15-441

Computer Networking

Internetworking - Forwarding
Feb. 13, 2006

Topics

- What's an Internet?
- IP forwarding
- 1980 / 8 = 247.5

Slides

- Hui Zhang, Randy Bryant, Dave Eckhardt

Synchronization

Textbook

- Start reading Chapter 4 (mammoth!)
- Today
  - "Internetworking"
  - Section 4.1, plus some, minus some
- Upcoming
  - Routing (3 lectures): Section 4.2 (more or less)

The other kind of learning

- Which coding standard did you choose?
  - BSD/Linux/PDL?
- Who has used source control?
- Consider scheduled P2 meetings with your partner
  - You will be responsible reading for your partner's code...

Prelude

What does “TCP” stand for?

- What does it do?

What does “IP” stand for?

- What does ***it*** do that TCP doesn't???

“Internetworking”??

How can we study Internetworking: only one Internet?

- ***Lots*** **of world-spanning digital networks**
  - **Telegraph, telephone**
  - **IBM VNET**
  - **DEC DECNET**
  - **X.25 public data network (Europe)**
  - **IBM SNA**
  - **Xerox Vines**

What makes “The” Internet special?

"The Internet Way"

What makes "The Internet" special?

- (Eckhardt's opinion)

1. Heterogeneity

- The "Internet Problem" (Cerf & Kahn): three networks
  - Land-based computer network (ARPANET, ≠ Internet)
  - Mobile packet radio network
  - Satellite radio network
- Each network "had its own ideas"
  - Node address, packet size range, medium access control, ...
  - Each network carefully designed to do "its thing" well
    - » Environments very different, solutions very different
    - » No way to declare "one way to do things"

“The Internet Way”

2. TCP $\neq$ IP

- This decision was not immediately obvious
  - ARPANET “NCP” was one protocol
  - X.25 was one protocol
  - Everybody liked & understood reliable stream protocols
- In some ways this decision was bad...
  - ...(forward ref to congestion control lecture)...
  - ...“See, it really ***wasn't*** obvious!”

"The Internet Way"

3. Semi-accidental "open standards" approach

- "Supercomputers" were very different
- From the beginning, lots of implementations of protocols
- Cooperative/competitive interoperability "bake-off" events
  - ...paid for by the (sole-source) funding agency.
- Result: "of course" protocol docs were widely available
  - Versus
    - » ISO, IEEE: development supported by people paying for access to standards documents

“The Internet Way”

4. The “RFC approach”

- They're not really “standards documents”
- More like “Hey, look what I did!”
- As opposed to: “Observe my cool design for the future...”
- “IETF credo” (Dave Clark, 1992)
  - We reject kings, presidents, and voting.
  - We believe in rough consensus and running code.

Results

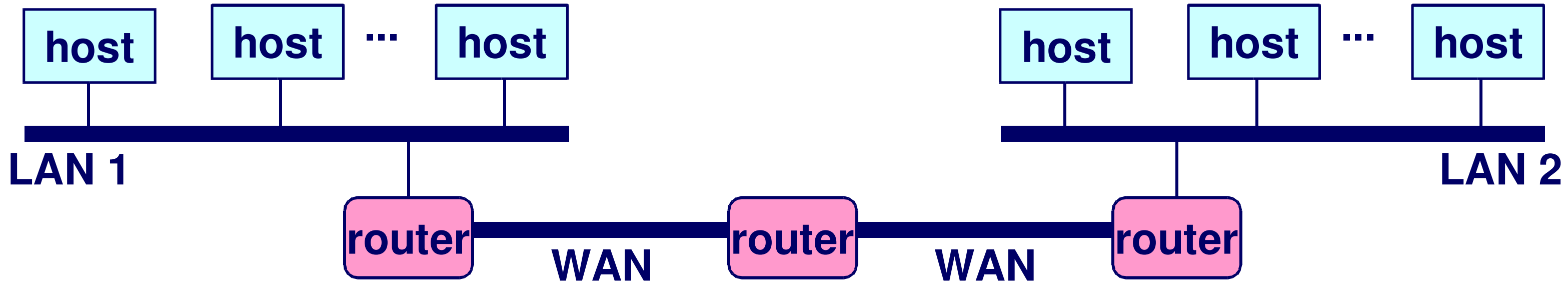
- Not just one network technology
- Not just one vendor's boxes, OS, database, ... (cf. IBM SNA)
- Room in the protocols for innovation
- Room in the culture for innovation

What is an 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 and ATM)

Issues in Designing an Internetwork

How do I designate a distant host?

- Addressing / naming

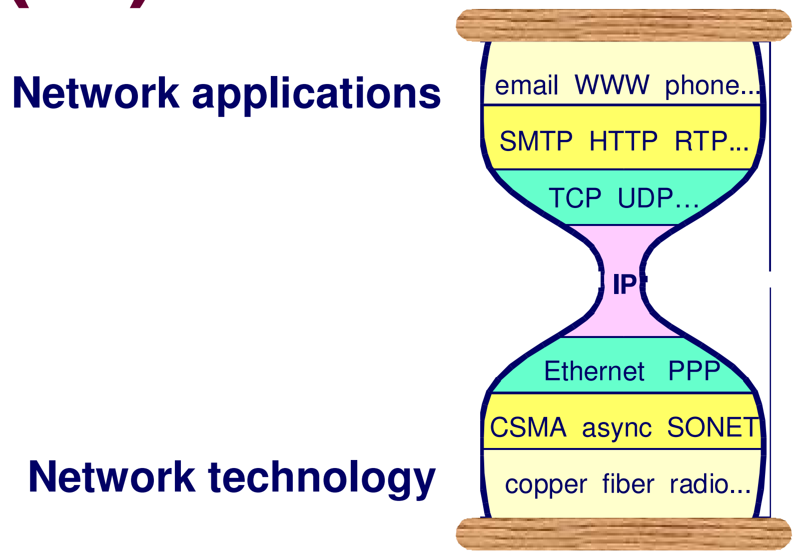
How do I send information to a distant host?

- "Service model"
  - What gets sent?
  - How fast will it go?
  - How often will it get there? Or else what?
- Routing – which path(s) will my information take?

Challenges

- Heterogeneity
  - Assembly from variety of different networks
- Scalability
  - Ensure ability to grow to worldwide scale

Internet Protocol (IP)



Steve Deering, CISCO

"Hour-glass" Model

- Abstraction layer hides underlying technology from network application software
- Make "as minimal as possible"
- Allow range of current & future technologies
- Can support many different types of applications

Agreeing, Disagreeing

How to address a distant host

- Or else we'll never get information there
- Ignore/work-around/use addressing method of local net

How to "containerize" data

- What goes in a link-layer "frame"?
  - Potentially many kinds of data (mux/de-mux)
  - Format of key control items (sender, receiver)
- Managing the size issue

We do ***not*** agree on

- Routing – Ethernet ≠ van-mounted packet radios
- Precise service model – Token ring has link-level ACK

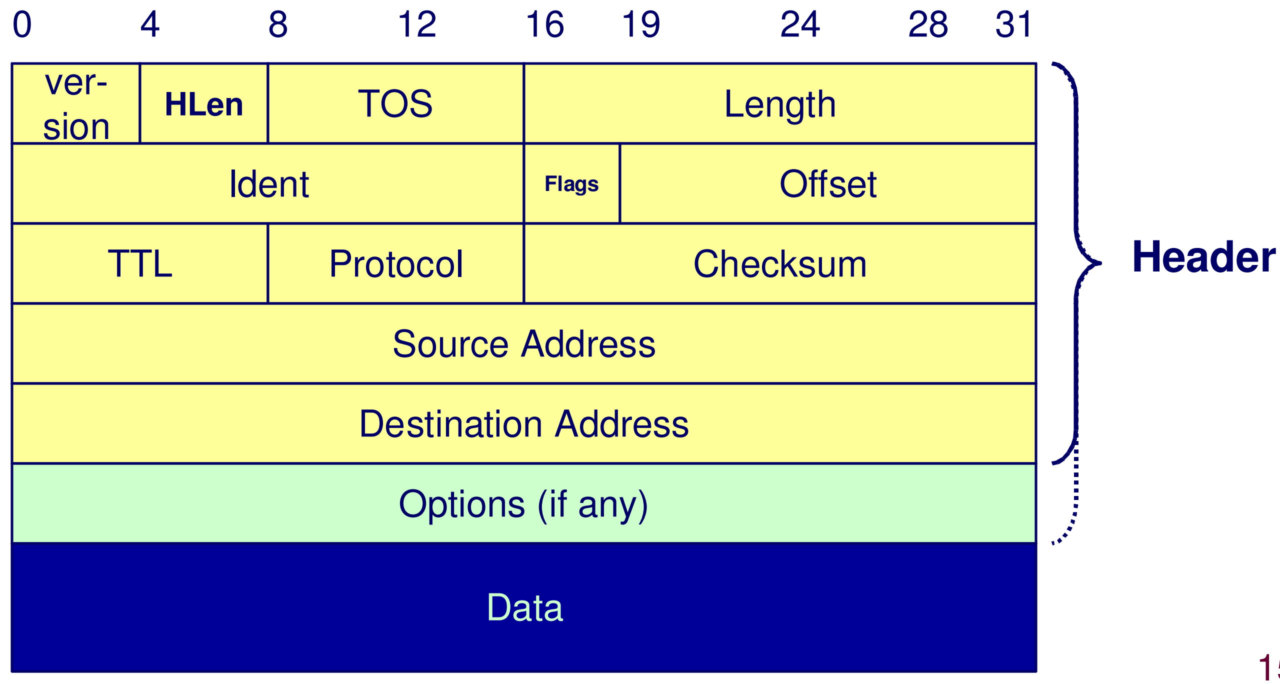
IP Service Model

- **Low-level communication model provided by Internet**

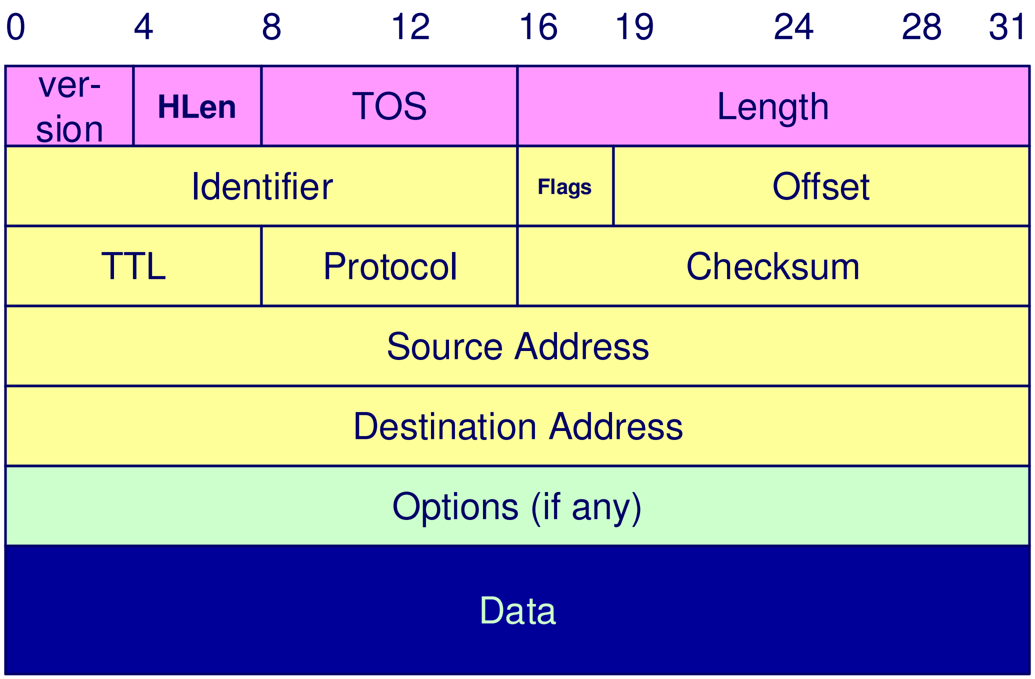
Datagram

- **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



IPv4 Header Fields: Word 1



Version: IP Version

- 4 for IPv4

HLen: Header Length

- 32-bit words (typically 5)

TOS: Type of Service

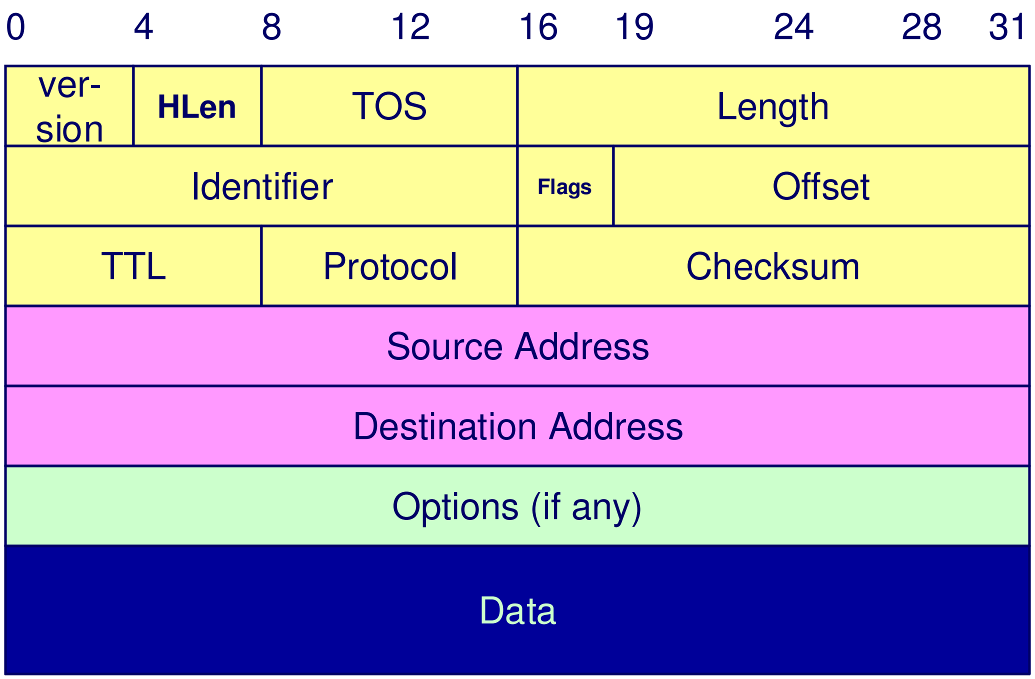
- Priority information

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, most "sub" networks work better with smaller packets than that**

IPv4 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 Addressing

IPv4: 32-bit addresses

- Typically written in "dotted quad" format
  - E.g., 128.2.198.135
  - Each number is decimal representation of byte
- Big-Endian Order

0	8	16	24	31	
128	2	198	135		Decimal
80	02	c6	87		Hexadecimal
0100 0000	0000 0010	1100 0110	1000 0111		Binary

Translation from Network Names

- Performed by "Domain Name System" (DNS)

```
unix> host bryant.vlsi.cs.cmu.edu
bryant.vlsi.cs.cmu.edu has address 128.2.198.135
```

IP Delivery Model

Best Effort Service

- Network will do its best to get packet to destination

Does *NOT* Guarantee...

- Any maximum latency–or even ultimate success
- Sender will be informed if packet doesn't make it
- Packets will arrive in same order sent
- Only one copy of packet will arrive

Implications

- Scales very well
- Higher level protocols must make up for shortcomings
  - Reliably delivering ordered sequence of bytes
- Some services not feasible
  - Latency or bandwidth guarantees

Basic Internet Components

An ***Internet backbone*** is a collection of routers (nationwide or worldwide) connected by high-speed point-to-point networks.

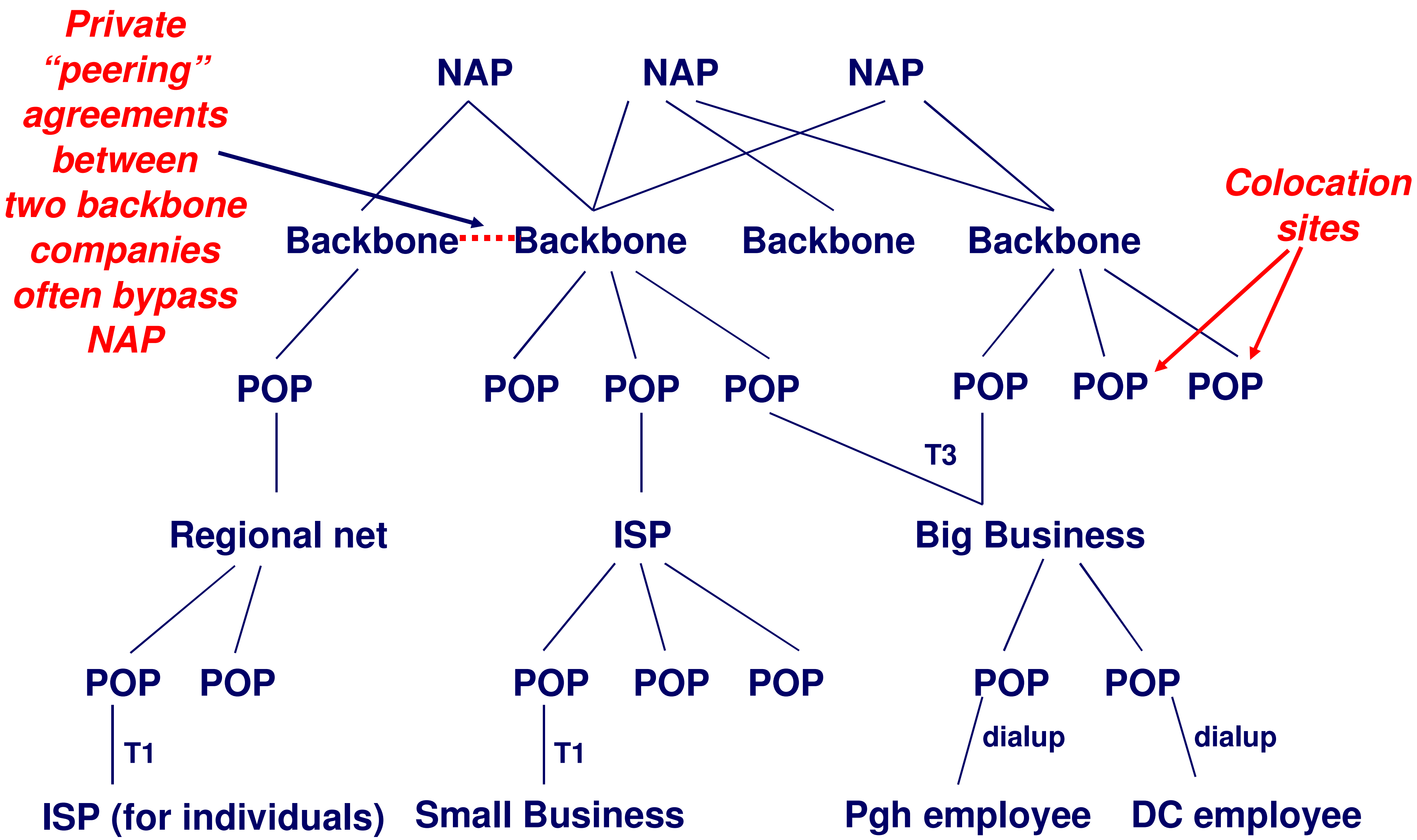
A ***Network Access Point*** ***(NAP)*** is a router that connects multiple backbones (sometimes referred to as *peers*).

Regional networks are smaller backbones that cover smaller geographical areas (e.g., cities or states)

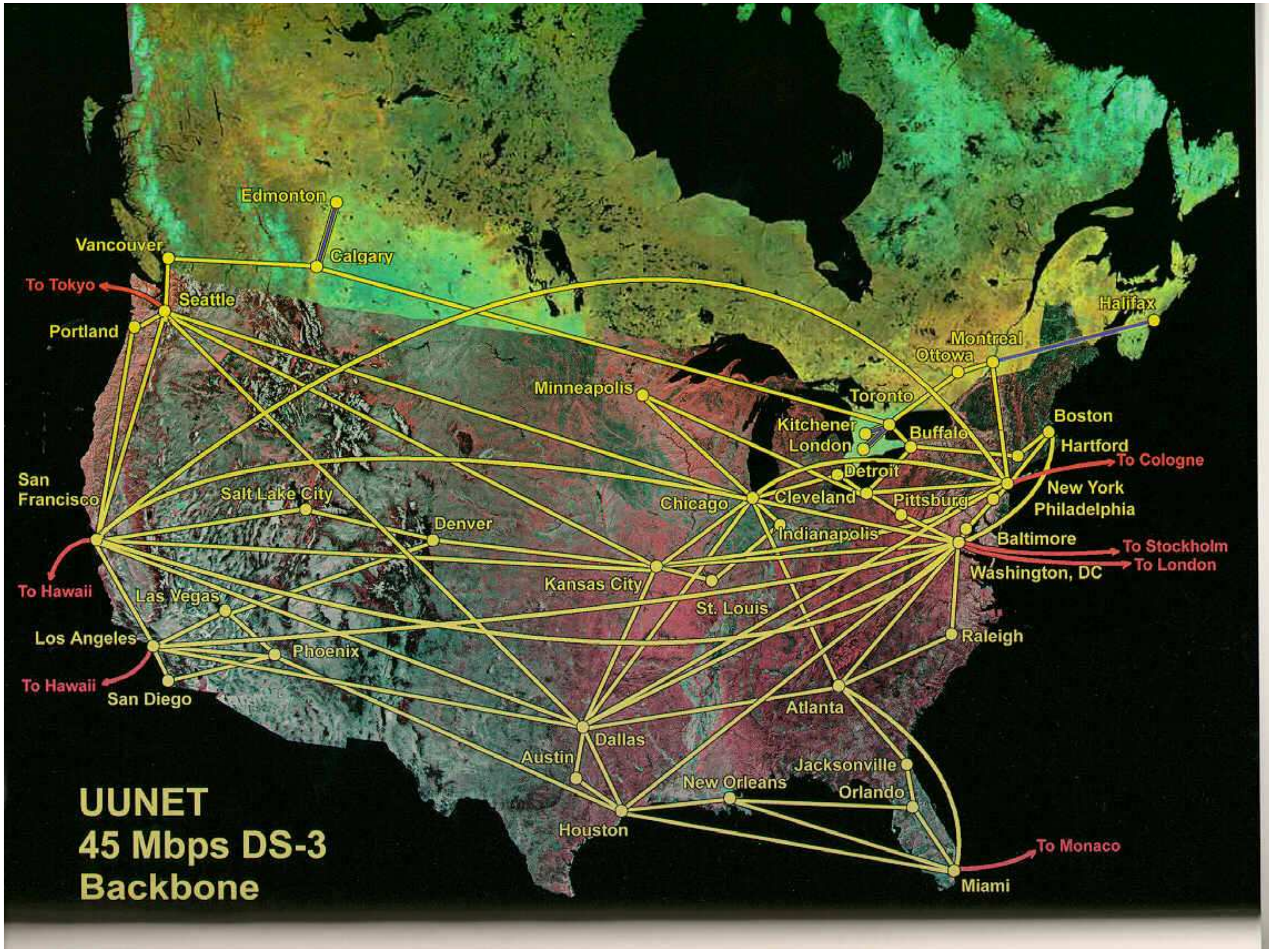
A ***point of presence*** ***(POP)*** is a machine that is connected to the Internet.

Internet Service Providers (ISPs) provide dial-up or direct access to POPs.

Internet Connection Hierarchy

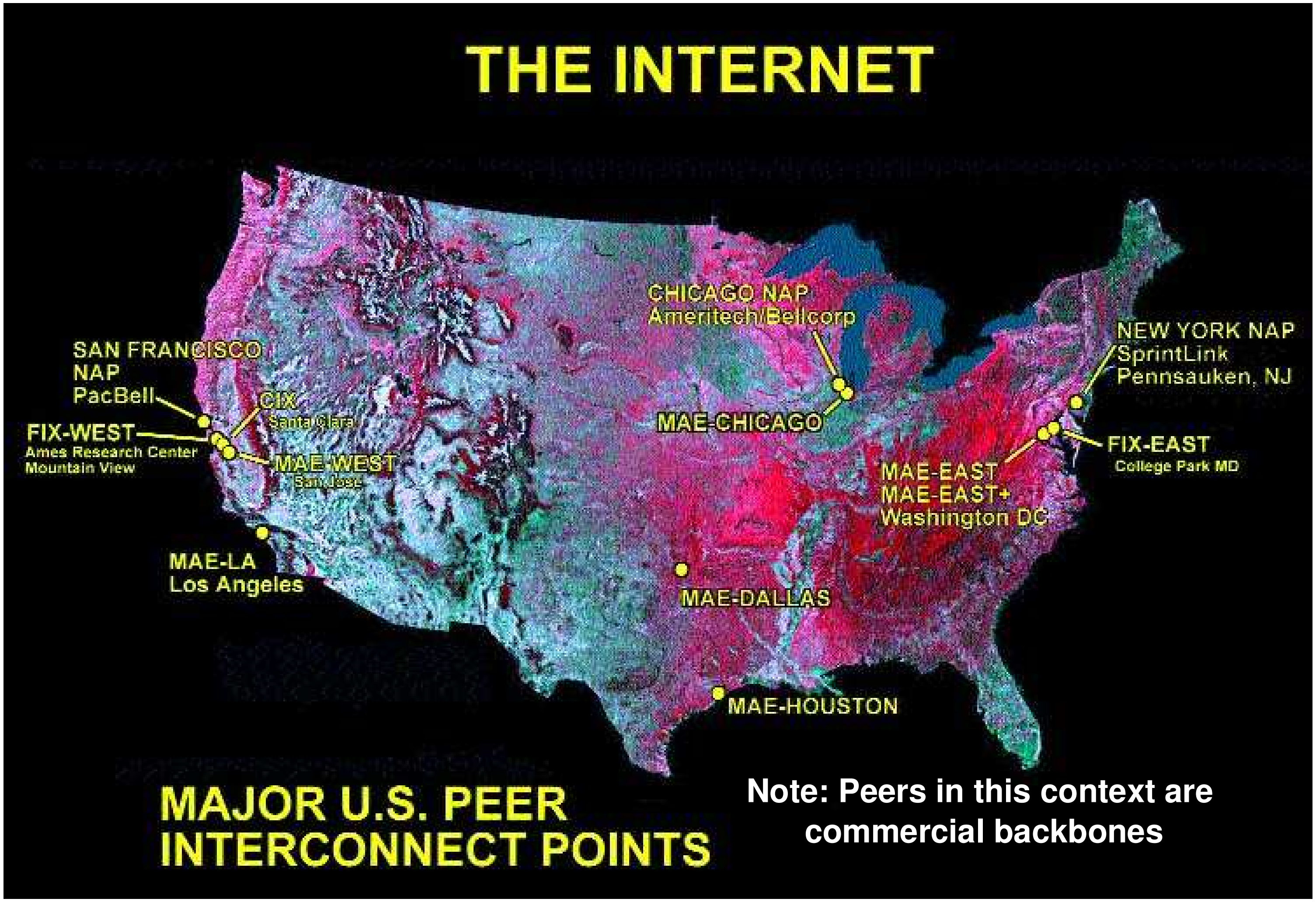


Backbone Provider



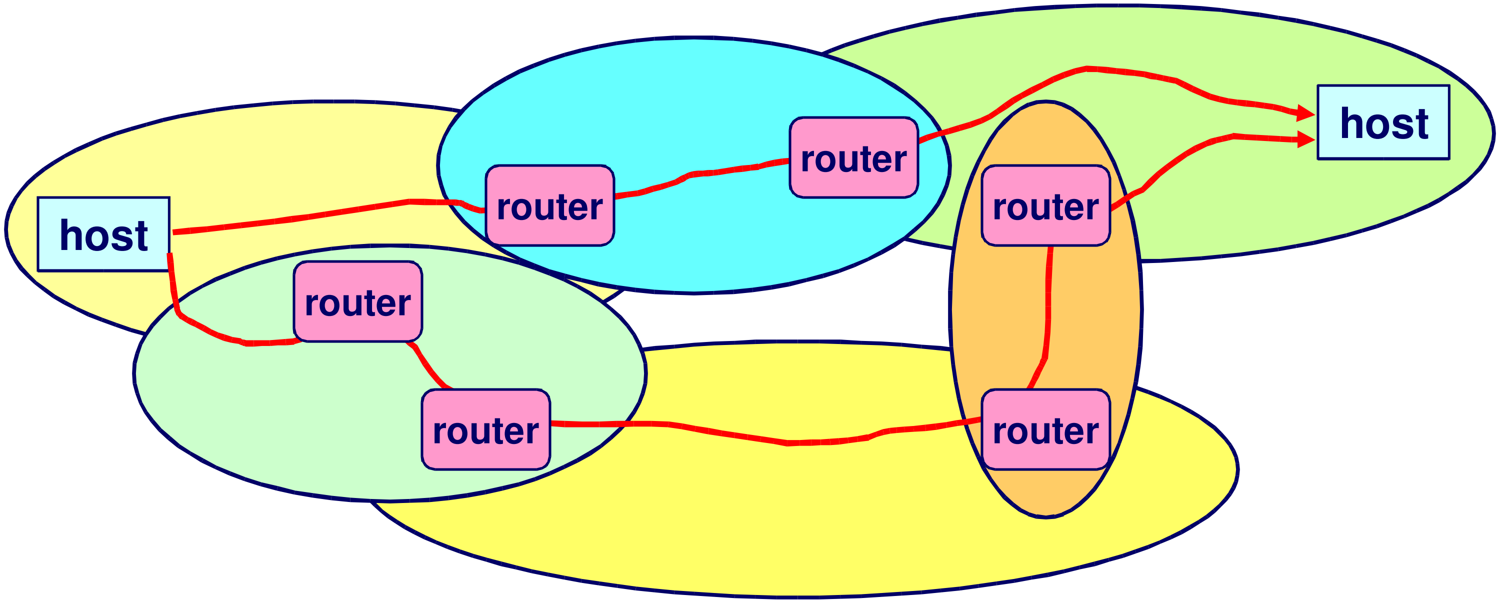
Source: Boardwatch.com

Network Access Points (NAPs)



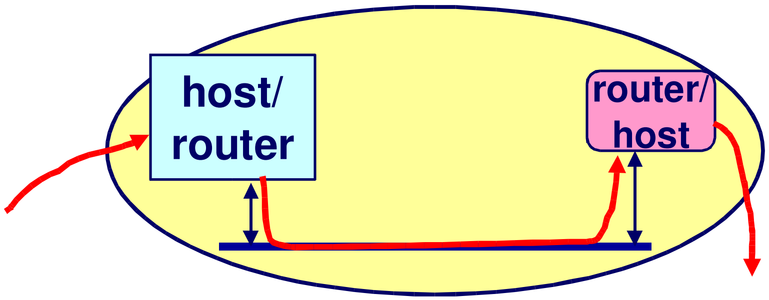
Source: Boardwatch.com

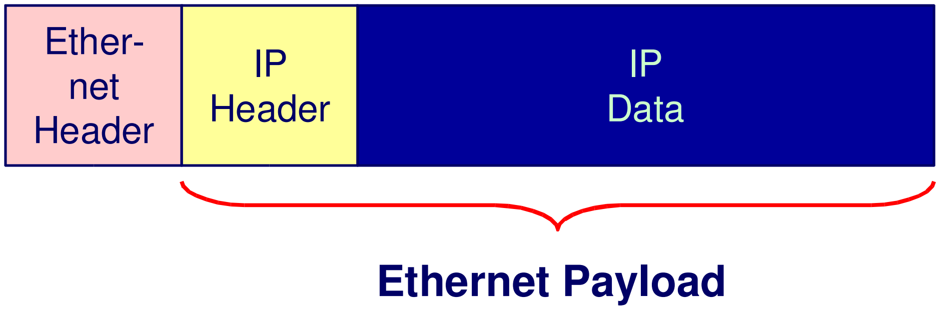
Logical Structure



- Ad hoc interconnection of networks
  - No particular topology
  - Vastly different router & link capacities
- Packets travel from source to destination by hopping through networks
  - Router forms "bridge" from one network to another
  - Different packets may take different routes
    - » OK, since IP doesn't guarantee ordering

Routing Through Single Network





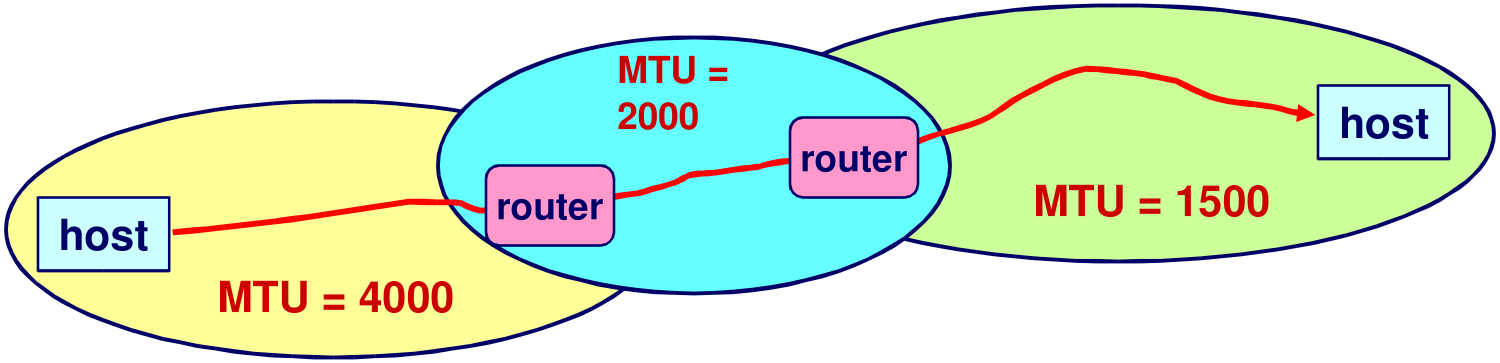
Path = series of hops

- Source ⇒ Router
- Router ⇒ Router (typically high-speed, point-to-point link)
- Router ⇒ Destination

Each hop crosses one link, uses that link-layer protocol

- Hop destination = function(IP destination)
- Encapsulate IP packet as payload for local subnetwork
  - Key step: link-layer address of next-hop router on this subnetwork
    - » Multi-point network (Ethernet): “MAC address” (see ARP, later)
    - » Point-to-point network (PPP, 15-441): no need for address

IP Fragmentation



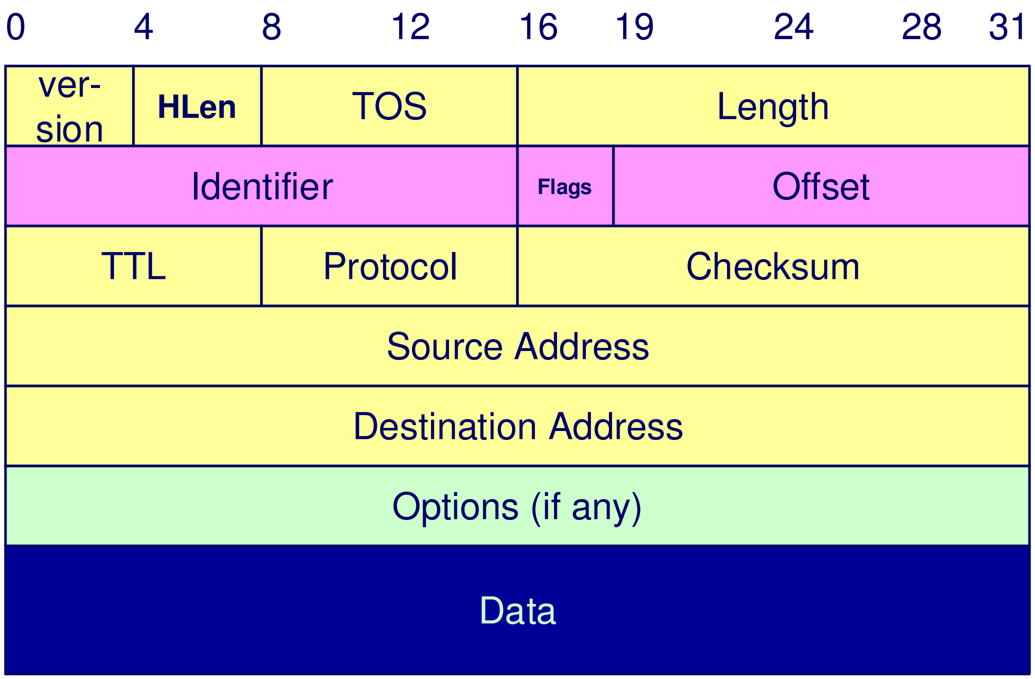
Every Network has Own Maximum Transmission Unit (MTU)

- 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 packet hits network with small MTU, break into *fragments*
  - Packet may fragment further on a later link
- Reassemble at the destination
  - If any fragment disappears, delete entire packet

IPv4 Header Fields: Word 2



- 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

Identifier

- Unique identifier for original datagram
  - Historically, source increments counter every time sends packet

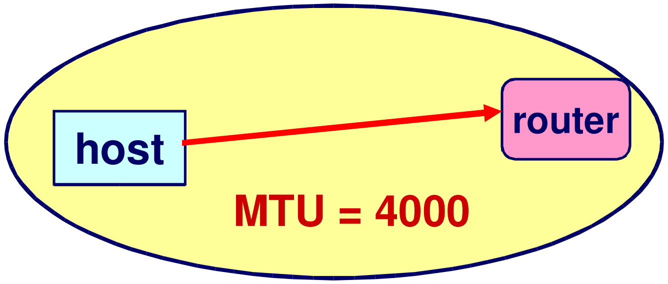
Flags (3 bits)

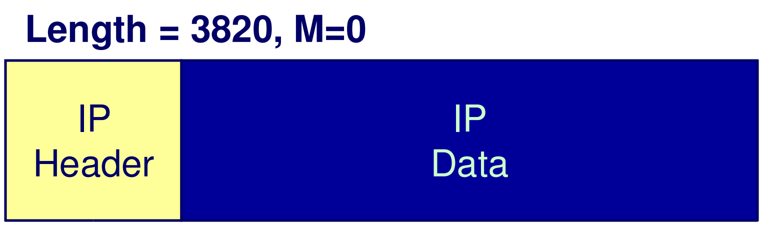
- "More fragments" flag: This is not the last fragment

Offset

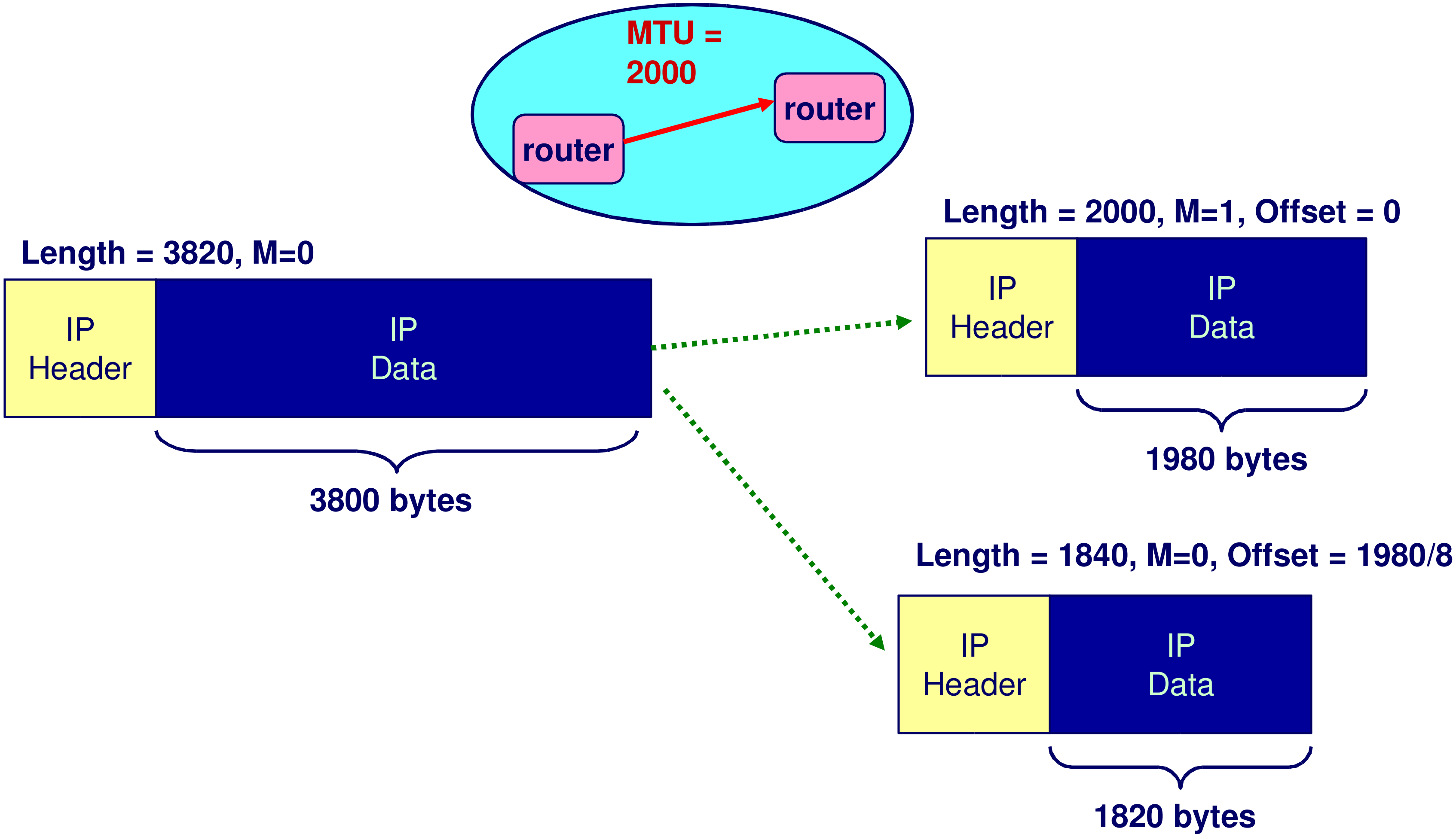
- Byte position of first byte in fragment ÷ 8
- Byte position must be multiple of 8

IP Fragmentation Example #1





IP Fragmentation Example #2



One Tiny Problem

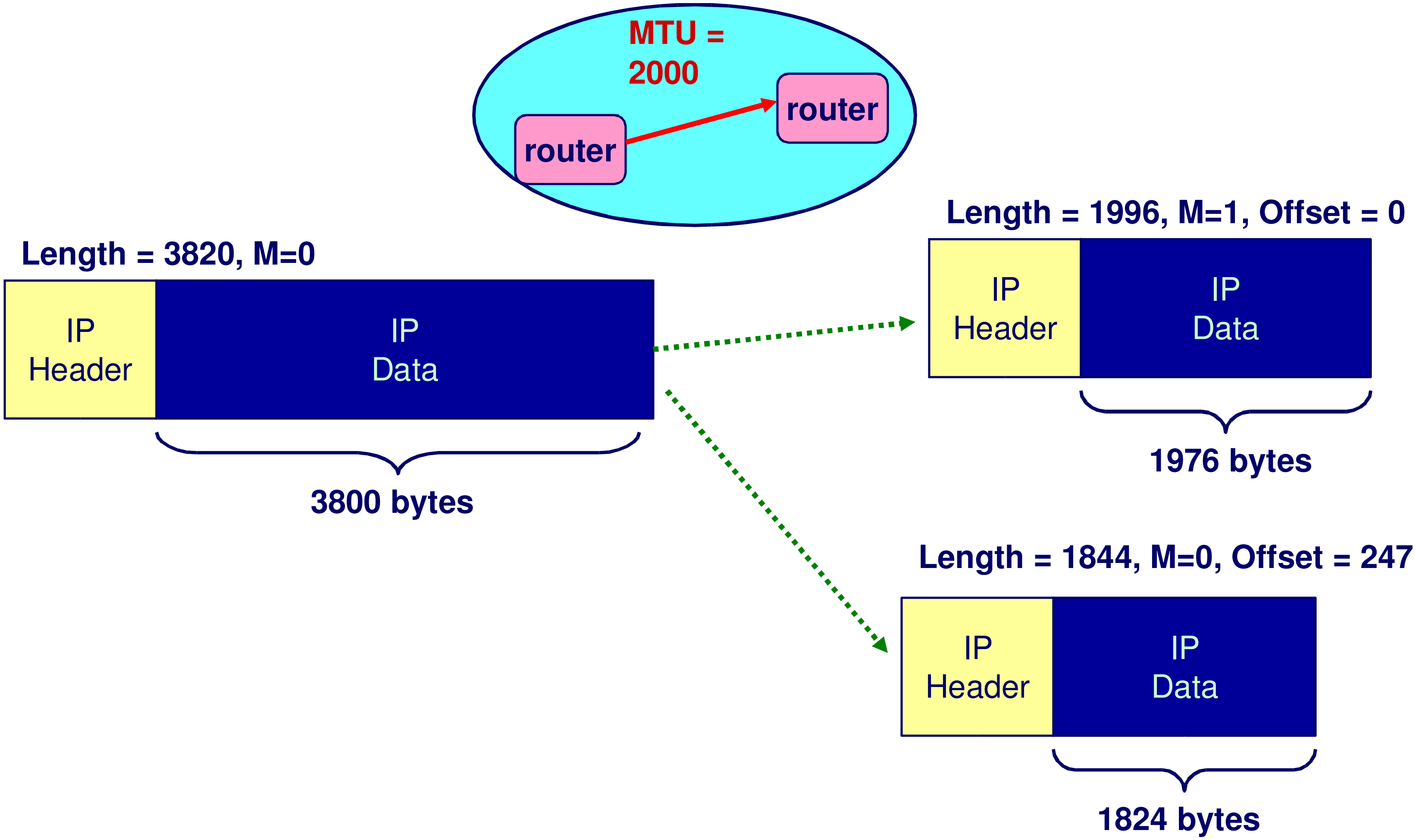
Offset field counts 8-byte chunks

- 1980 / 8 = 247.5

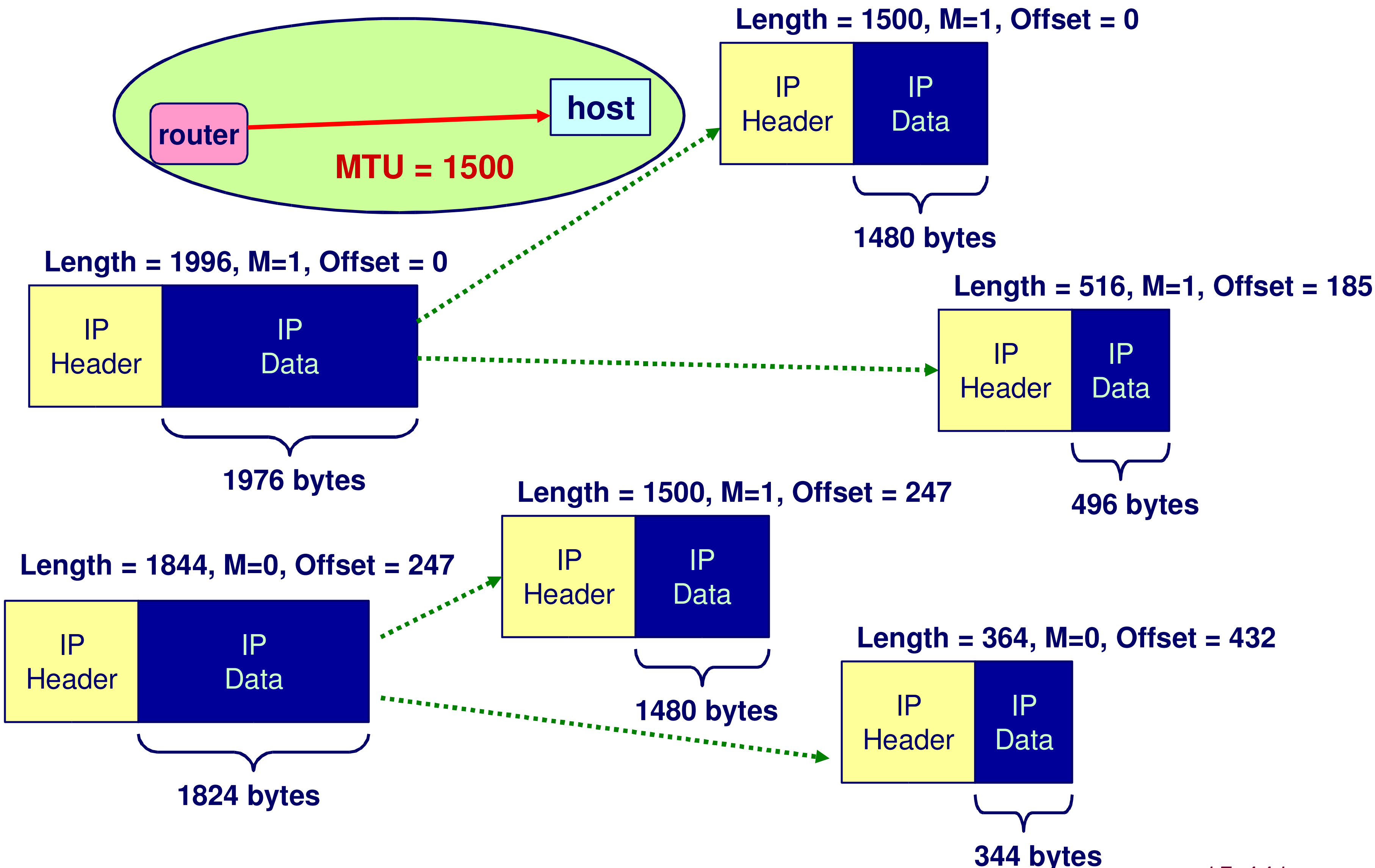
Back to the drawing board

- Can't fragment as 3800 = 1980 + 1820
- Can fragment as 3800 = 1976 + 1824

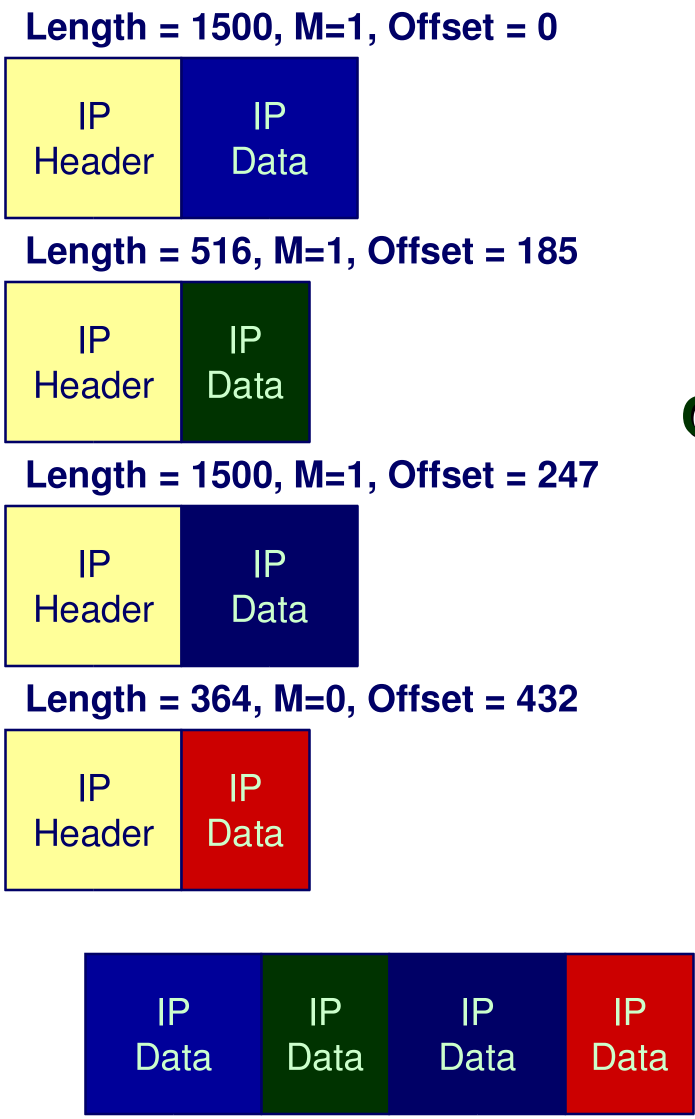
IP Fragmentation Example #2



IP Fragmentation Example #3



IP Reassembly



- **Performed at final destination**
- **Fragment with M=0 determines overall length**
  - **(432 * 8) + (364-20) = 3800**

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**
  - **See code in book**

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
- Assumes every packet will follow same route
  - Routes tend to change slowly over time

Common Theme in System Design

- Assure correctness by implementing complete protocol
- Optimize common cases to avoid full complexity

Summary: Forwarding Layer Tasks

Hacker's inventory approach

- Examine each bit field, read what RFC says

Higher-level approach

- Mini-integrity check
  - Sanity-check link layer and IP layer of your neighbor ("peer")
- Housekeeping/manipulation step
  - Loop detection, ...
- Consult your "next-hop oracle" (routing system)
- Adapt datagram to next-hop network
  - Size, priority/queue policy, ...
- Transmit