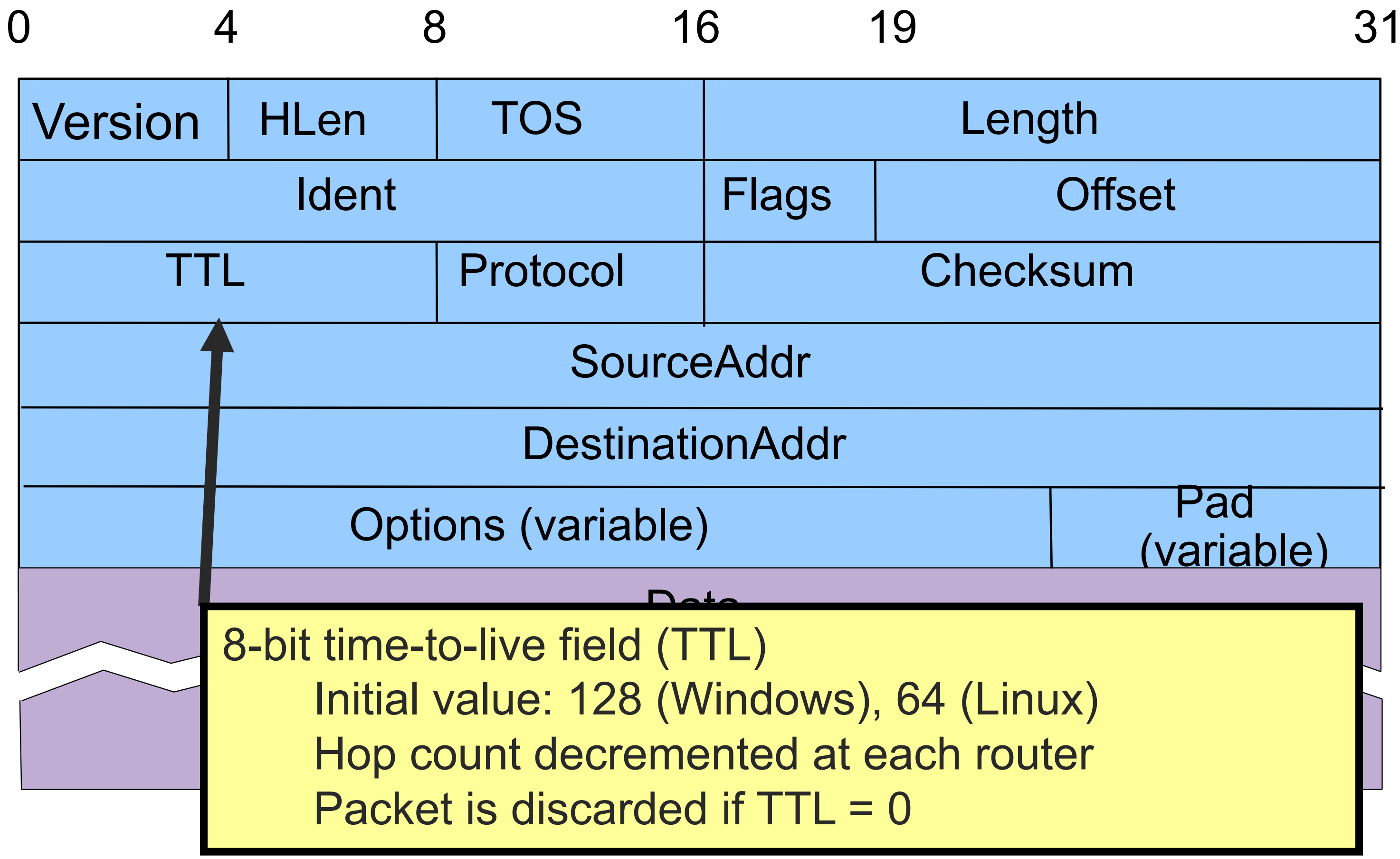


13-bit fragment offset into packet (Fragmentation)

Indicates where in packet this fragment belongs (first fragment has offset zero, fragment starting at byte X has offset of X/8)

Counted in 8-byte words

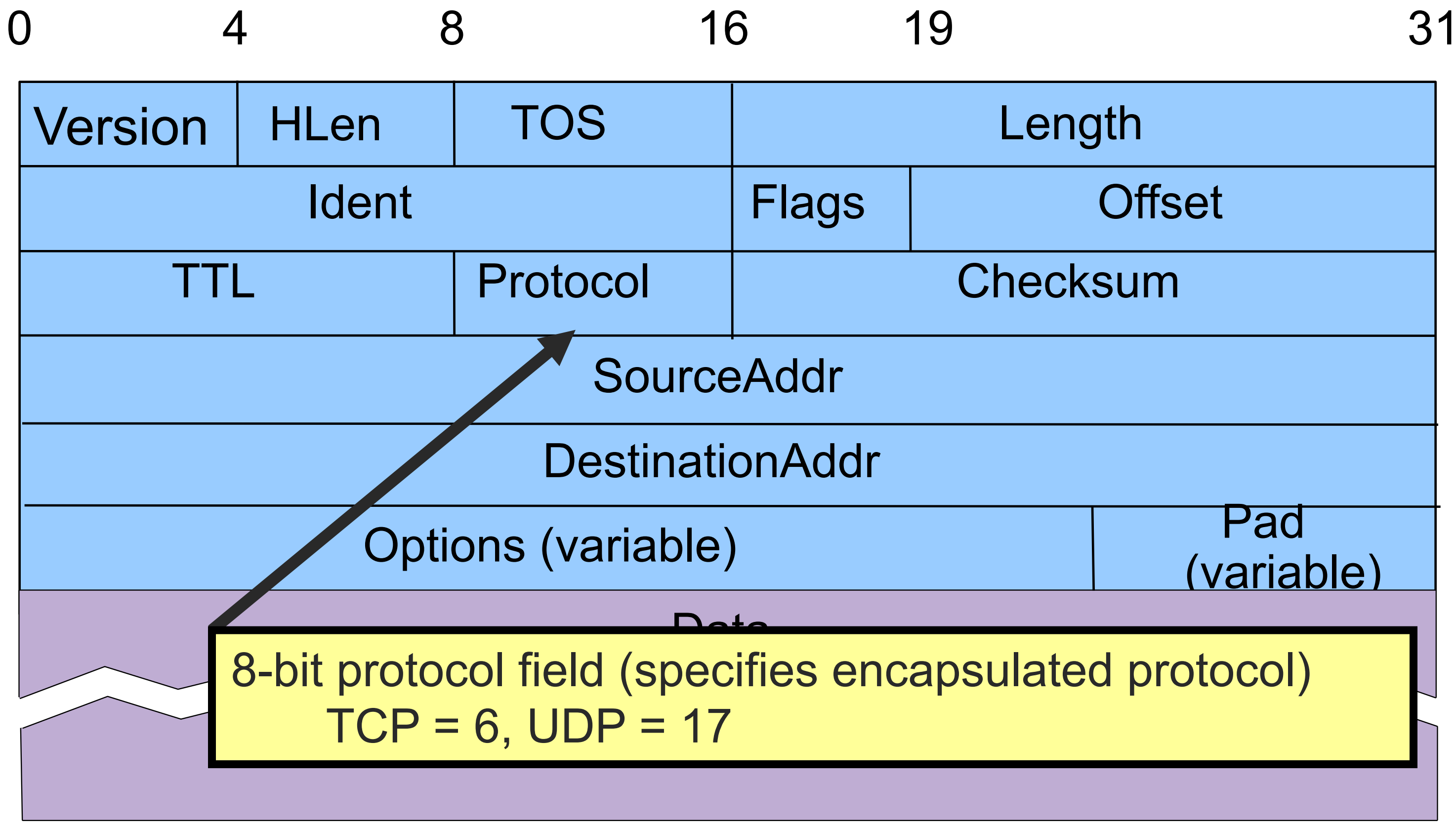
IP Packet Format



8-bit time-to-live field (TTL)

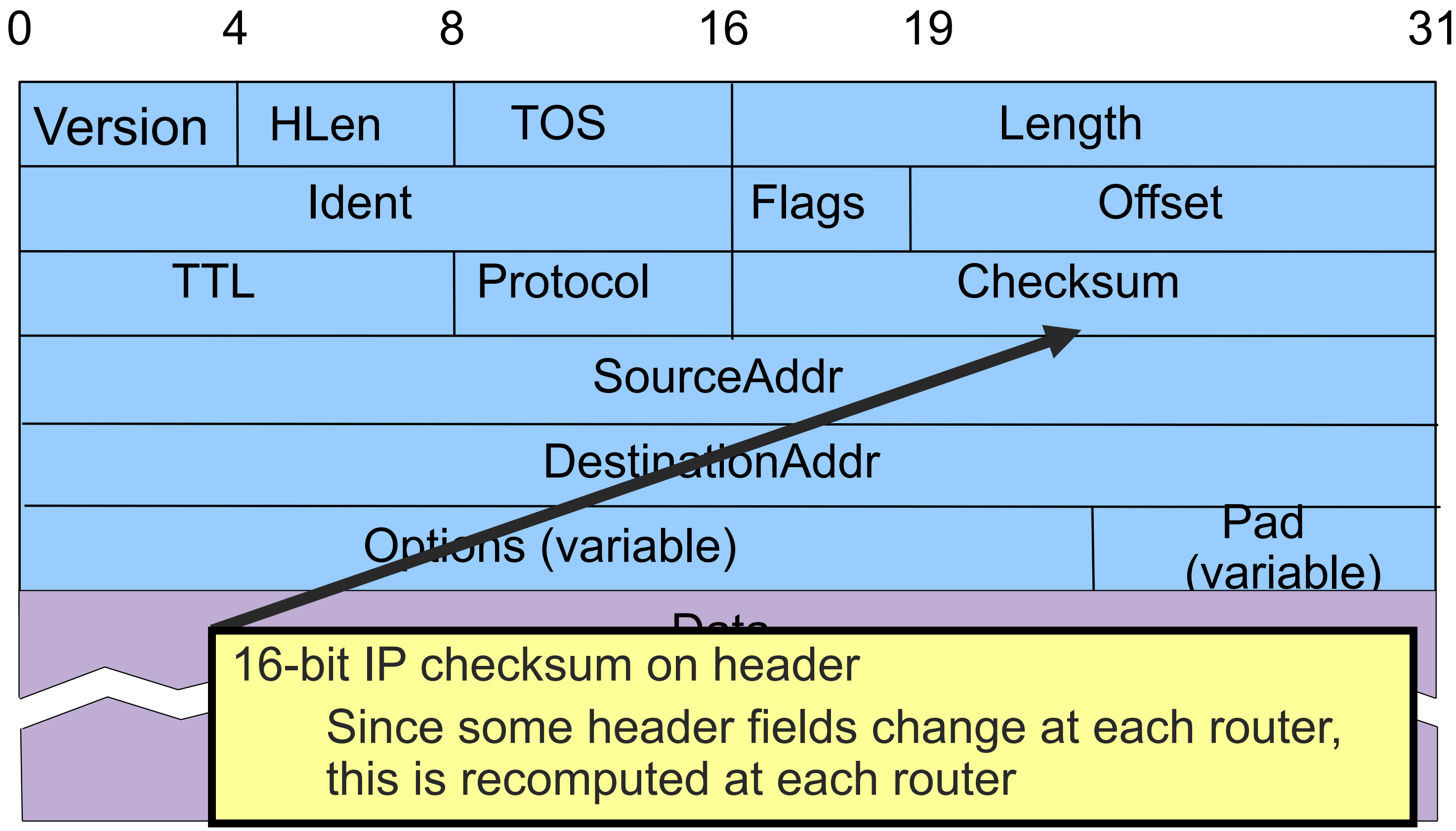
- Initial value: 128 (Windows), 64 (Linux)
- Hop count decremented at each router
- Packet is discarded if TTL = 0

IP Packet Format



8-bit protocol field (specifies encapsulated protocol)
TCP = 6, UDP = 17

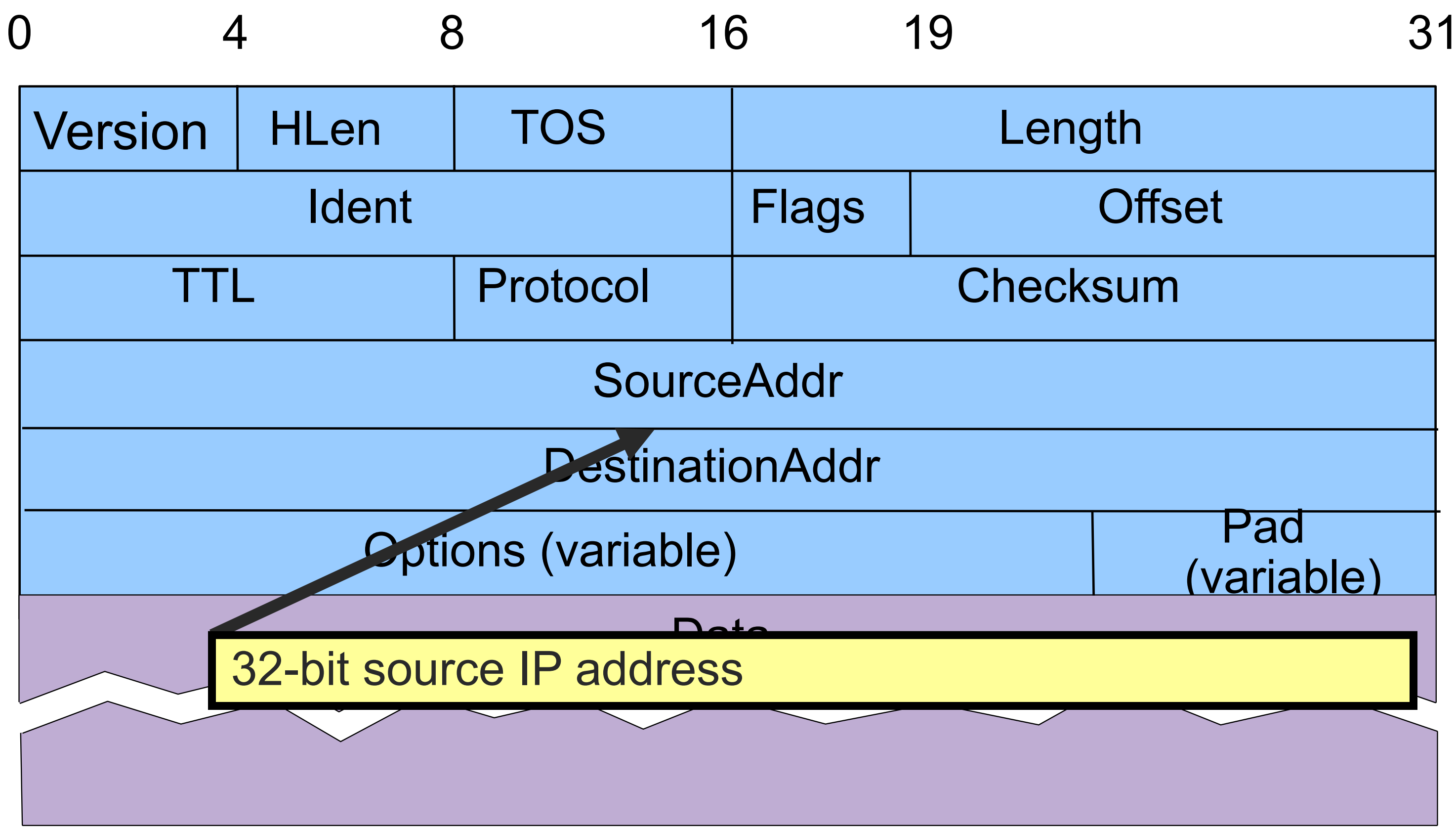
IP Packet Format



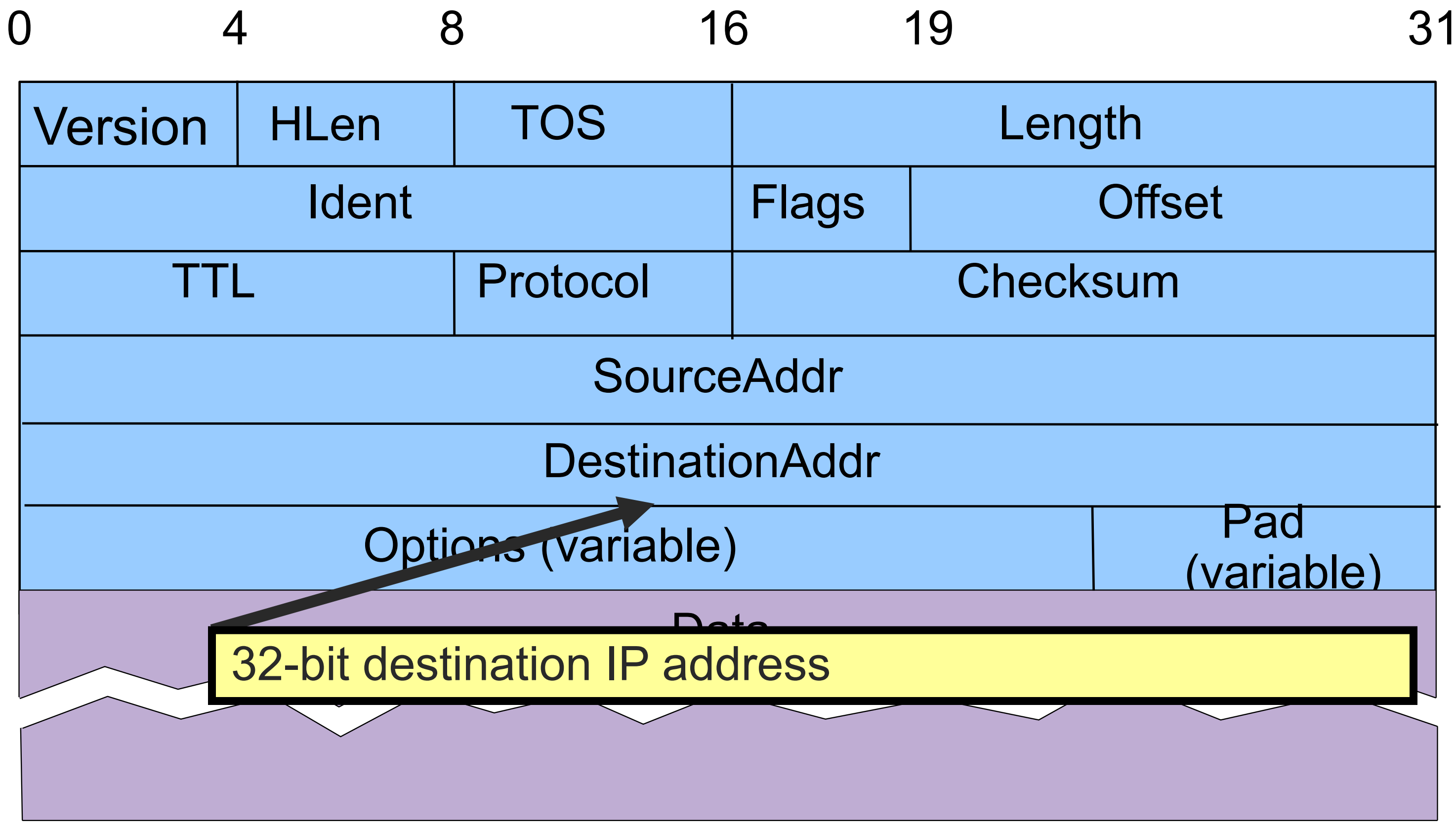
16-bit IP checksum on header

Since some header fields change at each router, this is recomputed at each router

IP Packet Format



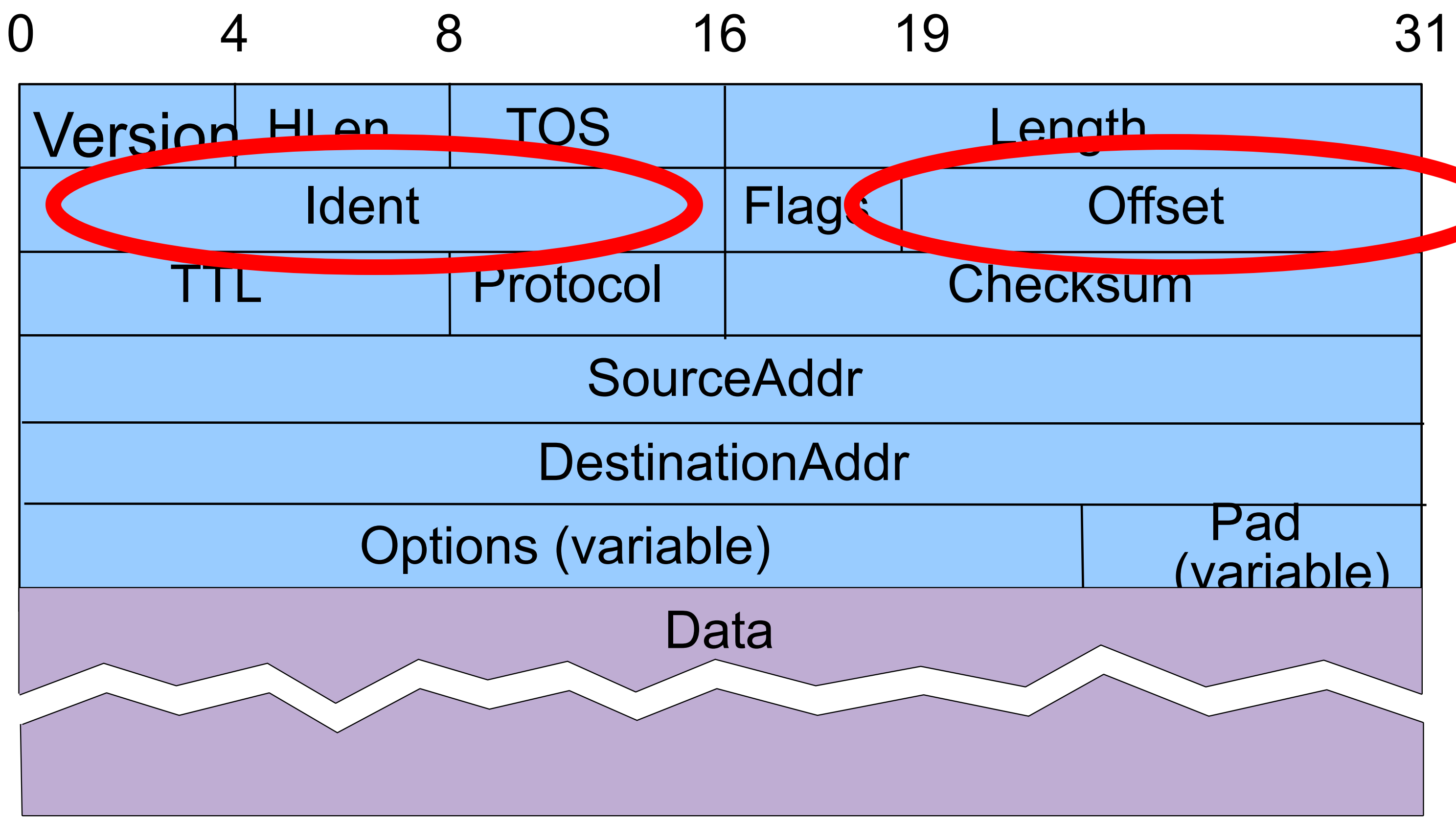
IP Packet Format



IP Packet Format

- Options
  - Variable size
  - Examples:
    - Source-based routing
    - Record route
- Padding
  - Fill to 32-bit boundaries

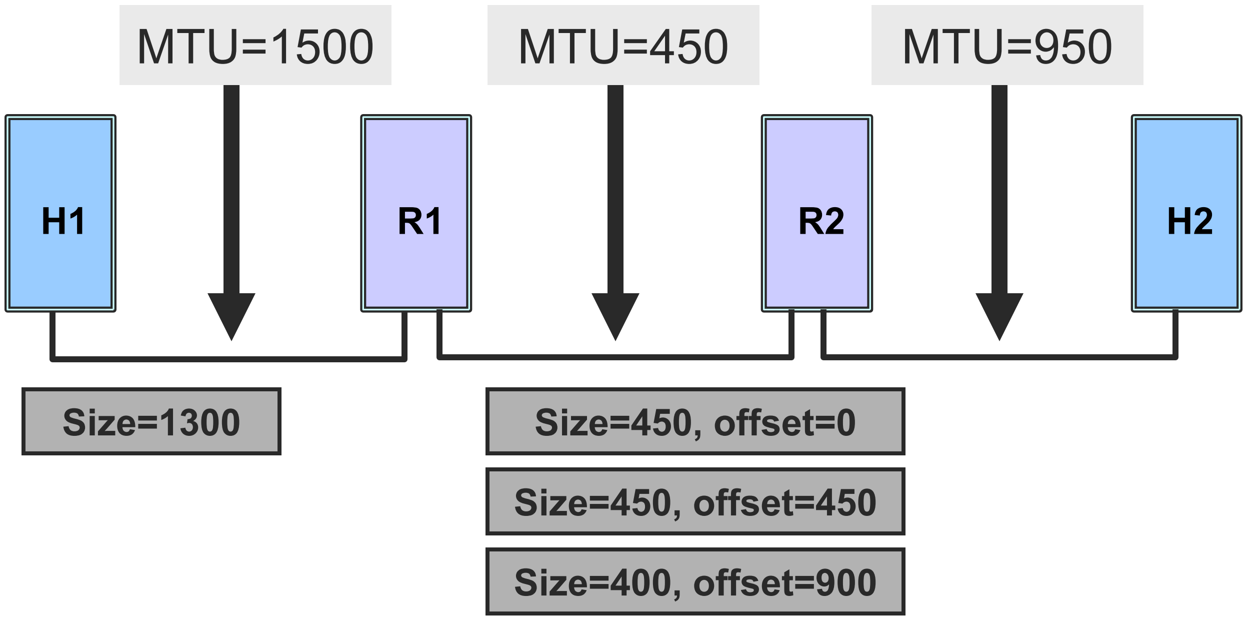
IP Packet Format



IP Packet Size

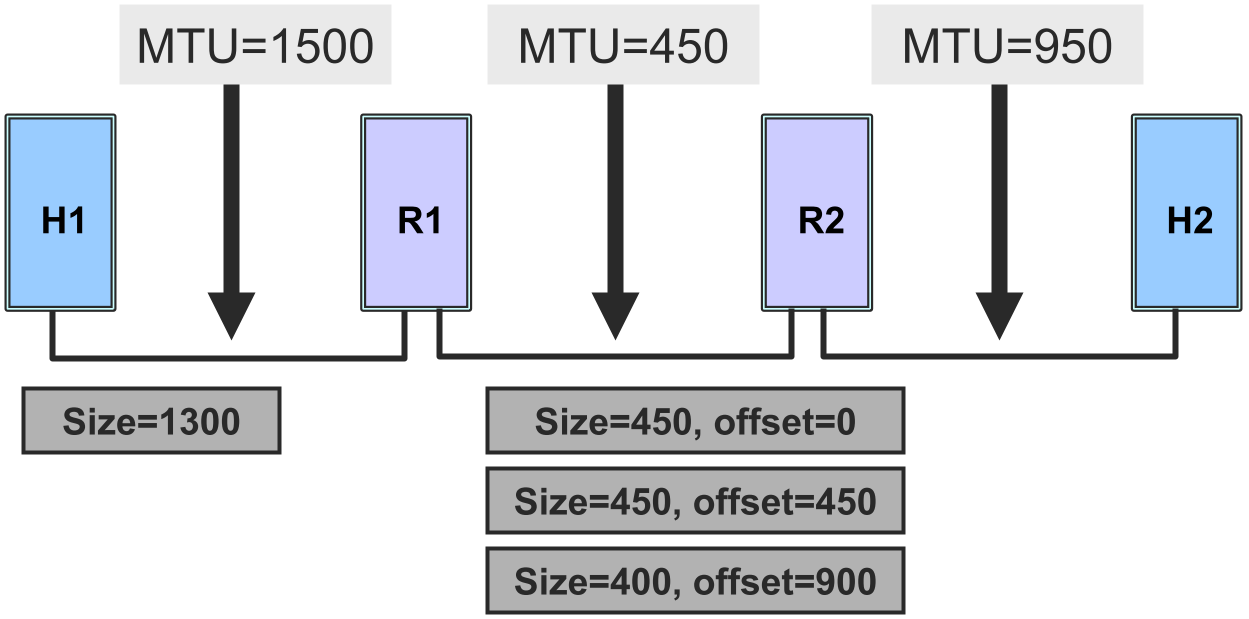
- Problem
  - Different physical layers provide different limits on frame length
    - Maximum transmission unit (MTU)
  - Source host does not know minimum value
    - Especially along dynamic routes

IP Fragmentation and Reassembly



- Solution
  - When necessary, split IP packet into acceptably sized packets prior to sending over physical link

IP Fragmentation and Reassembly



- Questions
  - Where should reassembly occur?
  - What happens when a fragment is damaged/lost?

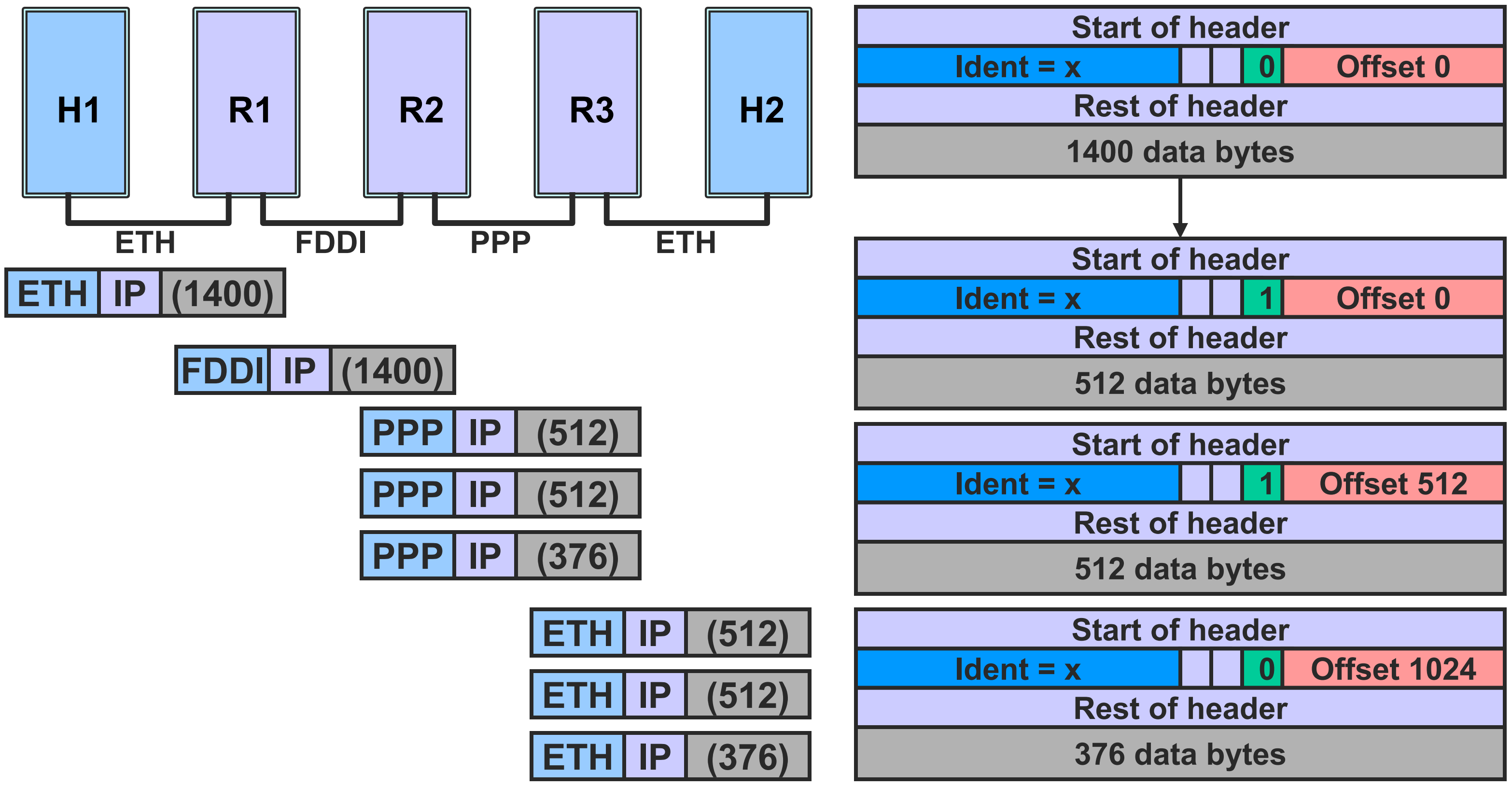
IP Fragmentation and Reassembly

- Fragments
  - self-contained IP datagrams
- Reassemble at destination
  - Minimizes refragmentation
- If one or more fragments are lost
  - Drop all fragments in packet
- Avoid fragmentation at source host
  - Transport layer should send packets small enough to fit into one MTU of local physical network
  - Must consider IP header

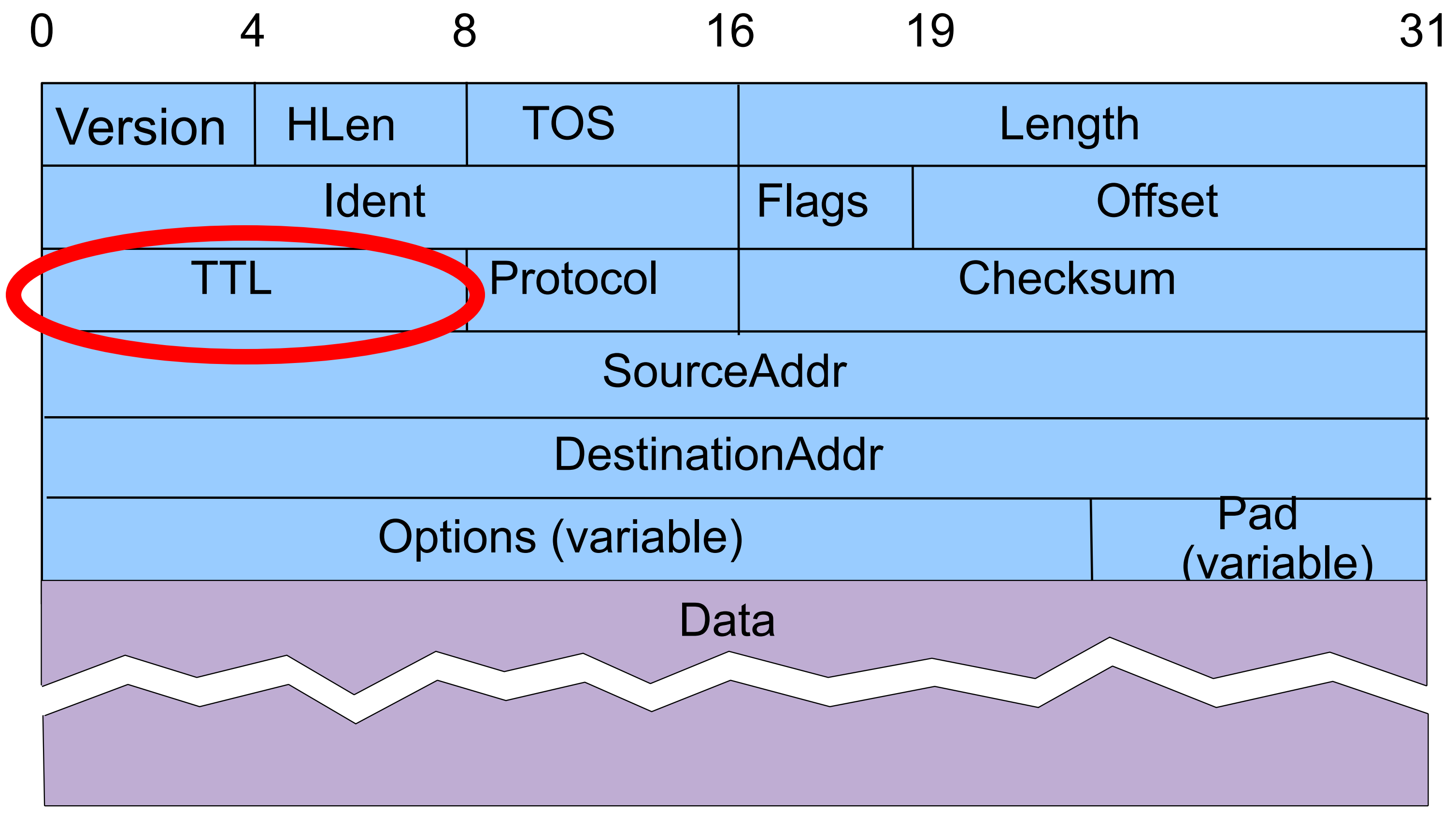
Path MTU discovery

- Set “don’t fragment” bit in IP header
  - Size is MTU of first hop
- Interface with too-small MTU
  - Responds back with “ICMP” message
  - Unfortunately, many networks drop ICMP traffic
- Reduce packet size
  - Repeat until smallest MTU on path discovered
- Binary search
  - Better yet: note there are small number of MTUs in the Internet

IP Fragmentation and Reassembly



IP Packet Format



Time to Live (TTL) field

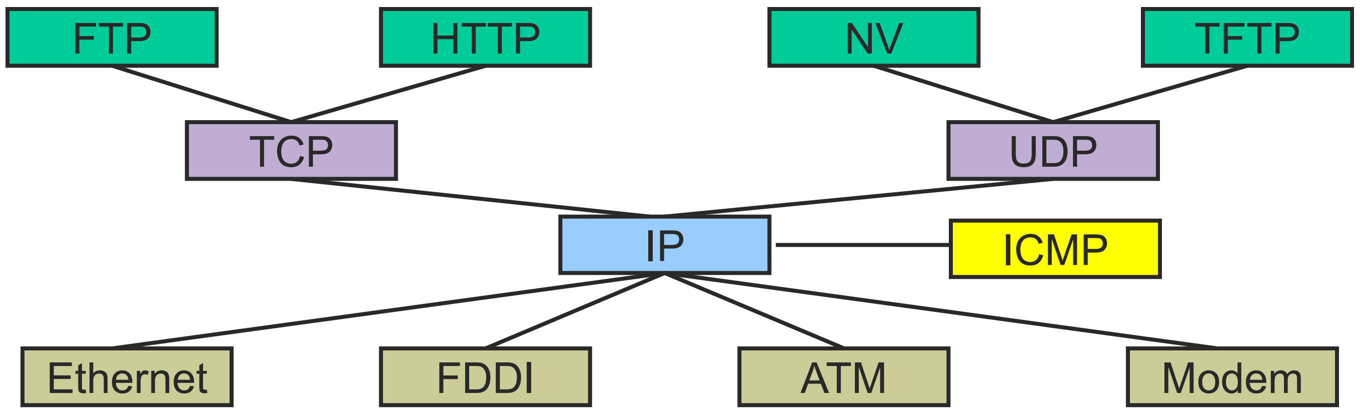
- Problem: forwarding loop
    - My FIB says to forward to you, yours says to forward to me
        - Or much more complicated scenarios with longer loops
    - Packets circle forever
    - After a few packets, 100% of capacity taken up by cycling packets

Time to Live (TTL) field

- Solution: TTL field
  - Hope we never have to use it…
  - Begins at source at some value (e.g., 255)
  - Decremented at each hop
  - Dropped at any hop where TTL = 0
    - "Time exceeded" message returned to source via ICMP
    - Traceroute is a trick based on this

Internet Control Message Protocol (ICMP)

- IP companion protocol
  - Handles error and control messages
  - Used for troubleshooting and measurement

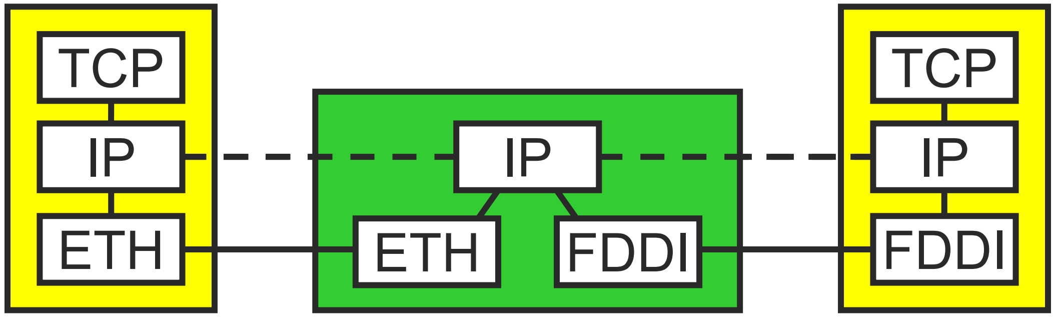


ICMP

- Use
  - Pings (probing remote hosts)
  - Traceroutes (learning set of routers along a path)
  - etc.
- Control Messages
  - Echo/ping request and reply
  - Echo/ping request and reply with timestamps
  - Route redirect
- Error Messages
  - Host unreachable
  - Reassembly failed
  - IP checksum failed
  - TTL exceeded (packet dropped)
  - Invalid header

IPv4 Address Translation support

- IP addresses to LAN physical addresses
- Problem
  - An IP route can pass through many physical networks
  - Data must be delivered to destination's physical network
  - Hosts only listen for packets marked with physical interface names
    - Each hop along route
    - Destination host



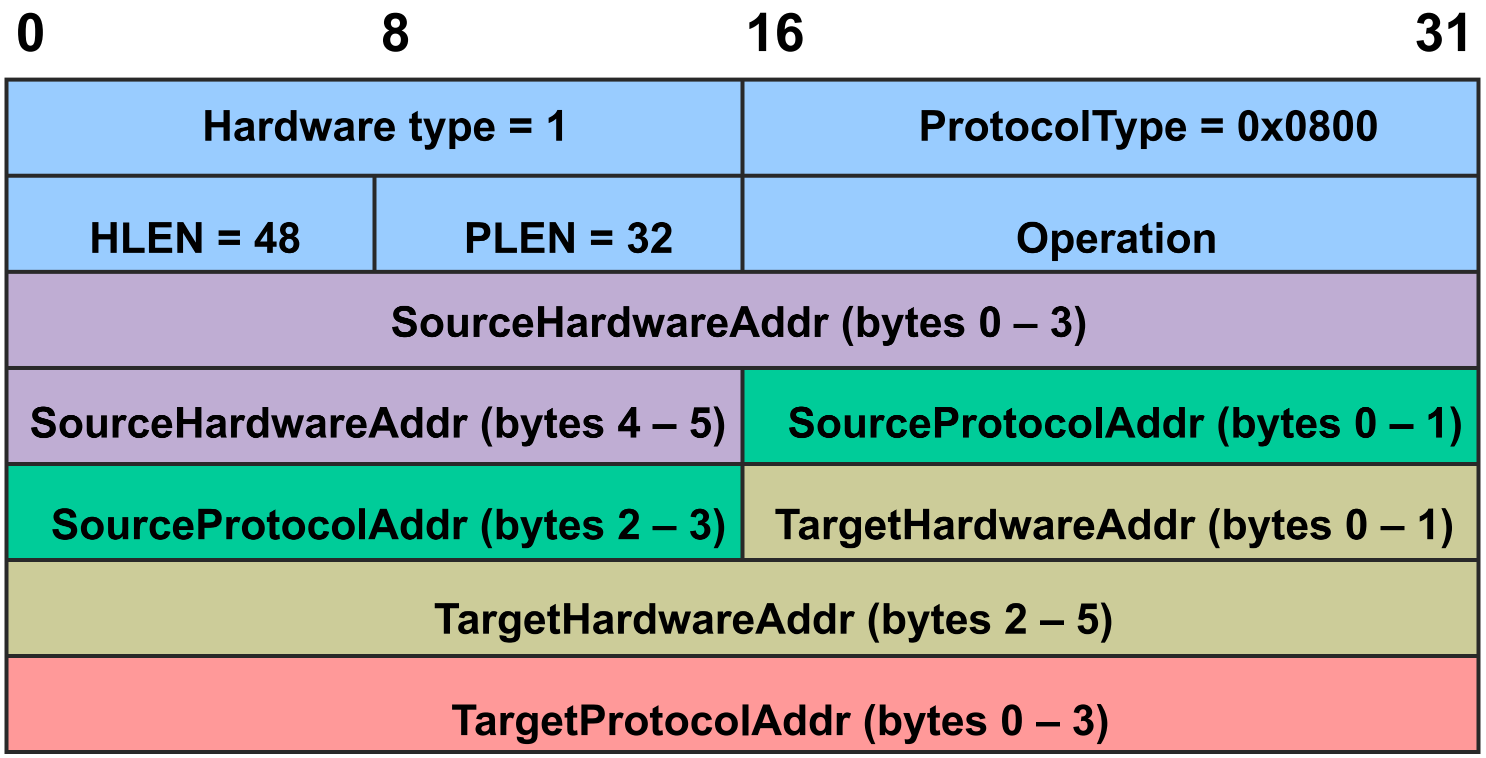
IP to Physical Address Translation

- Hard-coded
  - Encode physical address in IP address
  - Ex: Map Ethernet addresses to IP addresses
    - Makes it impossible to associate address with topology
- Fixed table
  - Maintain a central repository and distribute to hosts
    - Bottleneck for queries and updates
- Automatically generated table
  - Use ARP to build table at each host
  - Use timeouts to clean up table

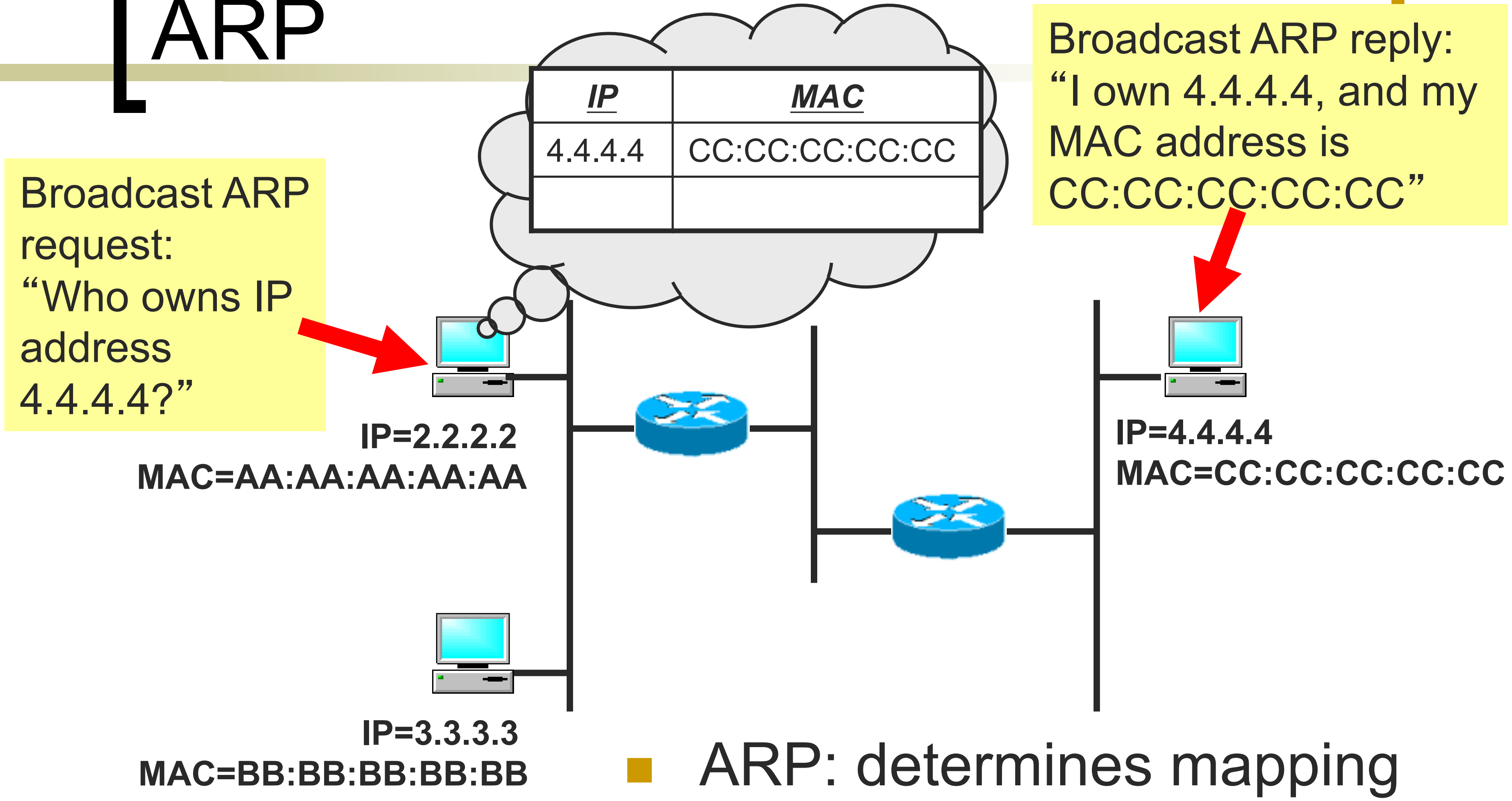
ARP: Address Resolution Protocol

- Check ARP table for physical address
- If address not present
  - Broadcast an ARP query, include querying host's translation
  - Wait for an ARP response
- Upon receipt of ARP query/response
  - Targeted host responds with address translation
  - If address already present
    - Refresh entry and reset timeout
  - If address not present
    - Add entry for requesting host
    - Ignore for other hosts
- Timeout and discard entries after O(10) minutes

ARP Packet


0
8
16
31
Hardware type = 1
ProtocolType = 0x0800
HLEN = 48
PLEN = 32
Operation
SourceHardwareAddr (bytes 0 – 3)
SourceHardwareAddr (bytes 4 – 5)
SourceProtocolAddr (bytes 0 – 1)
SourceProtocolAddr (bytes 2 – 3)
TargetHardwareAddr (bytes 0 – 1)
TargetHardwareAddr (bytes 2 – 5)
TargetProtocolAddr (bytes 0 – 3)

ARP


Broadcast ARP request: "Who owns IP address 4.4.4.4?"
Broadcast ARP reply: "I own 4.4.4.4, and my MAC address is CC:CC:CC:CC:CC"
IP=2.2.2.2 MAC=AA:AA:AA:AA:AA
IP=3.3.3.3 MAC=BB:BB:BB:BB:BB
IP=4.4.4.4 MAC=CC:CC:CC:CC:CC

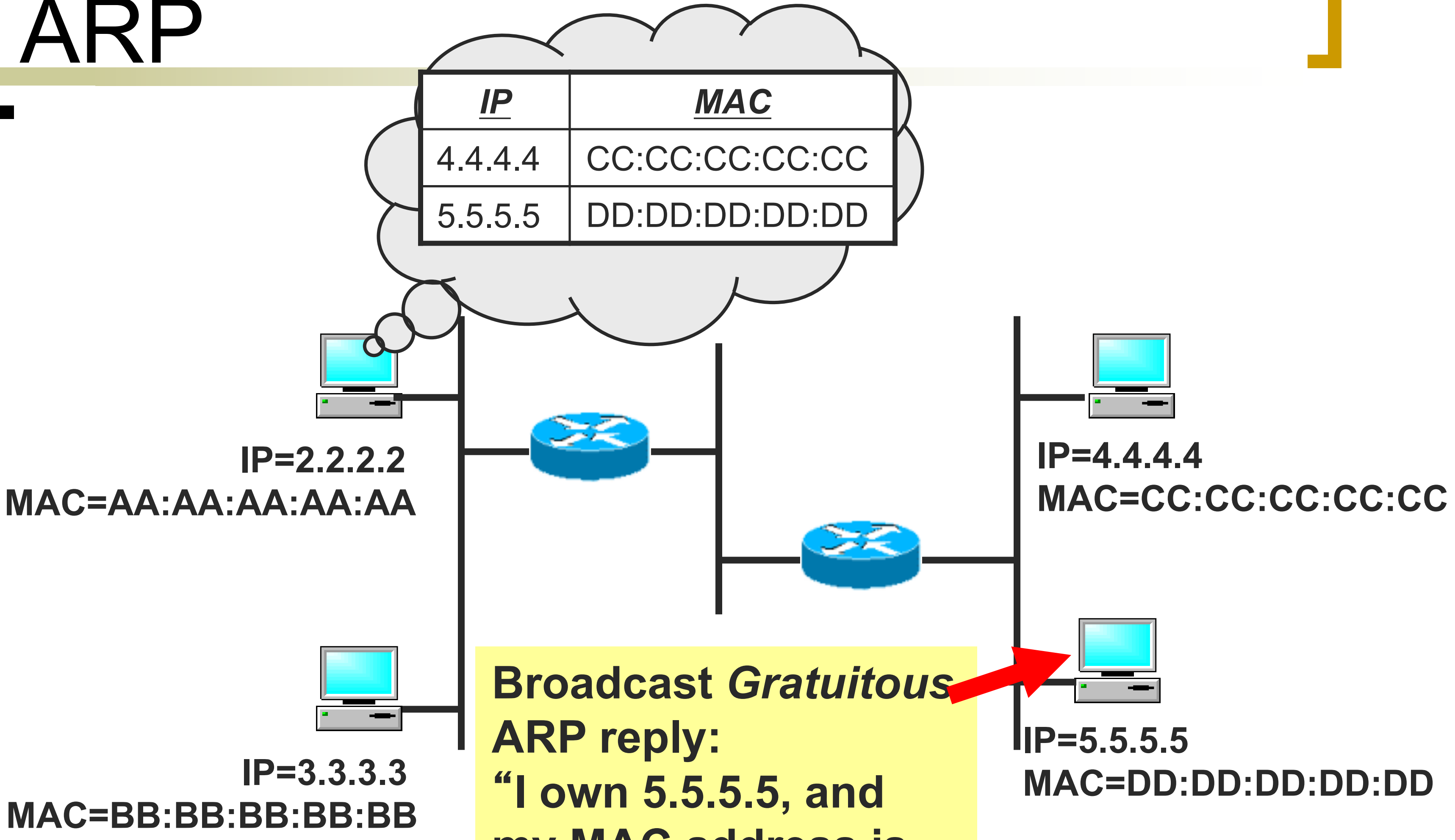
IP	***MAC***
4.4.4.4	CC:CC:CC:CC:CC

- ARP: determines mapping from IP to MAC address

ARP

- What if IP address is not on subnet?
  - Each host configured with “default gateway”
  - Use ARP to resolve its IP address
- Gratuitous ARP: tell network your IP to MAC mapping
  - Used to detect IP conflicts, IP address changes; update other machines’ ARP tables, update bridges’ learned information

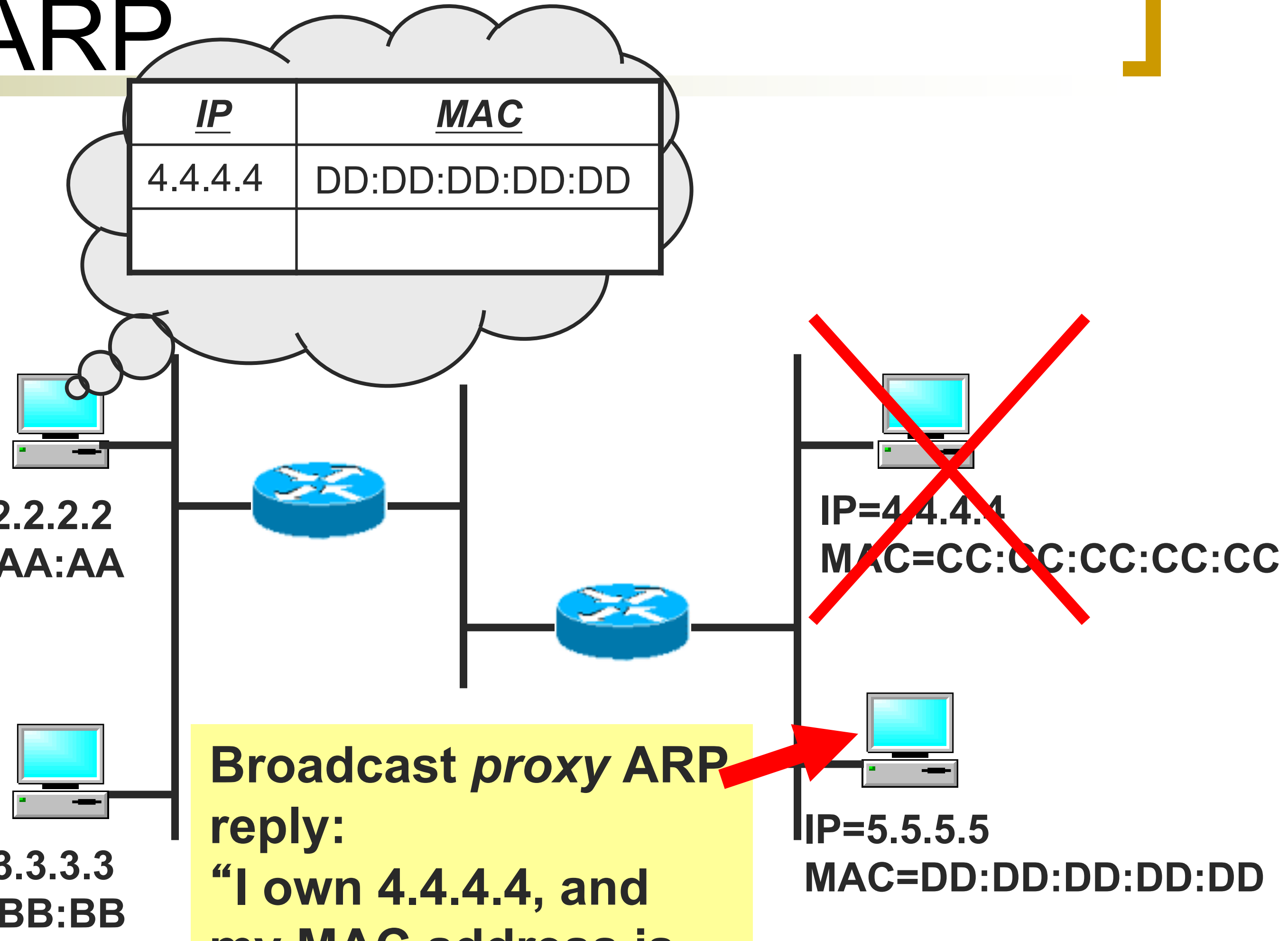
ARP



IP	***MAC***
4.4.4.4	CC:CC:CC:CC:CC
5.5.5.5	DD:DD:DD:DD:DD

Broadcast *Gratuitous* ARP reply: "I own 5.5.5.5, and my MAC address is DD:DD:DD:DD:DD"

Proxy ARP



IP	***MAC***
4.4.4.4	DD:DD:DD:DD:DD

Broadcast *proxy* ARP reply: "I own 4.4.4.4, and my MAC address is DD:DD:DD:DD:DD"

Host Configuration

- Plug new host into network
  - How much information must be known?
  - What new information must be assigned?
  - How can process be automated?
- Some answers
  - Host needs an IP address (must know it)
  - Host must also
    - Send packets out of physical (direct) network
    - Thus needs physical address of router

Host Configuration

- Reverse Address Resolution Protocol (RARP)
  - Translate physical address to IP address
  - Used to boot diskless hosts
  - Host broadcasts request to boot
  - RARP server tells host the host’s own IP address
- Boot protocol (BOOTP)
  - Use UDP packets for same purpose as RARP
  - Allows boot requests to traverse routers
  - IP address of BOOTP server must be known
  - Also returns file server IP, subnet mask, and default router for host

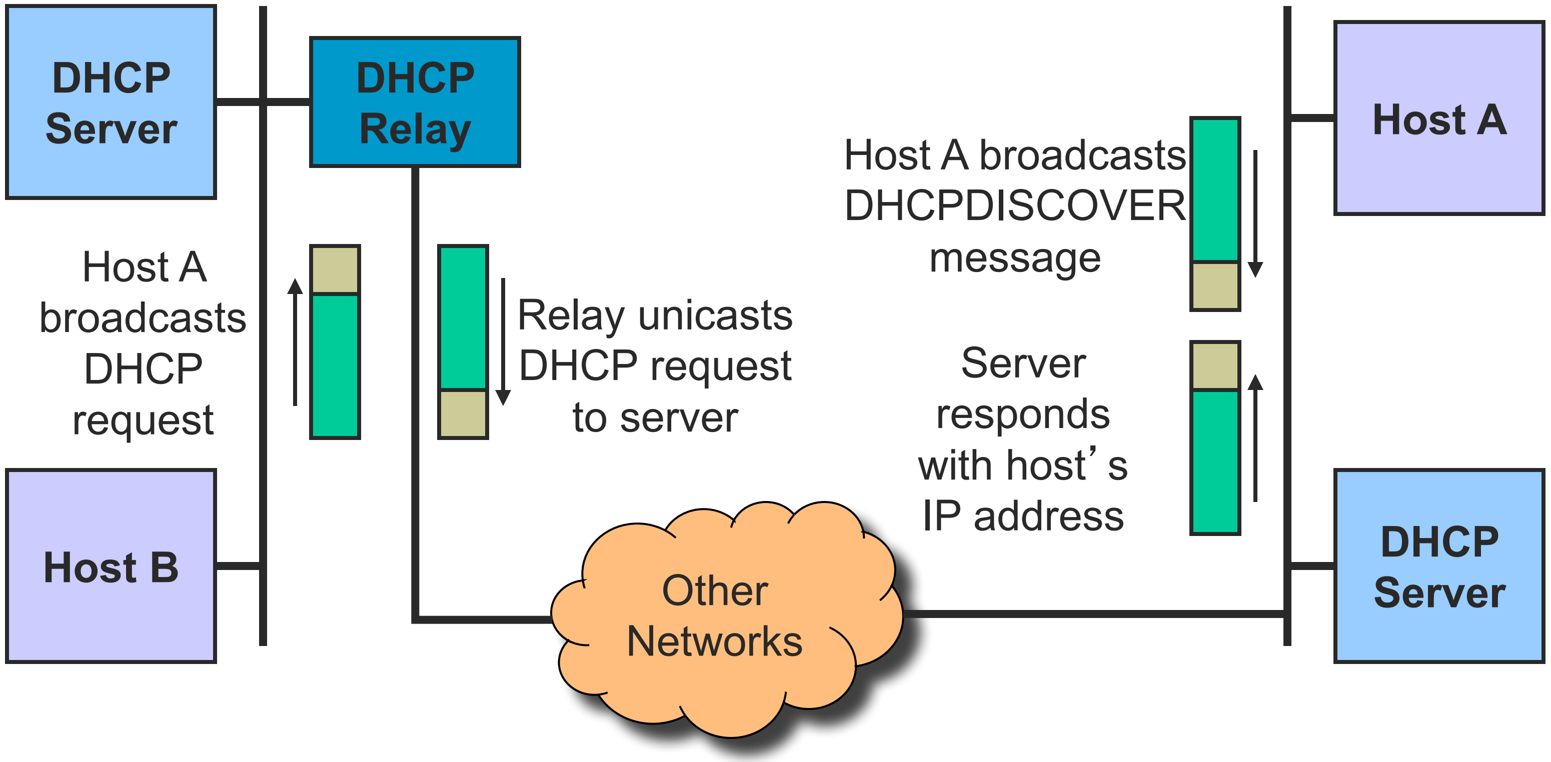
Dynamic Host Configuration Protocol (DHCP)

- A simple way to automate configuration information
  - Network administrator does not need to enter host IP address by hand
  - Good for large and/or dynamic networks

Dynamic Host Configuration Protocol (DHCP)

- New machine sends request to DHCP server for assignment and information
- Server receives
  - Directly
    - If new machine given server's IP address
  - Through broadcast
    - If on same physical network
    - Via DHCP relay nodes
      - Forward requests onto the server's physical network
- Server assigns IP address and provides other info
- Can be made secure
  - Present signed request or just a "valid" physical address

DHCP


DHCP Server
DHCP Relay
Host A broadcasts DHCP request
Relay unicasts DHCP request to server
Host A broadcasts DHCPDISCOVER message
Host A
Server responds with host's IP address
Host B
Other Networks
DHCP Server

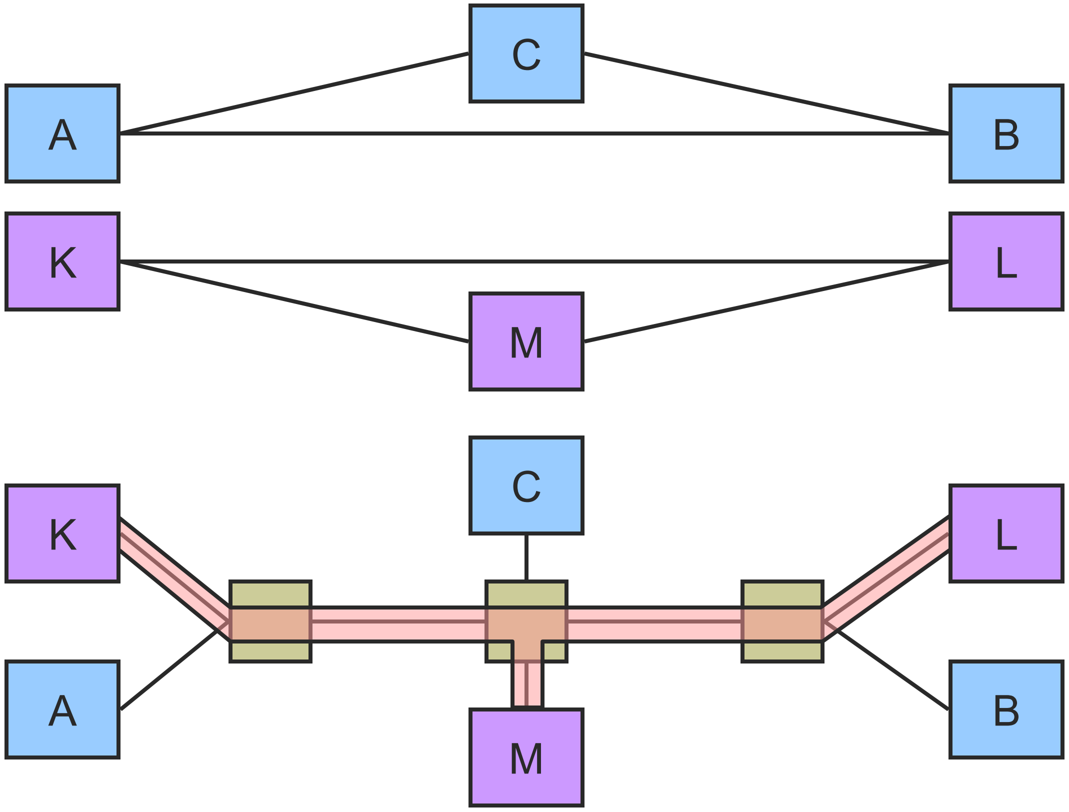
DHCP

- Remaining challenge: configuring DHCP servers
  - Need to ensure consistency across servers, between servers and network, address assignment across routers
  - But simpler than directly managing end hosts

Virtual Private Networks

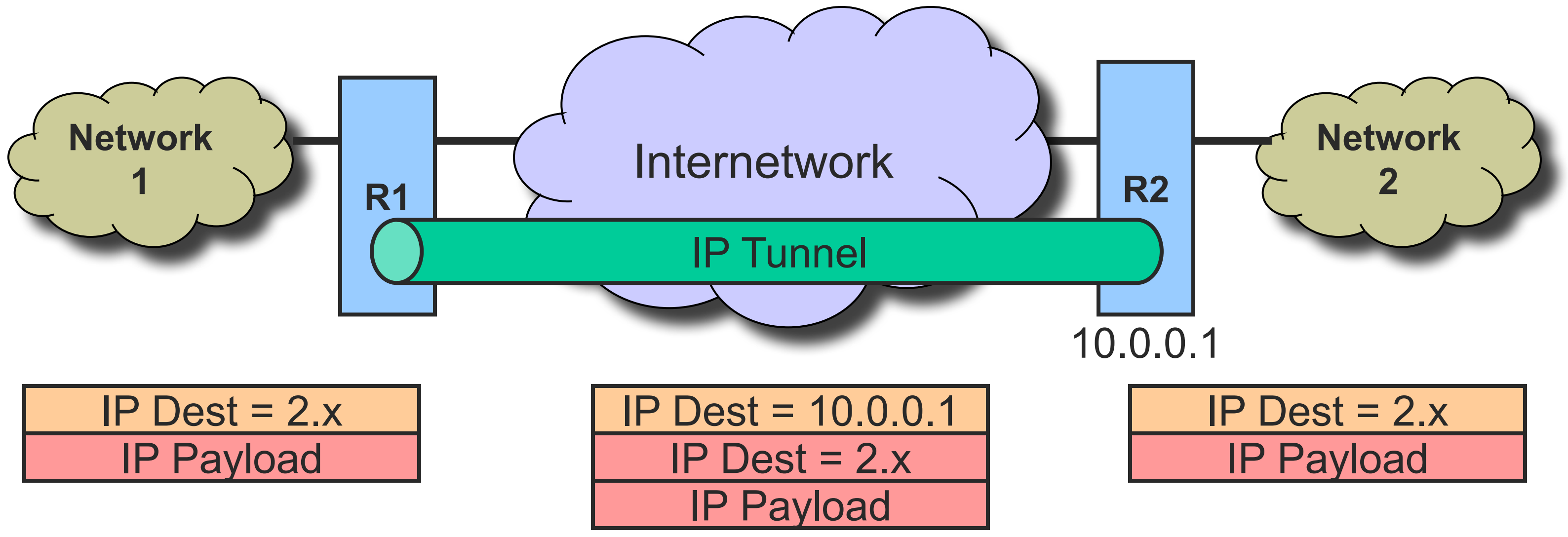
- Goal
  - Controlled connectivity
    - Restrict forwarding to authorized hosts
  - Controlled capacity
    - Change router drop and priority policies
    - provide guarantees on bandwidth, delay, etc.
- Virtual Private Network
  - A group of connected subnets
  - Connections may be over shared network
  - Similar to LANE, but over IP allowing the use of heterogeneous internets

Virtual Private Networks



Tunneling

- IP Tunnel
  - Virtual point-to-point link between an arbitrarily connected pair of nodes



Tunneling

- Advantages
  - Transparent transmission of packets over a heterogeneous network
  - Only need to change relevant routers
- Disadvantages
  - Increases packet size
  - Processing time needed to encapsulate and unencapsulate packets
  - Management at tunnel-aware routers