ELEC / COMP 177 – Fall 2011

Computer Networking → Internet Protocol (IP)

Some slides from Kurose and Ross, *Computer Networking*, 5th Edition

Schedule

- Topics
  - This week: Network layer (IP, ARP, ICMP)
  - Next week: More network layer (Routers and routing protocols)
- Assignments
  - **Project 1**: Wednesday is last *late* day to submit
  - **Homework 4:** Due Thursday, Nov 3rd
  - **Project 2:** Due Thursday, Nov 10th

Project #1

- **What was the most difficult part of this project?**
  - ***What solution did you find?***

Network Layer – IP

Why not just use Ethernet?

- Most computer systems use Ethernet networking
- Ethernet provides facilities to
  - Locate computers
  - Forward packets directly
  - Prevent loops
  - ...
- What are the drawbacks of Ethernet for global communication?

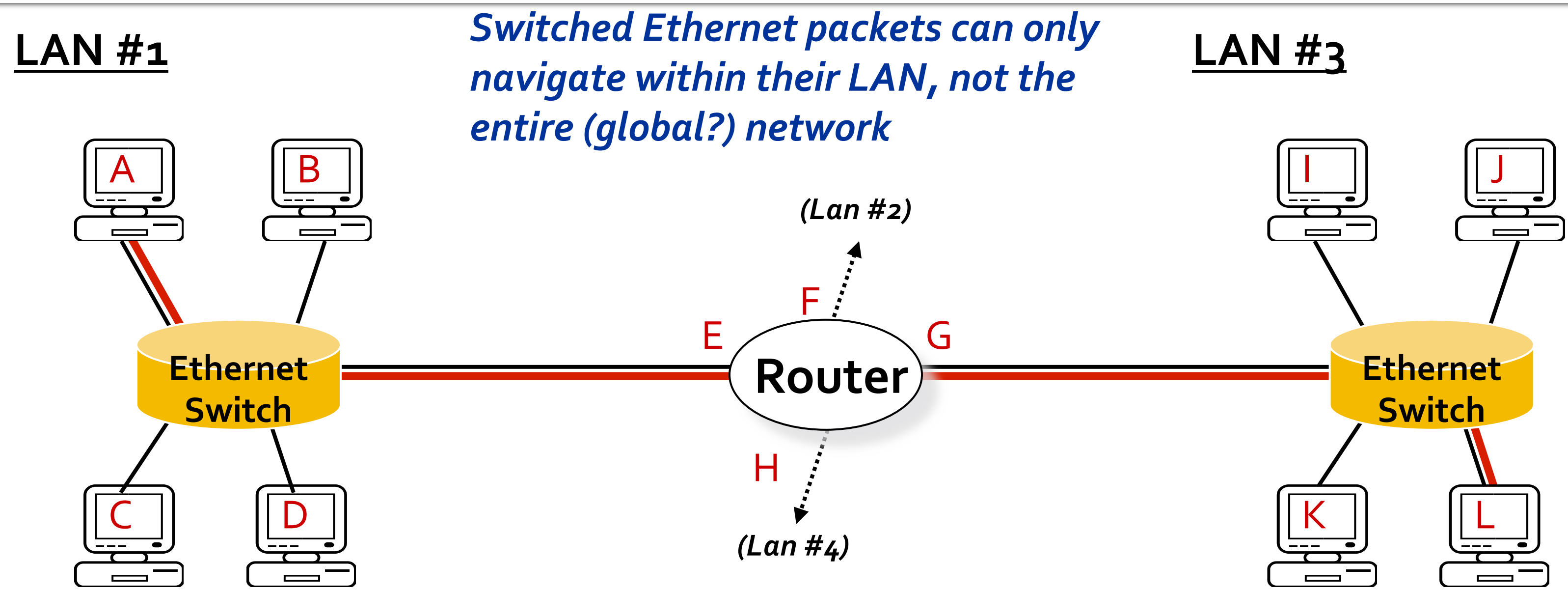
Ethernet Drawbacks

- Locating computers
  - Do we really want to broadcast across the Internet?
- Preventing loops
  - Do we really want to rebuild an Internet-wide spanning tree whenever the topology changes?
  - Do we really want packets to live forever if loops remain?
- Unreachable computers
  - What happens if the destination is unreachable?
  - I.e., it doesn't exist, is turned off, is broken, …

Network vs. Link Layer

- "Most" ≠ "All"
  - Not all networks are Ethernet
  - Why limit choice, innovation, etc. at the link level?
- Link layer
  - What is the best way to move local traffic (single hop)?
  - Old/new network, wired/wireless network, …
  - Different links can use different networks!
- Network layer
  - What is the best to handle multi-hop communication?
  - Addressing
  - Unreliable delivery mechanisms (routing)

Routing Between LANs



(1) A transmits to L using higher-level protocol (e.g. IP)
Ethernet frame destination is router

Frame:

DA (E)	SA (A)	Type / Data	CRC

(2) Switch forwards frame to router

(3) Router uses higher-level protocol to determine destination, and updates Ethernet frame destination, source and CRC

Frame:

DA (L)	SA (G)	Type / Data	CRC

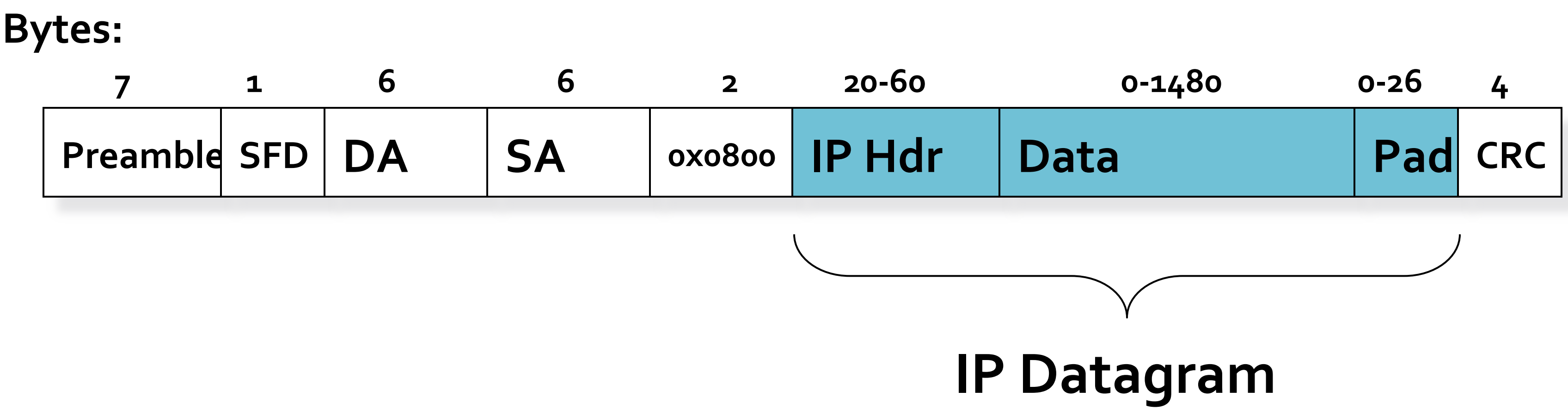
(4) Switch forwards frame to destination

The Internet Protocol

- Datagram
  - Each packet is individually routed
  - Packets may be fragmented or duplicated
    - Due to underlying networks
- Connectionless
  - No guarantee of delivery in sequence
- Unreliable
  - No guarantee of delivery
  - No guarantee of integrity of data
- Best effort
  - Only drop packets when necessary
  - No time guarantee for delivery

IP and Ethernet

- IP datagrams can be *encapsulated* in Ethernet frames



Understanding IP

- Datagram lifetimes
  - Time-to-live
- Handling disparate link layers
  - Fragmentation
- IP integrity
  - Header checksum
- What do datagrams look like?
  - Header format
- Addressing

Time-to-Live

- Sender sets a TTL value for each datagram
- Each router decrements the TTL
- When the TTL reaches 0
  - The router drops the datagram
  - The router sends an ICMP error (more later) to the sender
- Effectively a "maximum hop count"
- **Why is this useful / necessary?**

Traceroute

- Tool to find the route IP packets take through the Internet
- Exploits the TTL field
  - Send packets with successively increasing TTL values
  - See what routers respond with ICMP “Time Exceeded” errors
- Only shows us routers, not Ethernet switches
  - Only works at network layer, not link layer

Using Traceroute

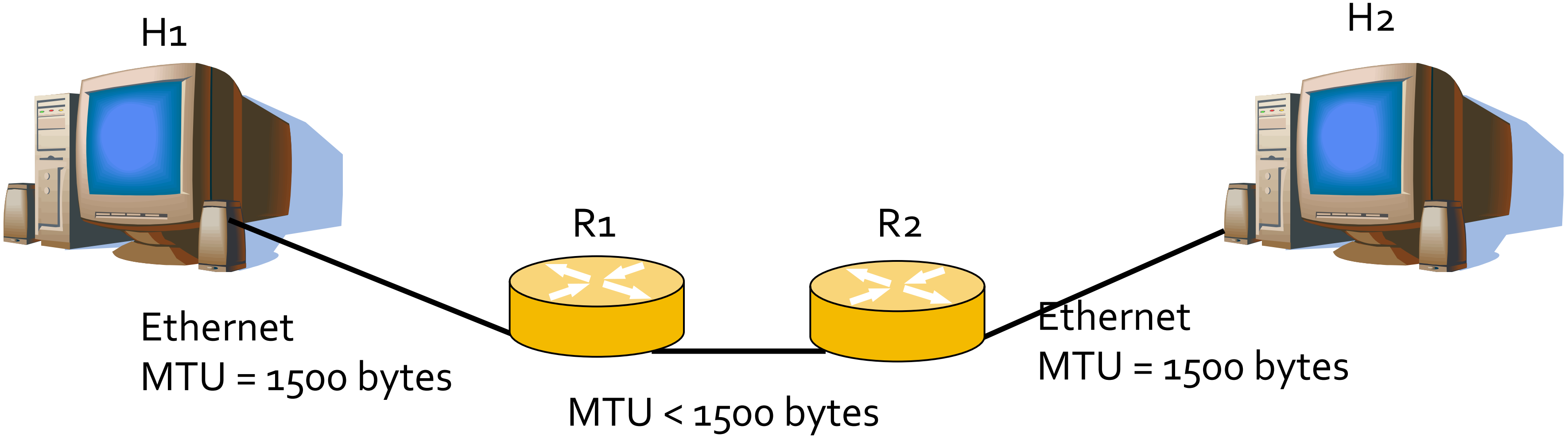
```
traceroute to www.l.google.com (74.125.224.52), 64 hops max, 52 byte packets
 1  10.10.207.254 (10.10.207.254)  0.737 ms  0.296 ms  0.304 ms
 2  10.0.0.133 (10.0.0.133)  0.387 ms  0.328 ms  0.344 ms
 3  10.0.0.105 (10.0.0.105)  0.401 ms  0.353 ms  0.357 ms
 4  138.9.253.252 (138.9.253.252)  0.748 ms  0.664 ms  1.319 ms
 5  74.202.6.5 (74.202.6.5)  6.836 ms  7.932 ms  5.986 ms
 6  pao1-pr1-ge-3-0-0-0.us.twtelecom.net (66.192.242.70)  7.275 ms  7.643 ms  7.529 ms
 7  216.239.49.250 (216.239.49.250)  8.627 ms  58.979 ms  17.394 ms
 8  64.233.174.15 (64.233.174.15)  17.445 ms  9.161 ms  8.453 ms
 9  74.125.224.52 (74.125.224.52)  8.016 ms  8.325 ms  8.505 ms
```

TTL Value

Router name/IP address

Round trip time of 3 probes

The Maximum Transmission Unit



- Not all networks have the same maximum transmission unit (MTU)
- IP datagrams can be larger (64KB) than the Ethernet MTU (1500 bytes)
- Would like IP datagrams to still get delivered!

Fragmentation

- **Routers fragment IP datagrams**
  - Break datagram into MTU-sized datagrams
  - Set "MF" (more fragments) flag, as necessary
  - Set fragment offset field appropriately
- May need to fragment already fragmented datagrams!
- Datagrams are reassembled by the receiver
  - Routers do not reassemble fragments
  - Once fragmented, a datagram remains fragmented

Routing Fragments

- Fragments are routed independently through the network
- Fragment could be lost or duplicated
- Receiver must reassemble fragments
  - May arrive out of order
  - May not all arrive – must drop entire datagram

Avoiding Fragmentation

- Source can prevent fragmentation with "DF" (don't fragment) flag
  - Routers send "ICMP" (more later) error to the sender if packet is too large for link MTU
- Hosts commonly try to avoid fragmentation
  - Use "path MTU Discovery" to find the smallest MTU on the path
  - Repeatedly send successively smaller datagrams until no fragmentation occurs
  - Try it yourself with "traceroute –F *host size*"

IP Checksum

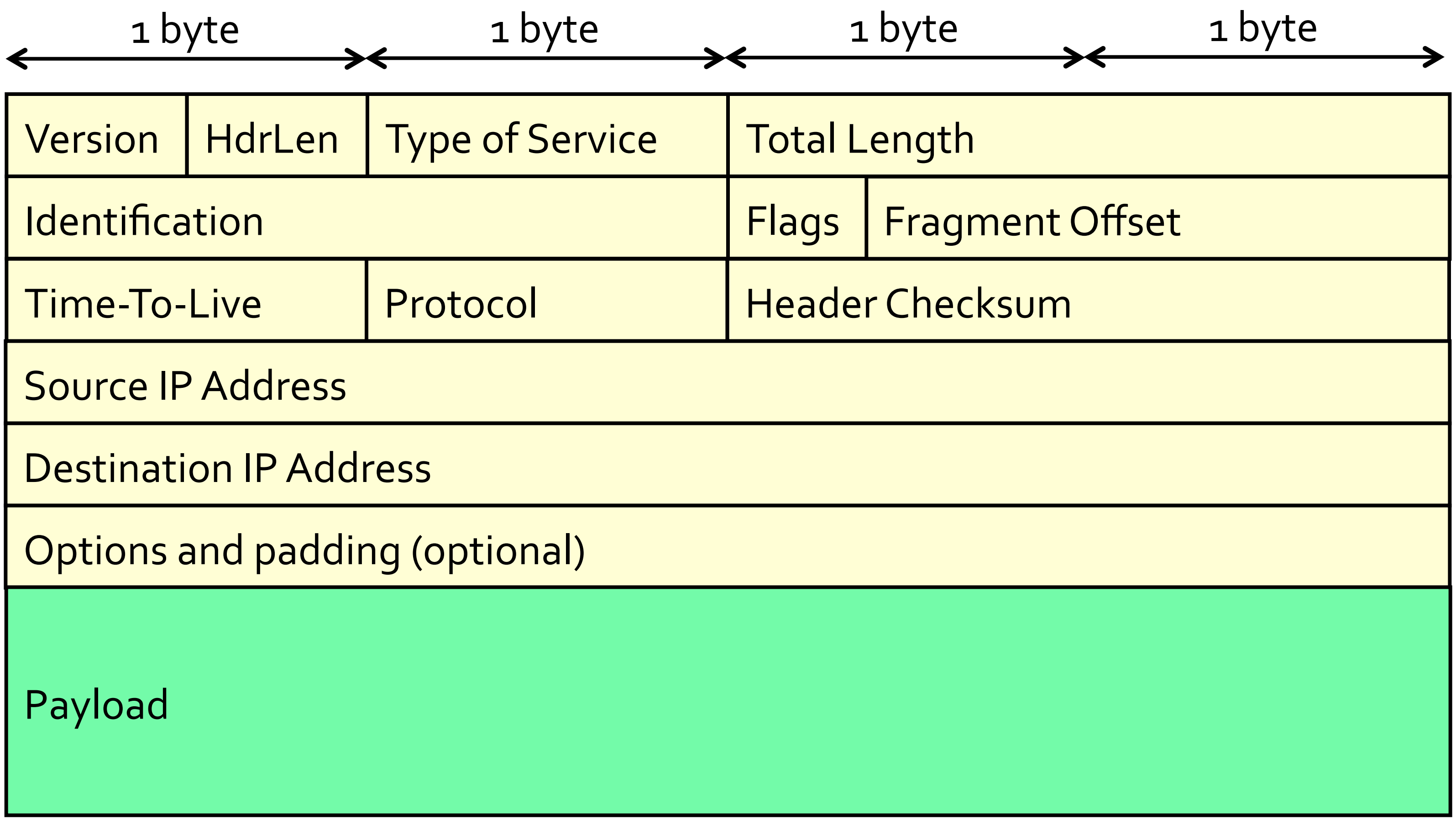
- 16-bit one's complement checksum
  - Allows hosts/routers to detect corruption in the IP header
    - Payload is not covered
  - Not enough information to correct errors
- Routers must modify the TTL of every IP datagram
  - Thus, checksum must be recomputed **by each router**!
- **Do checksums provide reliability?**
  - **Why are they included in the IP header?**

IP Header Format

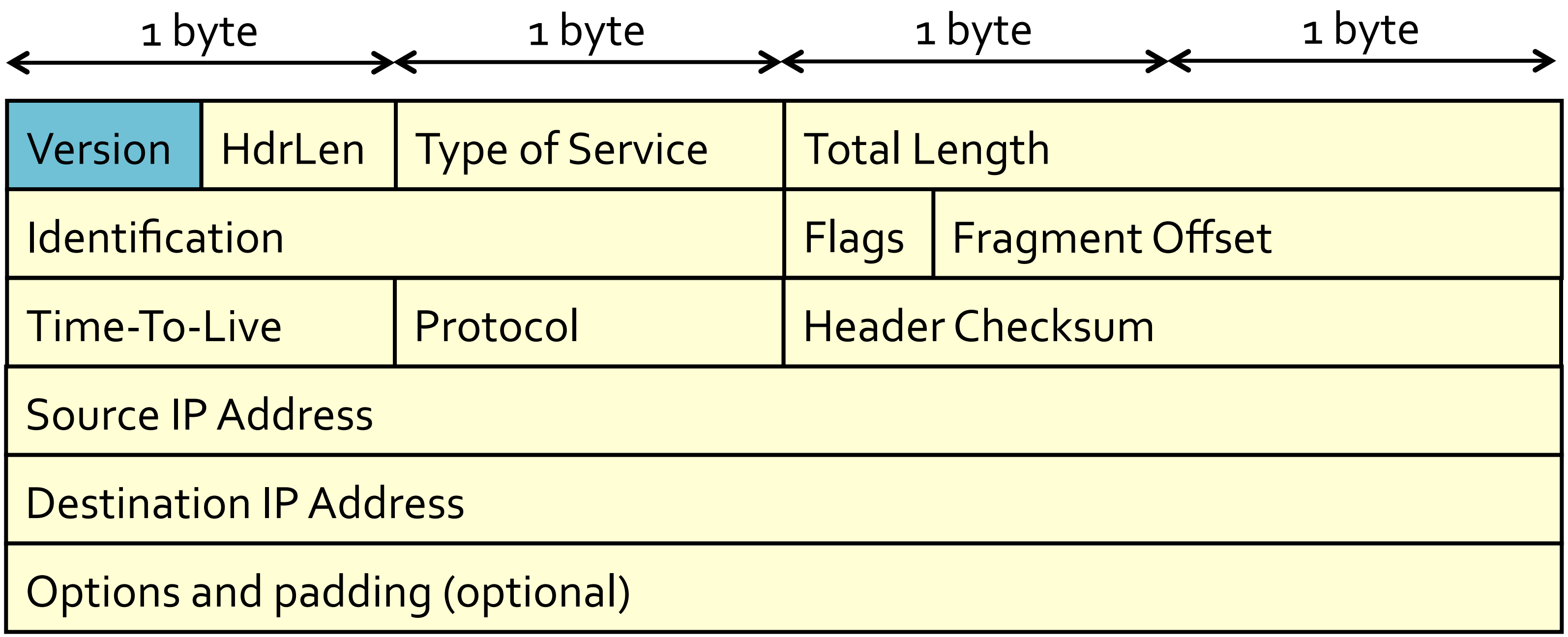
Packet Header Formats

- You will be dealing with these headers throughout the class
- It is easy to be off by a byte or forget something
- www.networksorcery.com is a great resource

An IP Datagram

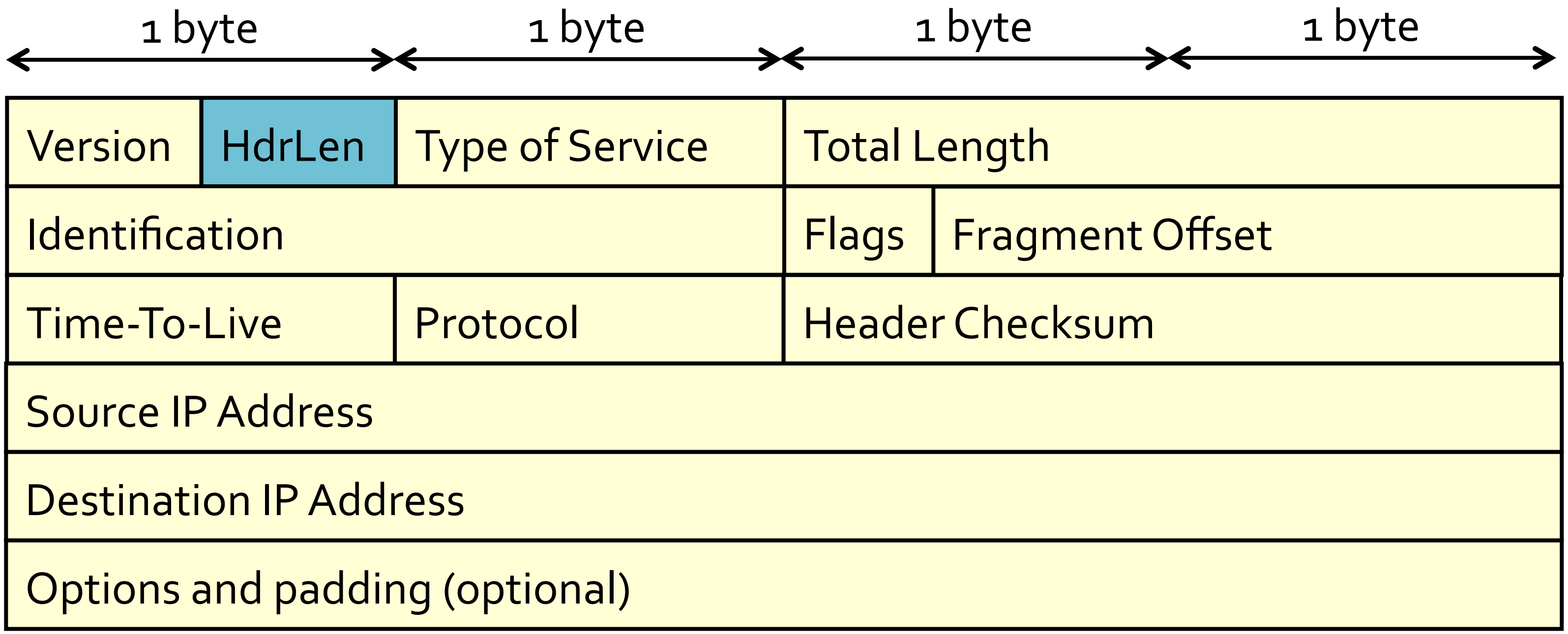


IP Version



- IPv4 or IPv6
  - Also other, uncommon, options

Header Length



- Number of 32-bit words in the header
- Need to know how many options are present

Type of Service

1 byte	1 byte	1 byte	1 byte
Version, HdrLen	Type of Service	Total Length	
Identification		Flags, Fragment Offset	
Time-To-Live	Protocol	Header Checksum	
Source IP Address			
Destination IP Address			
Options and padding (optional)			

- Routine, priority, immediate, control, etc.
- High/low delay/throughput/reliability

Type of Service

1 byte 1 byte 1 byte 1 byte

Version	HdrLen	Type of Service	Total Length	
Identification			Flags	Fragment Offset
Time-To-Live		Protocol	Header Checksum	
Source IP Address				
Destination IP Address				
Options and padding (optional)				

- Need to know the payload length
- Number of total bytes of IP packet

Identification

1 byte	1 byte	1 byte	1 byte
Version / HdrLen	Type of Service	Total Length	
Identification		Flags / Fragment Offset	
Time-To-Live	Protocol	Header Checksum	
Source IP Address			
Destination IP Address			
Options and padding (optional)			

- Unique for each source/destination/protocol combination while the datagram is in-flight
- Can be used to determine which datagram a fragment came from

Flags

<table>
<tr><th colspan="2">1 byte</th><th colspan="2">1 byte</th><th colspan="2">1 byte</th><th colspan="2">1 byte</th></tr>
<tr><td>Version</td><td>HdrLen</td><td colspan="2">Type of Service</td><td colspan="4">Total Length</td></tr>
<tr><td colspan="4">Identification</td><td>Flags</td><td colspan="3">Fragment Offset</td></tr>
<tr><td colspan="2">Time-To-Live</td><td colspan="2">Protocol</td><td colspan="4">Header Checksum</td></tr>
<tr><td colspan="8">Source IP Address</td></tr>
<tr><td colspan="8">Destination IP Address</td></tr>
<tr><td colspan="8">Options and padding (optional)</td></tr>
</table>

- 3 bits: Reserved/DF/MF
- DF: Don’t fragment this packet
- MF: More fragments follow this packet

Fragment Offset

1 byte		1 byte	1 byte	1 byte
Version	HdrLen	Type of Service	Total Length	
Identification			Flags	Fragment Offset
Time-To-Live		Protocol	Header Checksum	
Source IP Address				
Destination IP Address				
Options and padding (optional)				

- Offset of fragment in original datagram
- 13 bits wide, but measures units of 8 bytes each
  - $2^{13} * 8 = 64k$ (so we can fragment the entire packet)

Time-To-Live

<table>
<tr><th colspan="2">1 byte</th><th colspan="2">1 byte</th><th colspan="2">1 byte</th><th colspan="2">1 byte</th></tr>
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<tr><td colspan="8">Source IP Address</td></tr>
<tr><td colspan="8">Destination IP Address</td></tr>
<tr><td colspan="8">Options and padding (optional)</td></tr>
</table>

- "Hop count" – decrement each hop
- Discard datagrams with 0 TTL

Protocol

<table>
<tr><th colspan="2">1 byte</th><th colspan="2">1 byte</th><th colspan="2">1 byte</th><th colspan="2">1 byte</th></tr>
<tr><td>Version</td><td>HdrLen</td><td colspan="2">Type of Service</td><td colspan="4">Total Length</td></tr>
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<tr><td colspan="8">Source IP Address</td></tr>
<tr><td colspan="8">Destination IP Address</td></tr>
<tr><td colspan="8">Options and padding (optional)</td></tr>
</table>

- What is encapsulated in this IP datagram?
  - 1 = ICMP, 6 = TCP, 17 = UDP, etc…

Header Checksum

<table>
<tr><th colspan="2">1 byte</th><th colspan="2">1 byte</th><th colspan="2">1 byte</th><th colspan="2">1 byte</th></tr>
<tr><td>Version</td><td>HdrLen</td><td colspan="2">Type of Service</td><td colspan="4">Total Length</td></tr>
<tr><td colspan="4">Identification</td><td>Flags</td><td colspan="3">Fragment Offset</td></tr>
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<tr><td colspan="8">Source IP Address</td></tr>
<tr><td colspan="8">Destination IP Address</td></tr>
<tr><td colspan="8">Options and padding (optional)</td></tr>
</table>

- Inverted 16-bit one’s complement sum of the IP header and options

IP Addresses

1 byte	1 byte	1 byte	1 byte
Version | HdrLen	Type of Service	Total Length	
Identification		Flags | Fragment Offset	
Time-To-Live	Protocol	Header Checksum	
Source IP Address			
Destination IP Address			
Options and padding (optional)			

- IP address of source and destination

Options

<table>
<tr><th colspan="2">1 byte</th><th colspan="2">1 byte</th><th colspan="2">1 byte</th><th colspan="2">1 byte</th></tr>
<tr><td>Version</td><td>HdrLen</td><td colspan="2">Type of Service</td><td colspan="4">Total Length</td></tr>
<tr><td colspan="4">Identification</td><td>Flags</td><td colspan="3">Fragment Offset</td></tr>
<tr><td colspan="2">Time-To-Live</td><td colspan="2">Protocol</td><td colspan="4">Header Checksum</td></tr>
<tr><td colspan="8">Source IP Address</td></tr>
<tr><td colspan="8">Destination IP Address</td></tr>
<tr><td colspan="8">Options and padding (optional)</td></tr>
</table>

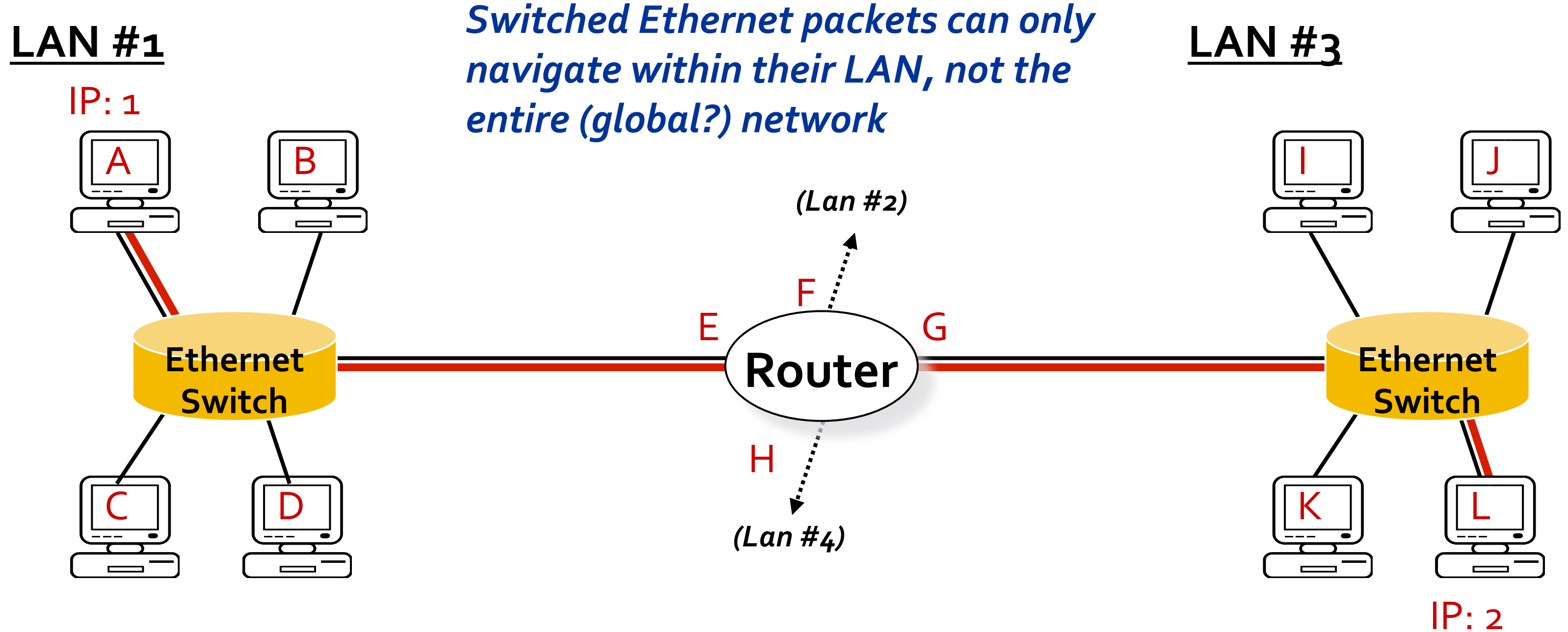
- Additional route information, timestamps, experimental information, etc.

IP encapsulated in Ethernet

<table>
<tr><td colspan="5">Destination MAC Address</td></tr>
<tr><td colspan="2">Destination MAC Address</td><td colspan="3">Source MAC Address</td></tr>
<tr><td colspan="5">Source MAC Address</td></tr>
<tr><td colspan="2">Type (0x0800)</td><td>Version</td><td>HdrLen</td><td>Type of Service</td></tr>
<tr><td colspan="2">Total Length</td><td colspan="3">Identification</td></tr>
<tr><td>Flags</td><td>Fragment Offset</td><td colspan="2">Time-To-Live</td><td>Protocol</td></tr>
<tr><td colspan="2">Header Checksum</td><td colspan="3">Source IP Address</td></tr>
<tr><td colspan="2">Source IP Address</td><td colspan="3">Destination IP Address</td></tr>
<tr><td colspan="2">Destination IP Address</td><td colspan="3">Options and Padding</td></tr>
<tr><td colspan="2">Options and Padding</td><td colspan="3">Payload</td></tr>
<tr><td colspan="5">Payload</td></tr>
<tr><td colspan="5">Ethernet CRC</td></tr>
</table>

Routing Between LANs

Switched Ethernet packets can only navigate within their LAN, not the entire (global?) network



(1) A (1) transmits to L (2) using IP.
Ethernet frame destination is router

Frame:

EDA (E)	ESA (A)	0x0800	IPDA (2)	IPSA (1)

(2) Switch forwards frame to router

(3) Router uses IP protocol to forward data.
Eth: update src/dst/crc IP: update TTL/checksum

Frame:

EDA (L)	ESA (G)	0x0800	IPDA (2)	IPSA (1)

(4) Switch forwards frame to destination

IP Address Format

IP Addresses

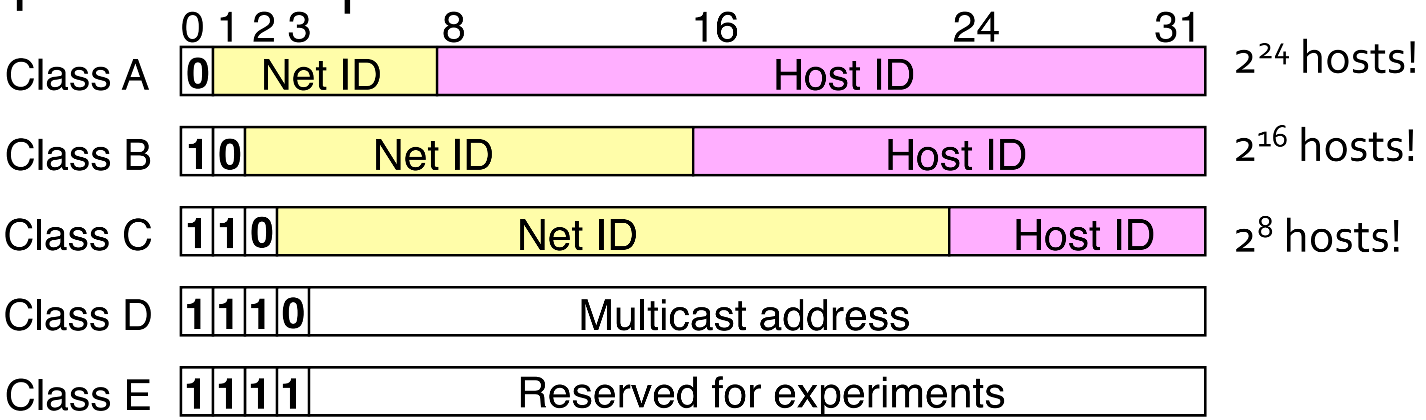
- IP version 4 addresses are 32-bits
  - Version 6 address are 128 bits
- Every network interface has at least one IP address
  - A computer might have 2 or more IP addresses
  - A router has many IP addresses
  - These addresses can be assigned statically or dynamically
- IP addresses are always in big-endian byte order (network byte order)
  - True in general for any integer transferred in a packet header from one machine to another
    - E.g., the port number used to identify a TCP connection

IP Address Format

- IPv4 addresses are usually displayed in dotted decimal notation
  - Each byte represented by decimal value
  - Bytes are separated by a period
  - IP address `0x8002C2F2 = 128.2.194.242`
- IP addresses are hierarchical
  - Address is composed of a network ID and a host ID
  - www.pacific.edu: `138.9.110.12`

IP Address Structure

- IPv4 Address space divided into classes:



- Special IP addresses
  - Loop-back address: 127.0.0.1
  - Unrouted (private) IP addresses:
    - 10.0.0.0 – 10.255.255.255
    - 172.16.0.0 – 172.31.255.255
    - 192.168.0.0 – 192.168.255.255

A Joke

http://xkcd.com/742/

IP Address Examples

- www.apple.com: 17.251.200.32
  - Class A: $0 < 17 < 128$
- www.mit.edu: 18.7.22.83
  - Class A: $0 < 18 < 128$
- www.pacific.edu: 138.9.110.12
  - Class B: $128 \leq 138 < 192$ $(128+64)$

Routing

- Routers in the Internet should only need to know about network IDs
- Routers inside an organization can route based on host IDs
- Problems?

Problems

- Address classes were too "rigid"
  - Class C is too small and Class B is too big in many situations
  - Inefficient use of address space
  - Leads to a shortage of addresses
- Small organizations wanted Class B networks
  - In case they grew to more than 255 hosts
  - But there are only about 16,000 Class B network IDs
- Larger organizations wanted many Class C networks
  - Separate network ID for each router link
- Every router in the Internet had to know about every network ID in every organization
  - Leads to large address tables in every router

Subnetting

- Divide the network within an organization
  - Basically consider one Class B network to be a collection of many smaller networks
  - Size of smaller networks can be selected by the organization (don't have to be Class C sized networks)
- Internet routers don't need to know about subnetting within an organization
  - Just route their traffic to the organization

Subnetting

Company's
Class B Network

2	14	16
10	Network ID	Host ID

Building 1 Network

2			12
10	Network ID	0001	Host ID

Subnet ID (18)

Department 4 network in Building 1

2				9
10	Network ID	0001	100	Host ID

Subnet ID (21)

Floor 13 network in Building 6

2				7
10	Network ID	0110	01101	Host ID

Subnet ID (23)

Subnetting

- Can recursively subnet addresses down to as fine a granularity as you want
  - Almost…
  - Minimum-sized subnet has 4 addresses
    - Address `00` names the subnet
    - Address `01` and `10` names hosts
    - Address `11` is the broadcast IP address
- Subnet sizes don't have to be the same
  - One building divided by department, one by floor
  - Department/floor subnets not the same size

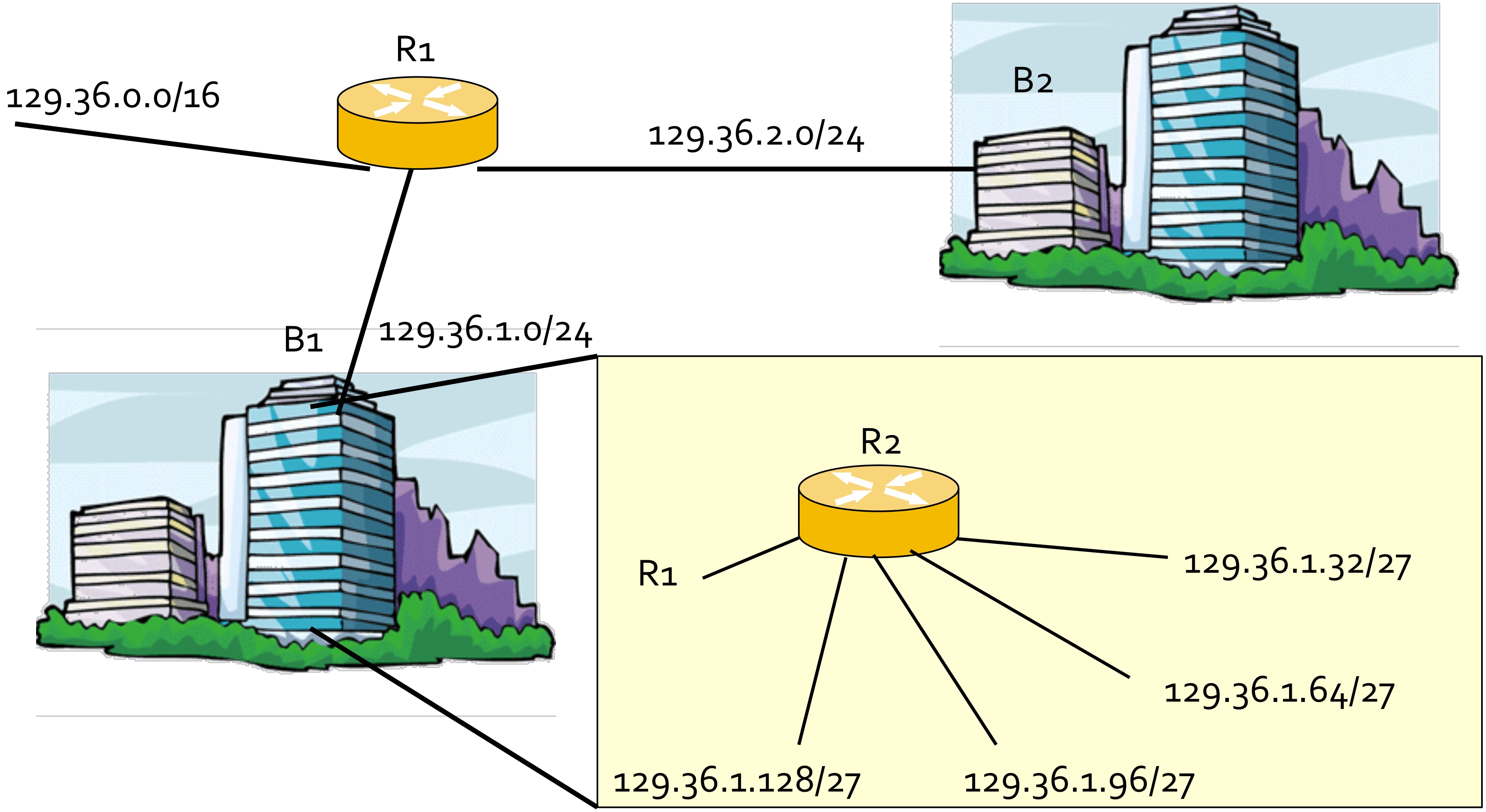
Subnet Notation

- A.B.C.D/X
  - IP address of the subnet (with 0's in all host ID bits)
  - X = number of bits in the subnet network address
- Examples:
  - 17.0.0.0/8 – Apple's entire class A address space
  - 17.2.3.0/24 – A class C sized subnet in Apple's network
- Alternatively represented by subnet IP and a bit mask (netmask)
  - 17.0.0.0/255.0.0.0
  - 17.2.3.0/255.255.255.0

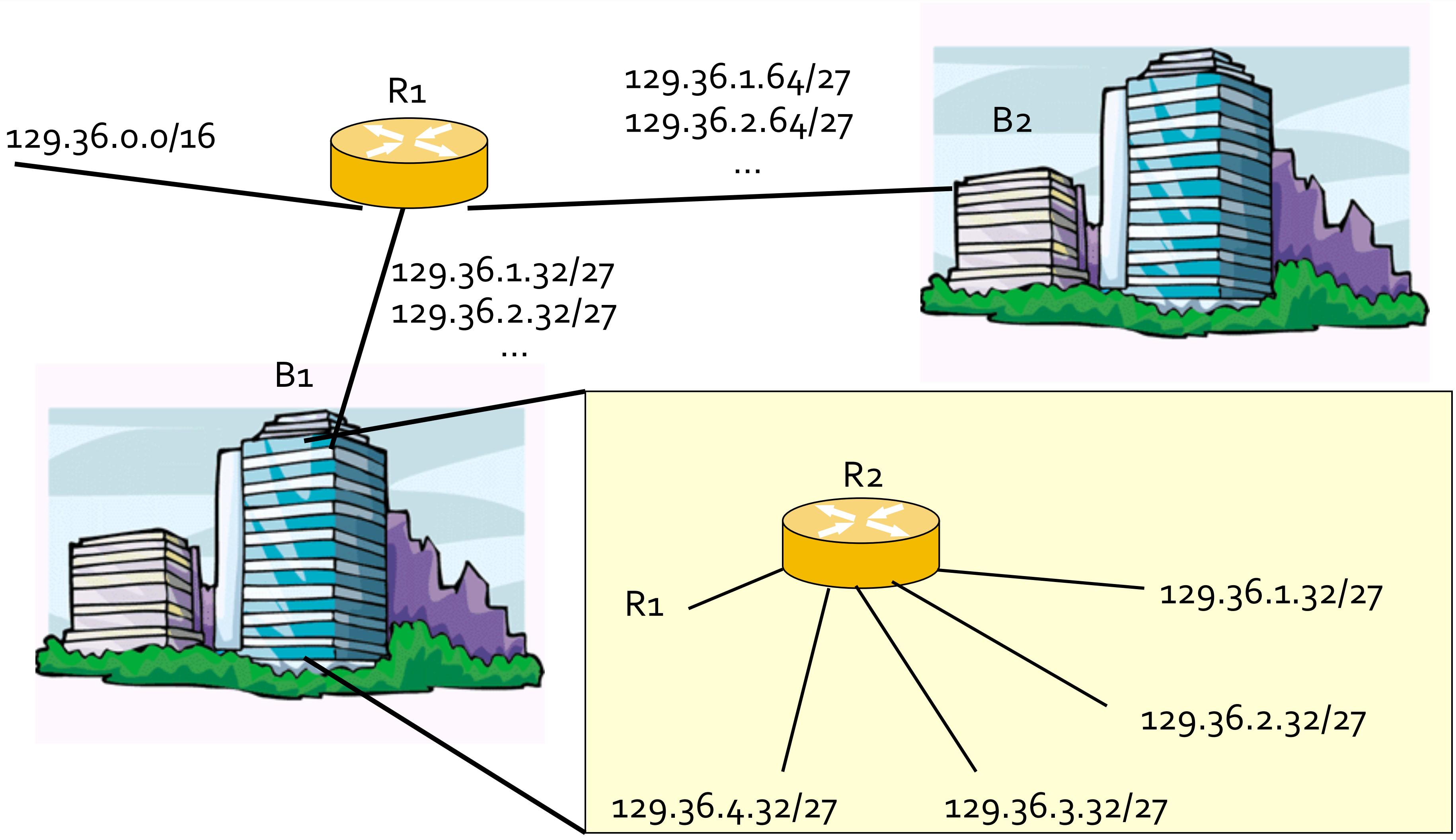
Subnet Meaning

- Subnets don't have to have physical meaning
  - Although easier to keep track of if they do…
- Good subnet assignment simplifies routing for internal routers
  - All traffic for "building 1" goes through this port
  - All traffic for "department 3" goes through that port
  - …

Route Aggregation



Little/No Route Aggregation



Classless InterDomain Routing

- CIDR introduced in 1993
  - Meant to provide more flexible routing
  - Eliminate dependences on "class" networks in routing
- "Supernetting"
  - Combine multiple contiguous networks into one larger network
  - Effectively reduces the number of entries needed in each routing table
  - Inverse of subnetting which takes one larger network and breaks it into multiple contiguous smaller networks

CIDR Idea

- Break up IP address space into *prefixes*
  - Same idea as subnets (138.9/16)
- Each prefix has its own routing entry
  - All traffic to Pacific (138.9/16) within the Internet should be routed the same way, regardless of how Pacific subnets its address space

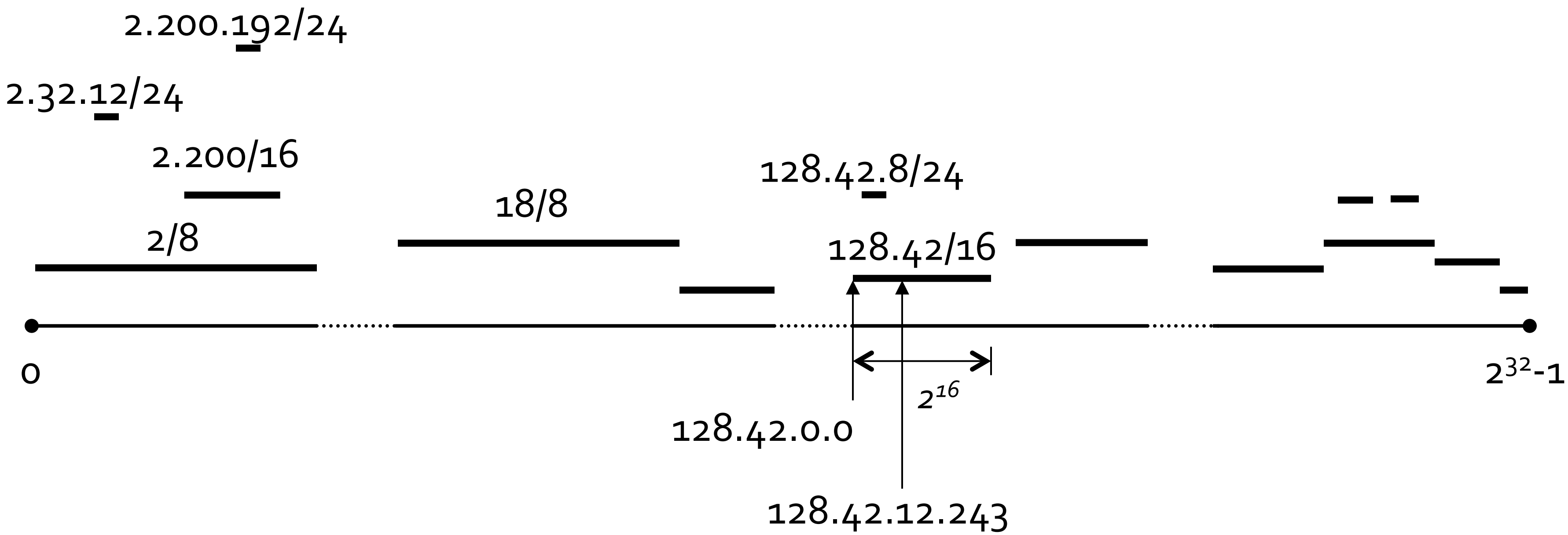
Route Aggregation

- Fundamental idea behind supernetting
  - Same type of aggregation as with subnets, but on a larger scale
- E.g., one ISP handles traffic for two corporate networks (129.32/16 and 129.33/16)
  - Aggregate route to 129.32/15 for both networks
  - Only break them apart when necessary for the last (few) hop(s)
- E.g., one ISP handles all 64/8 networks
  - All other routers know to route 64/8 traffic to that ISP
  - External routers don't care how the ISP breaks up the network addresses internally!
  - Internal ISP routers must route at a finer grain

What if there are holes?

- Rice builds a second campus
  - 128.42/16 needs to be routed to Houston
  - 128.42.8/24 needs to be routed to our satellite campus in Italy…
- Do we need to break routes up?
    - 128.42.0/20 (.0-.7)
    - 128.42.8/24 (.8)
    - 128.42.9/24 (.9), 128.42.10/24 (.10), 128.42.11/24 (.11)
    - 128.42.12/22 (.12-.15)
    - 128.42.16/20 (.16-.31)
    - 128.42.32/19 (.32-.63)
    - 128.42.64/18 (.64-.127)
    - 128.42.128/17 (.128-.255)

IP Prefixes



- IP address space can be viewed as a number line
  - Each segment represents an aggregated route
  - Segments can overlap
- Look for smallest segment that matches the destination address

Longest Prefix Match

- Allow more specific entries to supersede more general ones
  - 128.42.8/24
    - Route this traffic to Italy
  - 128.42/16
    - Route this traffic to Houston
    - Except for addresses that match a route with a longer prefix (i.e., 128.42.8/24)
- Allows significantly more route aggregation
- Simplifies things if companies move (physically or to another ISP) their block of IP addresses

IP Address Classes

- CIDR makes address classes less important
- With CIDR, routing is based on arbitrary subdivisions of the address space
  - Aggregate routes into largest possible group
  - Use longer prefixes to deal with exceptions
- Routing
  - Routers use longest prefix matching to determine routes
  - No longer deal with exact matches on class network IDs

Implementing Software LPM

- Simple software solution
  - Keep list of prefixes and masks
  - Search for all prefix matches
  - Choose result with longest prefix
- Trick
  - Sort list based on decreasing prefix length (stop search after first match)
- This is extremely inefficient for large forwarding tables!

ARIN WHOIS Database Search

Relevant Links: ARIN Home Page ARIN Site Map Training: *Querying ARIN's WHOIS*

Search ARIN WHOIS for: 138.9.1.21

Submit

```
OrgName:    University of the Pacific
OrgID:      UNIVER-95
Address:    3601 Pacific Ave.
City:       Stockton
StateProv:  CA
PostalCode: 95211
Country:    US

NetRange:   138.9.0.0 - 138.9.255.255
CIDR:       138.9.0.0/16
NetName:    UOP
NetHandle:  NET-138-9-0-0-1
Parent:     NET-138-0-0-0-0
NetType:    Direct Assignment
NameServer: NS1.PACIFIC.EDU
NameServer: NS2.PACIFIC.EDU
Comment:
RegDate:    1990-01-17
Updated:    2007-09-07

RAbuseHandle: DAVEA-ARIN
RAbuseName:   Lundy, Dave A.
RAbusePhone:  +1-209-946-3951
RAbuseEmail:  dlundy@pacific.edu

RTechHandle: EES7-ARIN
RTechName:   Escalante, Edgar
RTechPhone:  +1-209-946-3190
RTechEmail:  eescalante@pacific.edu

OrgTechHandle: DAVEA-ARIN
OrgTechName:   Lundy, Dave A.
OrgTechPhone:  +1-209-946-3951
OrgTechEmail:  dlundy@pacific.edu
```