CS4700/CS5700 Fundamentals of Computer Networks

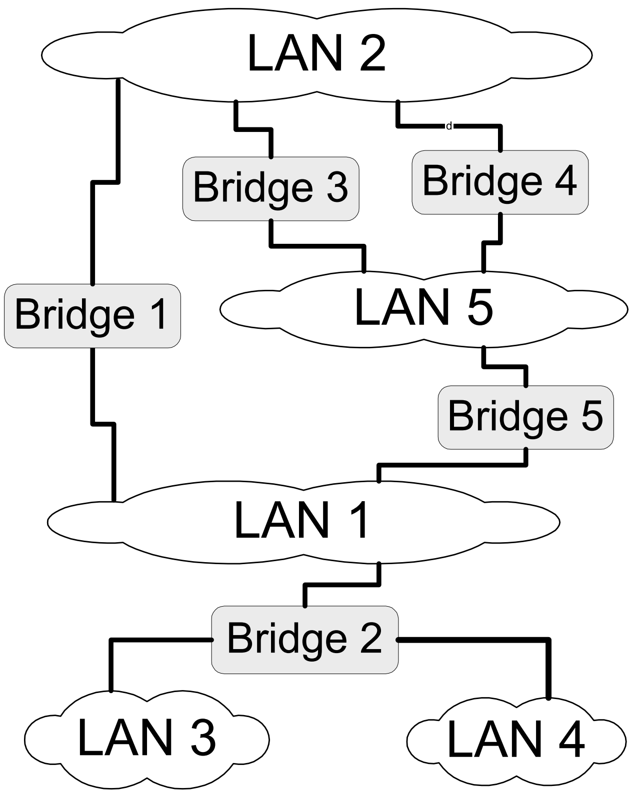
Lecture 10: Internet Protocol (IP)

Slides used with permissions from Edward W. Knightly, T. S. Eugene Ng, Ion Stoica, Hui Zhang

Recap

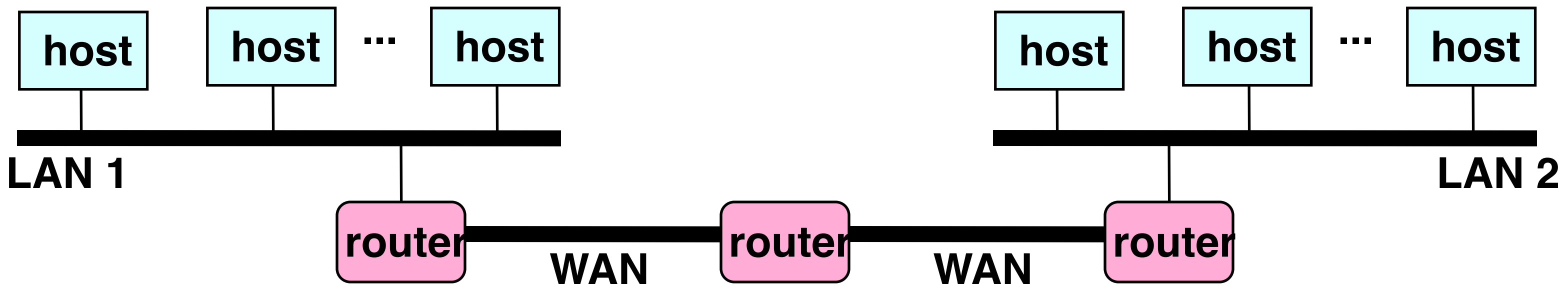
- Cannot build a global network such as the Internet using Ethernet bridges
- Problem 1: Addressing
- Problem 2: Routing

- Additionally, a global network should allow heterogeneous technologies (e.g. ATM, circuit-switched networks, Ethernet, etc)



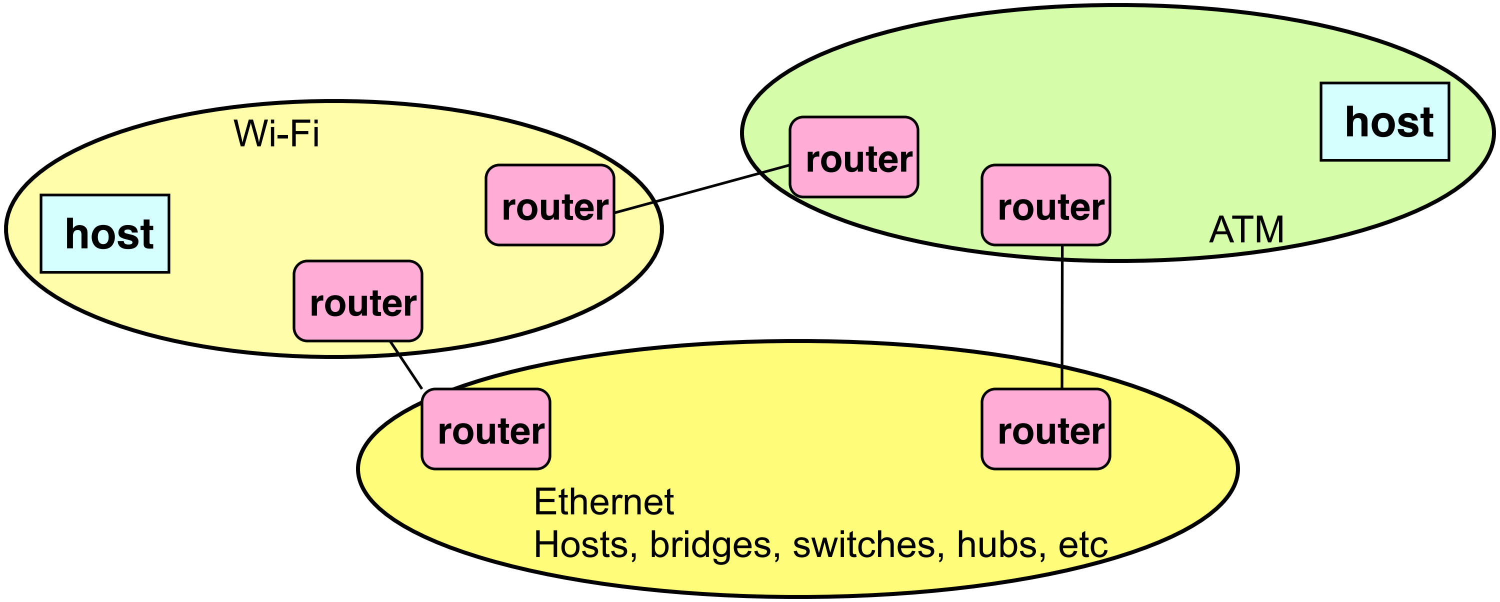
New Word: Internetwork

- Multiple incompatible LANs can be physically connected by specialized computers called *routers.*
- The connected networks are called an *internetwork*.
  - The "*Internet*" is one (very big & successful) example of an internetwork



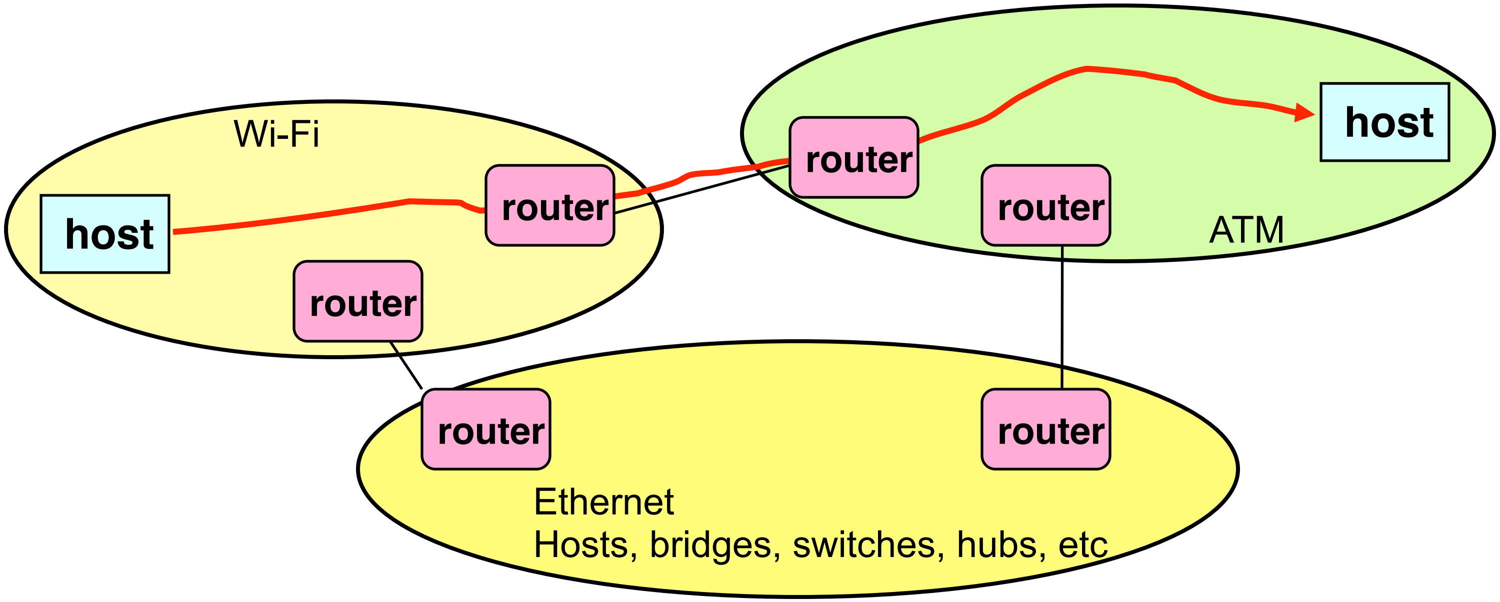
LAN 1 and LAN 2 might be completely different, totally incompatible LANs (e.g., Ethernet, Wi-Fi, ATM, Circuit-switched)

Logical Structure of Internet



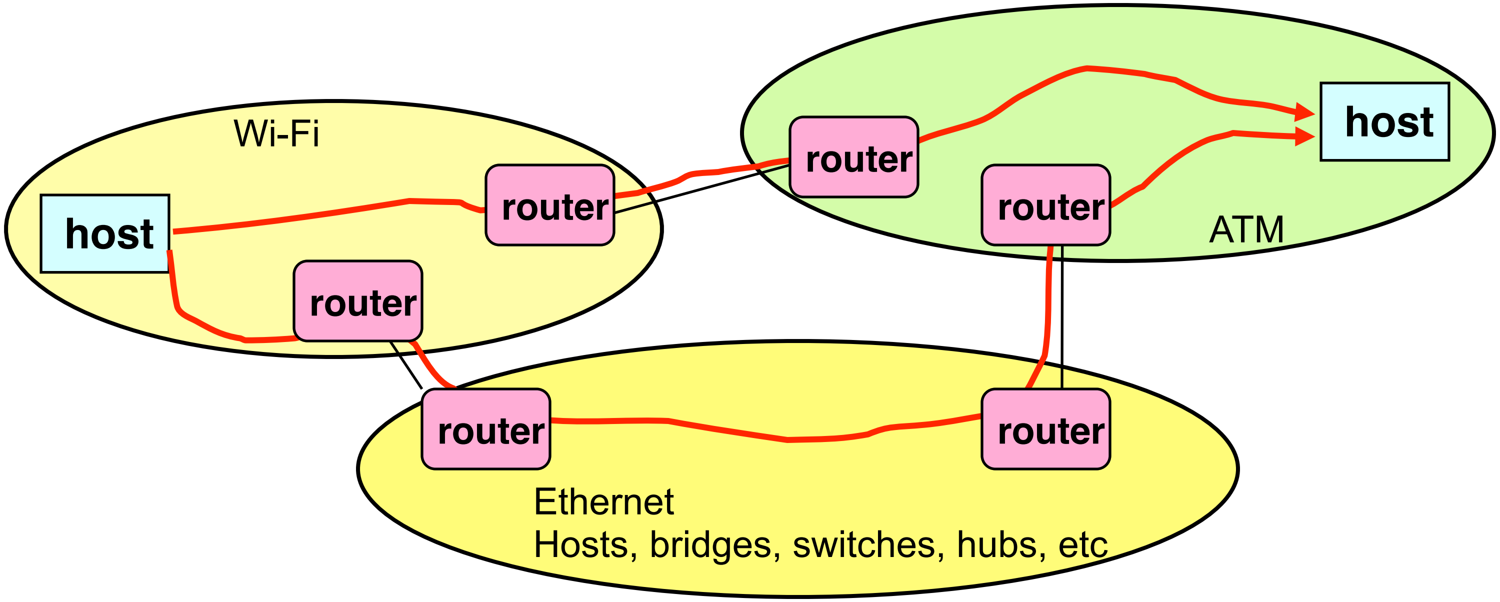
- Ad hoc interconnection of networks
  - No particular topology
  - Vastly different router & link capacities
- Send packets from source to destination by hopping through networks
  - Router connects one network to another
  - Different packets may take different routes

Logical Structure of Internet



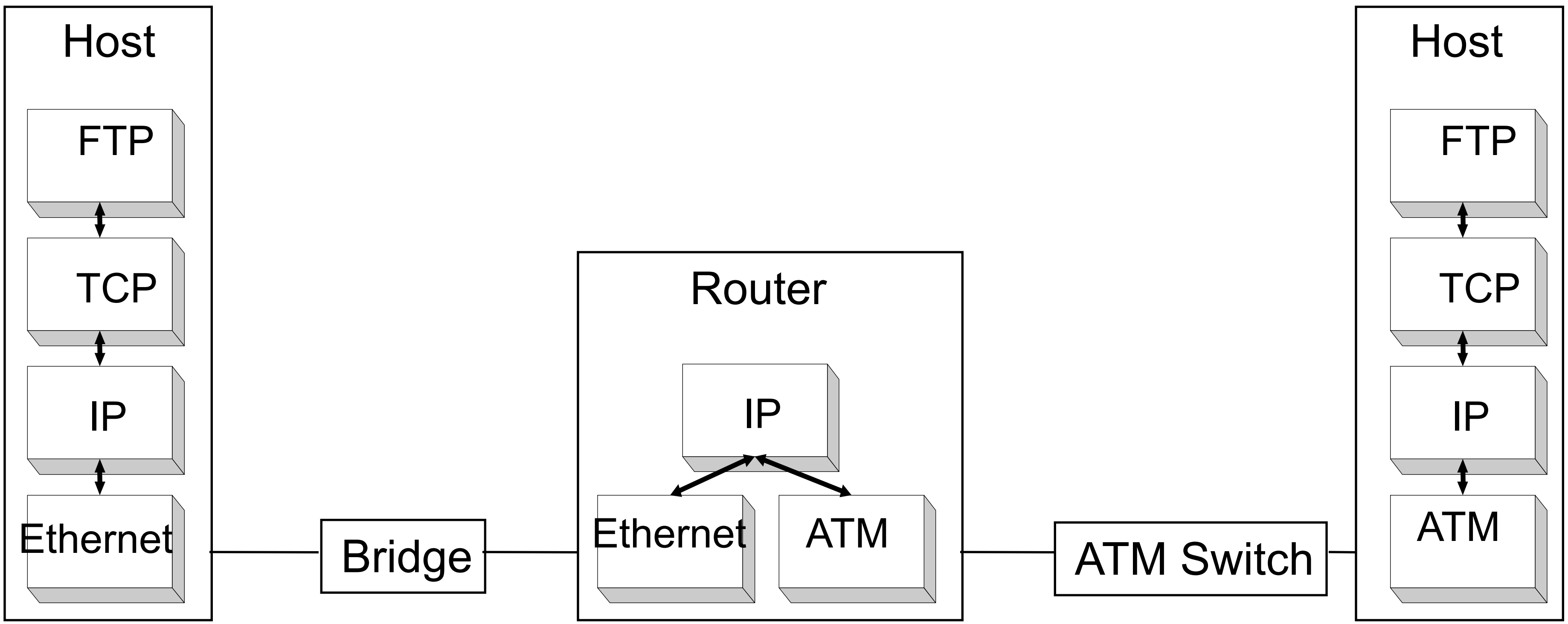
- Ad hoc interconnection of networks
  - No particular topology
  - Vastly different router & link capacities
- Send packets from source to destination by hopping through networks
  - Router connects one network to another
  - Different packets may take different routes

Logical Structure of Internet



- Ad hoc interconnection of networks
  - No particular topology
  - Vastly different router & link capacities
- Send packets from source to destination by hopping through networks
  - Router connects one network to another
  - Different packets may take different routes

Adding an Internetwork Layer (IP) for Interoperability



Issues in Designing an Internetwork

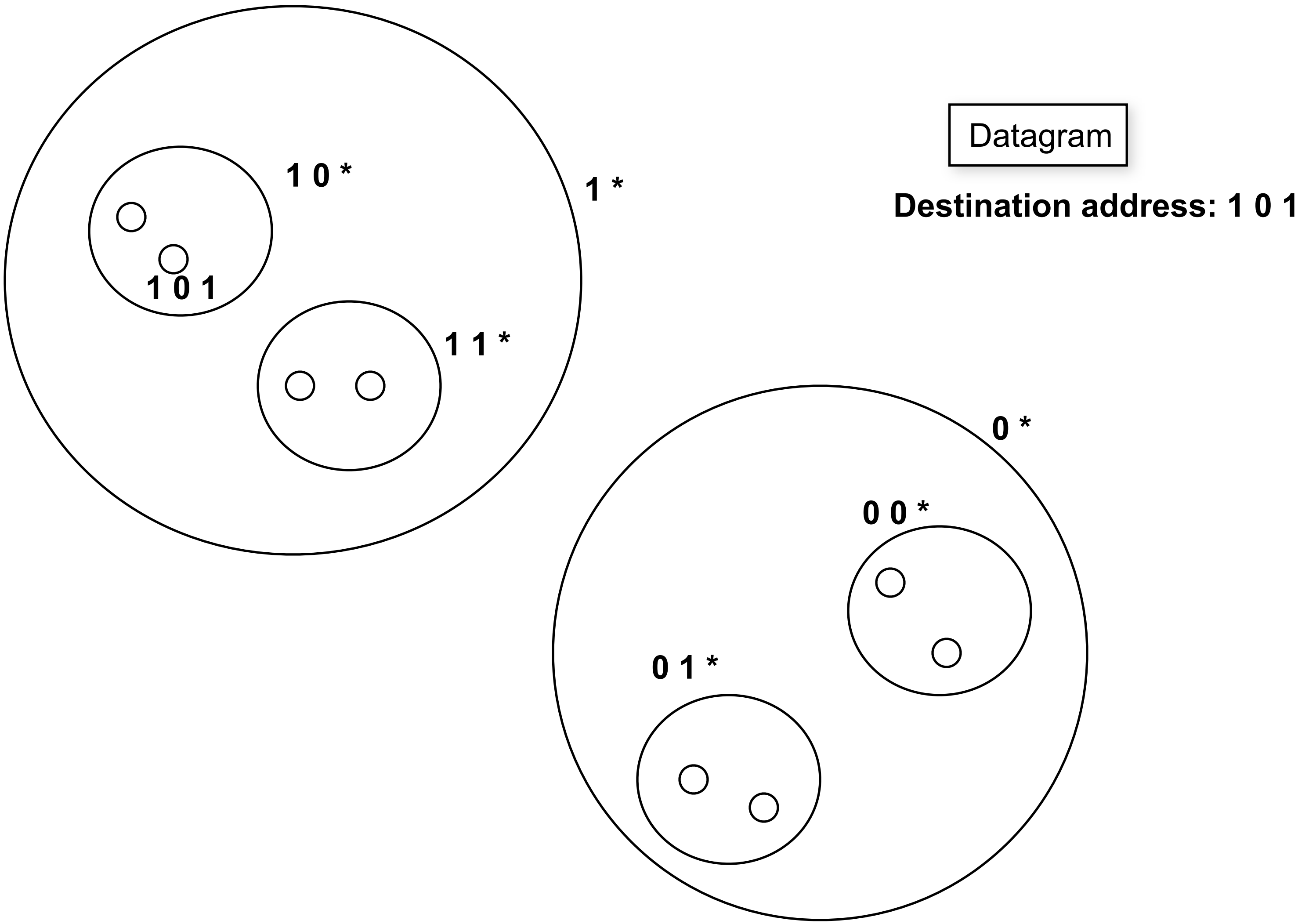
- How do I designate a distant host?
  - Addressing / naming
- How do I send information to a distant host?
  - Underlying service model
    - What gets sent?
    - How fast will it go?
    - What happens if it doesn't get there?
  - Routing
- Challenges
  - Heterogeneity
    - Assembly from variety of different networks
  - Scalability
    - Ensure ability to grow to worldwide scale

Internet: Best-effort, datagram network
A kind of lowest common denominator

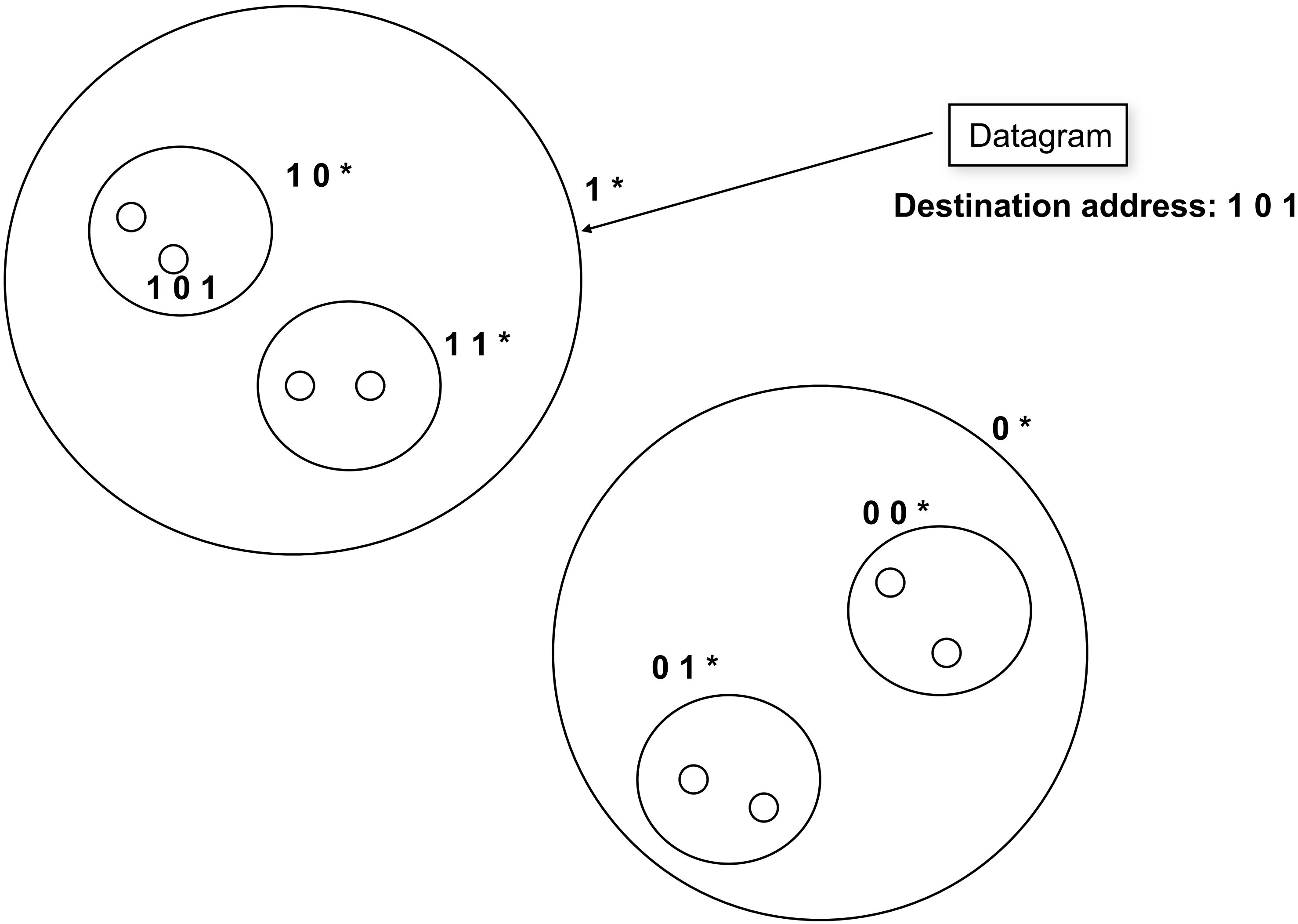
Possible Addressing Schemes

- Flat
  - e.g., every host identified by its 48-bit MAC address
  - Router would need entry for every host in the world
    - Too big (although technology can help this)
    - Too hard to maintain as hosts come & go
- Hierarchy
  - Address broken into segments of increasing specificity
    - 713 (Houston) – 348 (Rice area) – 2000 (Particular phone)
  - Route to general region and then work toward specific destination
  - As people and organizations shift, only update affected routing tables

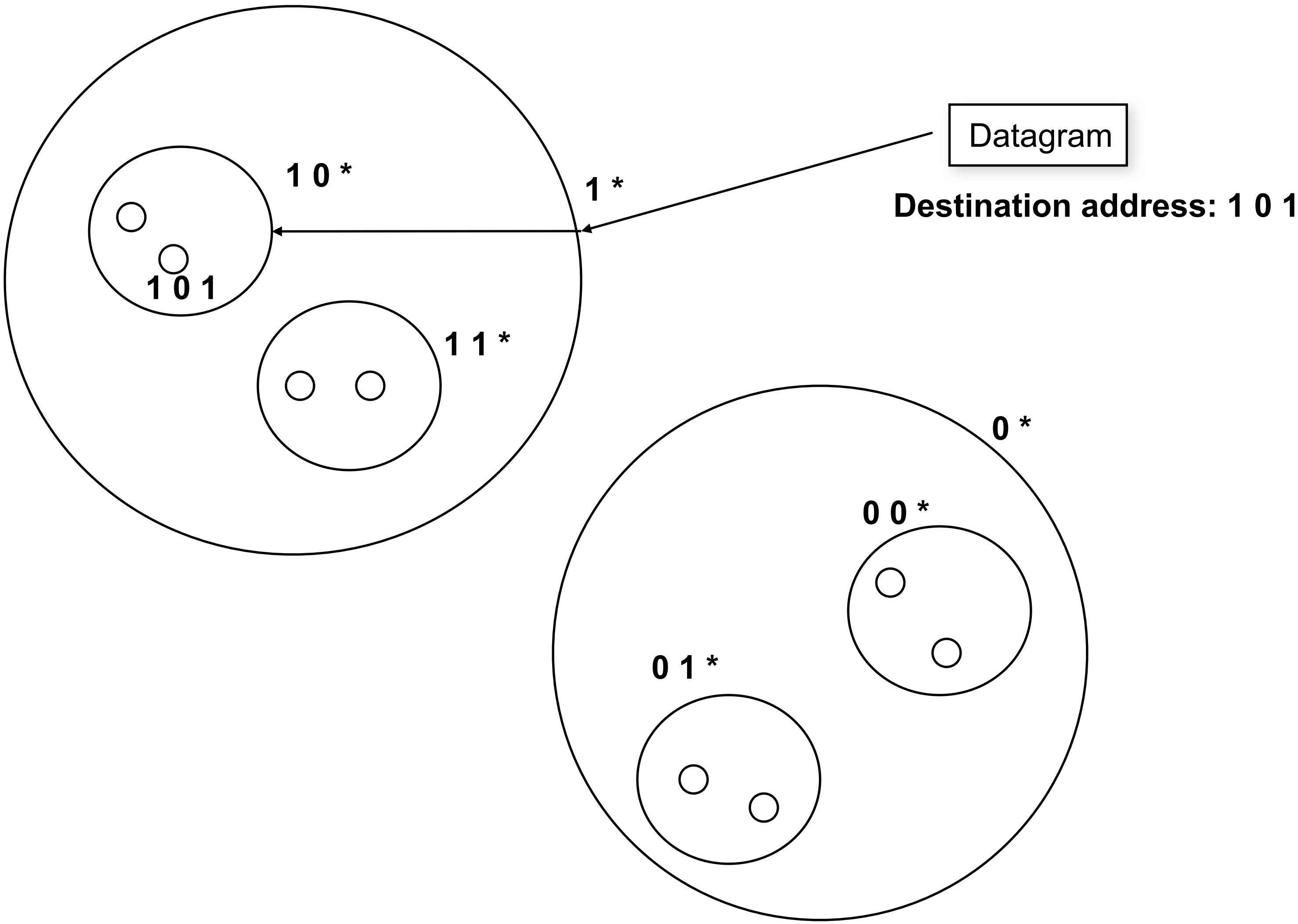
An Example of a Binary Hierarchy



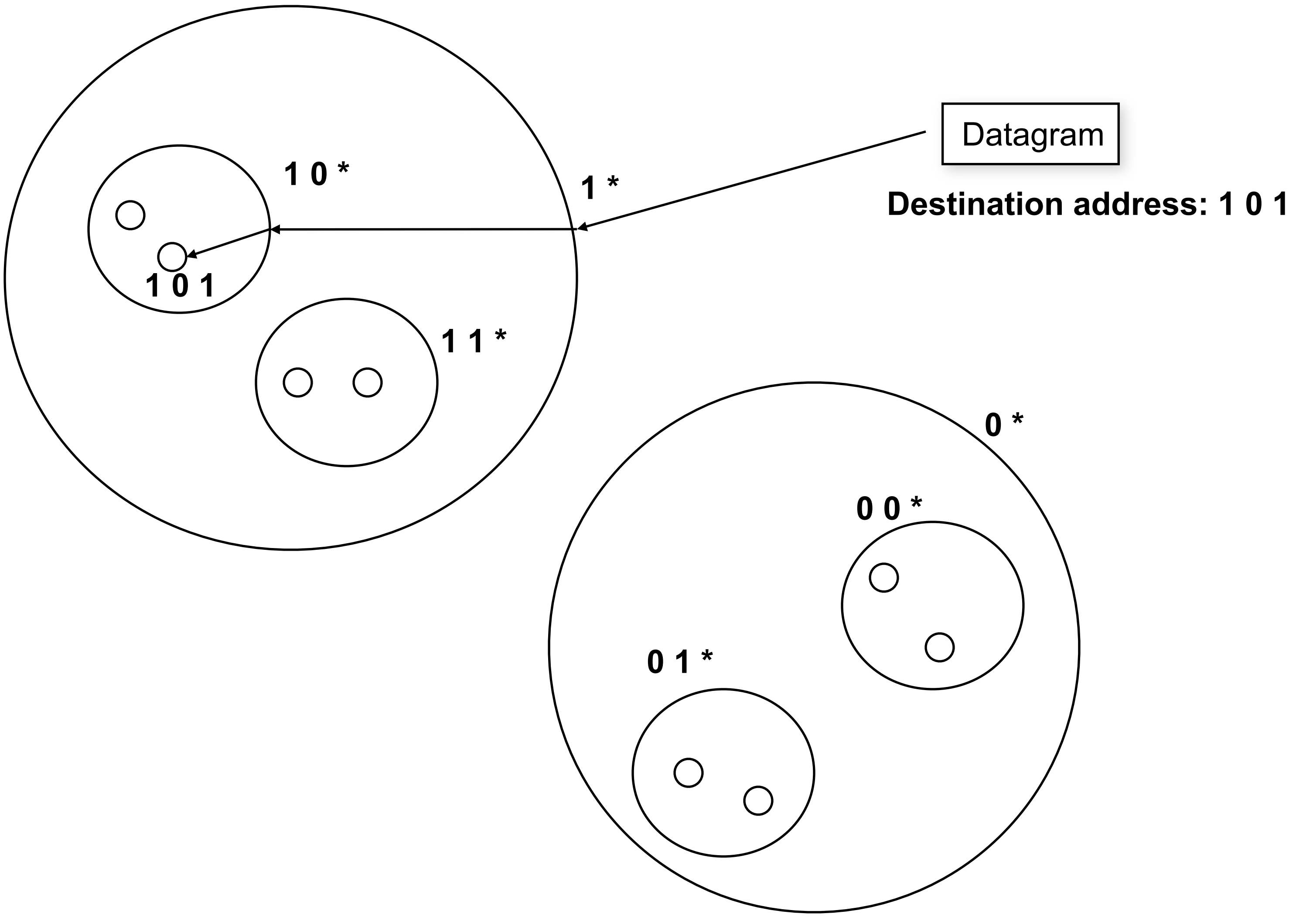
An Example of a Binary Hierarchy



An Example of a Binary Hierarchy



An Example of a Binary Hierarchy



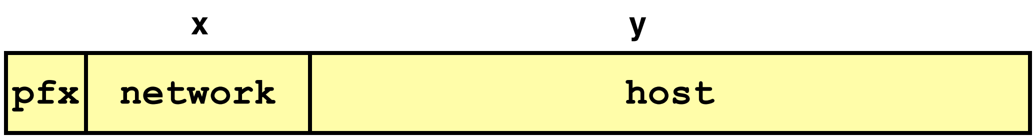
IP Addressing

- IPv4: 32-bit addresses
  - Typically, write in dotted decimal format
    - E.g., 128.42.198.135
    - Each number is decimal representation of byte
  - Big-Endian Order

0	8	16	24 31	
128	42	198	135	**Decimal**
80	2a	c6	87	**Hexadecimal**
0100 0000	0010 1010	1100 0110	1000 0111	**Binary**

IP Addressing and Forwarding

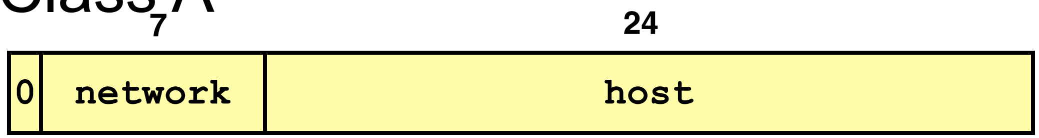
- Routing Table Requirement
  - For every possible destination IP address, give next hop
  - Nearly 2^{32} (4.3×10^9) possibilities!
- Hierarchical Addressing Scheme



  - Address split into network ID and host ID

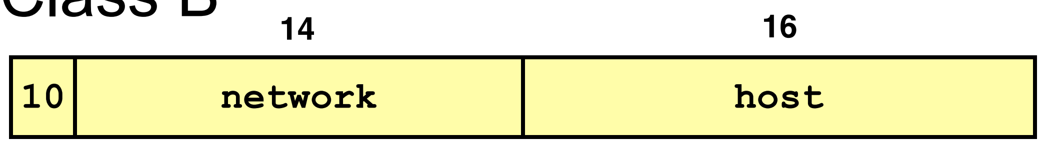
IP Address Classes

- Class A



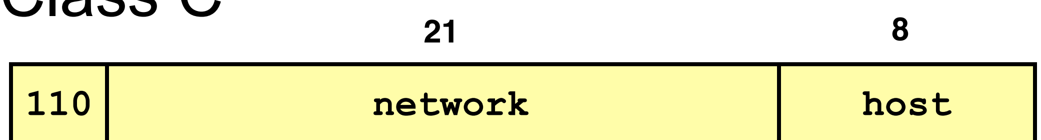
First octet: 1–126

  - mit.edu: 18.7.22.69
- Class B



First octet: 128–191

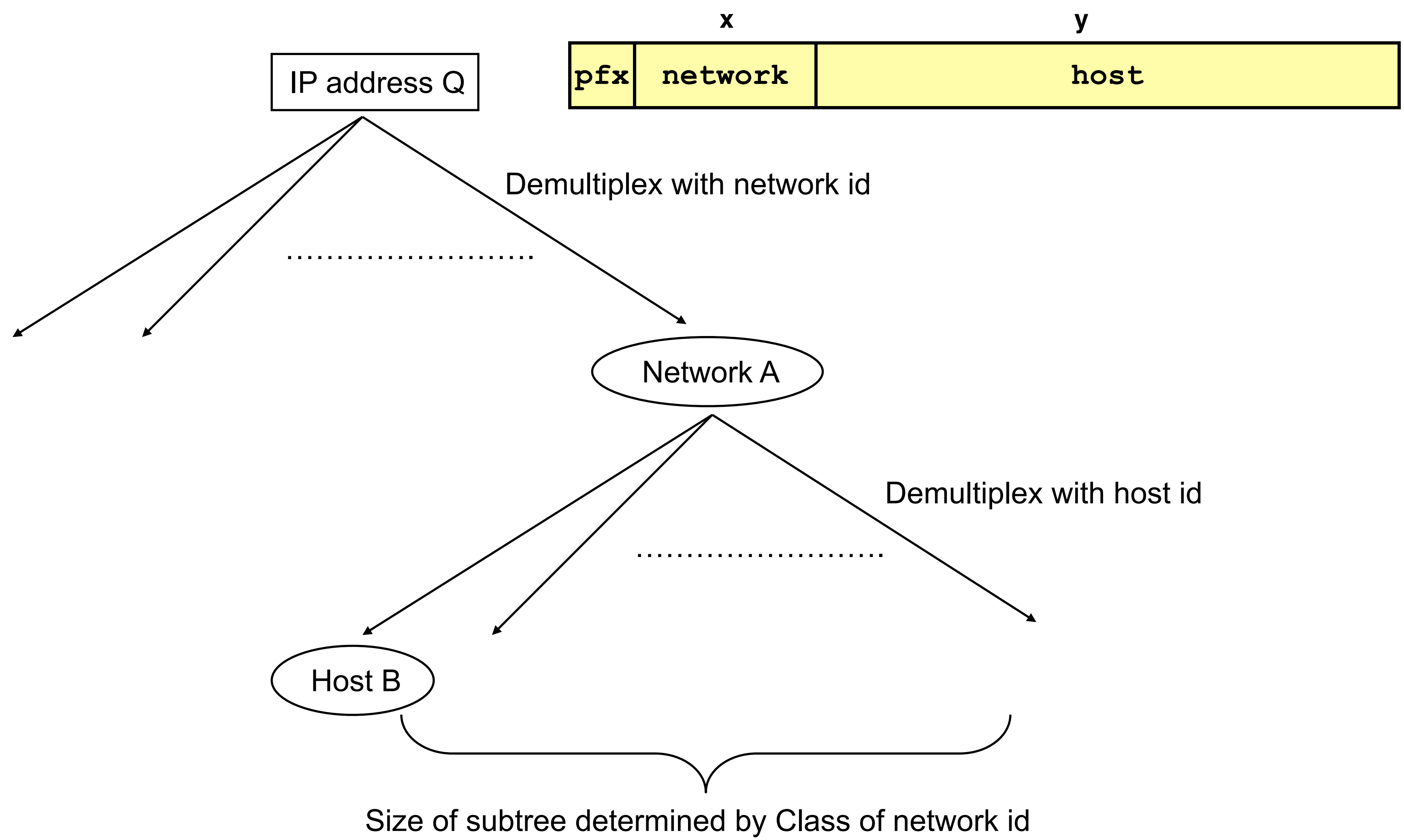
  - rice.edu: 128.42.129.23
- Class C



First octet: 192–223

  - adsl-216-63-78-18.dsl.hstntx.swbell.net: 216.63.78.18
- Classes D, E, F
  - Not commonly used

Two Level Hierarchy of Basic IP addressing



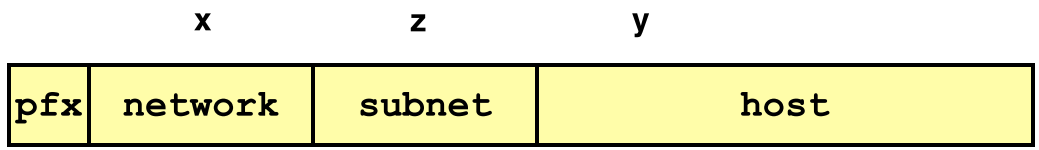
IP Address Classes

Class	Count	Hosts
A	2^7-2 = 126 (0 & 127 reserved)	2^{24}-2 = 16,777,214 (all 0s, all 1s reserved)
B	2^{14} = 16,398	2^{16}-2 = 65,534 (all 0s, all 1s reserved)
C	2^{21} = 2,097,512	2^8-2 = 254 (all 0s, all 1s reserved)
Total	2,114,036	

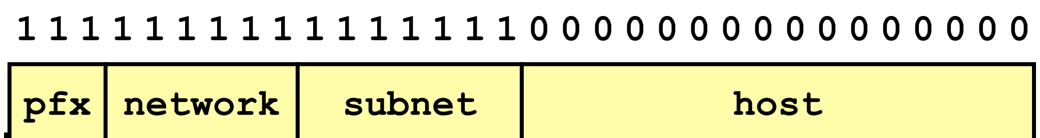
- Partitioning too Coarse
  - No local organization needs 16.7 million hosts
    - Large organization likely to be geographically distributed
  - Many organizations must make do with multiple class C's
- Too many different Network IDs
  - Routing tables must still have 2.1 million entries

Within Organization: Subnetting

- Add Another Layer to Hierarchy

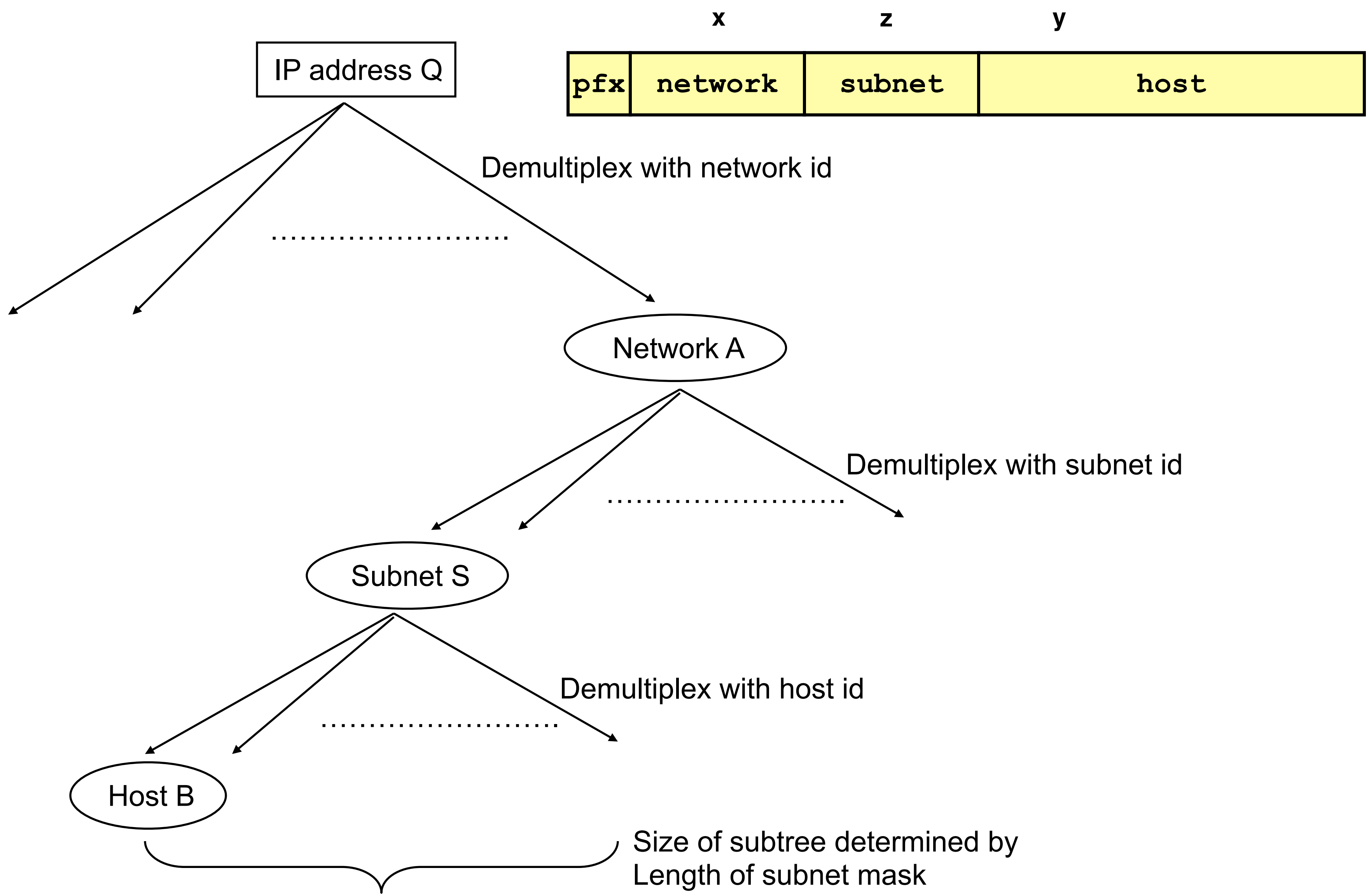


  - From the outside, appears as one monolithic network
    - Single entry in routing table
  - Within network, manage as multiple subnetworks
    - Internal routers must route according to subnet ID
- Subnet Mask
  - Way to specify break between subnet ID and host ID



  - Similar masks used in many contexts

Subnetting


x
z
y
pfx
network
subnet
host
IP address Q
Demultiplex with network id
Network A
Demultiplex with subnet id
Subnet S
Demultiplex with host id
Host B
Size of subtree determined by
Length of subnet mask

Routing Table

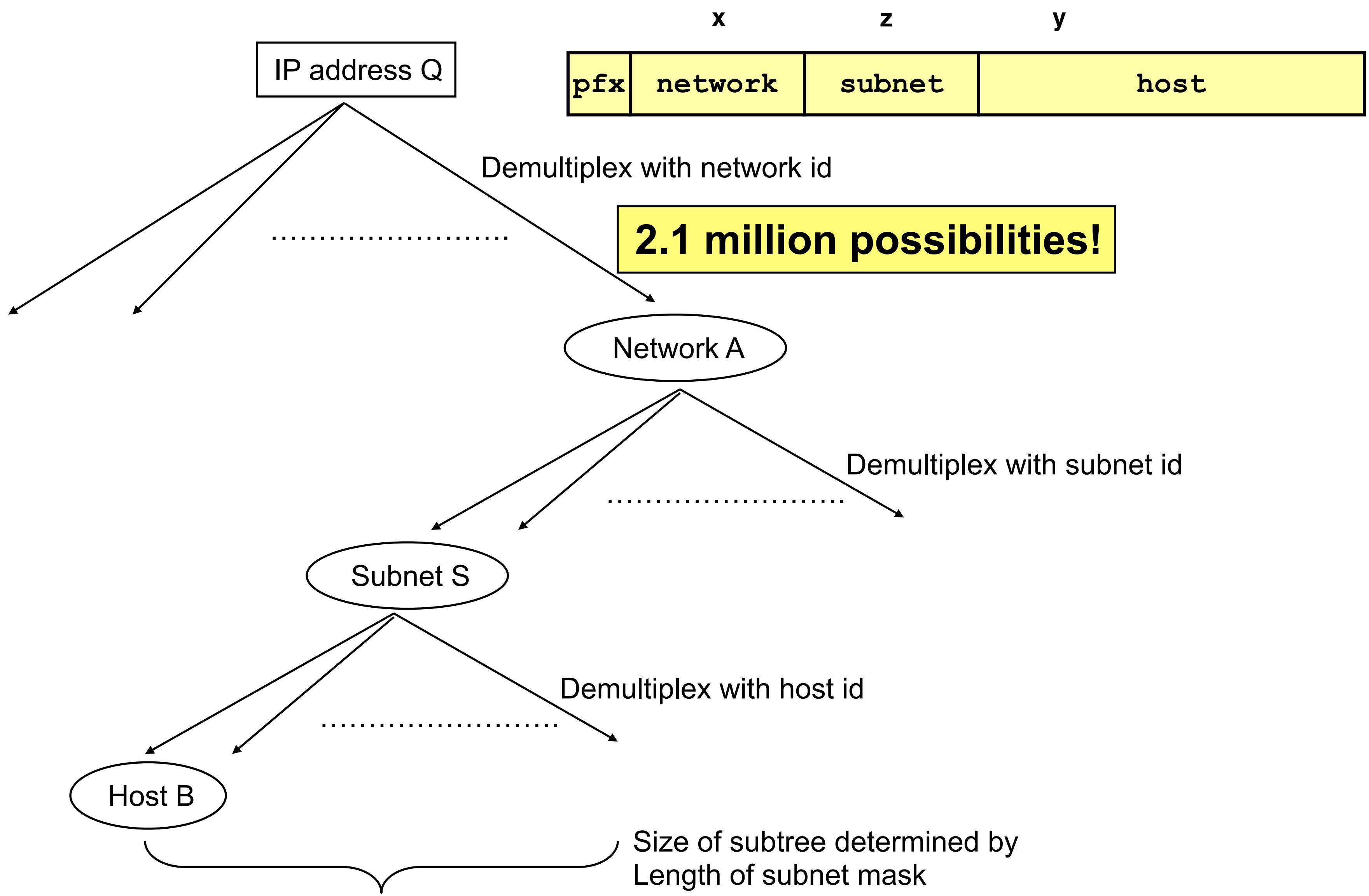
Address Pattern	Subnet Mask	Next Hop
128.42.222.0	255.255.255.0	R1
128.42.128.0	255.255.128.0	R2
18.0.0.0	255.0.0.0	R3
0.0.0.0	0.0.0.0	R4
128.42.0.0	255.255.0.0	R5

- Address 128.42.222.198 matches 4 entries
- Longest Prefix Match
  - Select entry with longest sequence of 1's in mask
  - Most specific case

Improving the Hierarchy

- Basic Idea of Hierarchy is Good
  - Organizations of different sizes can be assigned different numbers of IP addresses
- Shortcomings of Class-Based Addressing
  - Class A too coarse; Class C too fine; not enough Class B's
  - When fully deployed would have too many entries in routing table (2.1 million)
- Solution
  - Hierarchy with finer gradation of network/host ID split

Subnetting


x
z
y
pfx
network
subnet
host
IP address Q
Demultiplex with network id
2.1 million possibilities!
Network A
Demultiplex with subnet id
Subnet S
Demultiplex with host id
Host B
Size of subtree determined by
Length of subnet mask

Classless Interdomain Routing

- CIDR, pronounced “cider”
- Arbitrary Split Between Network & Host IDs
  - Specify either by mask or prefix length

`1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0`

network	host

  - E.g., Rice can be specified as
    - 128.42.0.0 with netmask 255.255.0.0
    - 128.42.0.0/16

Aggregation with CIDR

– Original Use: Aggregate Class C Addresses
– One organization assigned contiguous range of class C's
  - e.g., Microsoft given all addresses 207.46.192.X -- 207.46.255.X
  - Specify as CIDR address 207.46.192.0/18

0	8	16	24 31	
207	46	192	0	**Decimal**
cf	2e	c0	00	**Hexadecimal**
1100 1111	0010 1110	11xx xxxx	xxxx xxxx	**Binary**

Upper 18 bits frozen **Lower 14 bits arbitrary**

- Represents $2^6 = 64$ class C networks

Routing Table Entry Examples

- Snapshot From MAE-West Routing Table
  - Probably out of date

Address	Prefix Length	Third Byte	Byte Range
207.46.0.0	19	$000xxxxx_2$	0 – 31
207.46.32.0	19	$001xxxxx_2$	32 – 63
207.46.64.0	19	$010xxxxx_2$	64 – 95
207.46.128.0	18	$10xxxxxx_2$	128 – 191
207.46.192.0	18	$11xxxxxx_2$	192 – 255

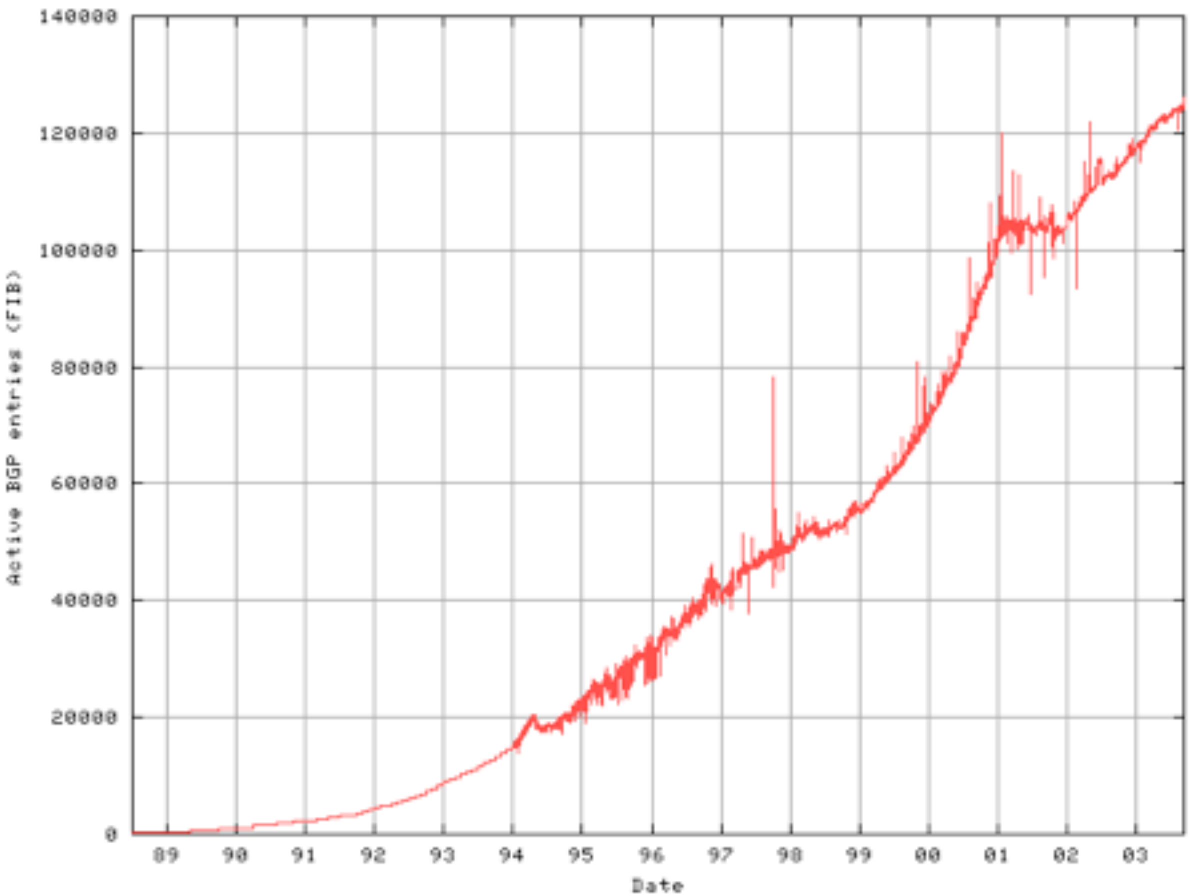
microsoft.com: 207.46.245.214 & 207.46.245.222

  - Note hole in table: Nothing covers bytes 96 – 127

Splitting with CIDR

- Expose subnetting structure to external routers
- Example
  - Class A address 12.X.X.X has 413 entries in routing table
  - Prefix lengths 8--24
  - attbi.com
    - Backbone services of AT&T
  - Geographically distributed
    - Don't want all packets to concentrate to single region

Size of Complete Routing Table



– Source: www.cidr-report.org
– Shows that CIDR has kept # table entries in check
  - Currently require 124,894 entries for a complete table
  - Only required by backbone routers

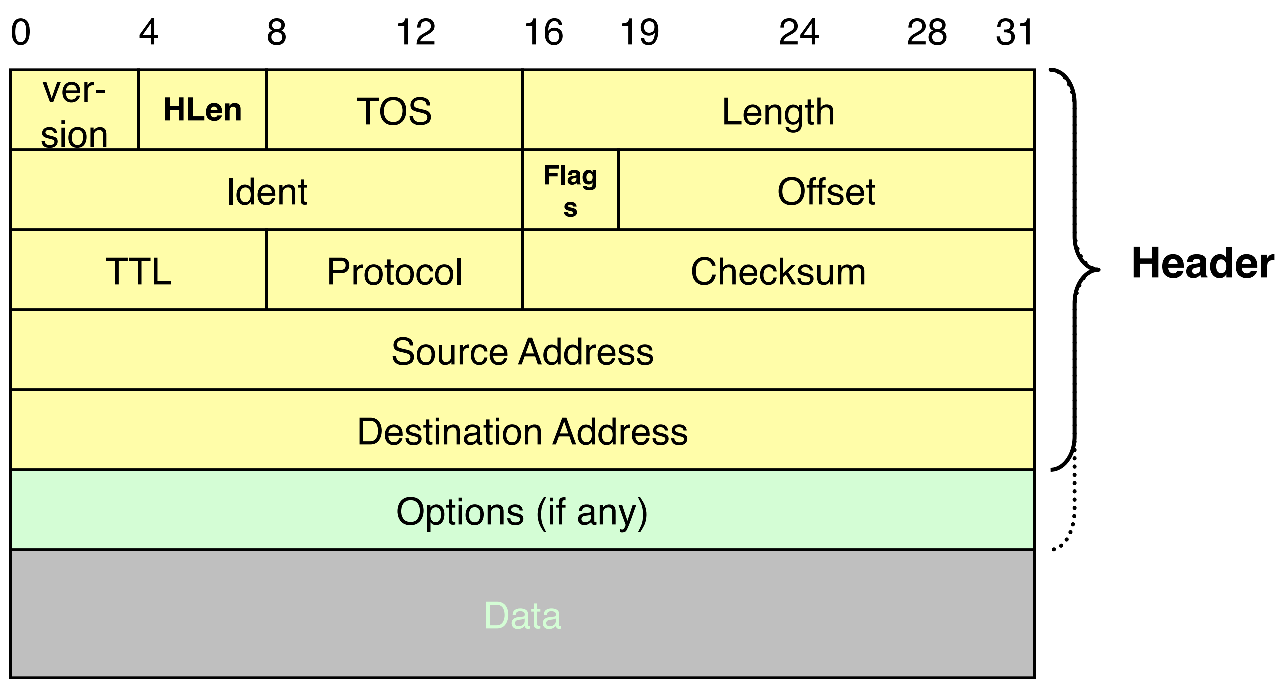
Important Concepts

- Hierarchical addressing critical for scalable system
  - Don't require everyone to know everyone else
  - Reduces amount of updating when something changes
- Non-uniform hierarchy useful for heterogeneous networks
  - Class-based addressing too coarse
  - CIDR helps
  - Move to IPv6 due to limited number of 32-bit addresses
- Implementation Challenge
  - Longest prefix matching much more difficult than when no ambiguity

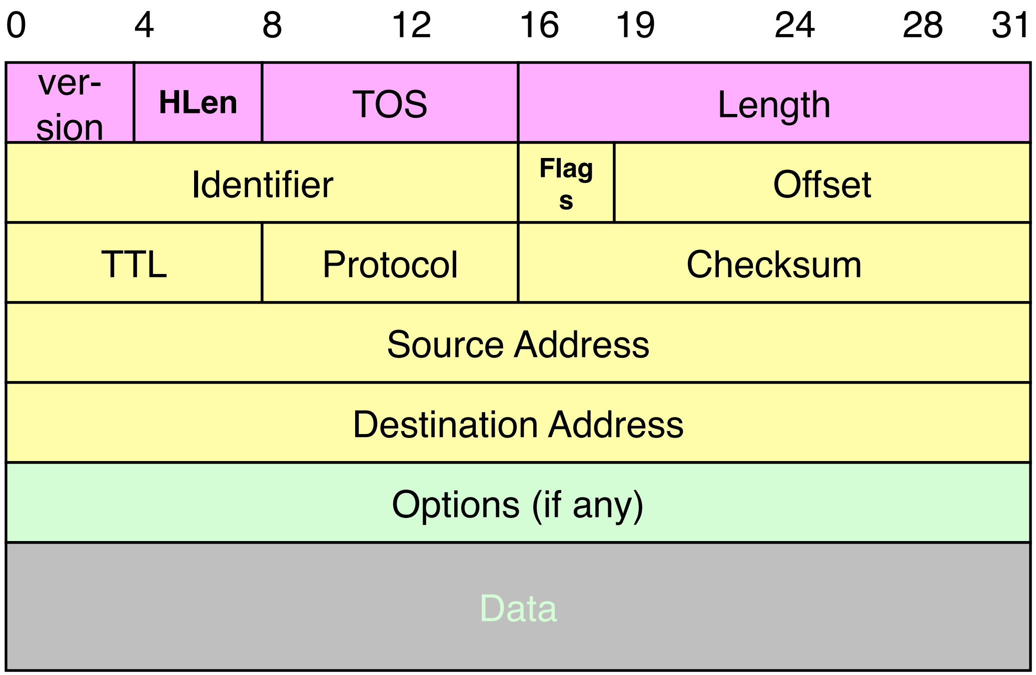
IP Service Model

- Datagram
  - Each packet self-contained
    - All information needed to get to destination
    - No advance setup or connection maintenance
  - Analogous to letter or telegram

IPv4 Packet Format



IP Header Fields: Word 1



- Version: IP Version
  - 4 for IPv4
- HLen: Header Length
  - 32-bit words (typically 5)
- TOS: Type of Service
  - Priority information
- Length: Packet Length
  - Bytes (including header)

- Header format can change with versions
  - First byte identifies version
- Length field limits packets to 65,535 bytes
  - In practice, break into much smaller packets for network performance considerations

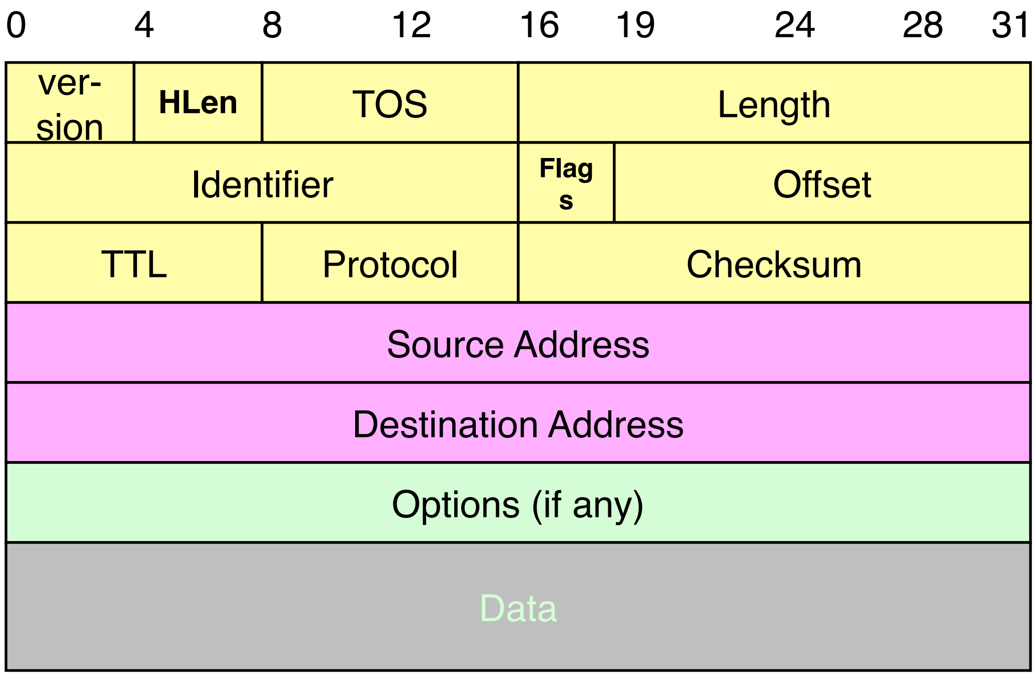
IP Header Fields: Word 3

0	4	8	12	16	19	24	28	31
ver-sion	HLen	TOS		Length				
Identifier				Flags	Offset			
TTL		Protocol		Checksum				
Source Address								
Destination Address								
Options (if any)								
Data								

- TTL: time to live
  - Decrement by one at each intermediate router
  - Prevent looping forever
- Protocol
  - Protocol of next layer (in “data”)
  - E.g. TCP (6), UDP (17)
- Checksum
  - Of IP header

- Protocol field used for demultiplexing
- Checksum re-computed at each router
  - Why?
- TTL field used to implement traceroute

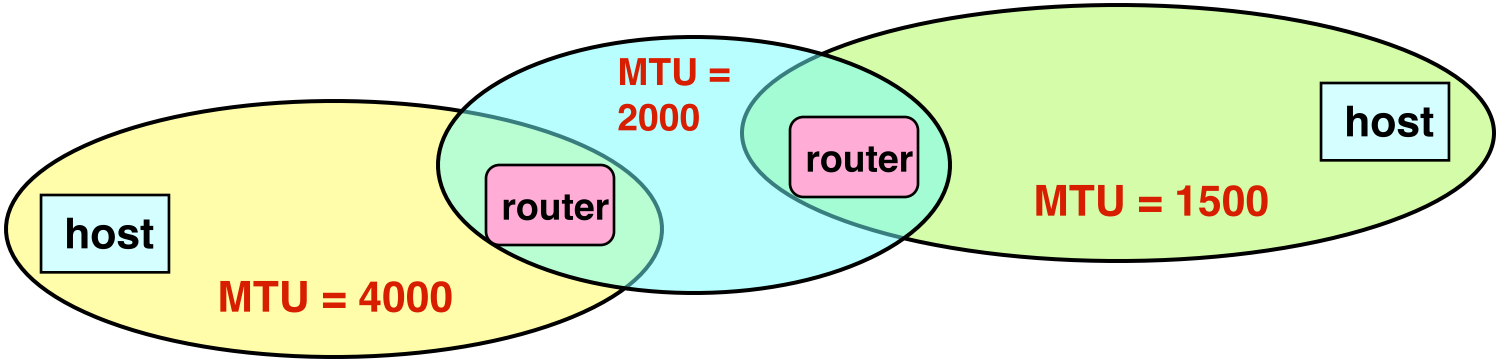
IP Header Fields: Words 4&5



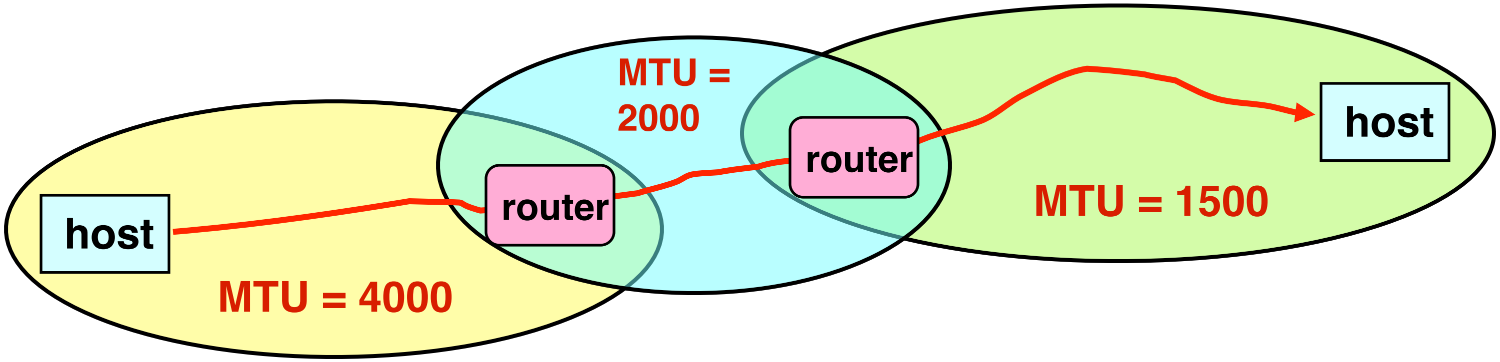
- Source Address
  - 32-bit IP address of sender
- Destination Address
  - 32-bit IP address of destination

- Like the addresses on an envelope
- In principle, globally unique identification of sender & receiver
  - In practice, there are contexts where either source or destination are not the ultimate addressees

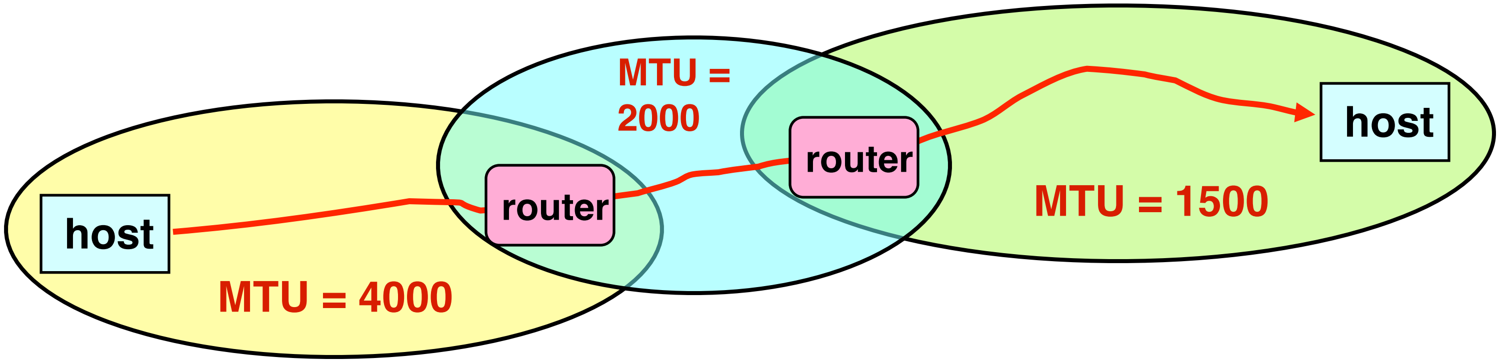
IP Fragmentation



IP Fragmentation

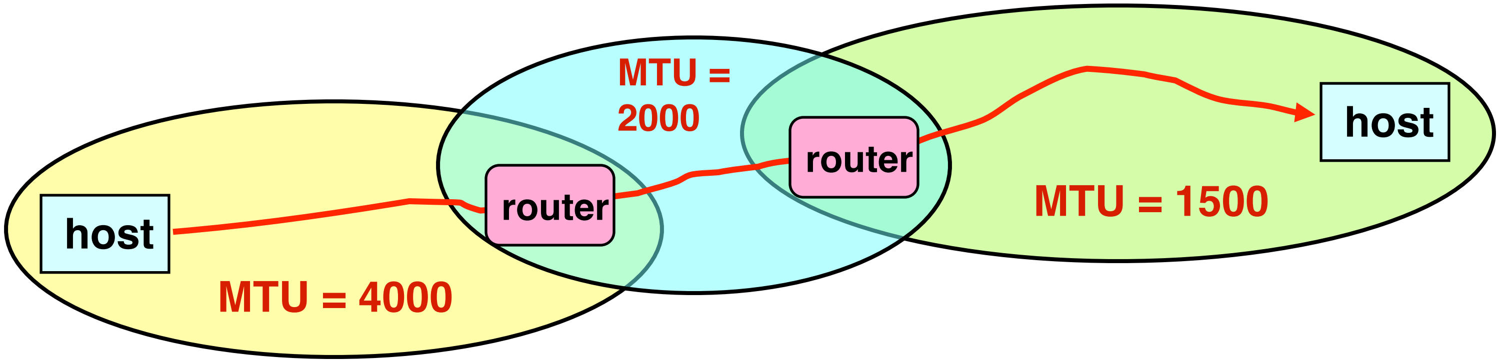


IP Fragmentation



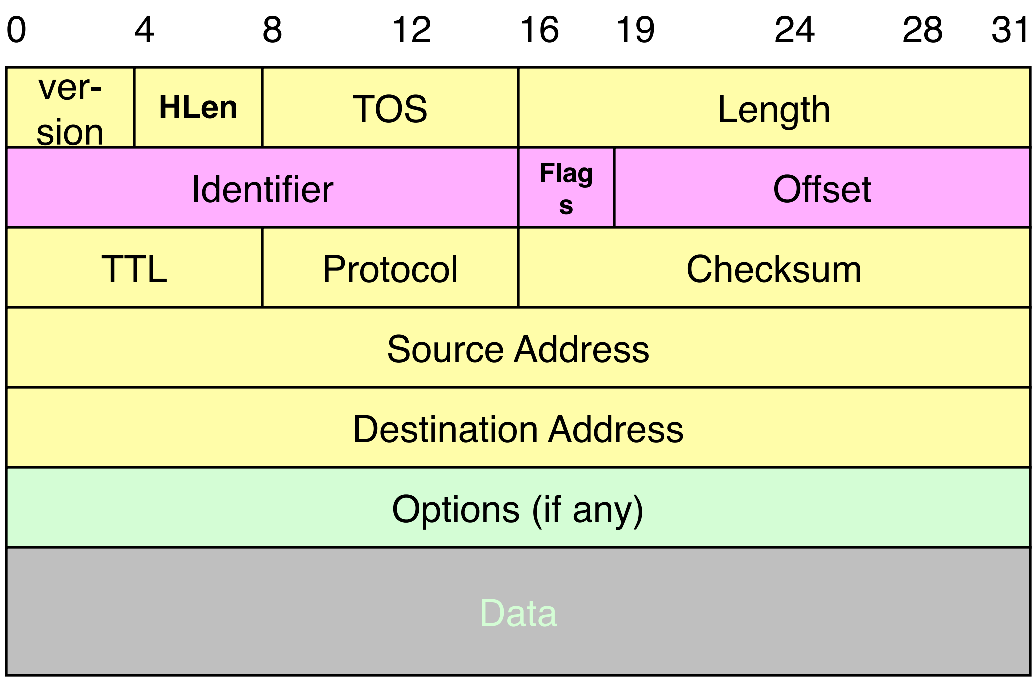
- Every Network has Own Maximum Transmission Unit (MTU)
  - Largest IP datagram it can carry within its own packet frame
    - E.g., Ethernet is 1500 bytes
  - Don't know MTUs of all intermediate networks in advance

IP Fragmentation



- Every Network has Own Maximum Transmission Unit (MTU)
  - Largest IP datagram it can carry within its own packet frame
    - E.g., Ethernet is 1500 bytes
  - Don’t know MTUs of all intermediate networks in advance
- IP Solution
  - When hit network with small MTU, fragment packets
    - Might get further fragmentation as proceed farther
  - Reassemble at the destination
    - If any fragment disappears, delete entire packet

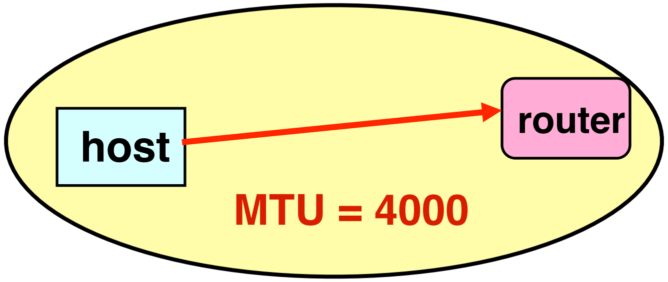
IP Header Fields: Word 2

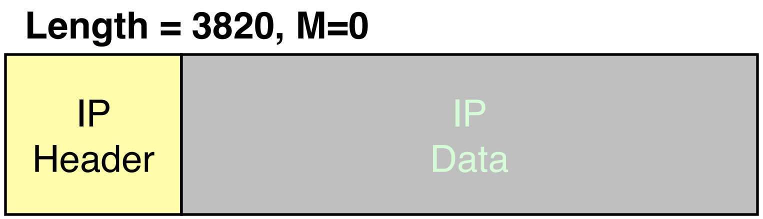


- Identifier
  - Unique identifier for original datagram
    - Typically, source increments counter every time sends packet
- Flags (3 bits)
  - M flag: This is not the last fragment
- Offset
  - Byte position of first byte in fragment ÷ 8
  - Byte position must be multiple of 8

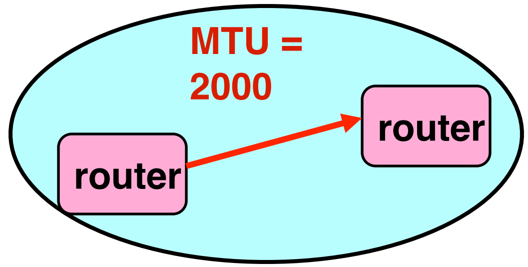
- Each fragment carries copy of IP header
  - All information required for delivery to destination
- All fragments comprising original datagram have same identifier
- Offsets indicate positions within datagram

IP Fragmentation Example #1

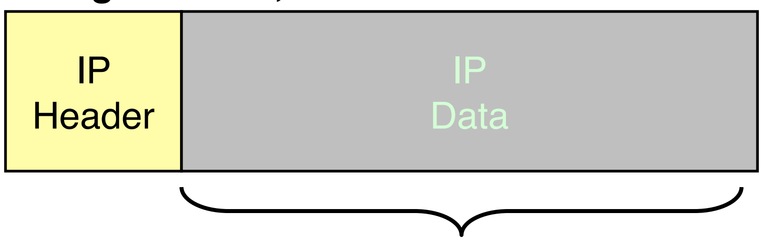




IP Fragmentation Example #2



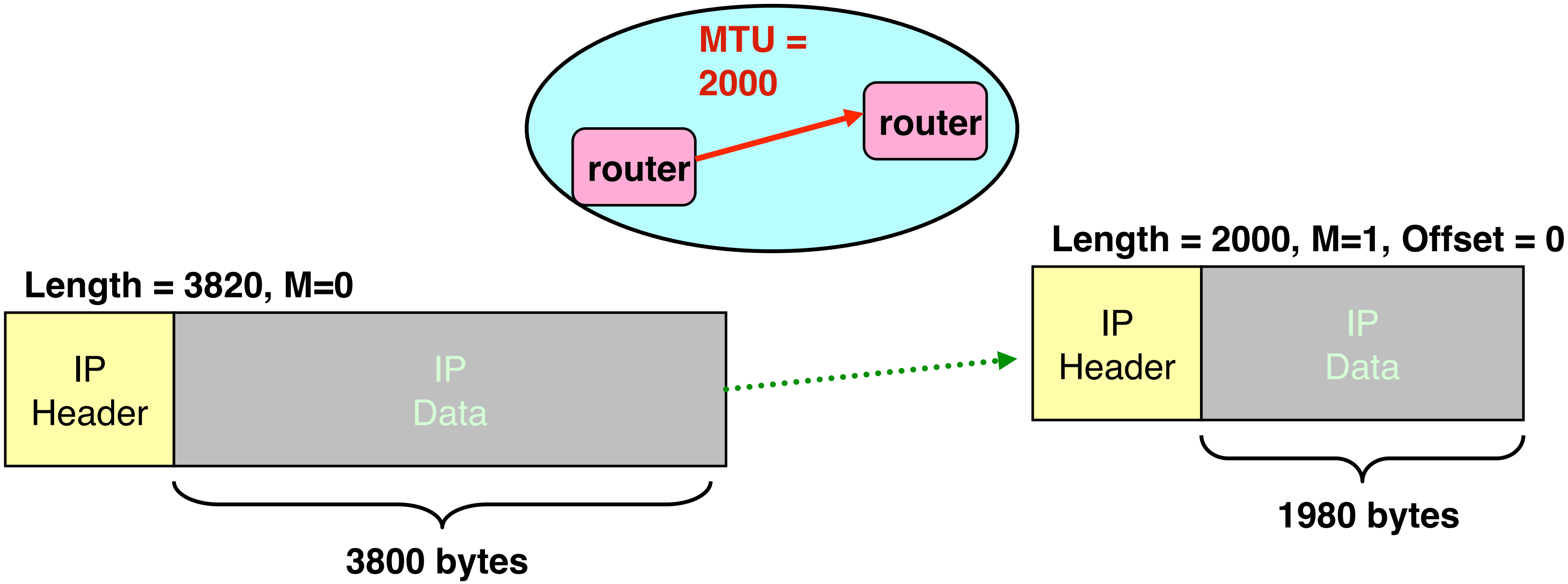
Length = 3820, M=0



3800 bytes

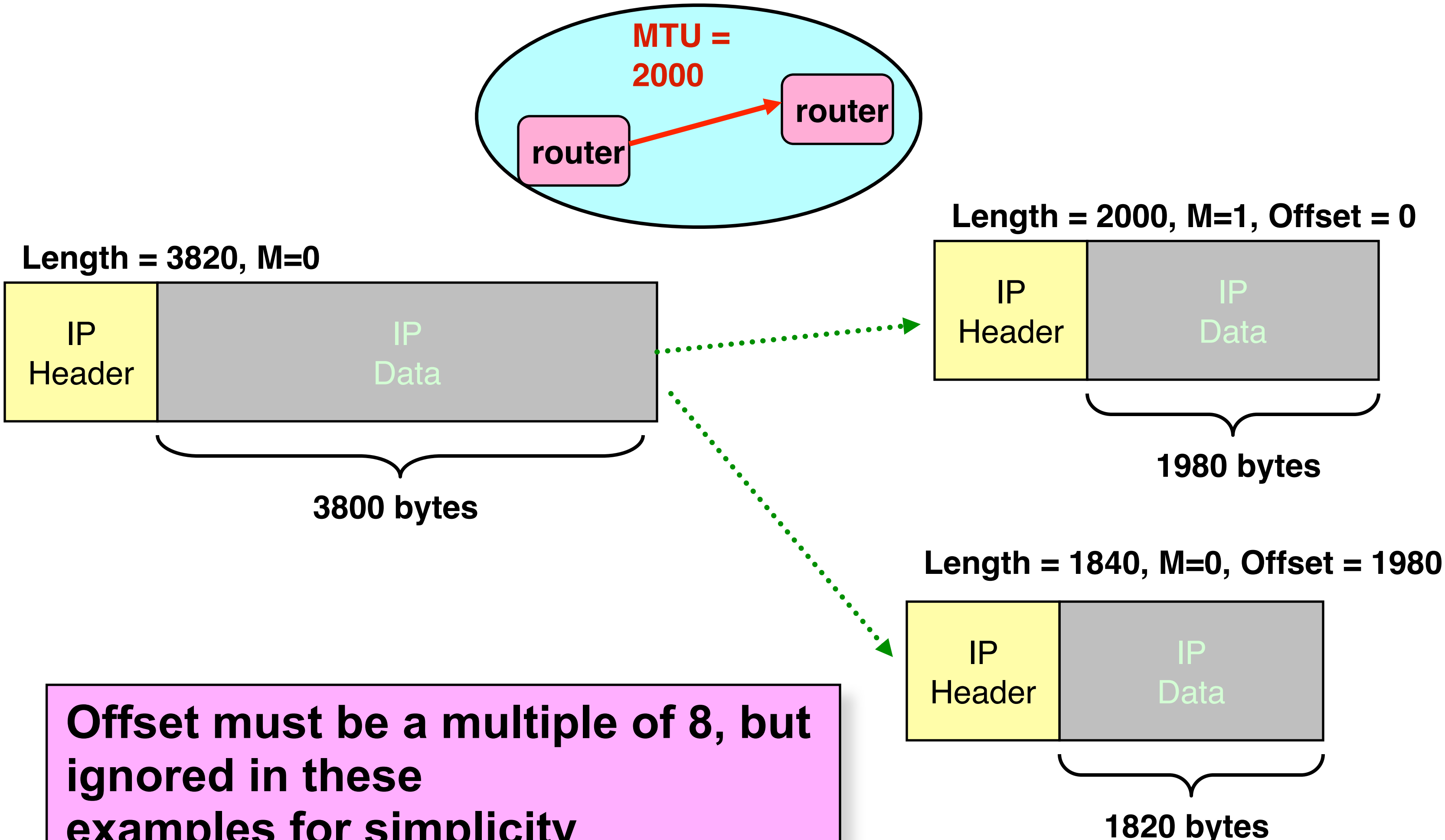
Offset must be a multiple of 8, but ignored in these examples for simplicity

IP Fragmentation Example #2



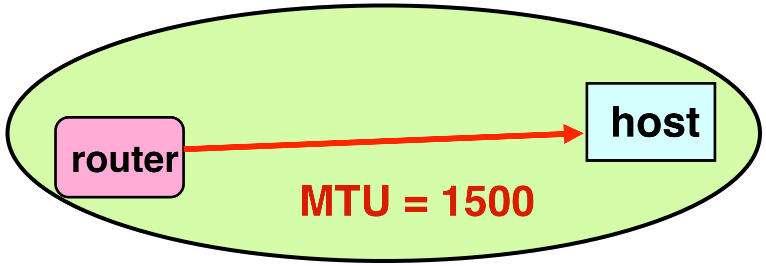
Offset must be a multiple of 8, but ignored in these examples for simplicity

IP Fragmentation Example #2

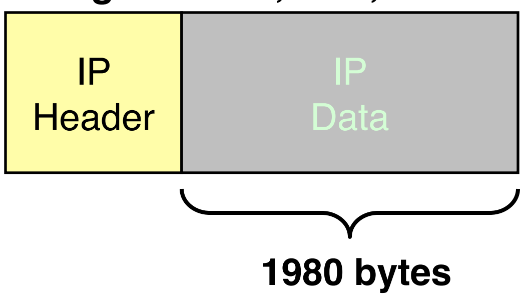


Offset must be a multiple of 8, but ignored in these examples for simplicity

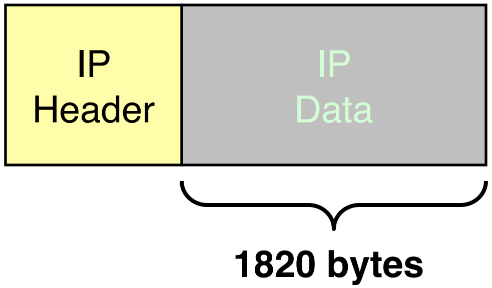
IP Fragmentation Example #3



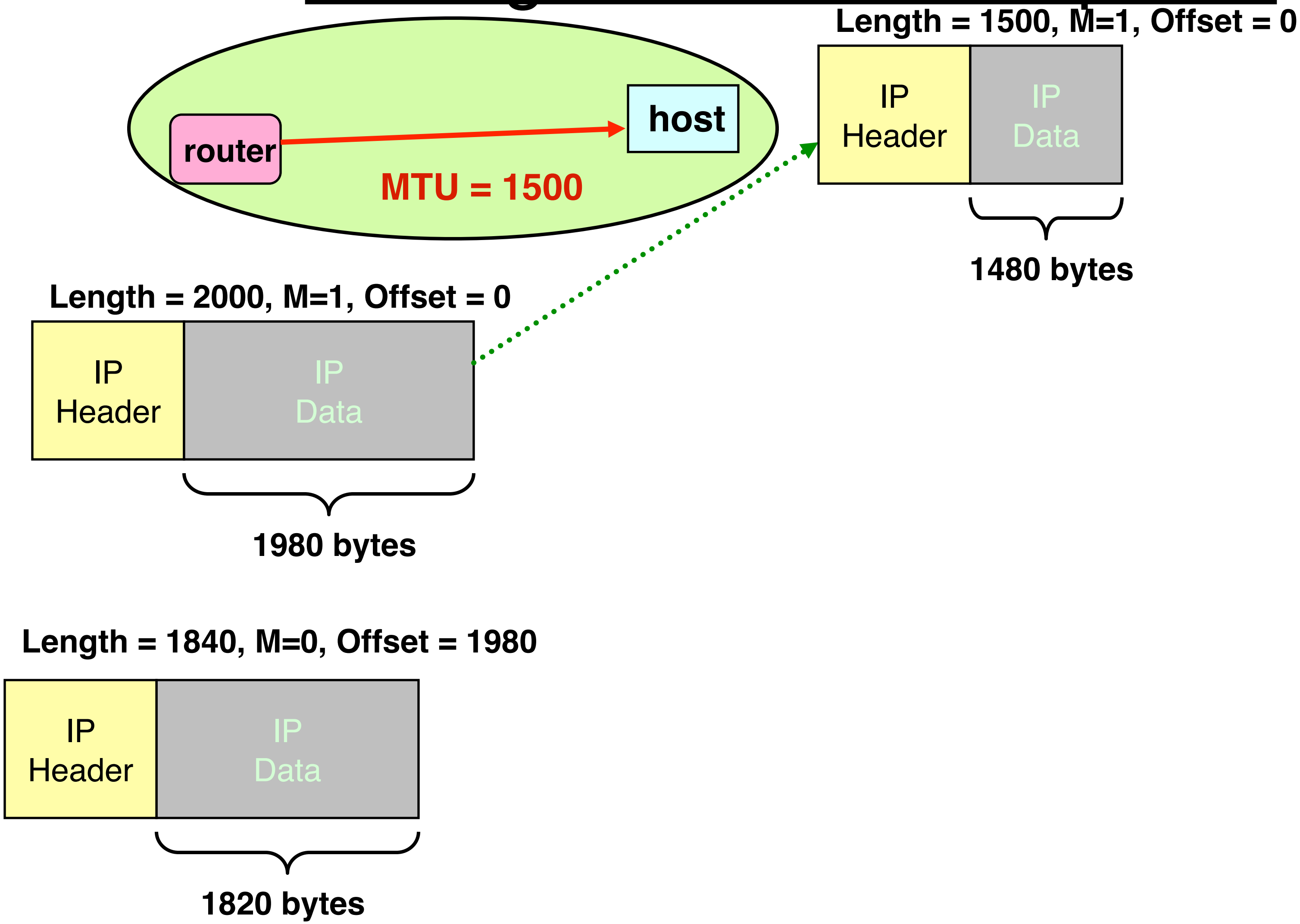
Length = 2000, M=1, Offset = 0



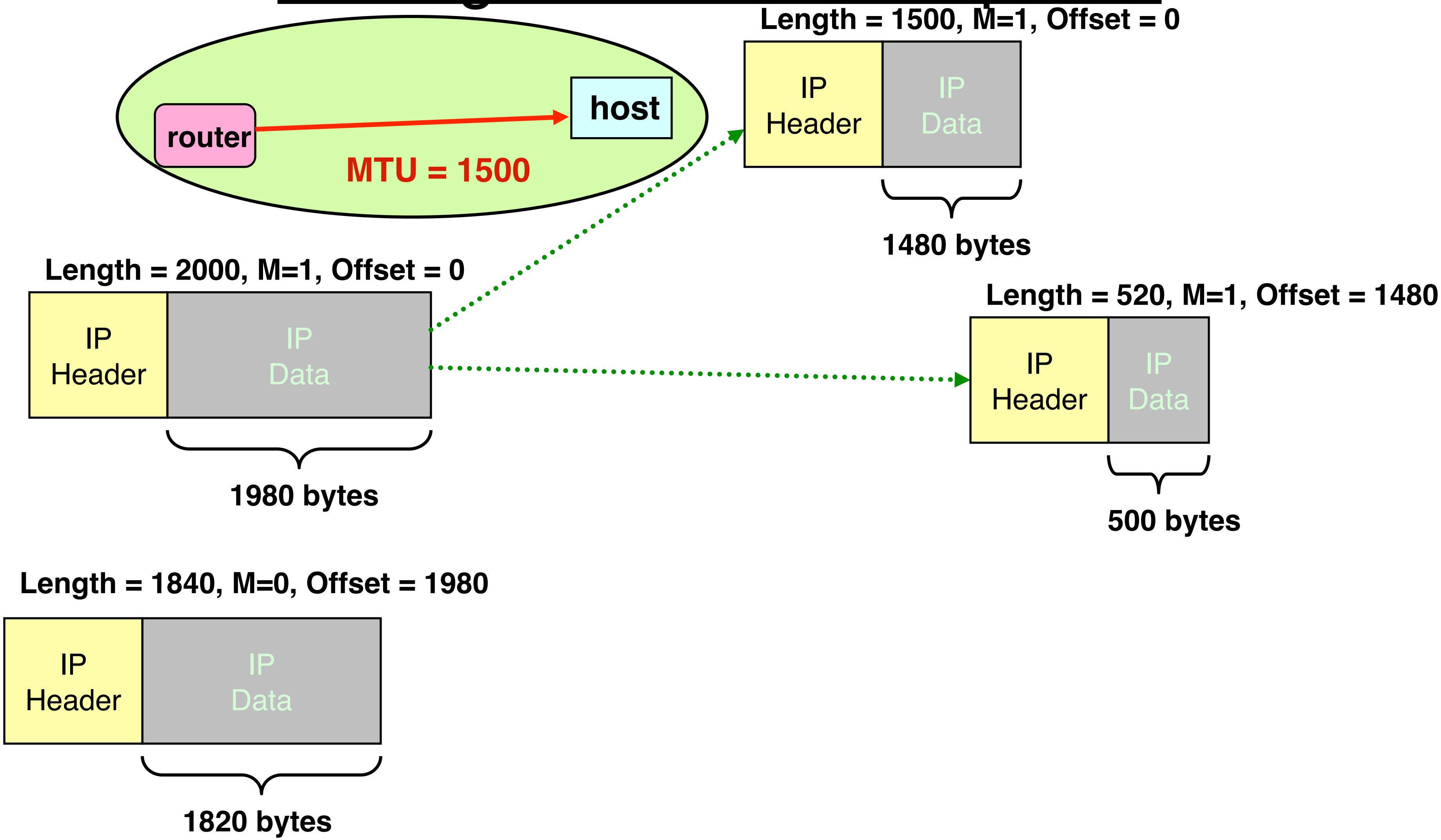
Length = 1840, M=0, Offset = 1980



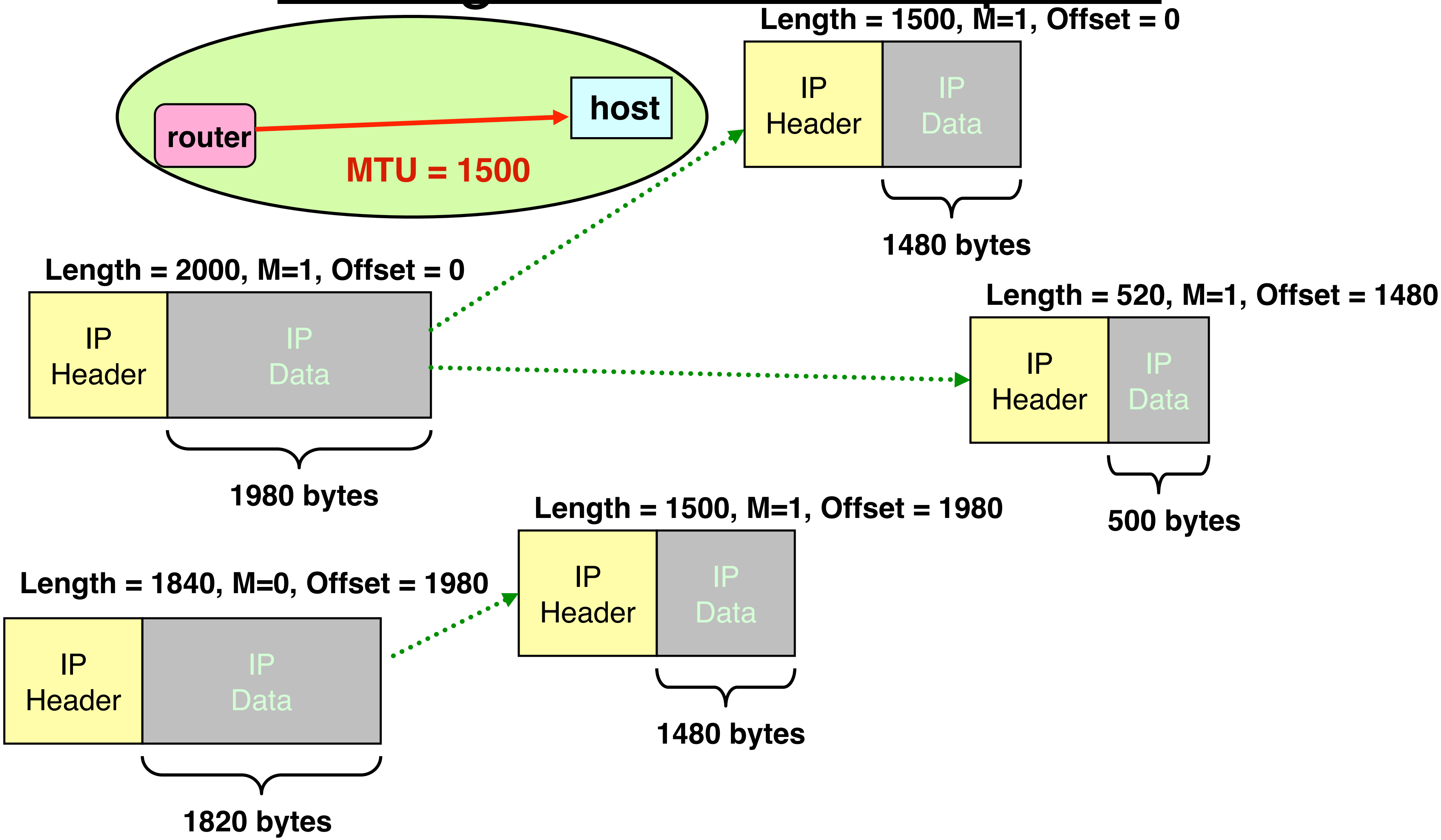
IP Fragmentation Example #3



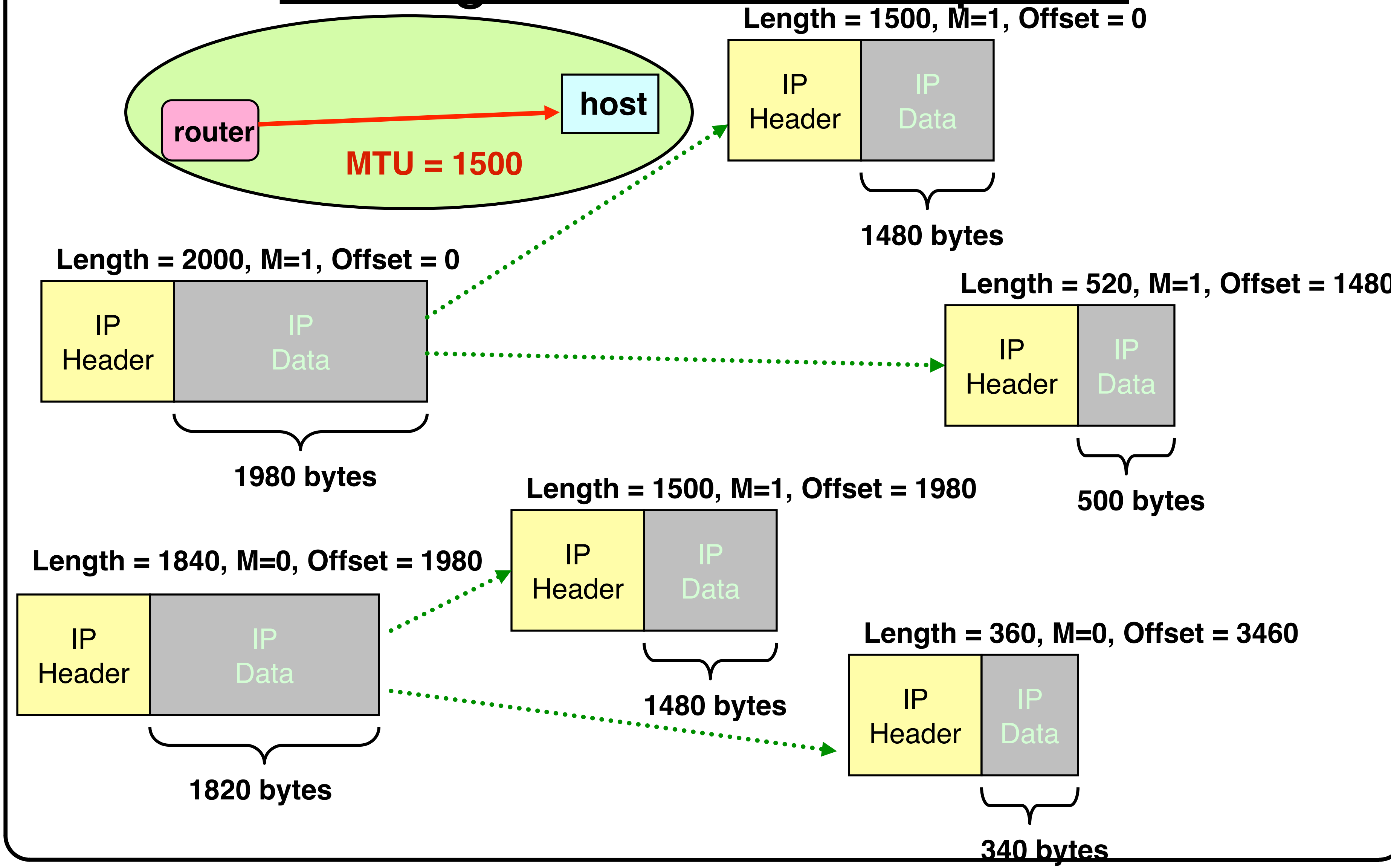
IP Fragmentation Example #3



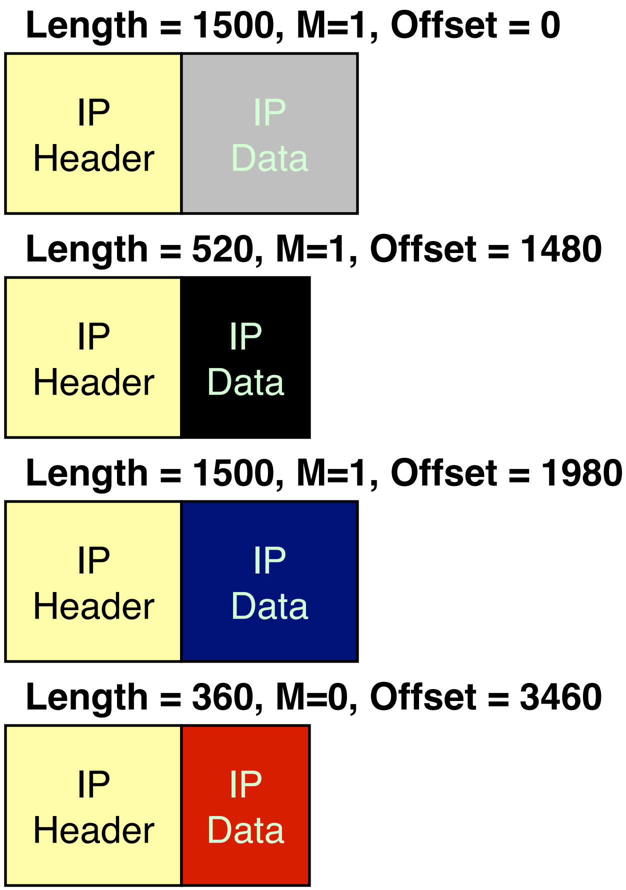
IP Fragmentation Example #3



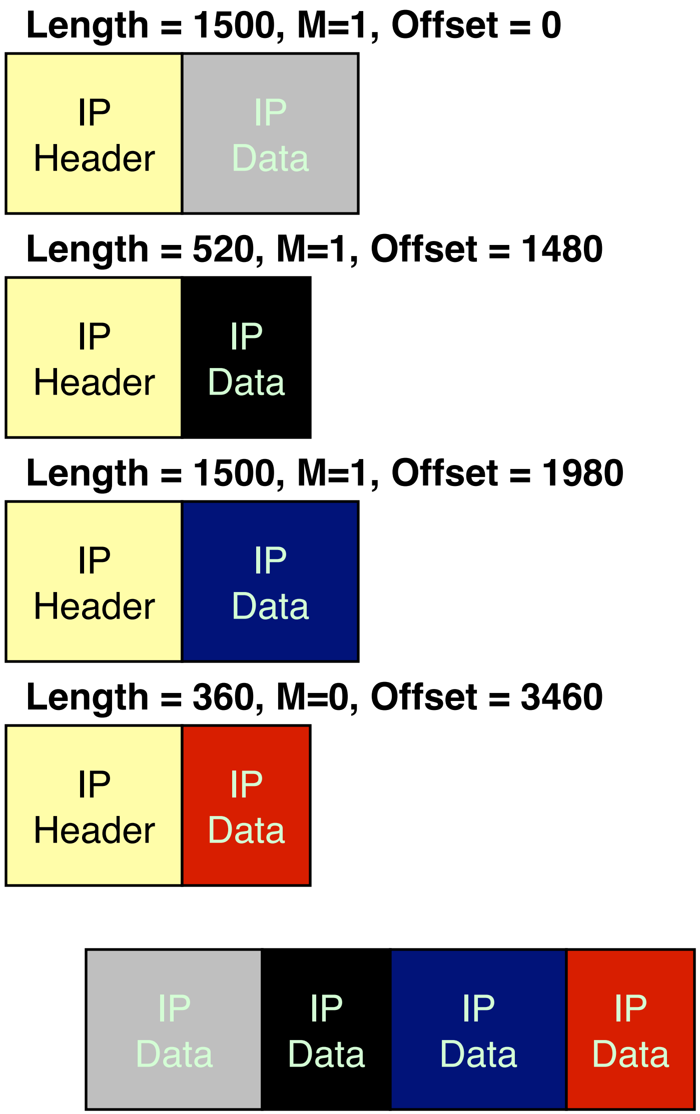
IP Fragmentation Example #3



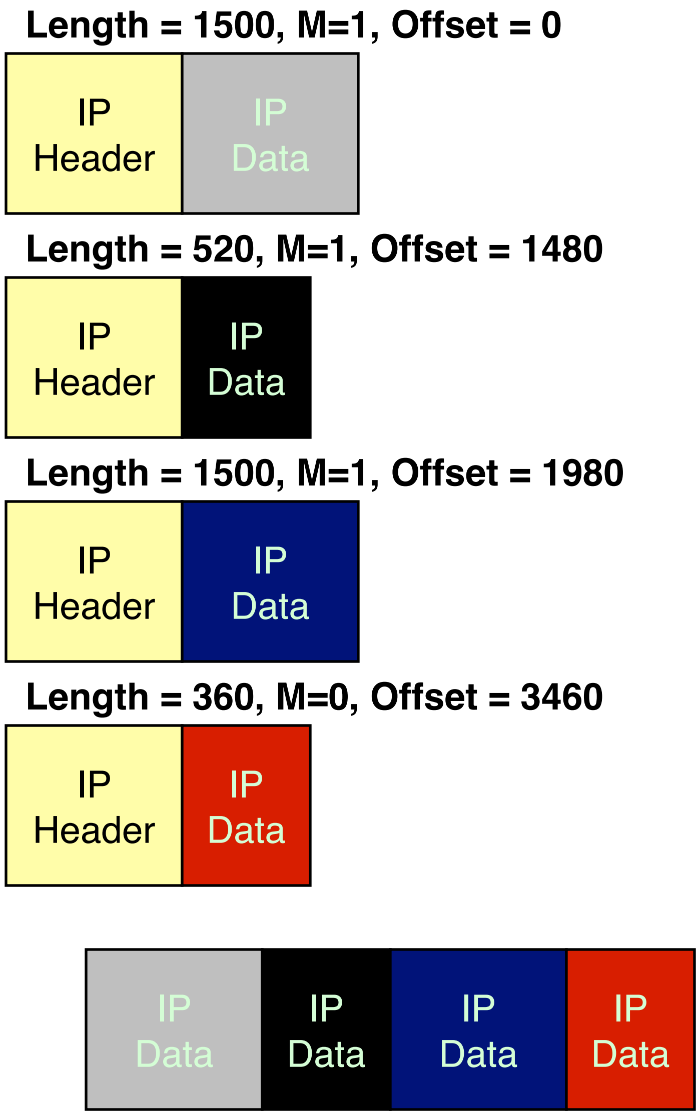
IP Reassembly



IP Reassembly

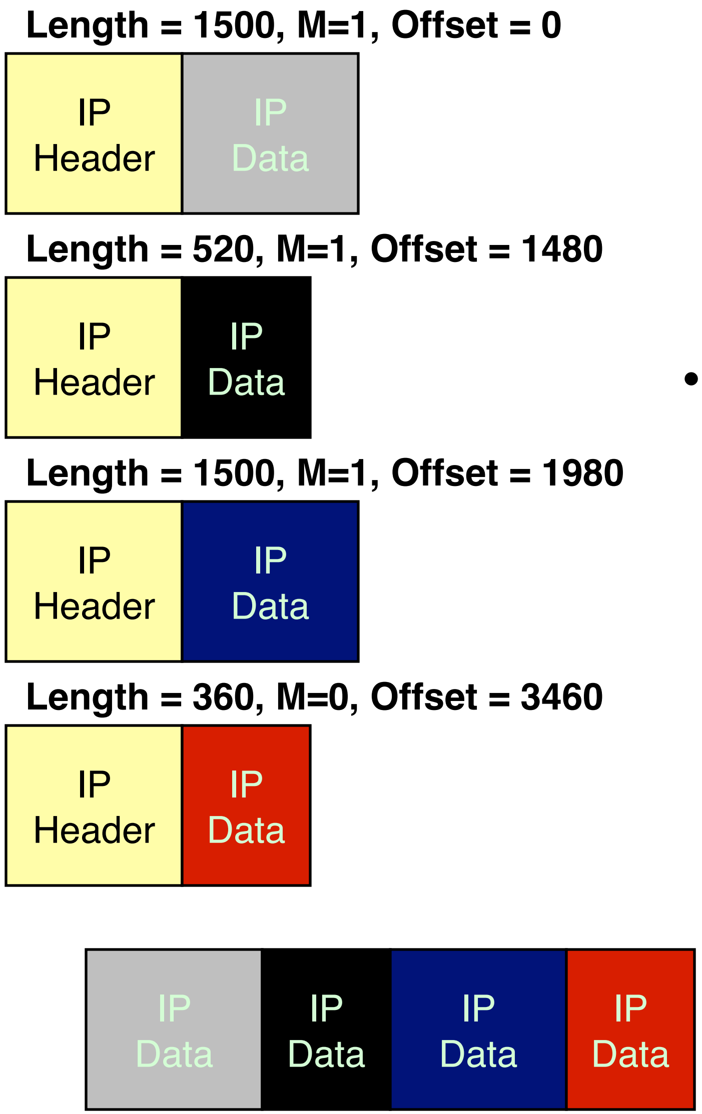


IP Reassembly



- Performed at final destination
- Fragment with M=0 determines overall length
  - (360-20)+3460

IP Reassembly



- Performed at final destination
- Fragment with M=0 determines overall length
  - (360-20)+3460

- Challenges
  - Fragments might arrive out-of-order
    - Don't know how much memory required until receive final fragment
  - Some fragments may be duplicated
    - Keep only one copy
  - Some fragments may never arrive
    - After a while, give up entire process
  - Significant memory management issues

Frag. & Reassembly Concepts

  - Demonstrates Many Internet Concepts
- Decentralized
  - Every network can choose MTU
- Connectionless Datagram Protocol
  - Each (fragment of) packet contains full routing information
  - Fragments can proceed independently and along different routes
- Fail by Dropping Packet
  - Destination can give up on reassembly
  - No need to signal sender that failure occurred
- Keep Most Work at Endpoints
  - Reassembly

Frag. & Reassembly Reality

- Reassembly Fairly Expensive
  - Copying, memory allocation
  - Want to avoid
- MTU Discovery Protocol
  - Protocol to determine MTU along route
    - Send packets with “don’t fragment” flag set
    - Keep decreasing message lengths until packets get through
    - May get a “can’t fragment error” message from router which contains the correct MTU
  - Assumes every packet will follow same route
    - Routes tend to change slowly over time
- Common Theme in System Design
  - Fragmentation is handled as a special case by slower general processor in router
  - Assure correctness by implementing complete protocol
  - Optimize common cases to avoid full complexity