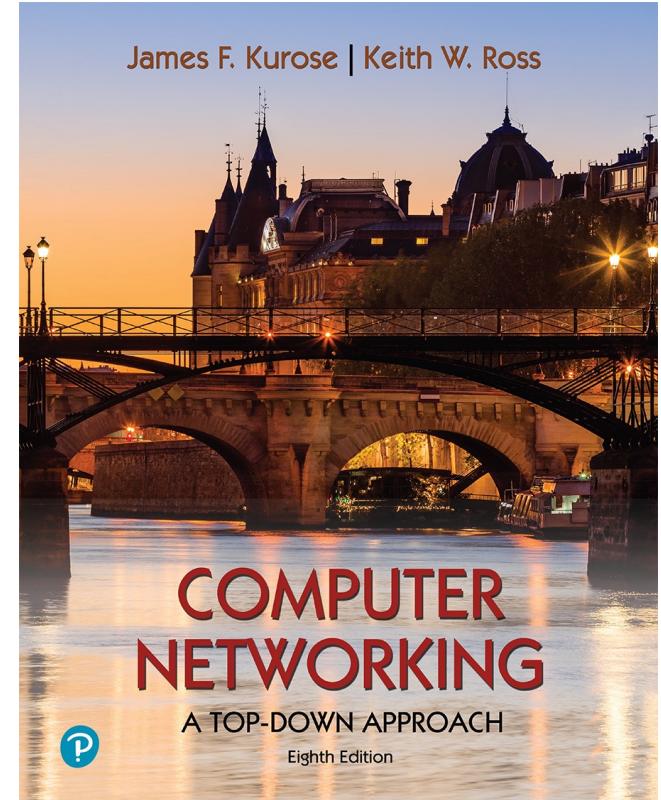


Final-exam Review

Yaxiong Xie

Department of Computer Science and Engineering
University at Buffalo, SUNY

Adapted from the slides of the book's authors



*Computer Networking: A
Top-Down Approach*
8th edition
Jim Kurose, Keith Ross
Pearson, 2020

Two key network-layer functions

network-layer functions:

- *forwarding*: move packets from a router's input link to appropriate router output link
- *routing*: determine route taken by packets from source to destination
 - *routing algorithms*

analogy: taking a trip

- *forwarding*: process of getting through single interchange
- *routing*: process of planning trip from source to destination



forwarding

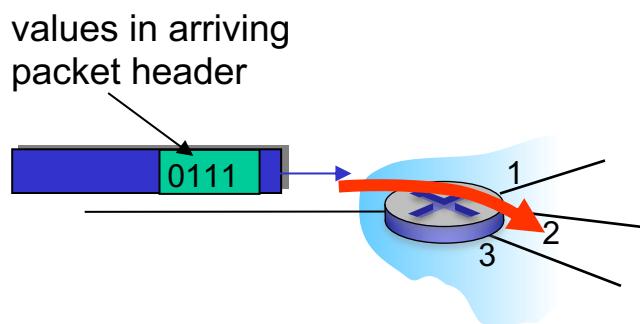


routing

Network layer: data plane, control plane

Data plane:

- *local*, per-router function
- determines how datagram arriving on router input port is forwarded to router output port

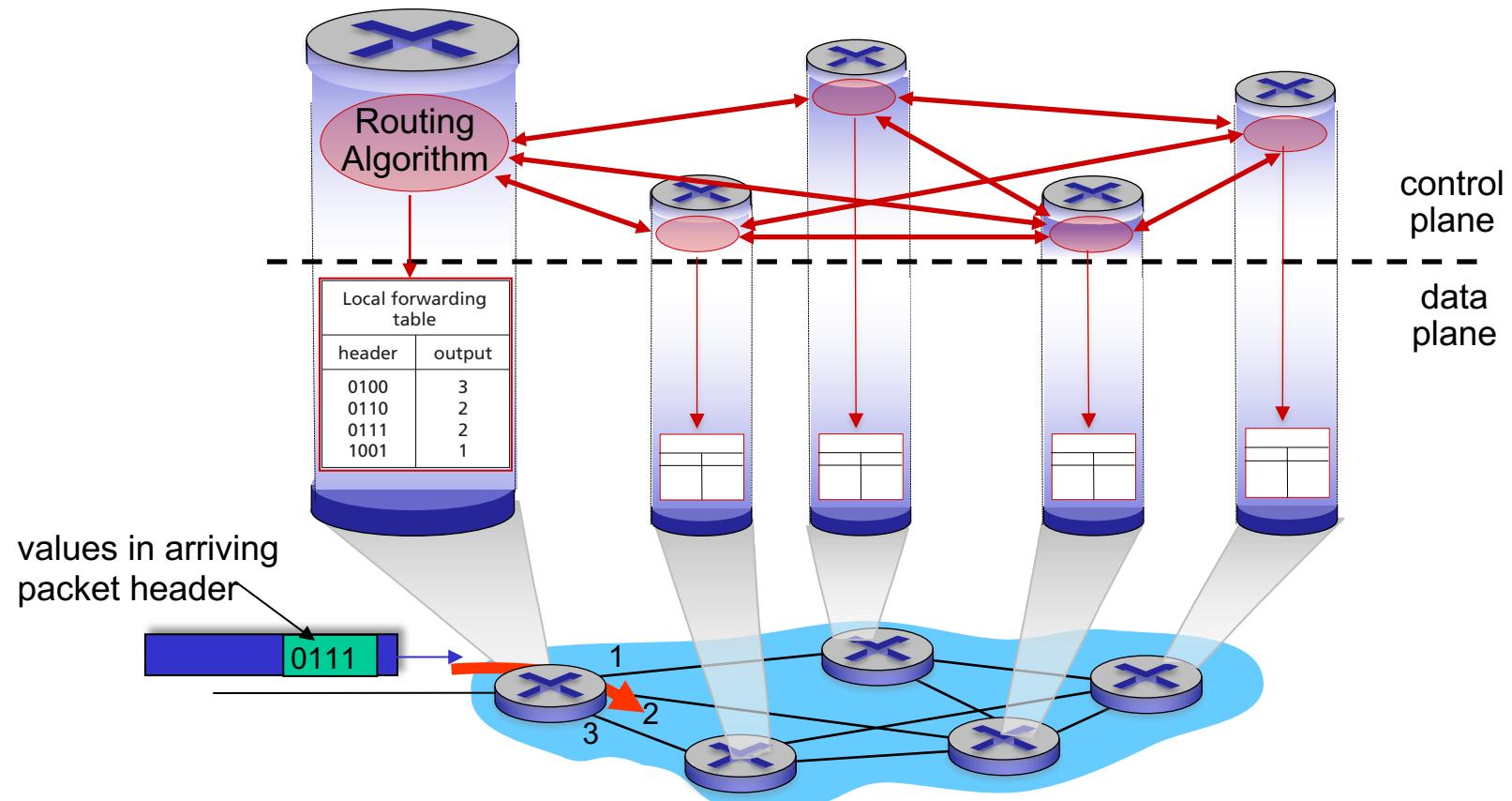


Control plane

- *network-wide* logic
- determines how datagram is routed among routers along end-end path from source host to destination host
- two control-plane approaches:
 - *traditional routing algorithms*: implemented in routers
 - *software-defined networking (SDN)*: implemented in (remote) servers

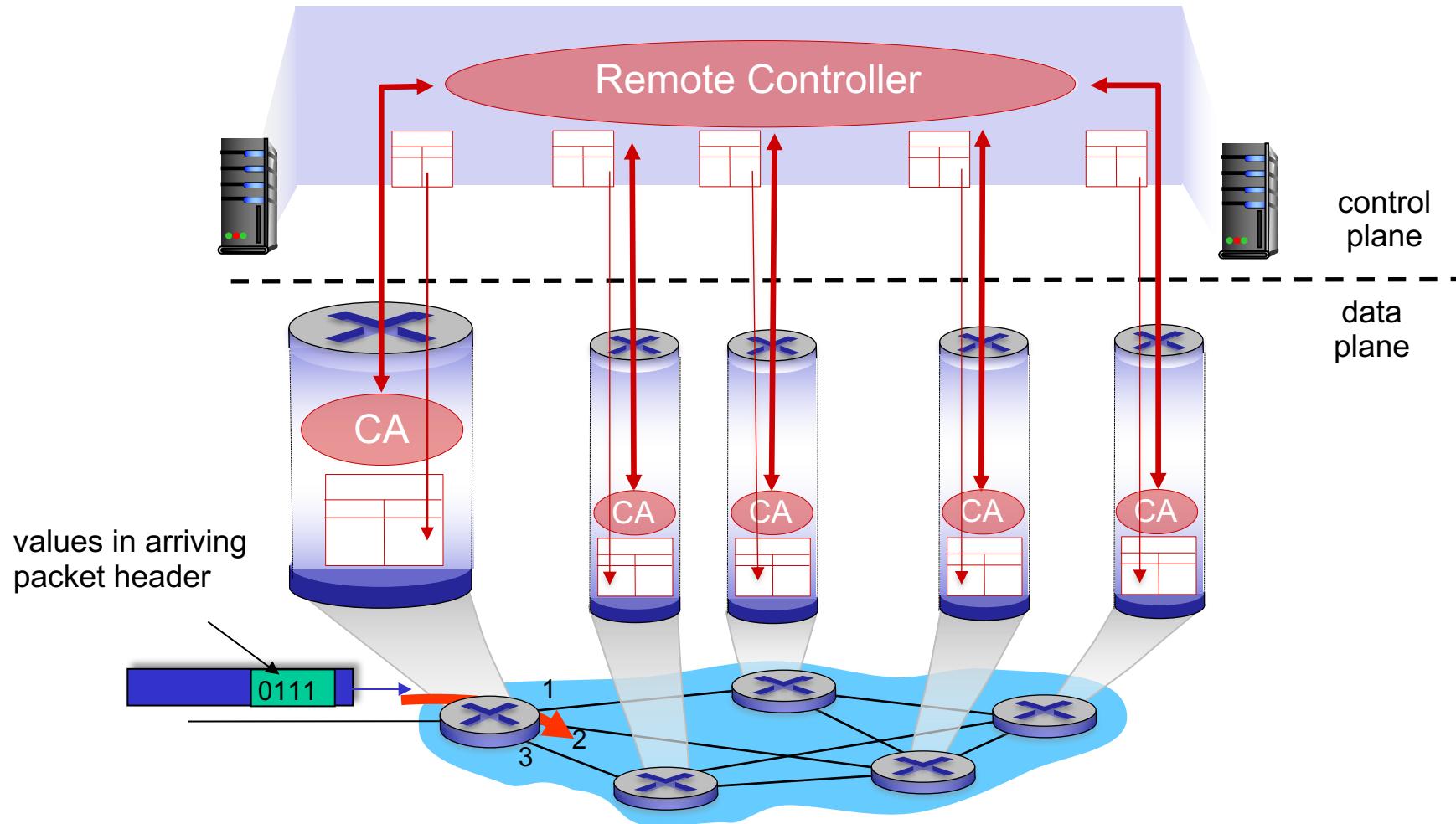
Per-router control plane

Individual routing algorithm components *in each and every router* interact in the control plane



Software-Defined Networking (SDN) control plane

Remote controller computes, installs forwarding tables in routers



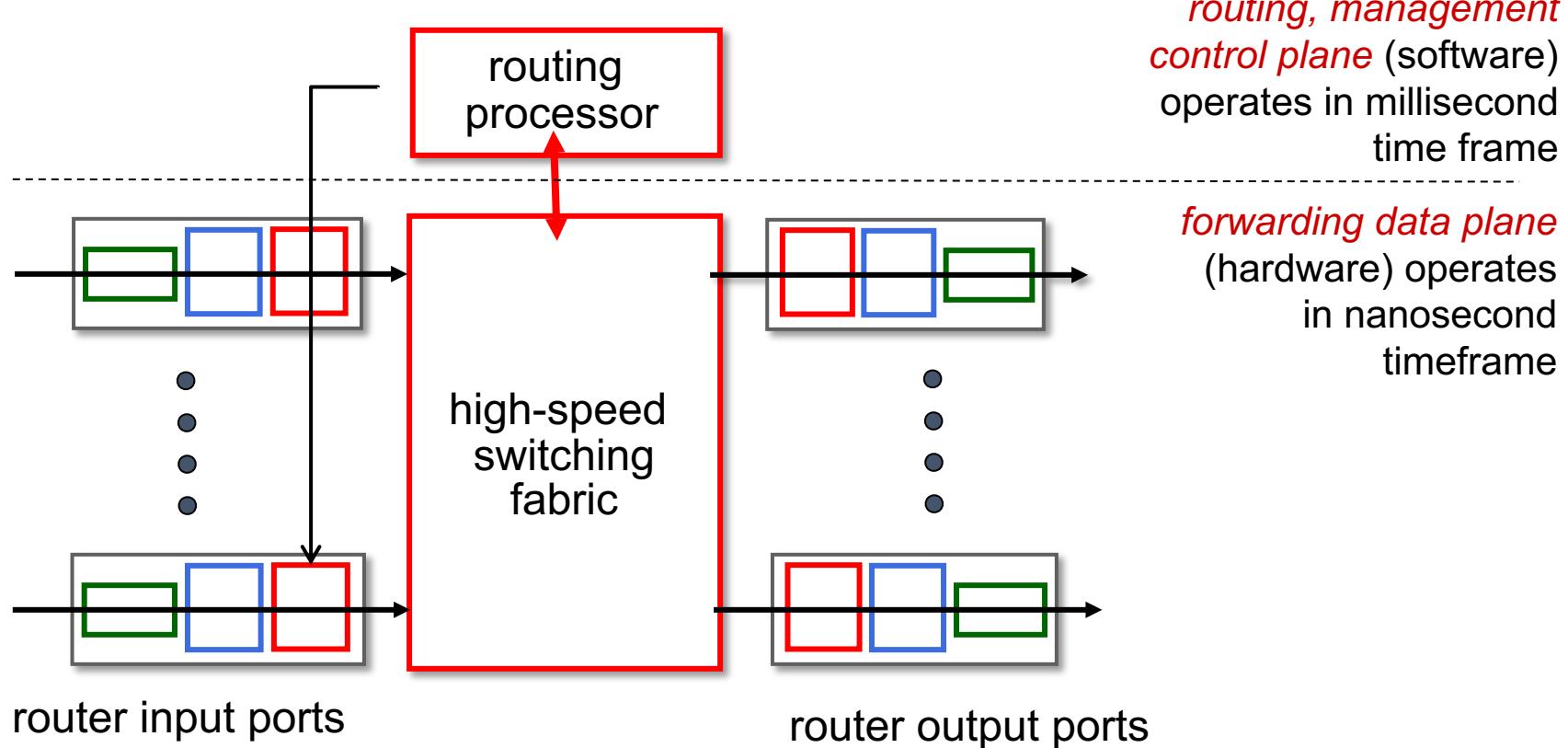
Network layer: “data plane” roadmap

- Network layer: overview
 - data plane
 - control plane
- What's inside a router
 - input ports, switching, output ports
 - buffer management, scheduling
- IP: the Internet Protocol
 - datagram format
 - addressing
 - network address translation
 - IPv6
- Generalized Forwarding, SDN
 - Match+action
 - OpenFlow: match+action in action
- Middleboxes

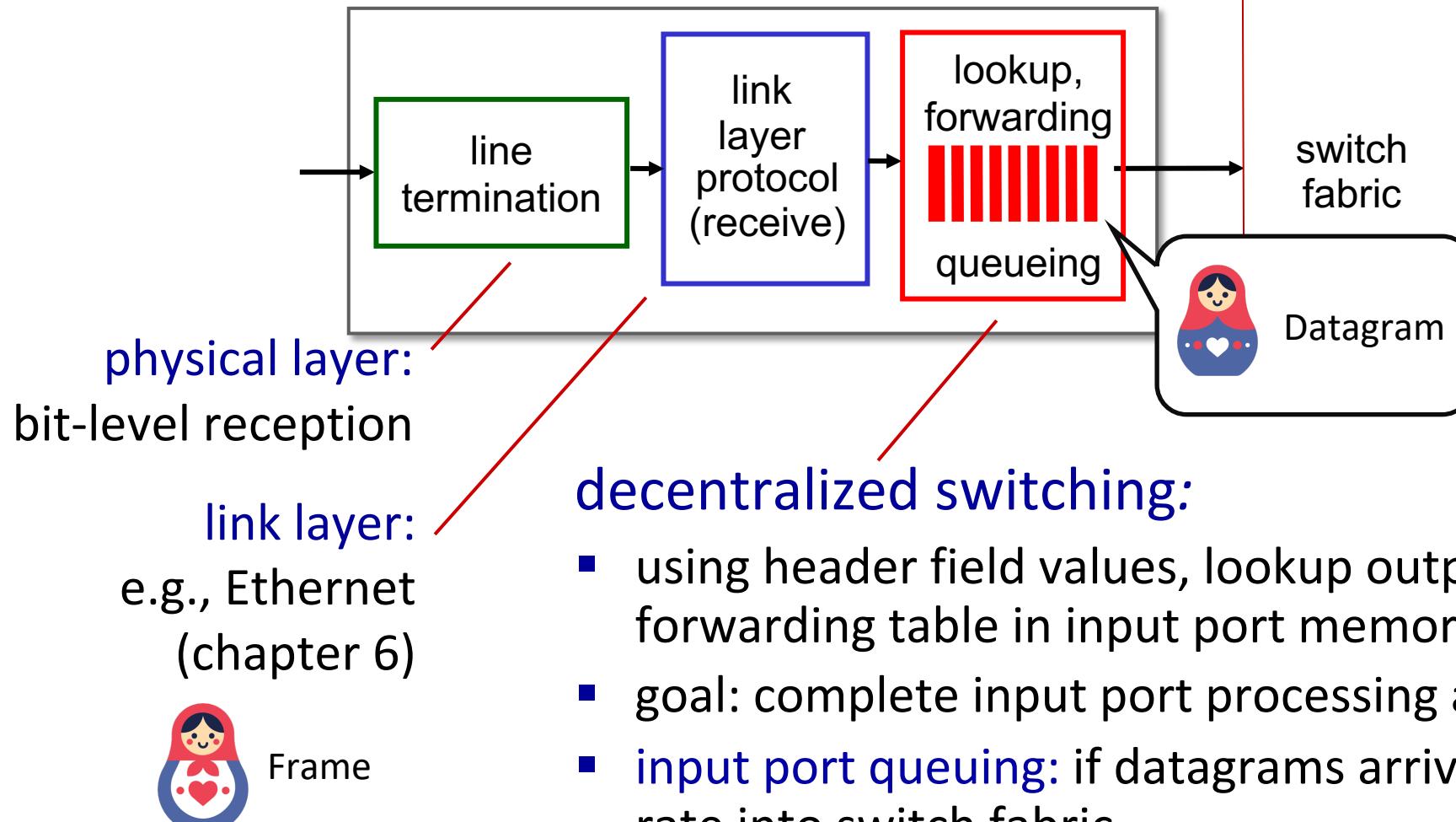


Router architecture overview

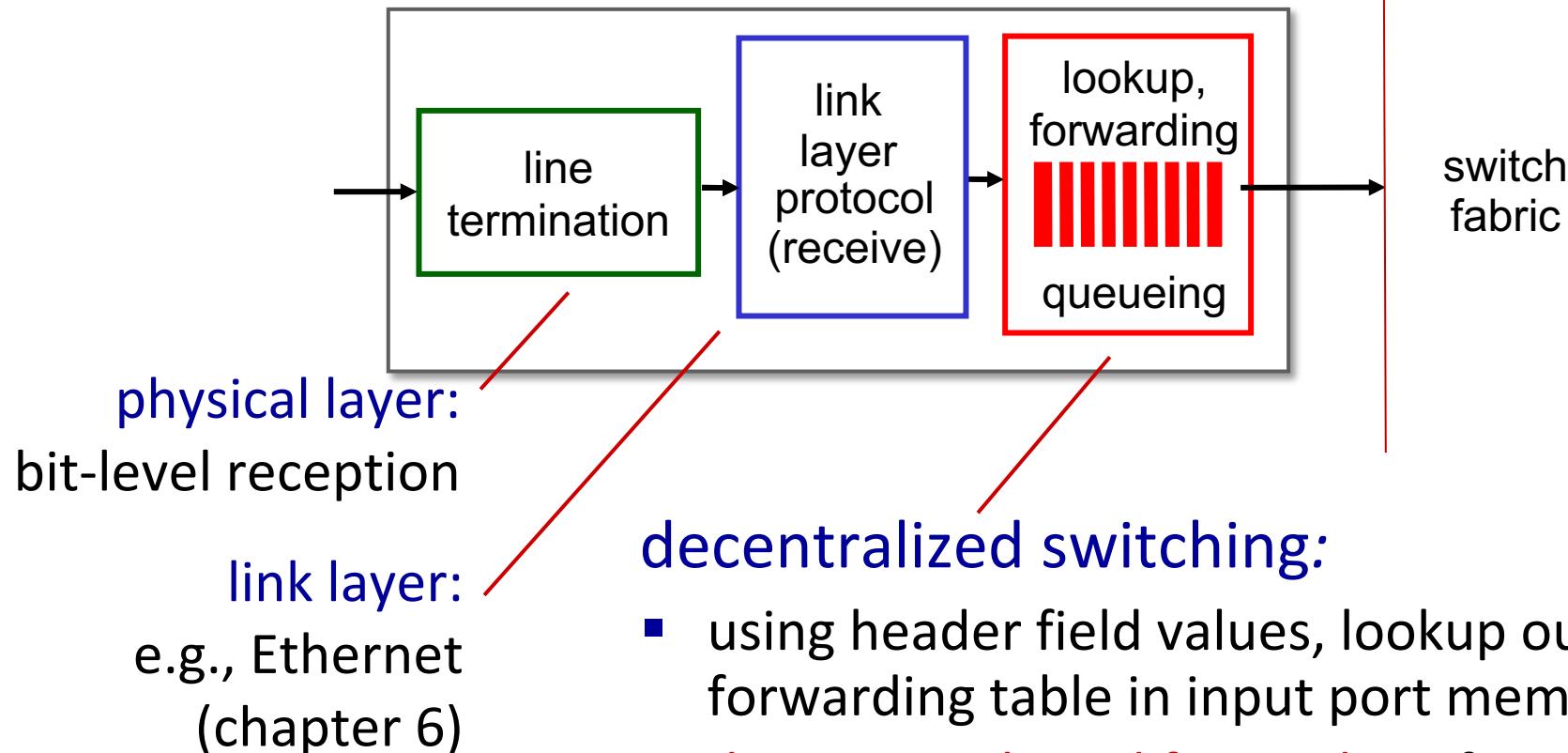
high-level view of generic router architecture:



Input port functions



Input port functions



decentralized switching:

- using header field values, lookup output port using forwarding table in input port memory ("*match plus action*")
- **destination-based forwarding**: forward based only on destination IP address (traditional)
- **generalized forwarding**: forward based on any set of header field values

Longest prefix matching

longest prefix match

when looking for forwarding table entry for given destination address, use *longest* address prefix that matches destination address.

Destination Address Range	Link interface
11001000 00010111 00010*** *****	0
11001000 00010111 00011000 *****	1
11001000 00010111 00011*** *****	2
otherwise	3

examples:

- | | |
|-------------------------------------|------------------|
| 11001000 00010111 00010110 10100001 | which interface? |
| 11001000 00010111 00011000 10101010 | which interface? |

Longest prefix matching

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examples:

11001000 00010111 00010110 10100001 which interface?

11001000 00010111 00011000 10101010 which interface?

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11001000	00010111	00011000	*****	*	1
11001000	00010111	00011***	*****	*	2
otherwise					3

match!

examples:

11001000	00010111	00010110	10100001	which interface?
11001000	00010111	00011000	10101010	which interface?

Longest prefix matching

longest prefix match

when looking for forwarding table entry for given destination address, use *longest* address prefix that matches destination address.

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match!

examples:

11001000	00010111	00010110	10100001	which interface?
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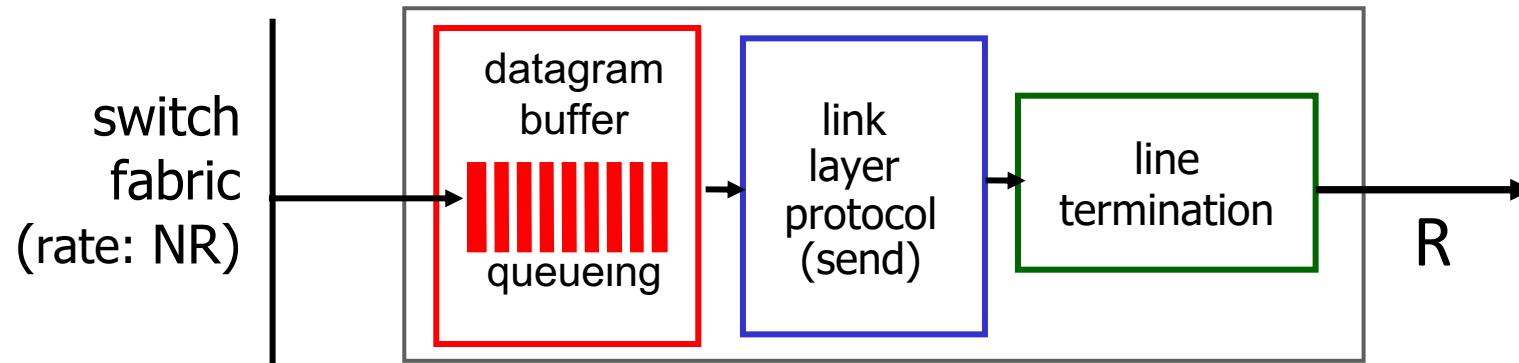
Longest prefix matching

- we'll see *why* longest prefix matching is used shortly, when we study addressing
- longest prefix matching: often performed using ternary content addressable memories (TCAMs)
 - *content addressable*: present address to TCAM: retrieve address in one clock cycle, regardless of table size
 - Cisco Catalyst: ~1M routing table entries in TCAM

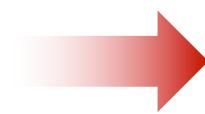
Output port queuing



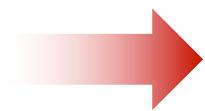
This is a really important slide



- **Buffering** required when datagrams arrive from fabric faster than link transmission rate. **Drop policy:** which datagrams to drop if no free buffers?
- **Scheduling discipline** chooses among queued datagrams for transmission

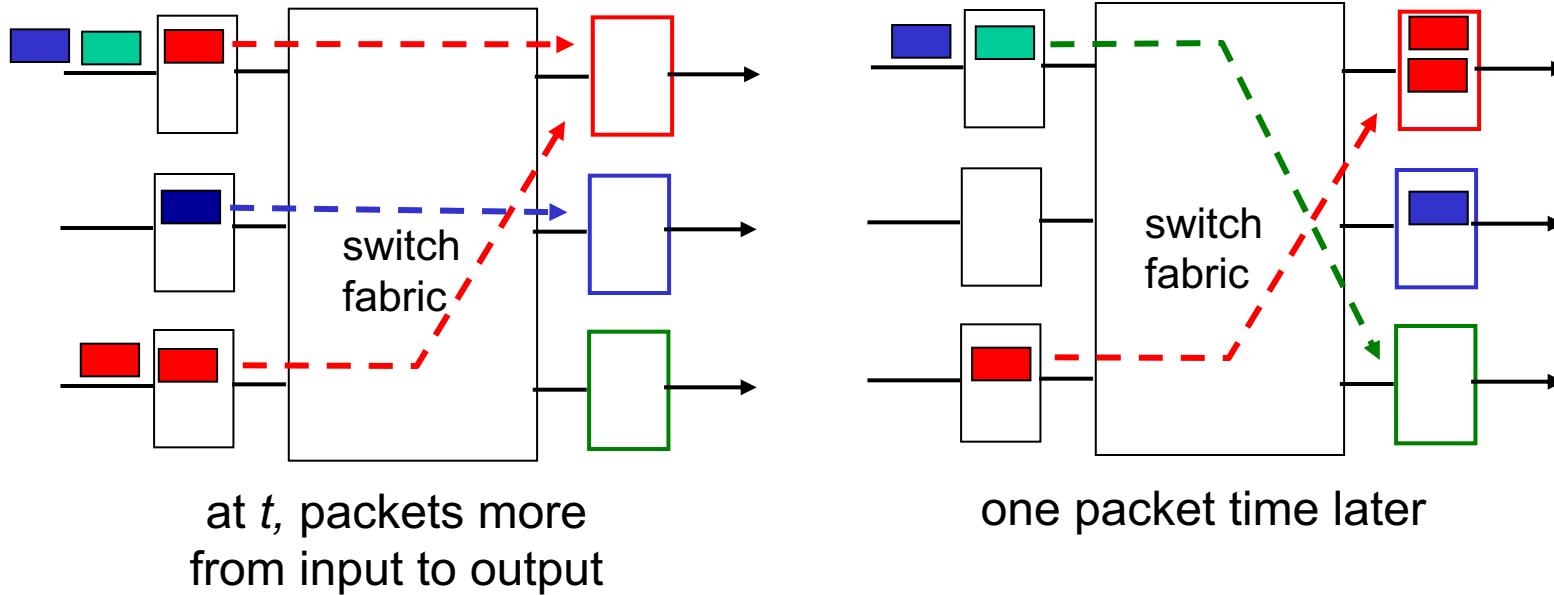


Datagrams can be lost due to congestion, lack of buffers



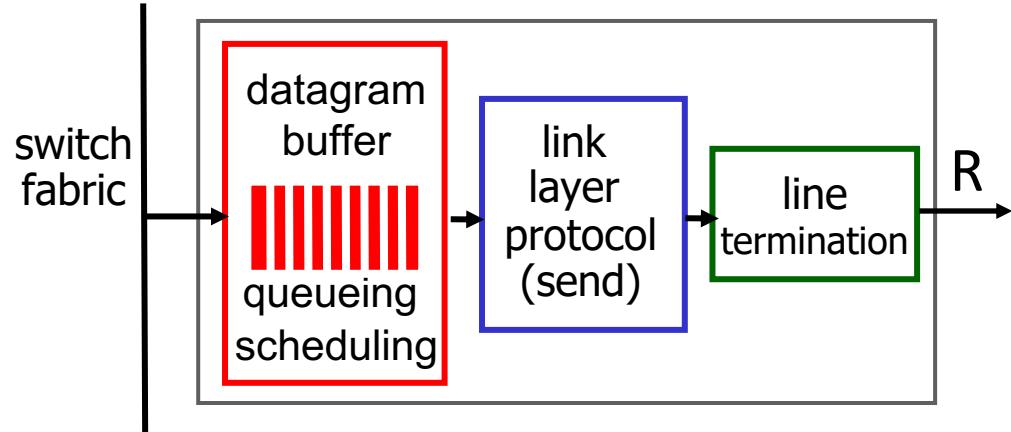
Priority scheduling – who gets best performance, network neutrality

Output port queuing

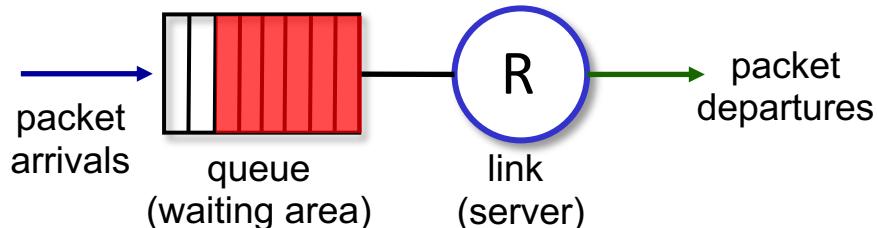


- buffering when arrival rate via switch exceeds output line speed
- *queueing (delay) and loss due to output port buffer overflow!*

Buffer Management



Abstraction: queue



buffer management:

- **drop:** which packet to add, drop when buffers are full
 - tail drop: drop arriving packet
 - priority: drop/remove on priority basis
- **marking:** which packets to mark to signal congestion (ECN, RED)

Packet Scheduling: FCFS

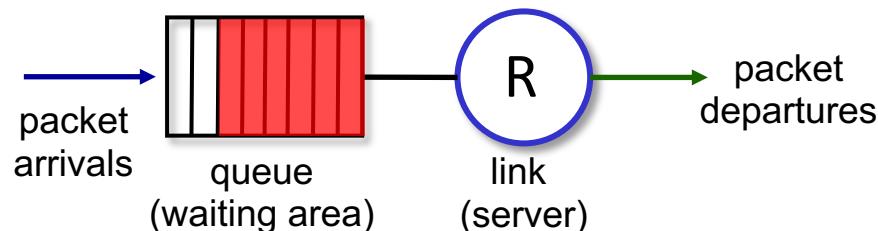
packet scheduling: deciding which packet to send next on link

- first come, first served
- priority
- round robin
- weighted fair queueing

FCFS: packets transmitted in order of arrival to output port

- also known as: First-in-first-out (FIFO)
- real world examples?

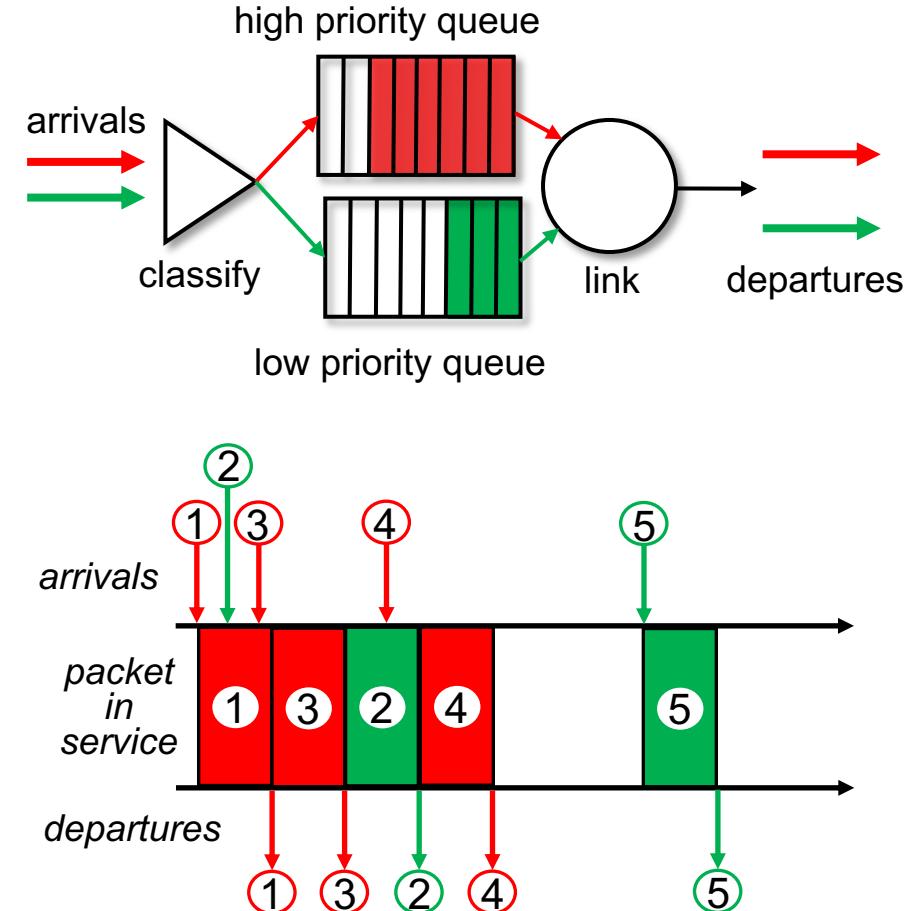
Abstraction: queue



Scheduling policies: priority

Priority scheduling:

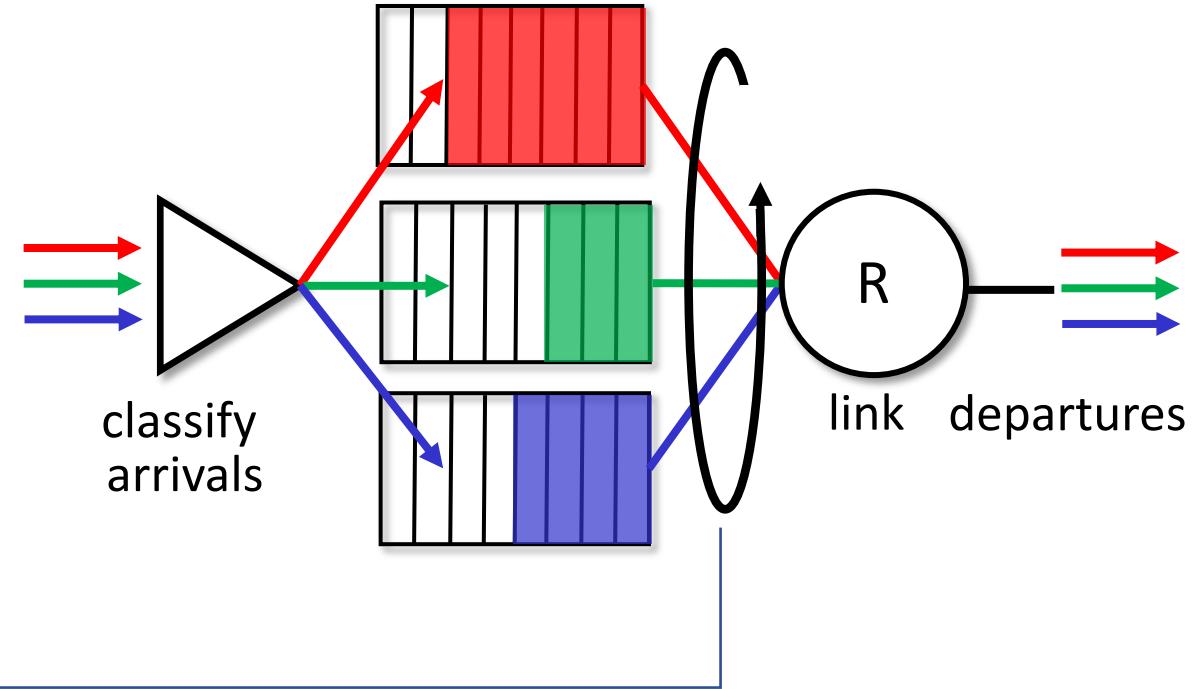
- arriving traffic classified, queued by class
 - any header fields can be used for classification
- send packet from highest priority queue that has buffered packets
 - FCFS within priority class



Scheduling policies: round robin

Round Robin (RR) scheduling:

- arriving traffic classified, queued by class
 - any header fields can be used for classification
- server cyclically, repeatedly scans class queues, sending one complete packet from each class (if available) in turn



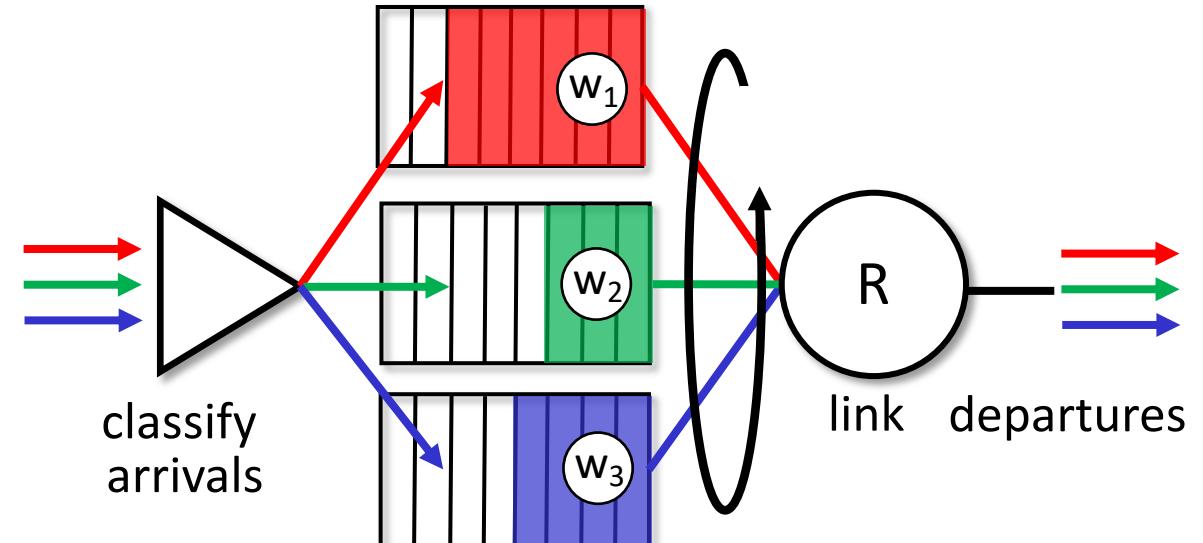
Scheduling policies: weighted fair queueing

Weighted Fair Queueing (WFQ):

- generalized Round Robin
- each class, i , has weight, w_i , and gets weighted amount of service in each cycle:

$$\frac{w_i}{\sum_j w_j}$$

- minimum bandwidth guarantee (per-traffic-class)



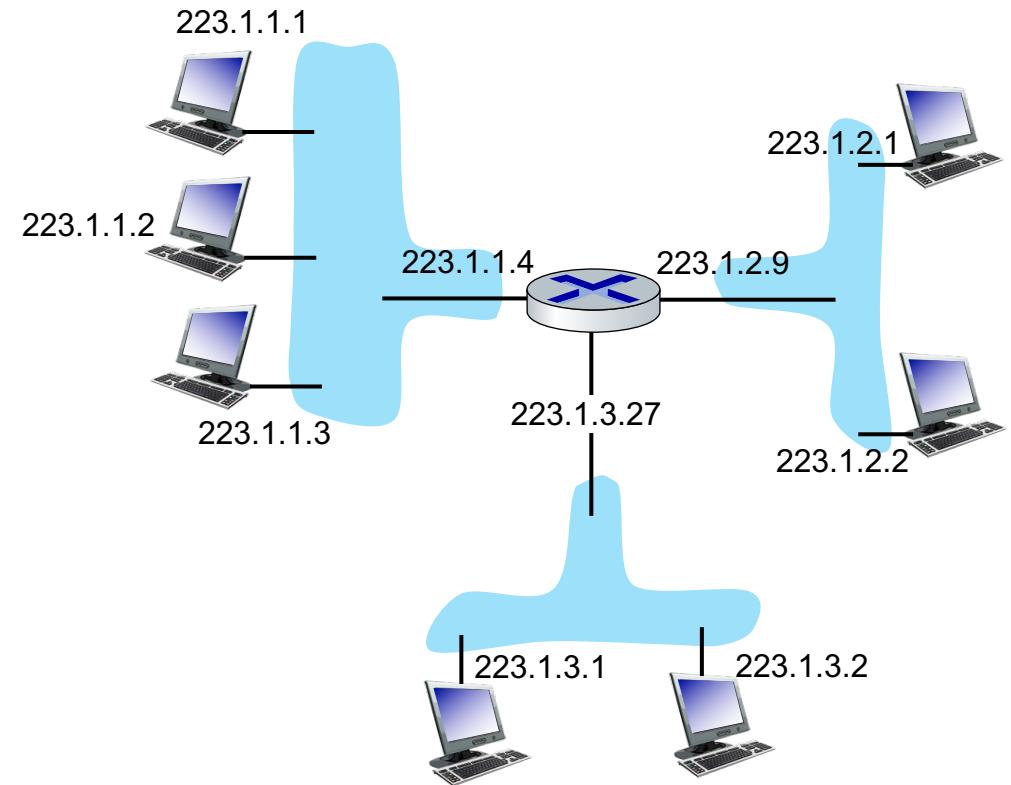
Network layer: “data plane” roadmap

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IP addressing: introduction

- **IP address:** 32-bit identifier associated with each host or router *interface*
- **interface:** connection between host/router and physical link
 - router's typically have multiple interfaces
 - host typically has one or two interfaces (e.g., wired Ethernet, wireless 802.11)



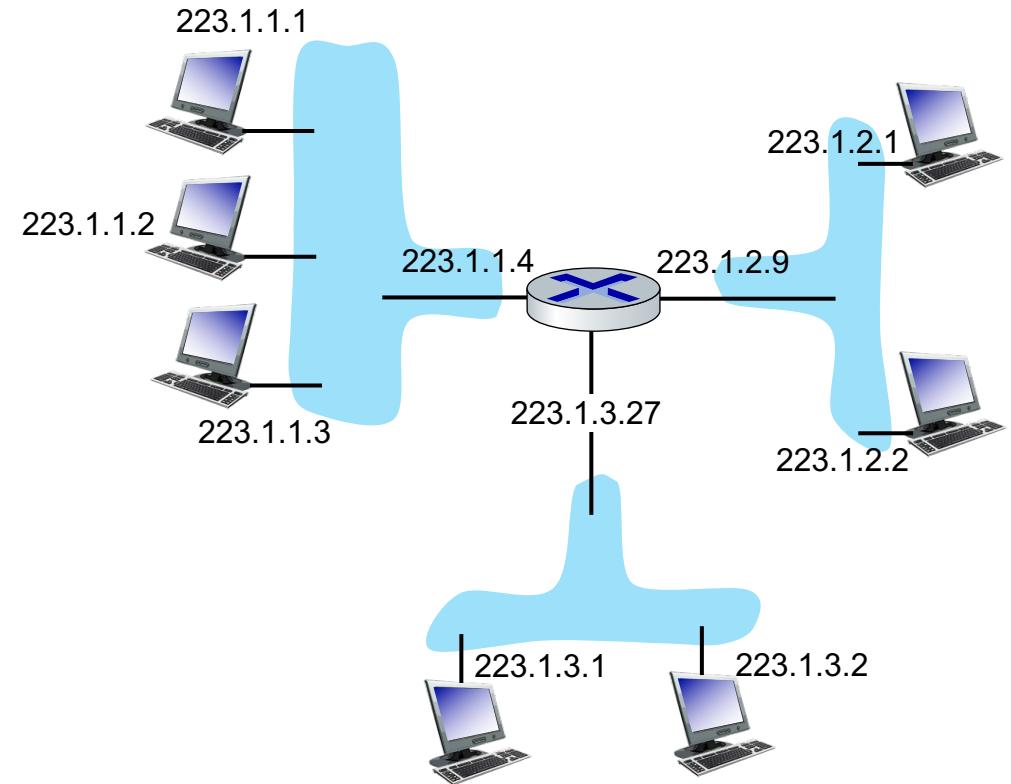
dotted-decimal IP address notation:

223.1.1.1 = $\begin{array}{cccc} 11011111 & 00000001 & 00000001 & 00000001 \end{array}$

223 1 1 1
Network Layer: 4-23

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dotted-decimal IP address notation:

223.1.1.1 = 11011111 00000001 00000001 00000001

223 1 1 1
1 1 1 1

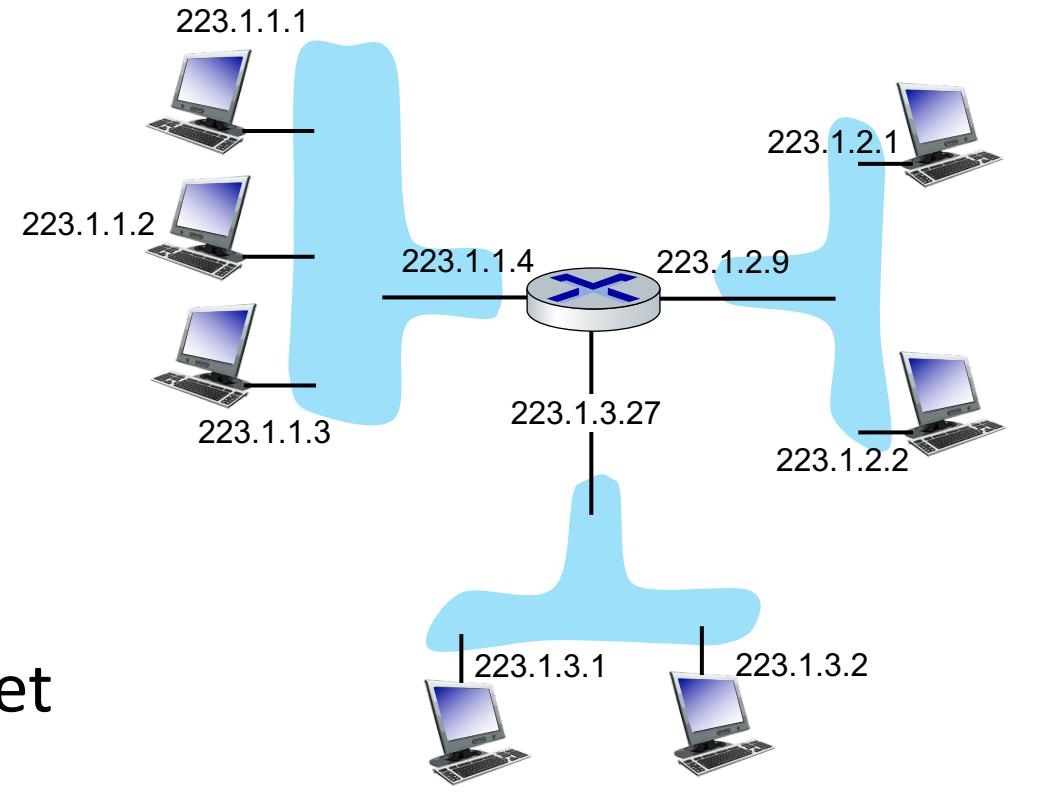
Subnets

- *What's a subnet ?*

- device interfaces that can physically reach each other **without passing through an intervening router**

- IP addresses have structure:

- **subnet part:** devices in same subnet have common high order bits
- **host part:** remaining low order bits

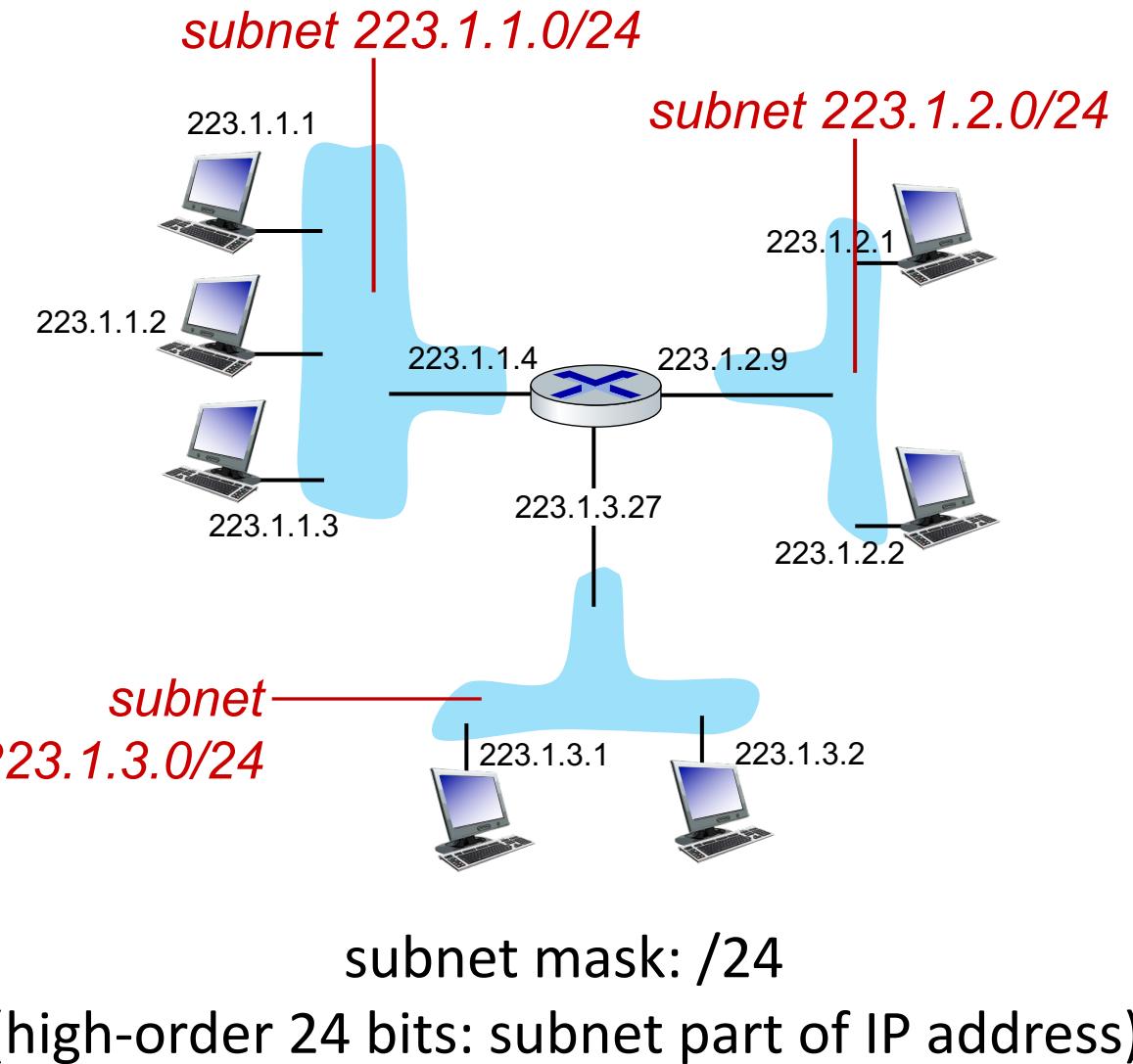


network consisting of 3 subnets

Subnets

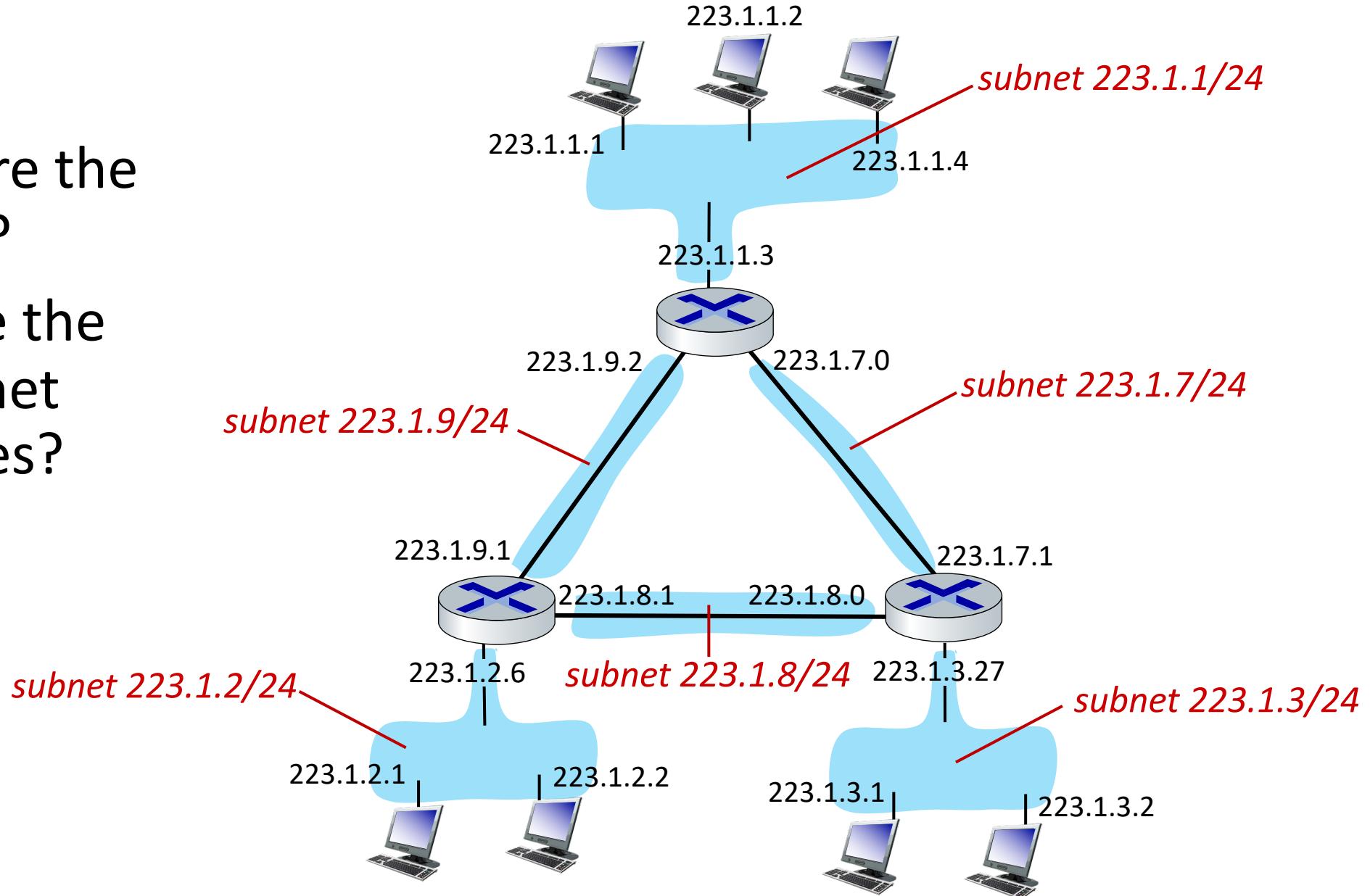
Recipe for defining subnets:

- detach each interface from its host or router, creating “islands” of isolated networks
- each isolated network is called a *subnet*



Subnets

- where are the subnets?
- what are the /24 subnet addresses?



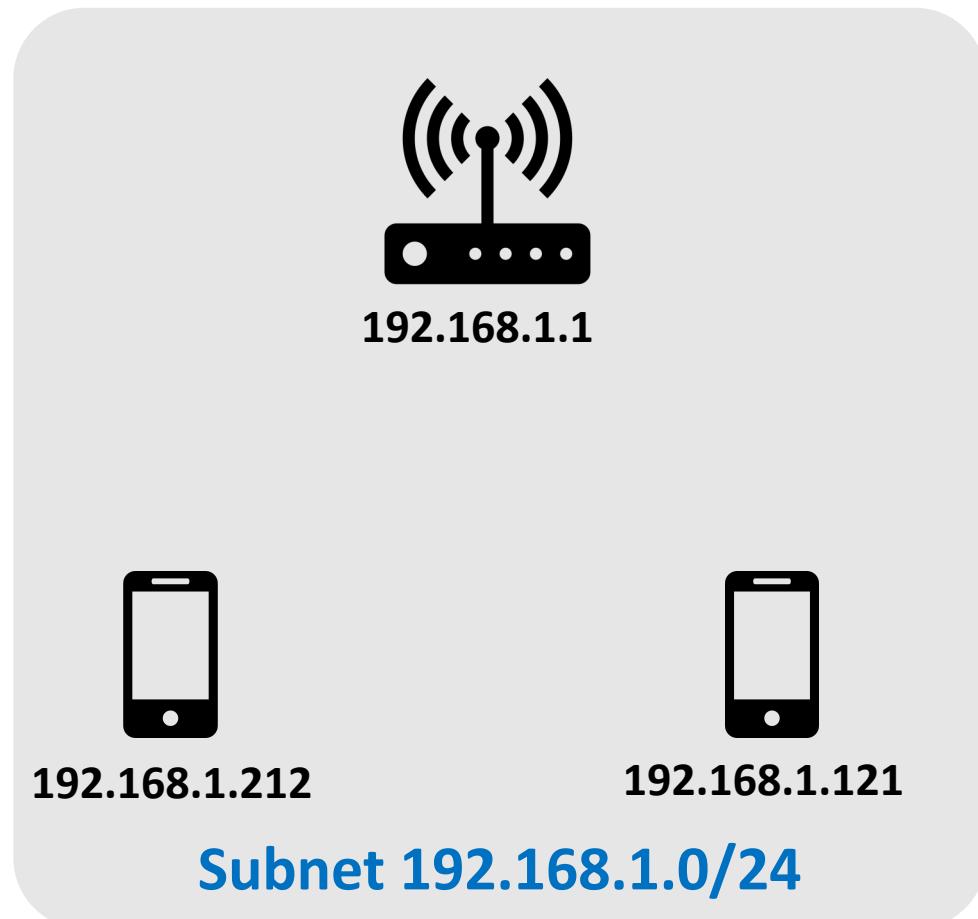
IP addressing: CIDR

CIDR: Classless InterDomain Routing (pronounced “cider”)

- subnet portion of address of arbitrary length
- address format: $a.b.c.d/x$, where x is # bits in subnet portion of address



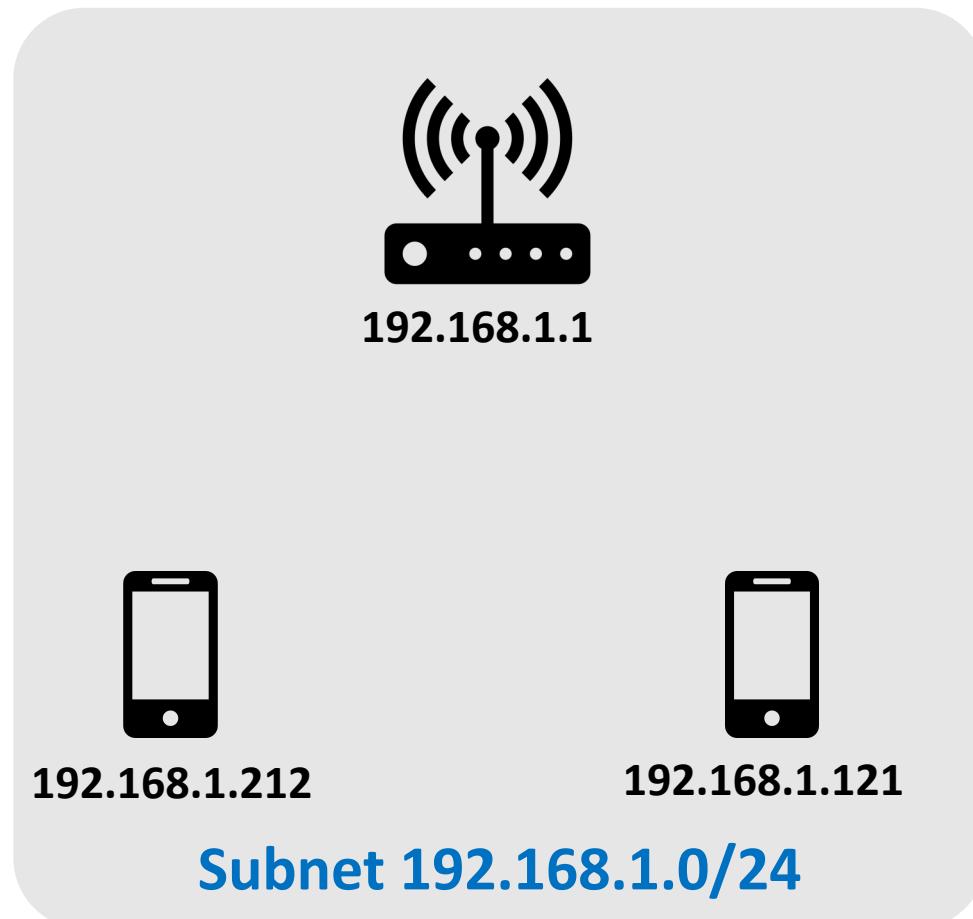
DHCP: Dynamic Host Configuration Protocol



goal: host *dynamically* obtains IP address from network server when it “joins” network

- can renew its lease on address in use
- allows reuse of addresses (only hold address while connected/on)
- support for mobile users who join/leave network

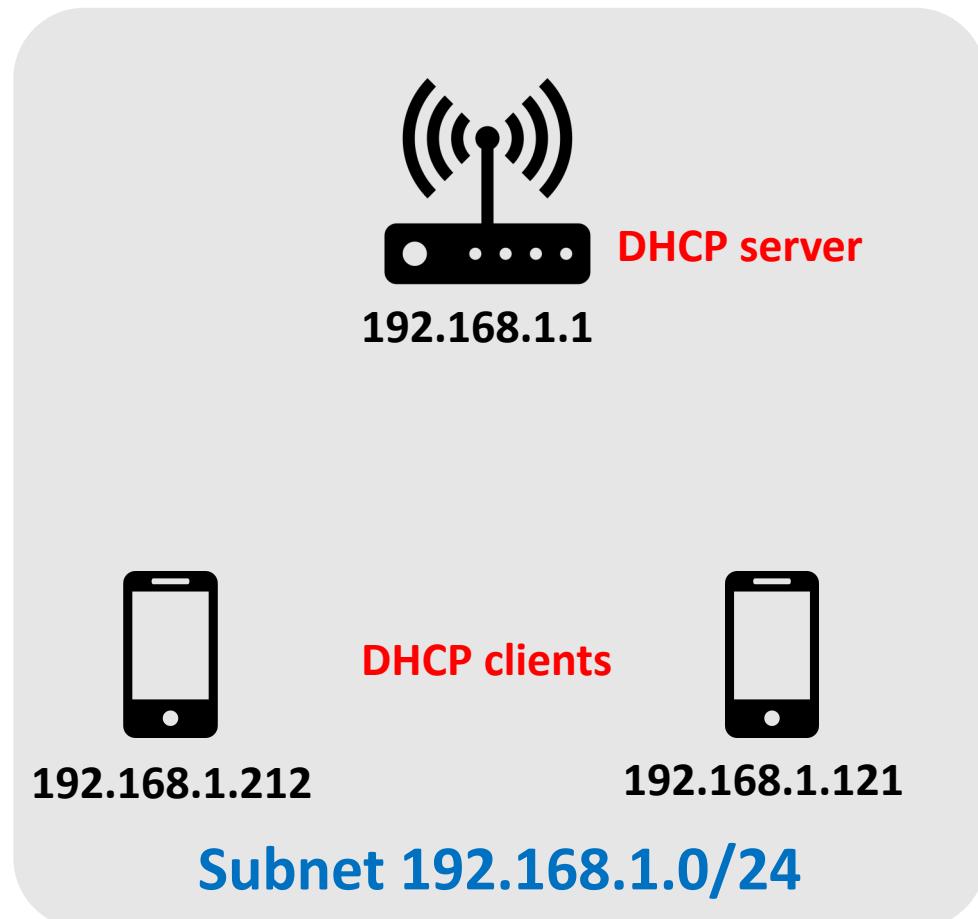
DHCP: Dynamic Host Configuration Protocol



DHCP overview:

- host broadcasts **DHCP discover** msg [optional]
- DHCP server responds with **DHCP offer** msg [optional]
- host requests IP address: **DHCP request** msg
- DHCP server sends address: **DHCP ack** msg

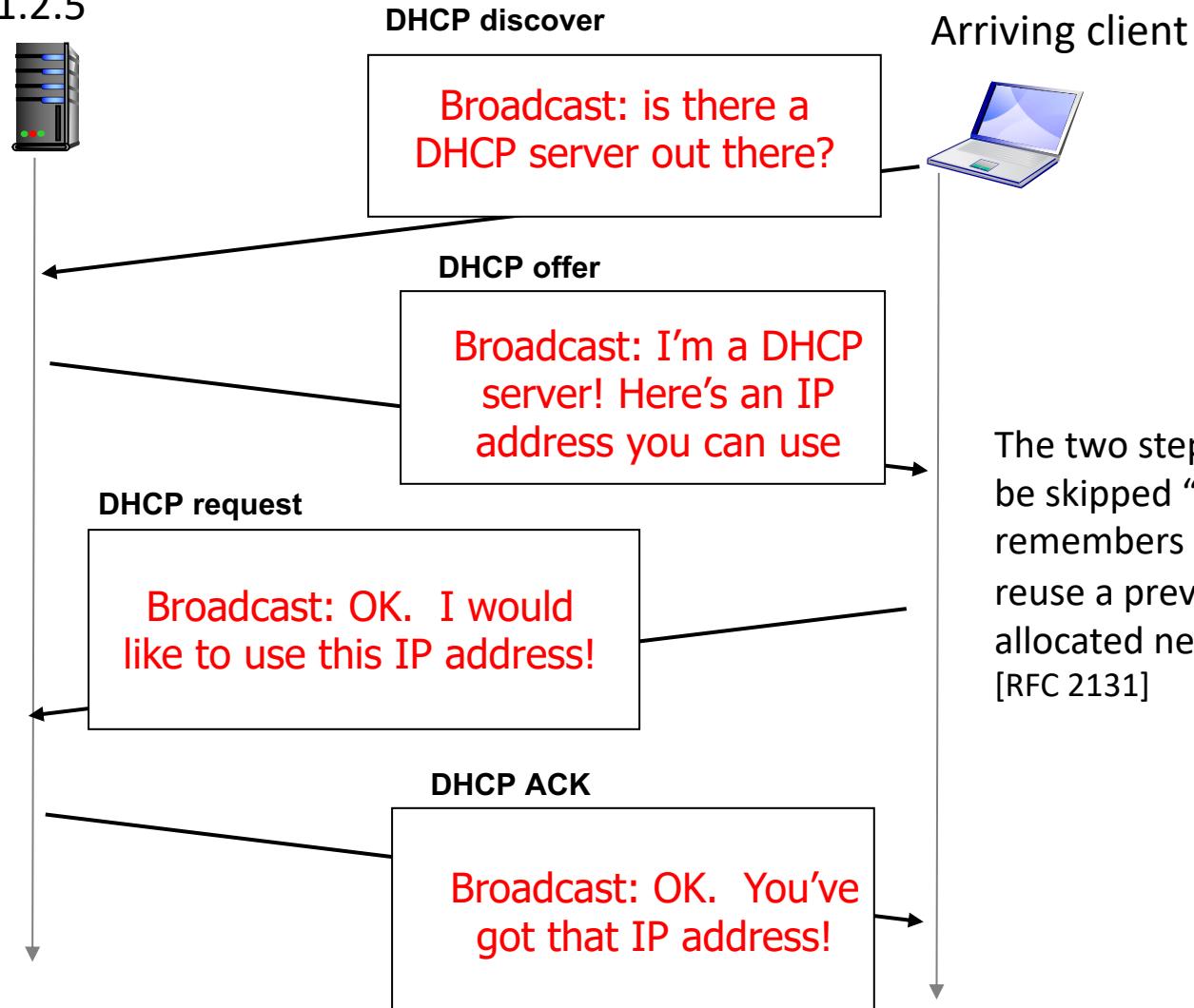
DHCP: client-server



Typically, DHCP server will be co-located in router, serving all subnets to which router is attached

DHCP client-server scenario

DHCP server: 223.1.2.5



DHCP: more than IP addresses

DHCP can return more than just allocated IP address on subnet:

- address of first-hop router for client
- name and IP address of DNS sever
- network mask (indicating network versus host portion of address)

IP addresses: how to get one?

Q: how does *network* get subnet part of IP address?

A: gets allocated portion of its provider ISP's address space

ISP's block	<u>11001000</u> <u>00010111</u> <u>00010000</u> <u>00000000</u>	200.23.16.0/20
-------------	---	----------------

ISP can then allocate out its address space in 8 blocks:

Organization 0	<u>11001000</u> <u>00010111</u> <u>00010000</u> <u>00000000</u>	200.23.16.0/23
----------------	---	----------------

Organization 1	<u>11001000</u> <u>00010111</u> <u>00010010</u> <u>00000000</u>	200.23.18.0/23
----------------	---	----------------

Organization 2	<u>11001000</u> <u>00010111</u> <u>00010100</u> <u>00000000</u>	200.23.20.0/23
----------------	---	----------------

...

.....

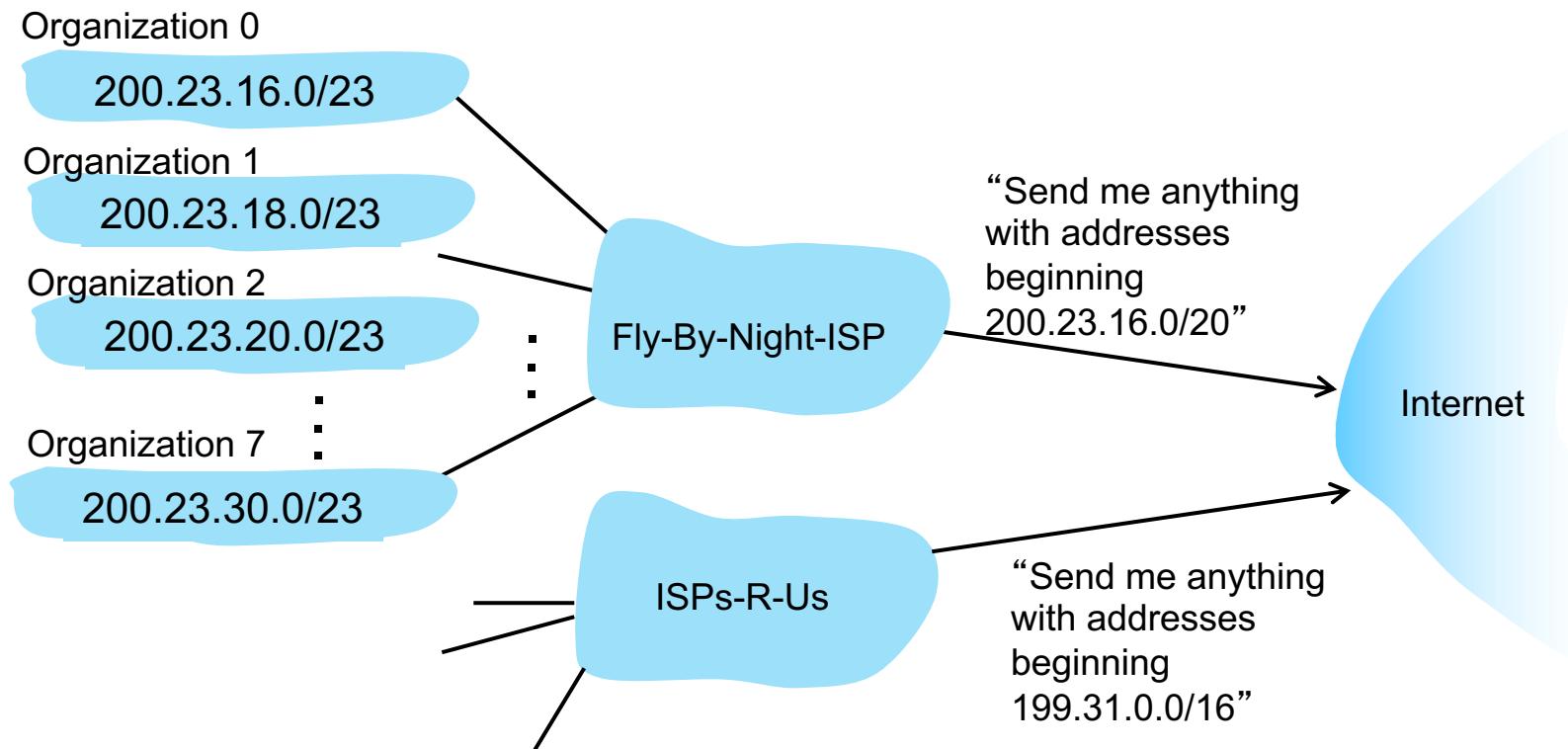
.....

.....

Organization 7	<u>11001000</u> <u>00010111</u> <u>00011110</u> <u>00000000</u>	200.23.30.0/23
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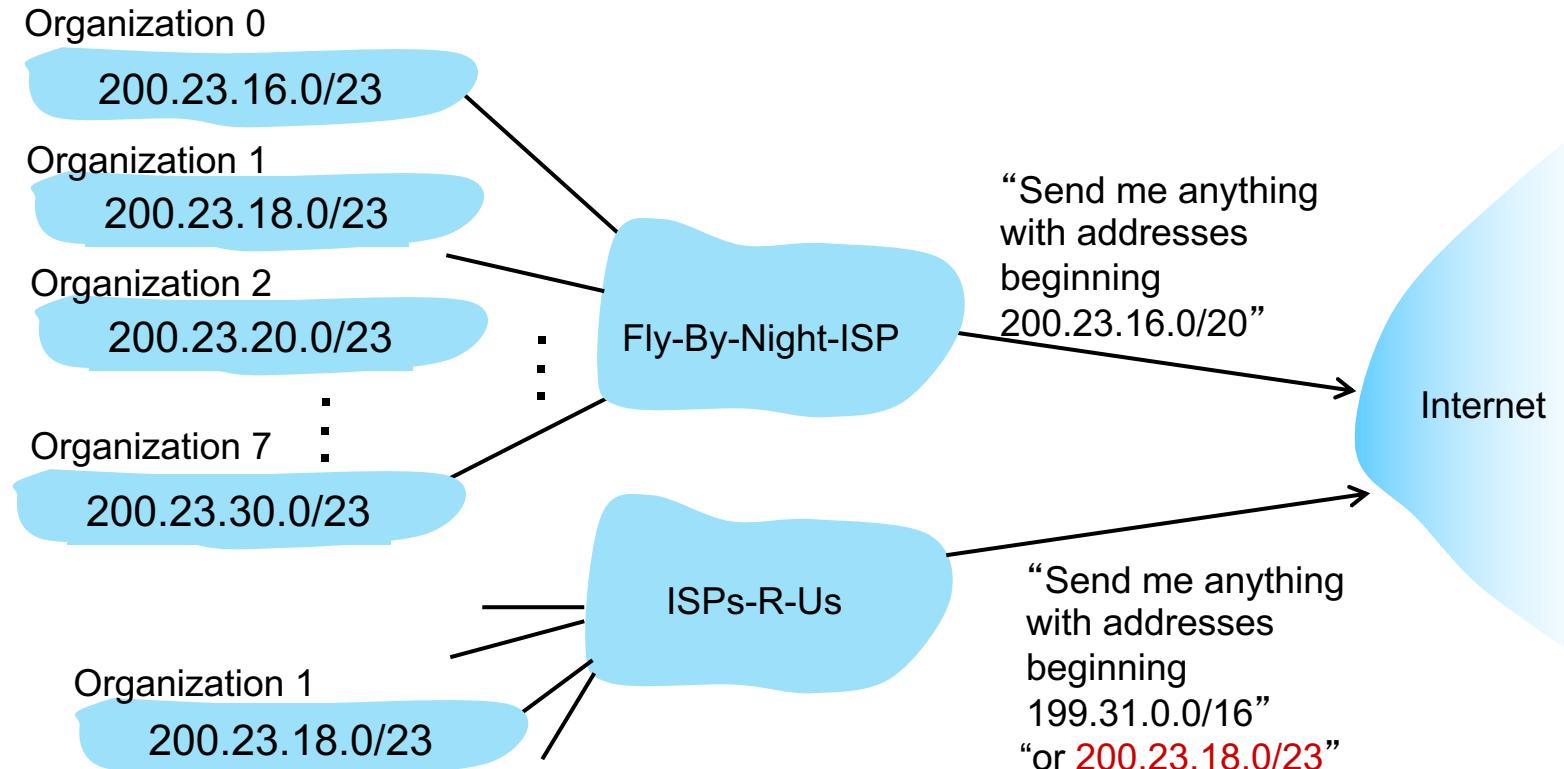
Hierarchical addressing: route aggregation

hierarchical addressing allows efficient advertisement of routing information:



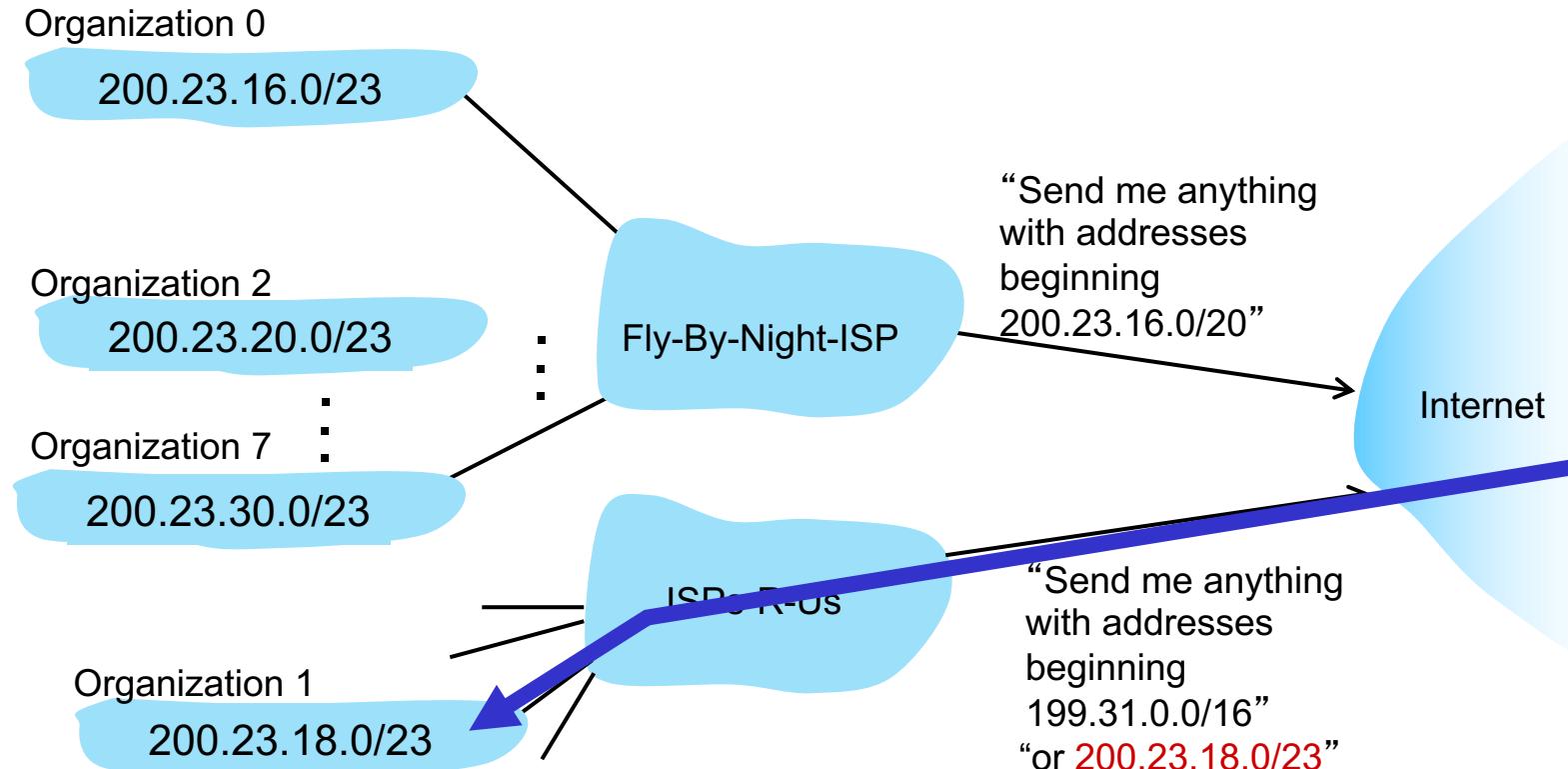
Hierarchical addressing: more specific routes

- Organization 1 moves from Fly-By-Night-ISP to ISPs-R-Us
- ISPs-R-Us now advertises a more specific route to Organization 1



Hierarchical addressing: more specific routes

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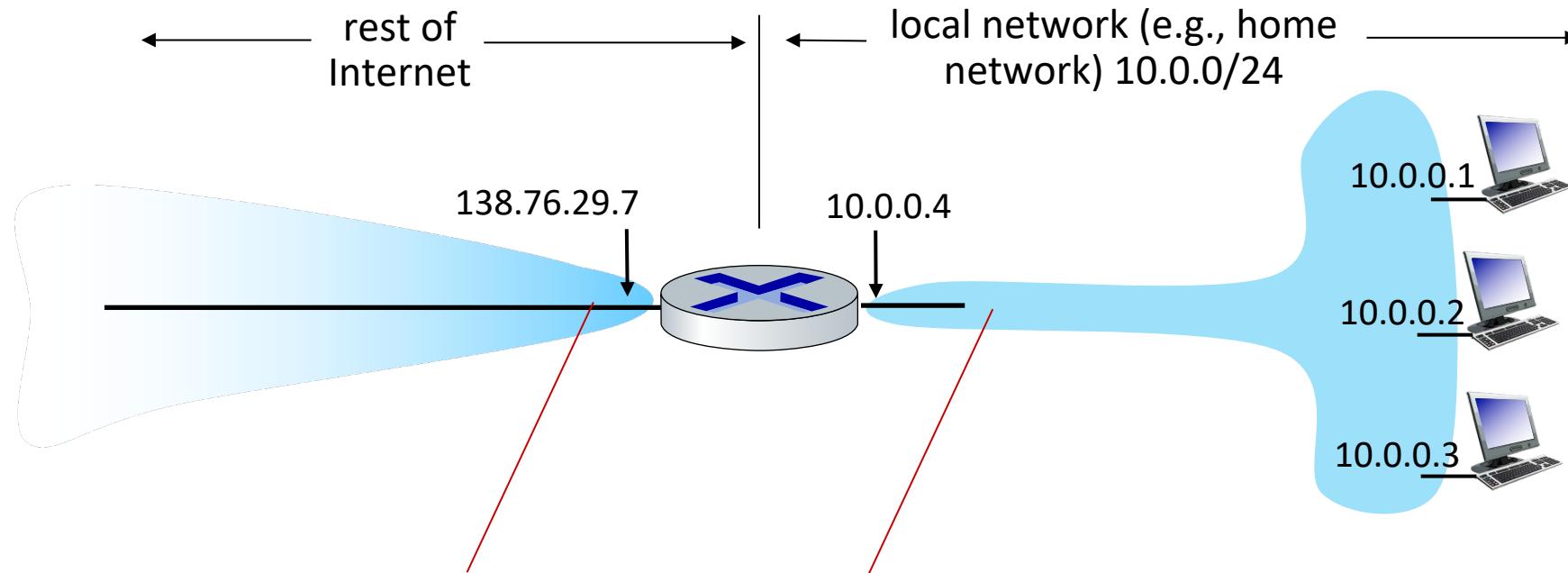
Network layer: “data plane” roadmap

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NAT: network address translation

NAT: all devices in local network share just **one** IPv4 address as far as outside world is concerned



all datagrams *leaving* local network have *same* source NAT IP address: 138.76.29.7, but *different* source port numbers

datagrams with source or destination in this network have 10.0.0/24 address for source, destination (as usual)

NAT: network address translation

- all devices in local network have 32-bit addresses in a “private” IP address space (10/8, 172.16/12, 192.168/16 prefixes) that can only be used in local network
- advantages:
 - just **one** IP address needed from provider ISP for ***all*** devices
 - can change addresses of host in local network without notifying outside world
 - can change ISP without changing addresses of devices in local network
 - security: devices inside local net not directly addressable, visible by outside world

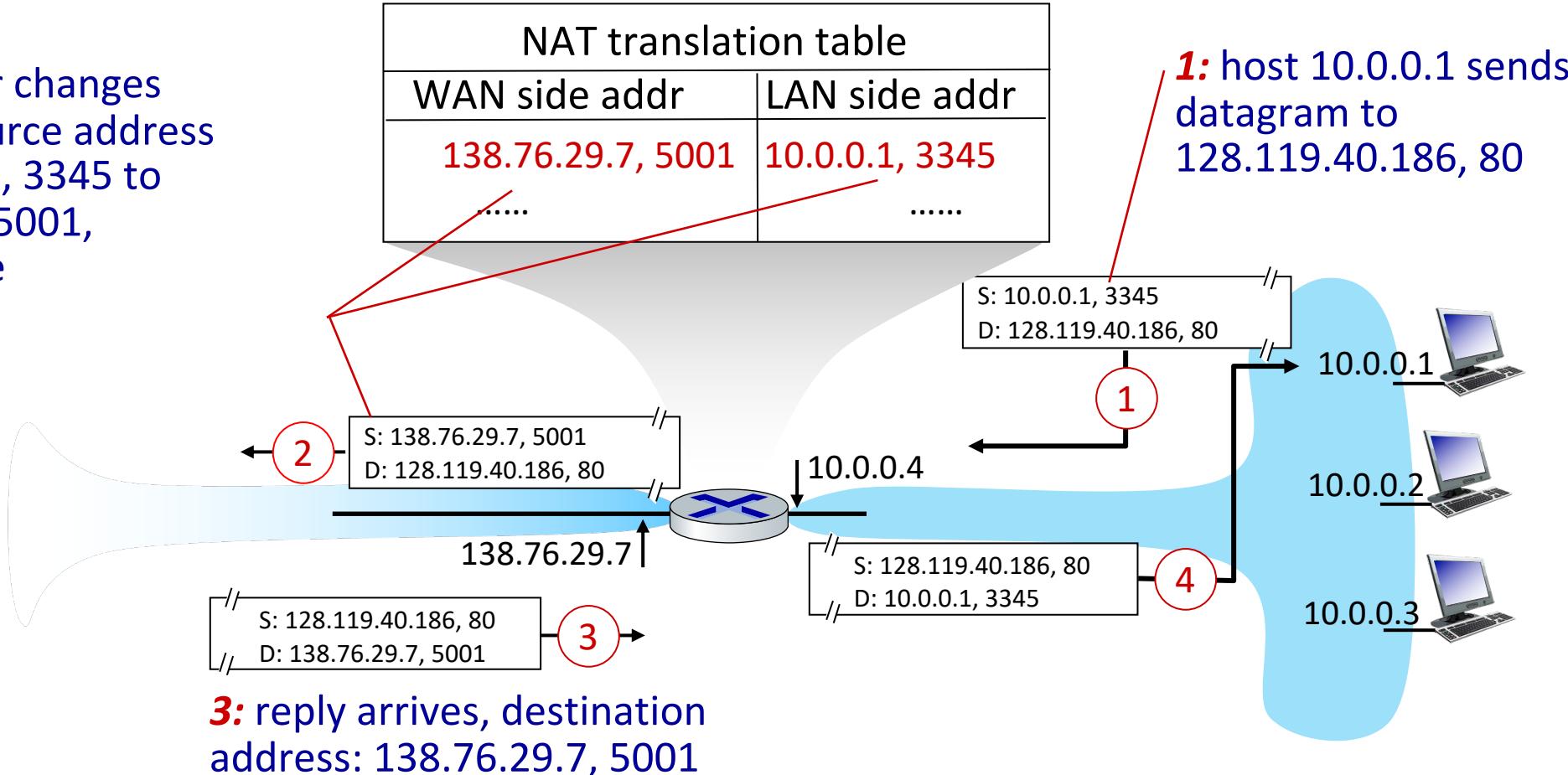
NAT: network address translation

implementation: NAT router must (transparently):

- outgoing datagrams: replace (source IP address, port #) of every outgoing datagram to (NAT IP address, new port #)
 - remote clients/servers will respond using (NAT IP address, new port #) as destination address
- remember (in NAT translation table) every (source IP address, port #) to (NAT IP address, new port #) translation pair
- incoming datagrams: replace (NAT IP address, new port #) in destination fields of every incoming datagram with corresponding (source IP address, port #) stored in NAT table

NAT: network address translation

2: NAT router changes datagram source address from 10.0.0.1, 3345 to 138.76.29.7, 5001, updates table



NAT: network address translation

- NAT has been controversial:
 - routers “should” only process up to layer 3
 - address “shortage” should be solved by IPv6
 - violates end-to-end argument (port # manipulation by network-layer device)
 - NAT traversal: what if client wants to connect to server behind NAT?
- but NAT is here to stay:
 - extensively used in home and institutional nets, 4G/5G cellular nets

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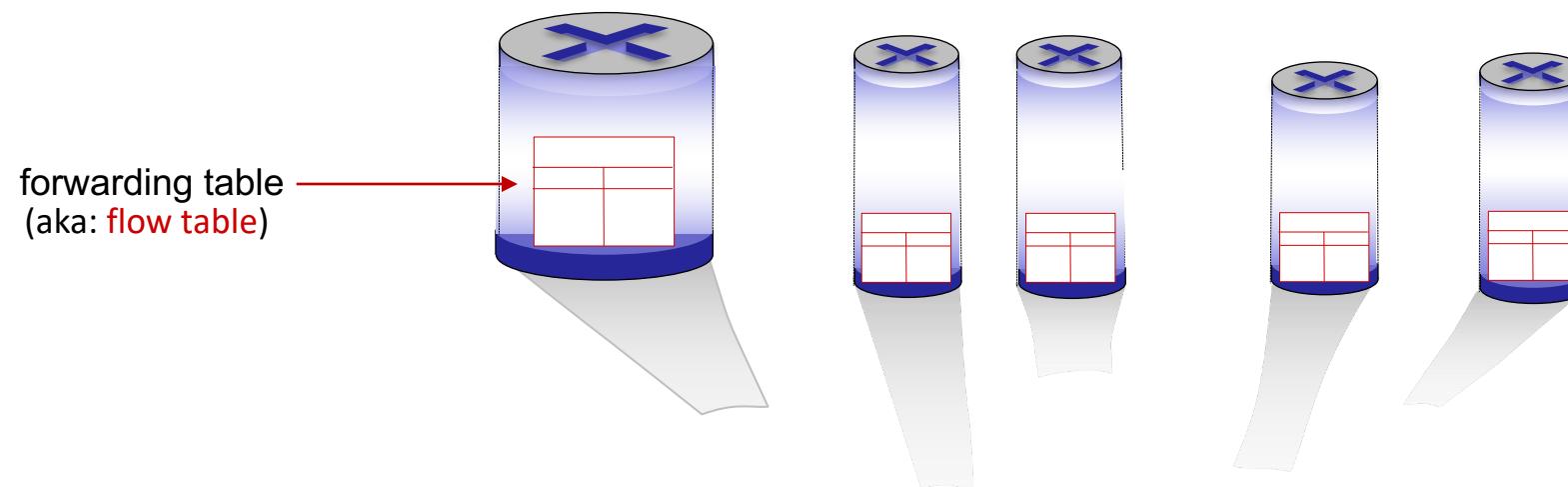


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Generalized forwarding: match plus action

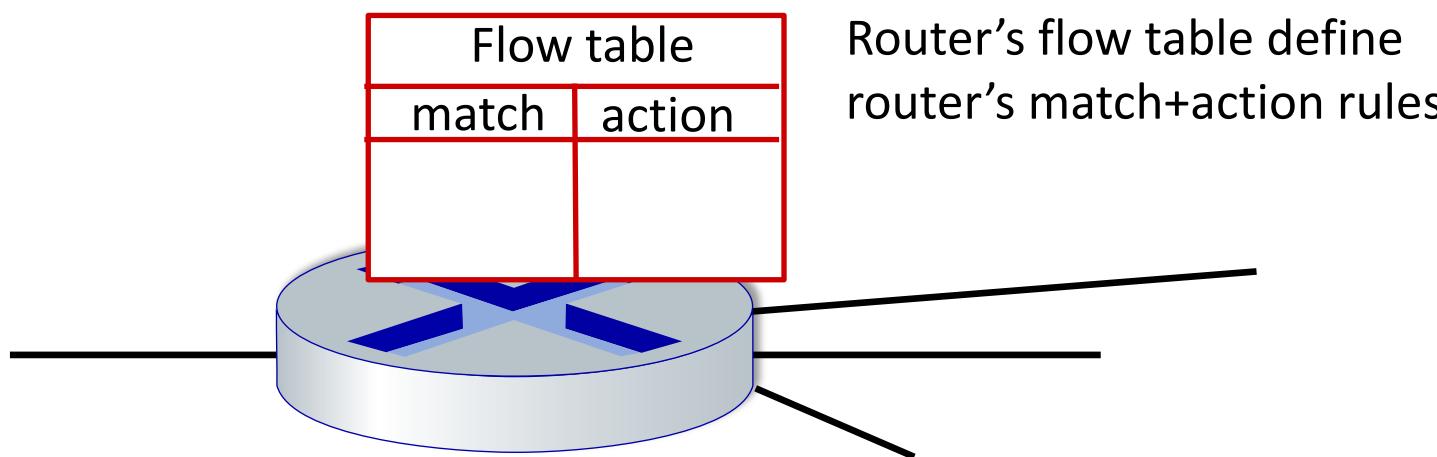
Review: each router contains a **forwarding table** (aka: **flow table**)

- “**match plus action**” abstraction: match bits in arriving packet, take action
 - *destination-based forwarding*: forward based on dest. IP address
 - *generalized forwarding*:
 - many header fields can determine action
 - many actions possible: drop/copy/modify/log packet



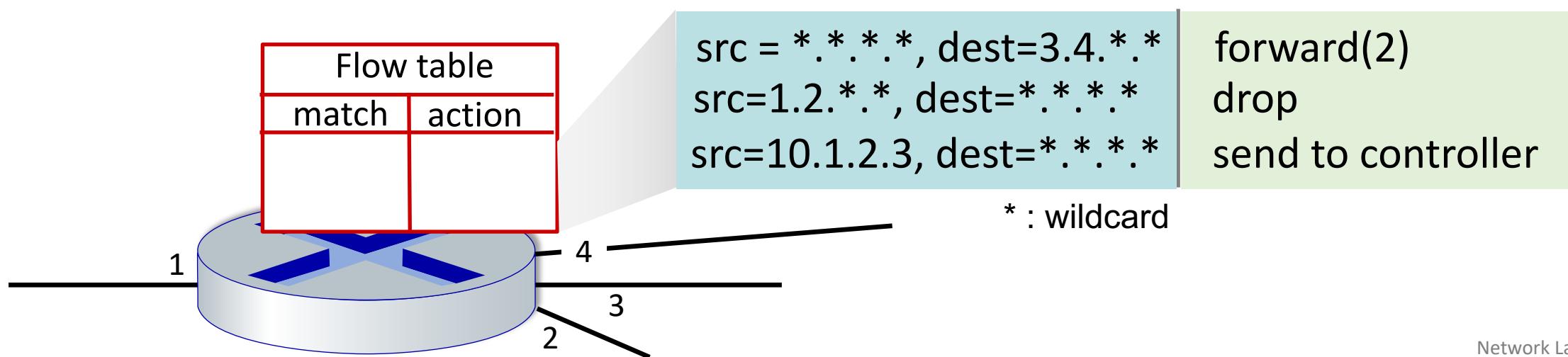
Flow table abstraction

- **flow:** defined by header field values (in link-, network-, transport-layer fields)
- **generalized forwarding:** simple packet-handling rules
 - **match:** pattern values in packet header fields
 - **actions:** for matched packet: drop, forward, modify, matched packet or send matched packet to controller
 - **priority:** disambiguate overlapping patterns
 - **counters:** #bytes and #packets



Flow table abstraction

- **flow:** defined by header fields
- **generalized forwarding:** simple packet-handling rules
 - **match:** pattern values in packet header fields
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Network layer: “control plane” roadmap

- introduction
- **routing protocols**

- link state
- distance vector



**Highly
important**

- intra-ISP routing: OSPF
- routing among ISPs: BGP
- SDN control plane
- Internet Control Message Protocol

- network management, configuration
 - SNMP
 - NETCONF/YANG



Network layer: “control plane” roadmap

- introduction
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- **intra-ISP routing: OSPF**
- routing among ISPs: BGP
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Internet approach to scalable routing

aggregate routers into regions known as “autonomous systems” (AS) (a.k.a. “domains”)

intra-AS (aka “intra-domain”):
routing among routers *within same AS (“network”)*

- all routers in AS must run same intra-domain protocol
- routers in different AS can run different intra-domain routing protocols
- **gateway router:** at “edge” of its own AS, has link(s) to router(s) in other AS'es

inter-AS (aka “inter-domain”):
routing *among* AS'es

- gateways perform inter-domain routing (as well as intra-domain routing)

Network layer: “control plane” roadmap

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- routing protocols
- intra-ISP routing: OSPF
- **routing among ISPs: BGP**
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No calculations



- network management, configuration
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- routing among ISPs: BGP
- **SDN control plane** 
- Internet Control Message Protocol 



- network management, configuration
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 - NETCONF/YANG

Link layer, LANs: roadmap

- introduction
- error detection, correction
- multiple access protocols
- LANs
 - addressing, ARP
 - Ethernet
 - switches
 - VLANs
- link virtualization: MPLS
- data center networking



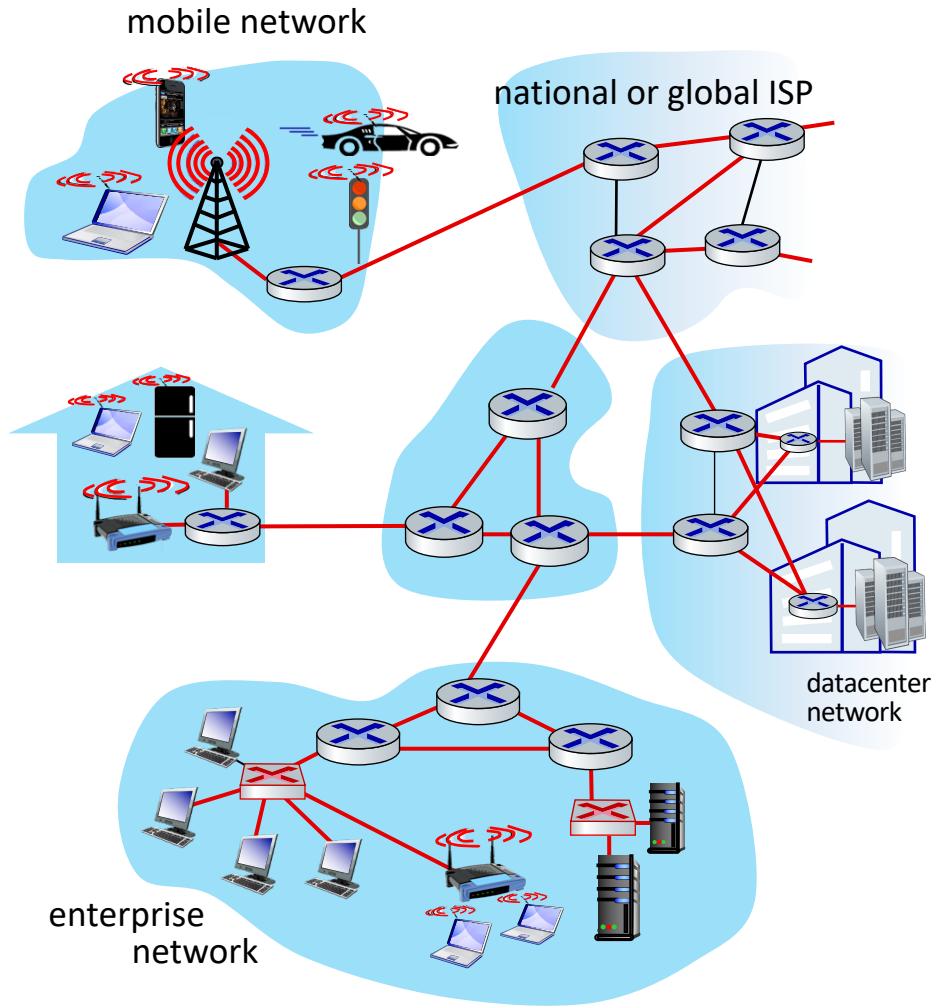
- a day in the life of a web request

Link layer: introduction

terminology:

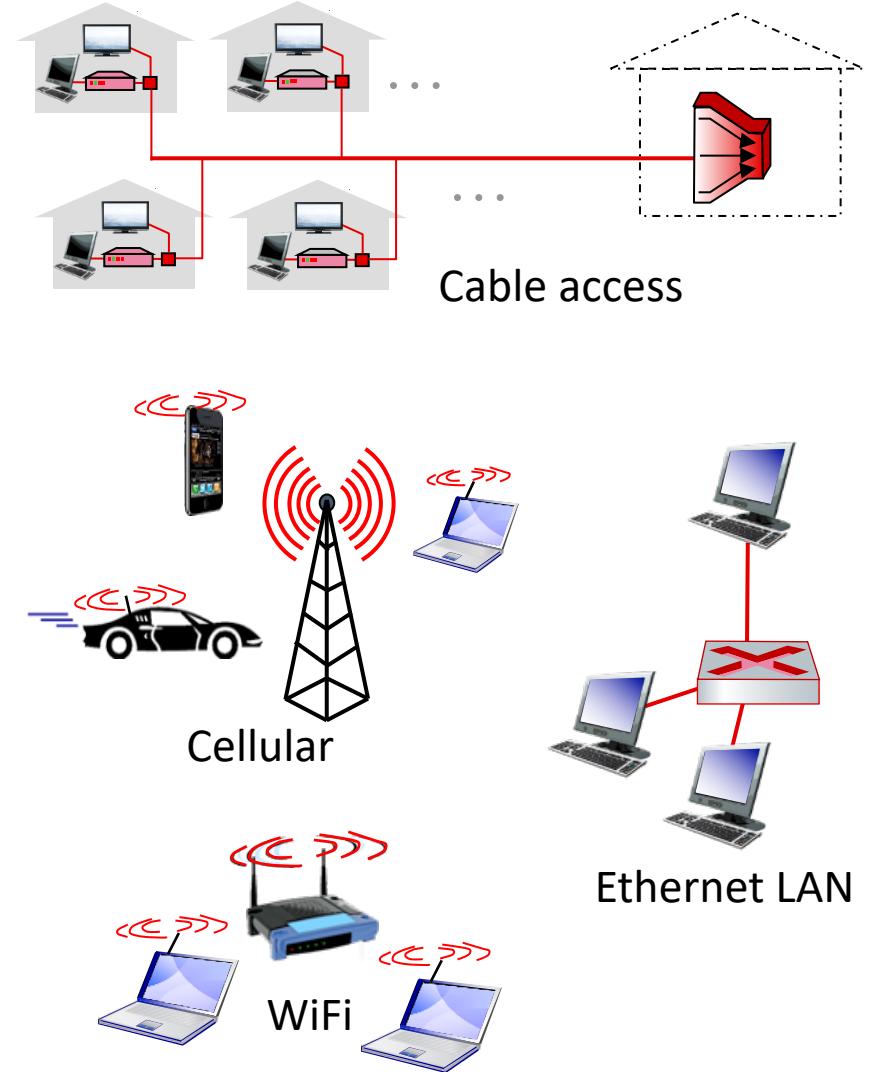
- hosts and routers: nodes
- communication channels that connect adjacent nodes along communication path: links
 - wired
 - wireless
 - LANs
- layer-2 packet: *frame*, encapsulates datagram

link layer has responsibility of transferring datagram from one node to *physically adjacent* node over a link



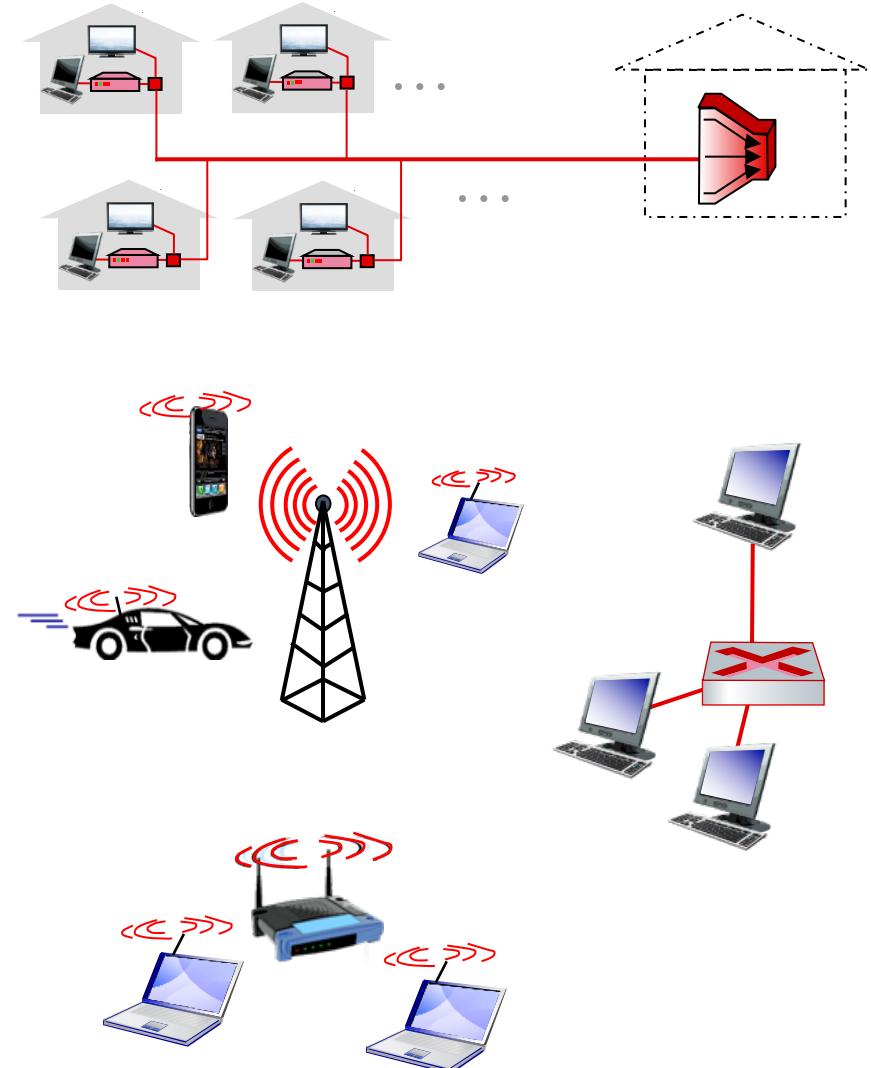
Link layer: services

- **framing, link access:**
 - encapsulate datagram into frame, adding header, trailer
 - channel access if shared medium
 - “MAC” addresses in frame headers identify source, destination (different from IP address!)
- **reliable delivery between adjacent nodes**
 - we already know how to do this!
 - seldom used on low bit-error links
 - wireless links: high error rates
 - Q: why both link-level and end-end reliability?



Link layer: services (more)

- **flow control:**
 - pacing between adjacent sending and receiving nodes
- **error detection:**
 - errors caused by signal attenuation, noise.
 - receiver detects errors, signals retransmission, or drops frame
- **error correction:**
 - receiver identifies *and corrects* bit error(s) without retransmission
- **half-duplex and full-duplex:**
 - with half duplex, nodes at both ends of link can transmit, but not at same time



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 - VLANs
- link virtualization: MPLS
- data center networking



- a day in the life of a web request

Cyclic Redundancy Check (CRC)

- more powerful error-detection coding
- can detect all burst errors less than $r+1$ bits
- widely used in practice (Ethernet, 802.11 WiFi)



Link layer, LANs: roadmap

- introduction
- error detection, correction
- **multiple access protocols**
- LANs
 - addressing, ARP
 - Ethernet
 - switches
 - VLANs
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Media Access Control (MAC) protocols

- single shared broadcast channel
- two or more simultaneous transmissions by nodes: interference
 - *collision* if node receives two or more signals at the same time

MAC protocol

- distributed algorithm that determines how nodes share channel, i.e., determine when node can transmit
- communication about channel sharing must use channel itself!
 - no out-of-band channel for coordination

An ideal multiple access protocol

given: multiple access channel of rate R bps

desiderata:

1. when one node wants to transmit, it can send at rate R .
2. when M nodes want to transmit, each can send at average rate R/M
3. fully decentralized:
 - no special node to coordinate transmissions
 - no synchronization of clocks, slots
4. simple

MAC protocols: taxonomy

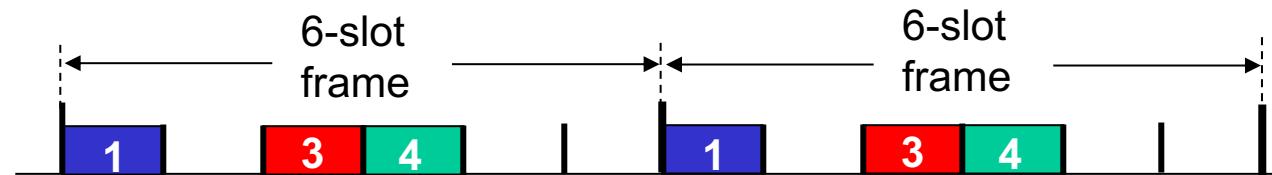
three broad classes:

- **channel partitioning**
 - divide channel into smaller “pieces” (time slots, frequency, code)
 - allocate piece to node for exclusive use
- *random access*
 - channel not divided, allow collisions
 - “recover” from collisions
- **“taking turns”**
 - nodes take turns, but nodes with more to send can take longer turns

Channel partitioning MAC protocols: TDMA

TDMA: time division multiple access

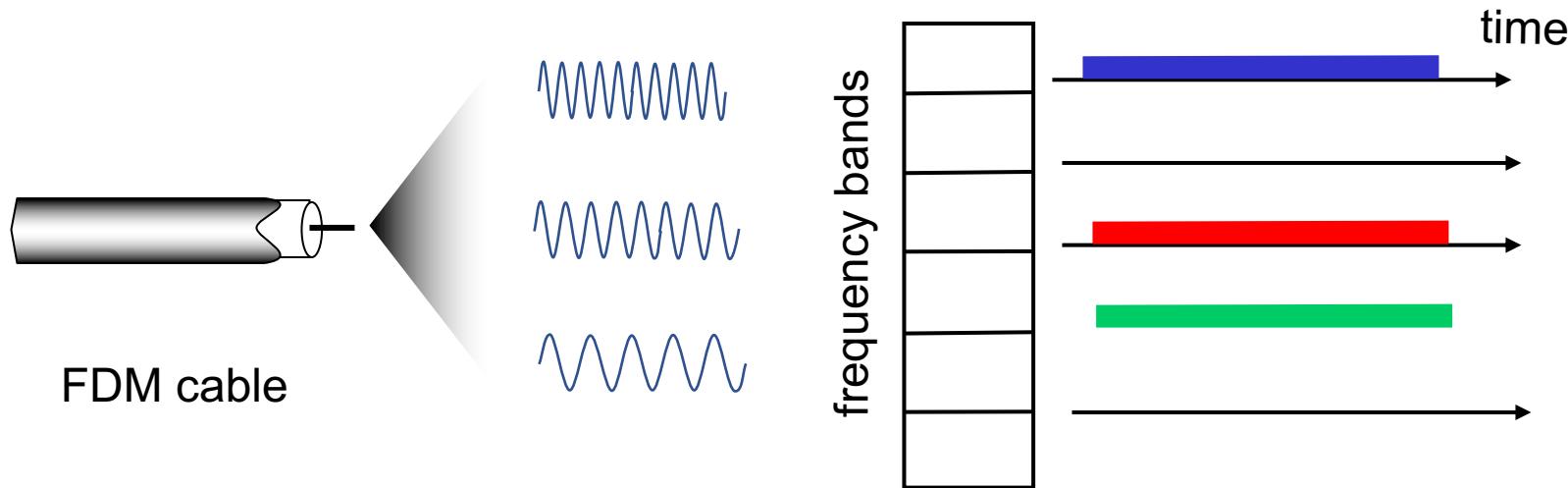
- access to channel in “rounds”
- each station gets fixed length slot (length = packet transmission time) in each round
- unused slots go idle
- example: 6-station LAN, 1,3,4 have packets to send, slots 2,5,6 idle



Channel partitioning MAC protocols: FDMA

FDMA: frequency division multiple access

- channel spectrum divided into frequency bands
- each station assigned fixed frequency band
- unused transmission time in frequency bands go idle
- example: 6-station LAN, 1,3,4 have packet to send, frequency bands 2,5,6 idle



Random access protocols

- when node has packet to send
 - transmit at full channel data rate R .
 - no *a priori* coordination among nodes
- two or more transmitting nodes: “collision”
- **random access MAC protocol** specifies:
 - when to send
 - how to detect collisions
 - how to recover from collisions (e.g., via delayed retransmissions)
- examples of random access MAC protocols:
 - ALOHA, slotted ALOHA
 - CSMA, CSMA/CD, CSMA/CA

Slotted ALOHA

assumptions:

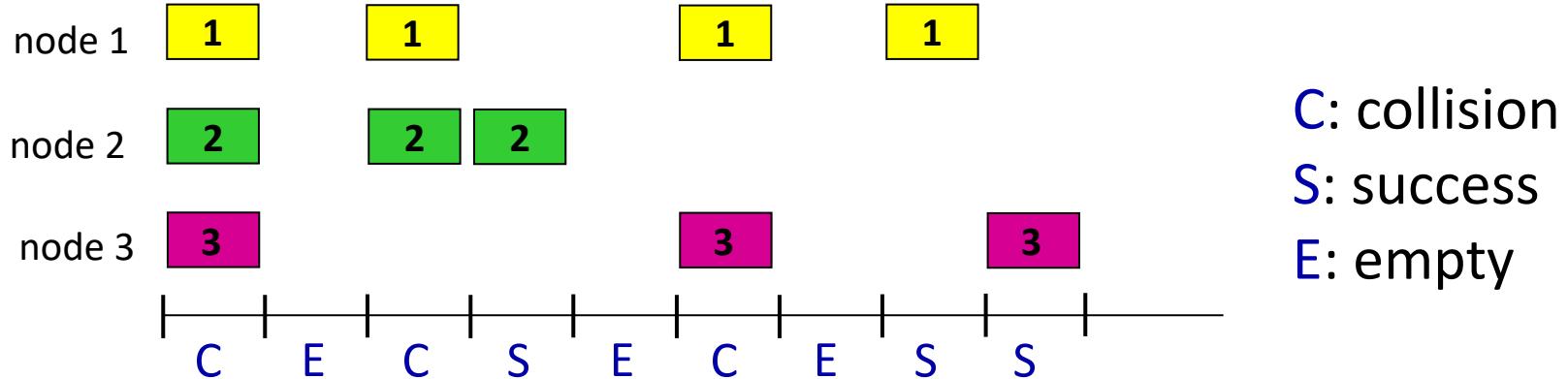
- all frames same size
- time divided into equal size slots (time to transmit 1 frame)
- nodes start to transmit only slot beginning
- nodes are synchronized
- if 2 or more nodes transmit in slot, all nodes detect collision

operation:

- when node obtains fresh frame, transmits in next slot
 - *if no collision*: node can send new frame in next slot
 - *if collision*: node retransmits frame in each subsequent slot with probability p until success

randomization – *why?*

Slotted ALOHA



Pros:

- single active node can continuously transmit at full rate of channel
- highly decentralized: only slots in nodes need to be in sync
- simple

Cons:

- synchronization
- collisions, “wasting slots”
- idle slots, “wasting slots”

Slotted ALOHA: efficiency

efficiency: long-run fraction of successful slots (many nodes, all with many frames to send)

- *suppose:* N nodes with many frames to send, each transmits in slot with probability p
 - prob that given node has success in a slot = $p(1-p)^{N-1}$
 - prob that *any* node has a success = $Np(1-p)^{N-1}$
 - max efficiency: find p^* that maximizes $Np(1-p)^{N-1}$
 - for many nodes, take limit of $Np^*(1-p^*)^{N-1}$ as N goes to infinity, gives:
max efficiency = $1/e = .37$
- *at best:* channel used for useful transmissions 37% of time!

CSMA (carrier sense multiple access)

simple **CSMA**: listen before transmit:

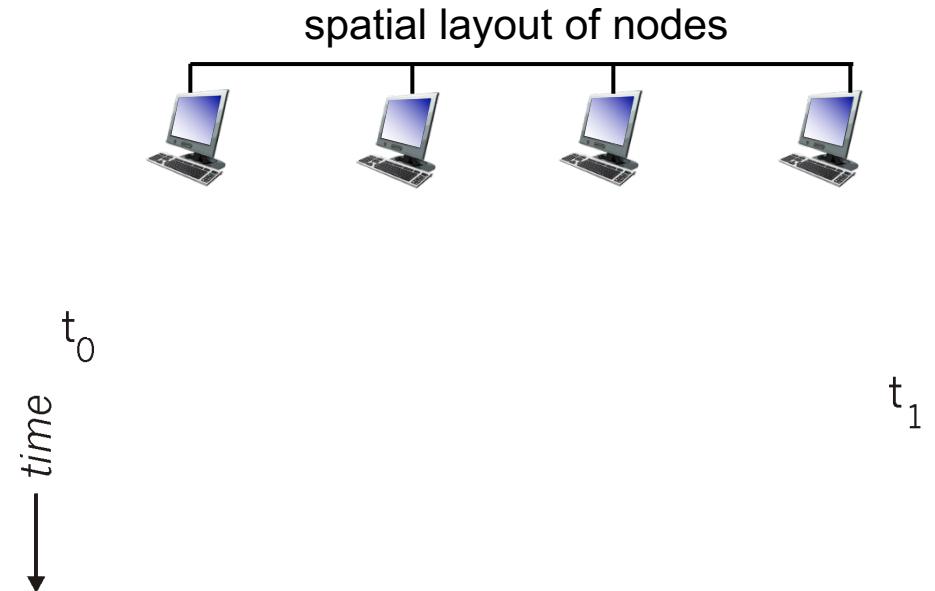
- if channel sensed idle: transmit entire frame
- if channel sensed busy: defer transmission
- human analogy: don't interrupt others!

CSMA/CD: CSMA with *collision detection*

- collisions *detected* within short time
- colliding transmissions aborted, reducing channel wastage
- collision detection easy in wired, difficult with wireless
- human analogy: the polite conversationalist

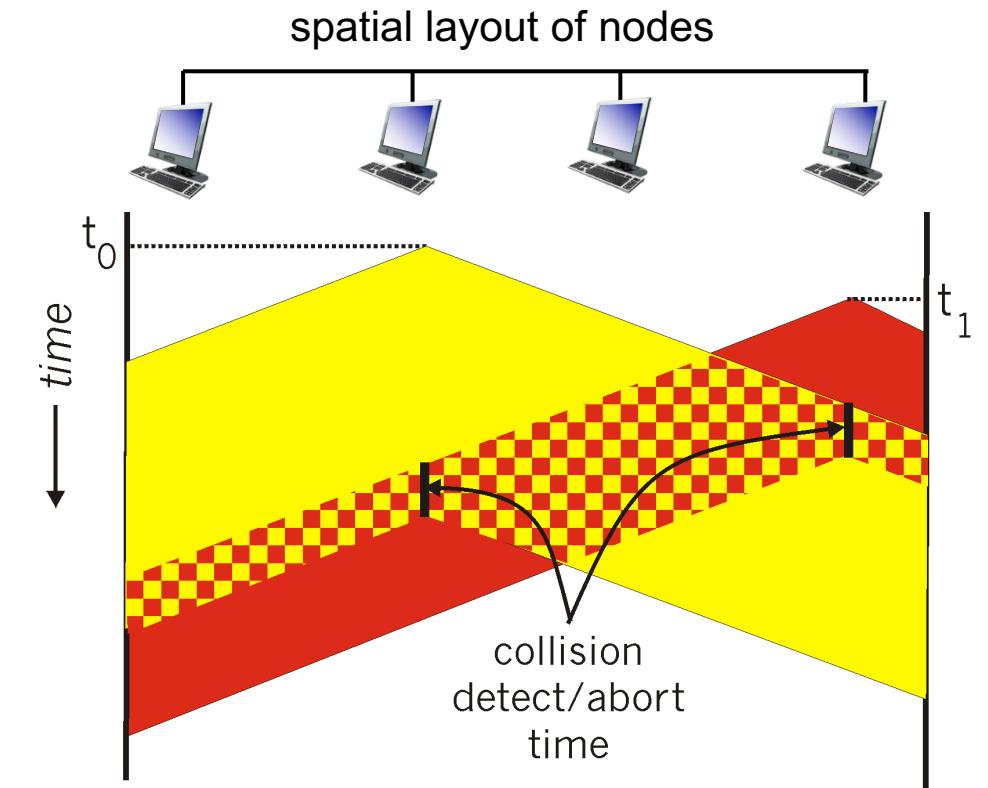
CSMA: collisions

- collisions *can* still occur with carrier sensing:
 - propagation delay means two nodes may not hear each other's just-started transmission
- **collision:** entire packet transmission time wasted
 - distance & propagation delay play role in determining collision probability



CSMA/CD:

- CSMA/CS reduces the amount of time wasted in collisions
 - transmission aborted on collision detection



Ethernet CSMA/CD algorithm

1. Ethernet receives datagram from network layer, creates frame
2. If Ethernet senses channel:
 - if **idle**: start frame transmission.
 - if **busy**: wait until channel idle, then transmit
3. If entire frame transmitted without collision – done!
4. If another transmission detected while sending: abort, send jam signal
5. After aborting, enters *binary (exponential) backoff*:
 - after m th collision, chooses K at random from $\{0,1,2, \dots, 2^m-1\}$. NIC waits $K \cdot 512$ bit times, returns to Step 2
 - more collisions: longer backoff interval

CSMA/CD efficiency

- T_{prop} = max prop delay between 2 nodes in LAN
- t_{trans} = time to transmit max-size frame

$$efficiency = \frac{1}{1 + 5t_{prop}/t_{trans}}$$

- efficiency goes to 1
 - as t_{prop} goes to 0
 - as t_{trans} goes to infinity
- better performance than ALOHA: and simple, cheap, decentralized!

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Self-learning
Forwarding table
Switch/Router difference



- a day in the life of a web request

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Chapter 7 outline

- **Introduction**

Wireless

- Wireless Links and network characteristics
- WiFi: 802.11 wireless LANs
- Cellular networks: 4G and 5G



Mobility

- Mobility management: principles
- Mobility management: practice
 - 4G/5G networks
 - Mobile IP
- Mobility: impact on higher-layer protocols

Wireless link characteristics (1)

important differences from wired link

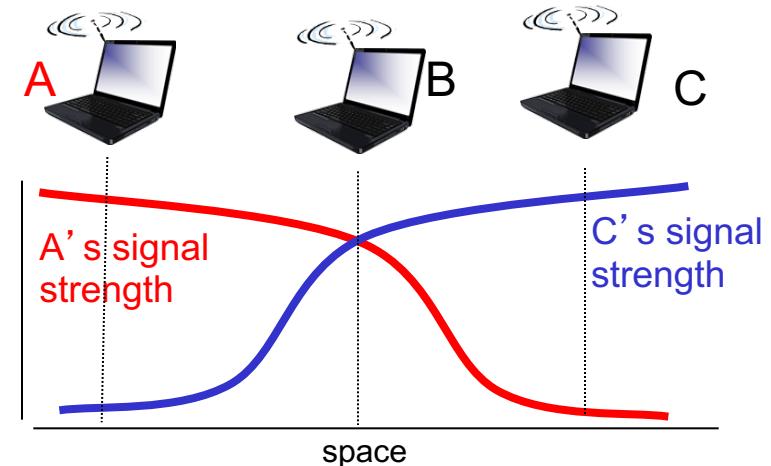
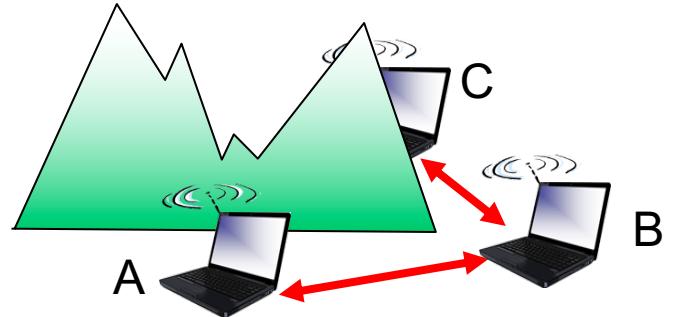
- **decreased signal strength:** radio signal attenuates as it propagates through matter (path loss)
- **interference from other sources:** wireless network frequencies (e.g., 2.4 GHz) shared by many devices (e.g., WiFi, cellular, motors): interference
- **multipath propagation:** radio signal reflects off objects ground, arriving at destination at slightly different times

.... make communication across (even a point to point) wireless link much more “difficult”



Wireless link characteristics (3)

Multiple wireless senders, receivers create additional problems (beyond multiple access):



Hidden terminal problem

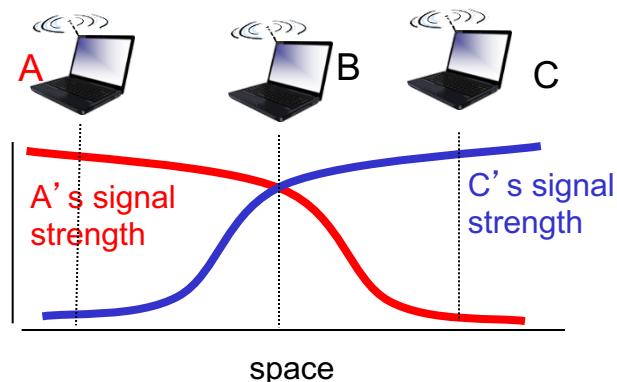
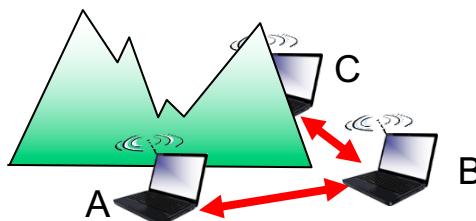
- B, A hear each other
- B, C hear each other
- A, C can not hear each other means A, C unaware of their interference at B

Signal attenuation:

- B, A hear each other
- B, C hear each other
- A, C can not hear each other interfering at B

IEEE 802.11: multiple access

- avoid collisions: 2^+ nodes transmitting at same time
- 802.11: CSMA - sense before transmitting
 - don't collide with detected ongoing transmission by another node
- 802.11: *no collision detection!*
 - difficult to sense collisions: high transmitting signal, weak received signal due to fading
 - can't sense all collisions in any case: hidden terminal, fading
 - goal: *avoid collisions*: CSMA/Collision Avoidance



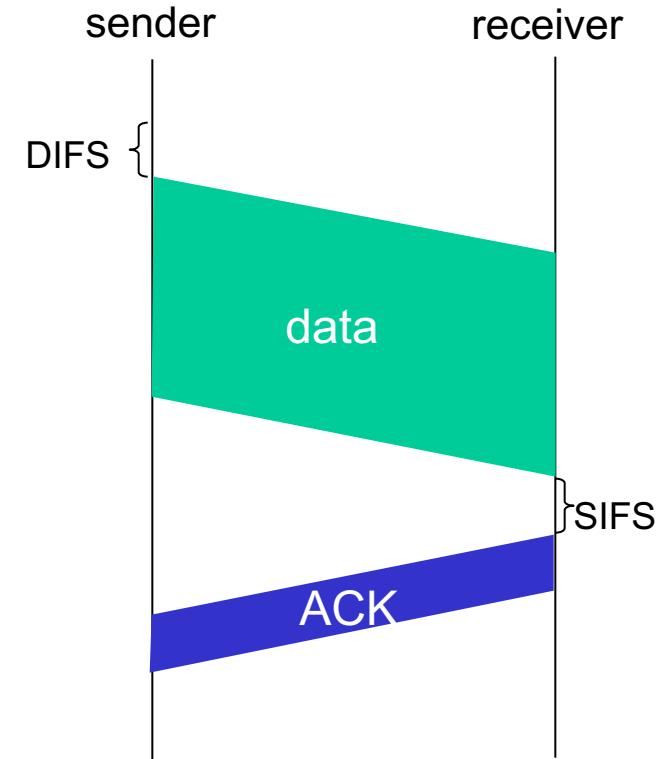
IEEE 802.11 MAC Protocol: CSMA/CA

802.11 sender

- 1 if sense channel idle for **DIFS** then
 transmit entire frame (no CD)
- 2 if sense channel busy then
 start random backoff time
 timer counts down while channel idle
 transmit when timer expires
 if no ACK, increase random backoff interval, repeat 2

802.11 receiver

if frame received OK
 return ACK after **SIFS** (ACK needed due to hidden
 terminal problem)

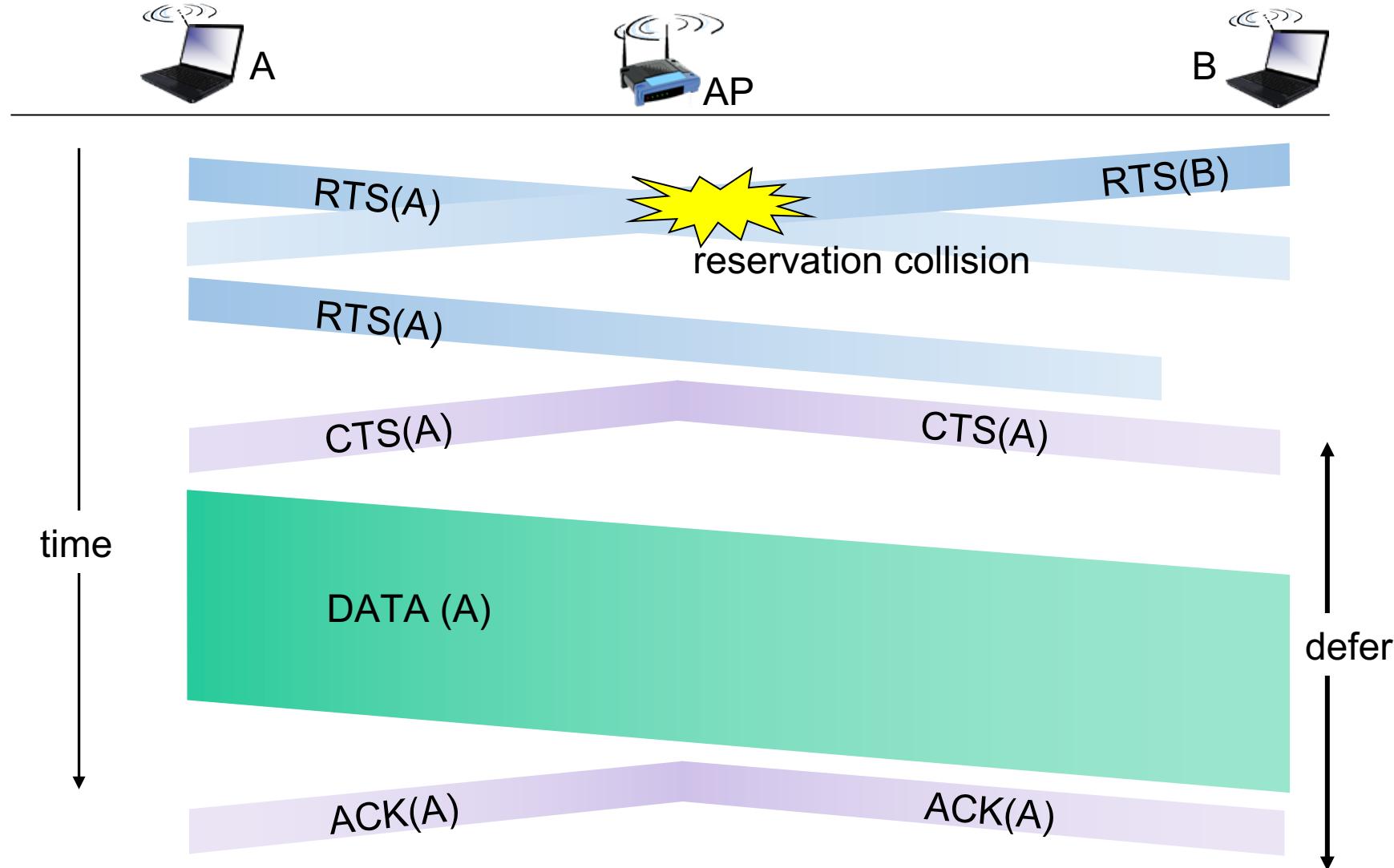


Avoiding collisions (more)

idea: sender “reserves” channel use for data frames using small reservation packets

- sender first transmits *small* request-to-send (RTS) packet to BS using CSMA
 - RTSs may still collide with each other (but they’re short)
- BS broadcasts clear-to-send (CTS) in response to RTS
- CTS heard by all nodes
 - sender transmits data frame
 - other stations defer transmissions

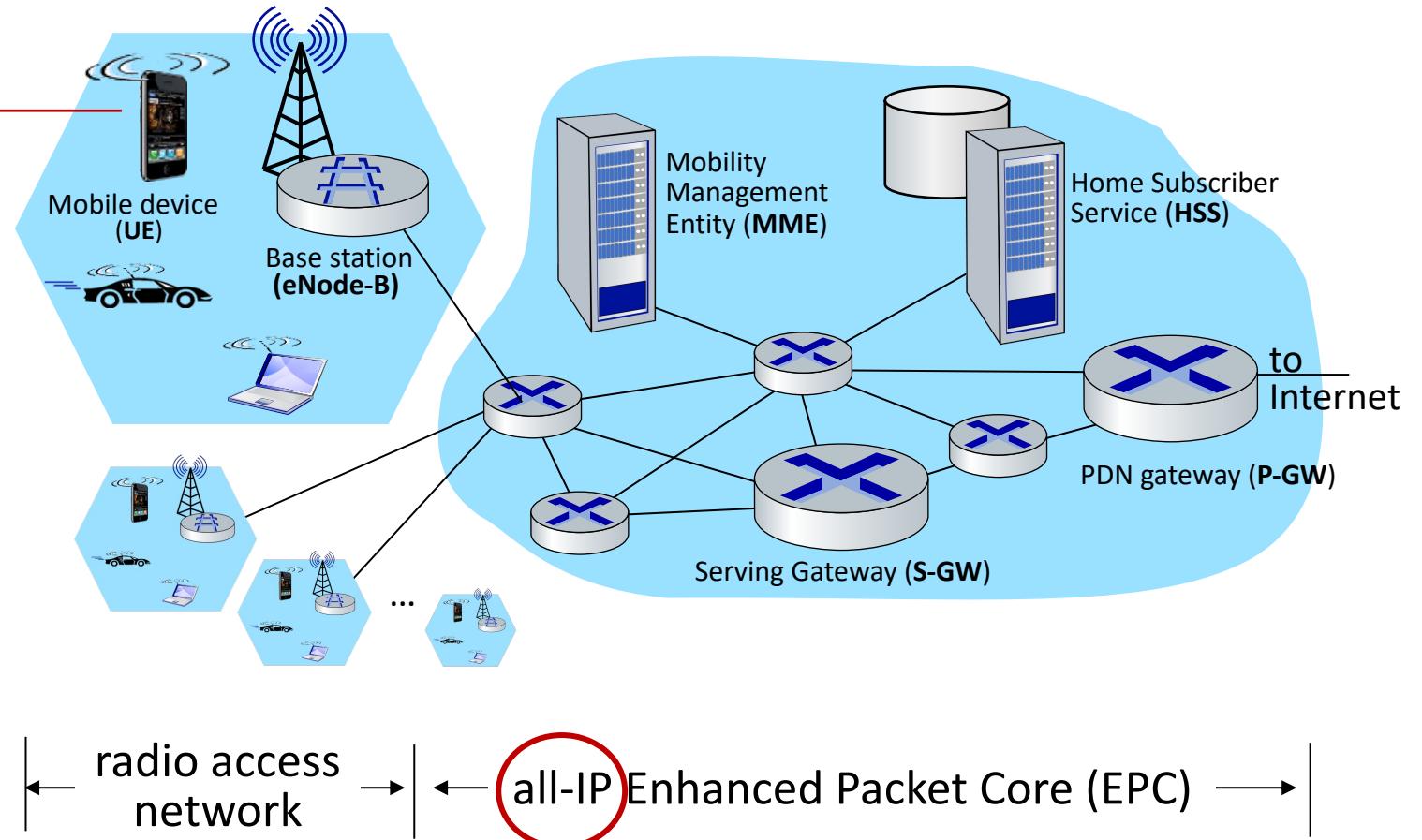
Collision Avoidance: RTS-CTS exchange



Elements of 4G LTE architecture

Mobile device:

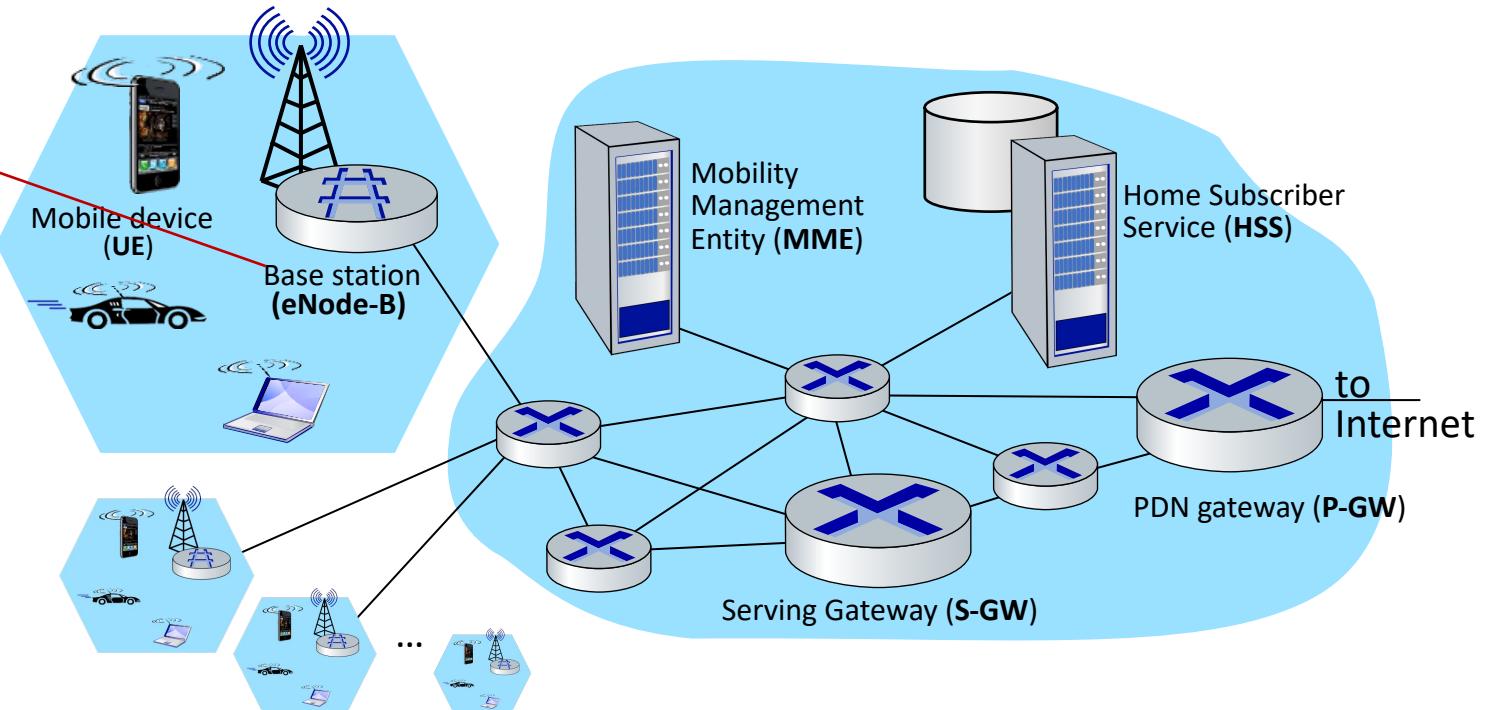
- smartphone, tablet, laptop, IoT, ... with 4G LTE radio
- 64-bit International Mobile Subscriber Identity (IMSI), stored on SIM (Subscriber Identity Module) card
- LTE jargon: User Equipment (UE)



Elements of 4G LTE architecture

Base station:

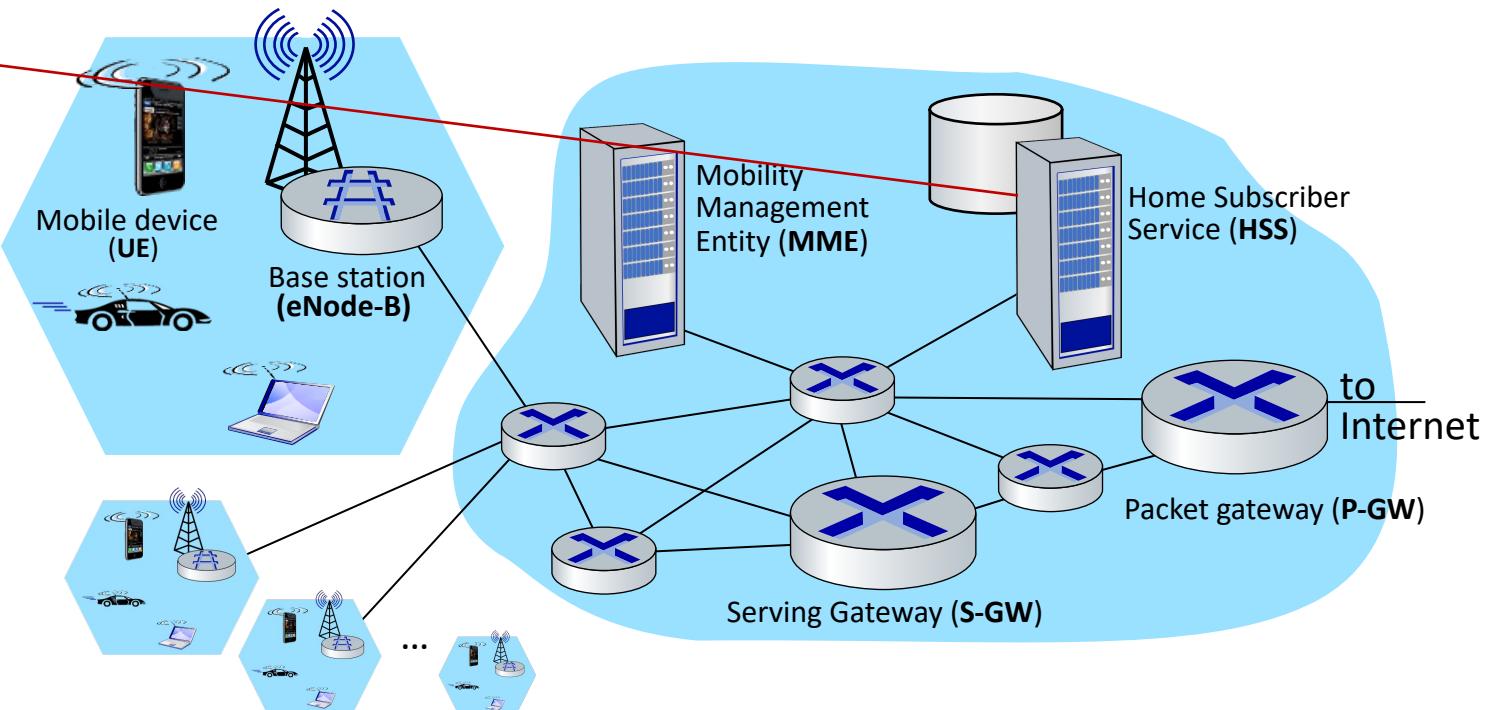
- at “edge” of carrier’s network
- manages wireless radio resources, mobile devices in its coverage area (“cell”)
- coordinates device authentication with other elements
- similar to WiFi AP but:
 - active role in user mobility
 - coordinates with nearby base stations to optimize radio use
- LTE jargon: eNode-B



Elements of 4G LTE architecture

Home Subscriber Service

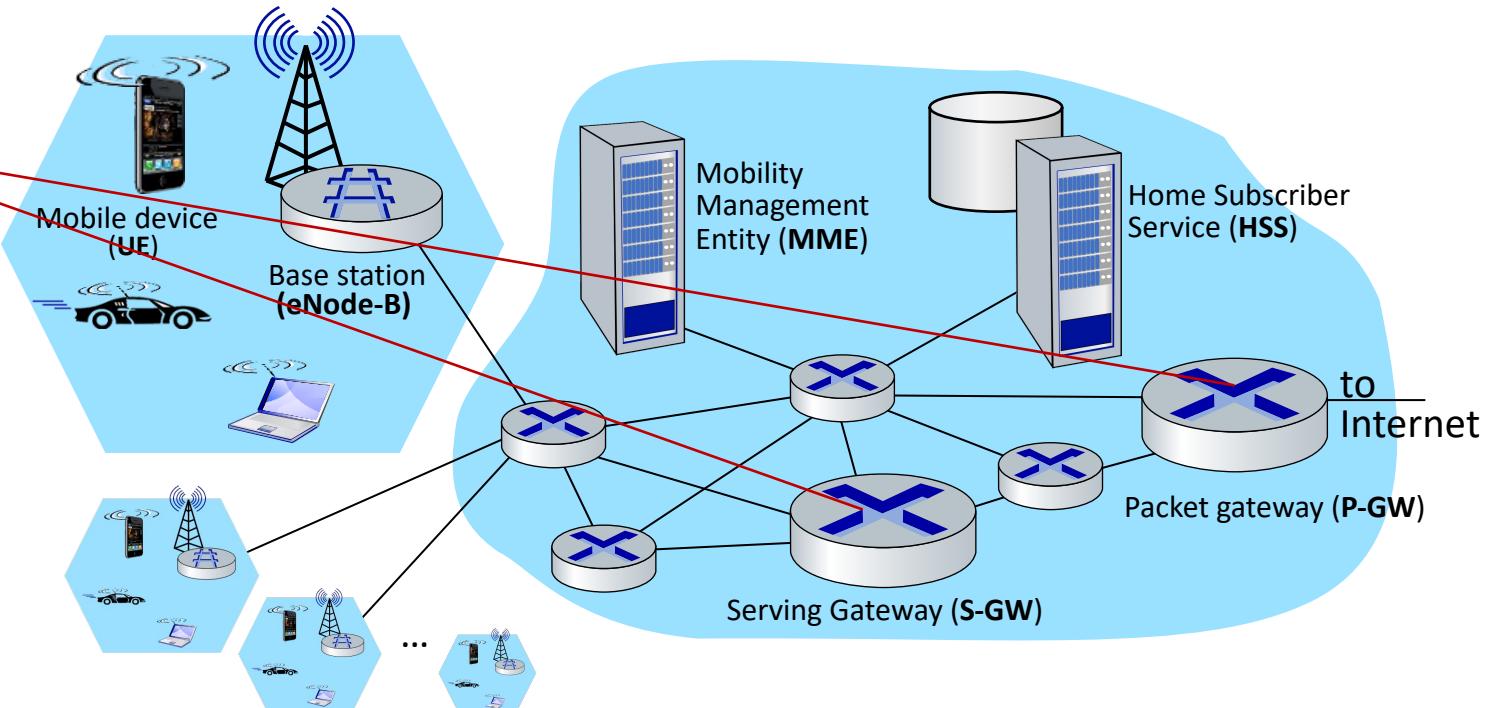
- stores info about mobile devices for which the HSS's network is their "home network"
- works with MME in device authentication



Elements of 4G LTE architecture

Serving Gateway (S-GW), Packet Gateway (P-GW)

- lie on data path from mobile to/from Internet
- P-GW
 - gateway to mobile cellular network
 - Looks like any other internet gateway router
 - provides NAT services
- other routers:
 - extensive use of tunneling



Elements of 4G LTE architecture

Mobility Management Entity

- device authentication (device-to-network, network-to-device) coordinated with mobile home network HSS
- mobile device management:
 - device handover between cells
 - tracking/paging device location
- path (tunneling) setup from mobile device to P-GW

