Computer Networks

Lecture 9: Network layer - Part I

Based on slides from D. Choffnes Northeastern U. and P. Gill from StonyBrook University
Revised Autumn 2015 by S. Laki

Bridges vs. Switches

- Bridges make it possible to increase LAN capacity
  - Reduces the amount of broadcast packets
  - No loops
- Switch is a special case of a bridge
  - Each port is connected to a single host
    - Either a client machine
    - Or another switch
  - Links are full duplex
  - Simplified hardware: no need for CSMA/CD!
  - Can have different speeds on each port

Switching the Internet

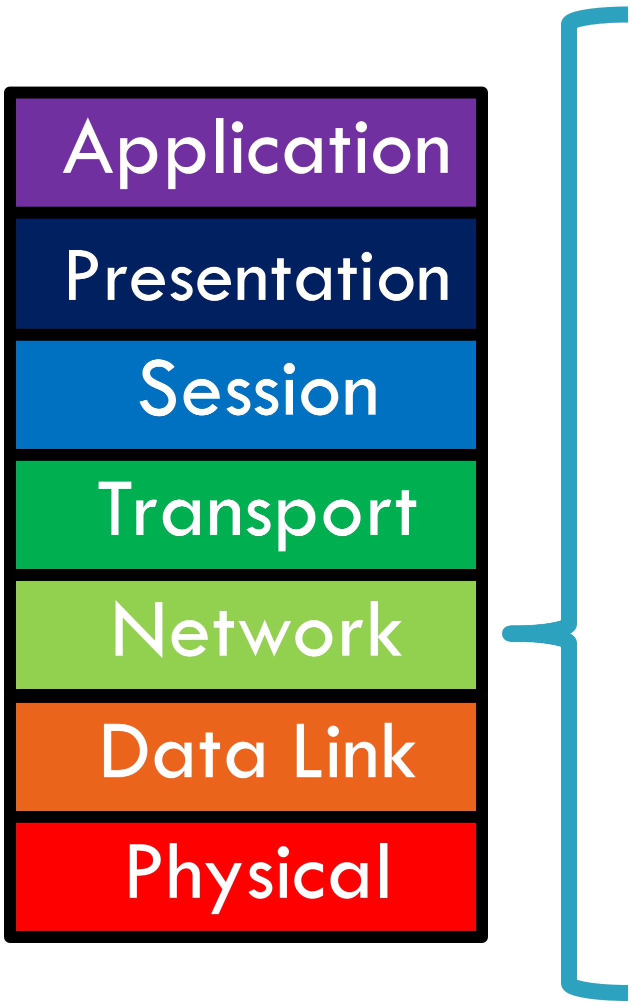
- Capabilities of switches:
  - Network-wide routing based on MAC addresses
  - Learn routes to new hosts automatically
  - Resolve loops
- Could the whole Internet be one switching domain?

NO

Limitations of MAC Routing

- Inefficient
  - Flooding packets to locate unknown hosts
- Poor Performance
  - Spanning tree does not balance load
  - Hot spots
- Extremely Poor Scalability
  - Every switch needs every MAC address on the Internet in its routing table!
- IP addresses these problems (next …)

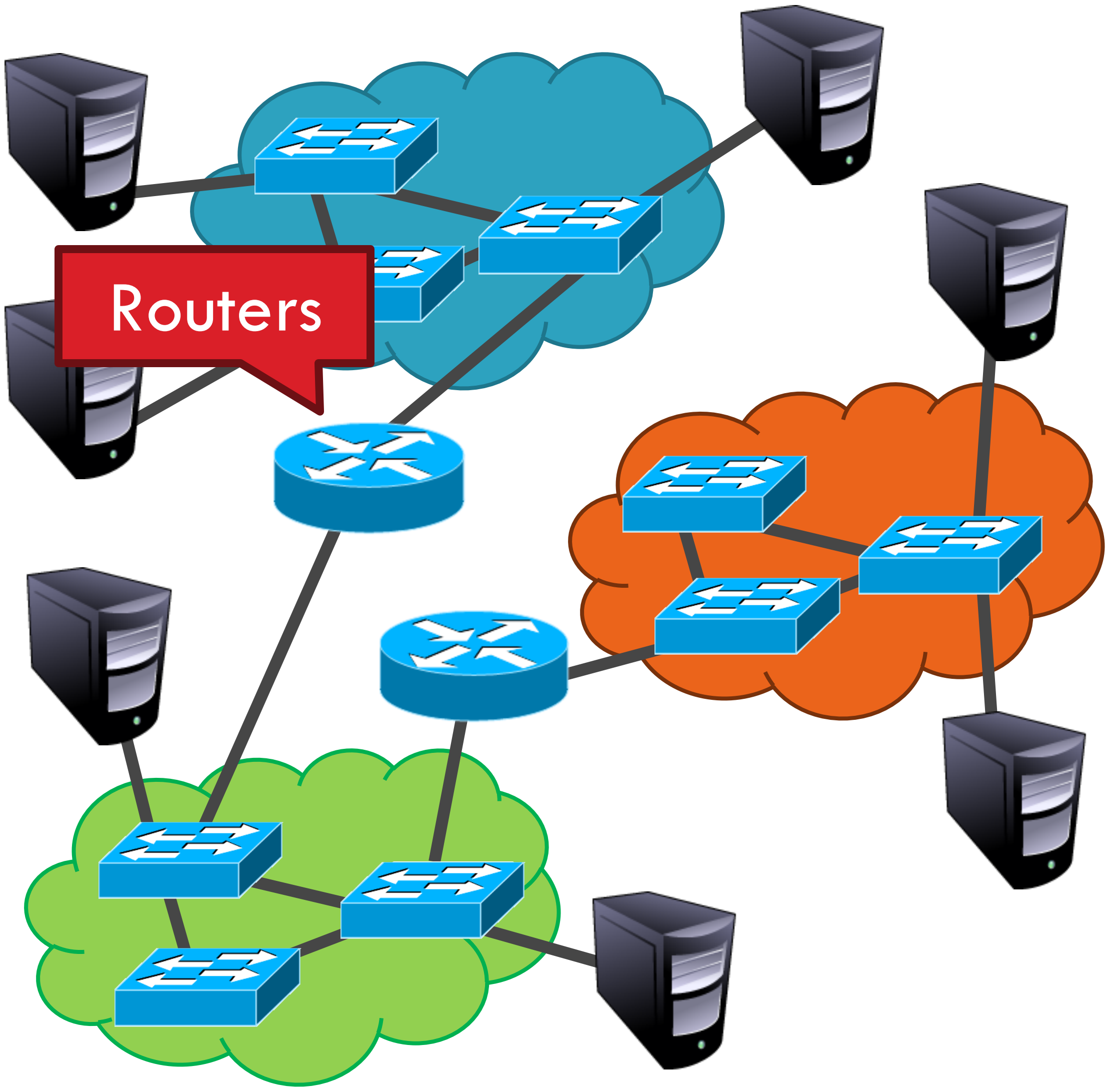
Network Layer



- Function:
  - Route packets end-to-end on a network, through multiple hops
- Key challenge:
  - How to represent addresses
  - How to route packets
    - Scalability
    - Convergence

Routers, Revisited

- How to connect multiple LANs?
- LANs may be incompatible
  - Ethernet, Wifi, etc…
- Connected networks form an internetwork
  - The Internet is the best known example



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Internet Service Model

- Best-effort (i.e. things may break)
- Store-and-forward datagram network

Lowest common denominator

- Service Model
  - What gets sent?
  - How fast will it go?
  - What happens if there are failures?
  - Must deal with heterogeneity
    - Remember, every network is different

Outline

- Addressing
  - Class-based
  - CIDR
- IPv4 Protocol Details
  - Packed Header
  - Fragmentation
- IPv6

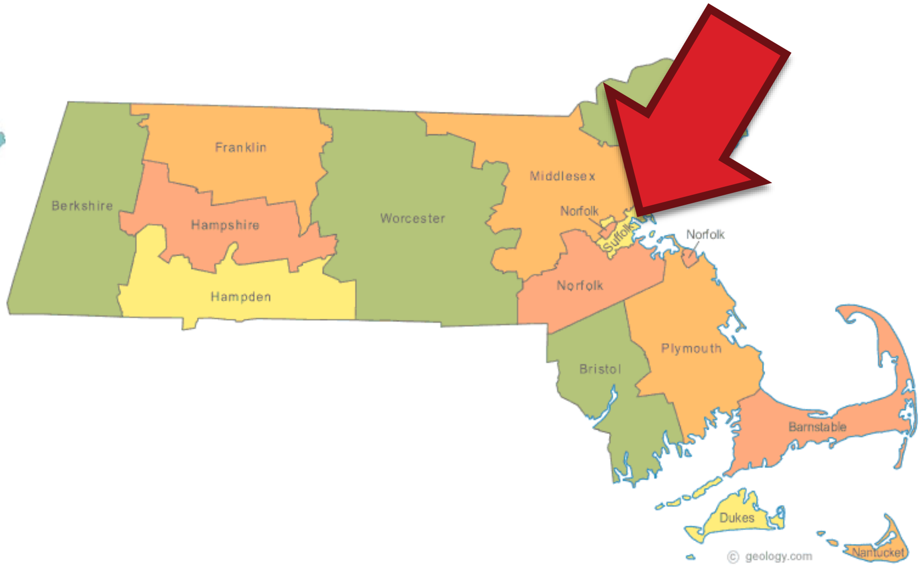
Possible Addressing Schemes

- Flat
  - e.g. each host is identified by a 48-bit MAC address
  - Router needs an entry for every host in the world
    - Too big
    - Too hard to maintain (hosts come and go all the time)
    - Too slow (more later)
- Hierarchy
  - Addresses broken down into segments
  - Each segment has a different level of specificity

Example: Telephone Numbers

1-617-373- 3278

Very General



Northeastern University

West Village H
Room 254

West Village G
Room 234

Updates are Local

Very Specific

IP Addressing

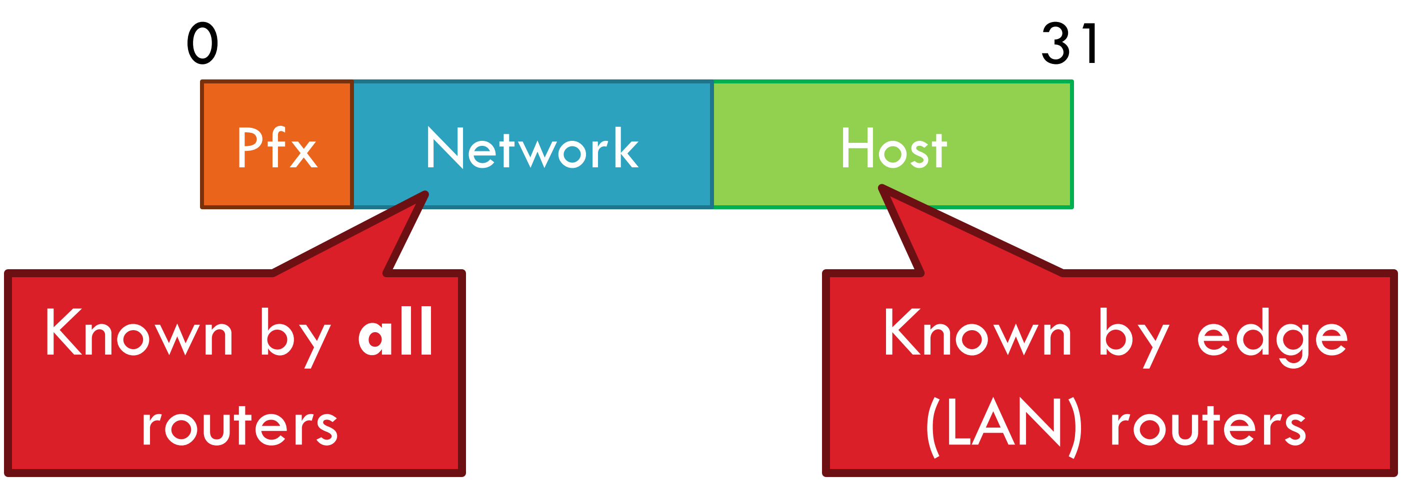
- IPv4: 32-bit addresses
  - Usually written in dotted notation, e.g. 192.168.21.76
  - Each number is a byte

0 8 16 24 31

Decimal	192	168	21	76
Hex	C0	A8	15	4C
Binary	11000000	10101000	00010101	01001100

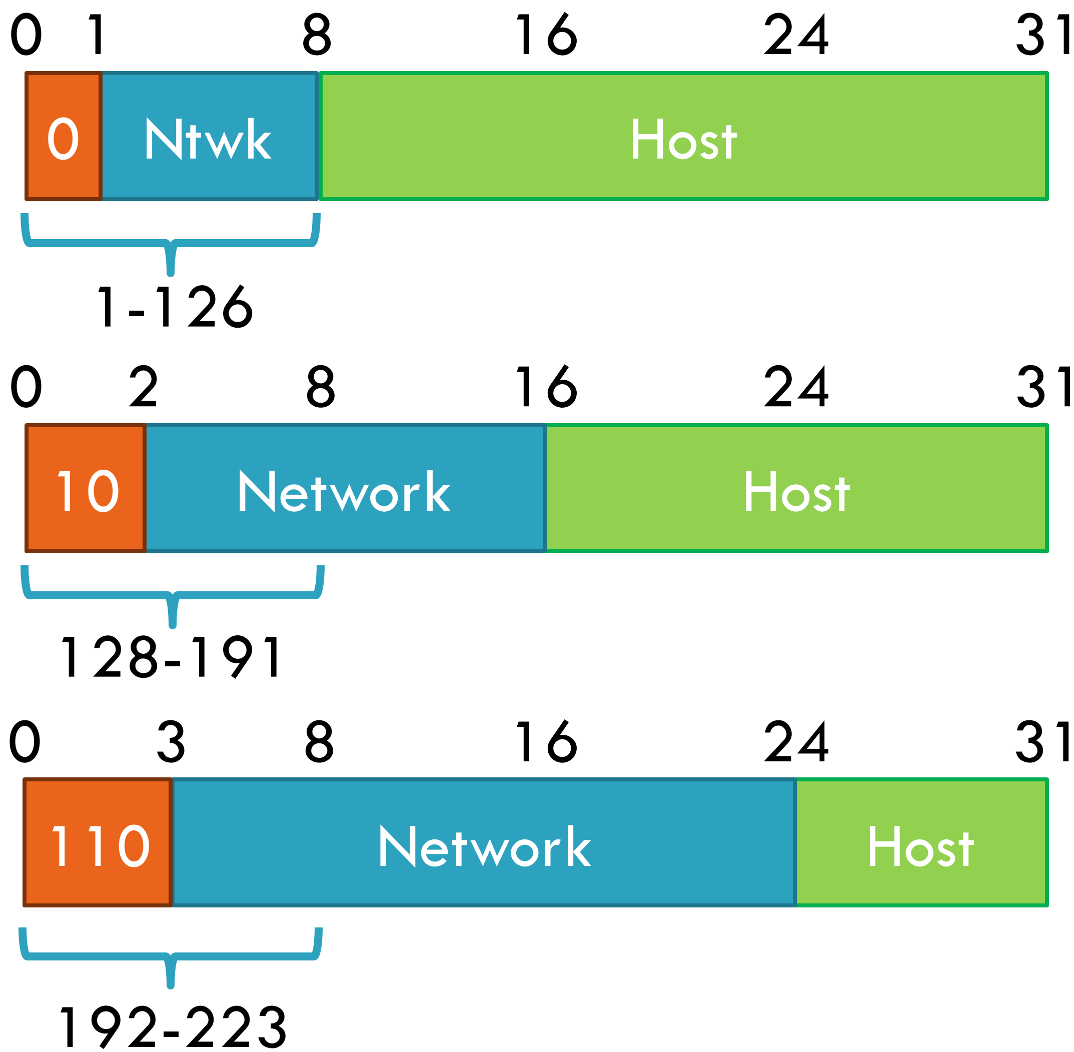
IP Addressing and Forwarding

- Routing Table Requirements
  - For every possible IP, give the next hop
  - But for 32-bit addresses, 2^{32} possibilities!
- Hierarchical address scheme
  - Separate the address into a network and a host



Classes of IP Addresses

- Class A
- Class B
- Class C



Example: MIT
18.*.*.*

Example: NEU
129.10.*.*

Example:
216.63.78.*

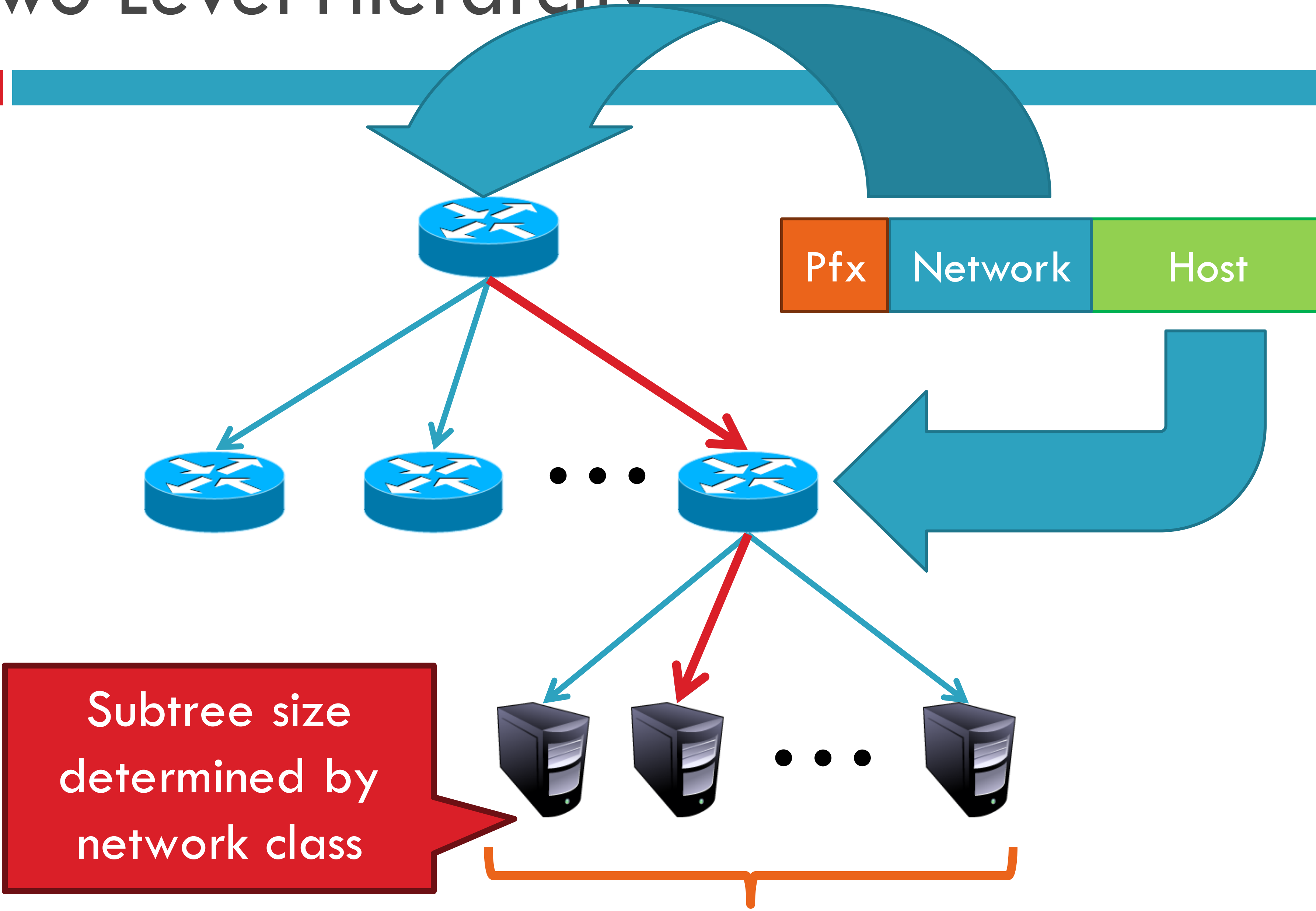
How Do You Get IPs?

- IP address ranges controlled by IANA

Internet Assigned Numbers Authority

  - Internet Assigned Number Authority
  - Roots go back to 1972, ARPANET, UCLA
  - Today, part of ICANN
- IANA grants IPs to regional authorities
  - ARIN (American Registry of Internet Numbers) may grant you a range of IPs
  - You may then advertise routes to your new IP range
  - There are now secondary markets, auctions, …

Two Level Hierarchy



Class Sizes

Way too big

Class	Prefix Bits	Network Bits	Number of Classes	[illegible]s per Class
A	1	7	$2^7 - 2 = 126$ (0 and 127 are reserved)	$2^{24} - 2 = 16{,}777{,}214$ (All 0 and all 1 are reserved)
B	2	14	$2^{14} = 16{,}398$	$2^{16} - 2 = 65{,}534$ (All 0 and all 1 are reserved)
C	3	21	$2^{21} = 2{,}097{,}512$	$2^8 - 2 = 254$ (All 0 and all 1 are reserved)
			Total: 2,114,036	

Too many network IDs

Too small to be useful

Subnets

- Problem: need to break up large A and B classes
- Solution: add another layer to the hierarchy
  - From the outside, appears to be a single network
    - Only 1 entry in routing tables
  - Internally, manage multiple subnetworks
    - Split the address range using a subnet mask

Subnet Mask: 11111111 11111111 11000000 00000000

Subnet Example

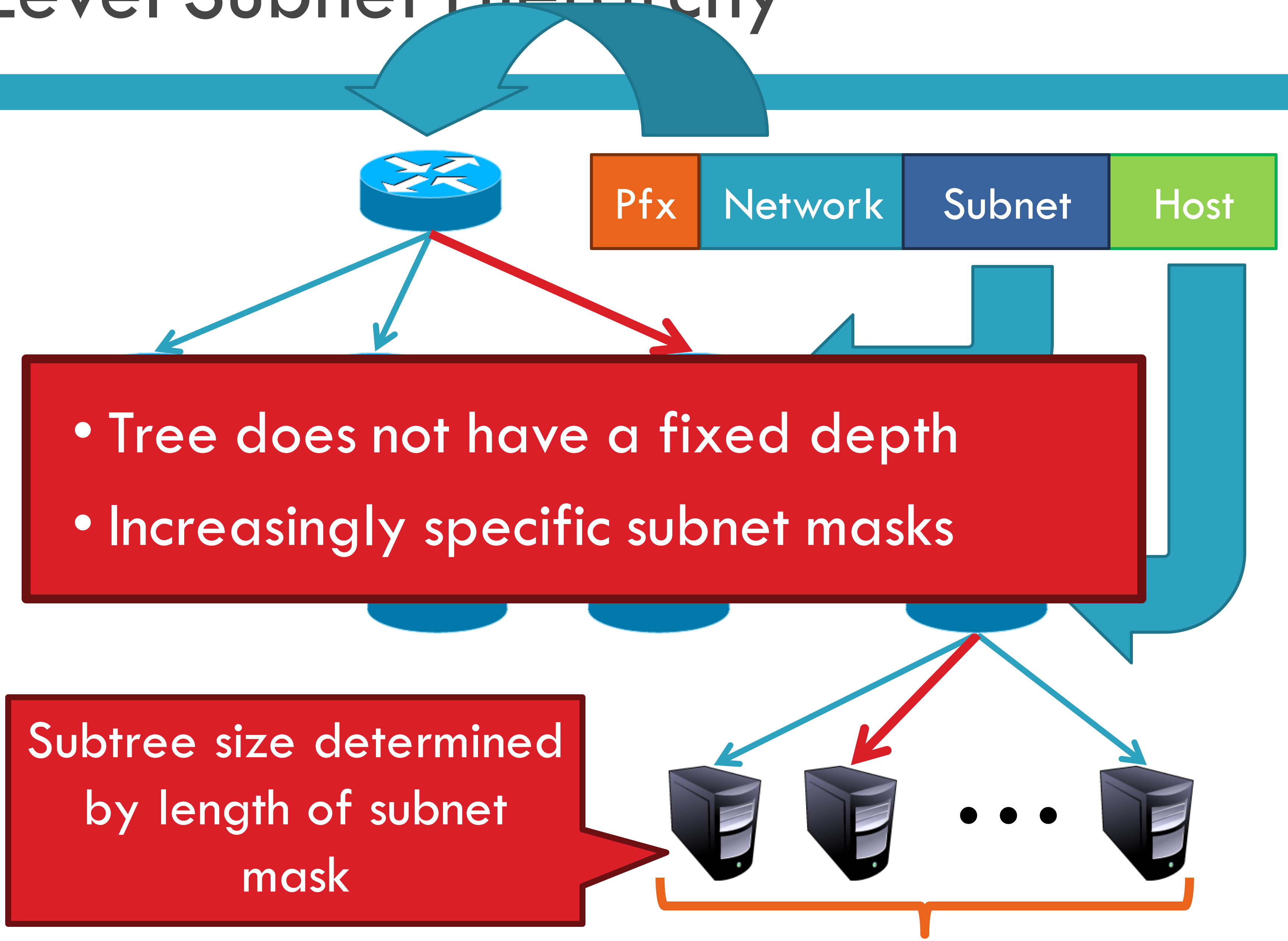
- Extract network:

IP Address:	10110101 11011101 01010100 01110010
Subnet Mask:	& 11111111 11111111 11000000 00000000
Result:	10110101 11011101 01000000 00000000

- Extract host:

IP Address:	10110101 11011101 01010100 01110010
Subnet Mask:	& ~(11111111 11111111 11000000 00000000)
Result:	00000000 00000000 00010100 01110010

N-Level Subnet Hierarchy



Example Routing Table

Address Pattern	Subnet Mask	Destination Router
0.0.0.0	0.0.0.0	Router 4
18.0.0.0	255.0.0.0	Router 2
128.42.0.0	255.255.0.0	Router 3
128.42.128.0	255.255.128.0	Router 5
128.42.222.0	2555.255.255.0	Router 1

- Question: 128.42.222.198 matches four rows
  - Which router do we forward to?
- Longest prefix matching
  - Use the row with the longest number of 1's in the mask
  - This is the most specific match

Subnetting Revisited

- Question: does subnetting solve all the problems of class-based routing?

NO

- Classes are still too coarse
  - Class A can be subnetted, but only 126 available
  - Class C is too small
  - Class B is nice, but there are only 16,398 available
- Routing tables are still too big
  - 2.1 million entries per router

Classless Inter Domain Routing

- CIDR, pronounced ‘cider’
- Key ideas:
  - Get rid of IP classes
  - Use bitmasks for all levels of routing
  - **Aggregation** to minimize FIB (forwarding information base)
- Arbitrary split between network and host
  - Specified as a bitmask or prefix length
  - Example: Stony Brook
    - 130.245.0.0 with netmask 255.255.0.0
    - 130.245.0.0 / 16

Aggregation with CIDR

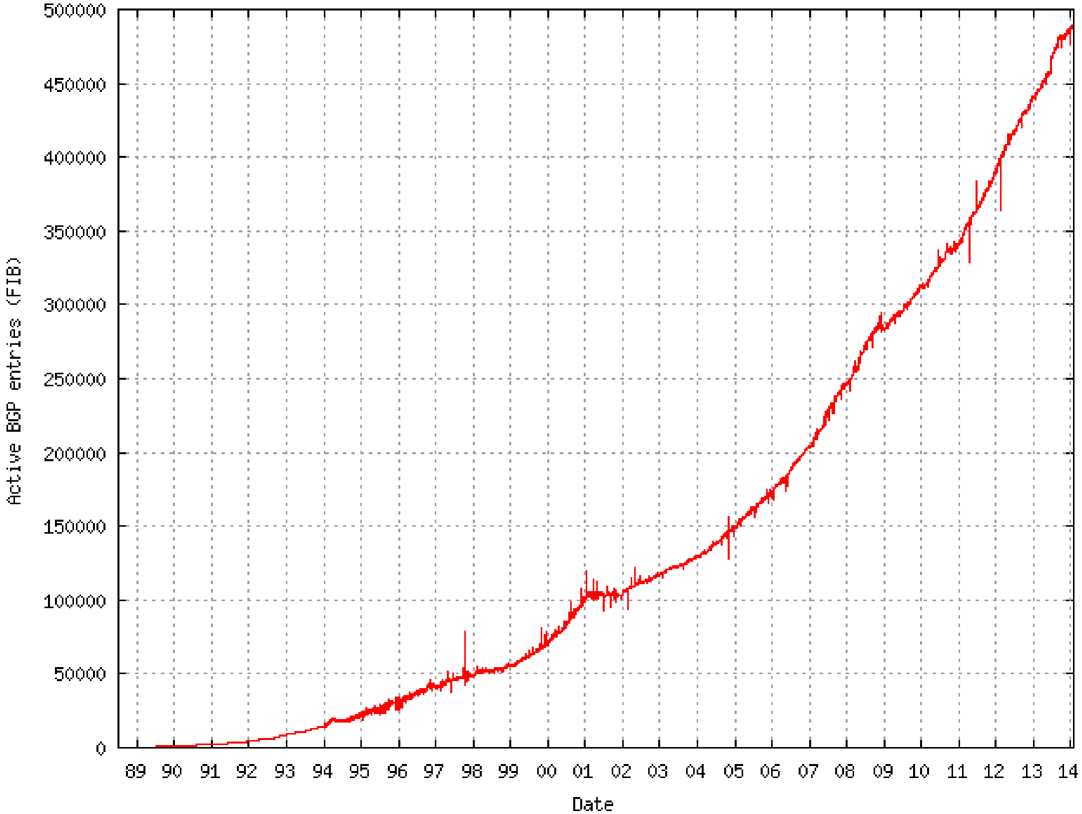
- Original use: aggregating class C ranges
- One organization given contiguous class C ranges
  - Example: Microsoft, 207.46.192.* – 207.46.255.*
  - Represents $2^6 = 64$ class C ranges
  - Specified as CIDR address 207.46.192.0/18

	0	8	16	24 31
Decimal	207	46	192	0
Hex	CF	2E	C0	00
Binary	11001111	00101110	11xxxxxx	xxxxxxxx

18 Bits Frozen By Netmask

14 Arbitrary Bits

Size of CIDR Routing Tables



- From www.cidr-report.org
- CIDR has kept IP routing table sizes in check
  - Currently ~500,000 entries for a complete IP routing table
  - Only required by backbone routers

We had a special day in summer 2014!

- 512K day – August 12, 2014
- Default threshold size for IPv4 route data in older Cisco routers → 512K routes
  - Some routers failed over to slower memory
    - RAM vs. CAM (content addressable memory)
  - Some routes dropped
- Cisco issues update in May anticipating this issue
  - Reallocated some IPv6 space for IPv4 routes
- Part of the cause
  - Growth in emerging markets
- http://cacm.acm.org/news/178293-internet-routing-failures-bring-architecture-changes-back-to-the-table/fulltext

Takeaways

- Hierarchical addressing is critical for scalability
  - Not all routers need all information
  - Limited number of routers need to know about changes
- Non-uniform hierarchy useful for heterogeneous networks
  - Class-based addressing is too course
  - CIDR improves scalability and granularity
- Implementation challenges
  - Longest prefix matching is more difficult than schemes with no ambiguity

Outline

- Addressing
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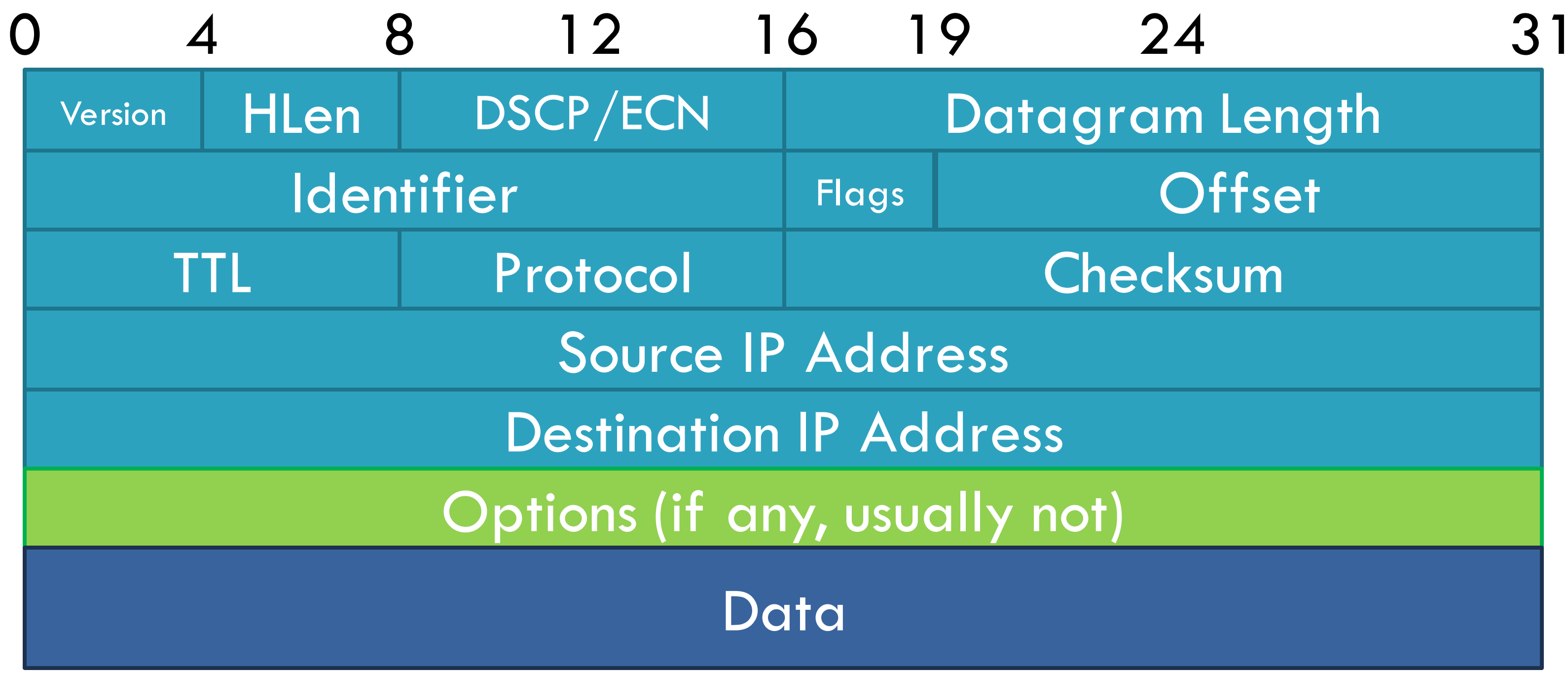
  - Fragmentation
- IPv6

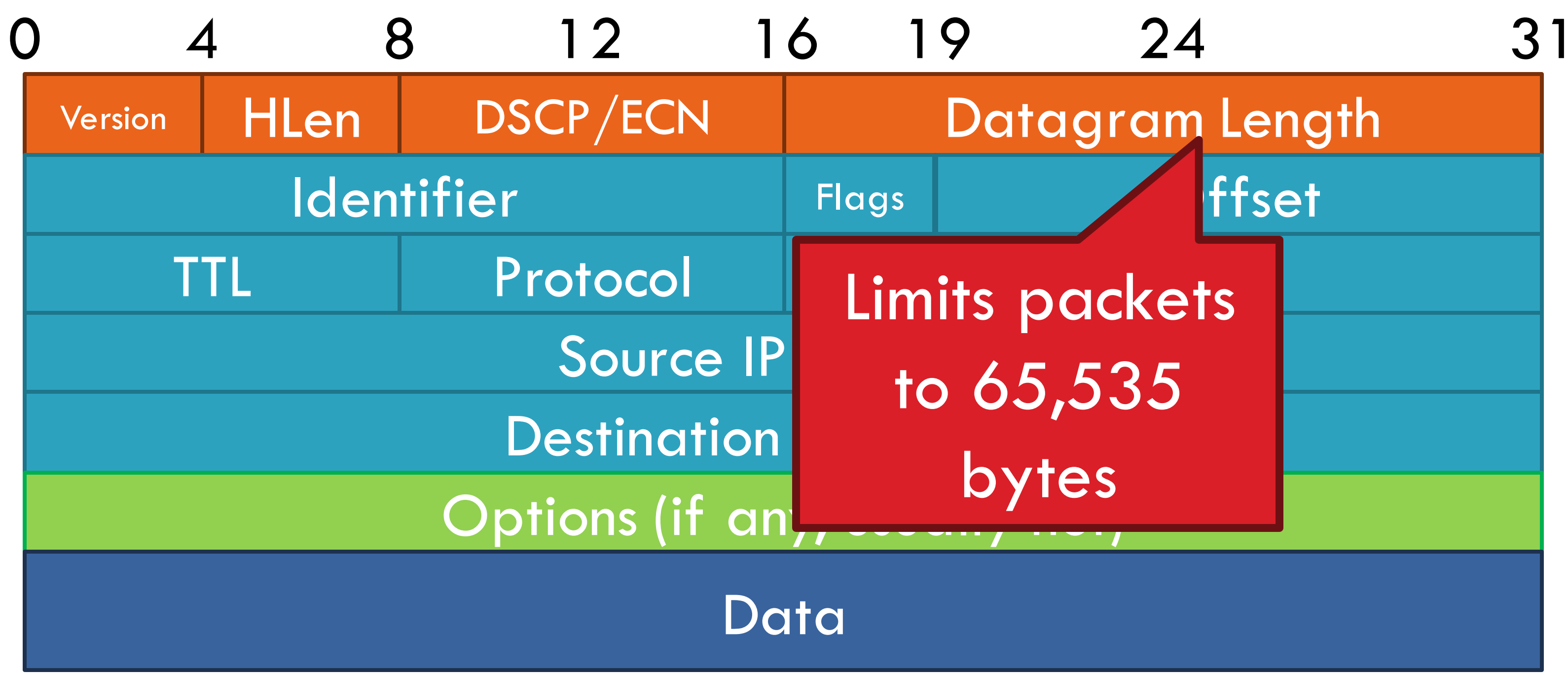
IP Datagrams

- IP Datagrams are like a letter
  - Totally self-contained
  - Include all necessary addressing information
  - No advanced setup of connections or circuits



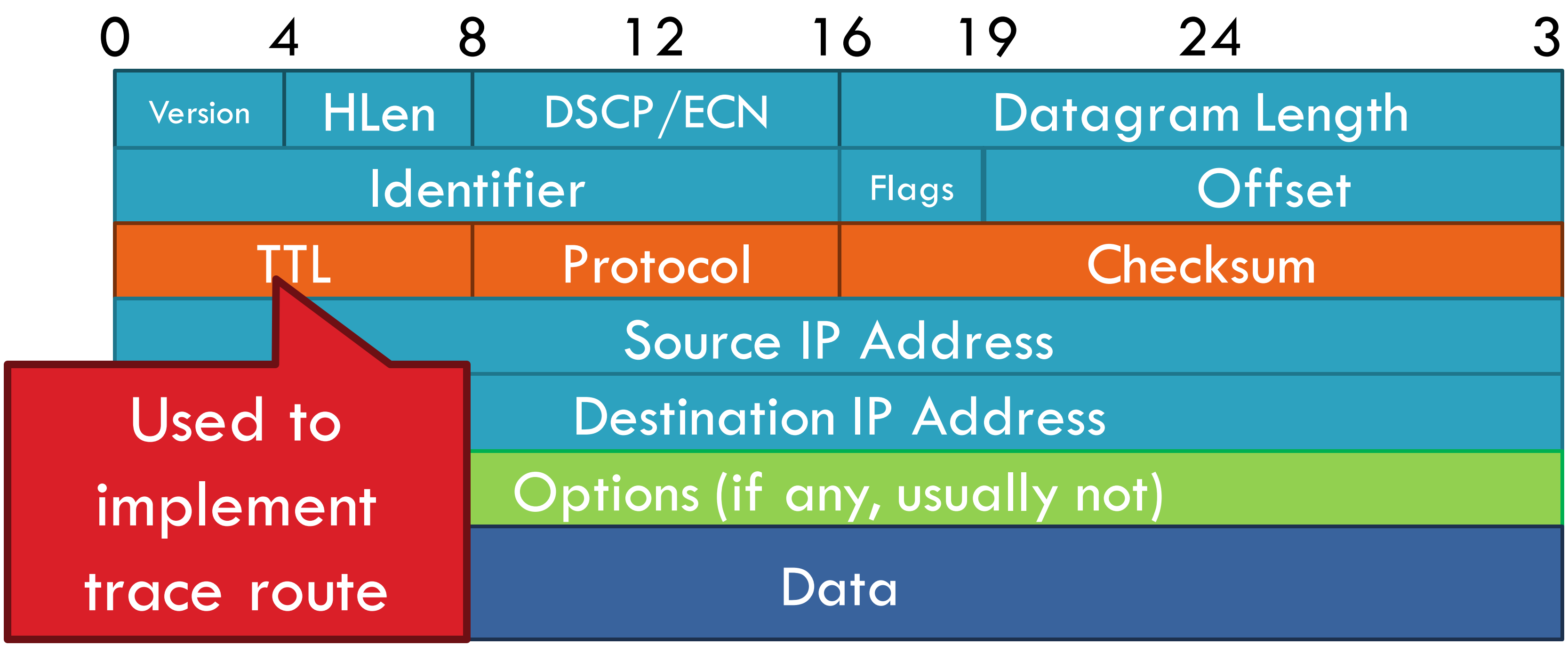
IP Header Fields: Word 1

- Version: 4 for IPv4
- Header Length: Number of 32-bit words (usually 5)
- Type of Service: Priority information (unused)
- Datagram Length: Length of header + data in bytes



IP Header Fields: Word 3

- Time to Live: decremented by each router
  - Used to kill looping packets
- Protocol: ID of encapsulated protocol
  - 6 = TCP, 17 = UDP
- Checksum

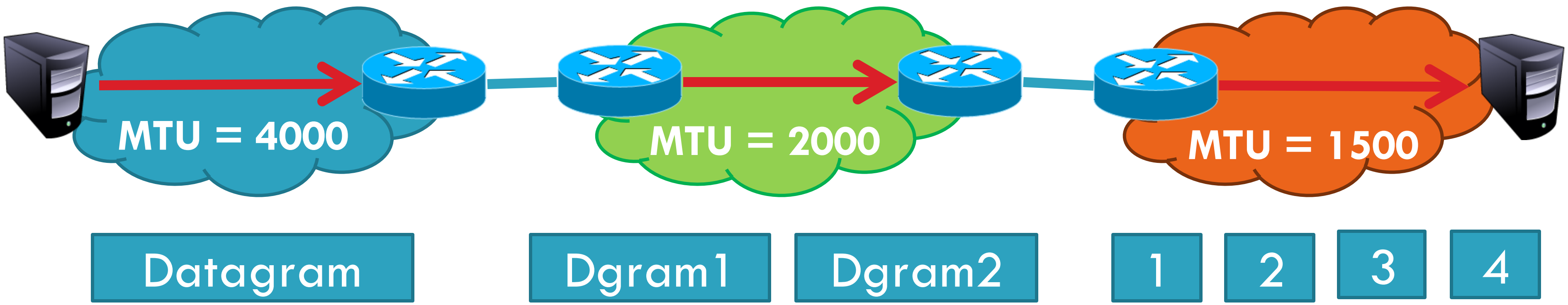


IP Header Fields: Word 4 and 5

- Source and destination address
  - In theory, must be globally unique
  - In practice, this is often violated

<table>
<tr><th>0</th><th>4</th><th>8</th><th>12</th><th>16</th><th>19</th><th>24 … 31</th></tr>
<tr><td>Version</td><td>HLen</td><td colspan="2">DSCP/ECN</td><td colspan="3">Datagram Length</td></tr>
<tr><td colspan="4">Identifier</td><td>Flags</td><td colspan="2">Offset</td></tr>
<tr><td colspan="2">TTL</td><td colspan="2">Protocol</td><td colspan="3">Checksum</td></tr>
<tr><td colspan="7">Source IP Address</td></tr>
<tr><td colspan="7">Destination IP Address</td></tr>
<tr><td colspan="7">Options (if any, usually not)</td></tr>
<tr><td colspan="7">Data</td></tr>
</table>

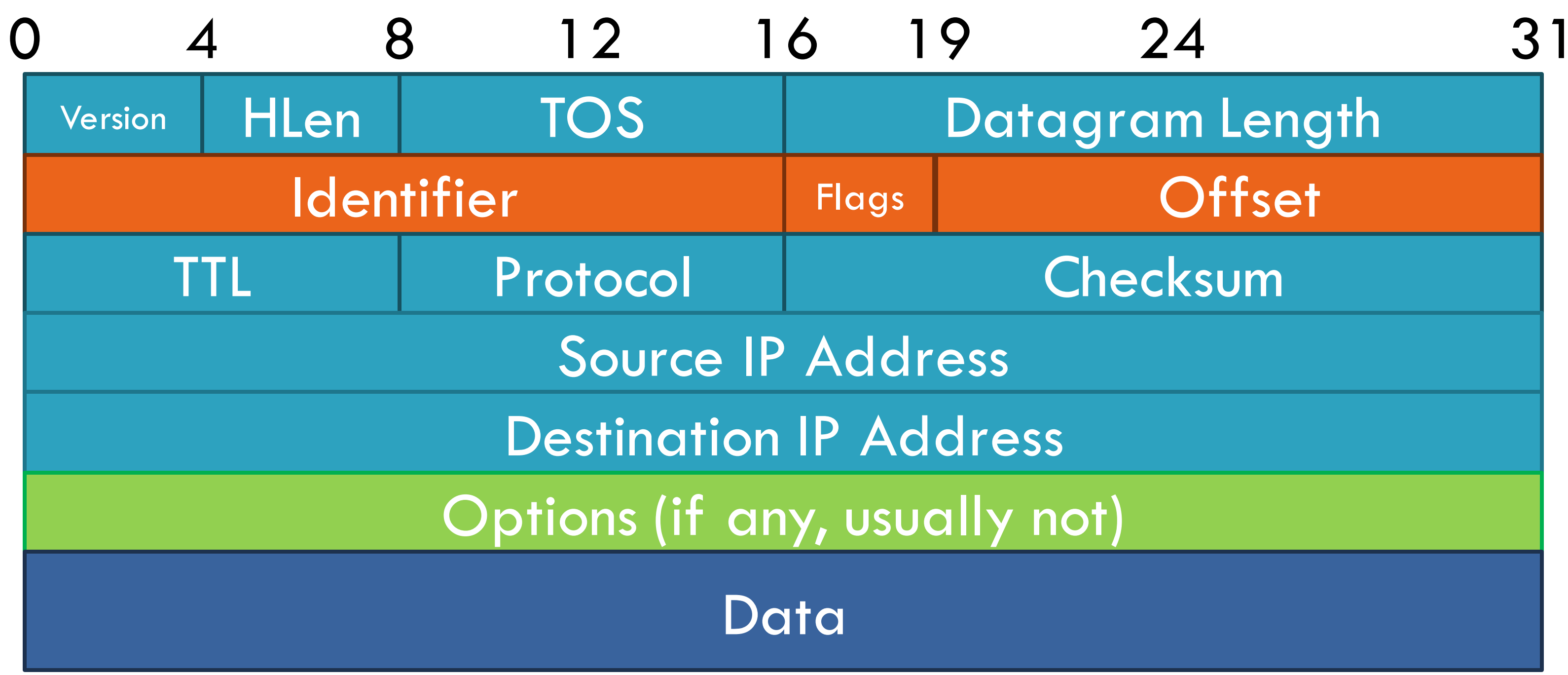
Problem: Fragmentation



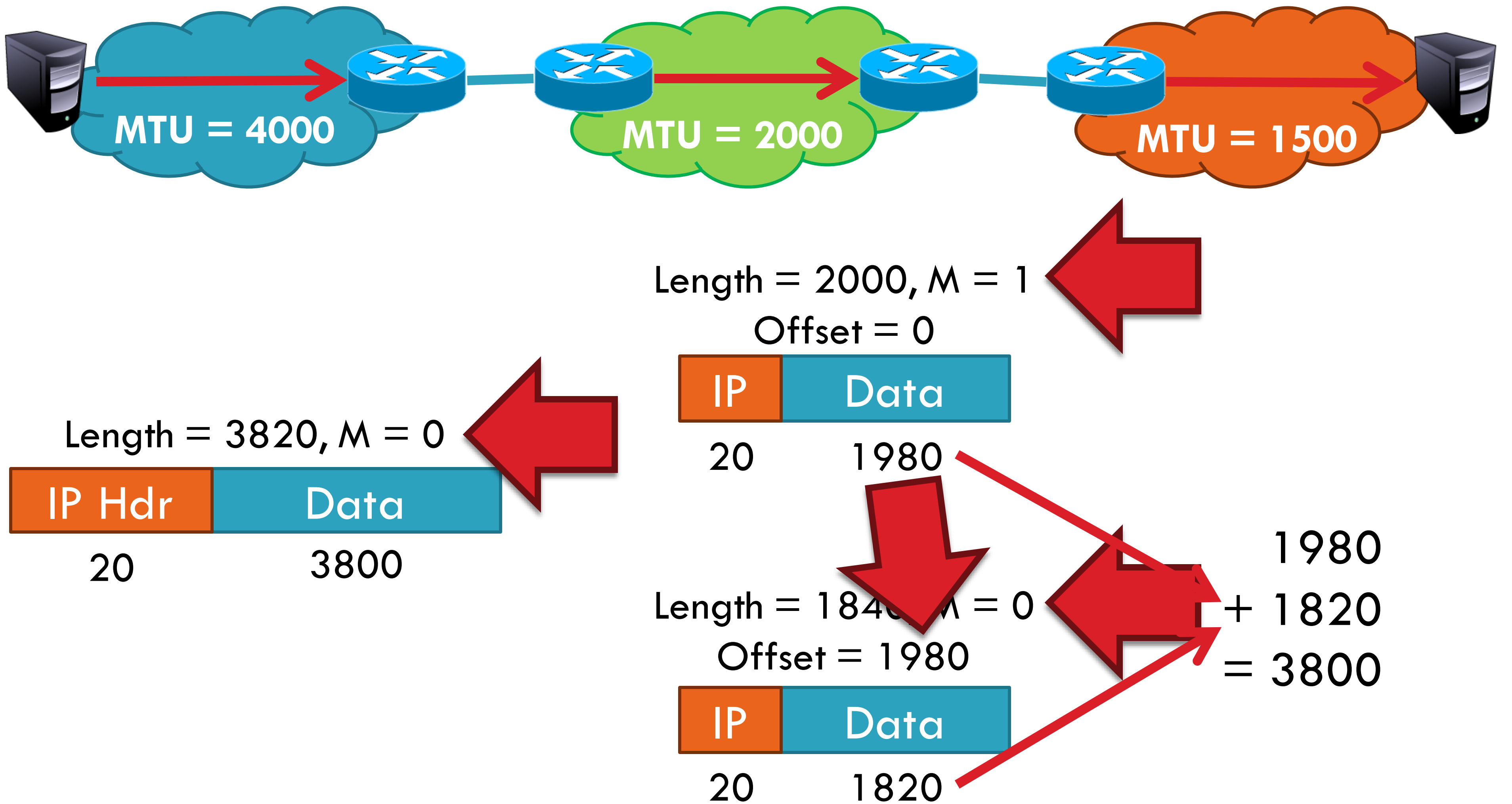
- Problem: each network has its own MTU
  - DARPA principles: networks allowed to be heterogeneous
  - Minimum MTU may not be known for a given path
- IP Solution: fragmentation
  - Split datagrams into pieces when MTU is reduced
  - Reassemble original datagram at the receiver

IP Header Fields: Word 2

- Identifier: a unique number for the original datagram
- Flags: M flag, i.e. this is the last fragment
- Offset: byte position of the first byte in the fragment
  - Divided by 8



Fragmentation Example



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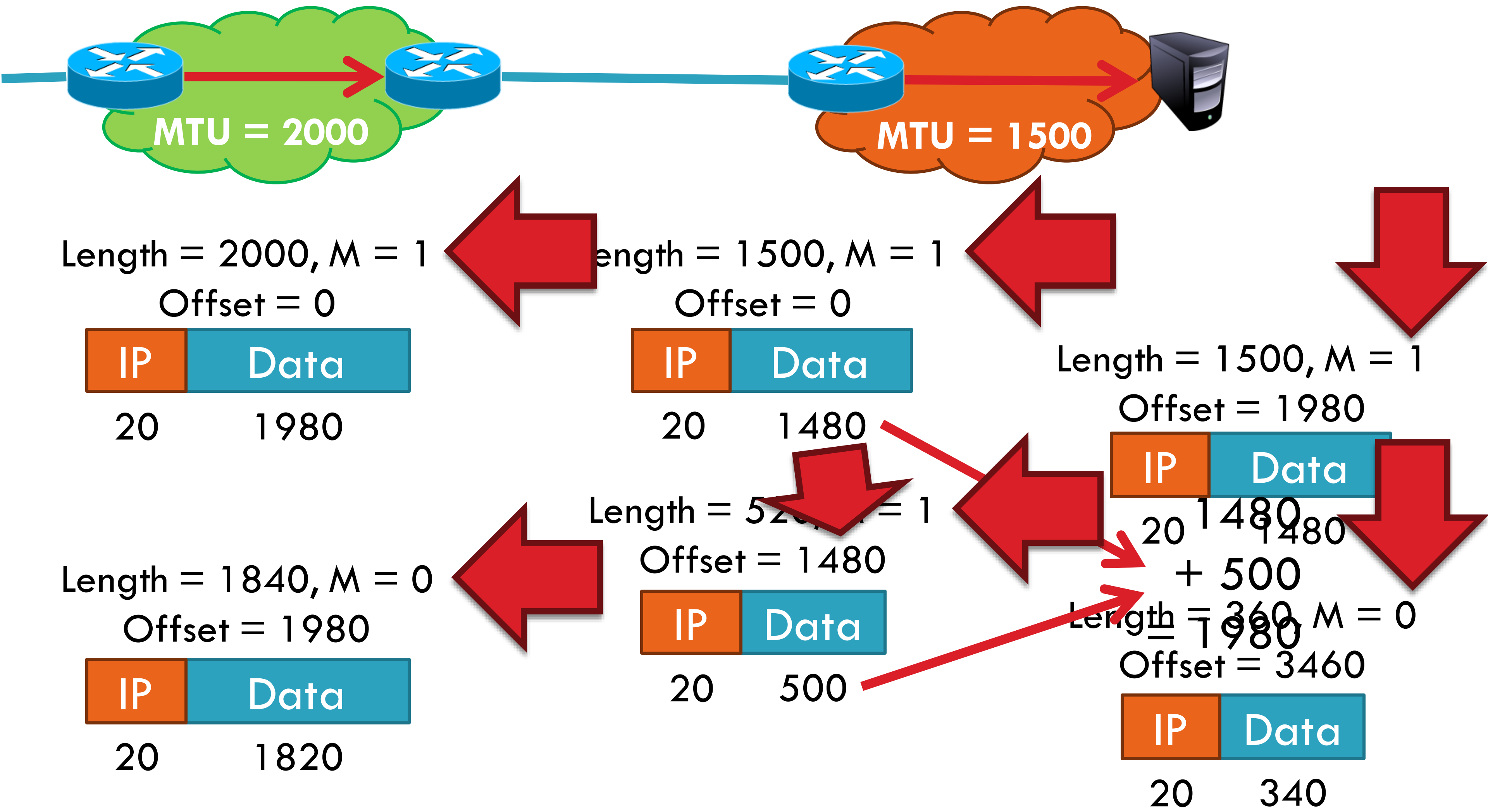

IP Fragment Reassembly

Length = 1500, M = 1, Offset = 0

IP | Data

20 1480

Length = 520, M = 1, Offset = 1480

IP | Data

20 500

Length = 1500, M = 1, Offset = 1980

IP | Data

20 1480

Length = 360, M = 0, Offset = 3460

IP | Data

20 340

- Performed at destination
- M = 0 fragment gives us total data size
  - 360 – 20 + 3460 = 3800
- Challenges:
  - Out-of-order fragments
  - Duplicate fragments
  - Missing fragments
- Basically, memory management nightmare

Fragmentation Concepts

- Highlights many key Internet characteristics
  - Decentralized and heterogeneous
    - Each network may choose its own MTU
  - Connectionless datagram protocol
    - Each fragment contains full routing information
    - Fragments can travel independently, on different paths
  - Best effort network
    - Routers/receiver may silently drop fragments
    - No requirement to alert the sender
  - Most work is done at the endpoints
    - i.e. reassembly

Fragmentation in Reality

- Fragmentation is expensive
  - Memory and CPU overhead for datagram reconstruction
  - Want to avoid fragmentation if possible
- MTU discovery protocol
  - Send a packet with "don't fragment" bit set
  - Keep decreasing message length until one arrives
  - May get "can't fragment" error from a router, which will explicitly state the supported MTU
- Router handling of fragments
  - Fast, specialized hardware handles the common case
  - Dedicated, general purpose CPU just for handling fragments

Outline

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The IPv4 Address Space Crisis

- Problem: the IPv4 address space is too small
  - $2^{32} = 4{,}294{,}967{,}296$ possible addresses
  - Less than one IP per person
- Parts of the world have already run out of addresses
  - IANA assigned the last /8 block of addresses in 2011

Region	Regional Internet Registry (RIR)	Exhaustion Date
Asia/Pacific	APNIC	April 19, 2011
Europe/Middle East	RIPE	September 14, 2012
North America	ARIN	13 Jan 2015 (Projected)
South America	LACNIC	13 Jan 2015 (Projected)
Africa	AFRINIC	17 Jan 2022(Projected)

IPv6

- IPv6, first introduced in 1998(!)
  - 128-bit addresses
  - $4.8 * 10^{28}$ addresses per person
- Address format
  - 8 groups of 16-bit values, separated by ':'
  - Leading zeroes in each group may be omitted
  - Groups of zeroes can be omitted using '::'

2001:0db8:<u>0000:0000:0000</u>:ff00:<u>00</u>42:8329

2001:0db8:<u>0:0:0</u>:ff00:42:8329

2001:0db8::ff00:42:8329

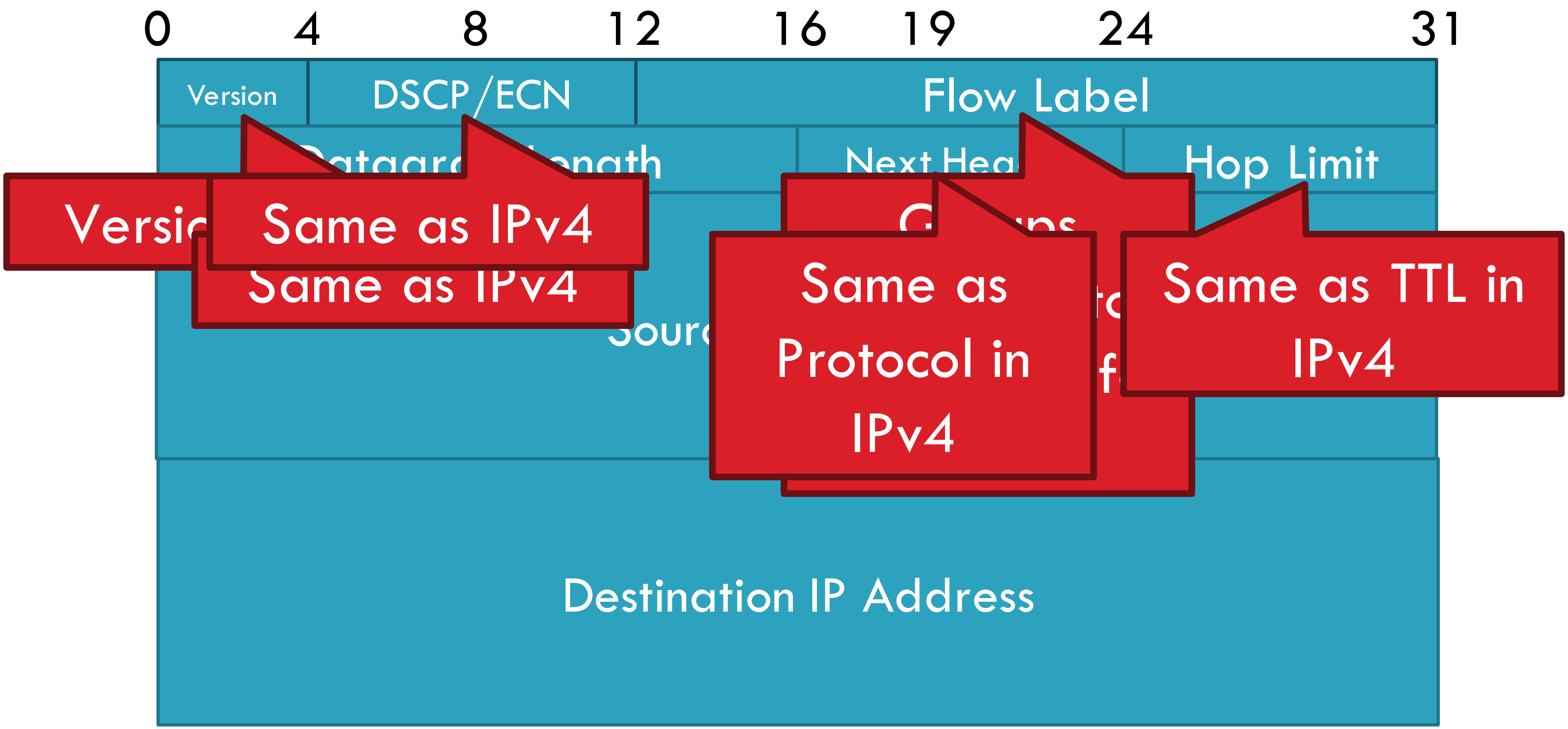
IPv6 Trivia

- Who knows the IP for localhost?
  - 127.0.0.1

- What is localhost in IPv6?
  - ::1

IPv6 Header

- Double the size of IPv4 (320 bits vs. 160 bits)



Differences from IPv4 Header

- Several header fields are missing in IPv6
  - Header length – rolled into Next Header field
  - Checksum – was useless, so why keep it
  - Identifier, Flags, Offset
    - IPv6 routers do not support fragmentation
    - Hosts are expected to use path MTU discovery
- Reflects changing Internet priorities
  - Today's networks are more homogeneous
  - Instead, routing cost and complexity dominate

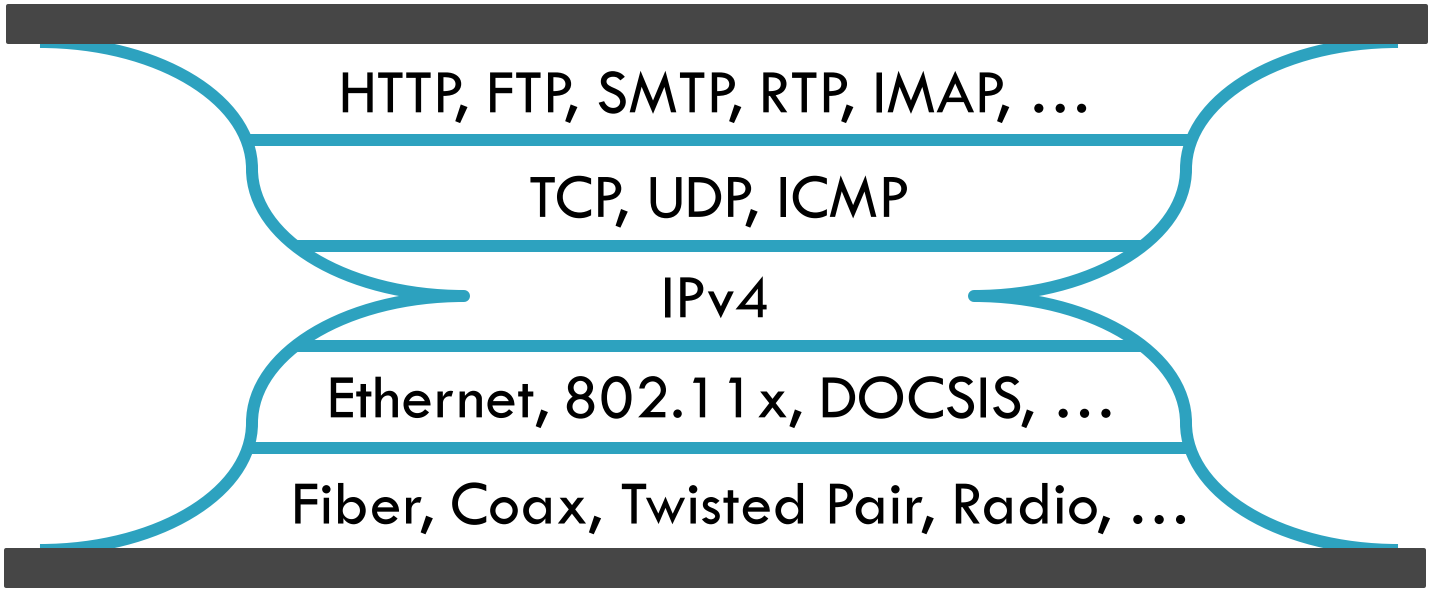
Performance Improvements

- No checksums to verify
- No need for routers to handle fragmentation
- Simplified routing table design
  - Address space is huge
  - No need for CIDR (but need for aggregation)
  - Standard subnet size is 2^{64} addresses
- Simplified auto-configuration
  - Neighbor Discovery Protocol
  - Used by hosts to determine network ID
  - Host ID can be random!

Additional IPv6 Features

- Source Routing
  - Host specifies the route to wants packet to take
- Mobile IP
  - Hosts can take their IP with them to other networks
  - Use source routing to direct packets
- Privacy Extensions
  - Randomly generate host identifiers
  - Make it difficult to associate one IP to a host
- Jumbograms
  - Support for 4Gb datagrams

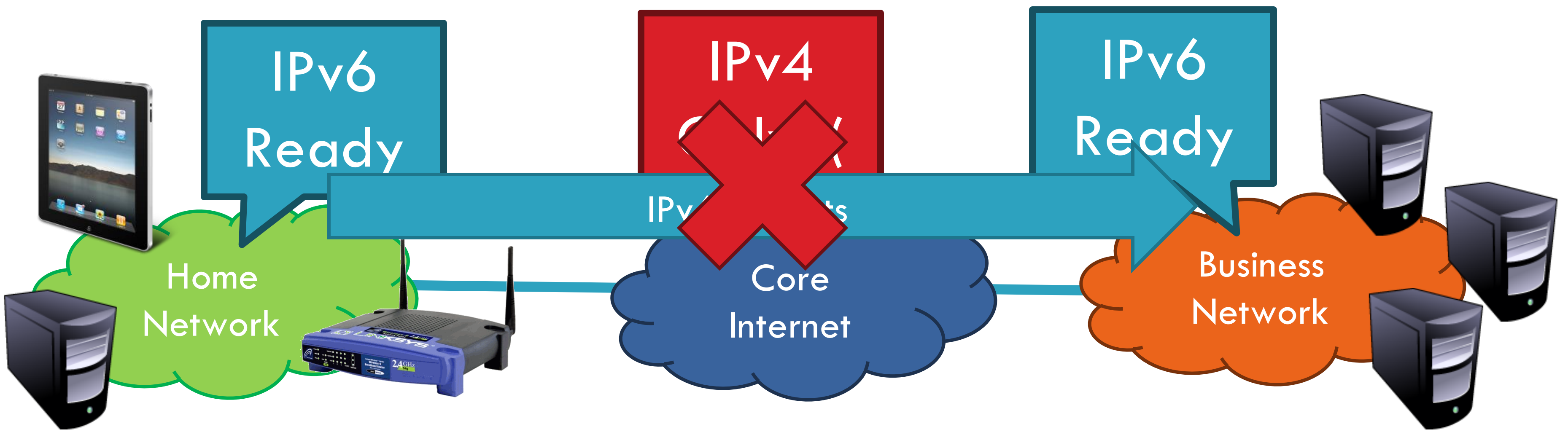
Deployment Challenges



- Switching to IPv6 is a whole-Internet upgrade
  - All routers, all hosts
  - ICMPv6, DHCPv6, DNSv6
- 2013: 0.94% of Google traffic was IPv6, 2.5% today

Transitioning to IPv6

- How do we ease the transition from IPv4 to IPv6?
  - Today, most network edges are IPv6 ready
    - Windows/OSX/iOS/Android all support IPv6
    - Your wireless access point probably supports IPv6
  - The Internet core is hard to upgrade
  - … but a IPv4 core cannot route IPv6 traffic



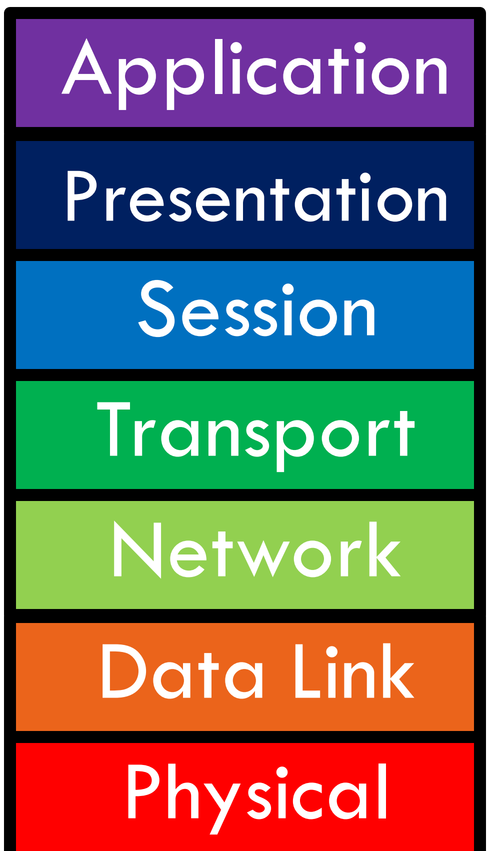
Transition Technologies

- How do you route IPv6 packets over an IPv4 Internet?
- Transition Technologies
  - Use tunnels to encapsulate and route IPv6 packets over the IPv4 Internet
  - Several different implementations
    - 6to4
    - IPv6 Rapid Deployment (6rd)
    - Teredo
    - … etc.

Network Layer, Control Plane

- Function:
  - Set up routes within a single network
- Key challenges:
  - Distributing and updating routes
  - Convergence time
  - Avoiding loops

Data Plane

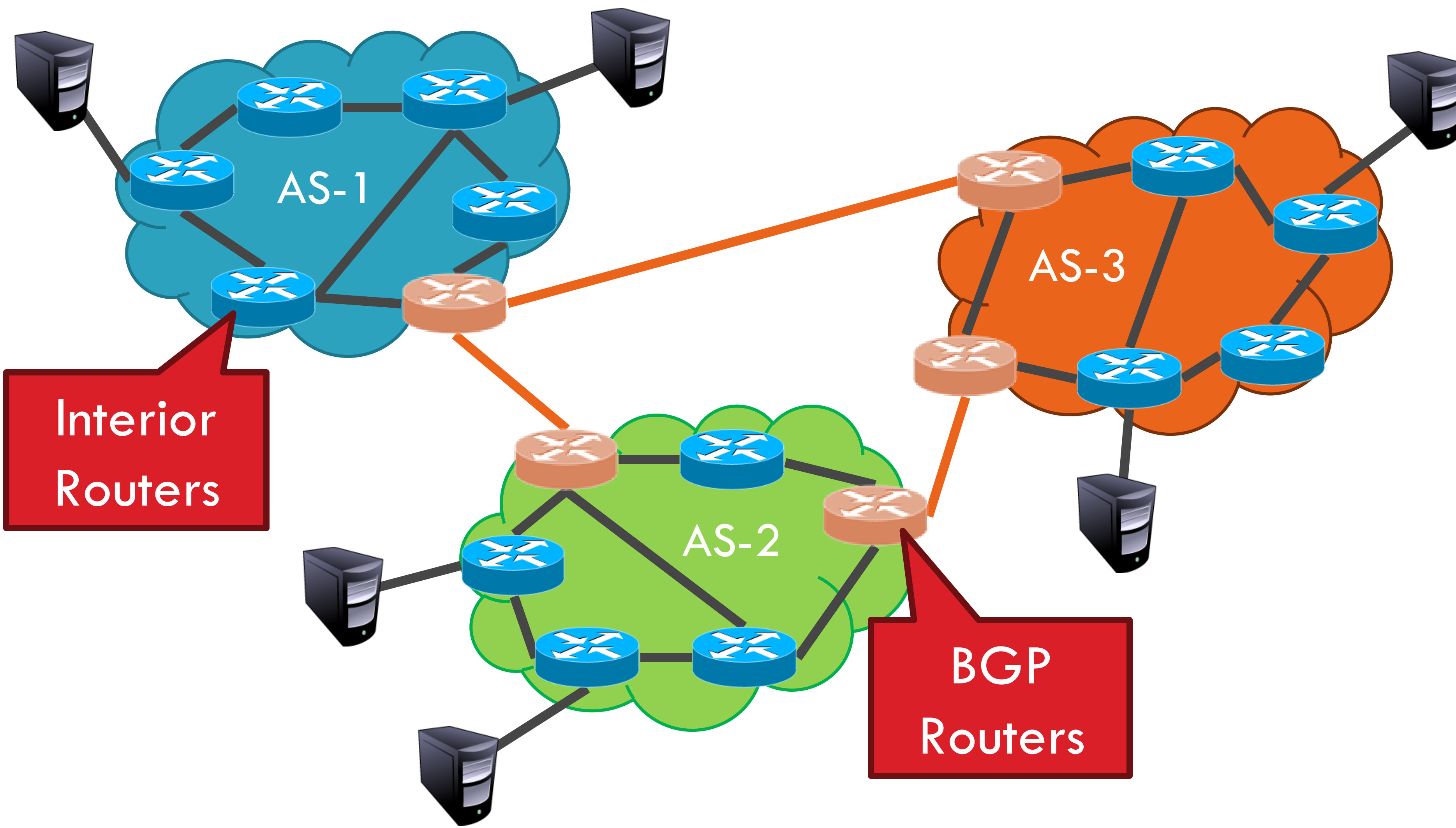


Control Plane

Internet Routing

- Internet organized as a two level hierarchy
- First level – autonomous systems (AS's)
  - AS – region of network under a single administrative domain
  - Examples: Comcast, AT&T, Verizon, Sprint, etc.
- AS's use intra-domain routing protocols internally
  - Distance Vector, e.g., Routing Information Protocol (RIP)
  - Link State, e.g., Open Shortest Path First (OSPF)
- Connections between AS's use inter-domain routing protocols
  - Border Gateway Routing (BGP)
  - De facto standard today, BGP-4

AS Example



Why Do We Need ASs?

- Routing algorithms are not efficient enough to execute on the entire Internet topology
- Diff... policies
- Allo... k stru...
- Allo... s each other (BGP)

- Easier to compute routes
- Greater flexibility
- More autonomy/independence

Routing on a Graph

- Goal: determine a "good" path through the network from source to destination
- What is a good path?
  - Usually means the shortest path
  - Load balanced
  - Lowest $$$ cost
- Network modeled as a graph
  - Routers → nodes
  - Link → edges
    - Edge cost: delay, congestion level, etc.