COMP 431
Internet Services & Protocols

The IP Internet Protocol

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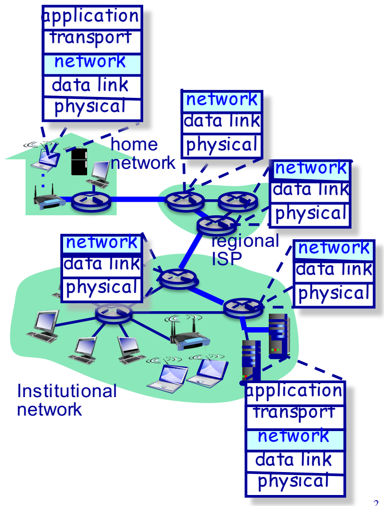
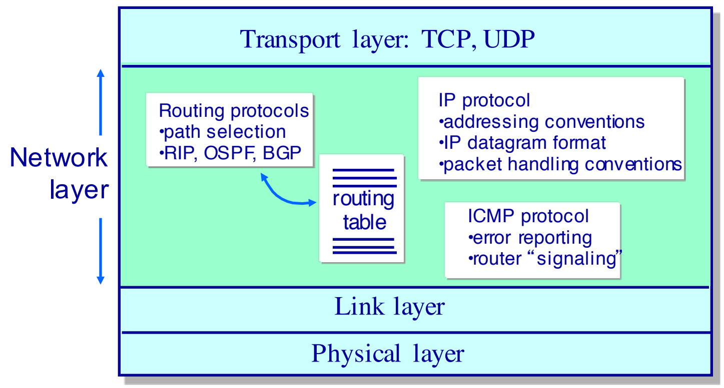
The Network Layer: Routing & Addressing
Outline

- Network layer services
- Routing algorithms
  - » Least cost path computation algorithms
- Hierarchical routing
  - » Connecting networks of networks
- IP Internet Protocol
  - » Addressing
  - » IPv6
- Routing on the Internet
  - » Intra-domain routing
  - » Inter-domain routing
- Router architecture



The Internet Network layer

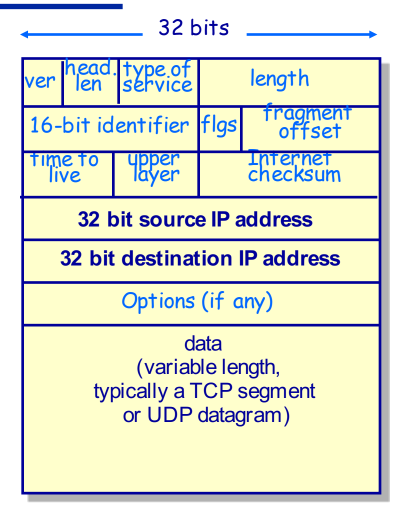
Host and router network layer functions



The Internet Network layer

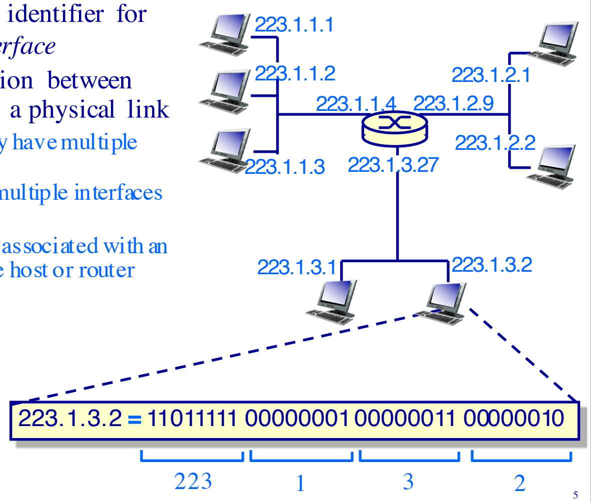
IP datagram format

- IP datagrams
  - » The protocol data units at the IP network layer)
- (Not to be confused with UDP datagrams)
  - » The protocol data units at the UDP transport layer are also called datagrams



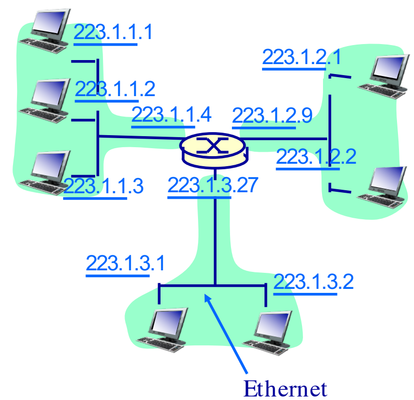
IP Addressing
Introduction

- IP address: 32-bit identifier for host or router *interface*
- Interface: connection between host or router and a physical link
  - » Routers typically have multiple interfaces
  - » Host *may* have multiple interfaces (typically not)
  - » IP addresses are associated with an interface, *not* the host or router



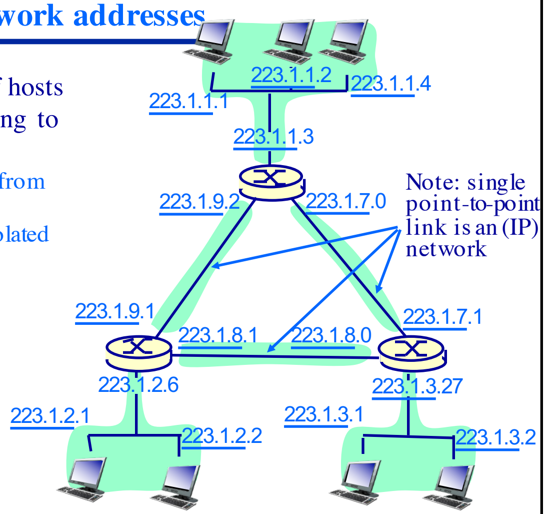
IP Addressing
Host address *v.* Network addresses

- IP address:
  - » Network part (high order bits)
  - » Host part (low order bits)
- What's a network?
  - » The set of devices that can communicate with each other without an intervening router
    - ❖ The devices attached to the same physical network
  - » From an IP address perspective its:
    - ❖ The set of device interfaces with IP addresses having a common network part

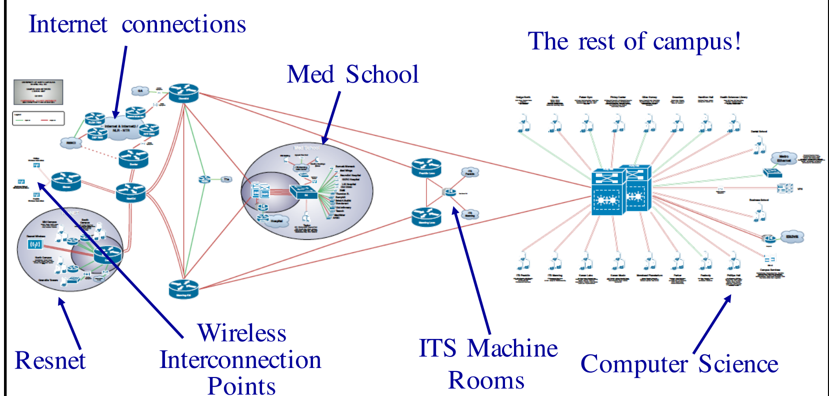


IP Addressing
Host address *v.* Network addresses

- A network is the set of hosts reachable without having to traverse a router
  - » Detach each interface from router or host
  - » Create "islands" of isolated networks

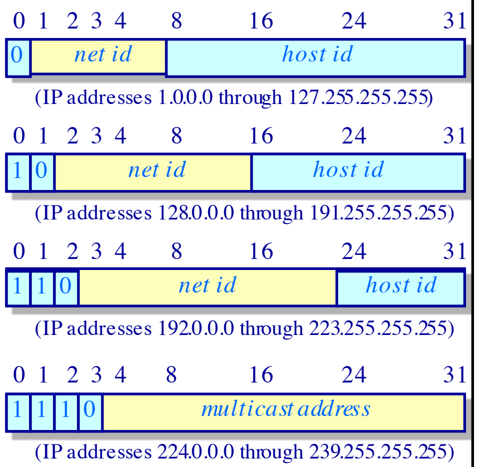


IP Addressing
UNC campus topology (2016)

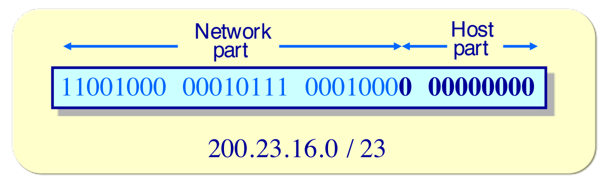


IP Addressing
Class-based addressing

- Class A addresses
  - » 128 networks
  - » 65,536 to 2^{24} hosts
- Class B addresses
  - » 16,384 networks
  - » 256 to 65,536 hosts
- Class C addresses
  - » 2^{21} networks
  - » less than 256 hosts
- Class D addresses
  - » 28-bit multicast addresses
  - » No origin or network information is encoded



IP Addressing
Classless Inter Domain Routing (CIDR)

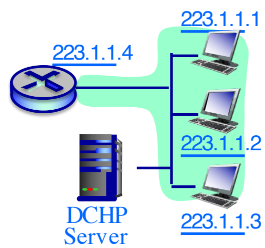


- Class-based addressing
  - » Inefficient use of address space, address space exhaustion
  - » e.g., class B network allocated enough addresses for 64K hosts, even if only 300 hosts in that network
- Classless addressing
  - » Network portion of address has an arbitrary length
  - » Address format: a.b.c.d/x, where x is the number of bits in network portion of address; called the network mask
    - Used only in routing tables, not IP datagram source/destination

IP addresses

How are IP addresses assigned?

- The network address is assigned by the ISP
  - » Hosts portion only; all hosts share the same network portion
- Host address
  - » Static assignment:
    - ❖ Configuration parameter (manually) set during system installation
  - » Dynamic assignment at boot/wake-up time
    - ❖ DHCP: Dynamic Host Configuration Protocol:
      - Host broadcasts a "DHCP discover" message
      - DHCP server responds with a "DHCP offer" message
      - Host requests IP address: "DHCP request" message
      - DHCP server sends address: "DHCP ack" message



IP addresses

How are network addresses assigned?

ISP's block	11001000 00010111 00010000 00000000	200.23.16.0/20
Organization 0	11001000 00010111 00010000 00000000	200.23.16.0/23
Organization 1	11001000 0001011 00010010 00000000	200.23.18.0/23
Organization 2	11001000 00010111 00010100 00000000	200.23.20.0/23
…	….. ….	….
Organization 7	11001000 00010111 00011110 00000000	200.23.30.0/23

- ISPs obtain a block of addresses from ICANN (Internet Corporation for Assigned Names and Numbers)
  - » ICANN allocates IP address blocks, manages DNS, (used to assign domain names), resolves disputes
- ISPs subdivide their block among their customers

Routing IP Datagrams

Example

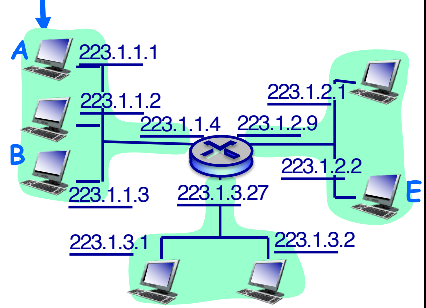
misc fields	source IP addr	dest IP addr	data

IP Datagram

- All routing is based on the IP destination address field in the IP header
- IP destination address (and data fields) never change!
  - » Delivery to intermediate hops involves link-layer addresses

Routing table in A

Dest. Net	next router	Nhops
223.1.1/24	-	1
*(default)	223.1.1.4	2



Routing IP Datagrams

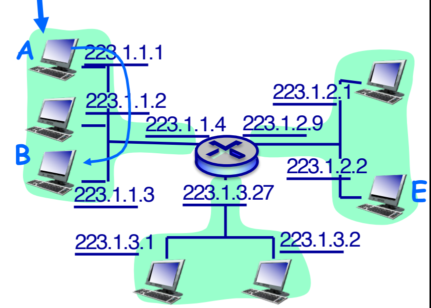
Routing to a local destination

misc fields	223.1.1.1	223.1.1.3	data

- An application on A generates an IP datagram addressed to B
  - » The IP layer on A looks up the network address of B...
  - » And determines that B is on same network as A (223.1.1)
- A's link layer sends the IP datagram directly to B inside link-layer frame
  - » B and A are assumed to be connected to the same physical network

Routing table in A

Dest. Net	next router	Nhops
223.1.1/24	-	1
*(default)	223.1.1.4	2



Routing IP Datagrams

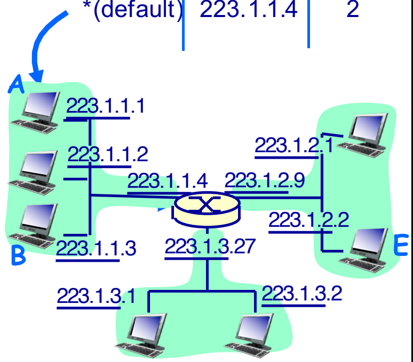
Routing to a remote destination

misc fields	223.1.1.1	223.1.2.2	data

Routing table in A

Dest. Net	next router	Nhops
223.1.1/24	-	1
*(default)	223.1.1.4	2

- Host A generates an IP datagram addressed to E
  - » The IP layer on A looks up up network address of E (223.1.2)
  - » A determines that E is NOT on same network as A
  - » A's routing table shows router 223.1.1.4 as the default for all networks
- A's link layer sends IP datagram to router inside link-layer frame



Routing IP Datagrams

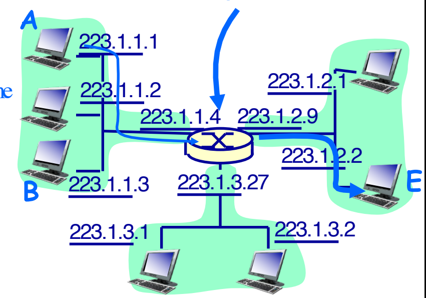
Routing to a remote destination

misc fields	223.1.1.1	223.1.2.2	data

Routing table in router

Dest. network	next router	Nhops	interface
223.1.1/24	-	1	223.1.1.4
223.1.2/24	-	1	223.1.2.9
223.1.3/24	-	1	223.1.3.27

- A's datagram addressed to E arrives at the router
  - » The router looks up network address of E (223.1.2)
  - » E has the *same* network address as router's interface 223.1.2.9
  - » Router is directly attached to the same network (223.1.2) as E
- Router's link layer sends the datagram to 223.1.2.2 inside a link-layer frame *via* interface 223.1.2.9
  - » Datagram arrives at 223.1.2.2



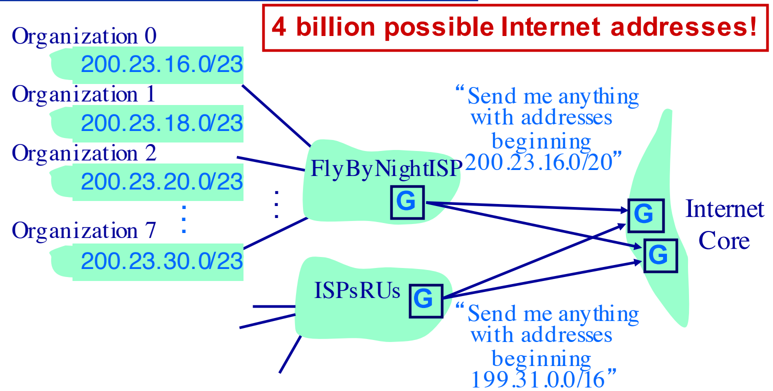
Routing IP Datagrams

NetMasks

```
<quintet.cs.unc.edu>$ ifconfig
eth0      Link encap:Ethernet  HWaddr 00:06:5B:F3:34:7F
          inet addr:152.2.128.80  Bcast:152.2.255.255  Mask:255.255.0.0
          inet6 addr: fe80::206:5bff:fef3:347f/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:59314376 errors:0 dropped:0 overruns:0 frame:0
          TX packets:7659872 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:401871884 (383.2 MiB)  TX bytes:2309337676 (2.1 GiB)
          Interrupt:193
```


Hierarchical addressing

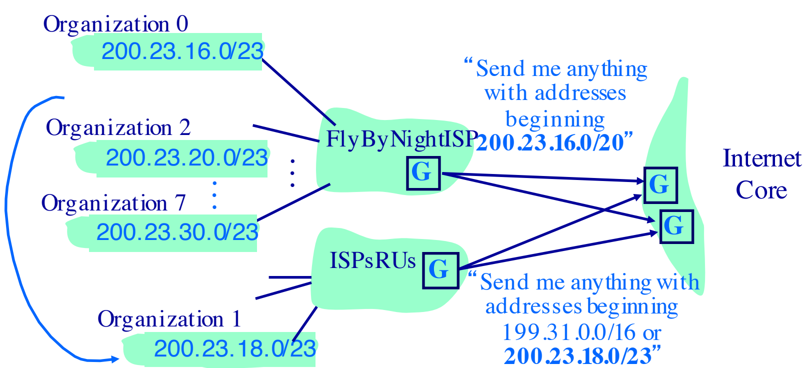
Route aggregation



- Hierarchical addressing allows efficient specification of routing information by gateway routers

Hierarchical addressing

Specific routes



- Q: If Organization 1 moves to ISPsRUs how will Internet core routers choose a route to Organization 1?
  - » A: Use "longest prefix match" on network part of IP destination address

Longest Prefix Matching

Destination Address Range	Port/Interface	Prefix To Match	Port/Interface
11001000 00010111 00010000 00000000 through 11001000 00010111 00010111 11111111	→ 0	11001000 00010111 00010	0
11001000 00010111 00011000 00000000 through 11001000 00010111 00011000 11111111	→ 1	11001000 00010111 00011000	1
11001000 00010111 00011001 00000000 through 11001000 00010111 00011111 11111111	→ 2	11001000 00010111 00011	2
otherwise	→ 3	otherwise	3

Examples (given destination IP address, forward to which interface?)

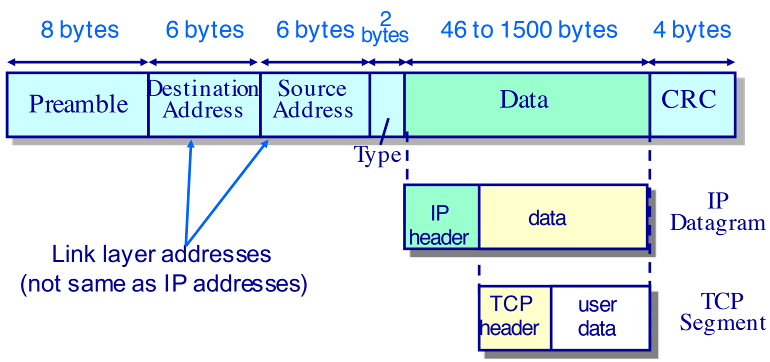
Destination Address:
11001000 00010111 00010110 10100001 → **??**

Destination Address:
11001000 00010111 00011000 10101010 → **??**

Destination Address:
11001001 00010111 00011001 10101010 → **??**

Datagram Routing and Transmission

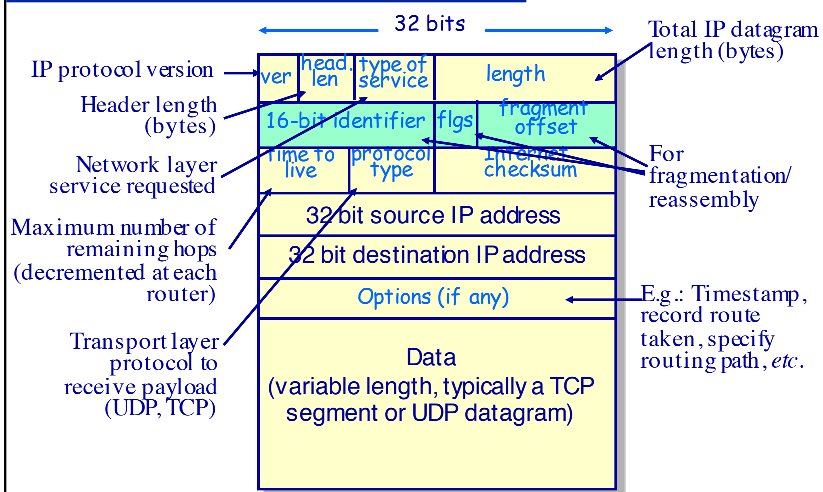
IP datagram encapsulation (Ethernet)



- Sending interface adapter encapsulates IP datagram (or other network layer protocol packet) in an *Ethernet frame*

Datagram Routing and Transmission

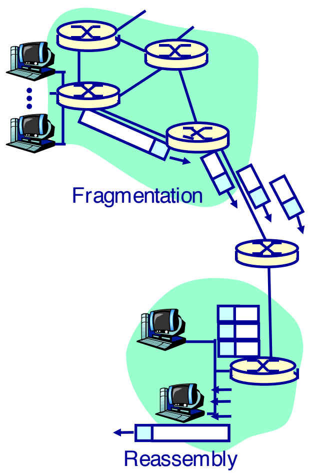
IP datagram format



IP Datagrams

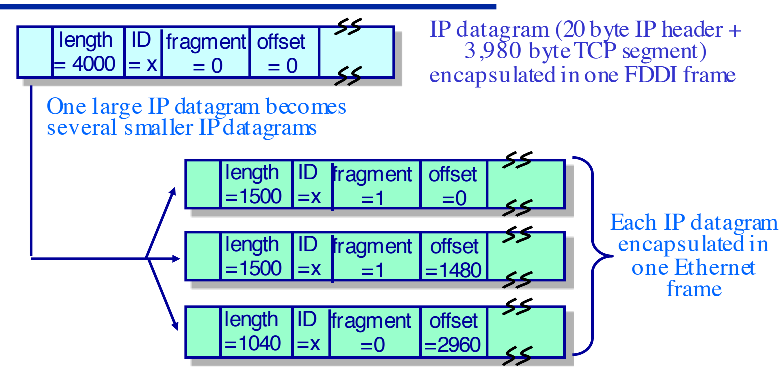
Fragmentation & Reassembly

- Network links have a maximum frame size
  - » Called the *maximum transmission unit* (MTU)
  - » Different link types, different MTUs
- Large IP datagrams must be "fragmented" to link MTU sizes
  - » One IP datagram becomes several IP datagrams as it transits networks
  - » "Fragments" reassembled only at the final destination
- All fragments carry the same IP identification number
  - » All fragments (except the last) have the fragment bit set



IP Fragmentation and Reassembly

Ethernet MTU example



- Consider a 3,980 byte message sent in an FDDI frame
- The message generates 3 fragments when it transits an Ethernet
  - » How much application data is in each fragment?

The Internet Network layer

IPv6

- Initial motivation:
  - » 32-bit address space completely allocated by 2008
- Additional motivation:
  - » Header format helps high-speed processing/forwarding
  - » Header changes to facilitate network-layer "services"
  - » New "anycast" address: route to "best" of several replicated servers
- IPv6 datagram format:
  - » Fixed-length 40 byte header
  - » No fragmentation allowed

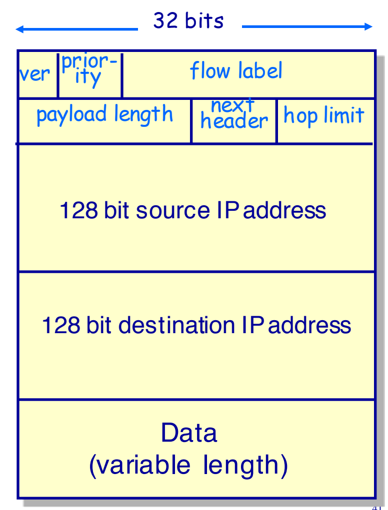
NAT is the reason why we haven't run out of IPv4

A machine can have an IPv6 and IPv6 address

IPv6

Header changes

- *Priority:* identify priority among datagrams in flow
- *Flow Label:* identify datagrams in same "flow."
  - » (Concept of "flow" not well defined)
- *Next header:* identify upper layer protocol for data
- Checksum?
  - » Removed entirely to reduce processing time at each hop
- Options?
  - » Allowed, but outside of header, indicated by "Next Header" field



hop limit is time to live, decremented at each router