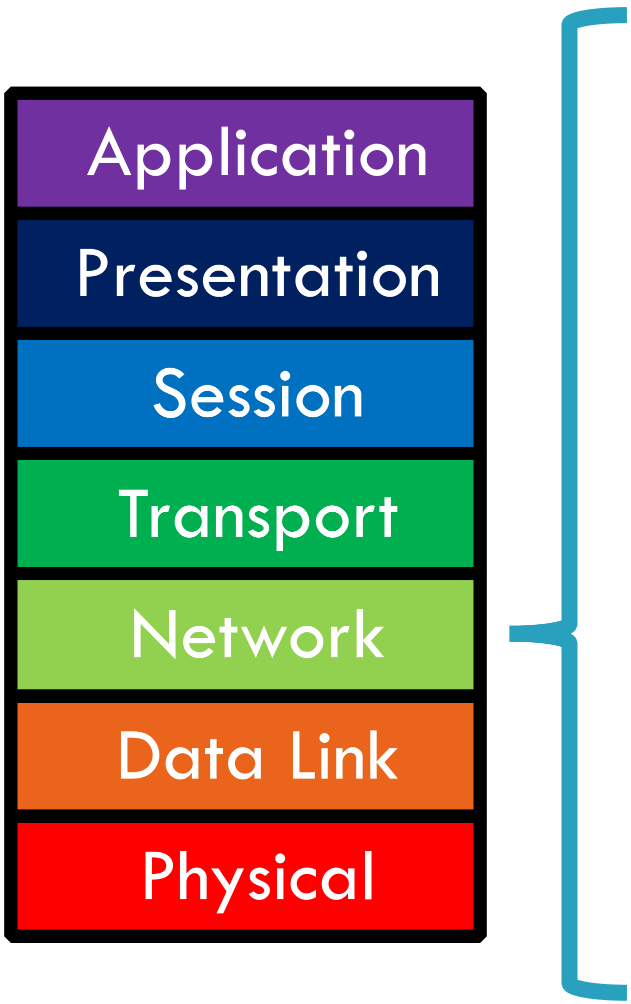
CS 3700
Networks and Distributed Systems

Lecture 6: Network Layer

Revised 1/25/2014

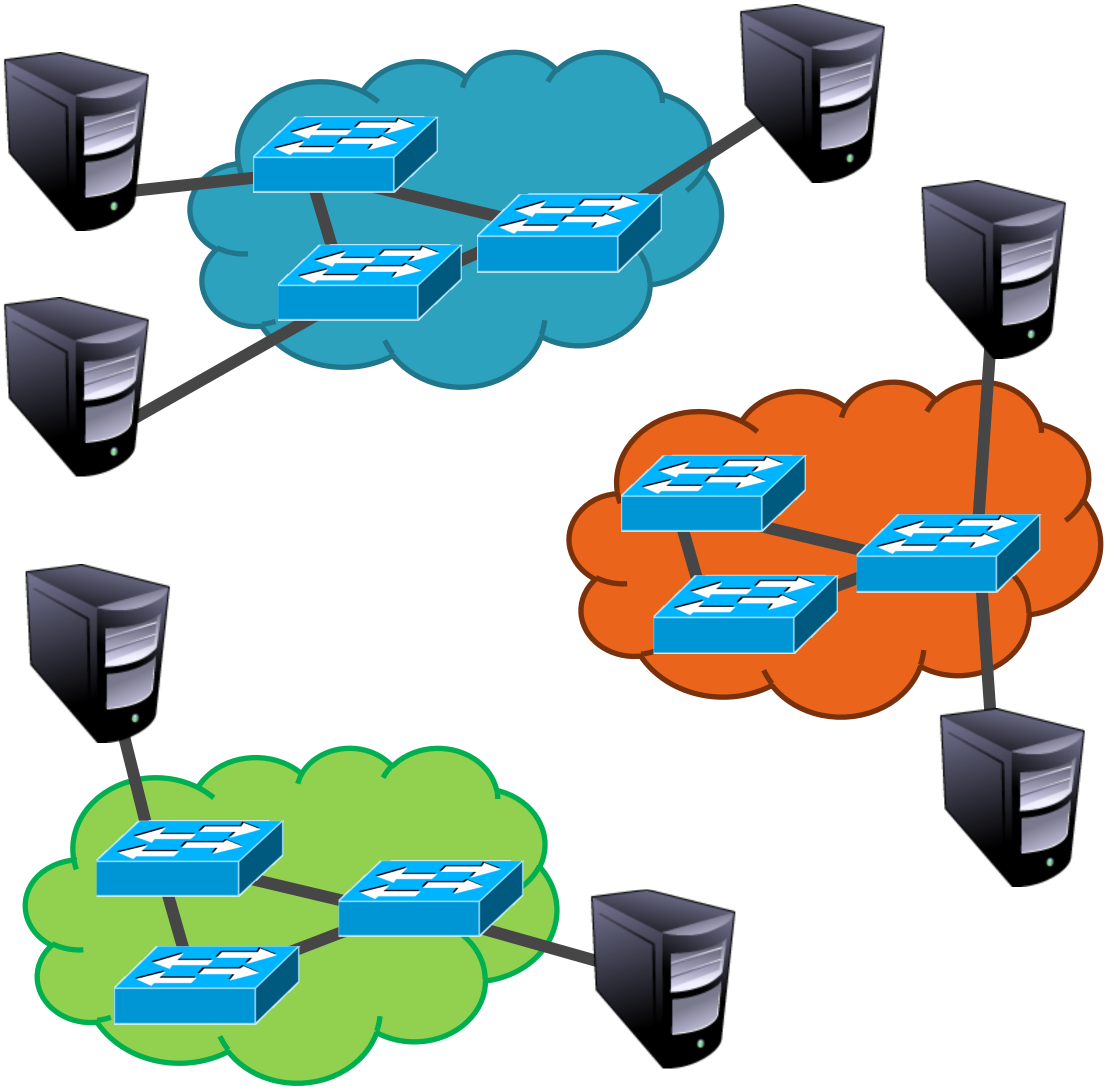
Network Layer



- 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…



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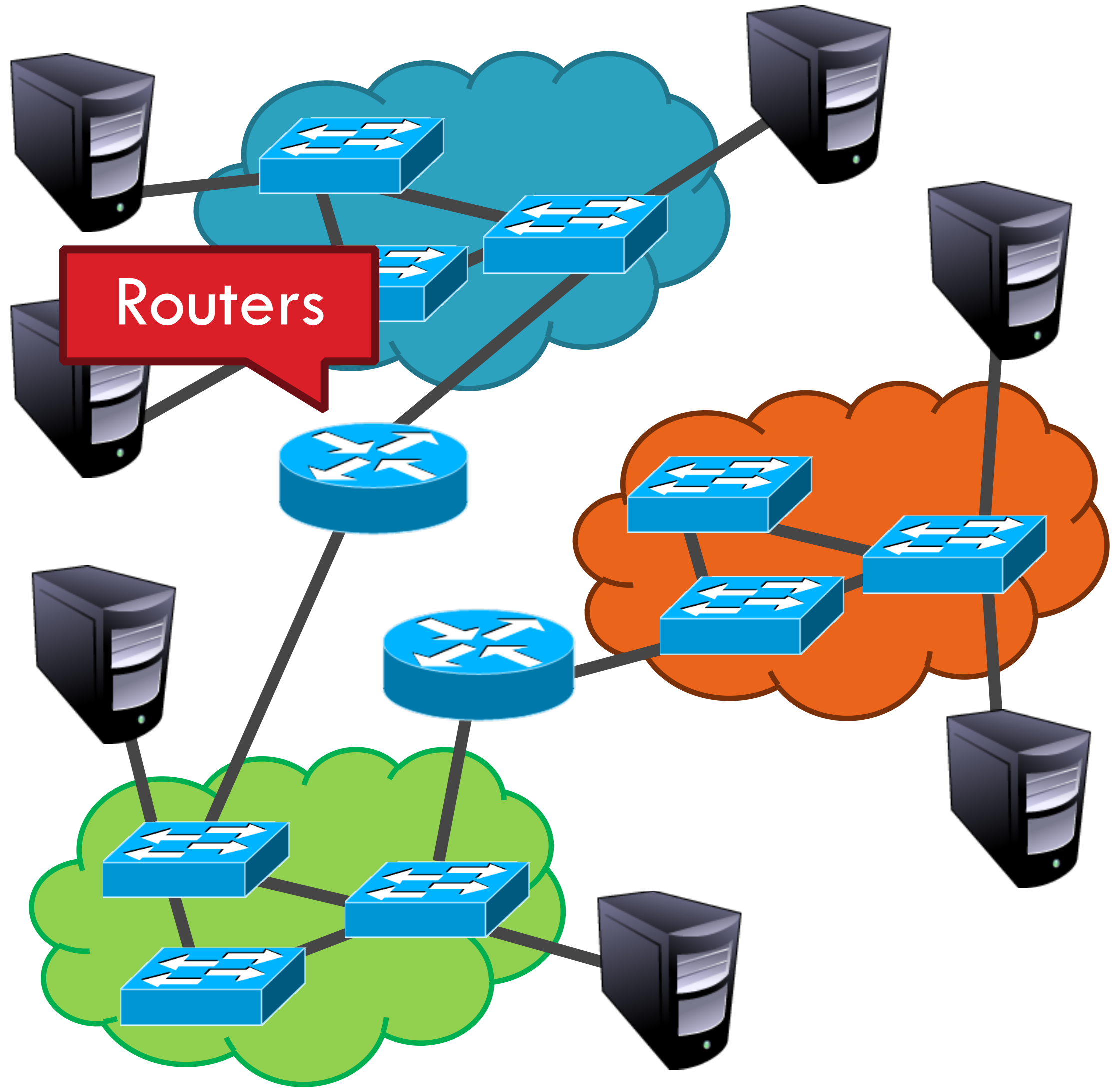
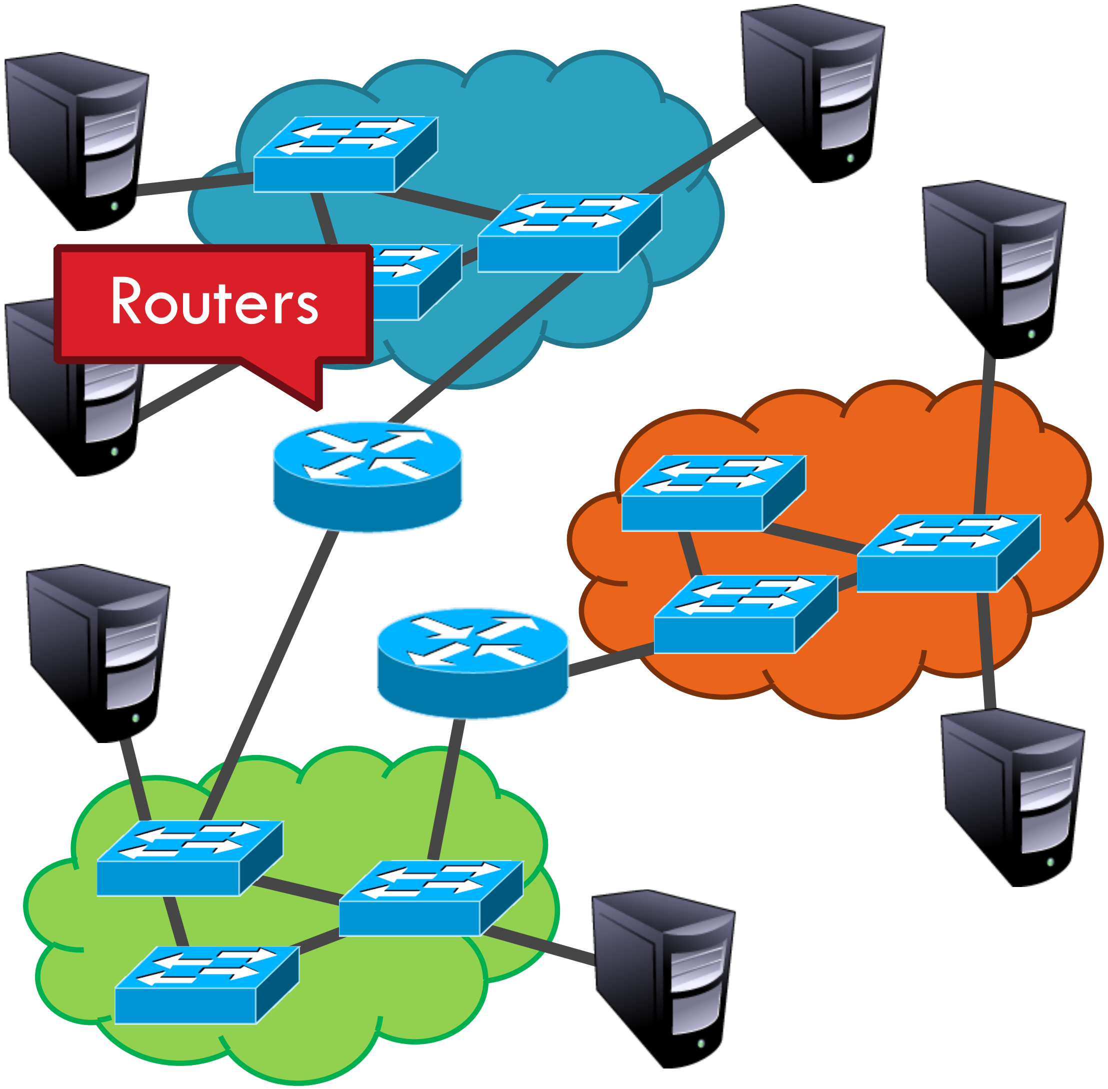
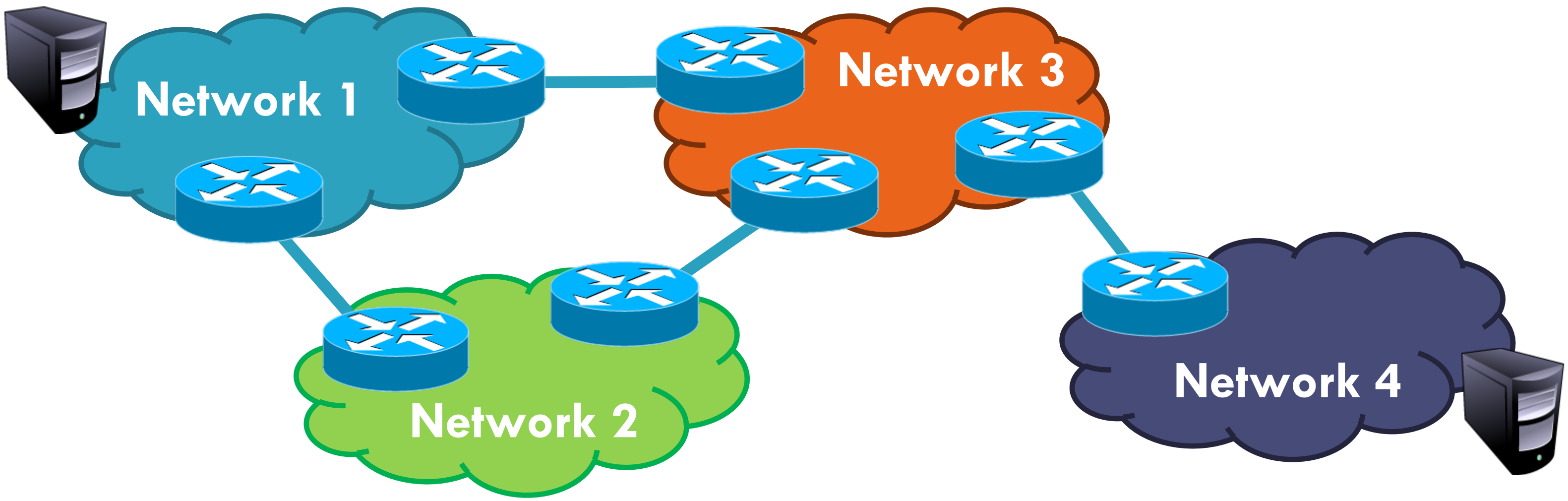


Routers, Revisited

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



Structure of the Internet



- Ad-hoc interconnection of networks
  - No organized topology
  - Vastly different technologies, link capacities
- Packets travel end-to-end by hopping through networks
  - Routers "peer" (connect) different networks
  - Different packets may take different routes

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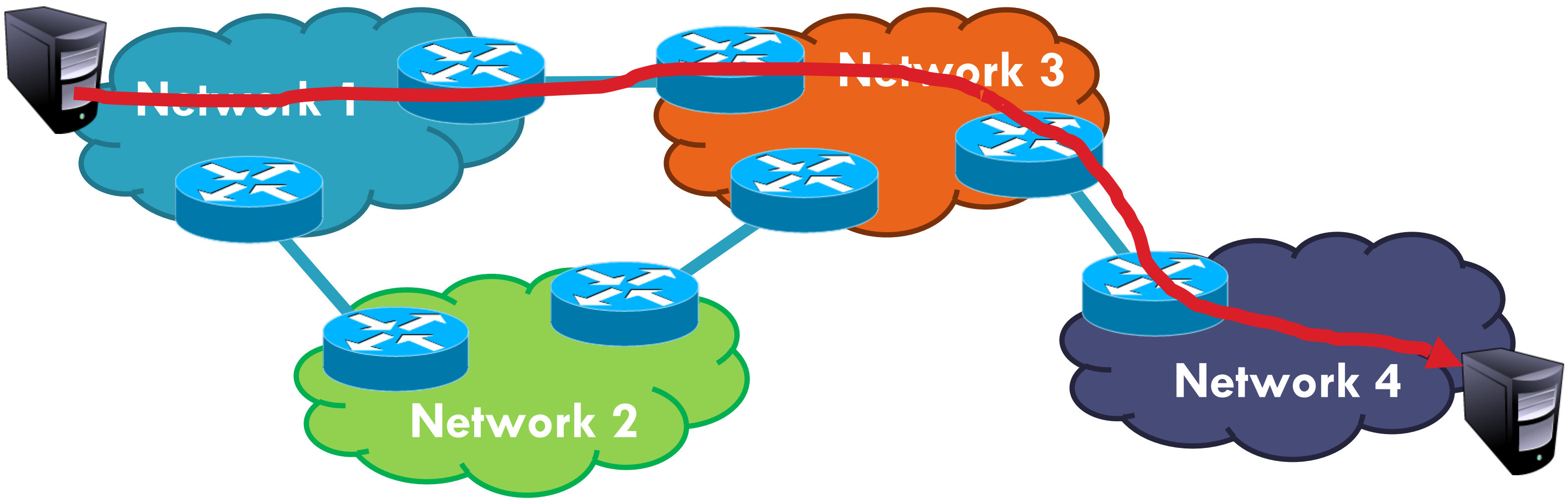

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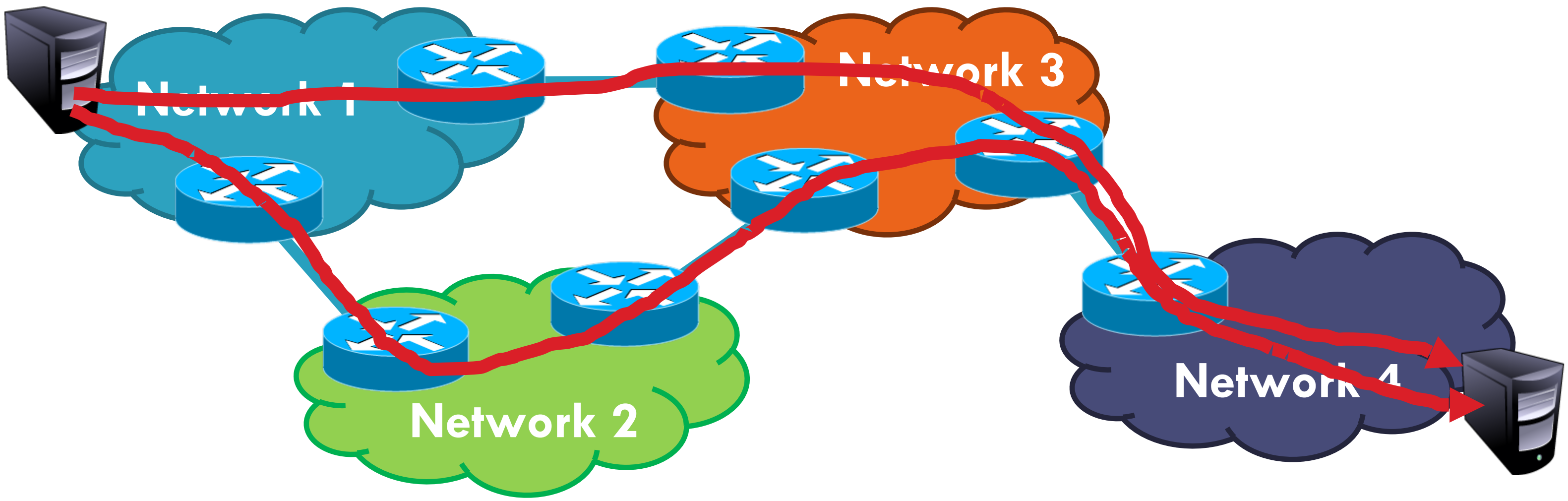

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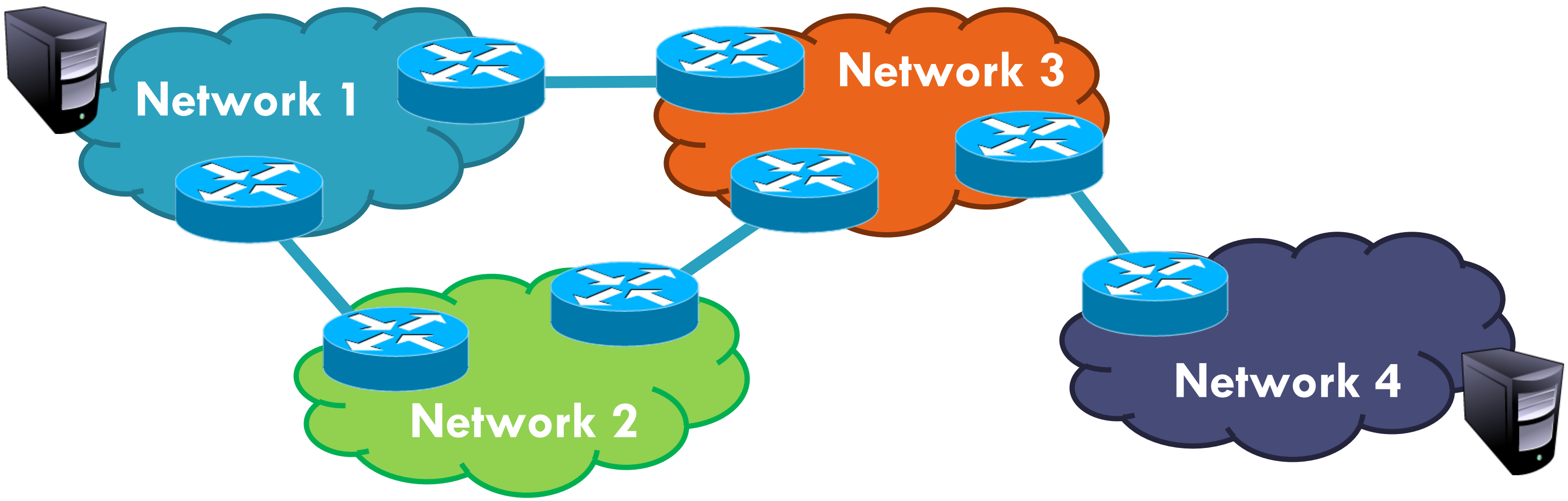

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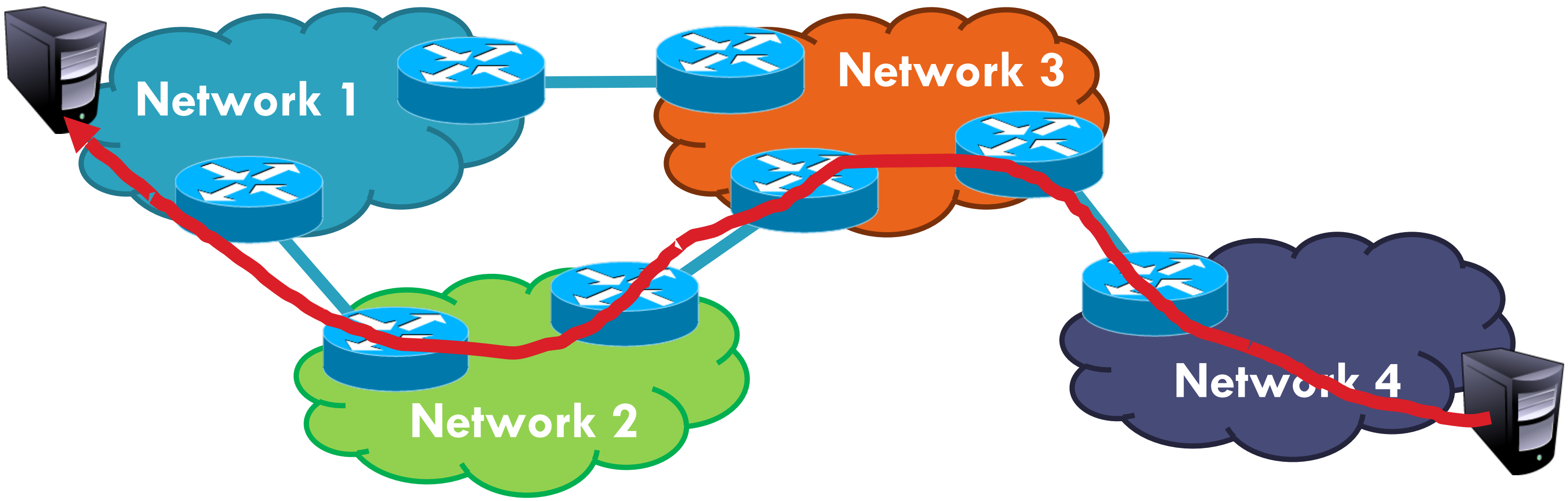

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Internetworking Issues

- Naming / Addressing
  - How do you designate hosts?

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- Routing
  - Must be scalable (i.e. a switched Internet won't work)

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  - How do you designate hosts?
- Routing
  - Must be scalable (i.e. a switched Internet won't work)
- 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

Inte

Internet Service Model

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

Lowest common denominator

- Nc
  -
- Ro
  -
- Service Model
  - What gets sent?
  - How fast will it go?
  - What happens if there are failures?
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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)

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- Hierarchy
  - Addresses broken down into segments
  - Each segment has a different level of specificity

Example: Telephone Numbers

1-617-373-1234

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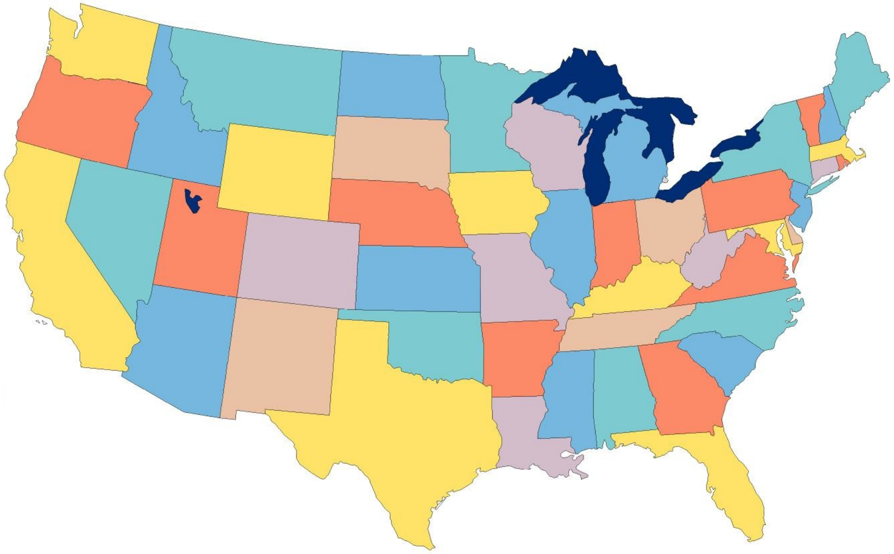

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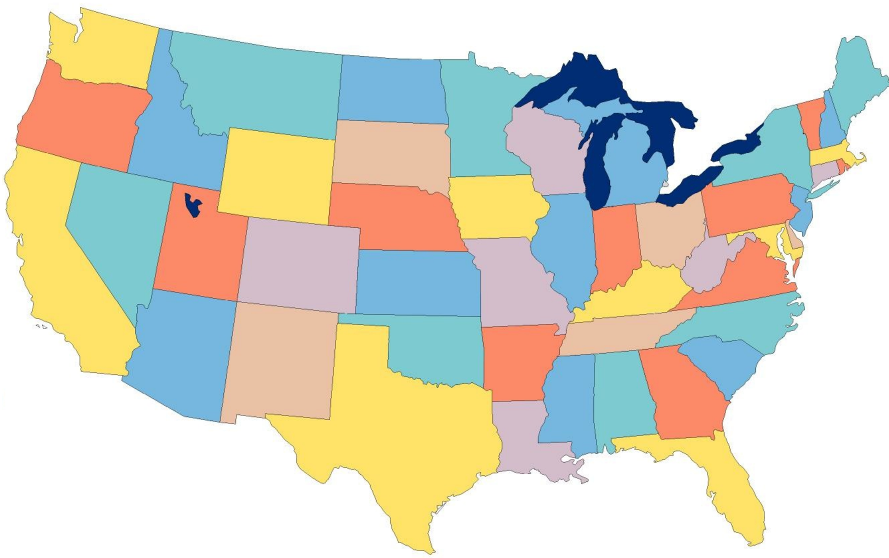

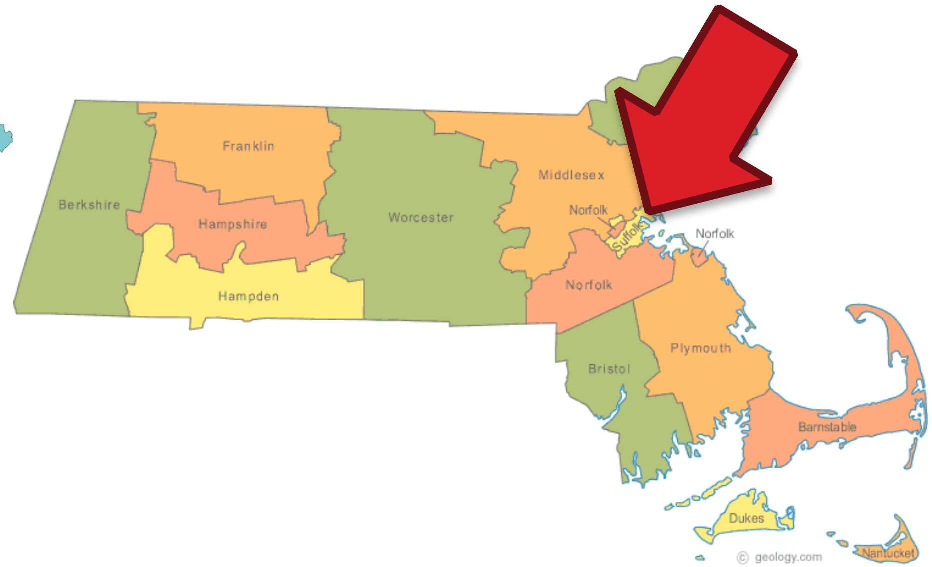

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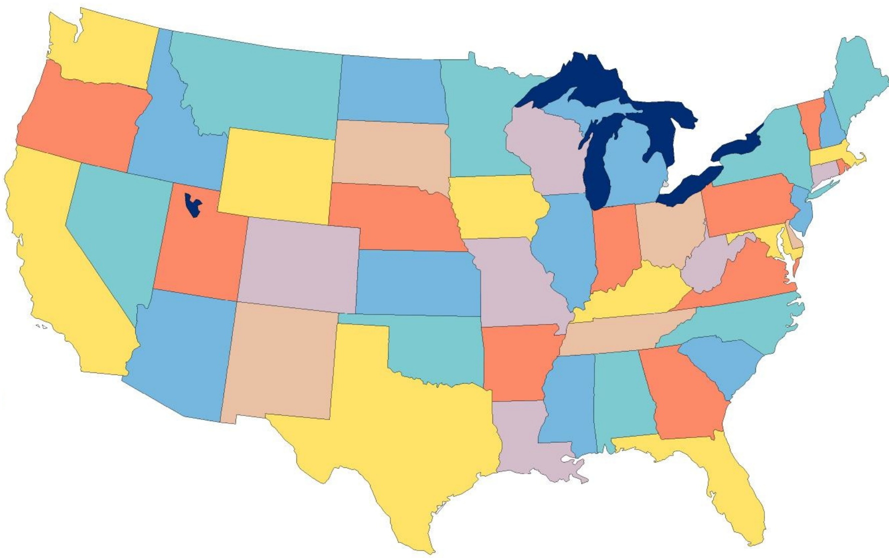

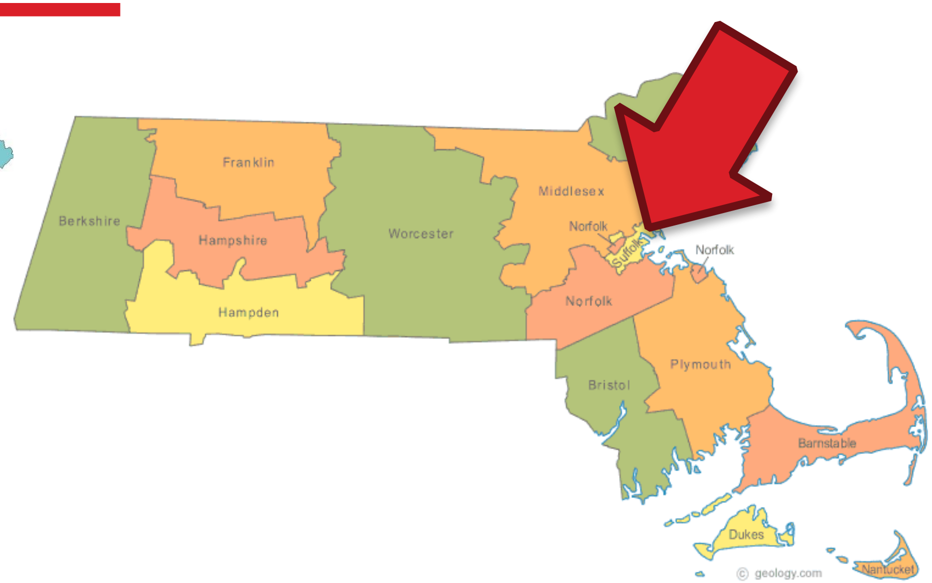

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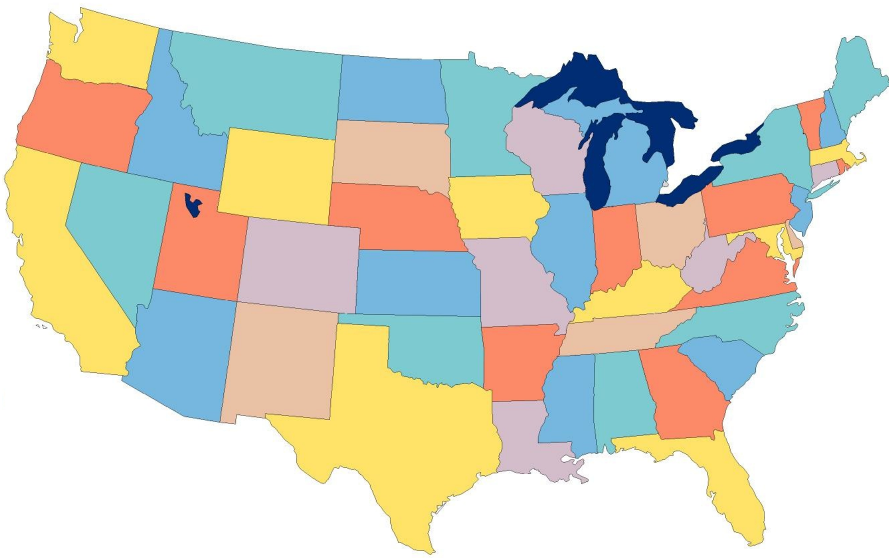

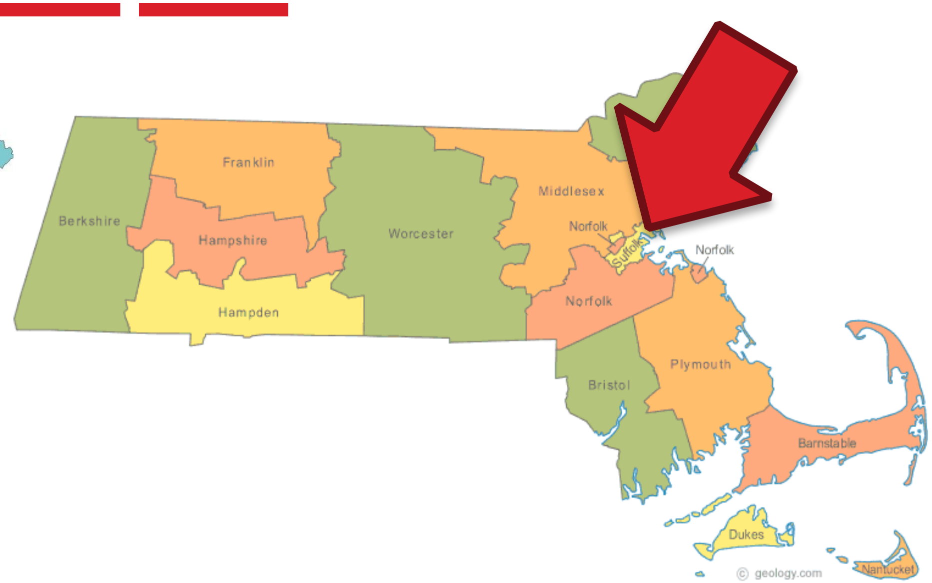

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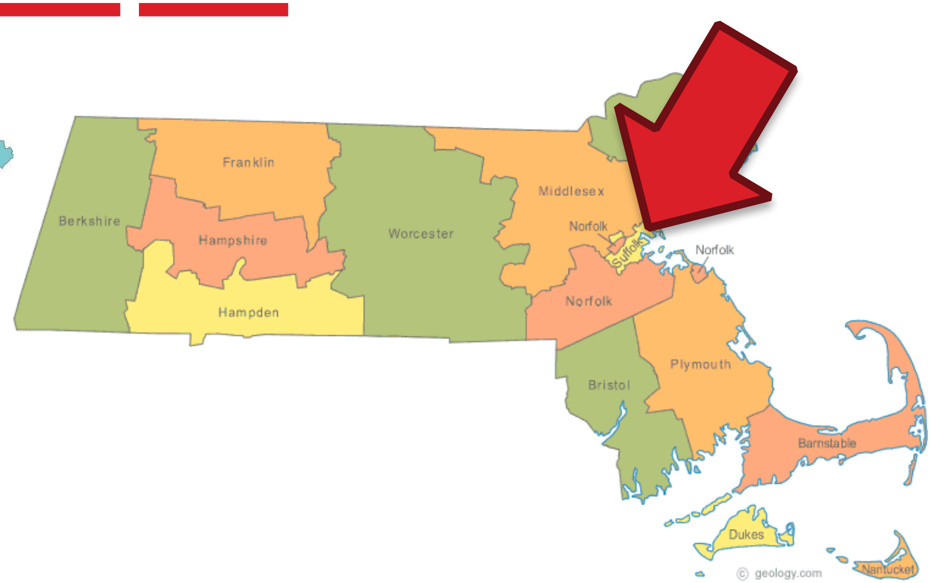
Example: Telephone Numbers

1-617-373-1234

Very General



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Very Specific

Example: Telephone Numbers

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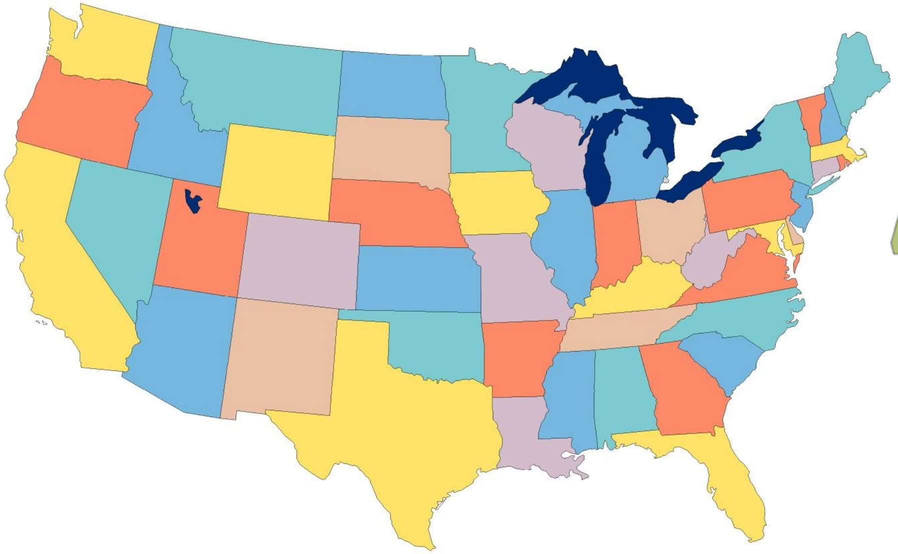

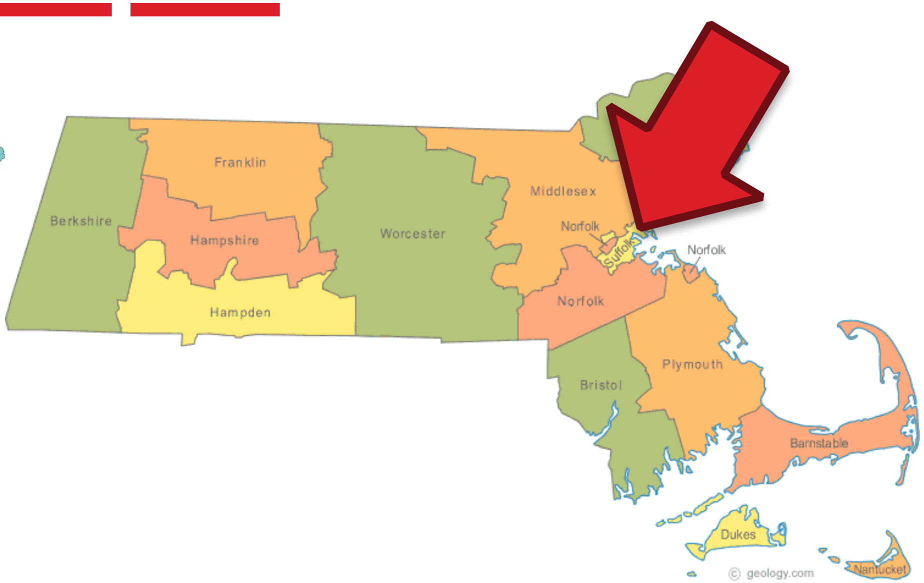

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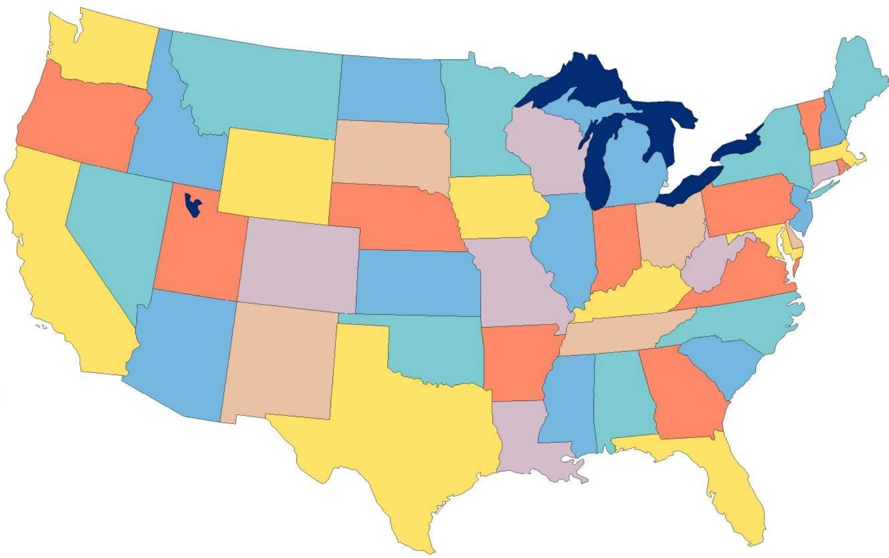
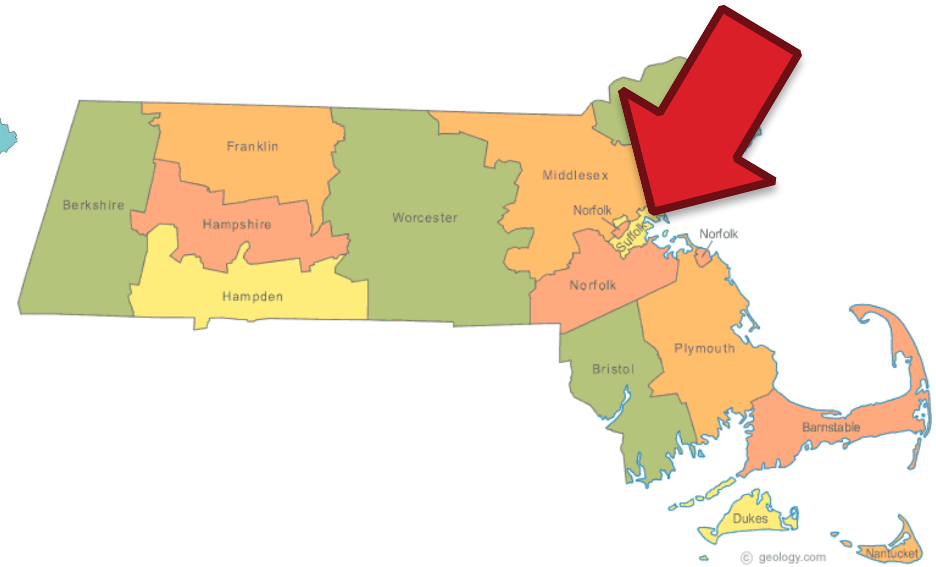
Example: Telephone Numbers

1-617-373- 3278





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Example: Telephone Numbers

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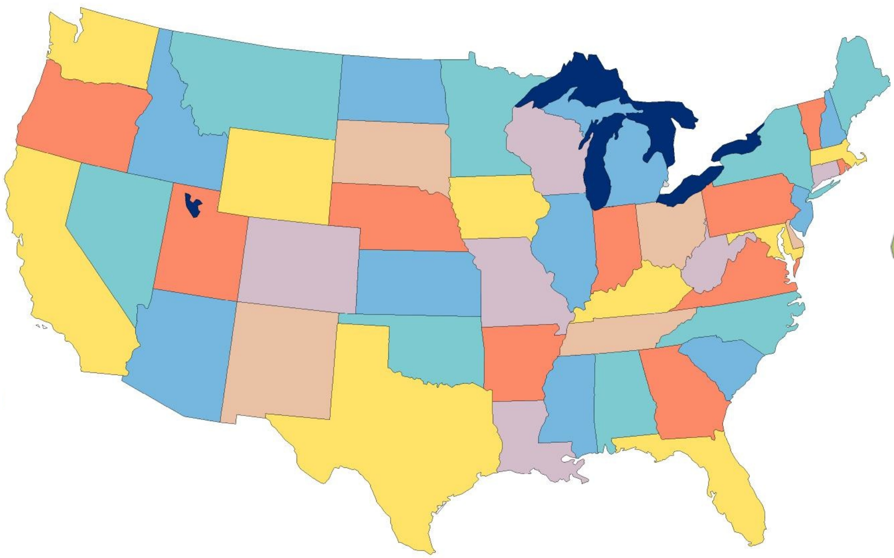

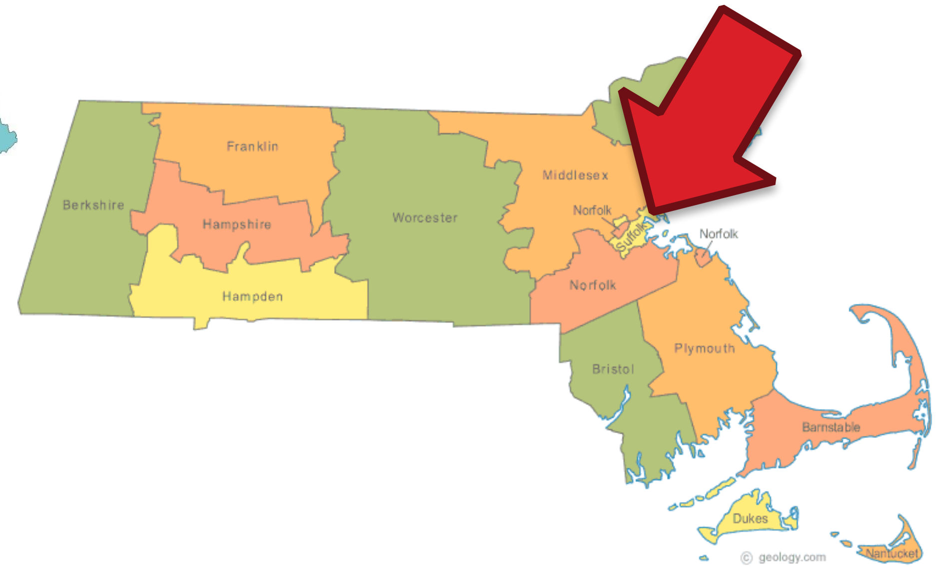

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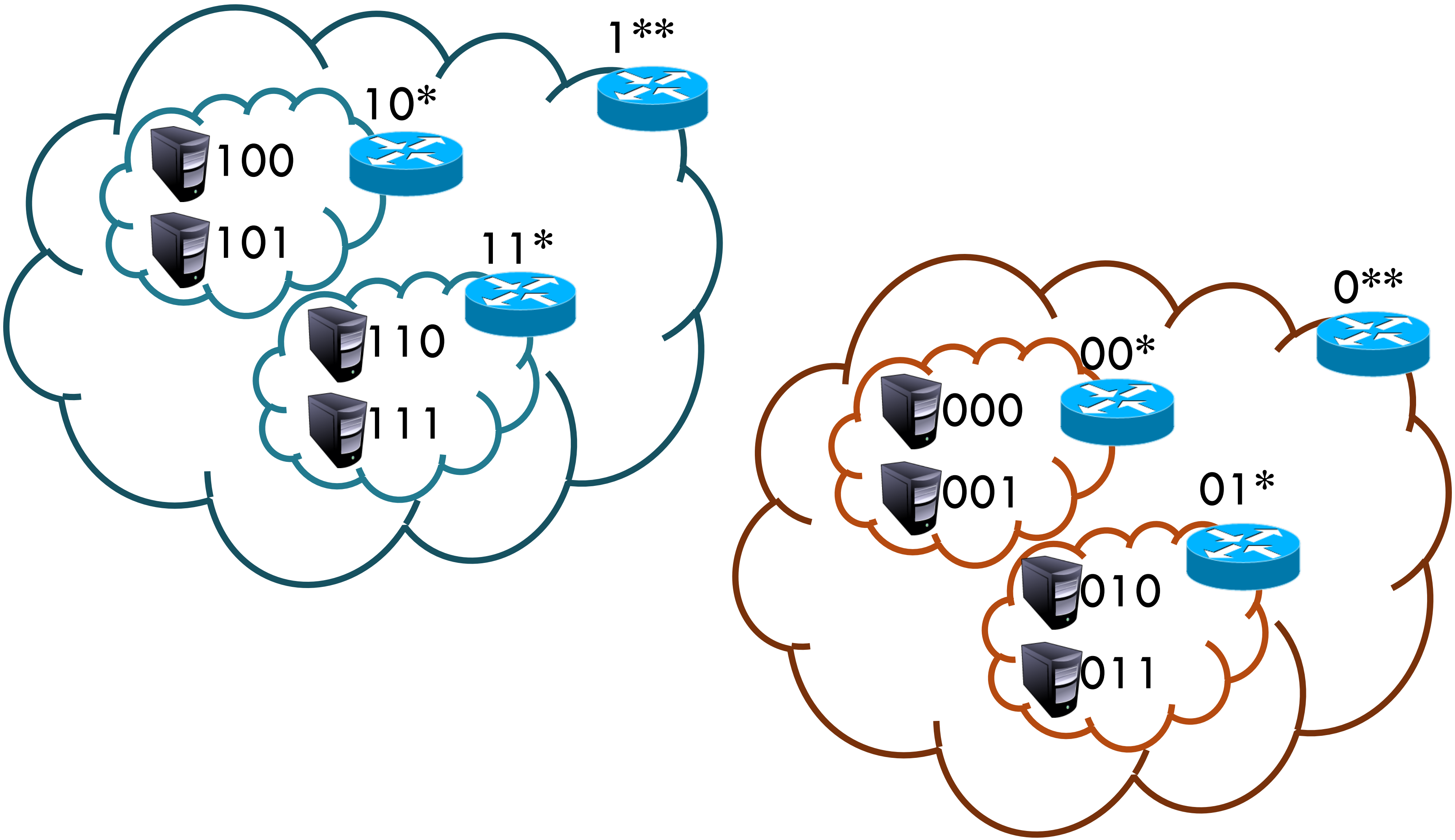
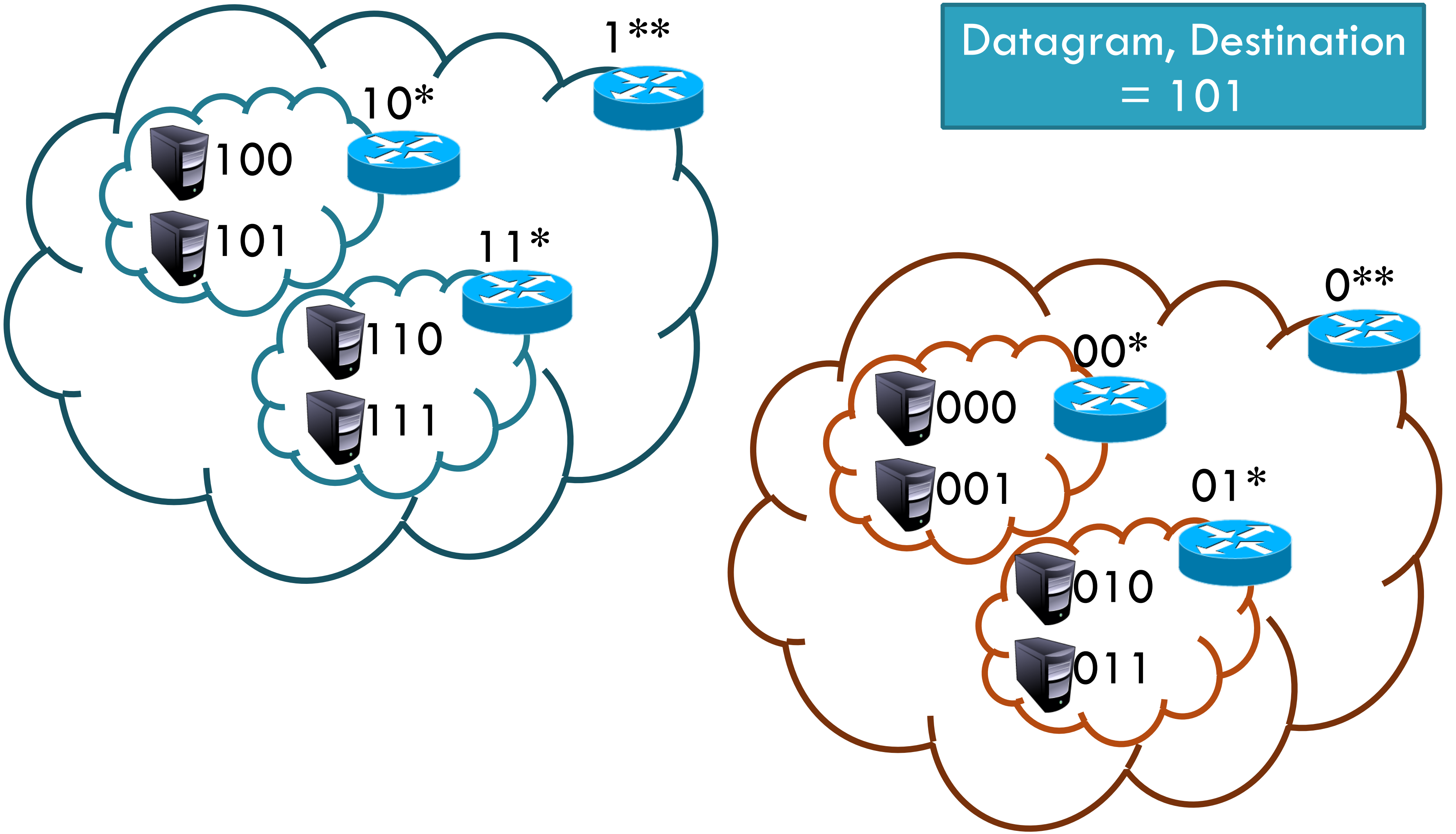
Updates are Local

Binary Hierarchy Example



Binary Hierarchy Example

Datagram, Destination = 101



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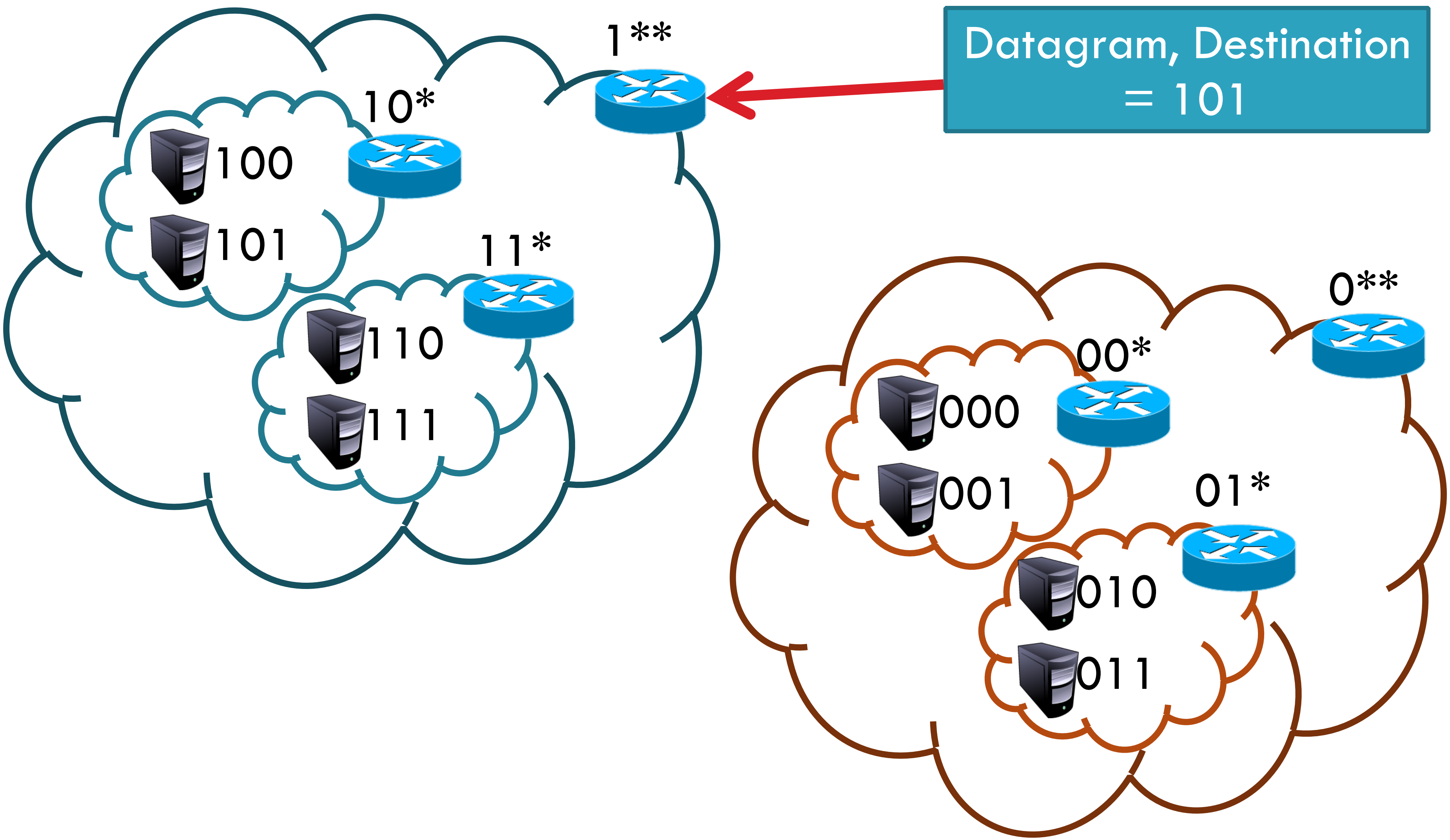

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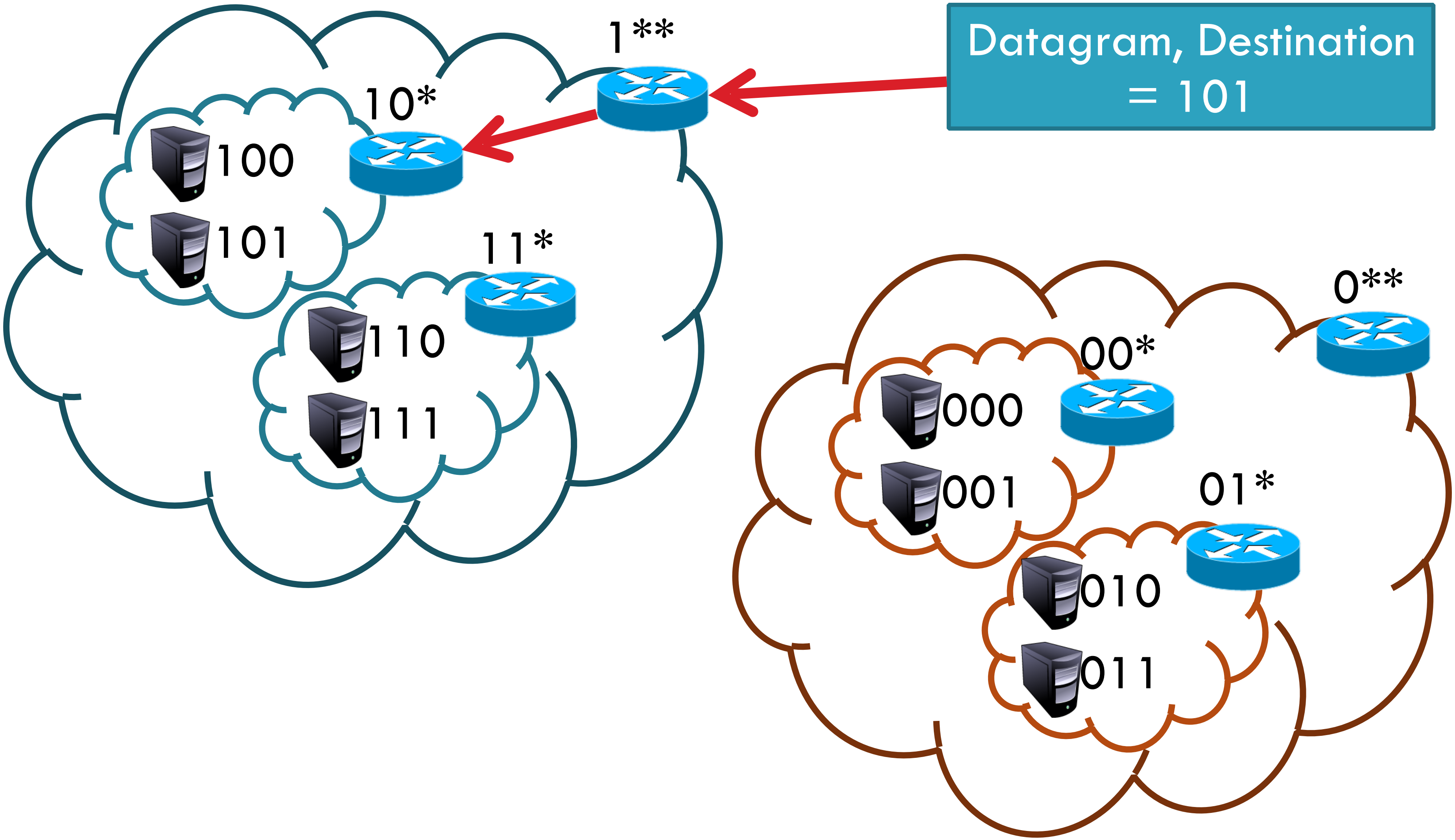

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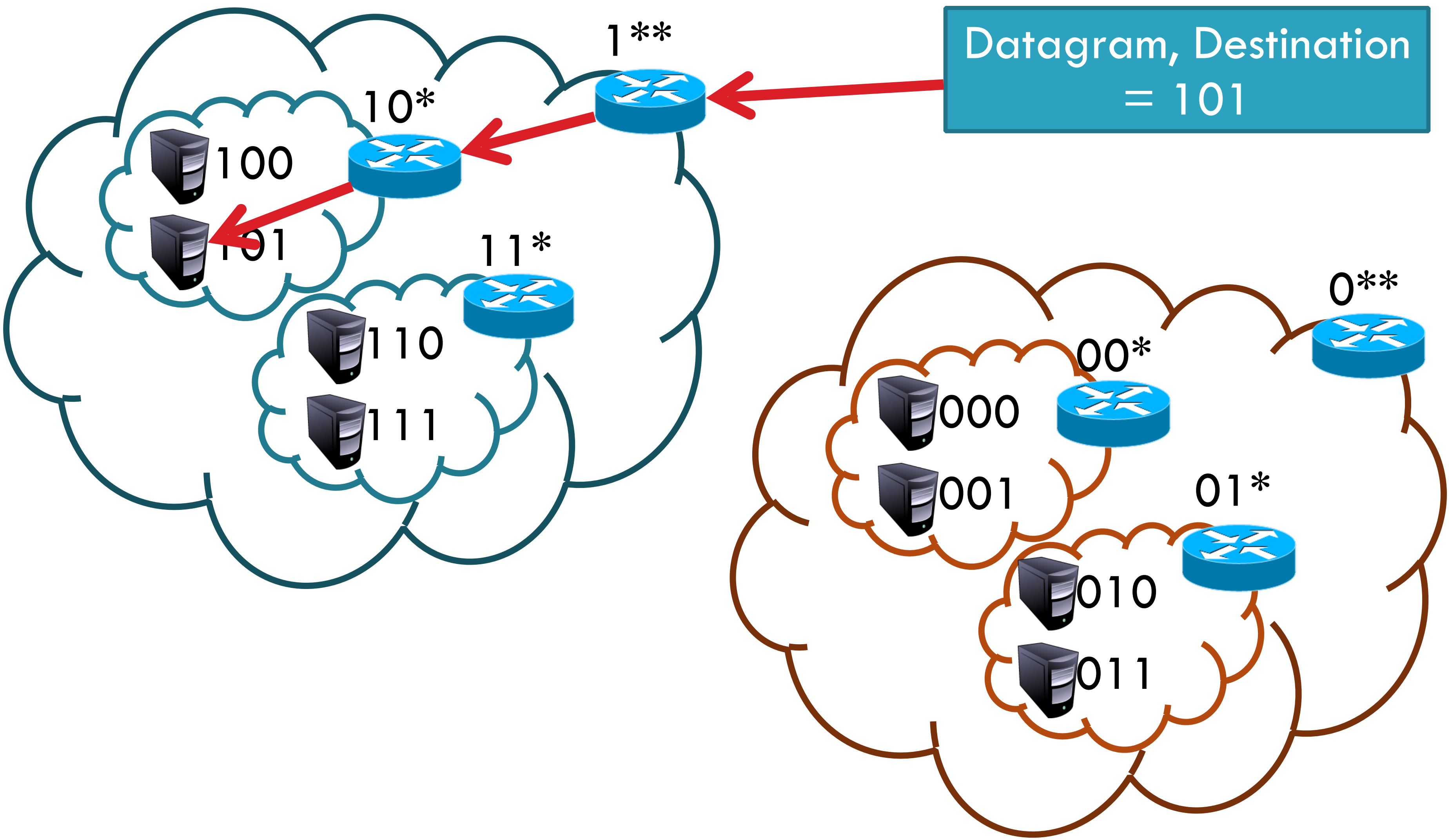

IP Addressing

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

	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!
  - **Too slow:** 48GE ports and 4x10GE needs 176Gbps bandwidth
    DRAM: ~1-6 Gbps; **TCAM** is fast, but 400x cost of DRAM

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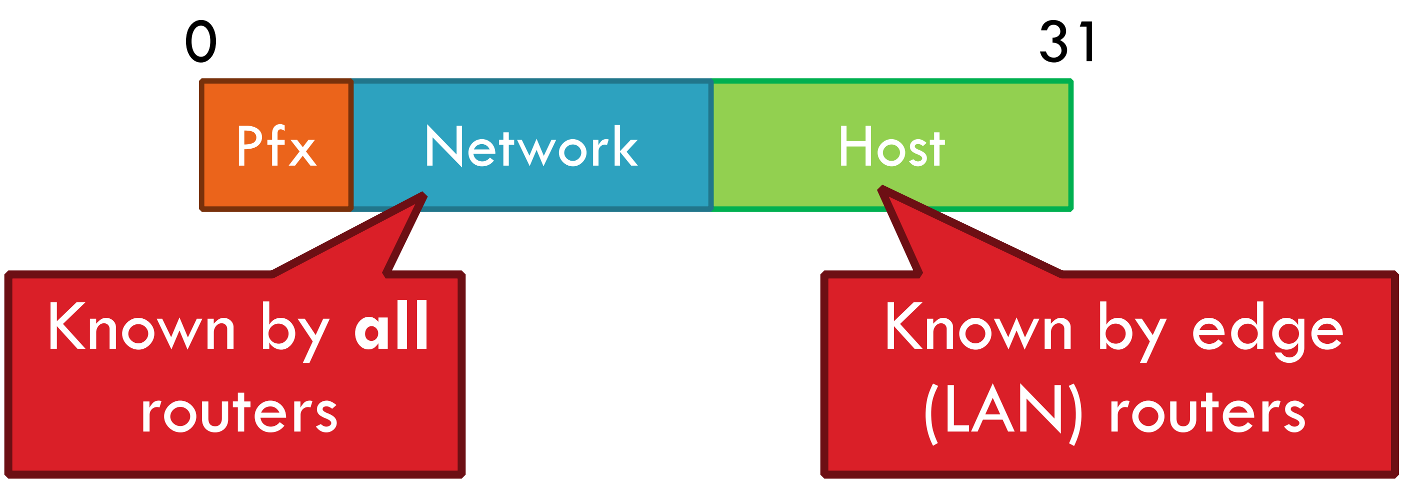

Classes of IP Addresses

- Class A

Example: MIT
18.*.*.*

Classes of IP Addresses

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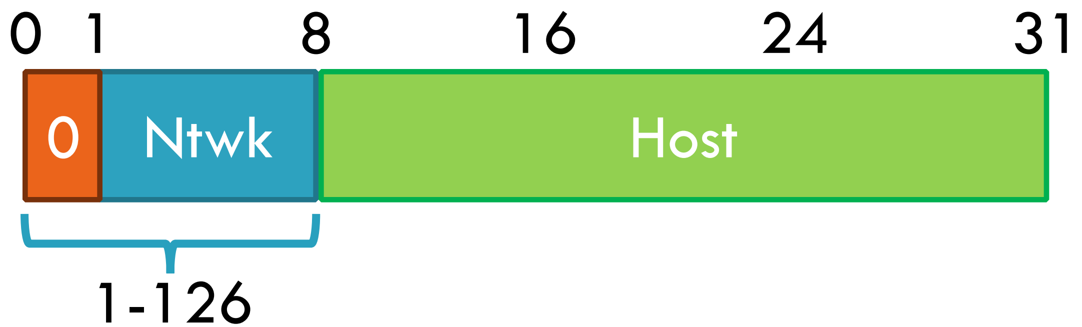

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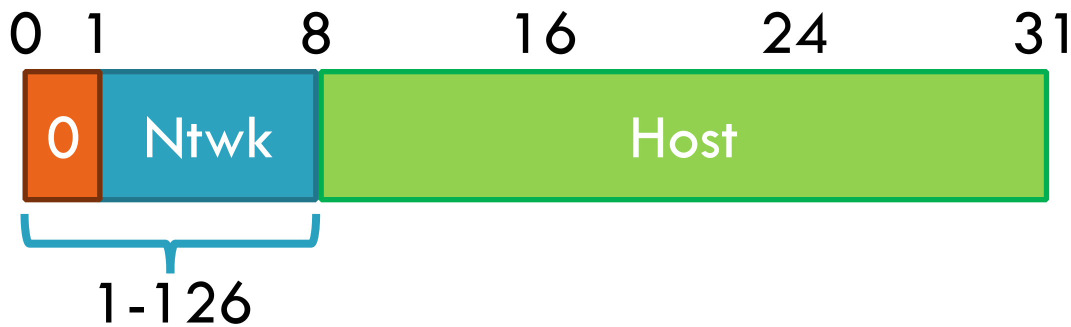

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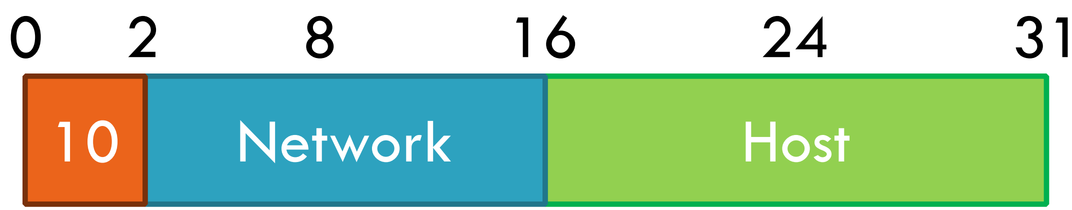
- Class B



Example: NEU
129.10.*.*

Classes of IP Addresses

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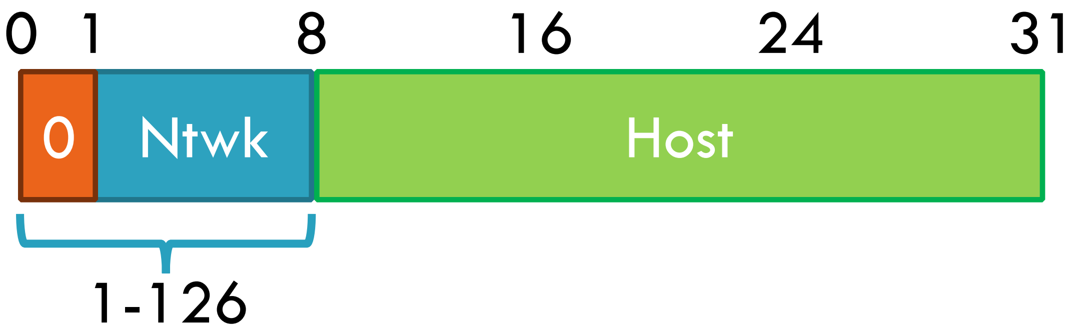

Example: MIT
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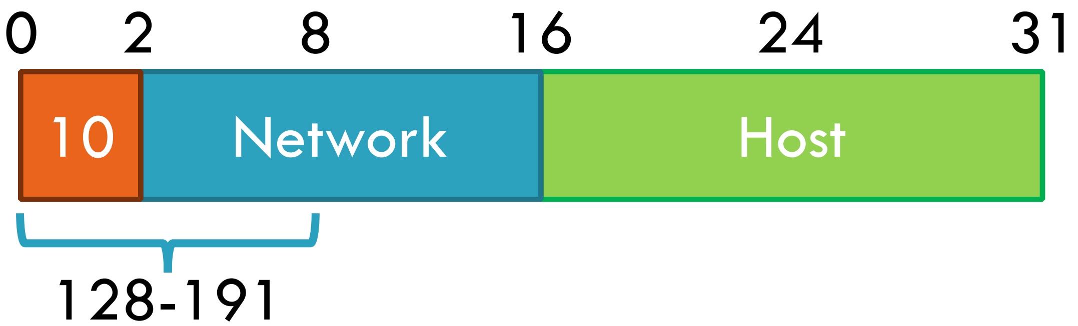
- Class B



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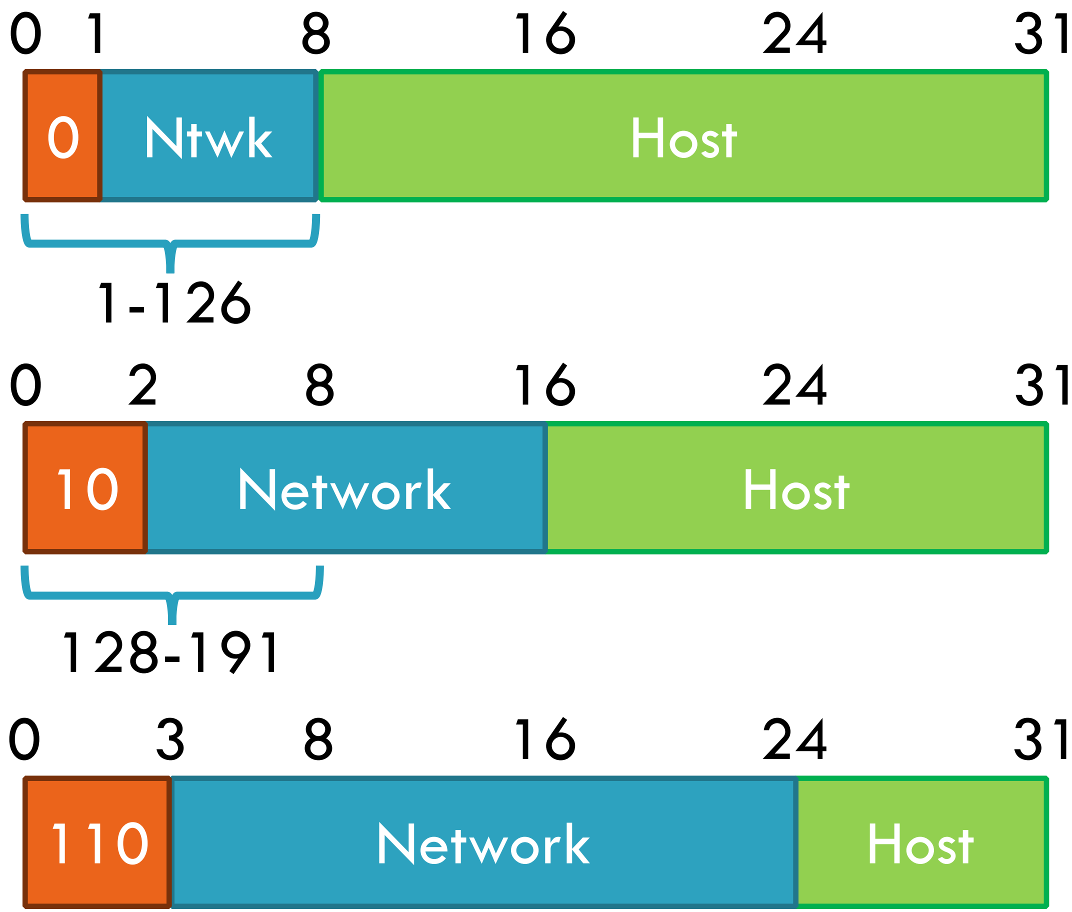
Classes of IP Addresses

- Class A
- Class B
- Class C



Example: MIT
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Example: NEU
129.10.*.*

Example:
216.63.78.*

Classes of IP Addresses

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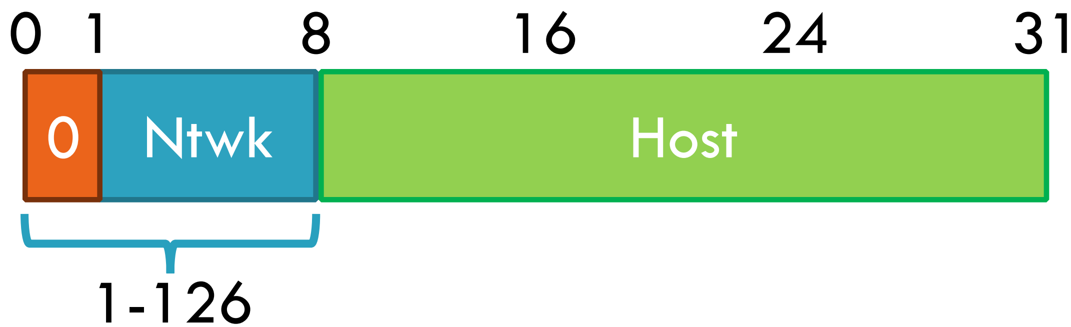
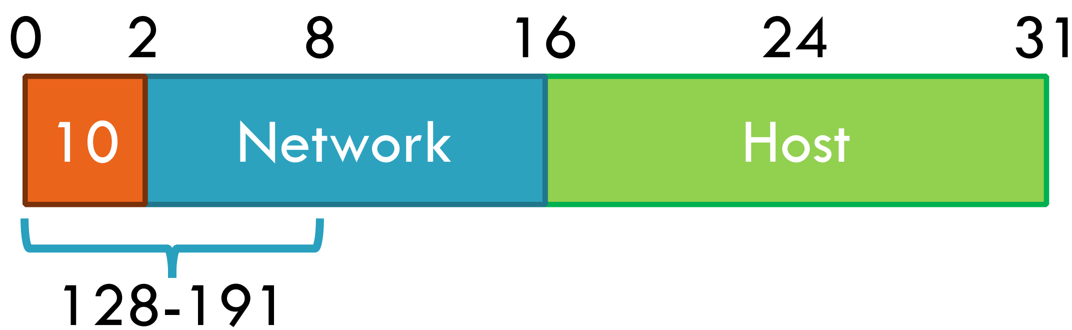


Example: MIT
18.*.*.*

- Class B



Example: NEU
129.10.*.*

- Class C

Example:
216.63.78.*

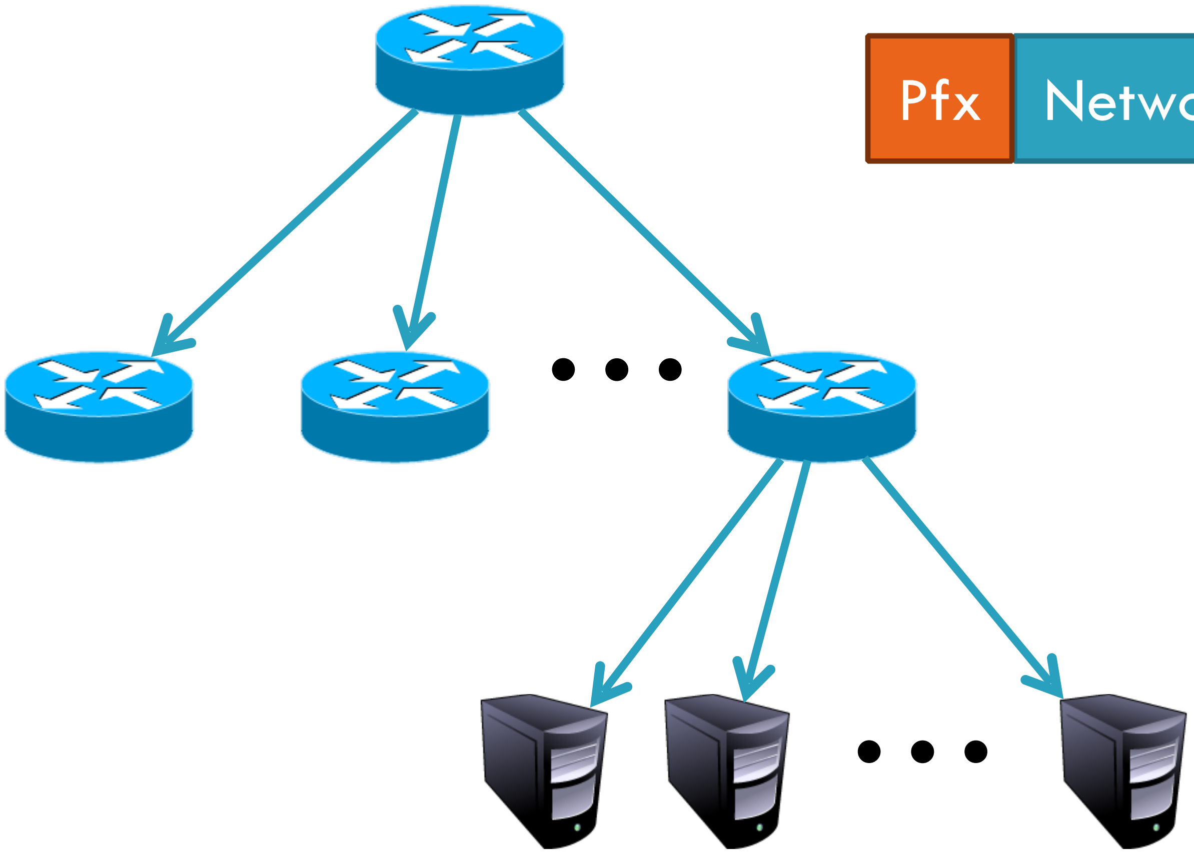
How Do You Get IPs?

- 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



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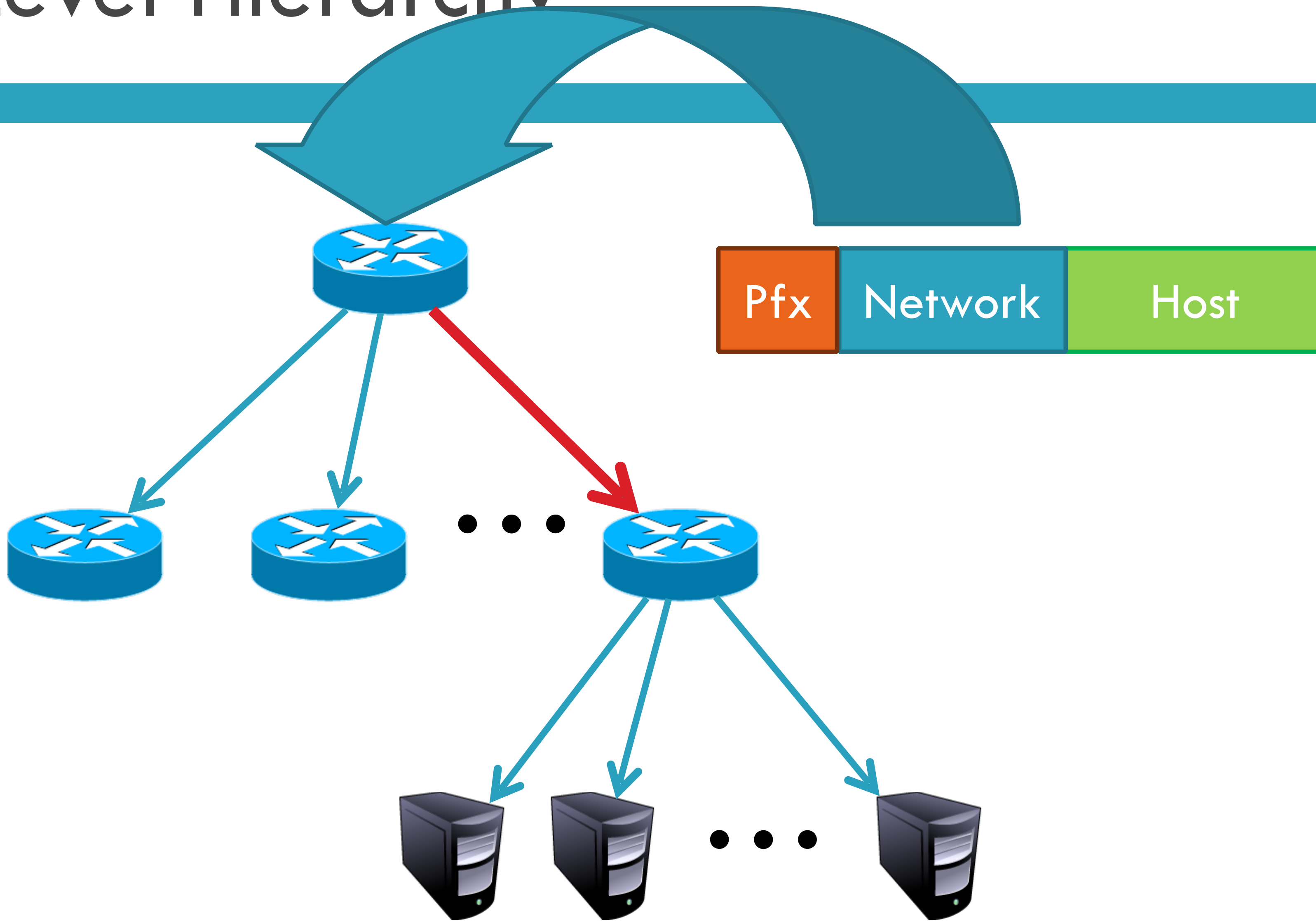

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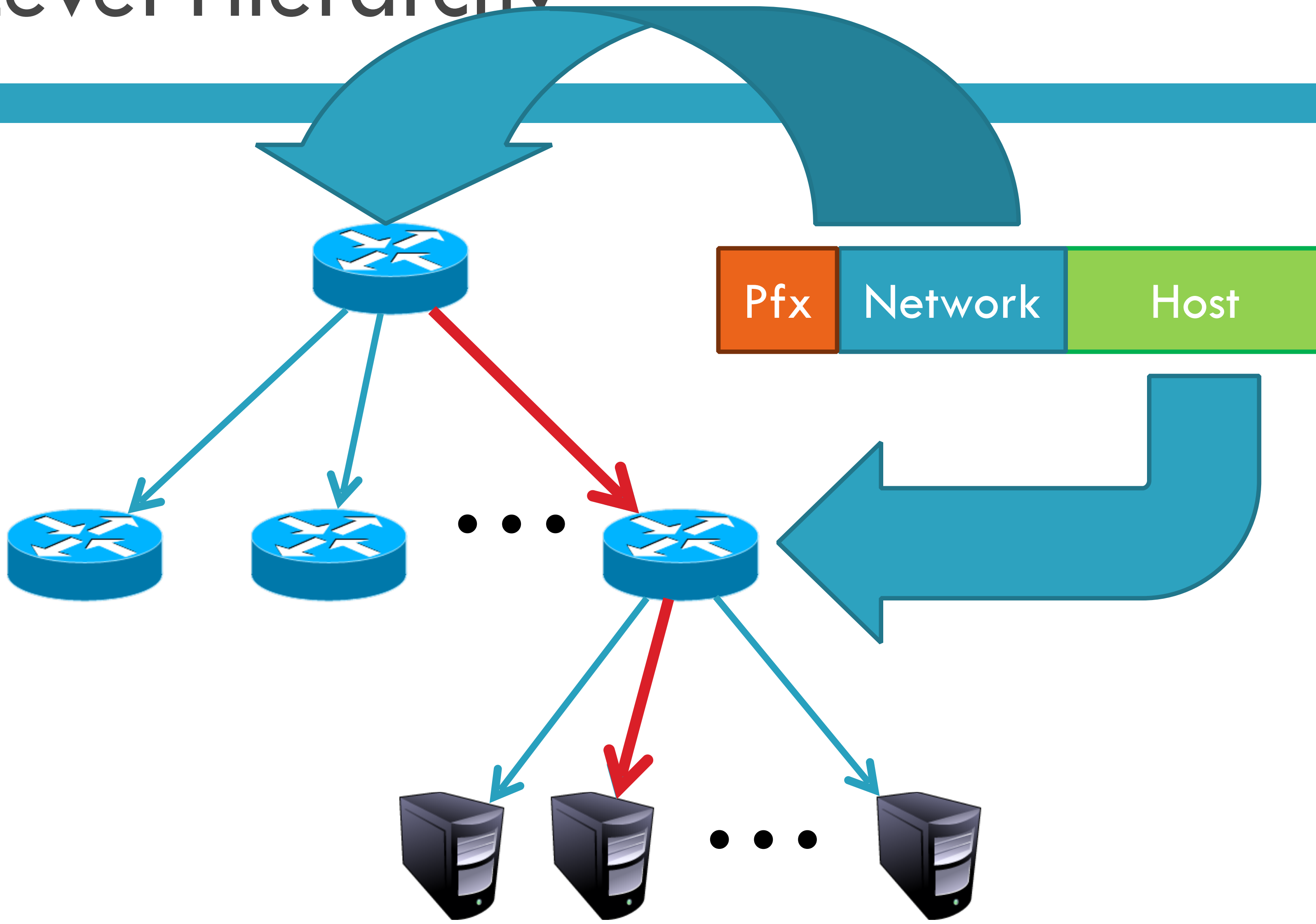

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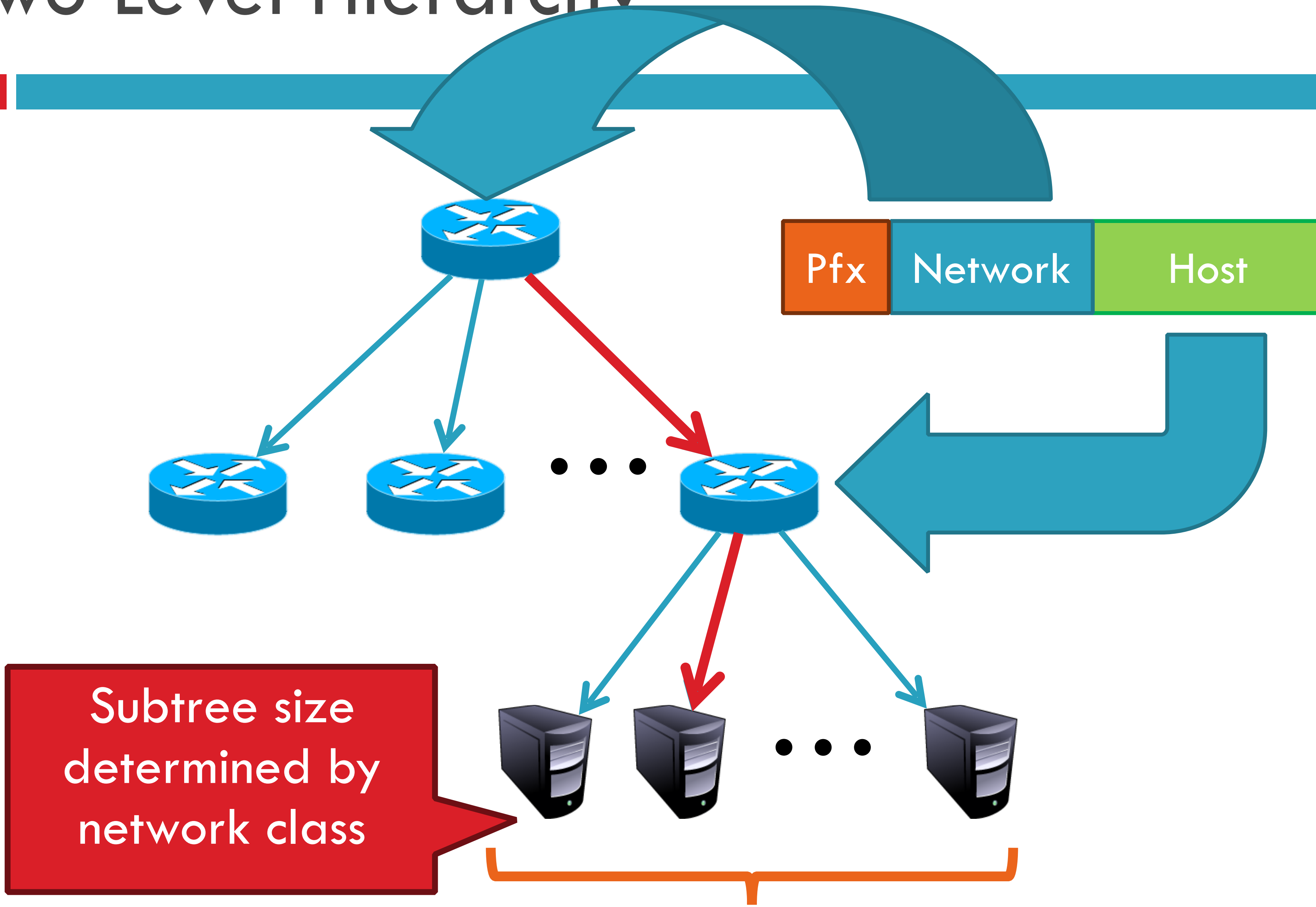

Class Sizes

Class	Prefix Bits	Network Bits	Number of Classes	Hosts 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	

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Too many network IDs

Class Sizes

Way too big

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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

Subnet Example

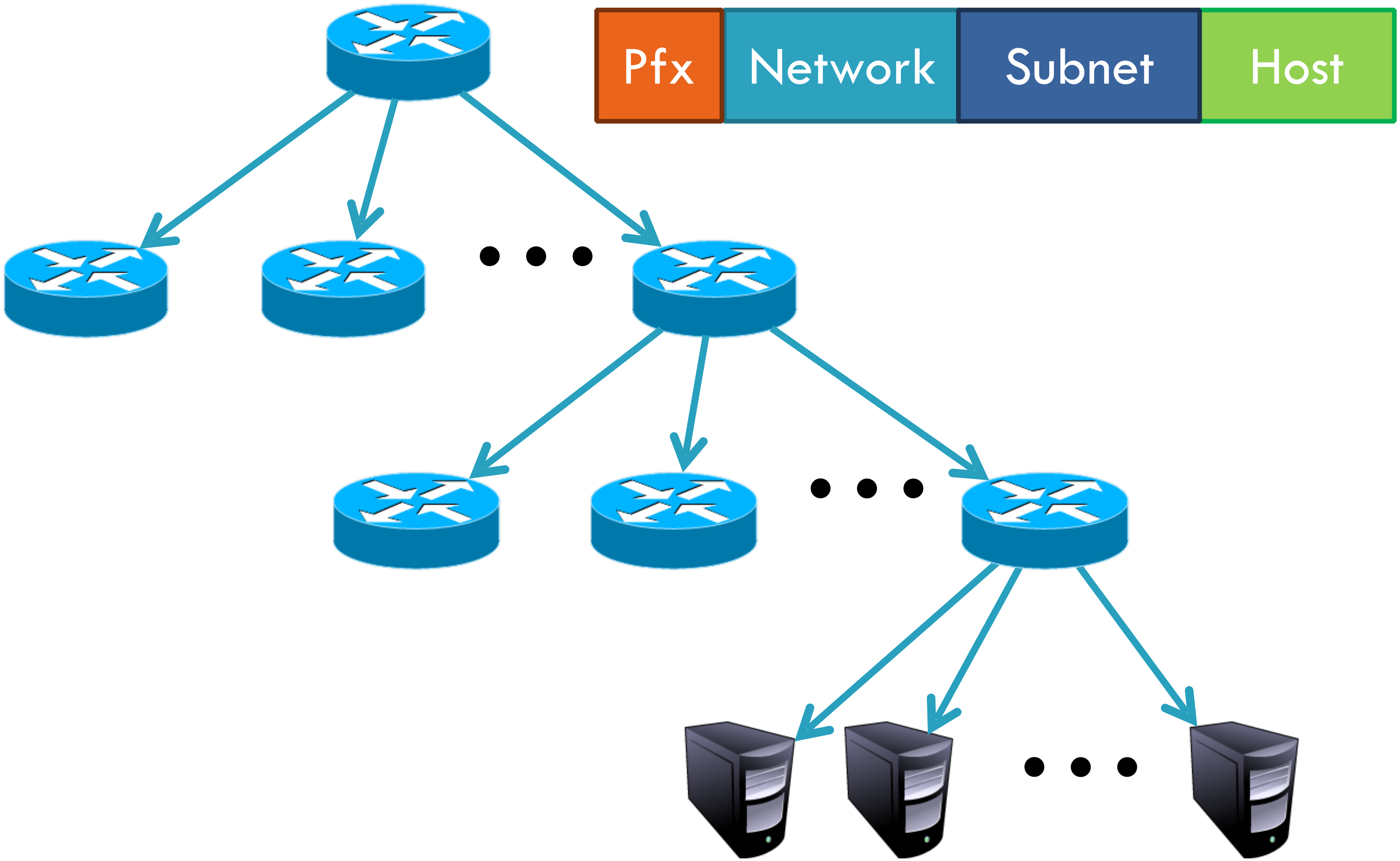
- Extract network:

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



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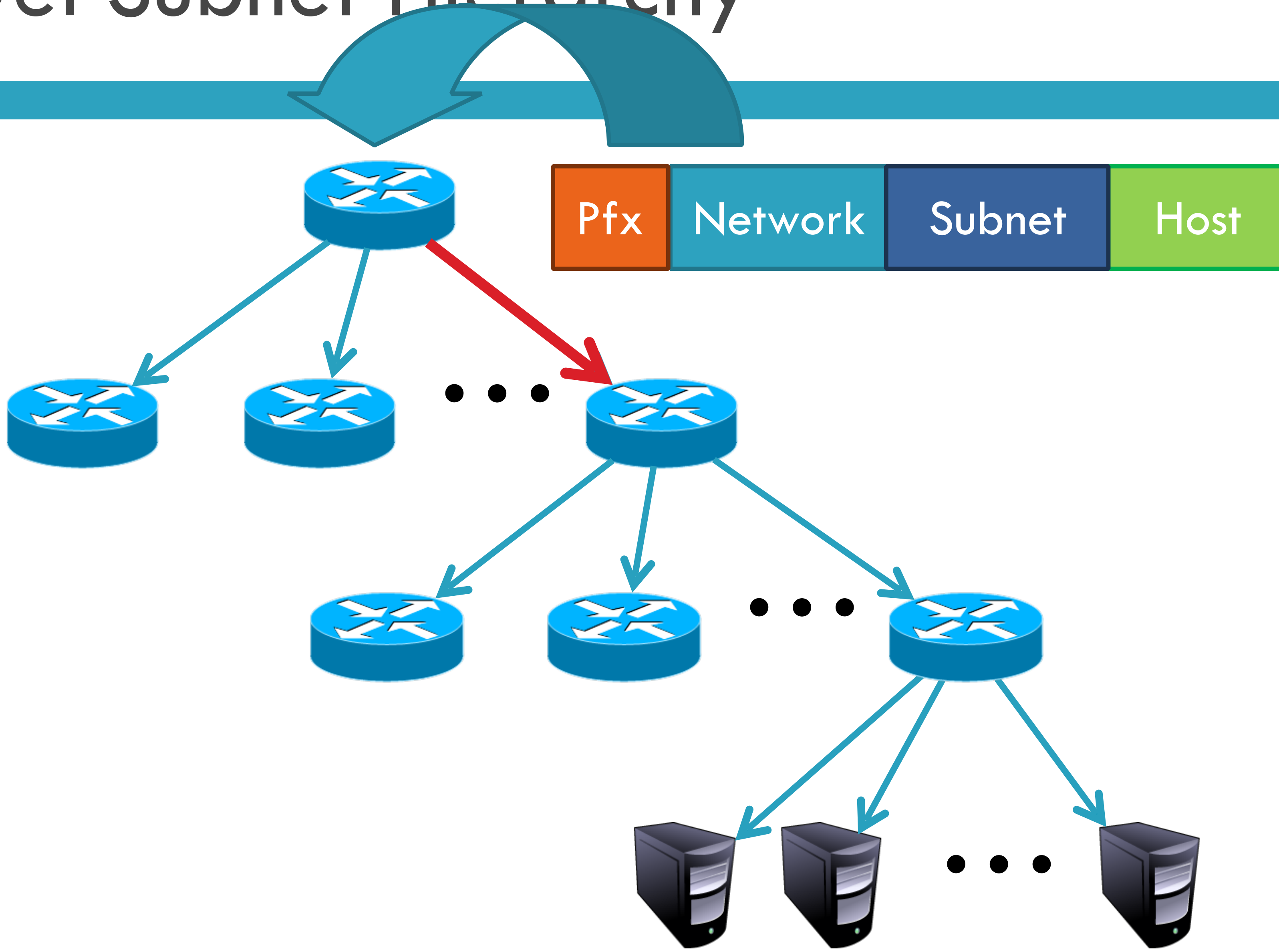
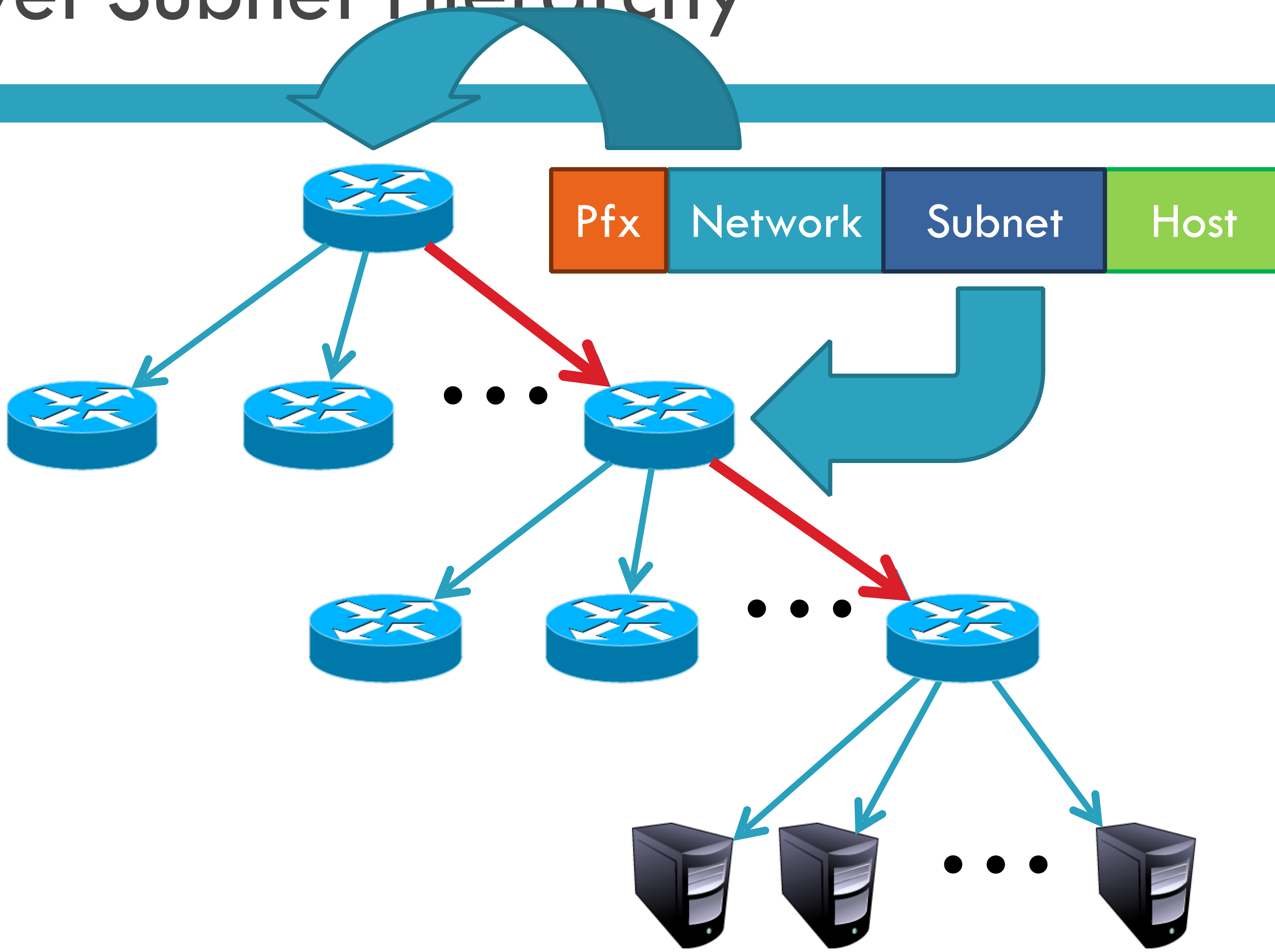


N-Level Subnet Hierarchy



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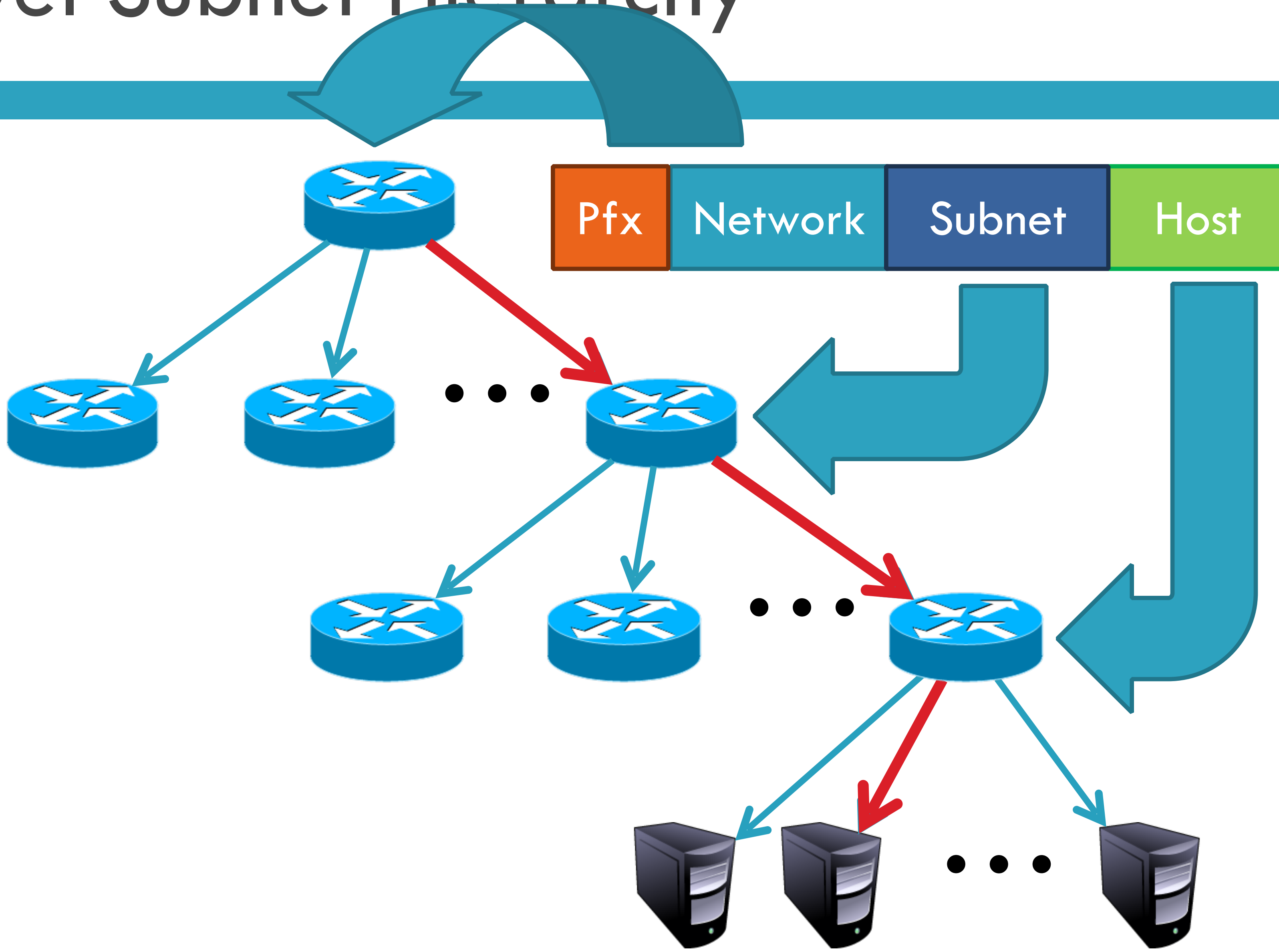

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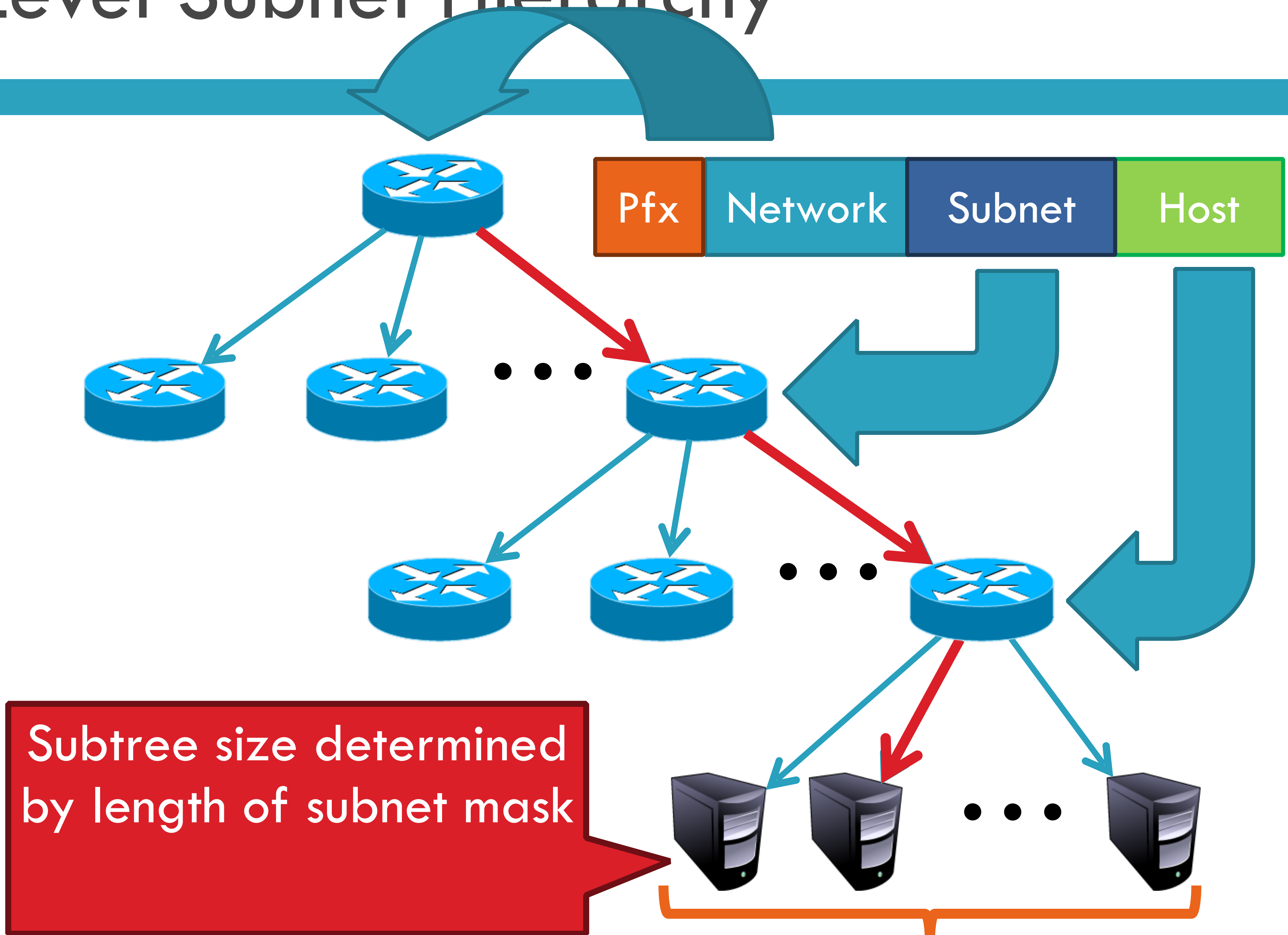

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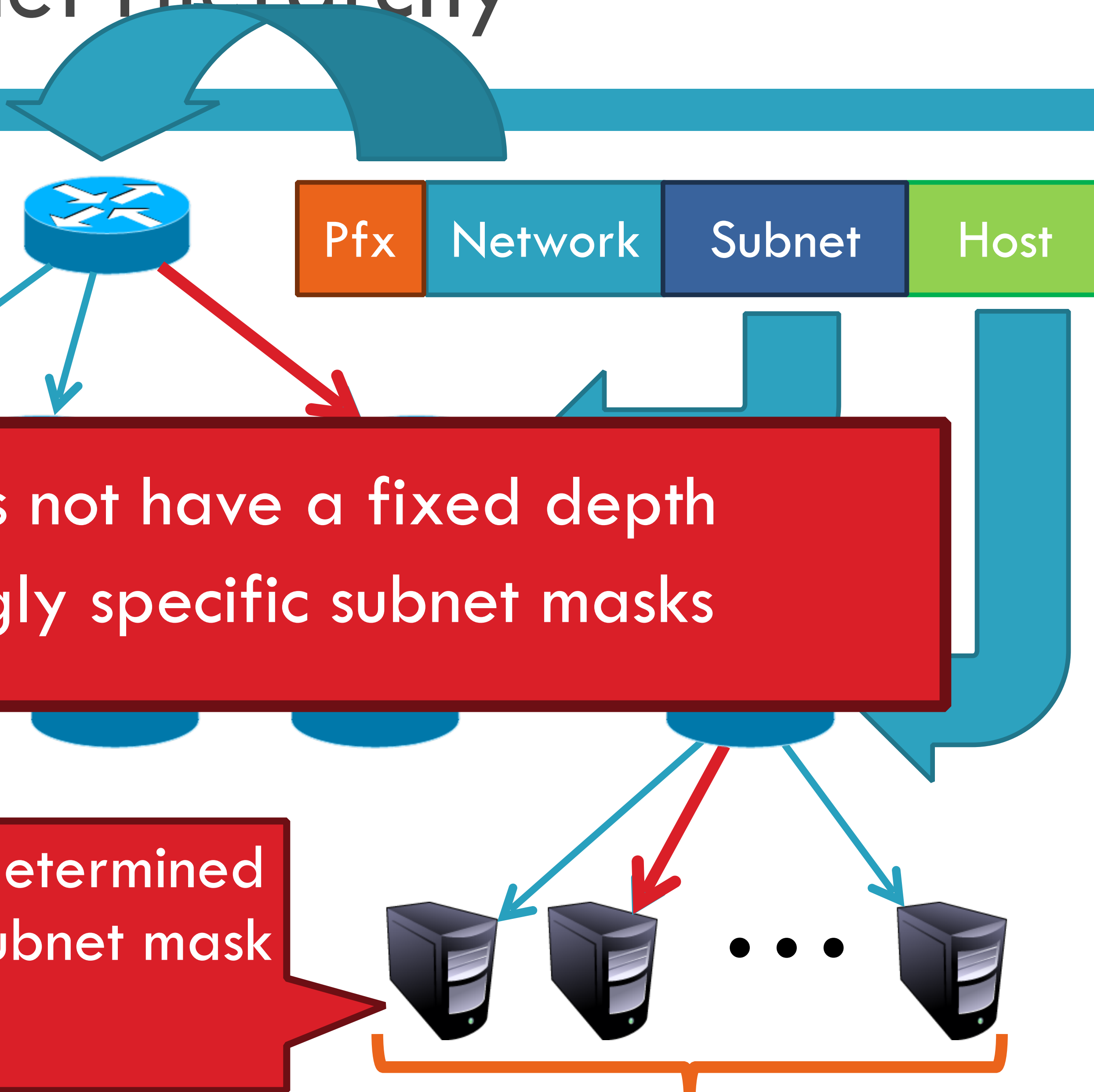

- Tree does not have a fixed depth
- Increasingly specific subnet masks

Subtree size determined by length of subnet mask

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*

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- Question: 128.42.222.198 matches four rows
  - Which router do we forward to?

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- 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?

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- 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

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)

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: Northeastern
    - 129.10.0.0 with netmask 255.255.0.0
    - 129.10.0.0 / 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

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0 8 16 24 31

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

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	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

Example CIDR Routing Table

Address	Netmask	Third Byte	Byte Range
207.46.0.0	*19*	*000xxxxx*	*0 – 31*
207.46.32.0	*19*	*001xxxxx*	*32 – 63*
207.46.64.0	*19*	*010xxxxx*	*64 – 95*
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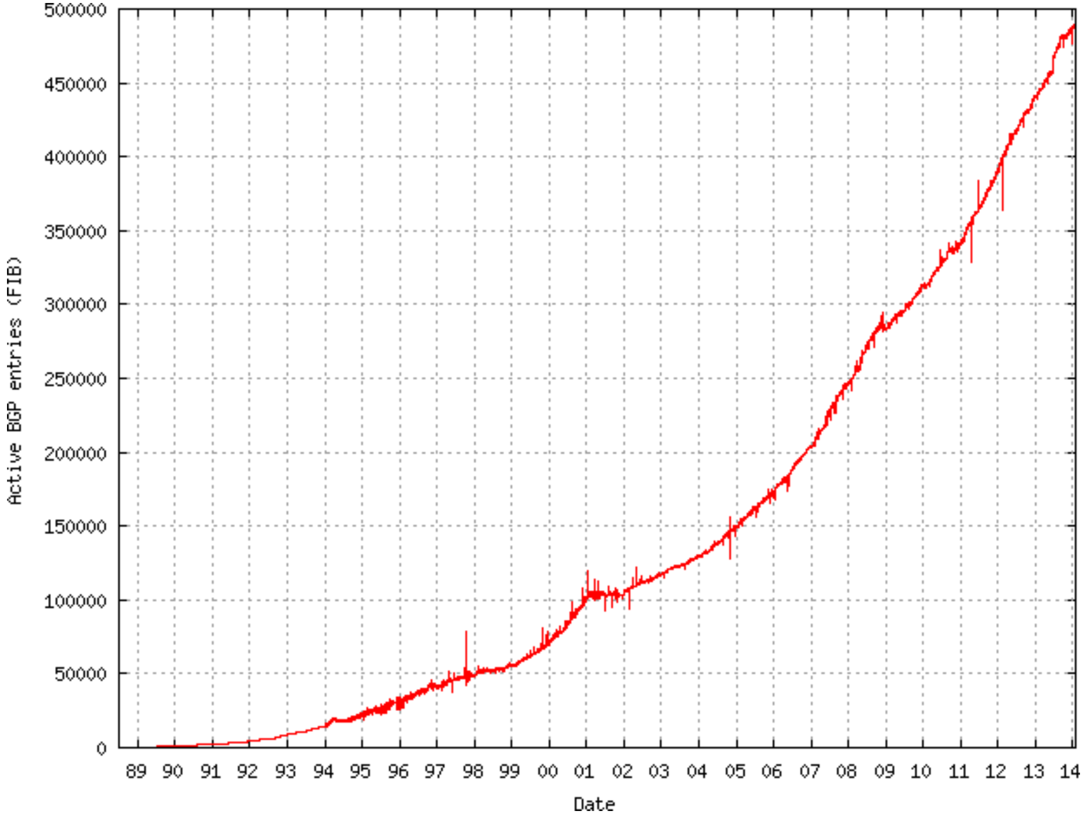
Hole in the Routing Table: No coverage for 96 – 127
207.46.96.0/19

Size of CIDR Routing Tables



- From www.cidr-report.org
- CIDR has kept IP routing table sizes in check
  - Currently ~450,000 entries for a complete IP routing table
  - Only required by backbone routers

Takeaways

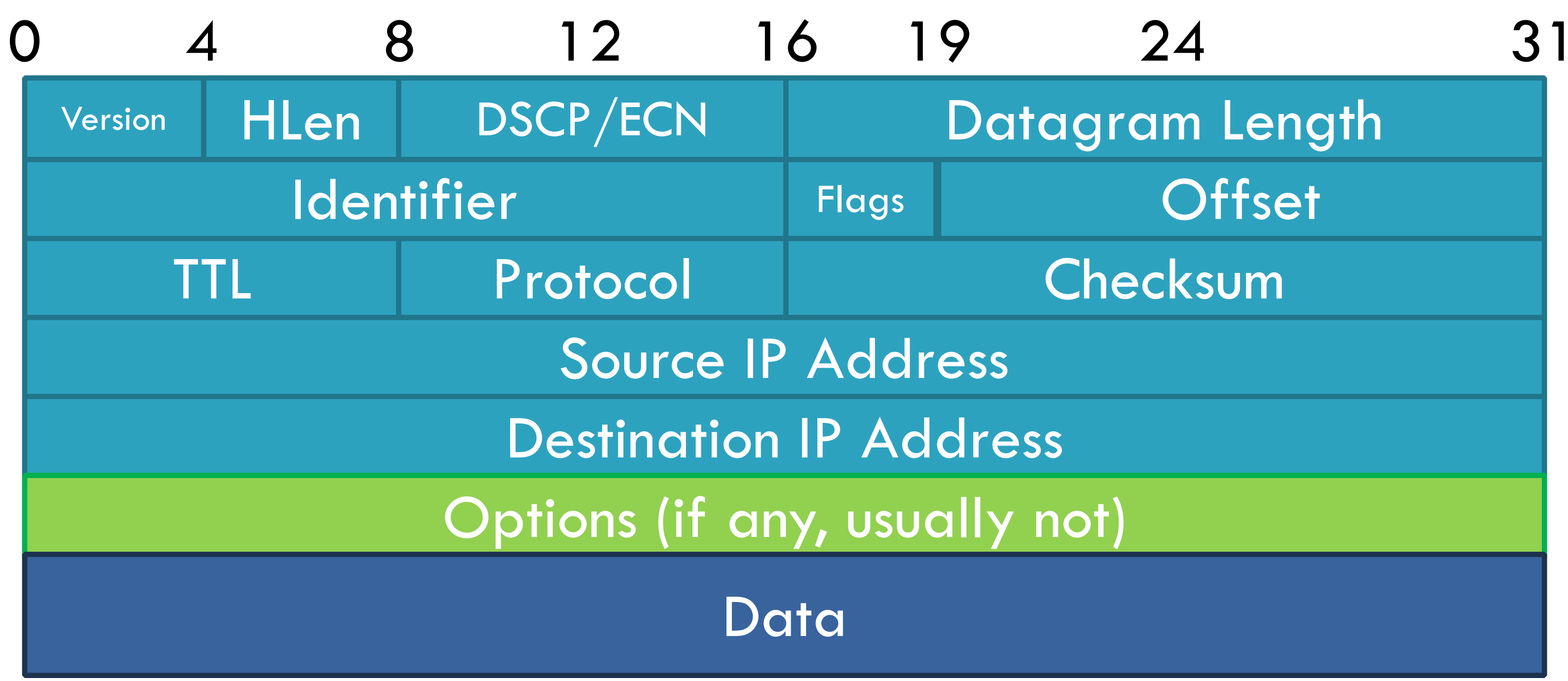
- Hierarchical addressing is critical for scalability
  - Not all routers need all information
  - Limited number of routers need to know about changes
- Non-uniform hierarchy useful for heterogeneous networks
  - Class-based addressing is too course
  - CIDR improves scalability and granularity
- Implementation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

Outline

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

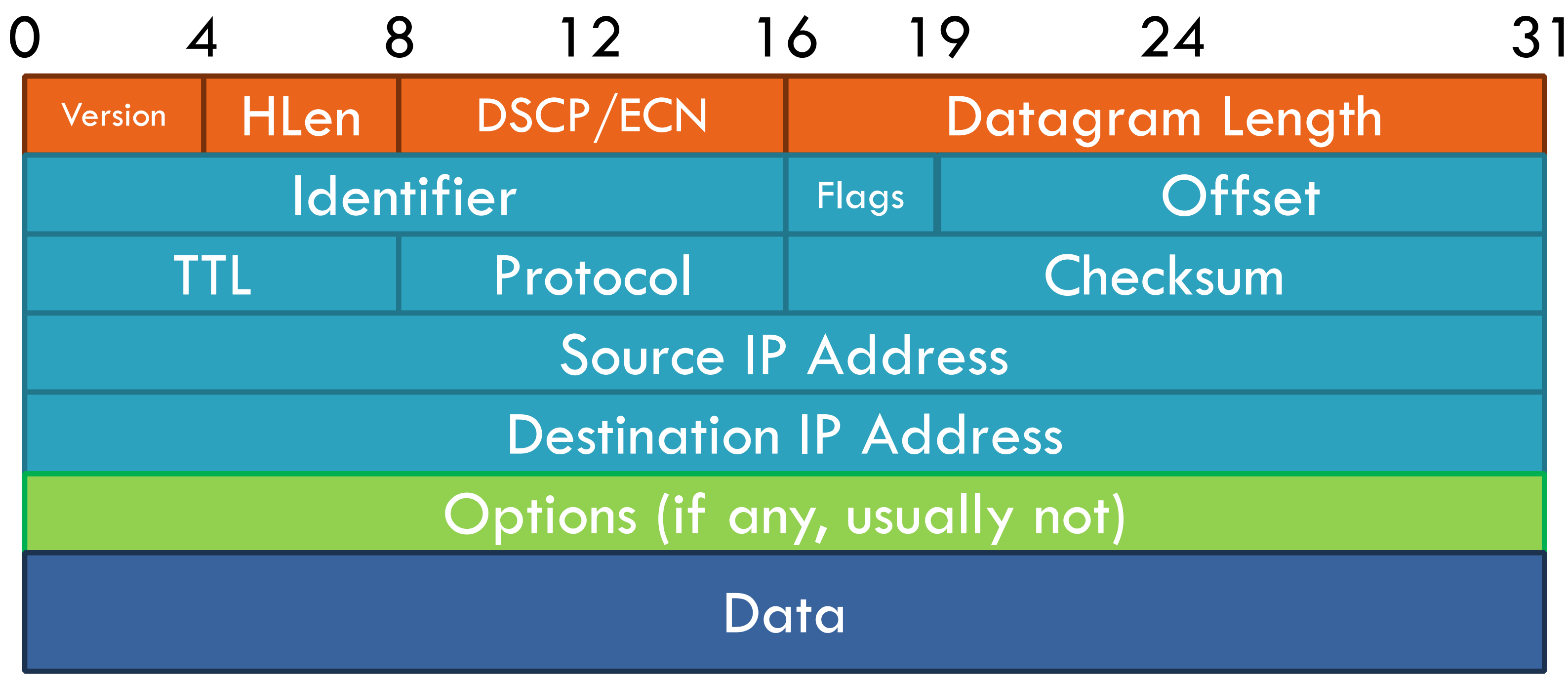
IP Datagrams

- 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



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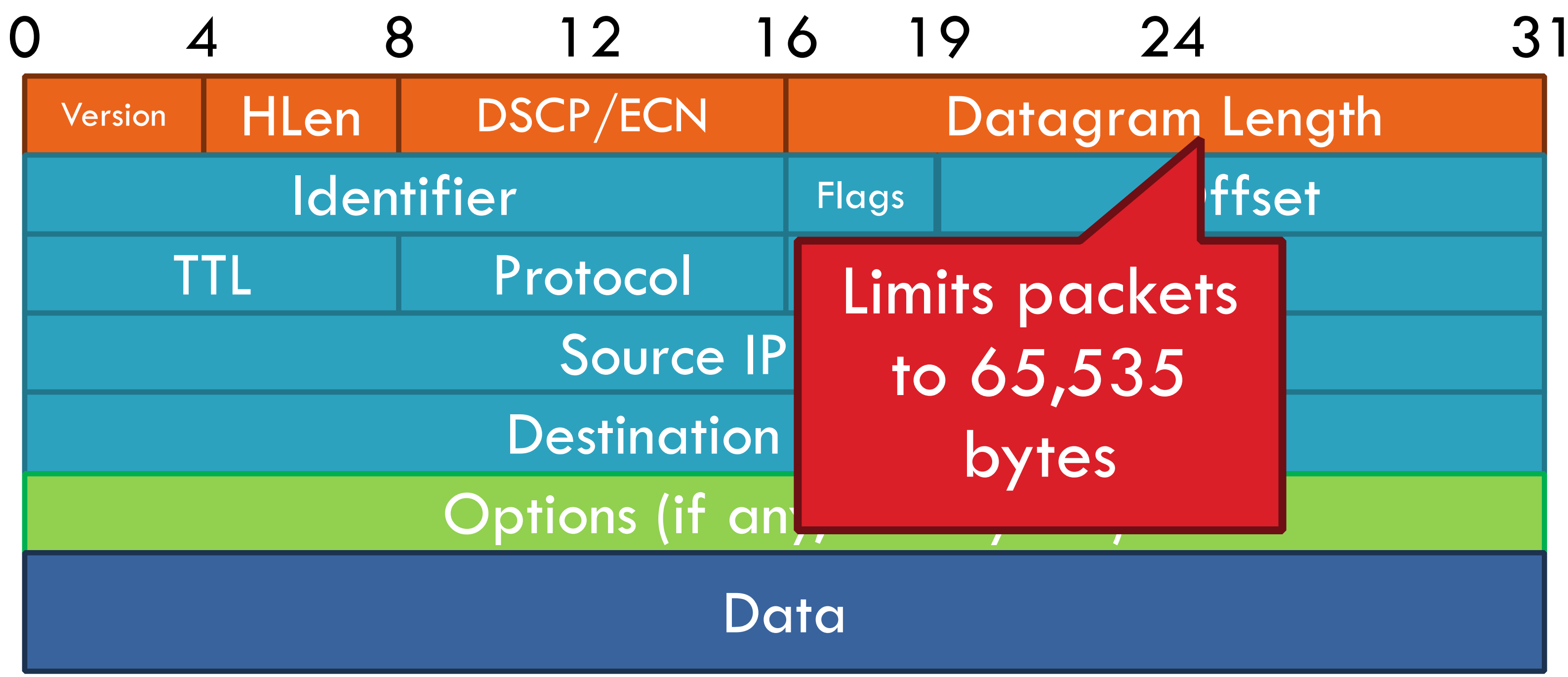
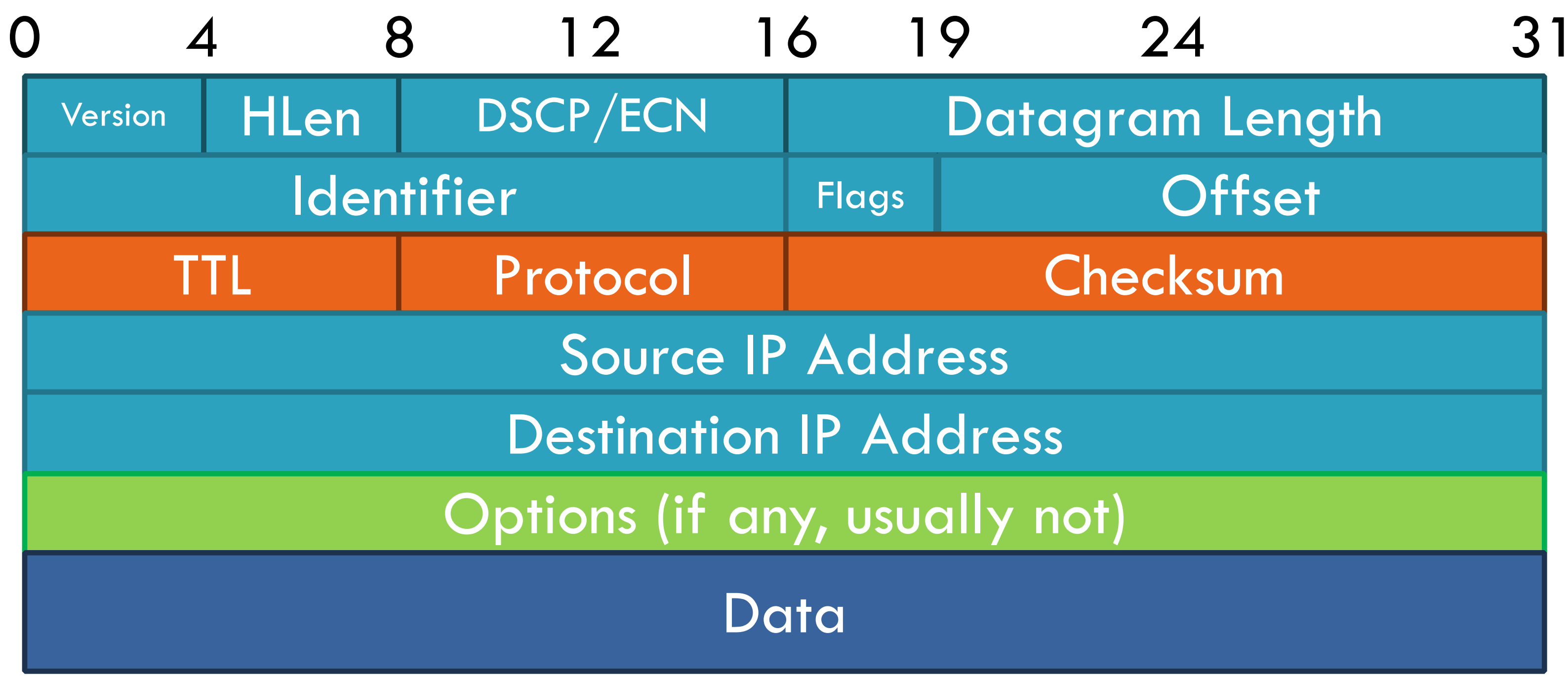


IP Header Fields: Word 3

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



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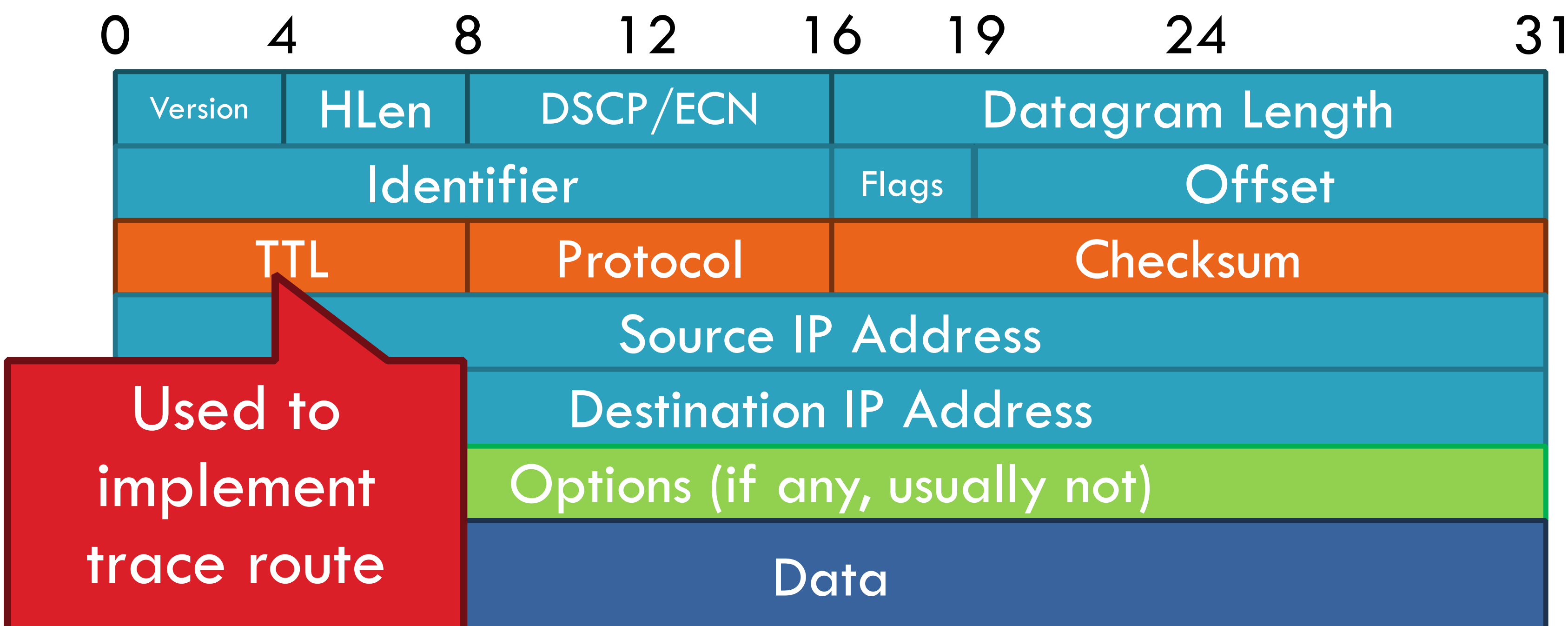
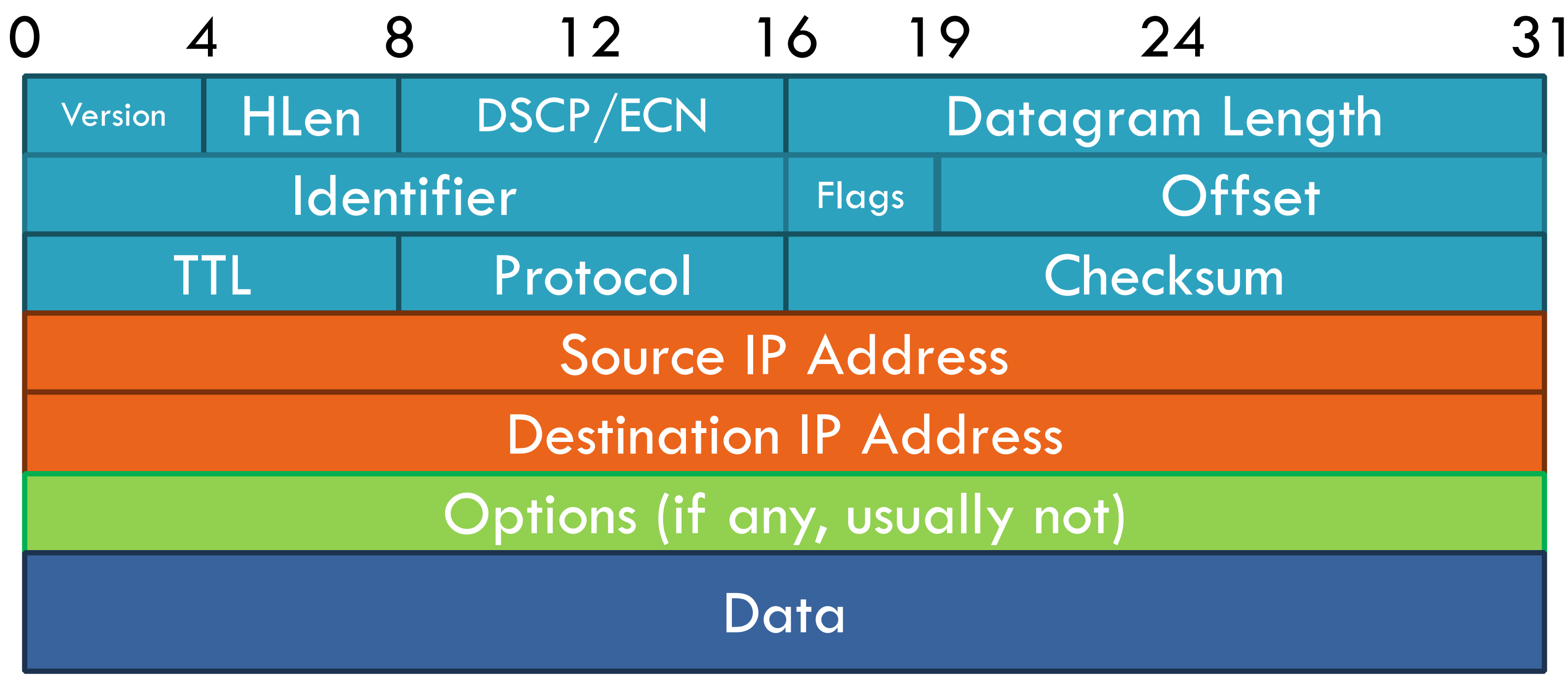
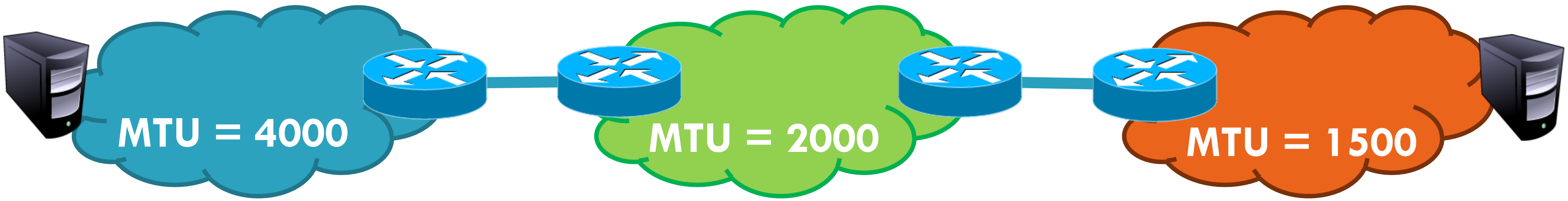


IP Header Fields: Word 4 and 5

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



Problem: Fragmentation



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  - Minimum MTU may not be known for a given path

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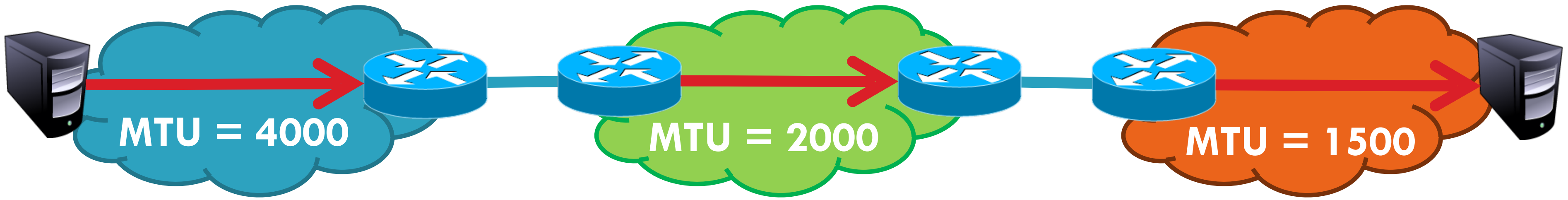

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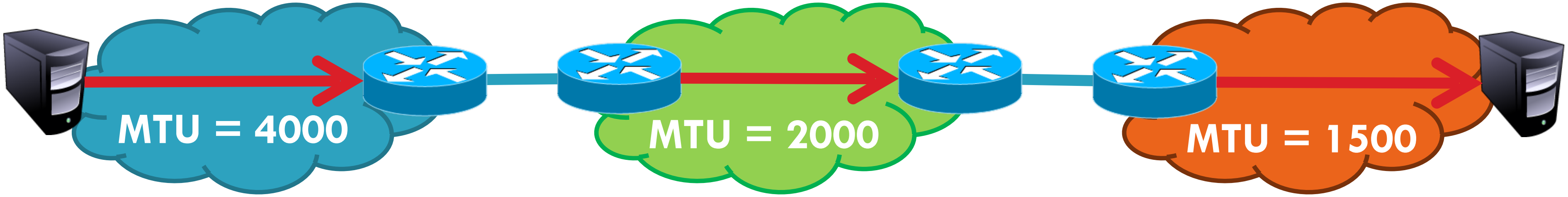

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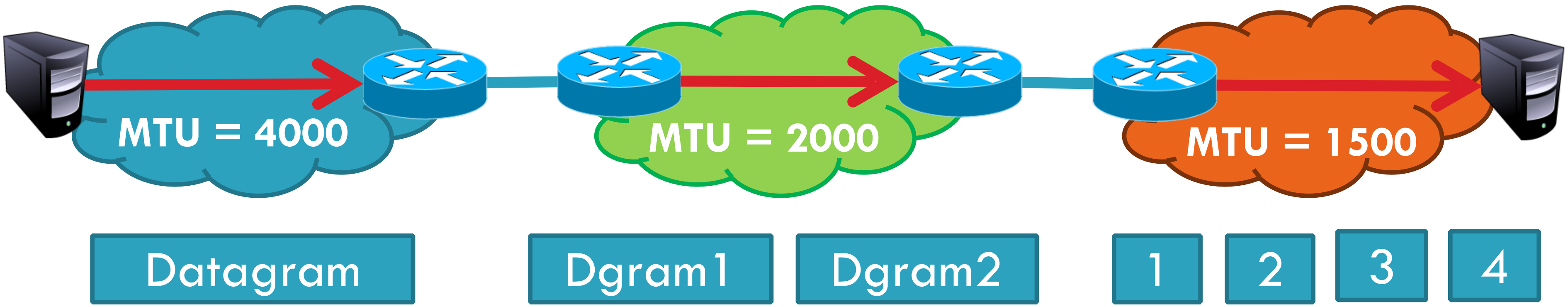

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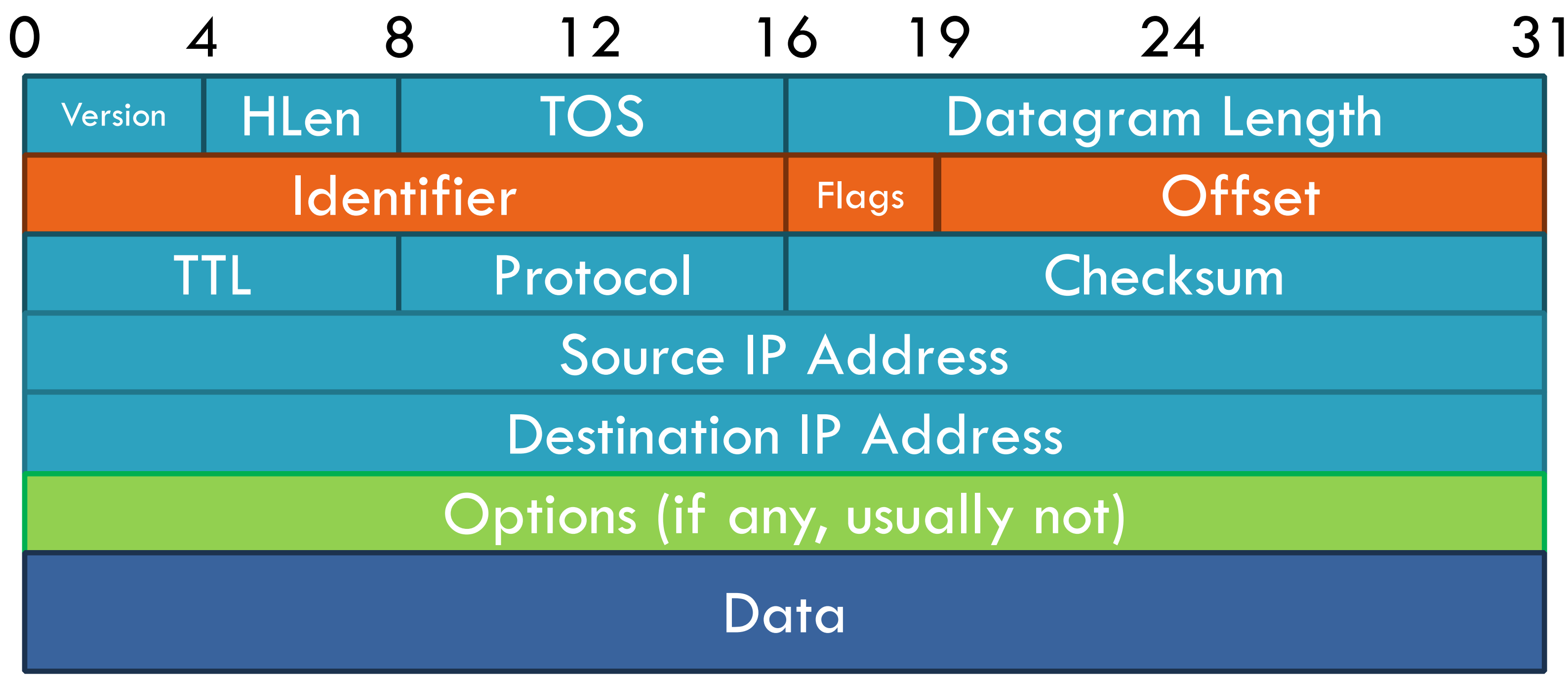
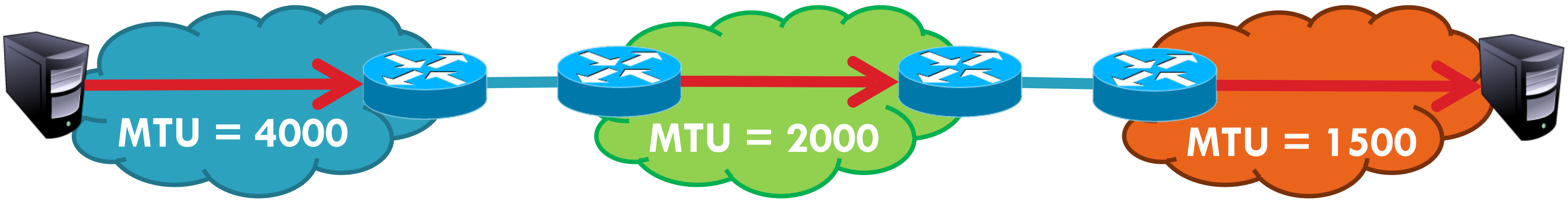
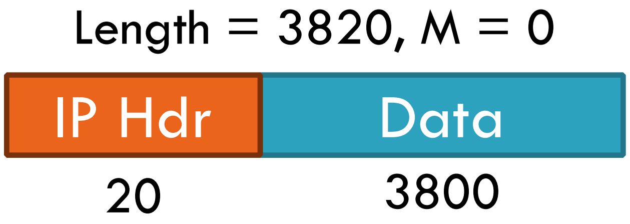
IP Header Fields: Word 2

- 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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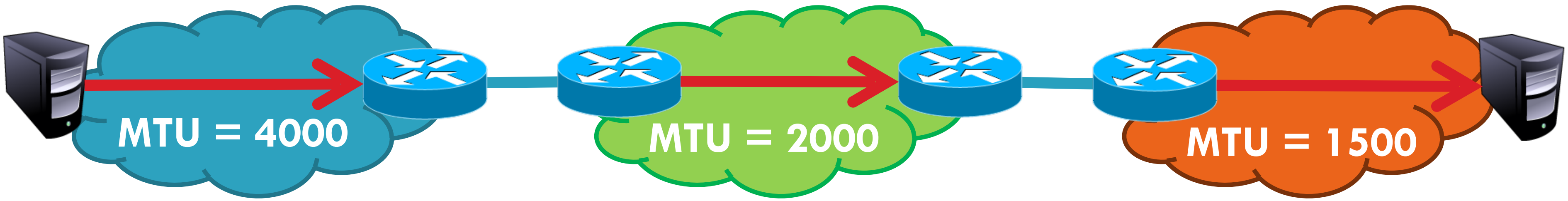


Length = 3820, M = 0

IP Hdr	Data
20	3800

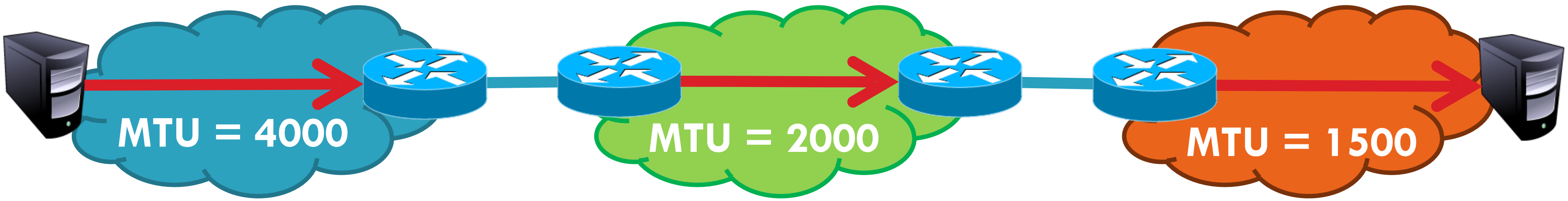
Length = 2000, M = 1
Offset = 0

IP	Data
20	1980

Length = 1840, M = 0
Offset = 1980

IP	Data
20	1820

Fragmentation Example



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1980
+ 1820
= 3800

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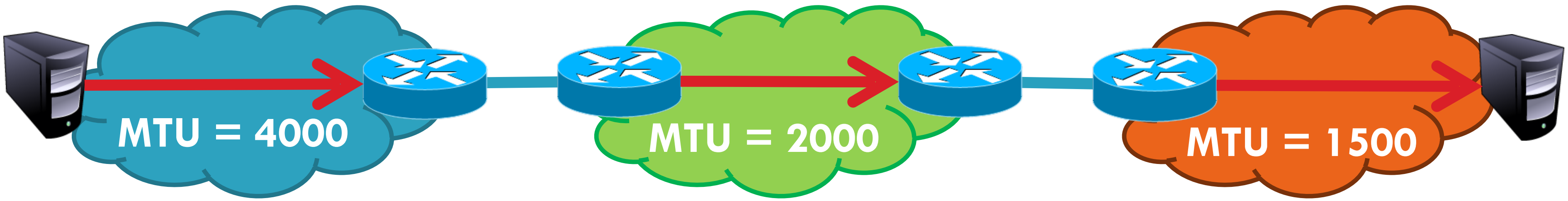


Length = 3820, M = 0

IP Hdr	Data
20	3800

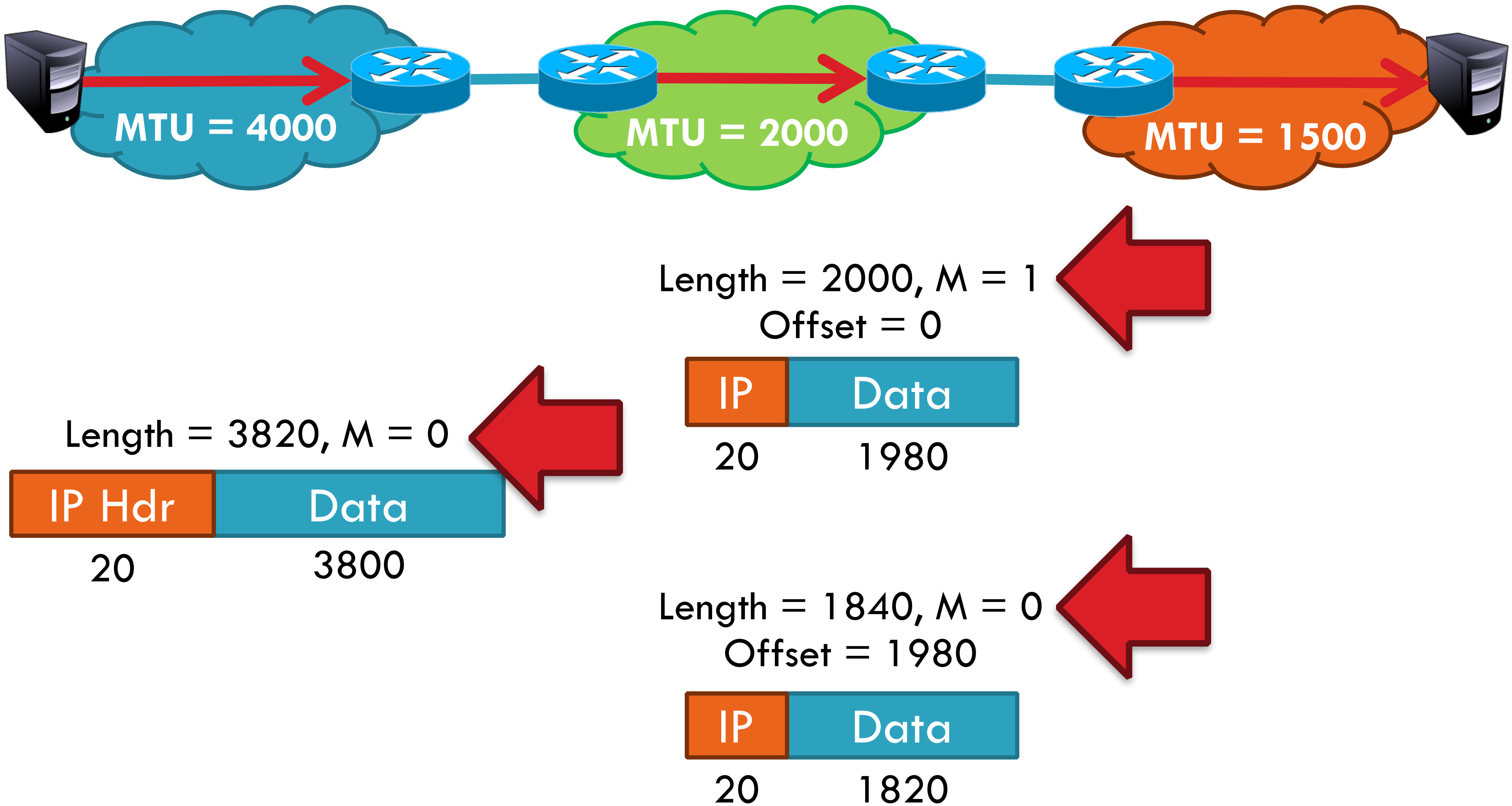
Length = 2000, M = 1
Offset = 0

IP	Data
20	1980

Length = 184[illegible] = 0
Offset = 1980

IP	Data
20	1820

Fragmentation Example



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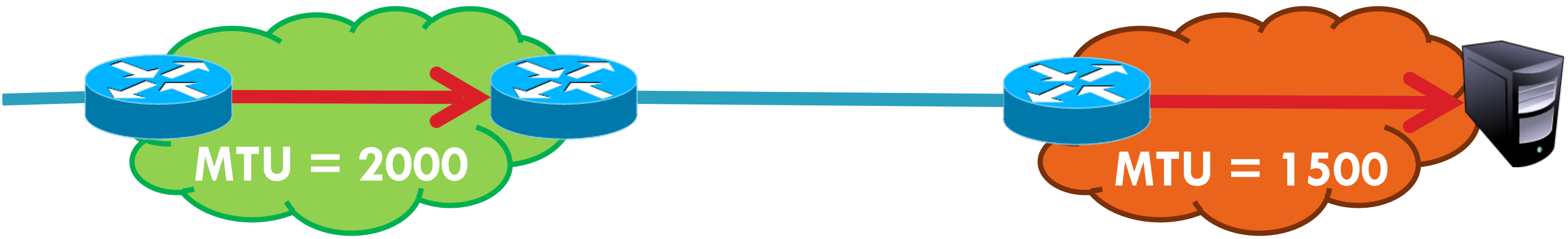


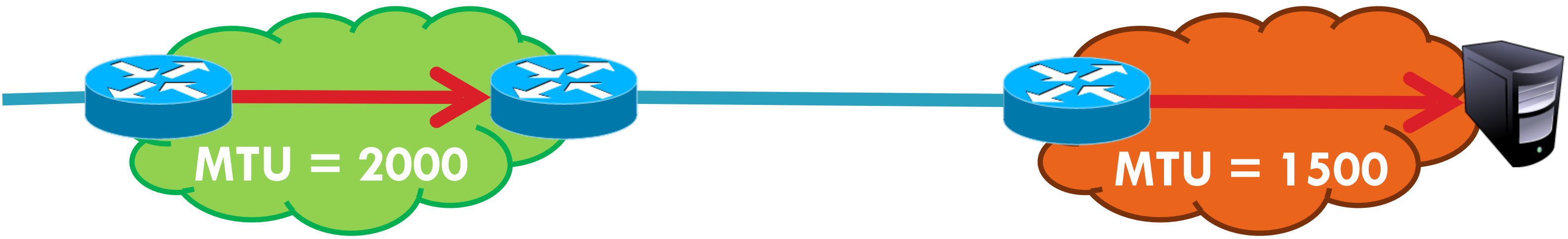
Length = 2000, M = 1
Offset = 0

IP	Data
20	1980

Length = 1840, M = 0
Offset = 1980

IP	Data
20	1820

Fragmentation Example



Length = 2000, M = 1
Offset = 0

IP	Data
20	1980

Length = 1500, M = 1
Offset = 0

IP	Data
20	1480

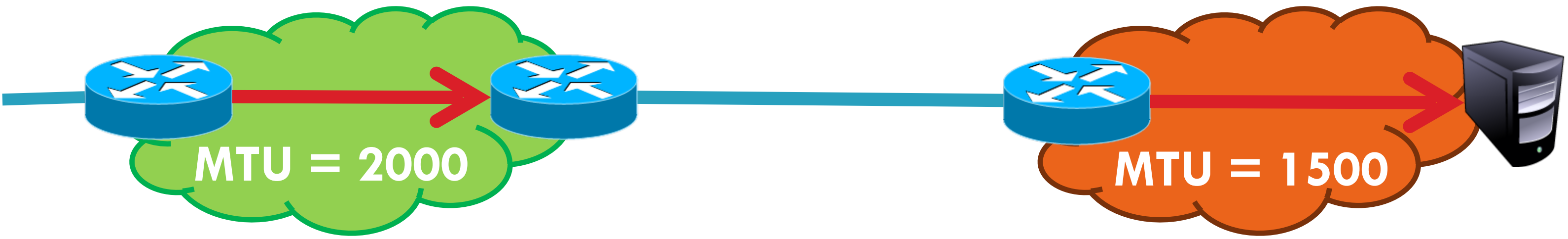
Length = 520, M = 1
Offset = 1480

IP	Data
20	500

Length = 1840, M = 0
Offset = 1980

IP	Data
20	1820

Fragmentation Example



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Length = 520, M = 1
Offset = 1480

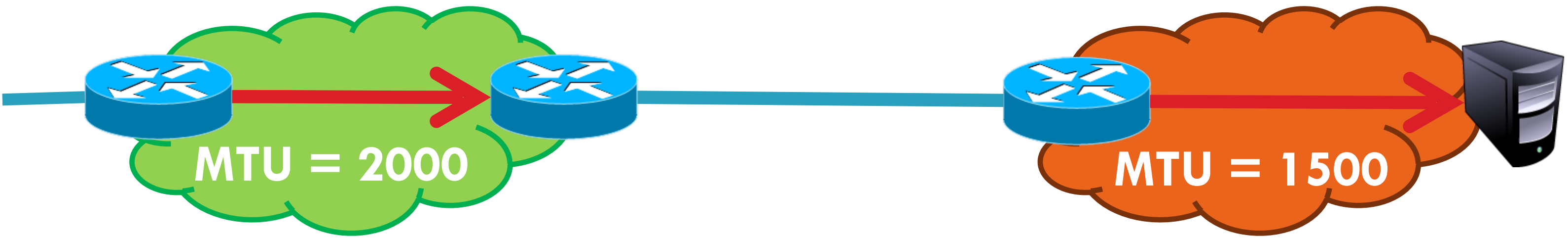
IP	Data
20	500

$$\begin{array}{r} 1480 \\ +\ 500 \\ =\ 1980 \end{array}$$

Length = 1840, M = 0
Offset = 1980

IP	Data
20	1820

Fragmentation Example



Length = 2000, M = 1
Offset = 0

IP	Data
20	1980

Length = 1500, M = 1
Offset = 0

IP	Data
20	1480

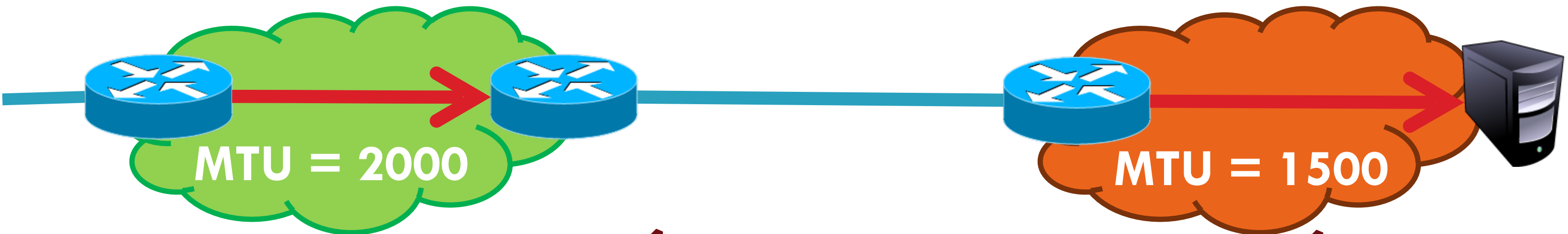
Length = 52 = 1
Offset = 1480

IP	Data
20	500

Length = 1840, M = 0
Offset = 1980

IP	Data
20	1820

Fragmentation Example



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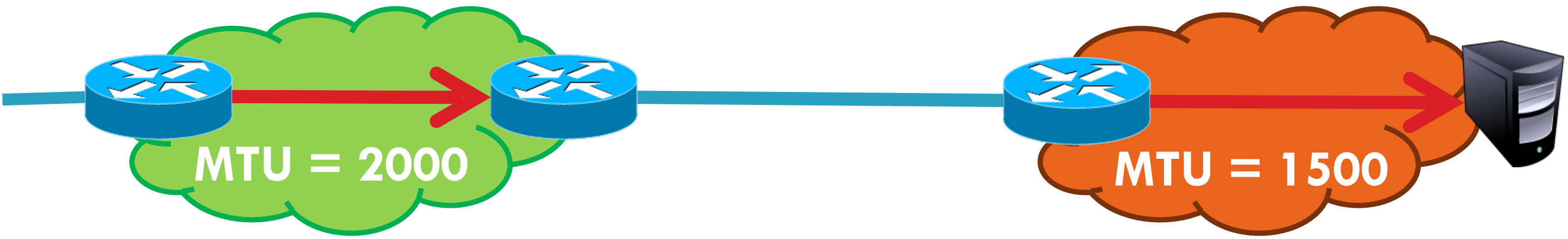

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IP	Data
20	1480

Length = 520, M = 1
Offset = 1480

IP	Data
20	500

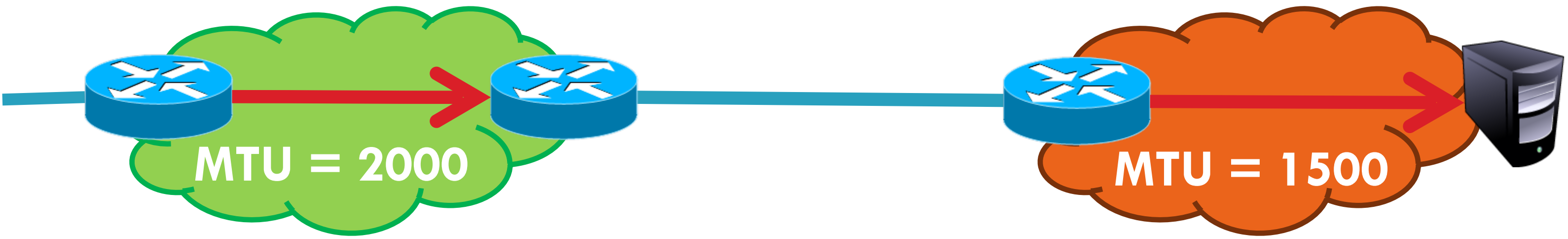
Length = 1500, M = 1
Offset = 1980

IP	Data
20	1480

Length = 360, M = 0
Offset = 3460

IP	Data
20	340

Fragmentation Example



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Offset = 3460

IP	Data
20	340

Length = 520, M = 1
Offset = 1480

IP	Data
20	500

Length = 1840, M = 0
Offset = 1980

IP	Data
20	1820

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

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- Challenges:
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  - Duplicate fragments
  - Missing fragments

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- 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
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  - 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

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

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 ':'

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  - 8 groups of 16-bit values, separated by ':'
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IPv6

- IPv6, first introduced in 1998(!)
  - 128-bit addresses
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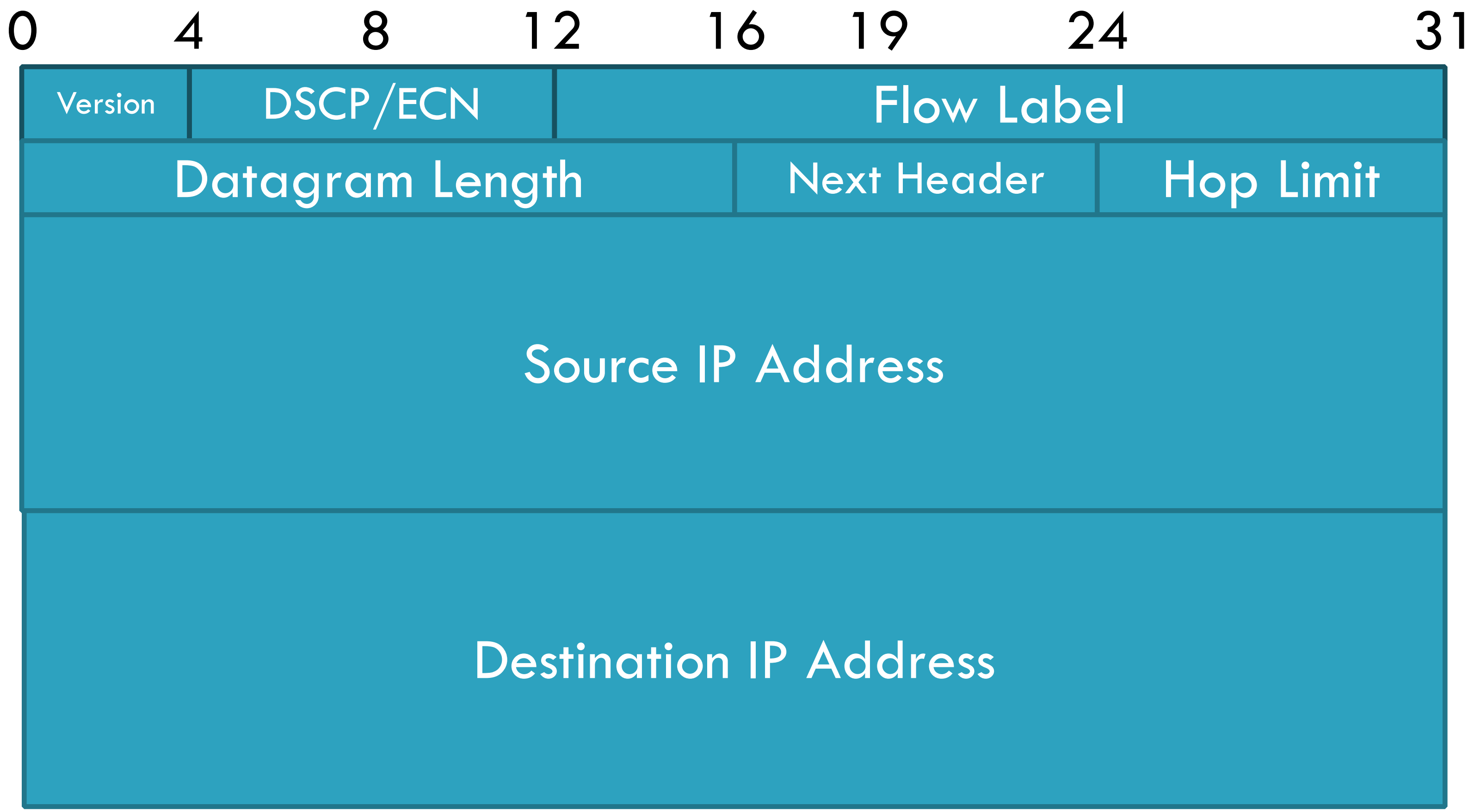
  - ::1

IPv6 Header

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



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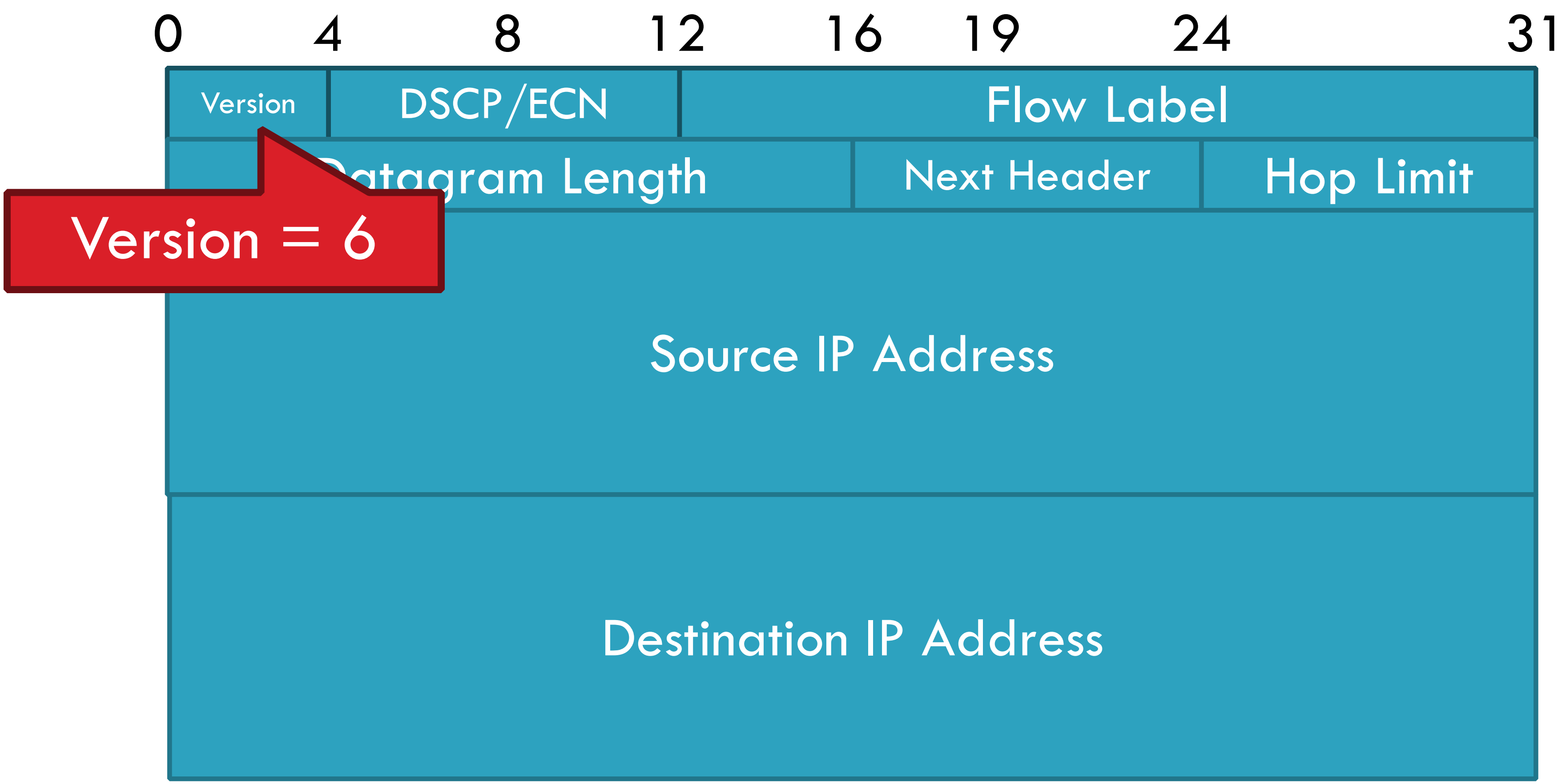

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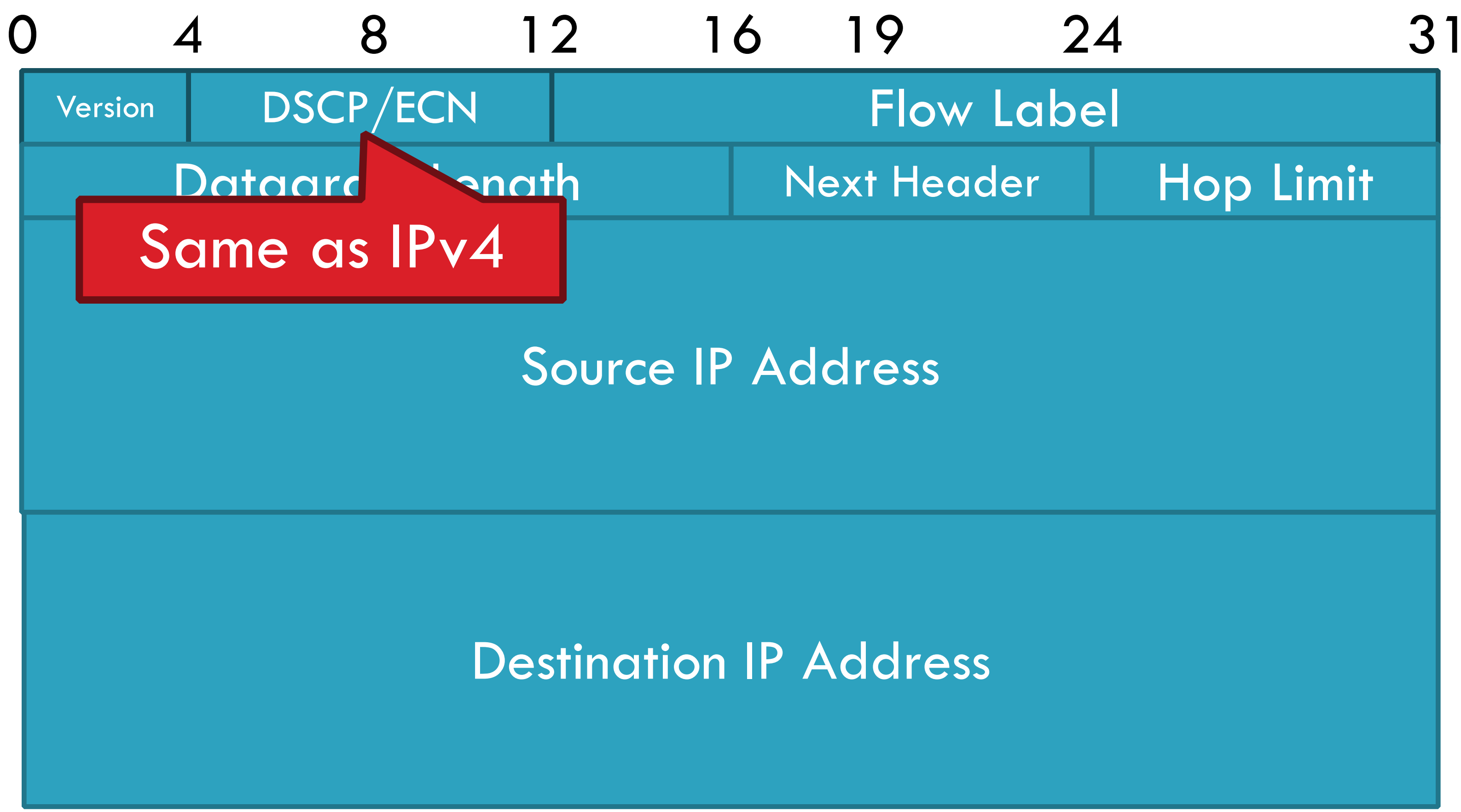

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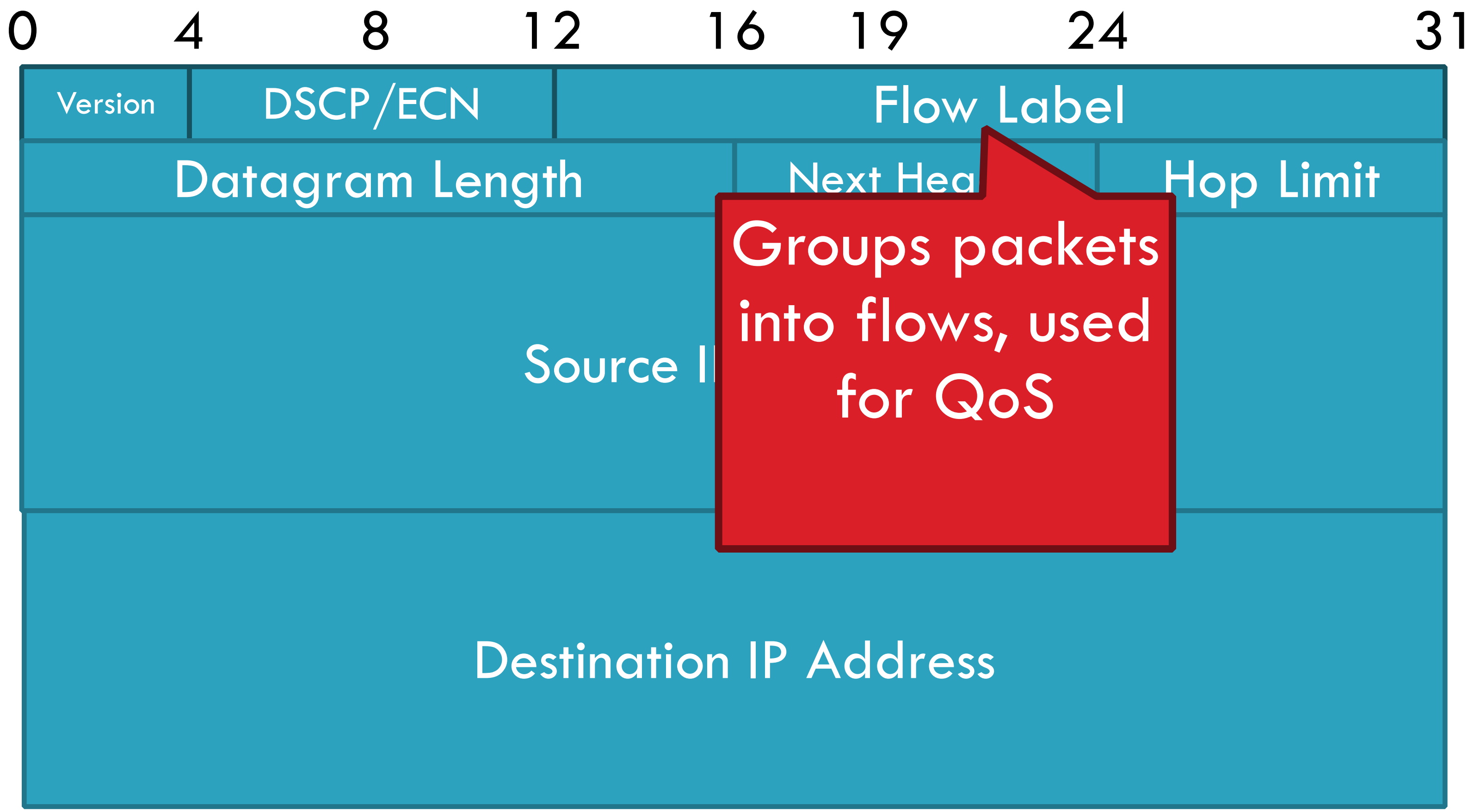

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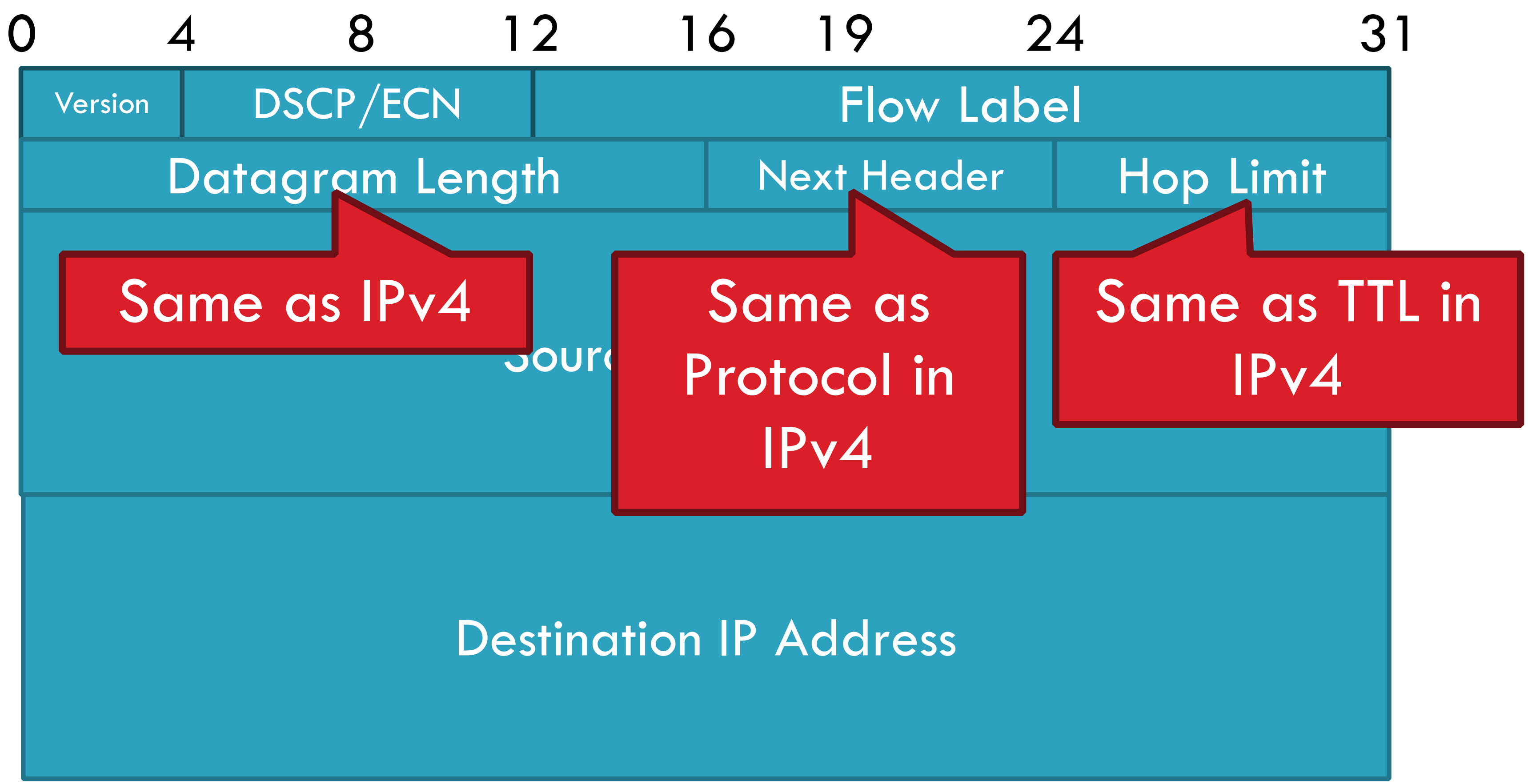

Differences from IPv4 Header

- 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
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  - 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
- No security vulnerabilities due to IP fragments

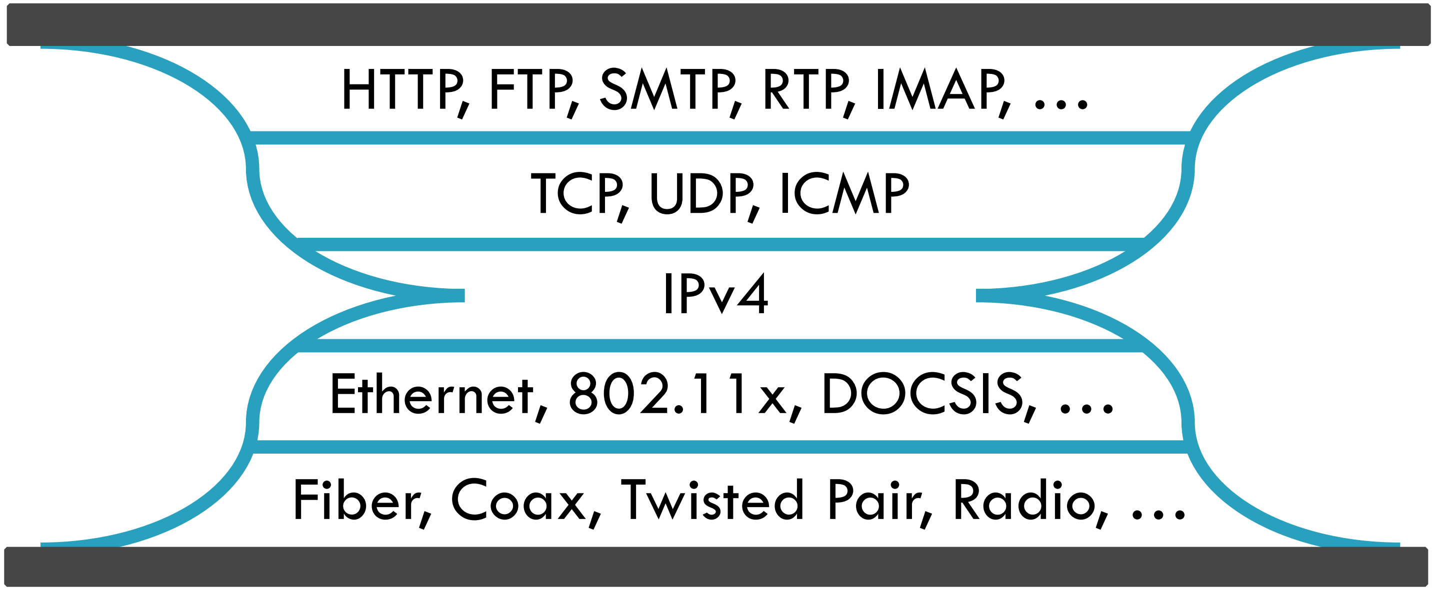
Performance Improvements

- 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

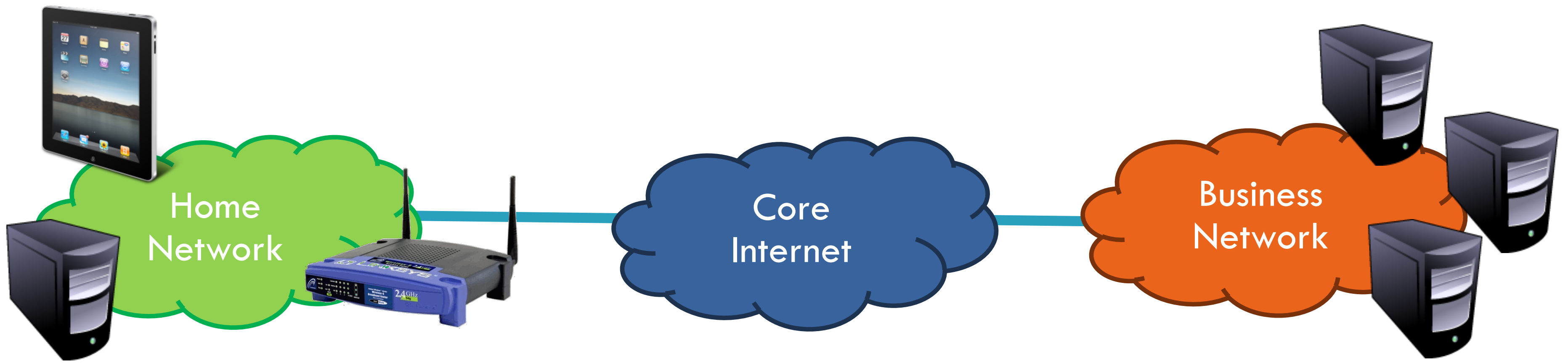
- Source Routing
  - Host specifies the route to wants packet to take
- Mobile IP
  - Hosts can take their IP with them to other networks
  - Use source routing to direct packets
- Privacy Extensions
  - Randomly generate host identifiers
  - Make it difficult to associate one IP to a host
- Jumbograms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



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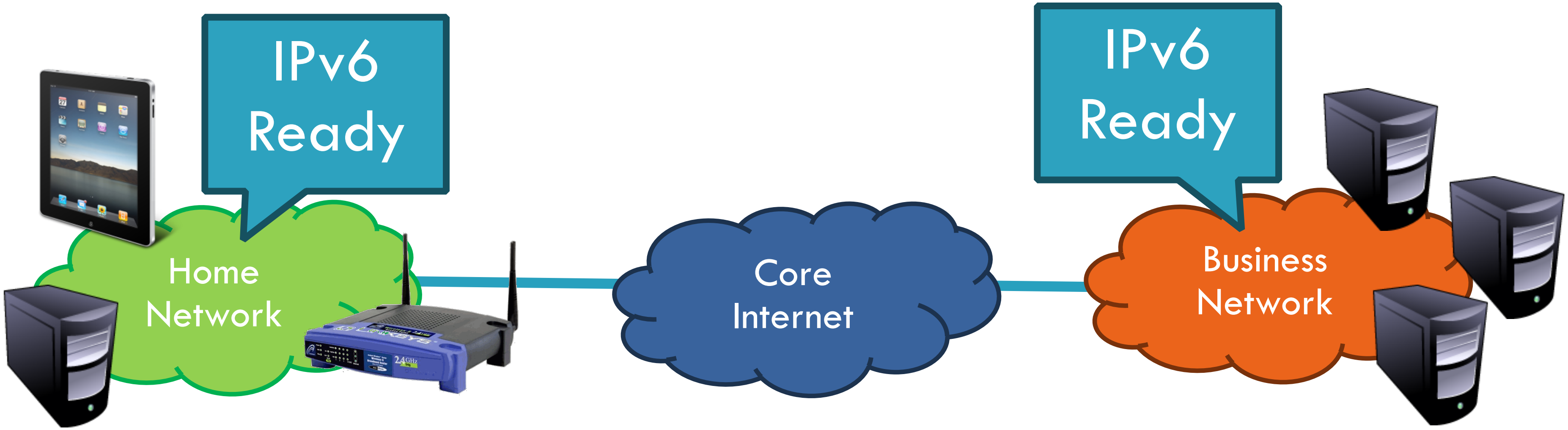

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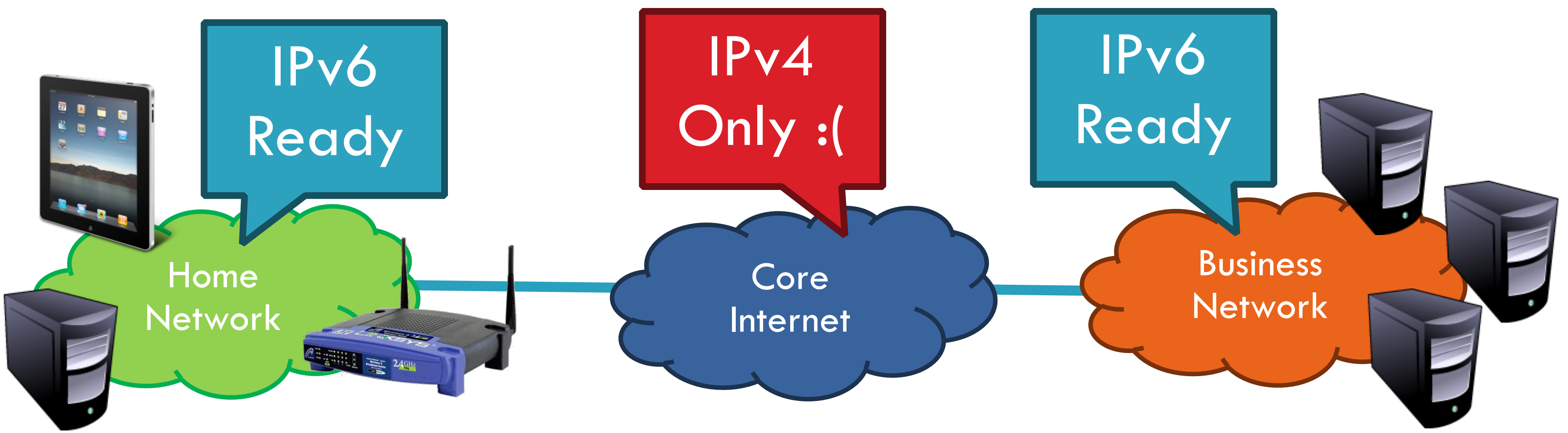
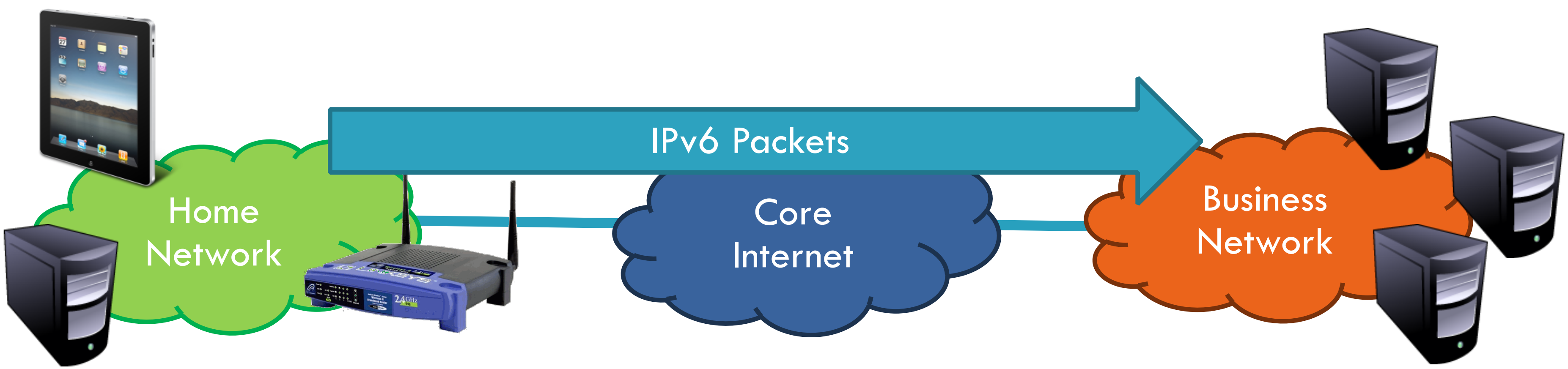


Transitioning to IPv6

- 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



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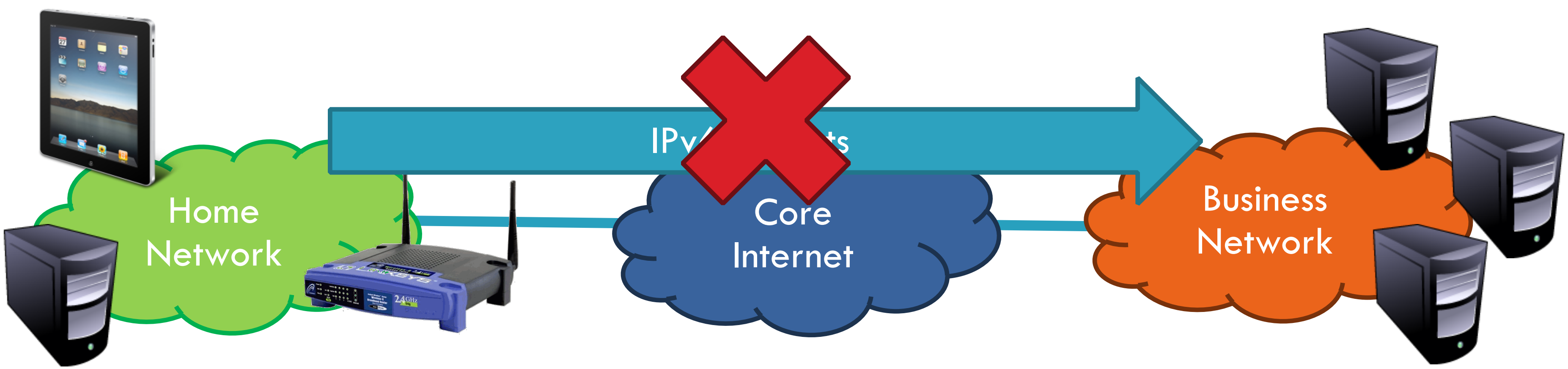

Transition Technologies

- 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.

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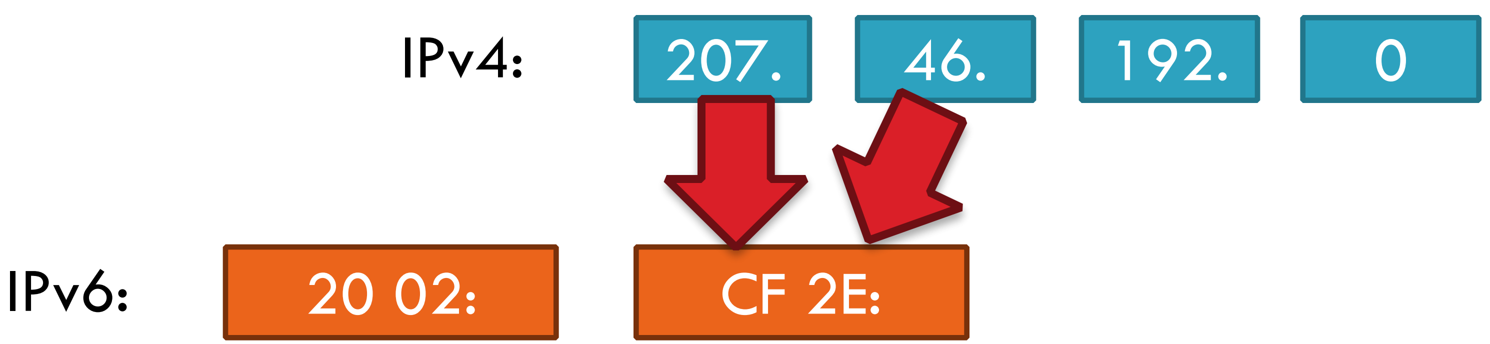

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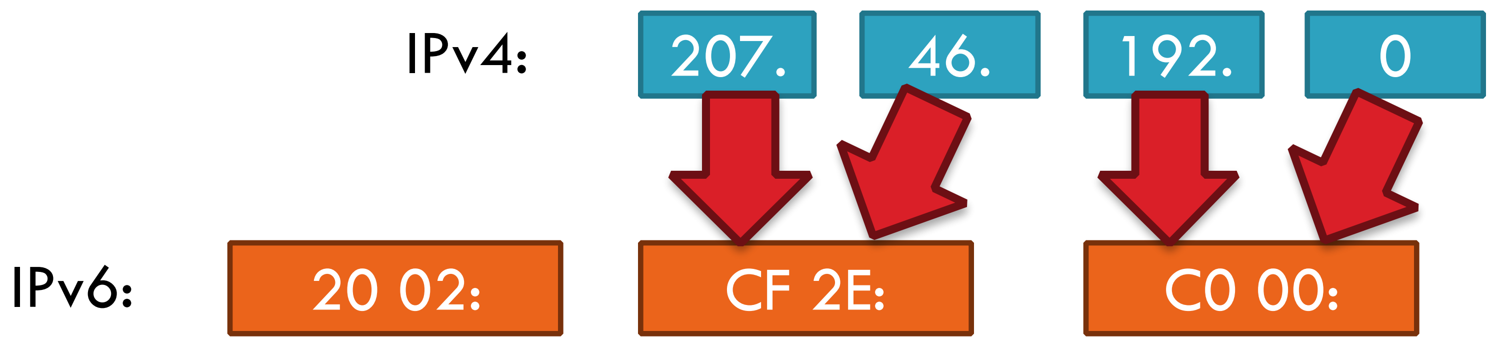

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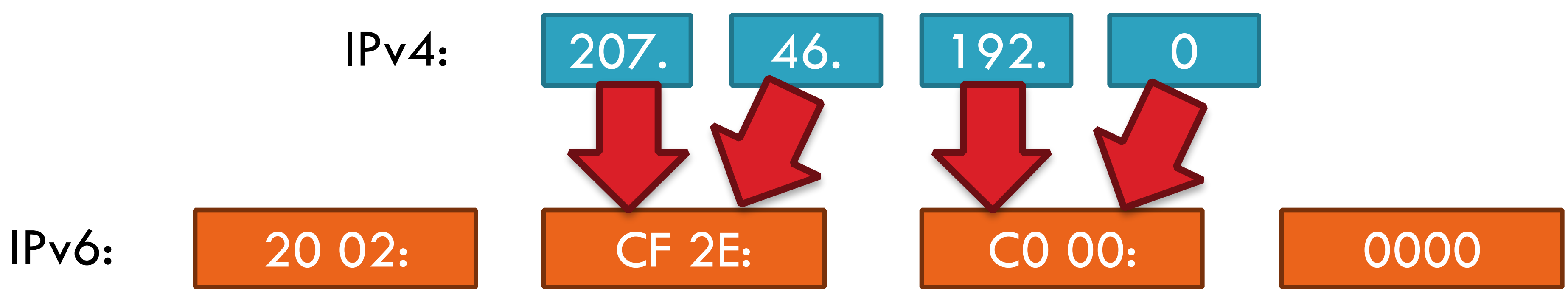

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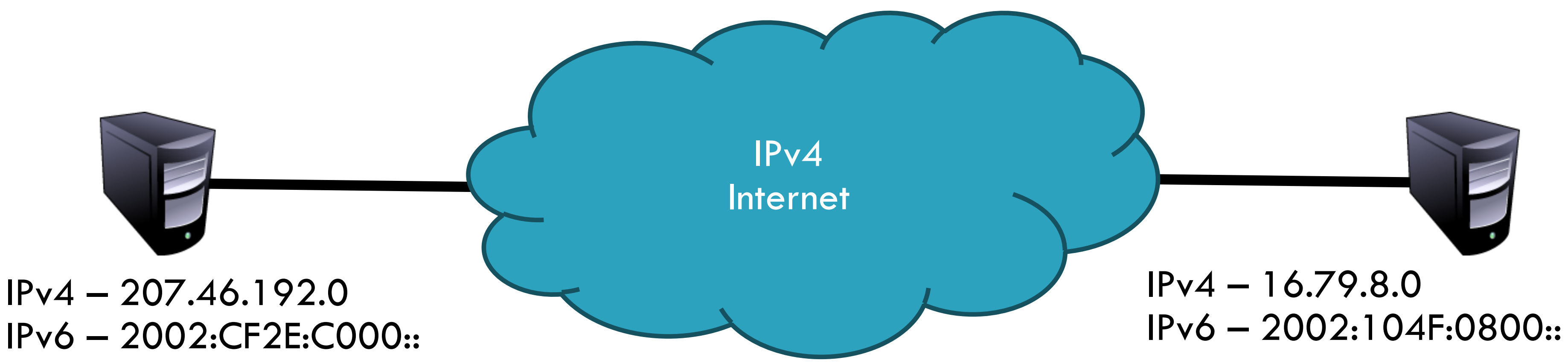

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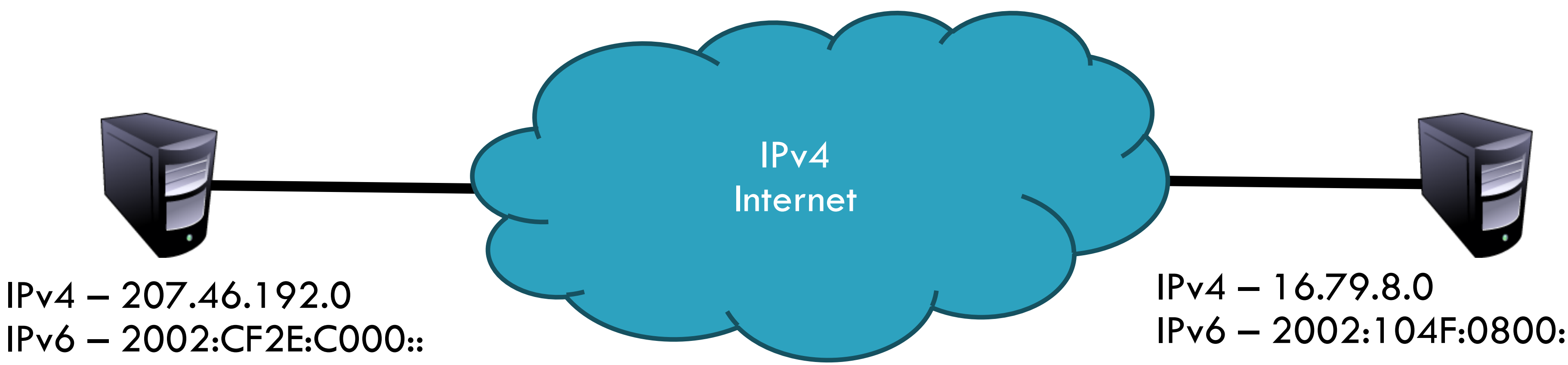

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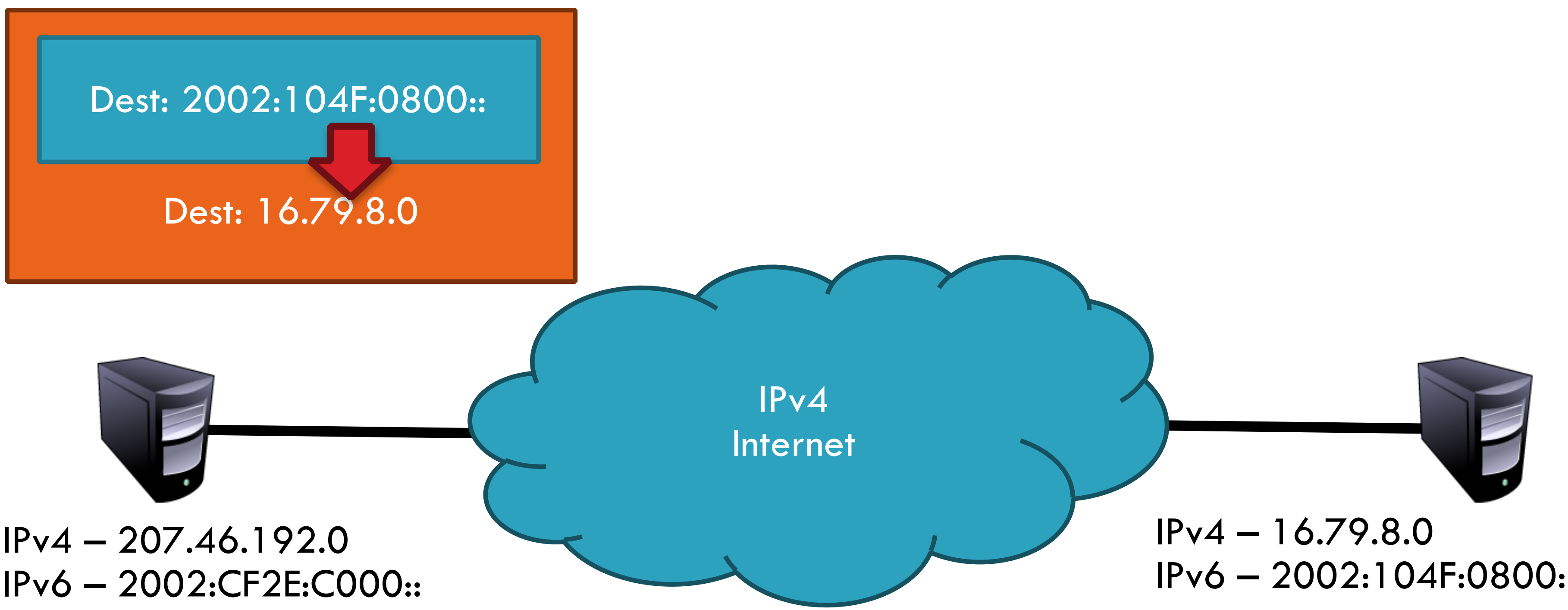

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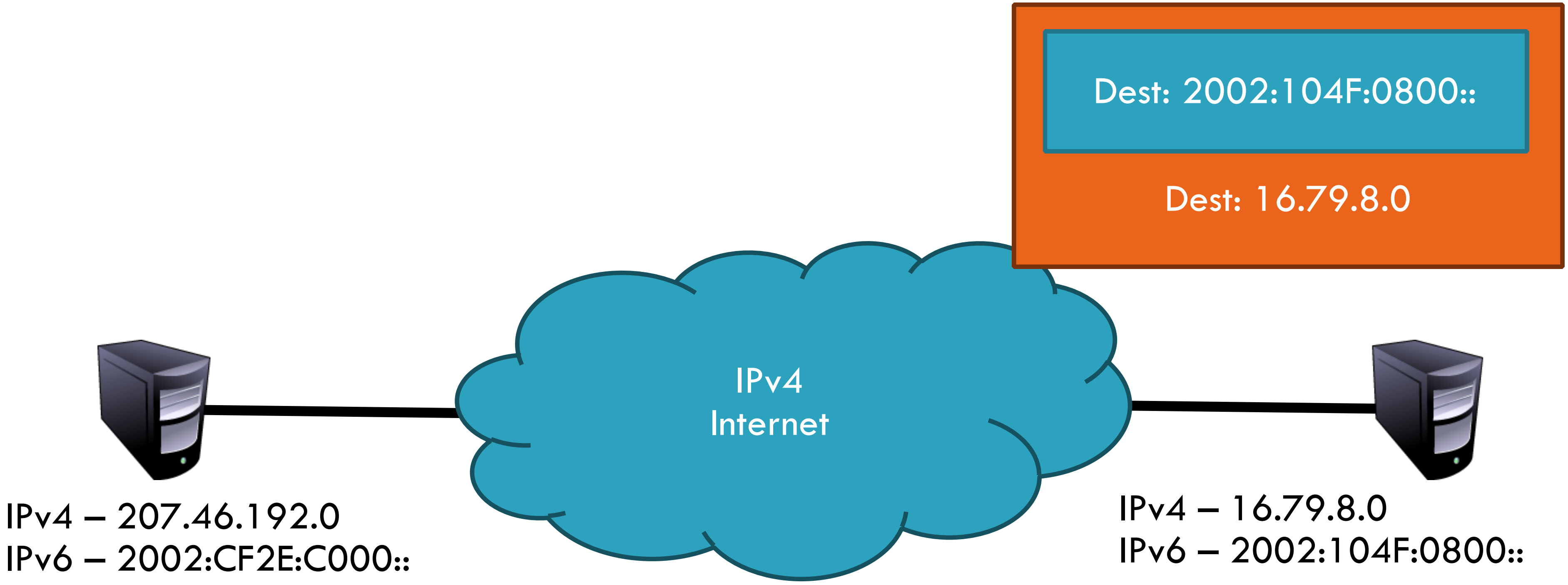

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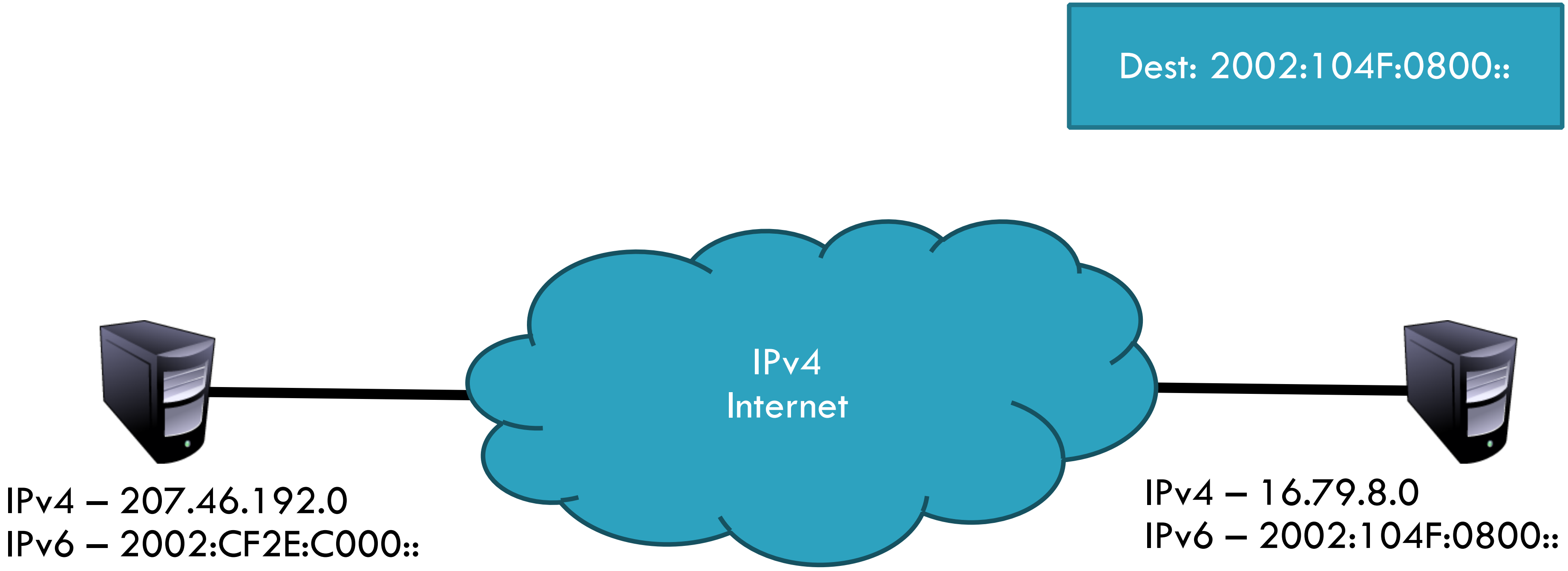

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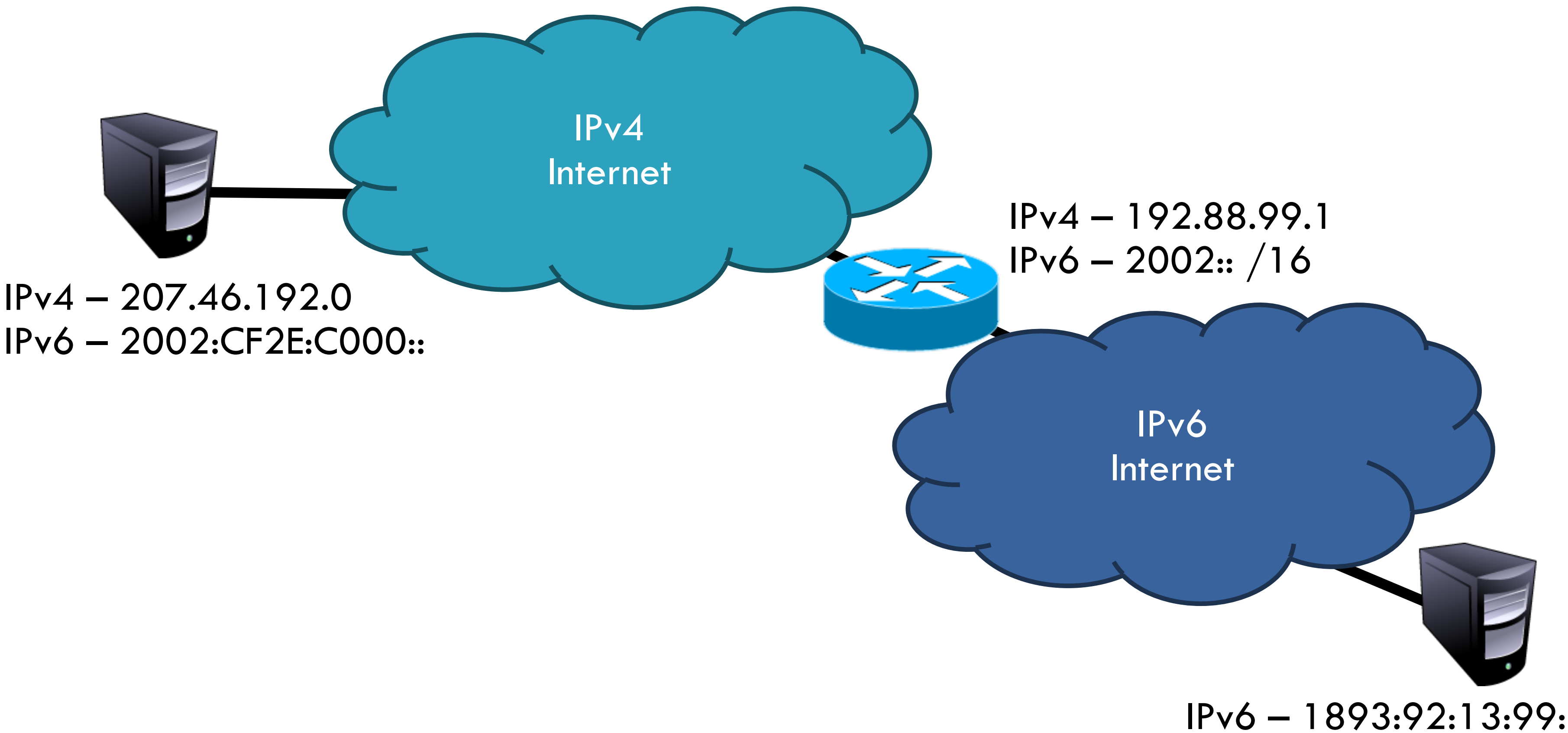

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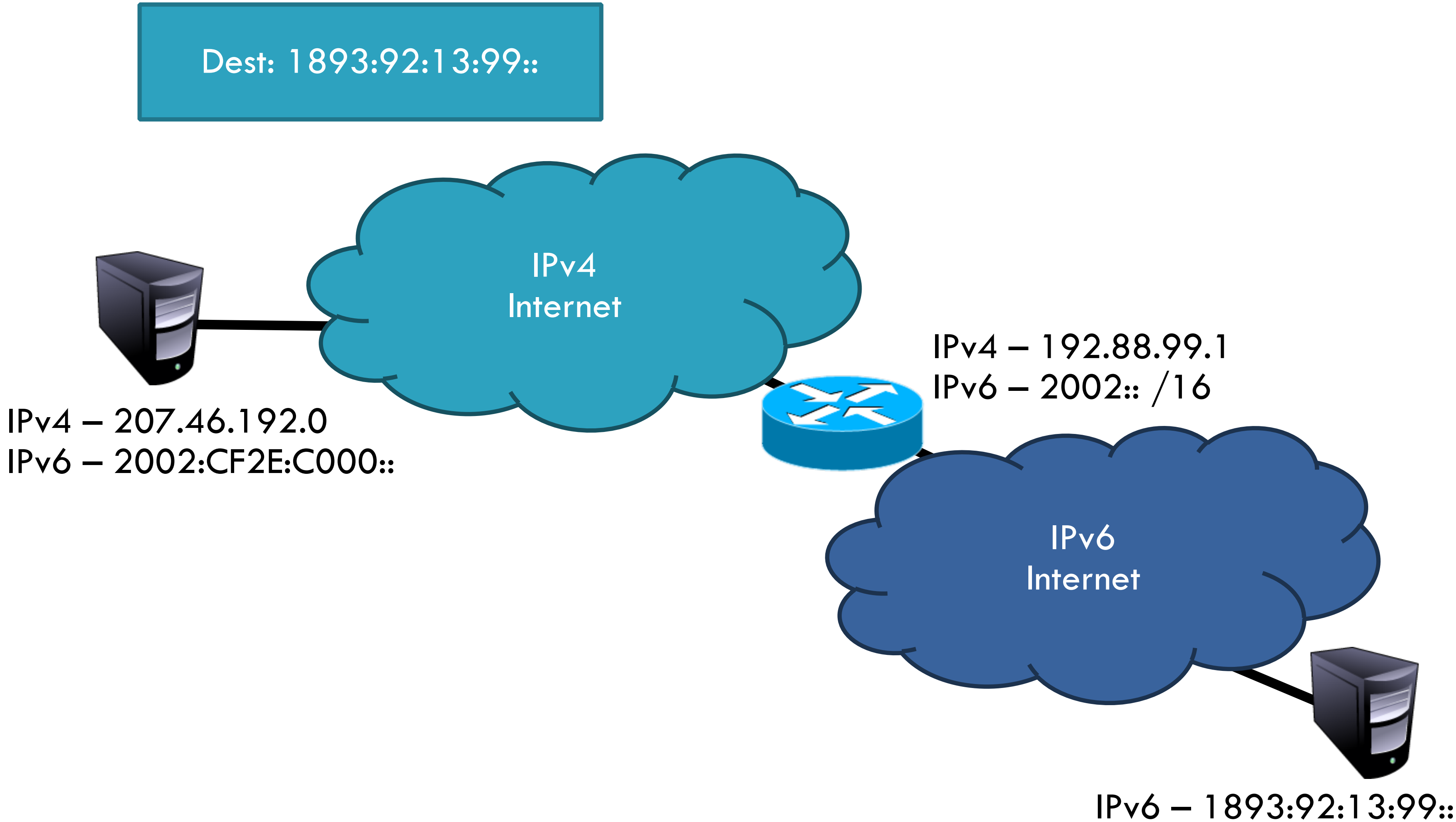

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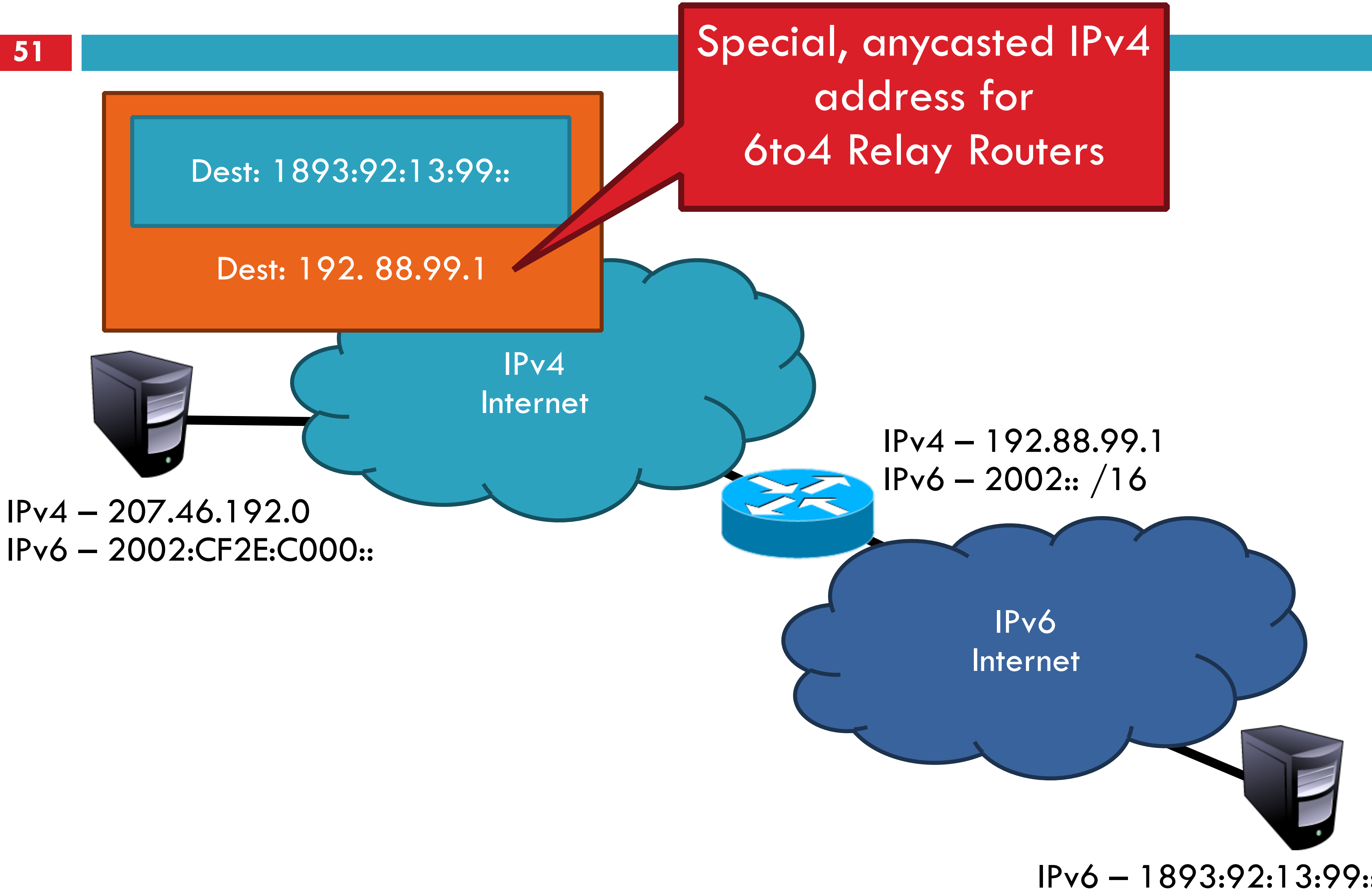

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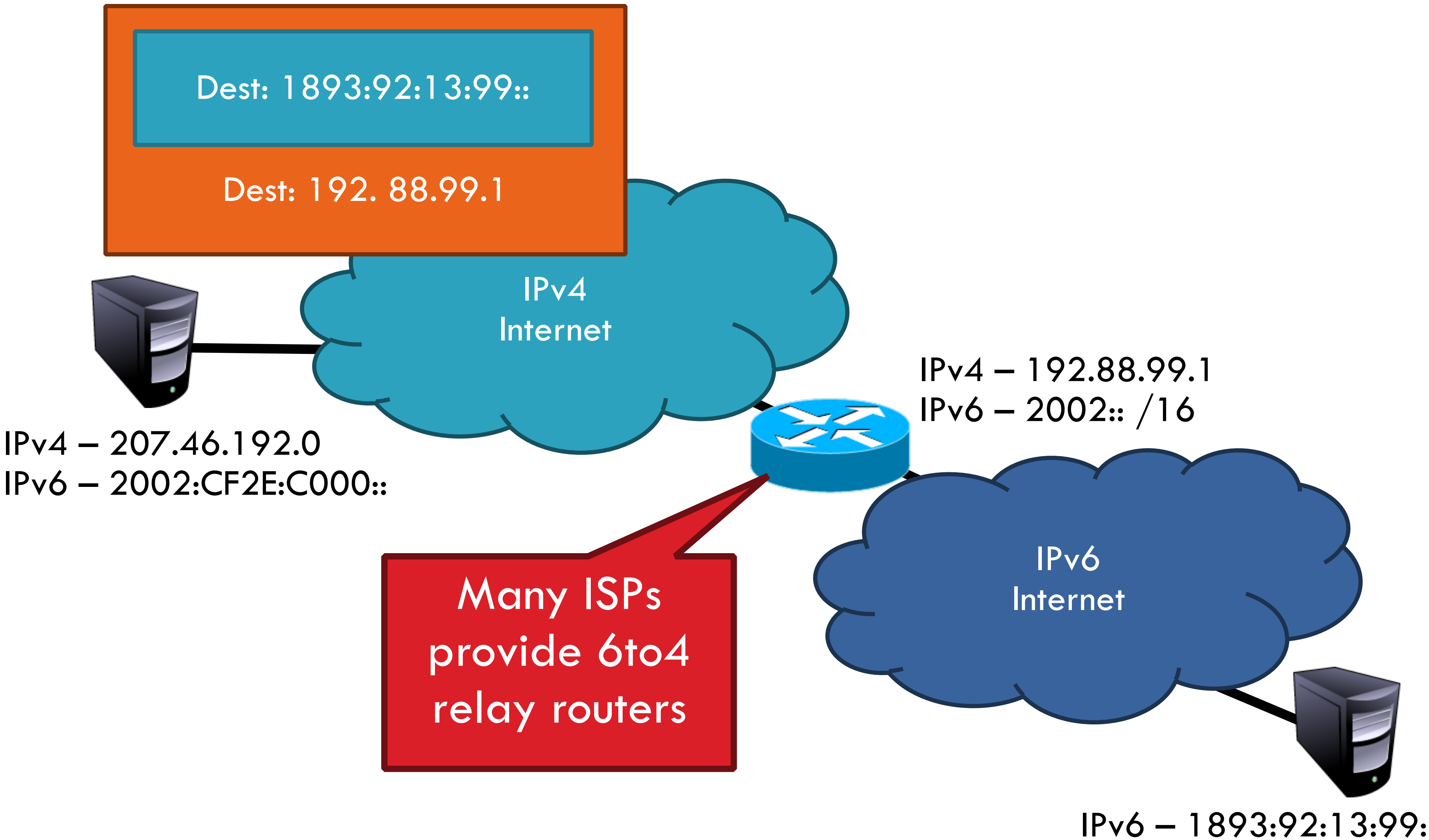

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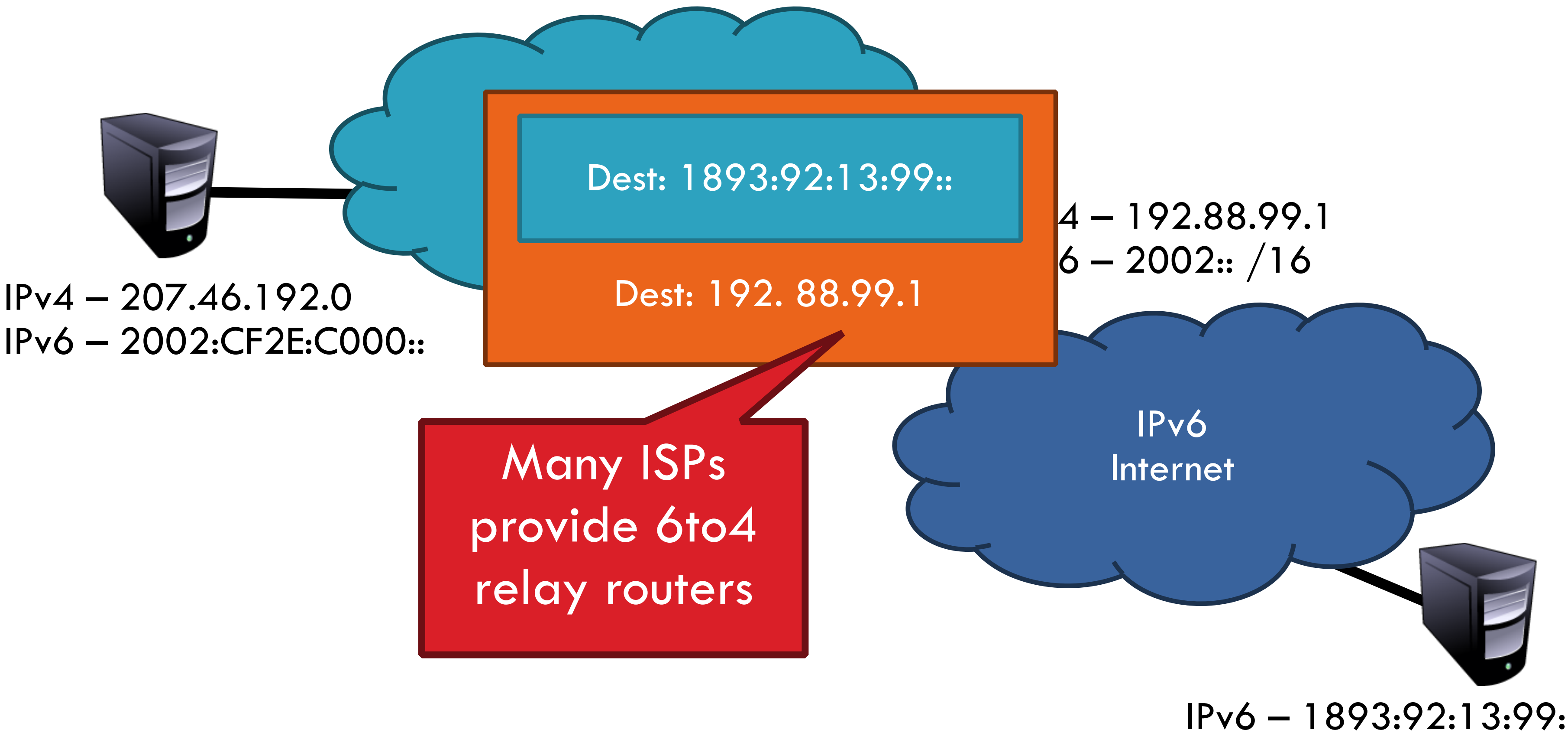

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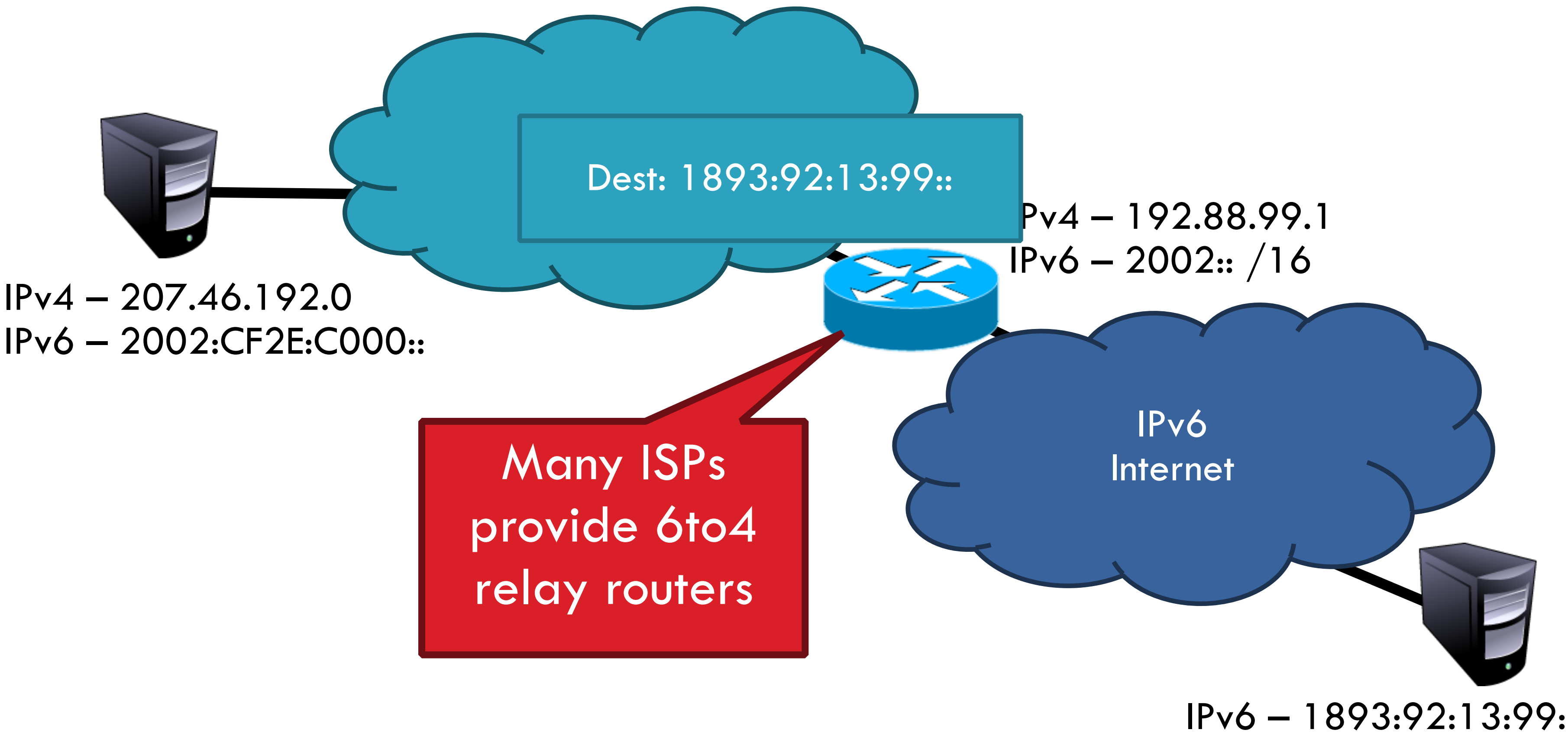

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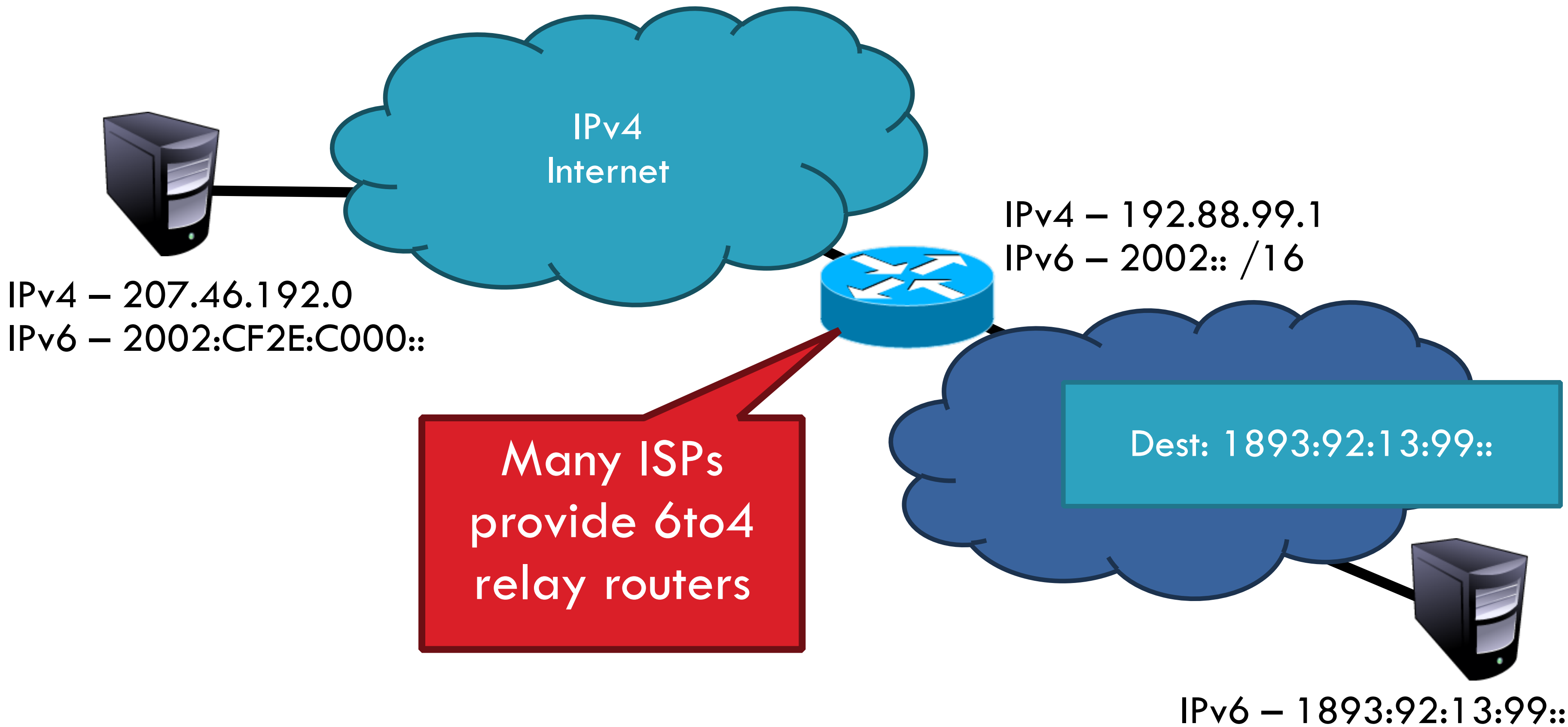

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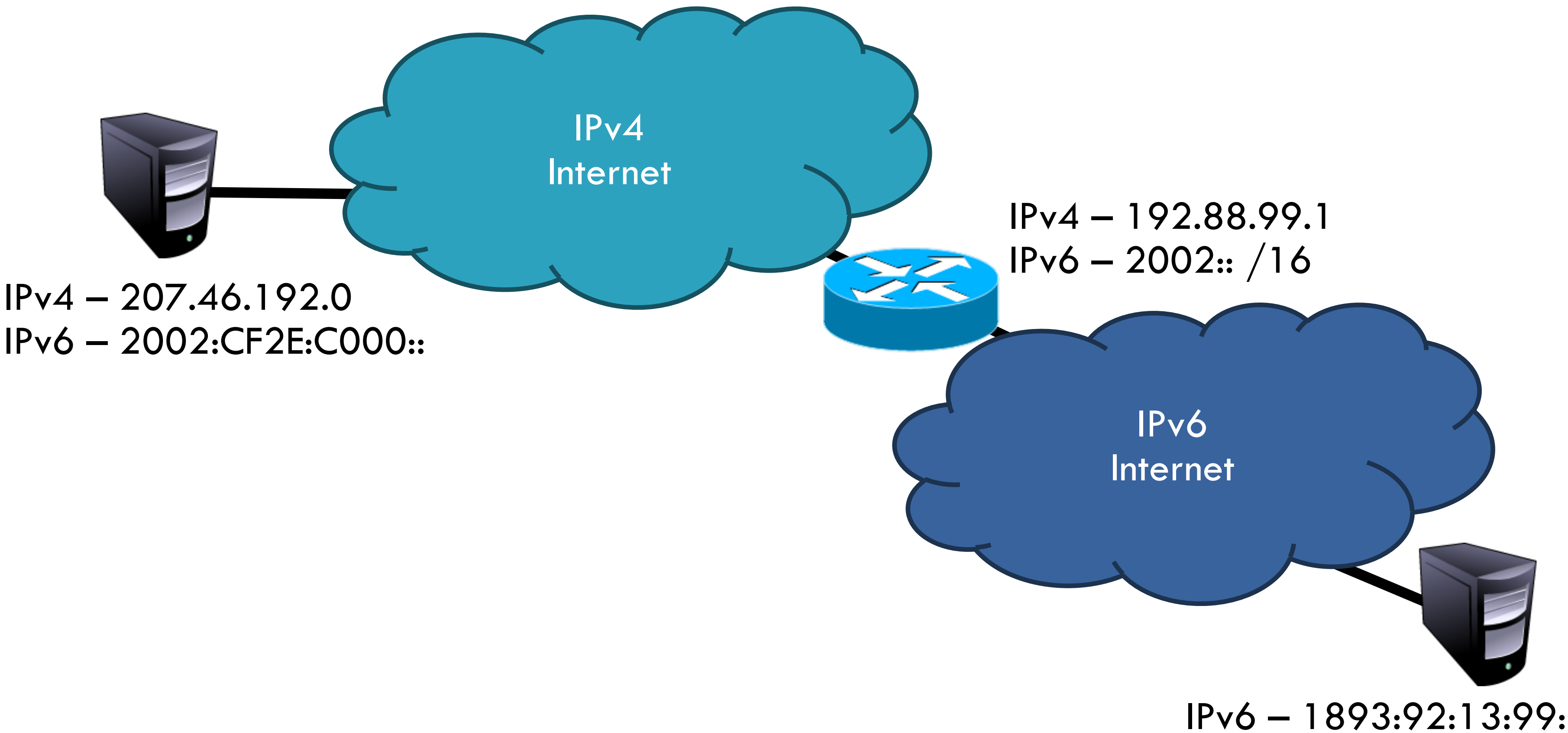

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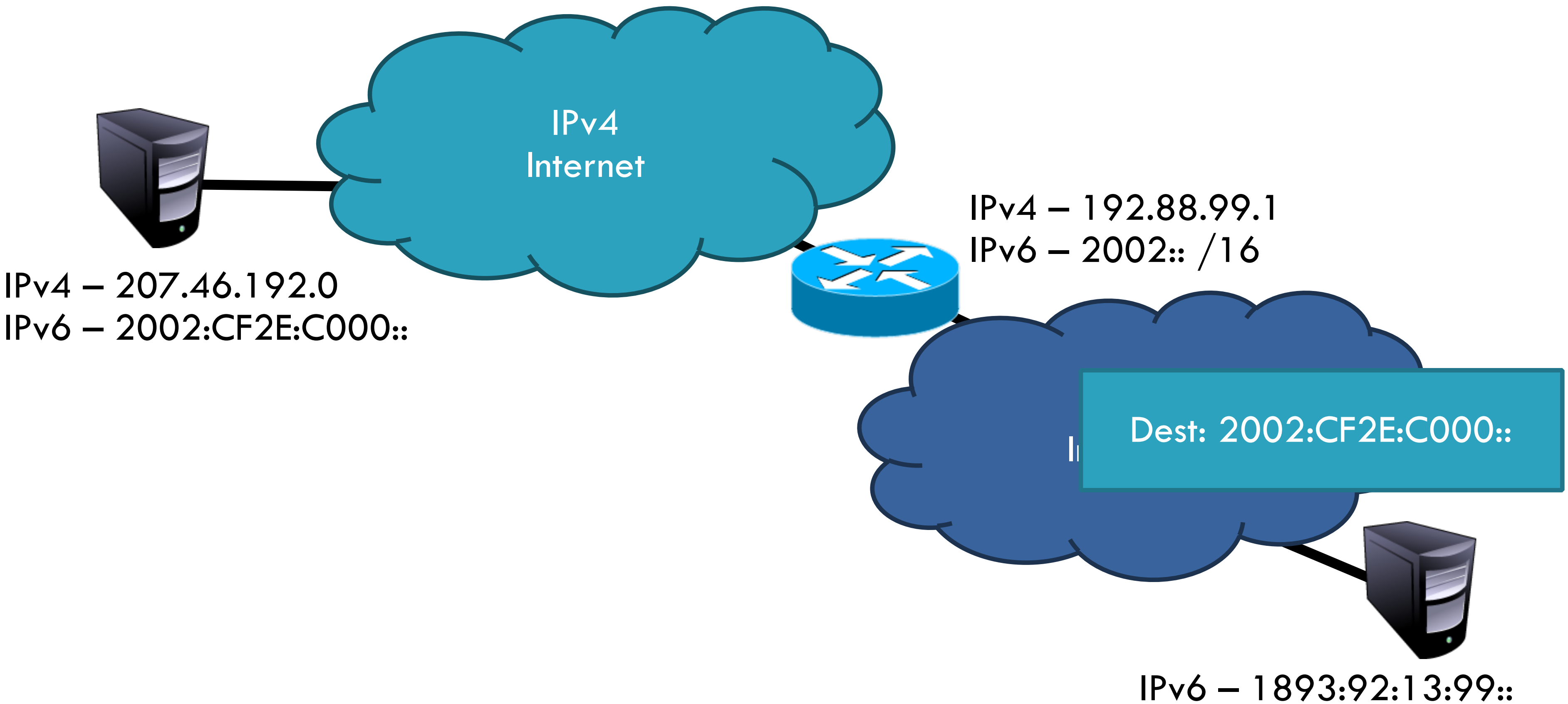

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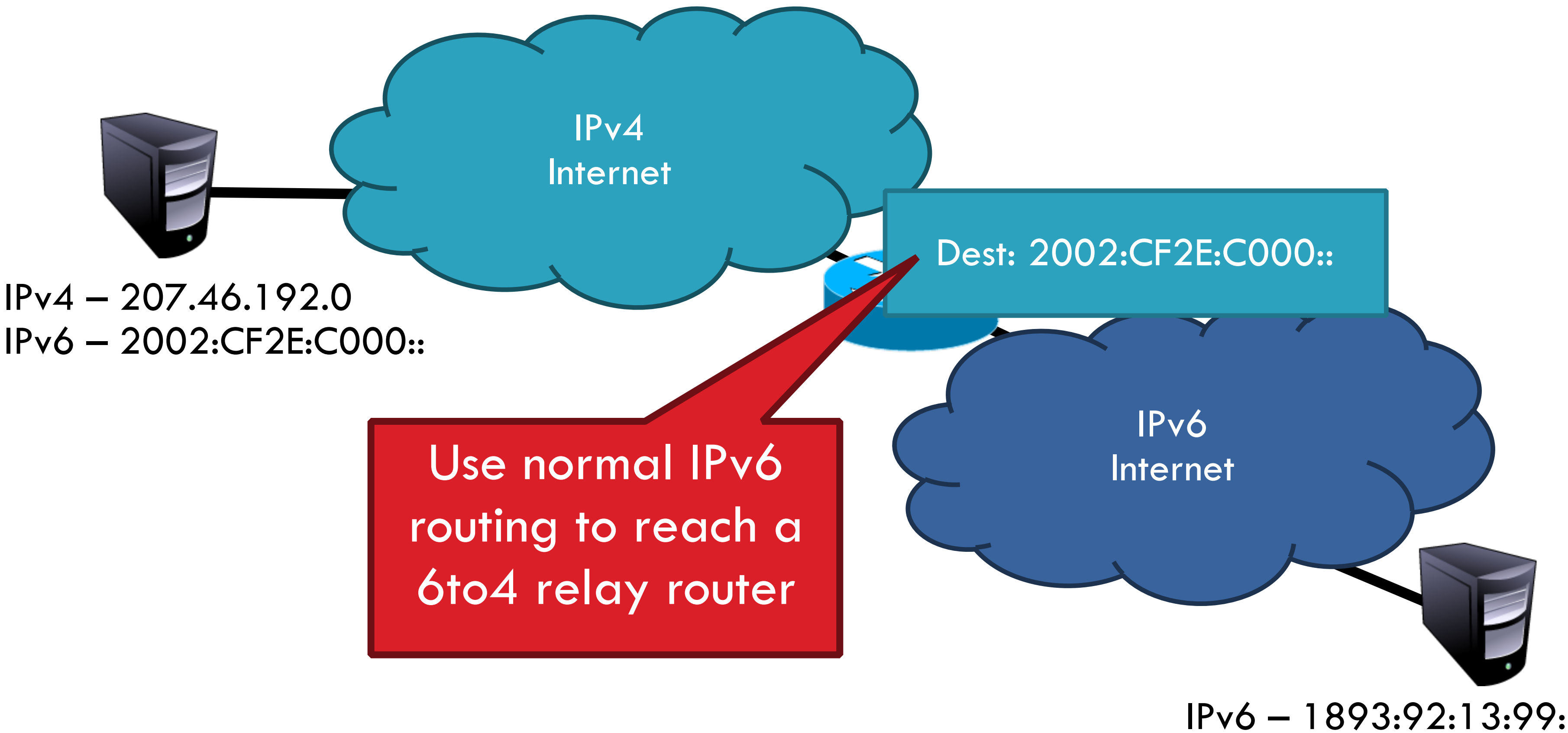

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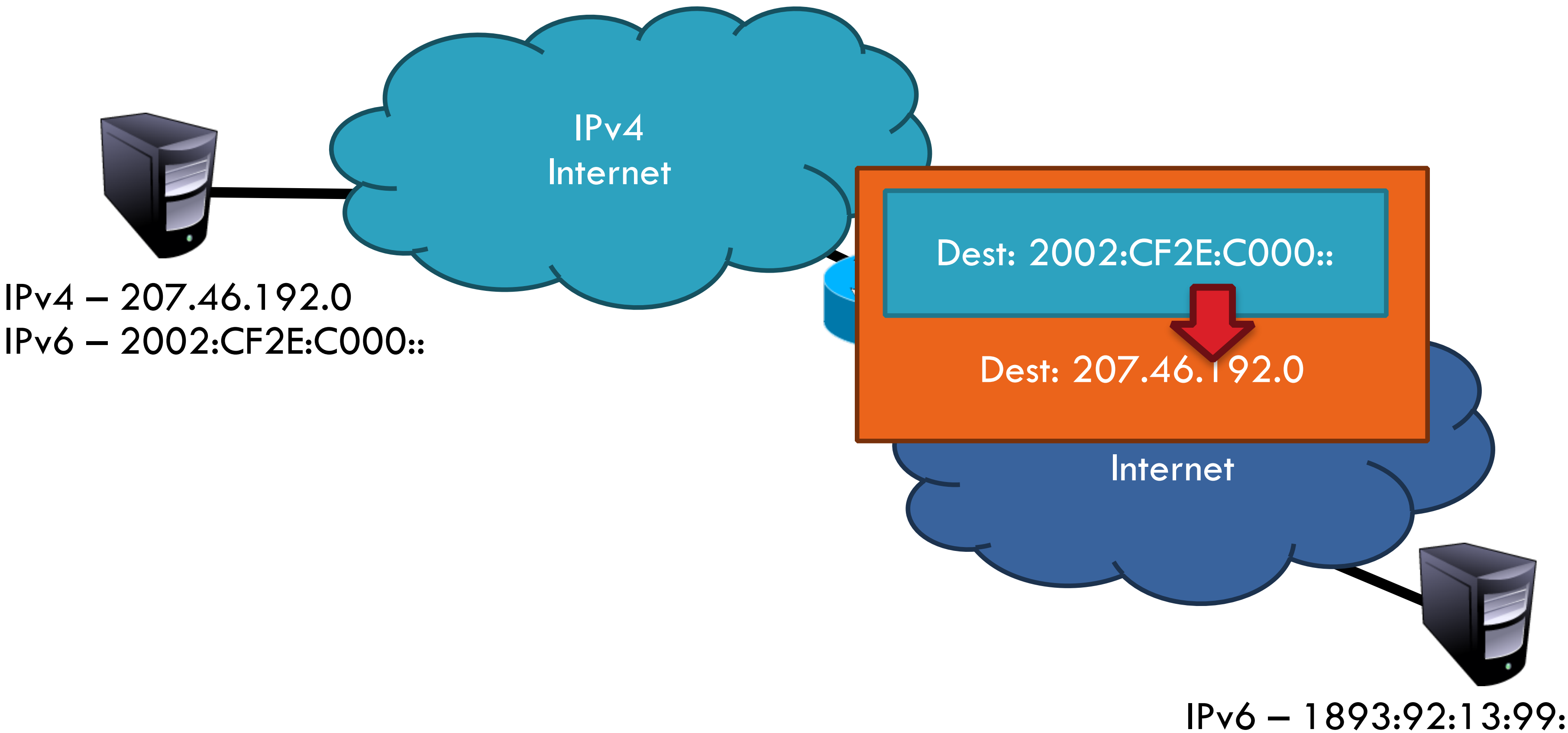

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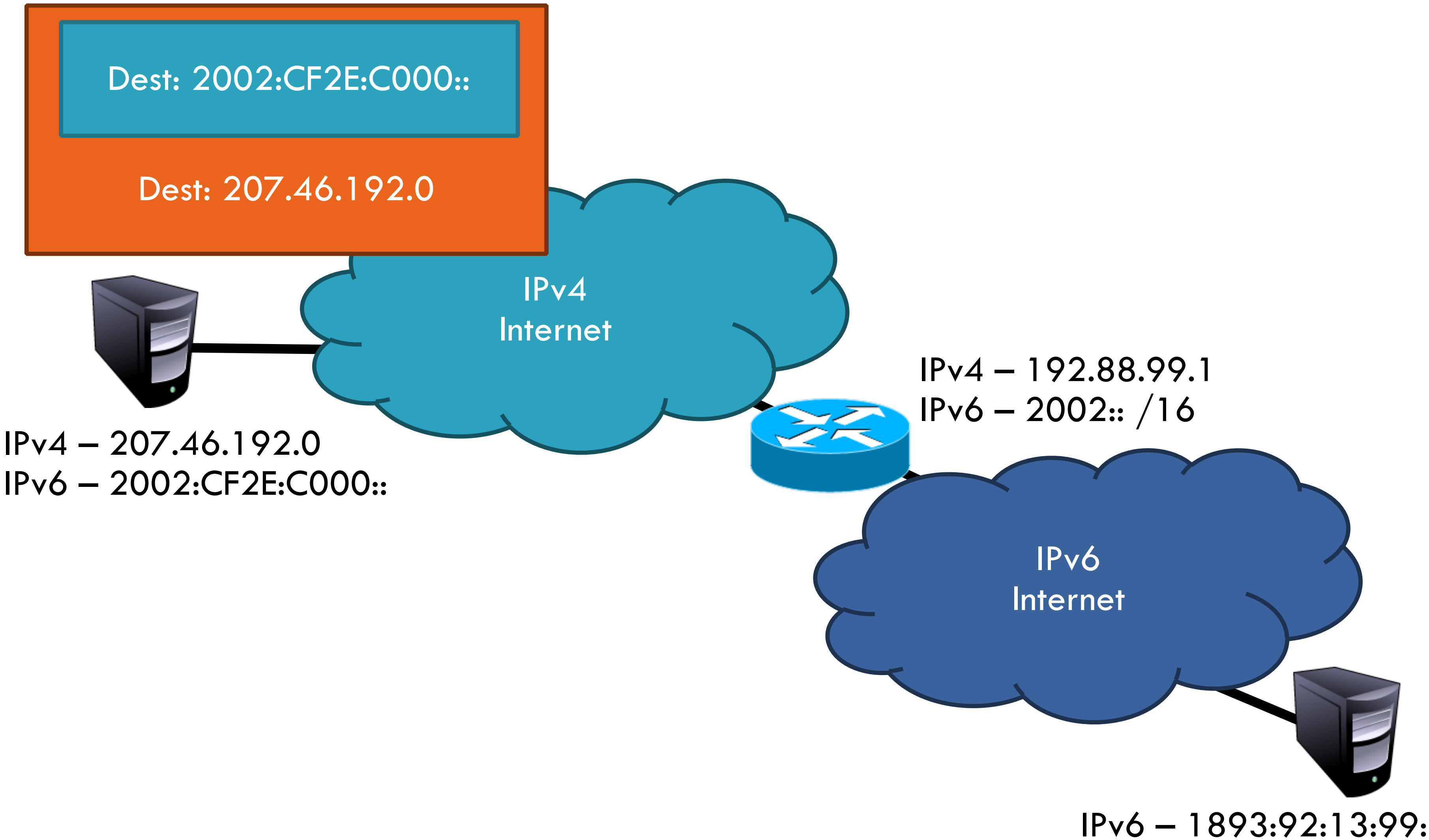

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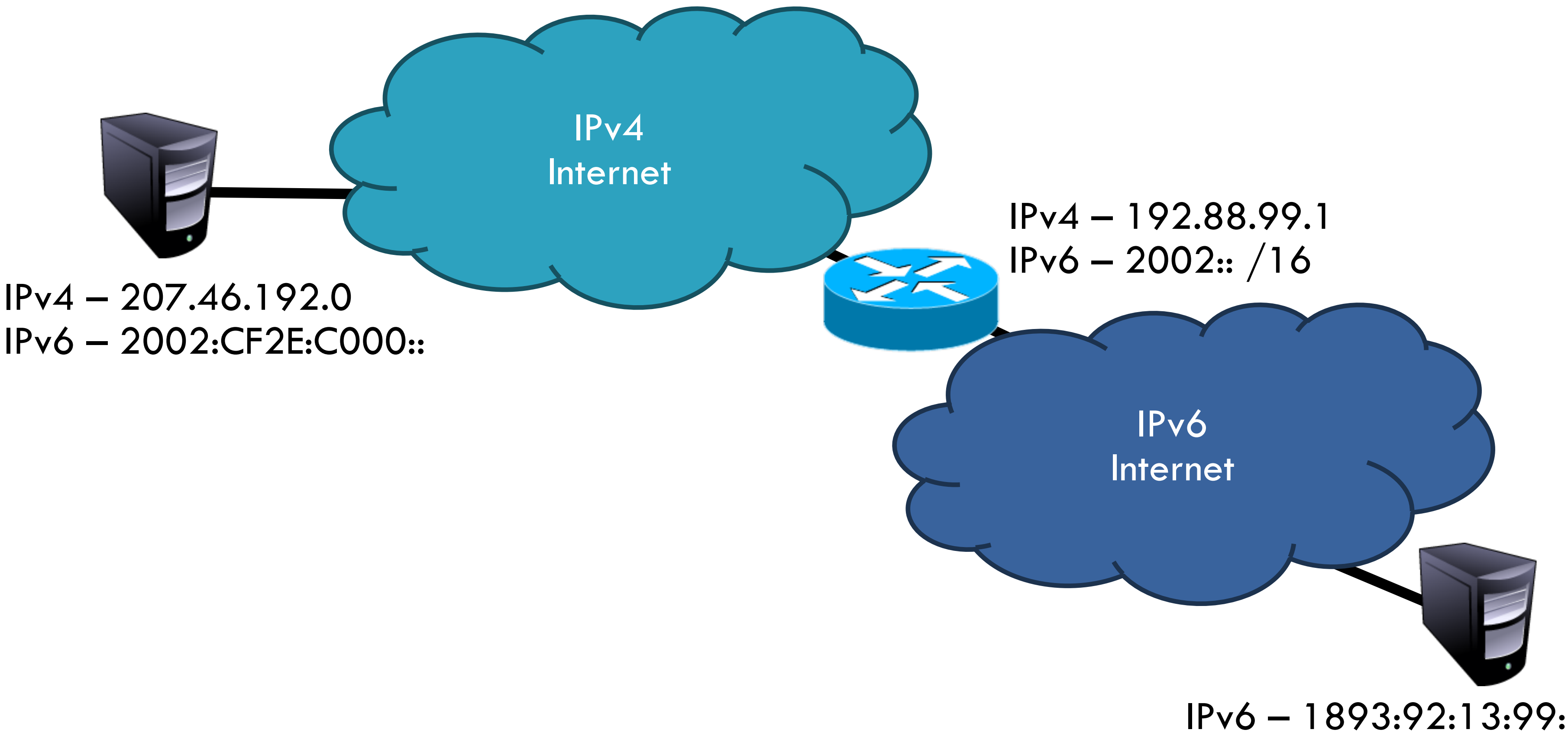
Dest: 2002:CF2E:C000::



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  - Teredo
    - Tunnels IPv6 packets through UDP/IPv4 tunnels
    - Can tunnel through NATs, but requires special relays

Consequences of IPv6

- Beware unintended consequences of IPv6
- Example: IP blacklists
  - Currently, blacklists track IPs of spammers/bots
  - Few IPv4 addresses mean list sizes are reasonable
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  - Acquiring new IP addresses is trivial