Chapter 4 Network Layer: The Data Plane

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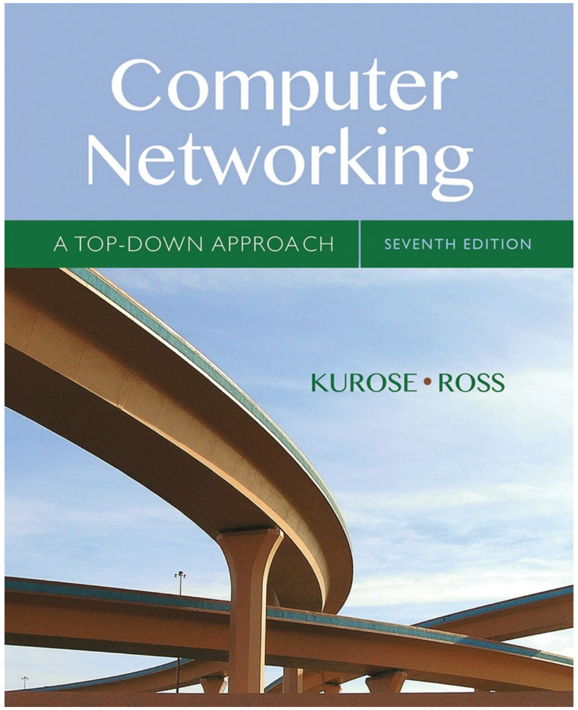

Computer Networking: A Top Down Approach

7th edition

Jim Kurose, Keith Ross

Pearson/Addison Wesley
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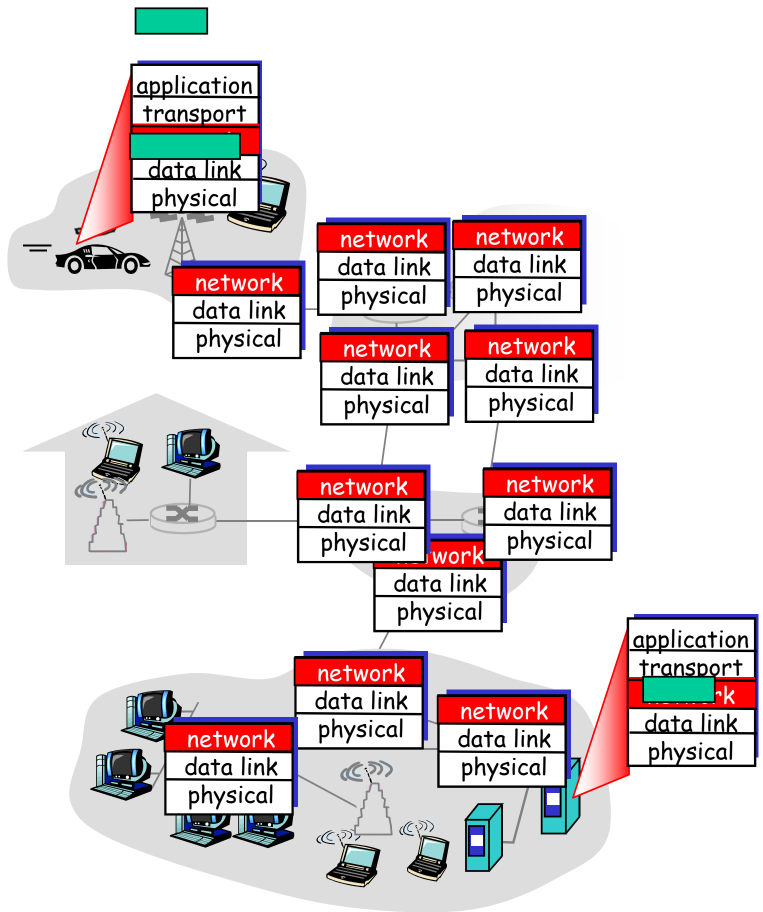
补充内容

Network layer

- transport segment from sending to receiving host
- on sending side encapsulates segments into datagrams
- on rcving side, delivers segments to transport layer
- network layer protocols in *every* host, router
- router examines header fields in all IP datagrams passing through it



补充内容

Network layer connection and connection-less service

- datagram network provides network-layer connectionless service
- VC network provides network-layer connection service
- analogous to the transport-layer services, but:
  - **service:** host-to-host
  - **no choice:** network provides one or the other
  - **implementation:** in network core

补充内容

Virtual circuits

"source-to-dest path behaves much like telephone circuit"
- performance-wise
- network actions along source-to-dest path

- call setup, teardown for each call *before* data can flow
- each packet carries VC identifier (not destination host address)
- *every* router on source-dest path maintains "state" for each passing connection
- link, router resources (bandwidth, buffers) may be *allocated* to VC (dedicated resources = predictable service)

补充内容

VC implementation

a VC consists of:

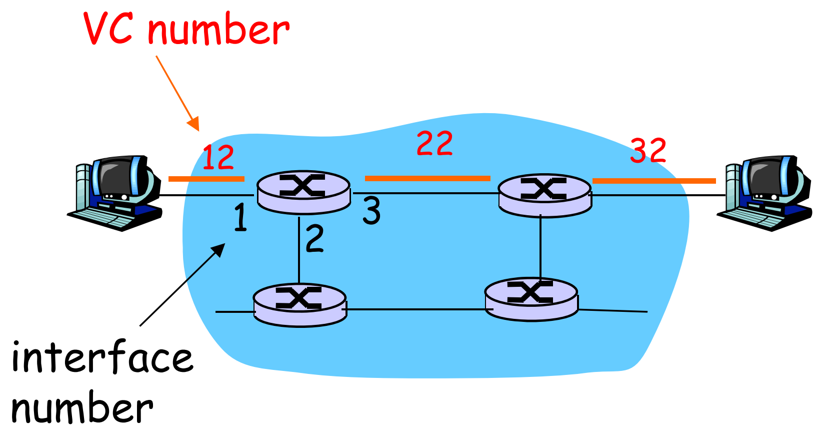
1. path from source to destination
2. VC numbers, one number for each link along path
3. entries in forwarding tables in routers along path

- packet belonging to VC carries VC number (rather than dest address)
- VC number can be changed on each link.
  - New VC number comes from forwarding table

补充内容

VC Forwarding table

Forwarding table in northwest router:



Incoming interface	Incoming VC #	Outgoing interface	Outgoing VC #
1	12	3	22
2	63	1	18
3	7	2	17
1	97	3	87
…	…		…

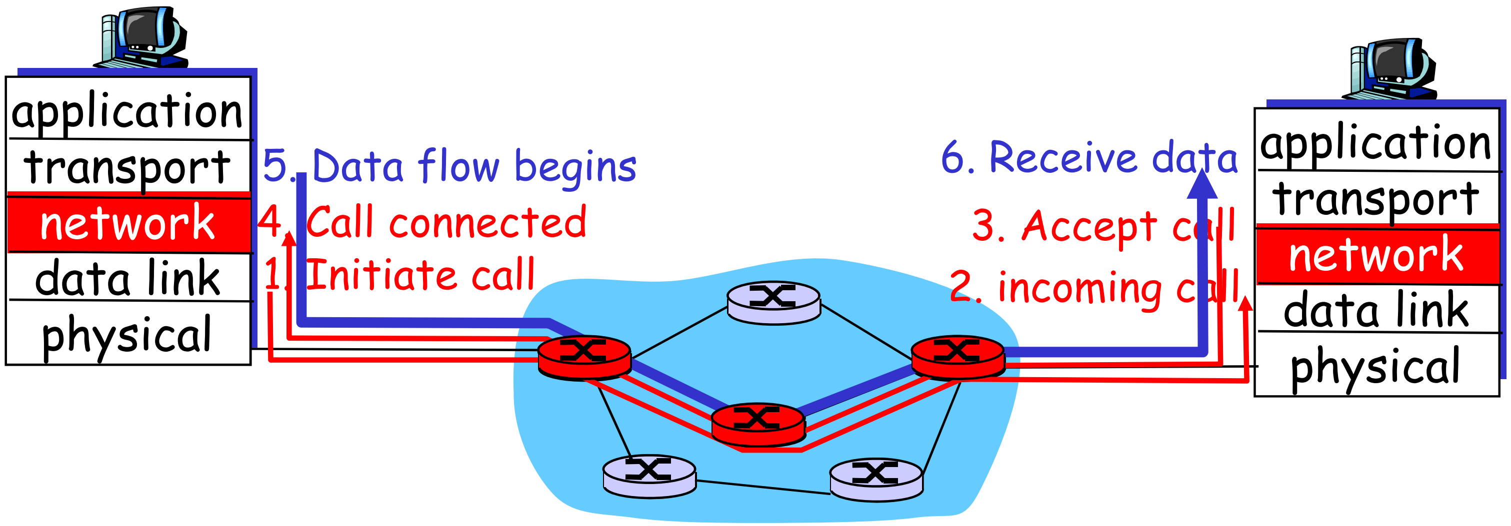
…

Routers maintain connection state information!

补充内容

Virtual circuits: signaling protocols

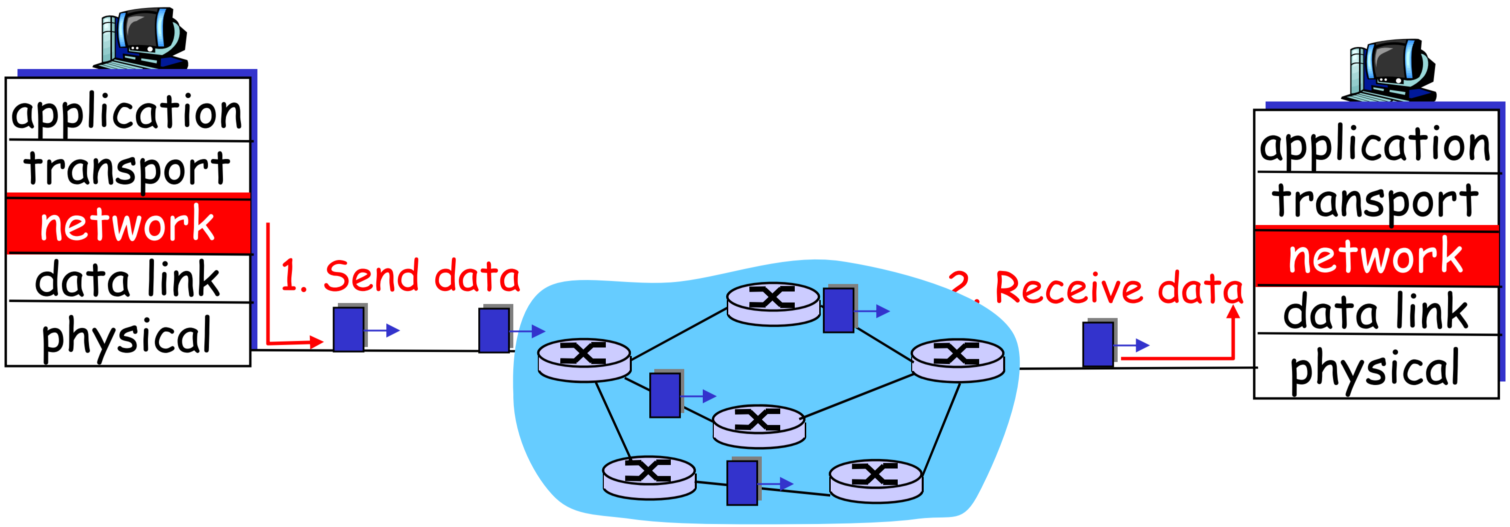
- used to setup, maintain teardown VC
- used in ATM, frame-relay, X.25
- not used in today's Internet



补充内容

Datagram networks

- no call setup at network layer
- routers: no state about end-to-end connections
  - no network-level concept of "connection"
- packets forwarded using destination host address
  - packets between same source-dest pair may take different paths



Chapter 4: outline

4.1 Overview of Network layer

- data plane
- control plane

4.2 What's inside a router

4.3 IP: Internet Protocol

- datagram format
- fragmentation
- IPv4 addressing
- network address translation
- IPv6

4.4 Generalized Forward and SDN

- match
- action
- OpenFlow examples of match-plus-action in action

Chapter 4: network layer

chapter goals:

- understand principles behind network layer services, focusing on data plane:
  - network layer service models
  - forwarding versus routing
  - how a router works
  - generalized forwarding
- instantiation, implementation in the Internet

Network layer

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- on receiving side, delivers segments to transport layer
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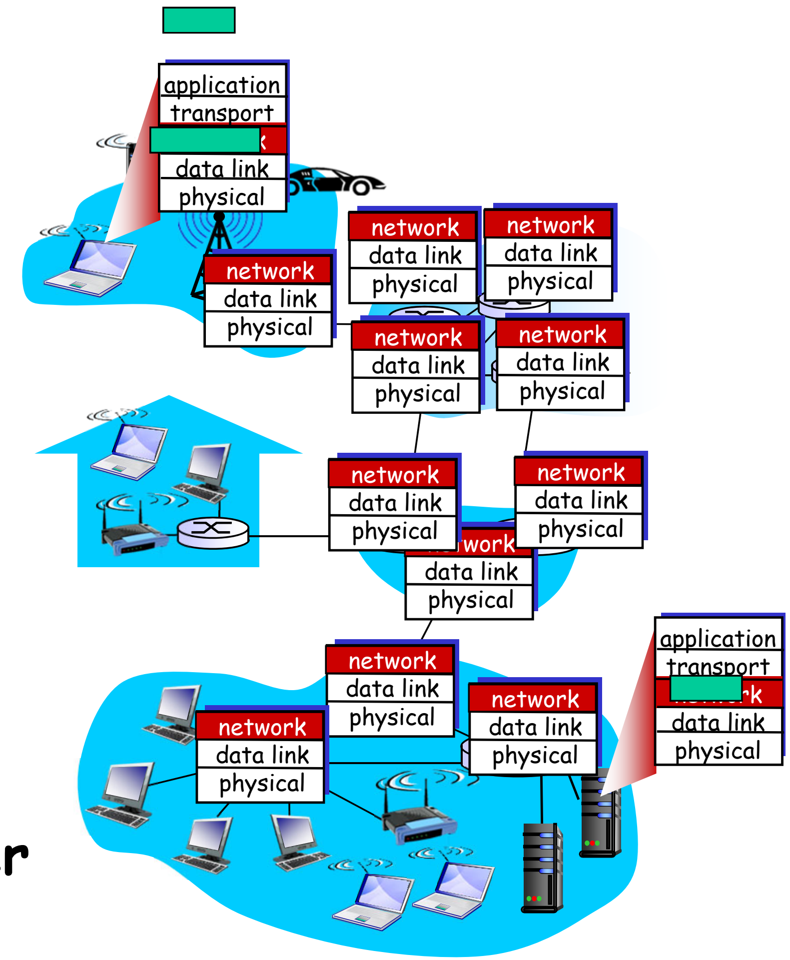


Two key network-layer functions

network-layer functions:

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

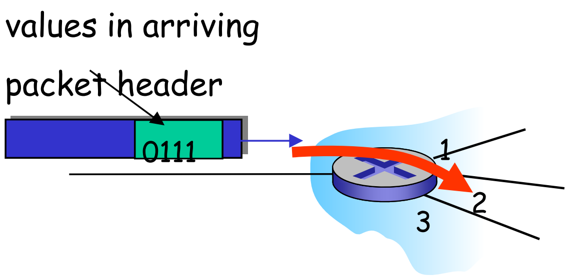
analogy: taking a trip

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

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
- forwarding function

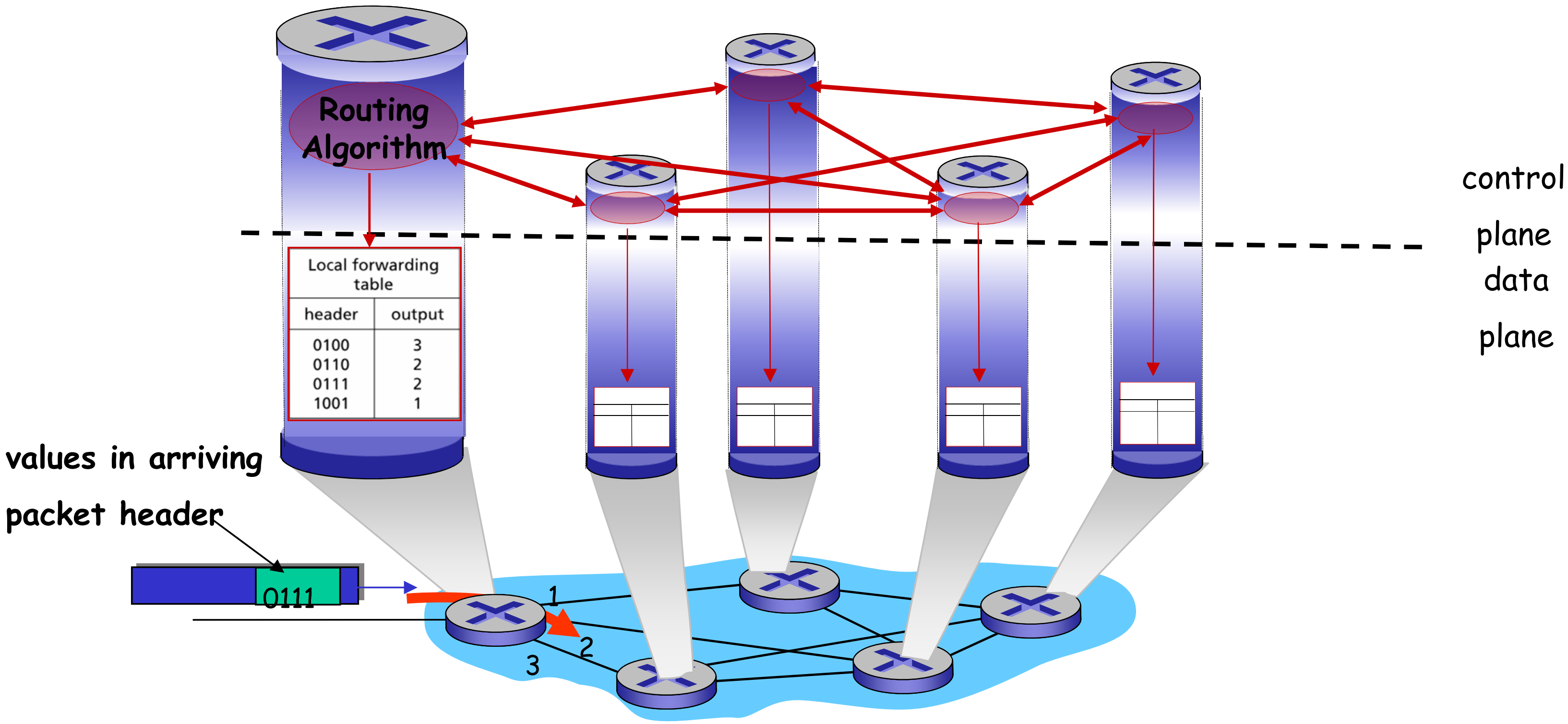


Control plane

- 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

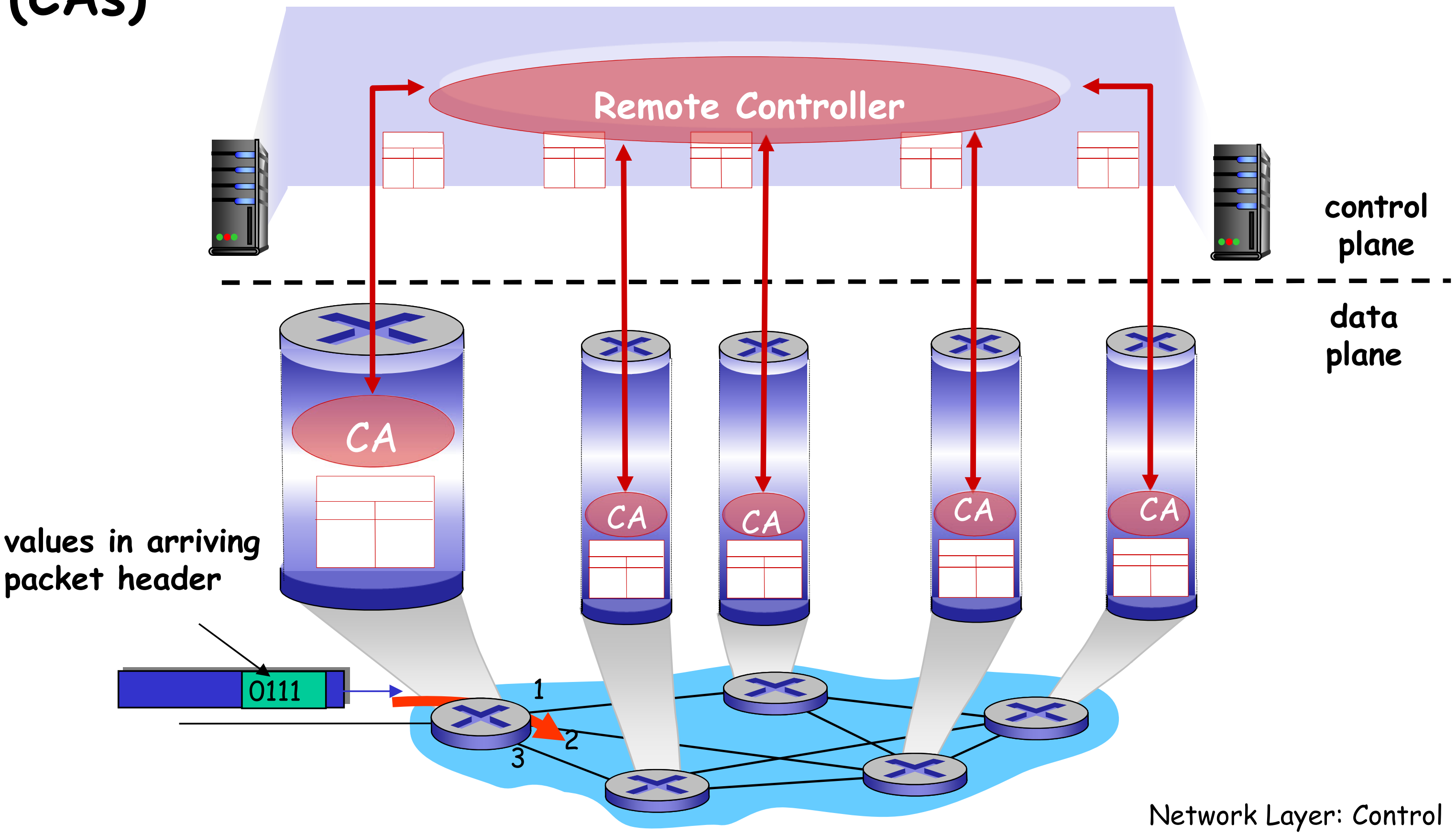
Per-router control plane

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



Logically centralized control plane

A distinct (typically remote) controller interacts with local control agents (CAs)



Network service model

Q: What *service model* for "channel" transporting datagrams from sender to receiver?

example services for individual datagrams:

- guaranteed delivery
- guaranteed delivery with less than 40 msec delay

example services for a flow of datagrams:

- in-order datagram delivery
- guaranteed minimum bandwidth to flow
- restrictions on changes in inter-packet spacing

Network layer service models:

Network Architecture	Service Model	Guarantees ? Bandwidth	Loss	Order	Timing	Congestion feedback
Internet	best effort	none	no	no	no	no (inferred via loss)
ATM	CBR	constant rate	yes	yes	yes	no congestion
ATM	VBR	guaranteed rate	yes	yes	yes	no congestion
ATM	ABR	guaranteed minimum	no	yes	no	yes
ATM	UBR	none	no	yes	no	no

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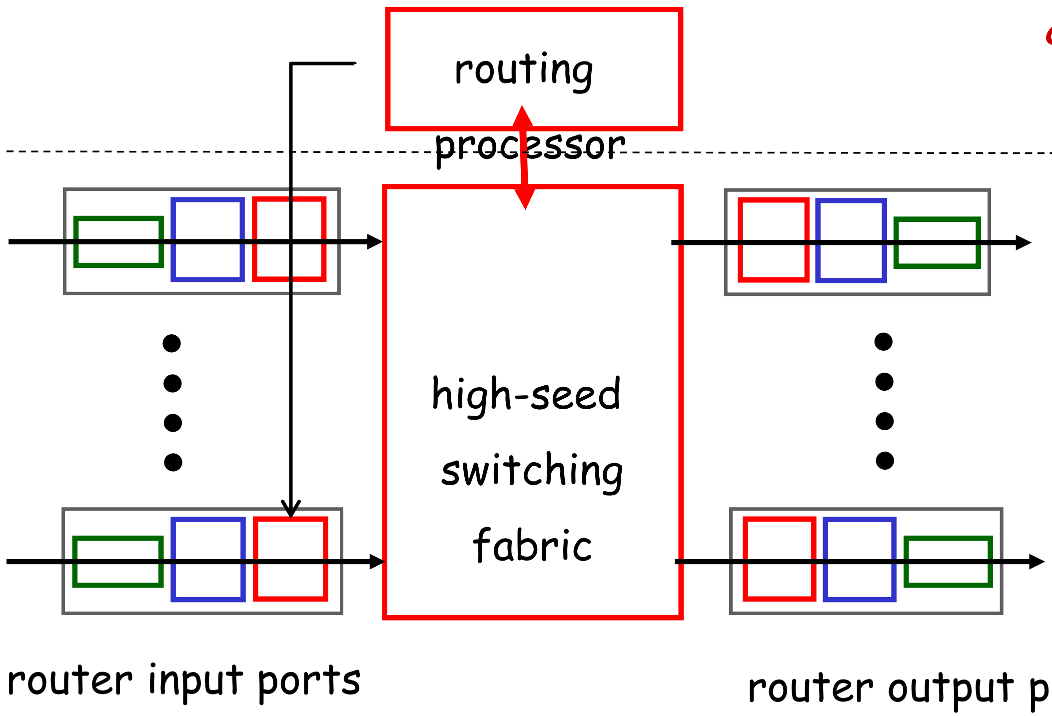
Router architecture overview

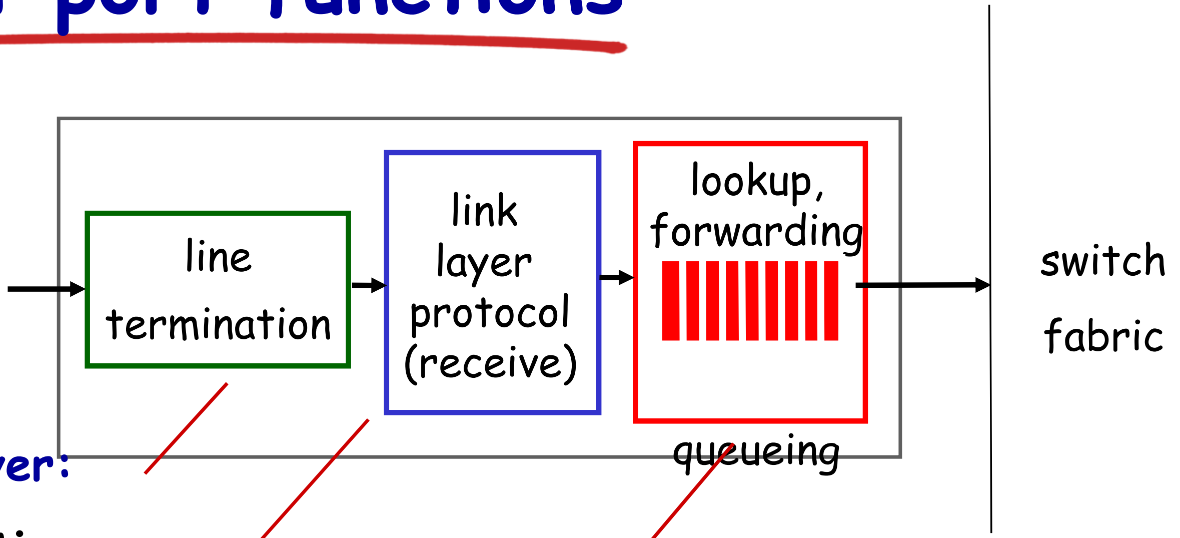
- high-level view of generic router architecture:



routing, management control plane (software) operates in millisecond time frame

forwarding data plane (hardware) operttes in nanosecond timeframe

Input port functions



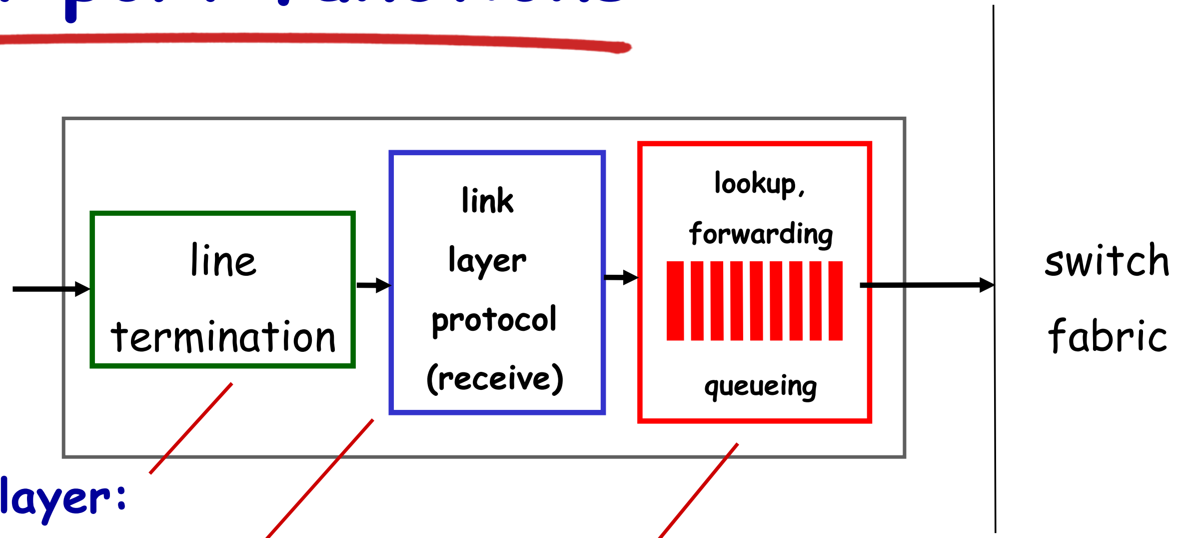
physical layer:
bit-level reception

data link layer:
e.g., Ethernet
see chapter 5

decentralized switching:

- using header field values, lookup output port using forwarding table in input port memory (*"match plus action"*)
- *goal*: complete input port processing at 'line speed'
- *queuing*: if datagrams arrive faster than forwarding rate into switch fabric

Input port functions



physical layer:

bit-level reception

data link layer:

e.g., Ethernet

see chapter 5

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

Destination-based forwarding

forwarding table

Destination Address Range	Link Interface
11001000 00010111 00010000 00000000 through 11001000 00010111 00010111 11111111	0
11001000 00010111 00011000 00000000 through 11001000 00010111 00011000 11111111	1
11001000 00010111 00011001 00000000 through 11001000 00010111 00011111 11111111	2
otherwise 默认路由	3

Q: but what happens if ranges don't divide up so nicely?

Longest prefix matching

longest prefix matching

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:

DA: 11001000 00010111 00010110 10100001 which interface?

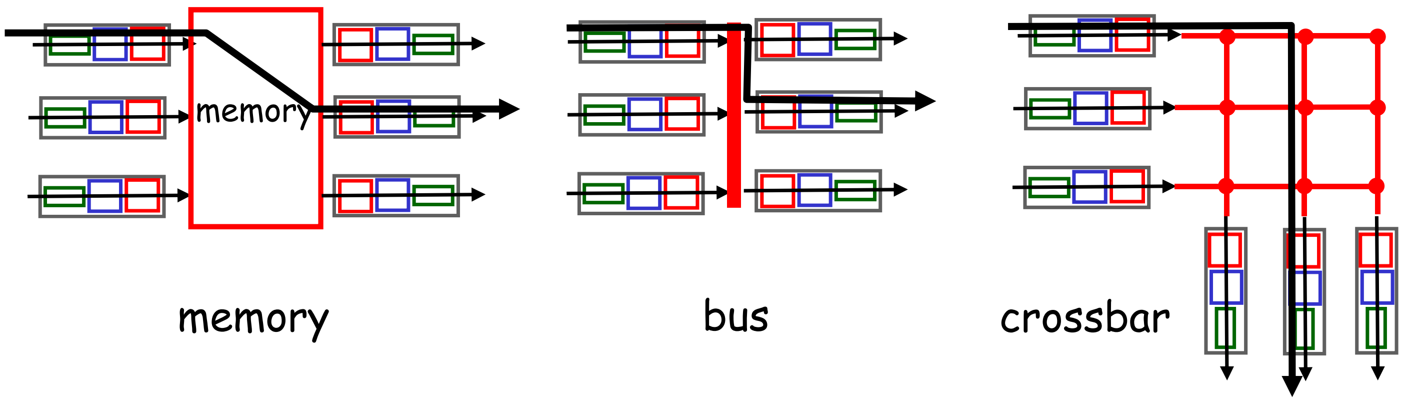
DA: 11001000 00010111 00011000 10101010 which interface?

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: can up ~1M routing table entries in TCAM

Switching fabrics

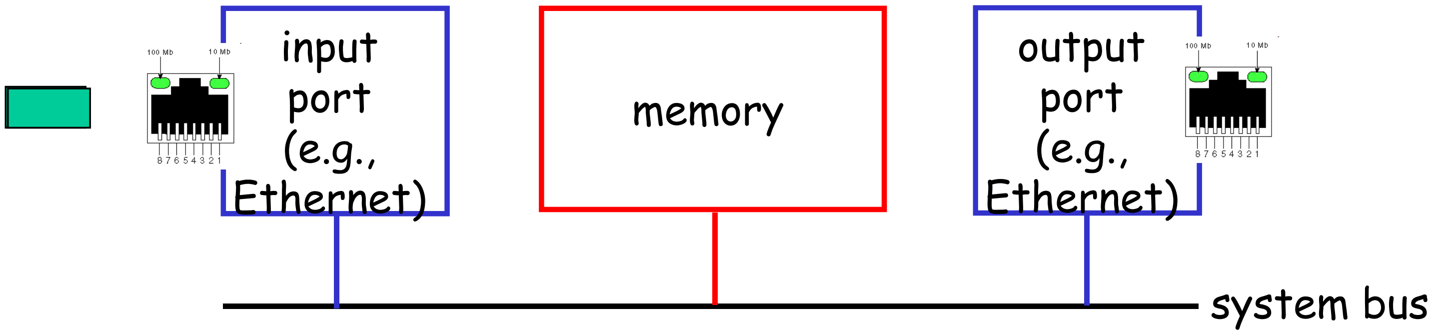
- transfer packet from input buffer to appropriate output buffer
- switching rate: rate at which packets can be transfer from inputs to outputs
  - often measured as multiple of input/output line rate
  - N inputs: switching rate N times line rate desirable
- three types of switching fabrics



Switching via memory

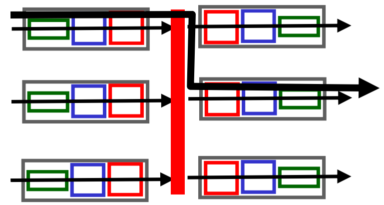
first generation routers:

- traditional computers with switching under direct control of CPU
- packet copied to system's memory
- speed limited by memory bandwidth (2 bus crossings per datagram)



Switching via a bus

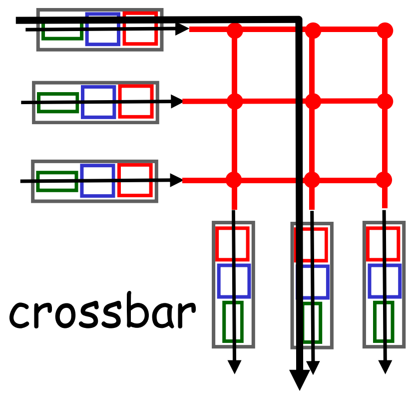
- datagram from input port memory
  to output port memory via a shared bus
- *bus contention:* switching speed limited by bus bandwidth
- 32 Gbps bus, Cisco 5600: sufficient speed for access and enterprise routers



bus

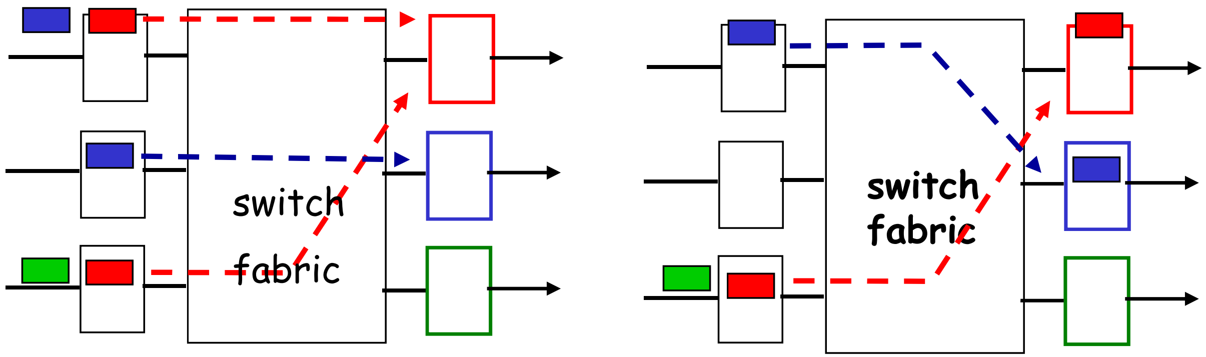
Switching via interconnection network

- overcome bus bandwidth limitations
- banyan networks, crossbar, other interconnection nets initially developed to connect processors in multiprocessor
- advanced design: fragmenting datagram into fixed length cells, switch cells through the fabric.
- Cisco 12000: switches 60 Gbps through the interconnection network



Input port queuing

- fabric slower than input ports combined -> queueing may occur at input queues
  - *queueing delay and loss due to input buffer overflow!*
- Head-of-the-Line (HOL) blocking: queued datagram at front of queue prevents others in queue from moving forward

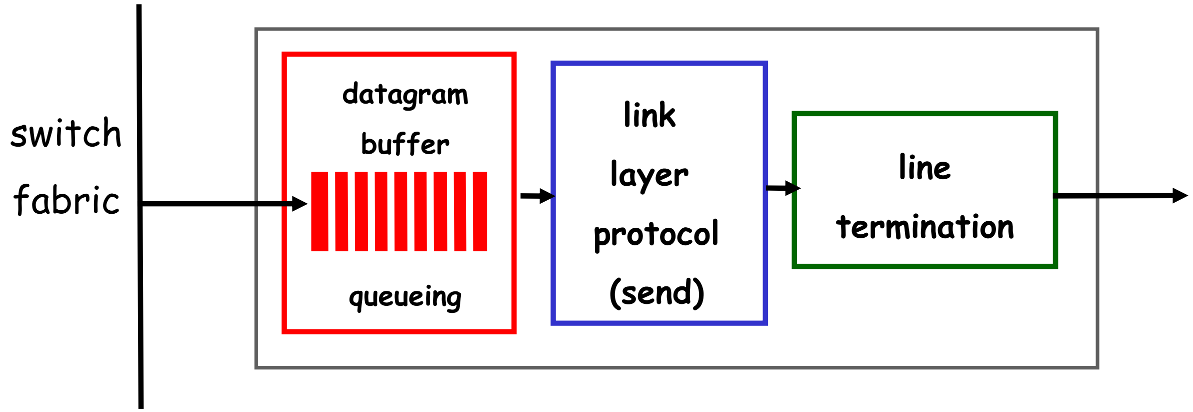


output port contention: only one red datagram can be transferred.
lower red packet is blocked

one packet time later: green packet experiences HOL blocking

Output ports

This slide in HUGELY important!

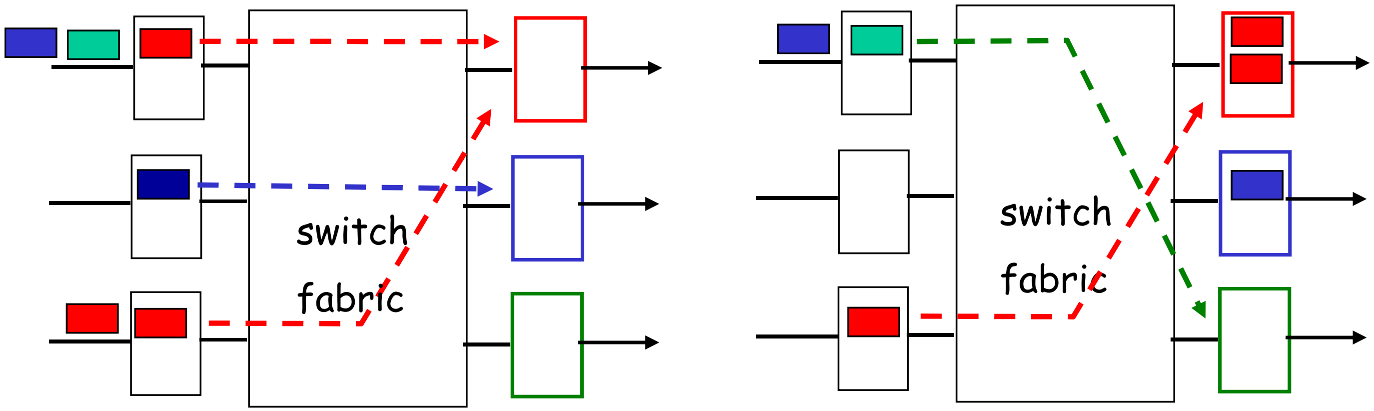


- *buffering* required when datagrams arrive from fabric faster than the transmission rate
- *scheduling discipline* chooses among queued datagrams for transmission

Datagram (packets) can be lost due to congestion, lack of buffers

Priority scheduling – who gets best performance, network neutrality

Output port queueing



at *t*, packets more from input to output

one packet time later

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

Chapter 4: outline

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- data plane
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4.2 What’ s inside a router

4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- network address translation
- IPv6

4.4 Generalized Forward and SDN
- match
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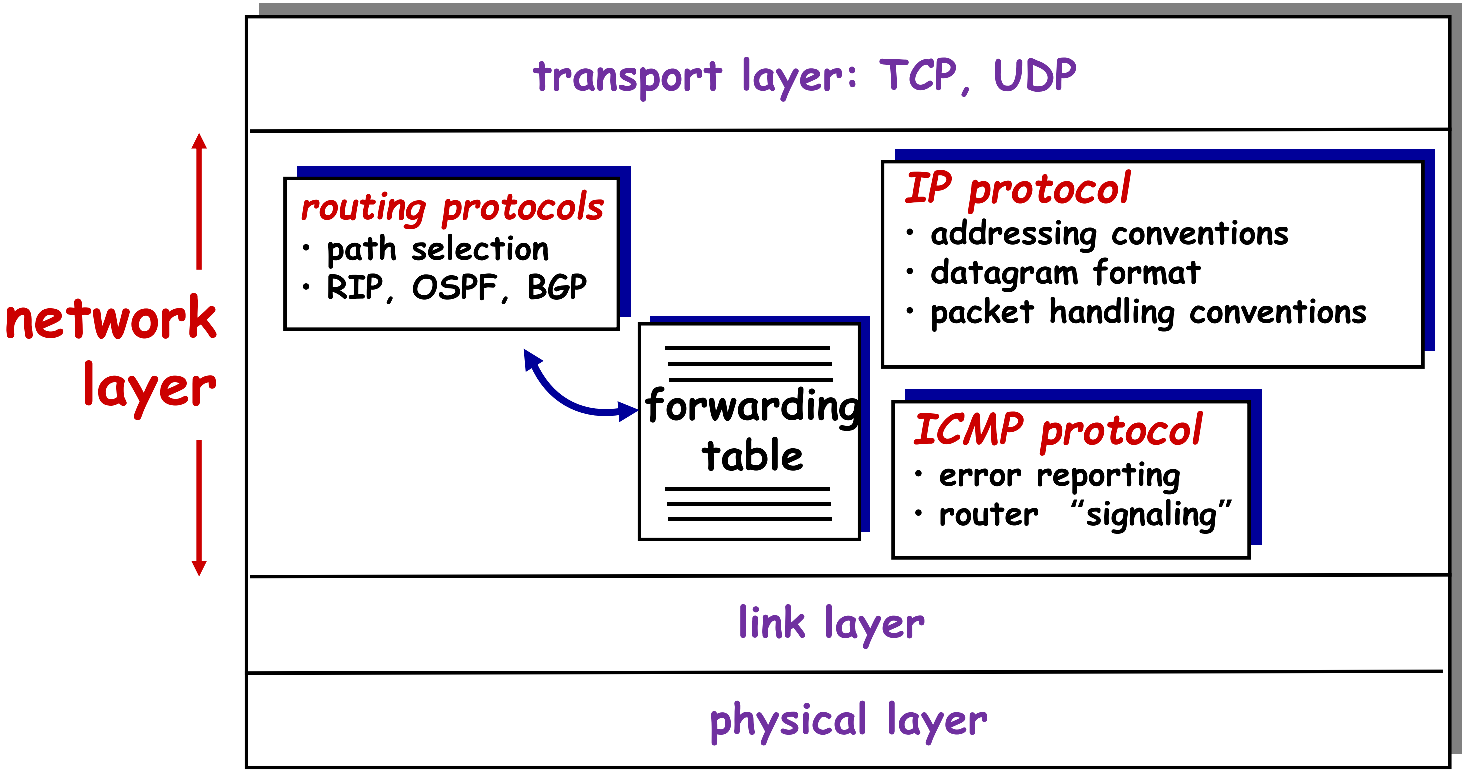
The Internet network layer

host, router network layer functions:



IP datagram format

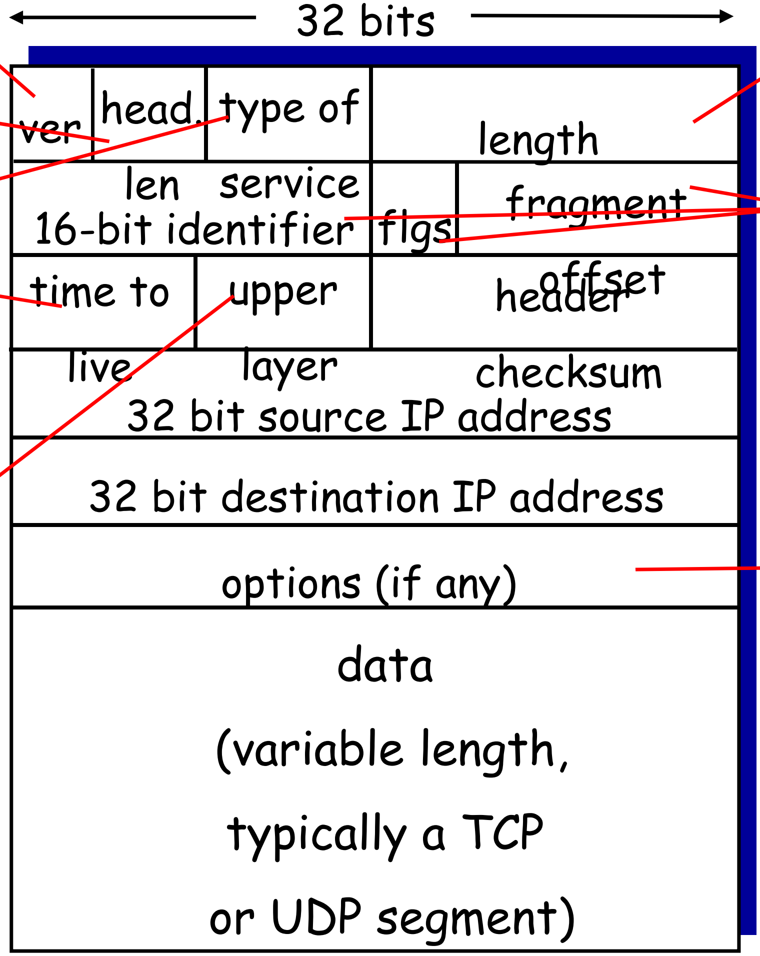
IP protocol version number

header length (bytes)

"type" of data

max number remaining hops (decremented at each router)

upper layer protocol to deliver payload to



total datagram length (bytes)

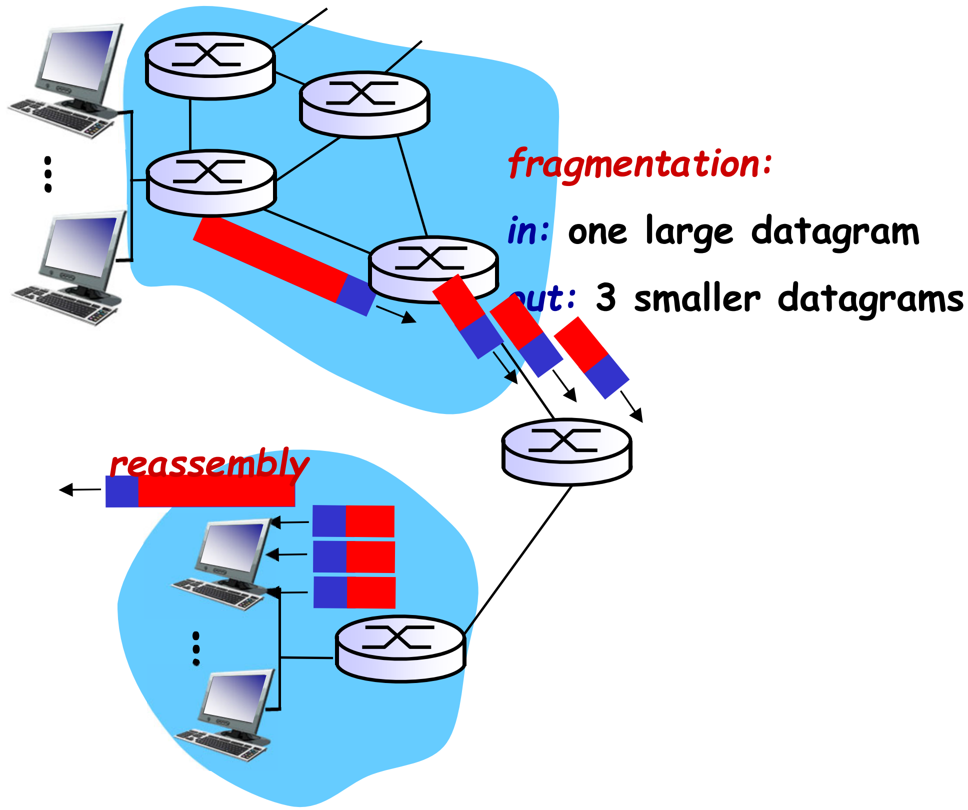
for fragmentation/ reassembly

e.g. timestamp, record route taken, specify list of routers to visit.

how much overhead?
- 20 bytes of TCP
- 20 bytes of IP
- = 40 bytes + app layer overhead

IP fragmentation, reassembly

- network links have MTU (max.transfer size) - largest possible link-level frame
  - different link types, different MTUs
- large IP datagram divided ("fragmented") within net
  - one datagram becomes several datagrams
  - "reassembled" only at final destination
  - IP header bits used to identify, order related fragments



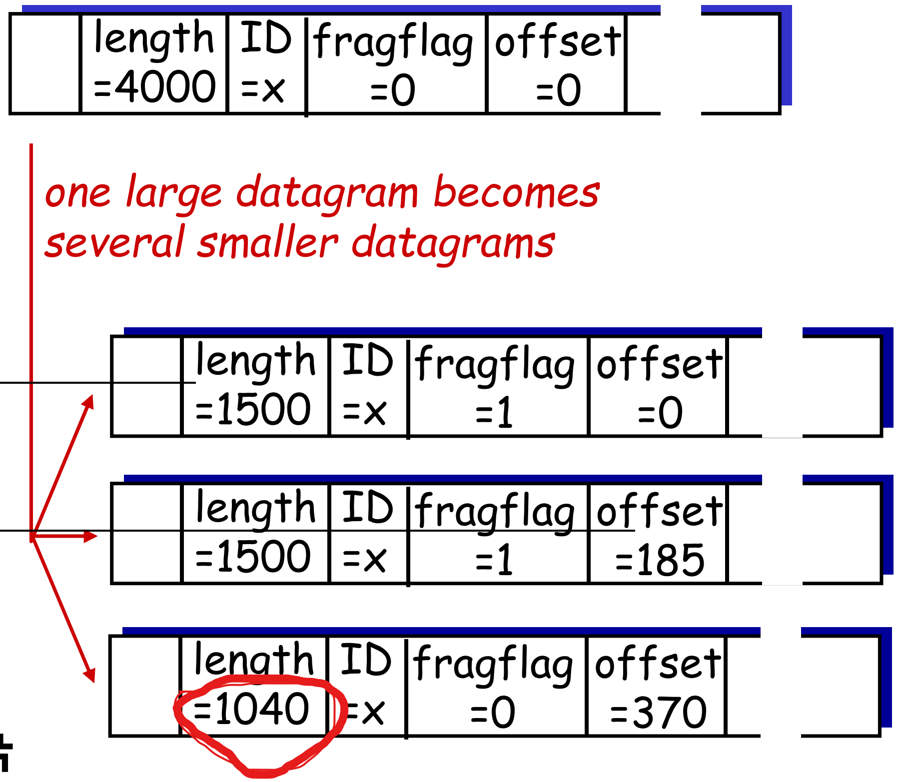
IP fragmentation, reassembly

example:

- **4000 byte datagram**
- **MTU = 1500 bytes**

1480 bytes in data field

offset = 1480/8



分片使用数据部分，所以3980B**需要分片**

每个MTU**能装**1480B**数据，除以得到**3**片**

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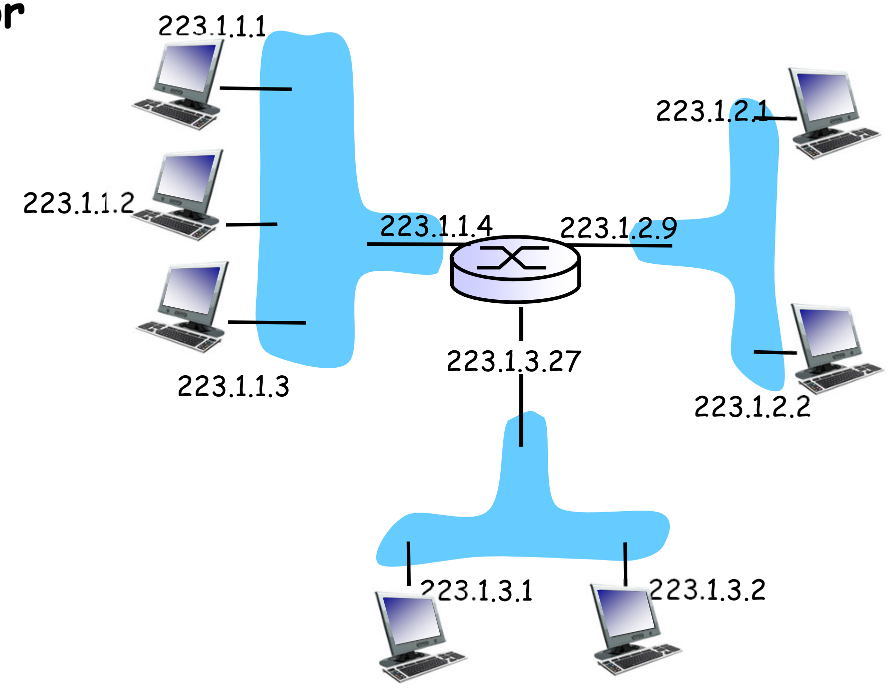
IP addressing: introduction

- *IP address:* 32-bit identifier for host, 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)
- *IP addresses associated with each interface*

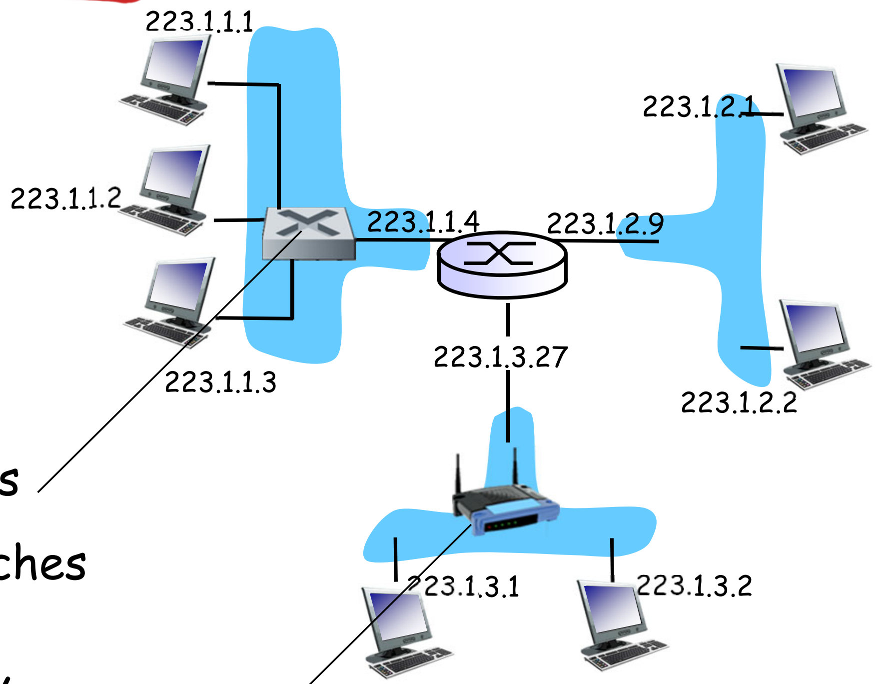


223.1.1.1 = $\underbrace{11011111}_{223}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}$

IP addressing: introduction

Q: how are interfaces actually connected?

A: we'll learn about that in chapter 5, 6.



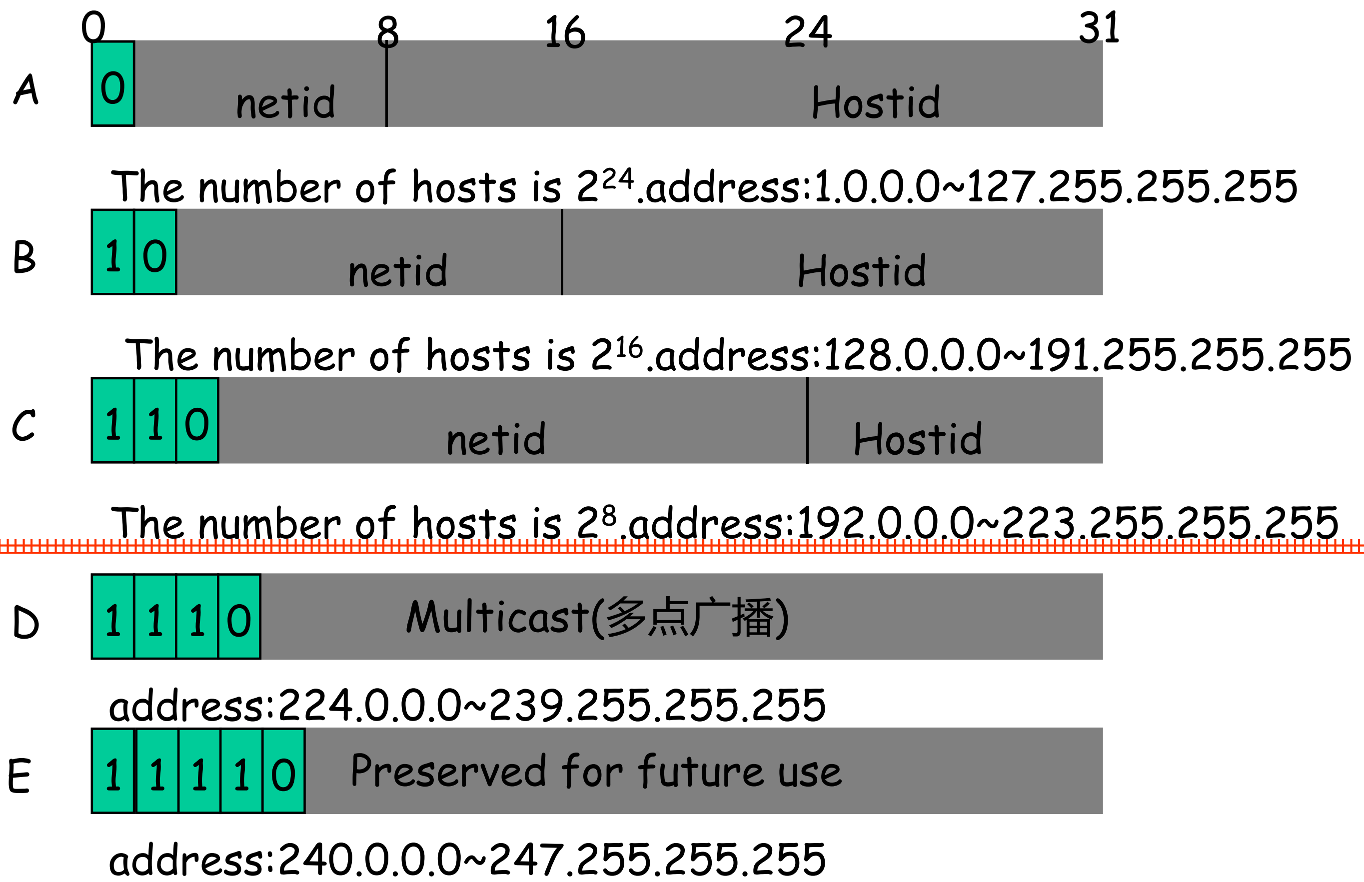
A: wired Ethernet interfaces connected by Ethernet switches

A: wireless WiFi interfaces connected by WiFi base station

For now: don't need to worry about how one interface is connected to another (with no intervening router)

补充内容

IP Address



Special IP Address

补充内容

1. broadcast address(广播地址):主机号全为1.向其它网络广播,必须有一个有效的网络号。

2. limited broadcast address (有限广播):255.255.255.255,向本网络的所有主机广播，不需要网络号

3.“0” address(“0”地址):0.0.0.0。本网络本主机

4. loopback address (回送地址):netid=127，将信息回送本机。

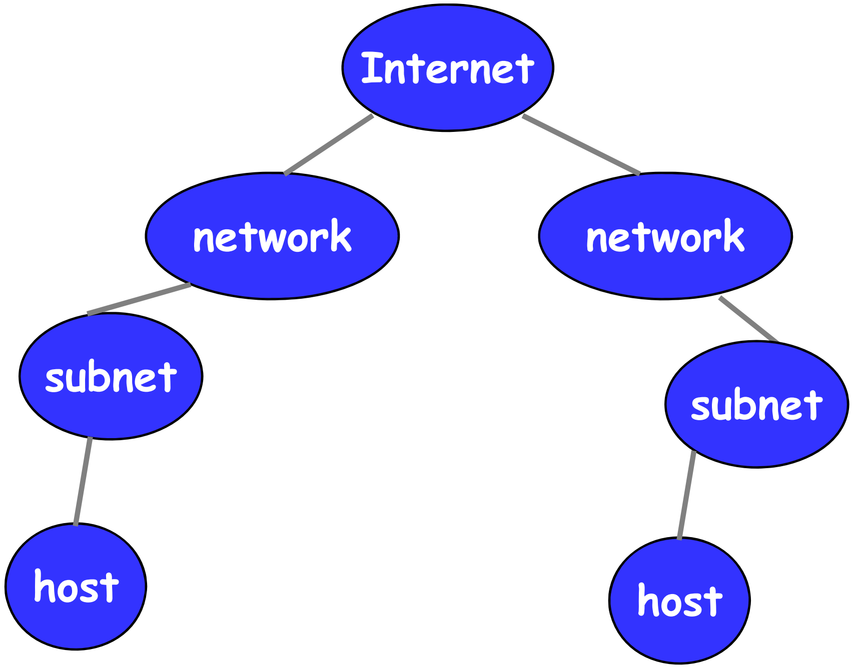
补充内容

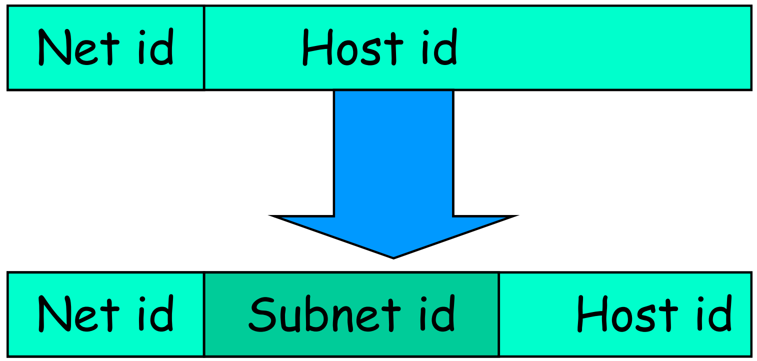
Special addresses

Class	Nerid	Total
A	10	1
B	172.16—172.31	16
C	192.168.0-192.168.255	256

补充内容

Subnetting 子网编址





補充内容

Subnet mask 子网掩码

11111111 11111111 00000000 00000000 255.255.0.0

Example of subnet mask

130.1.0.0

B类地址

255.255.255.0

subnet

130.1.1.0

⋮

130.1.254.0

host

130.1.1.1

130.1.1.254

补充内容

Notation of Subnet mask

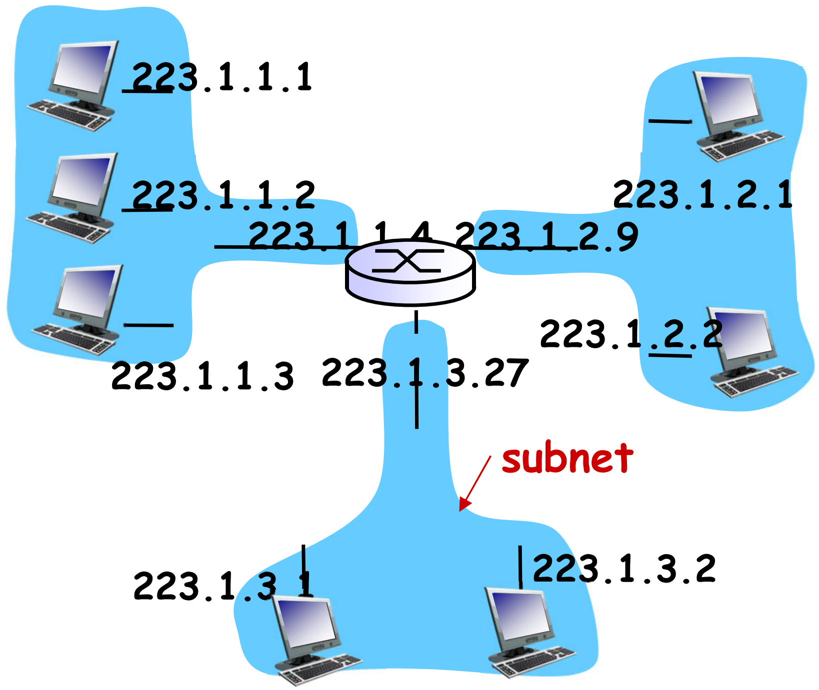
- Dotted-decimal notation

  255.255.255.0

- 193.1.1.0/24,subnet mask 有24个1

Subnets

- IP address:
  - subnet part - high order bits
  - host part - low order bits
- *what' s a subnet ?*
  - device interfaces with same subnet part of IP address
  - can physically reach each other *without intervening router*

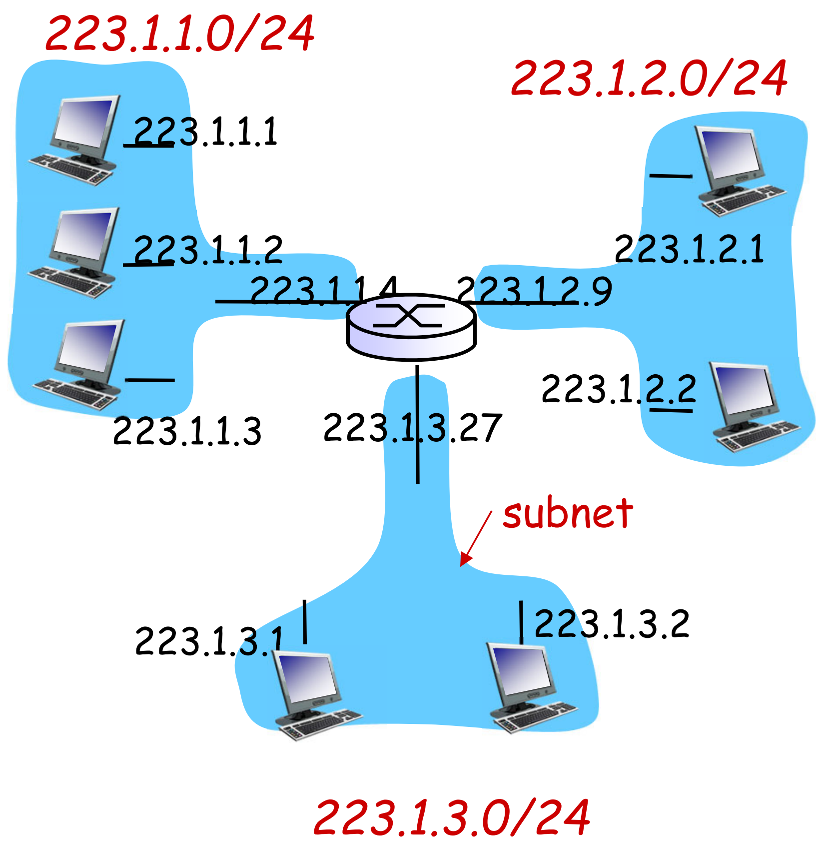


network consisting of 3 subnets

Subnets

recipe

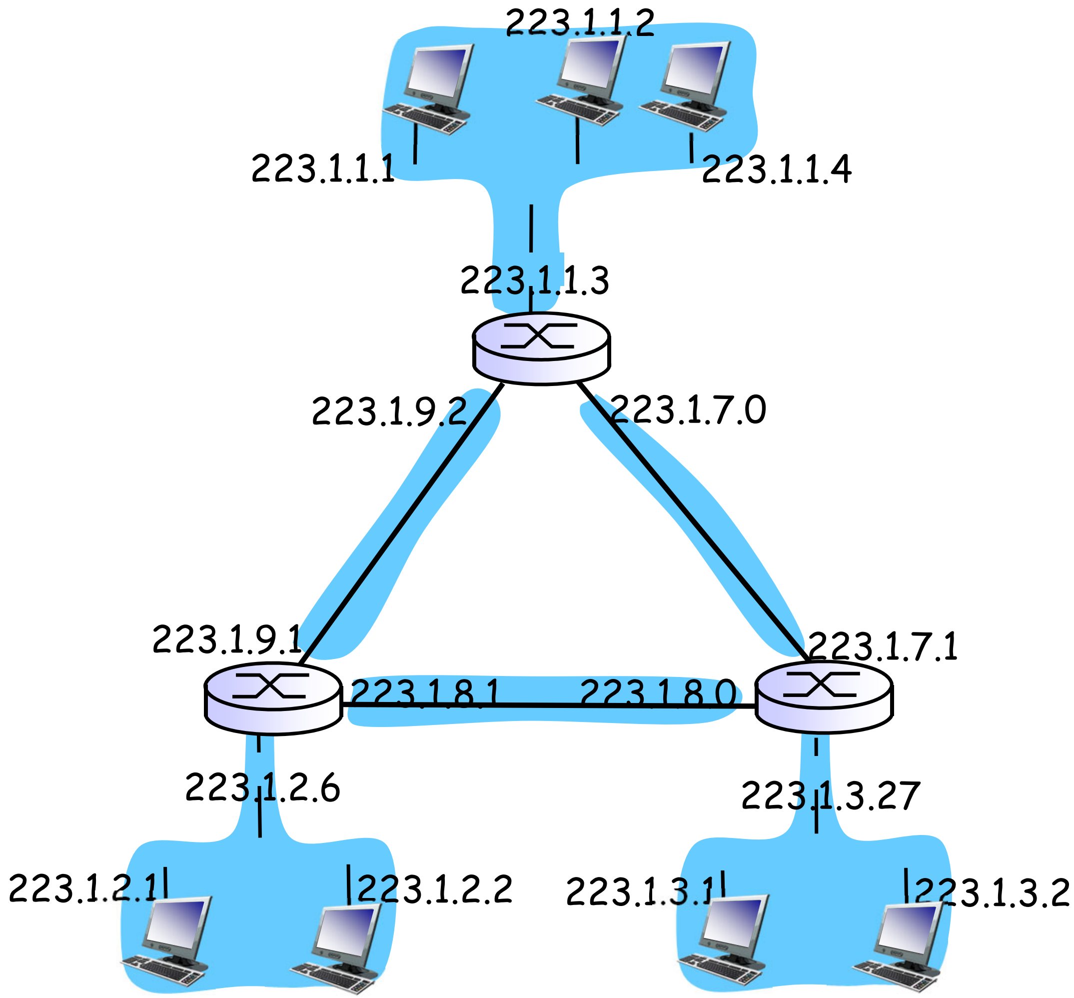
- to determine the subnets, detach each interface from its host or router, creating islands of isolated networks
- each isolated network is called a ***subnet***



subnet mask: /24

Subnets

how many?



补充内容

Address block 20.23.16.0/20,divide its address block into 8 equal-size smaller address blocks and one of these address blocks out t each of up to 8 organization

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	00010111	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

补充内容

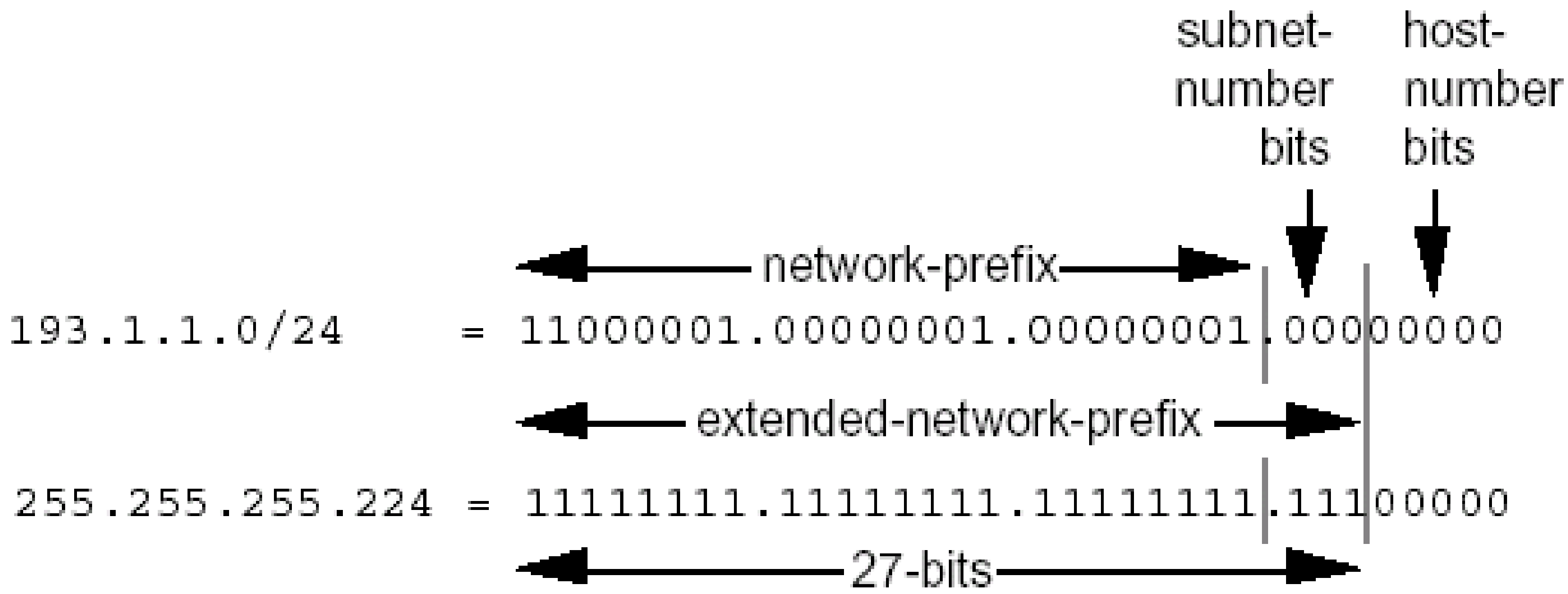
Given

An organization has been assigned the network number 193.1.1.0/24 and it needs to define 6 subnets. The largest subnet is required to support 25 hosts.

1. Define Each of the Subnet Number
2. Define Host Addresses for Each subnet
3. Define the Broadcast Address for Each Subnet

补充内容

Defining the Subnet Mask / Extended-Prefix Length



补充内容

Defining Each of the Subnet Numbers

```
Base Net:   11000001.00000001.00000001.00000000 = 193.1.1.0/24

Subnet #0:  11000001.00000001.00000001.00000000 = 193.1.1.0/27
Subnet #1:  11000001.00000001.00000001.00100000 = 193.1.1.32/27
Subnet #2:  11000001.00000001.00000001.01000000 = 193.1.1.64/27
Subnet #3:  11000001.00000001.00000001.01100000 = 193.1.1.96/27
Subnet #4:  11000001.00000001.00000001.10000000 = 193.1.1.128/27
Subnet #5:  11000001.00000001.00000001.10100000 = 193.1.1.160/27
Subnet #6:  11000001.00000001.00000001.11000000 = 193.1.1.192/27
Subnet #7:  11000001.00000001.00000001.11100000 = 193.1.1.224/27
```

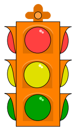
补充内容

Defining Host Addresses for Each Subnet

```
Subnet #2: 11000001.00000001.00000001.01000000 = 193.1.1.64/27

Host #1:   11000001.00000001.00000001.01000001 = 193.1.1.65/27
Host #2:   11000001.00000001.00000001.01000010 = 193.1.1.66/27
Host #3:   11000001.00000001.00000001.01000011 = 193.1.1.67/27
Host #4:   11000001.00000001.00000001.01000100 = 193.1.1.68/27
Host #5:   11000001.00000001.00000001.01000101 = 193.1.1.69/27

Host #15:  11000001.00000001.00000001.01001111 = 193.1.1.79/27
Host #16:  11000001.00000001.00000001.01010000 = 193.1.1.80/27
      .
      .
Host #27:  11000001.00000001.00000001.01011011 = 193.1.1.91/27
Host #28:  11000001.00000001.00000001.01011100 = 193.1.1.92/27
Host #29:  11000001.00000001.00000001.01011101 = 193.1.1.93/27
Host #30:  11000001.00000001.00000001.01011110 = 193.1.1.94/27
```



Host #31: 11000001.00000001.00000001.01011111

补充内容

Defining the Broadcast Address for Each Subnet

The broadcast address for Subnet #2 is the all 1's host address or:

11000001.00000001.00000001.01011111 = 193.1.1.95

The broadcast address for Subnet #6 is simply the all 1's host address or:

11000001.00000001.00000001.11011111 = 193.1.1.223

将主机部分全部设置为1

IP addressing: CIDR

CIDR: Classless InterDomain Routing

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

subnet part

host part

11001000 00010111 00010000 00000000

200.23.16.0/23

IP addresses: how to get one?

Q: How does a *host* get IP address?

- hard-coded by system admin in a file
  - Windows: control-panel->network->configuration->tcp/ip->properties
  - UNIX: /etc/rc.config
- **DHCP: D**ynamic **H**ost **C**onfiguration **P**rotocol: dynamically get address from as server
  - "plug-and-play"

DHCP: Dynamic Host Configuration Protocol

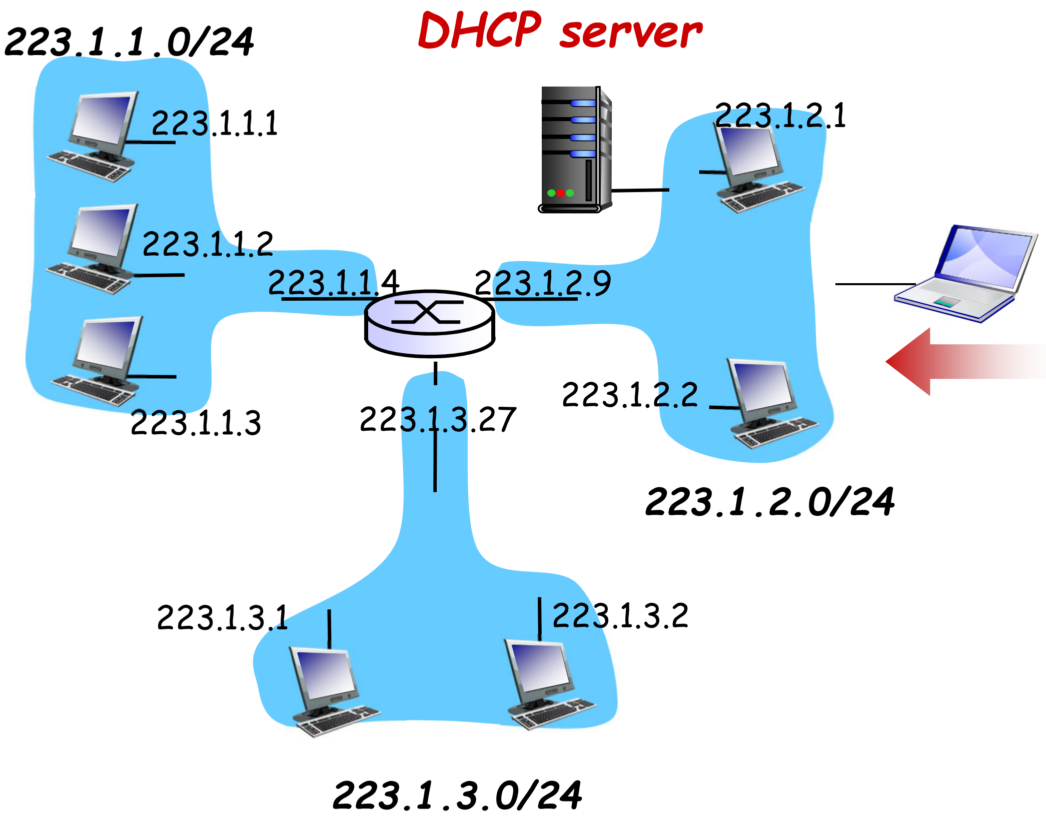
goal: allow host to *dynamically* obtain its IP address from network server when it joins network

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

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 scenario

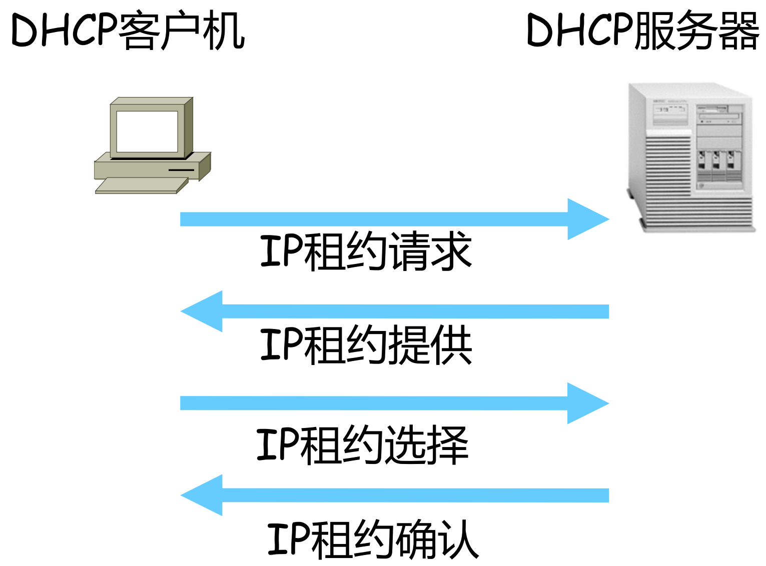


arriving DHCP client needs address in this network

补充内容

DHCP的工作过程

- **当作为DHCP客户端的计算机第一次启动时，它通过一系列的步骤以获得其TCP/IP配置信息，并得到IP地址的租期。租期是指DHCP客户端从DHCP服务器获得的完整的TCP/IP配置后对该TCP/IP配置的使用时间。DHCP客户端从DHCP服务器上获得完整的TCP/IP配置需要经过以下几个过程**



补充内容

（1）DHCP发现

DHCP工作过程的第一步是DHCP发现（DHCP Discover），该过程也称这为IP发现。以下几种情况需要进行DHCP发现

- 当客户端第一次发现DHCP客户端方式使用TCP/IP协议栈时，即第一次向DHCP服务器请求TCP/IP配置时。
- 客户端从使用固定IP地址转向使用DHCP时。
- 该DHCP客户端所租用的IP地址已被DHCP服务器收回，并已提供给其他的DHCP客户端使用时。

当DHCP客户端发出TCP/IP配置请求时，DHCP客户端既不知道自己的IP地址，也不知道服务器的IP地址。DHCP客户端使便将0.0.0.0作为自己的IP地址，255.255.255.255作为服务器的地址。然后在UDP（ 用户数据协议）的67或68端口广播发送一个DHCP发现信息。

补充内容

(2) DHCP提供

DHCP工作的第二个过程是DHCP提供（DHCP offer），是指当网络中的任何一个DHCP服务器（同一个网络中存在多个DHCP服务器时）在收到DHCP客户端的DHCP发现信息后，该DHCP服务器若能够提供IP地址，就从该DHCP服务器的IP地址池中选取一个没有出租的IP地址，然后利用广播方式提供给DHCP客户端。在还没有将该IP地址正式租用给DHCP客户端之前，这个IP 地址会暂时保留起来，以免再分配给其他的DHCP客户端。

补充内容

（3）DHCP请求

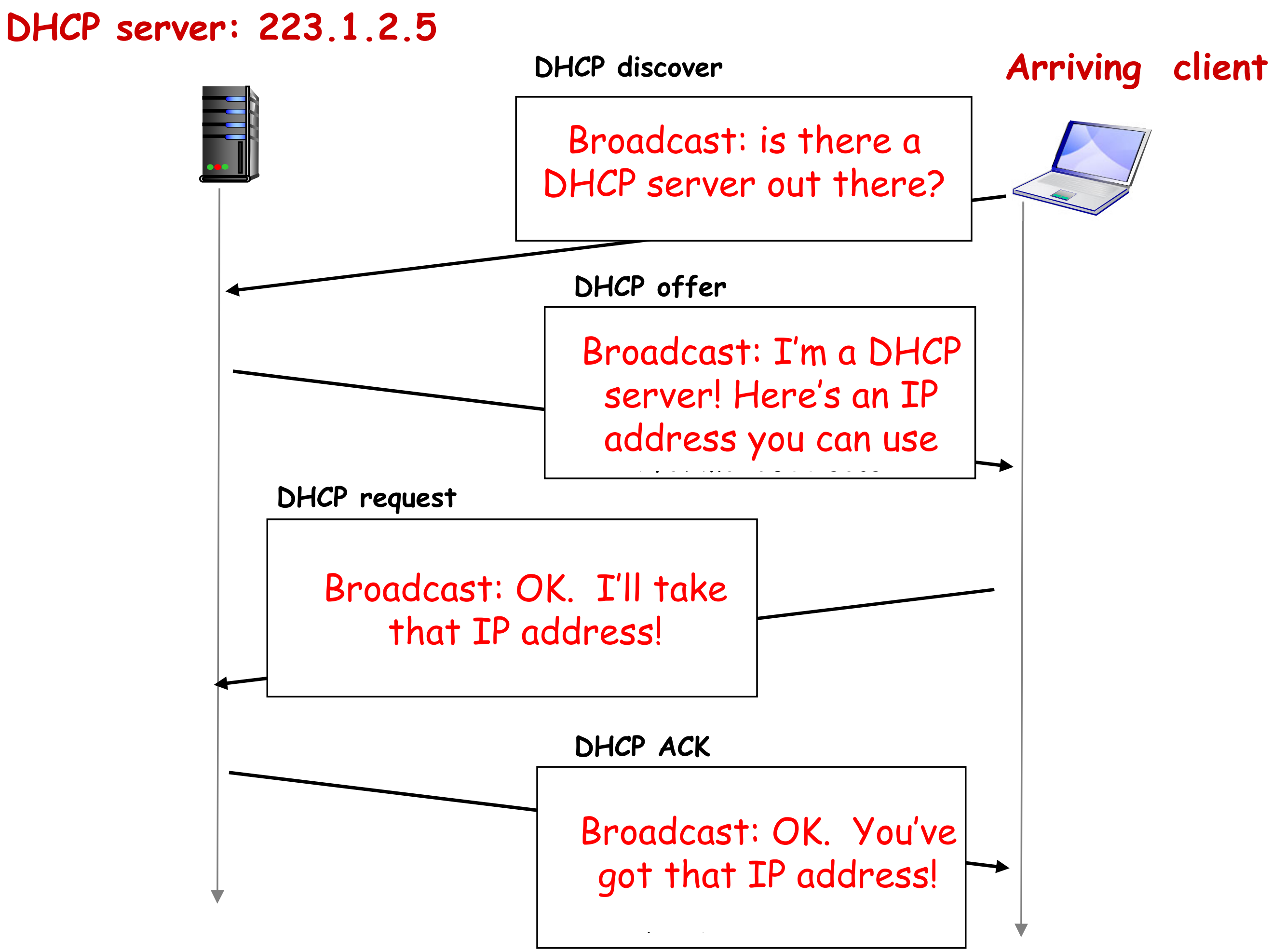
DHCP工作的第三个过程是DHCP请求（DHCP request），一旦DHCP客户端收到第一个由DHCP服务器提供的应答信息后，就进入此过程。当DHCP客户端收到第1个DHCP服务器响应信息后就以广播的方式发送一个DHCP请求信息给网络中所有的DHCP服务器。在DHCP请求信息中包含有所选择的DHCP服务器的IP地址。

补充内容

（4）DHCP应答

- DHCP工作的最后一个过程便是DHCP应答（DHCPACK）。一旦被选择的DHCP服务器接收到DHCP客户端的DHCP请求信息后，就将已保留的这个IP地址标识为已租用，然后也以广播方式发送一个DHCP应答信息给DHCP客户端。该DHCP客户端在接收DHCP应答信息后，就完成了获得IP地址的过程，便开始利用这个已租到的IP地址与网络中的其他计算机进行通信。
- 为什么在最后一个过程中DHCP服务器还使用广播方式呢？这是因为在此时，DHCP客户还没有真正获得IP地址。

DHCP client-server scenario

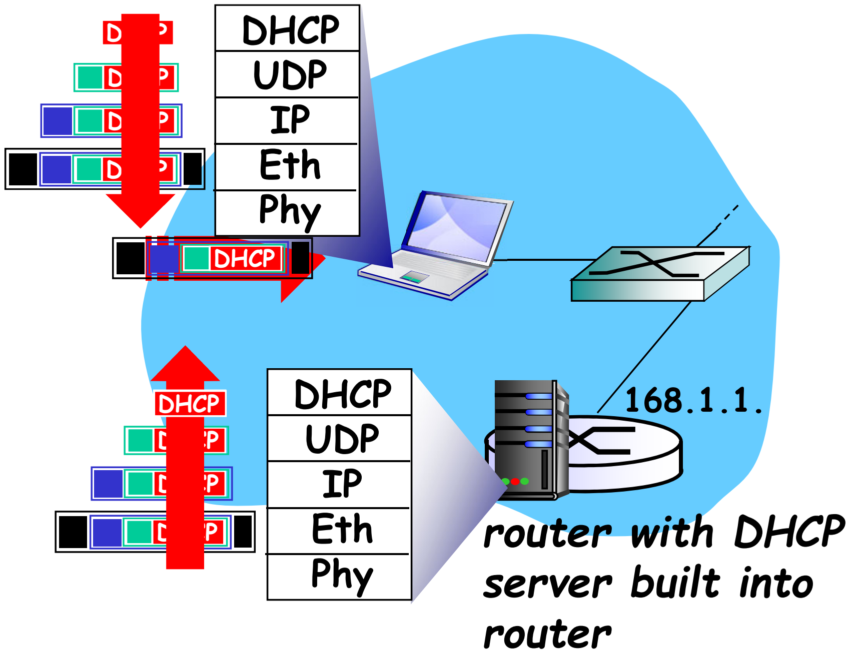


DHCP: more than IP addresses

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

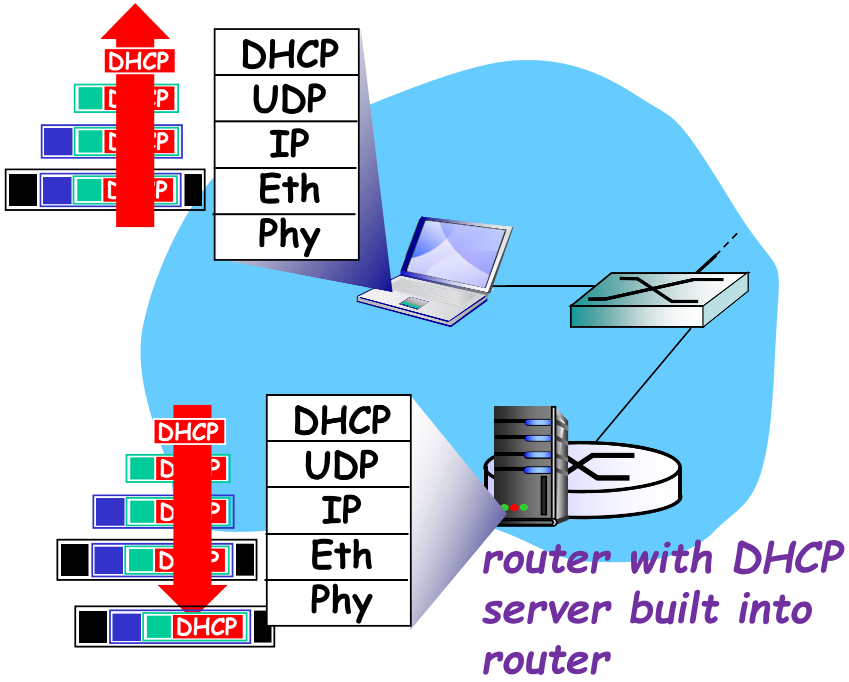
- address of first-hop router for client
- name and IP address of DNS sever
- network mask (indicating network versus host portion of address)

DHCP: example



- connecting laptop needs its IP address, addr of first-hop router, addr of DNS server: use DHCP
- DHCP request encapsulated in UDP, encapsulated in IP, encapsulated in 802.1 Ethernet
- Ethernet frame broadcast (dest: FFFFFFFFFFFF) on LAN, received at router running DHCP server
- Ethernet demuxed to IP demuxed, UDP demuxed to DHCP

DHCP: example



- DCP server formulates DHCP ACK containing client' s IP address, IP address of first-hop router for client, name & IP address of DNS server
- encapsulation of DHCP server, frame forwarded to client, demuxing up to DHCP at client
- client now knows its IP address, name and IP address of DSN server, IP address of its first-hop router

DHCP: Wireshark output (home LAN)

request

Message type: **Boot Request (1)**
Hardware type: Ethernet
Hardware address length: 6
Hops: 0
Transaction ID: 0x6b3a11b7
Seconds elapsed: 0
Bootp flags: 0x0000 (Unicast)
Client IP address: 0.0.0.0 (0.0.0.0)
Your (client) IP address: 0.0.0.0 (0.0.0.0)
Next server IP address: 0.0.0.0 (0.0.0.0)
Relay agent IP address: 0.0.0.0 (0.0.0.0)
Client MAC address: Wistron_23:68:8a (00:16:d3:23:68:8a)
Server host name not given
Boot file name not given
Magic cookie: (OK)
Option: (t=53,l=1) **DHCP Message Type = DHCP Request**
Option: (61) Client identifier
  Length: 7; Value: 010016D323688A;
  Hardware type: Ethernet
  Client MAC address: Wistron_23:68:8a (00:16:d3:23:68:8a)
Option: (t=50,l=4) Requested IP Address = 192.168.1.101
Option: (t=12,l=5) Host Name = "nomad"
Option: (55) Parameter Request List
  Length: 11; Value: 010F03062C2E2F1F21F92B
  1 = Subnet Mask; 15 = Domain Name
  3 = Router; 6 = Domain Name Server
  44 = NetBIOS over TCP/IP Name Server
  ……

reply

Message type: **Boot Reply (2)**
Hardware type: Ethernet
Hardware address length: 6
Hops: 0
Transaction ID: 0x6b3a11b7
Seconds elapsed: 0
Bootp flags: 0x0000 (Unicast)
Client IP address: 192.168.1.101 (192.168.1.101)
Your (client) IP address: 0.0.0.0 (0.0.0.0)
Next server IP address: 192.168.1.1 (192.168.1.1)
Relay agent IP address: 0.0.0.0 (0.0.0.0)
Client MAC address: Wistron_23:68:8a (00:16:d3:23:68:8a)
Server host name not given
Boot file name not given
Magic cookie: (OK)
Option: (t=53,l=1) DHCP Message Type = DHCP ACK
Option: (t=54,l=4) Server Identifier = 192.168.1.1
Option: (t=1,l=4) Subnet Mask = 255.255.255.0
Option: (t=3,l=4) Router = 192.168.1.1
Option: (6) Domain Name Server
  Length: 12; Value: 445747E2445749F244574092;
  IP Address: 68.87.71.226;
  IP Address: 68.87.73.242;
  IP Address: 68.87.64.146
Option: (t=15,l=20) Domain Name = "hsd1.ma.comcast.net."

IP addresses: how to get one?

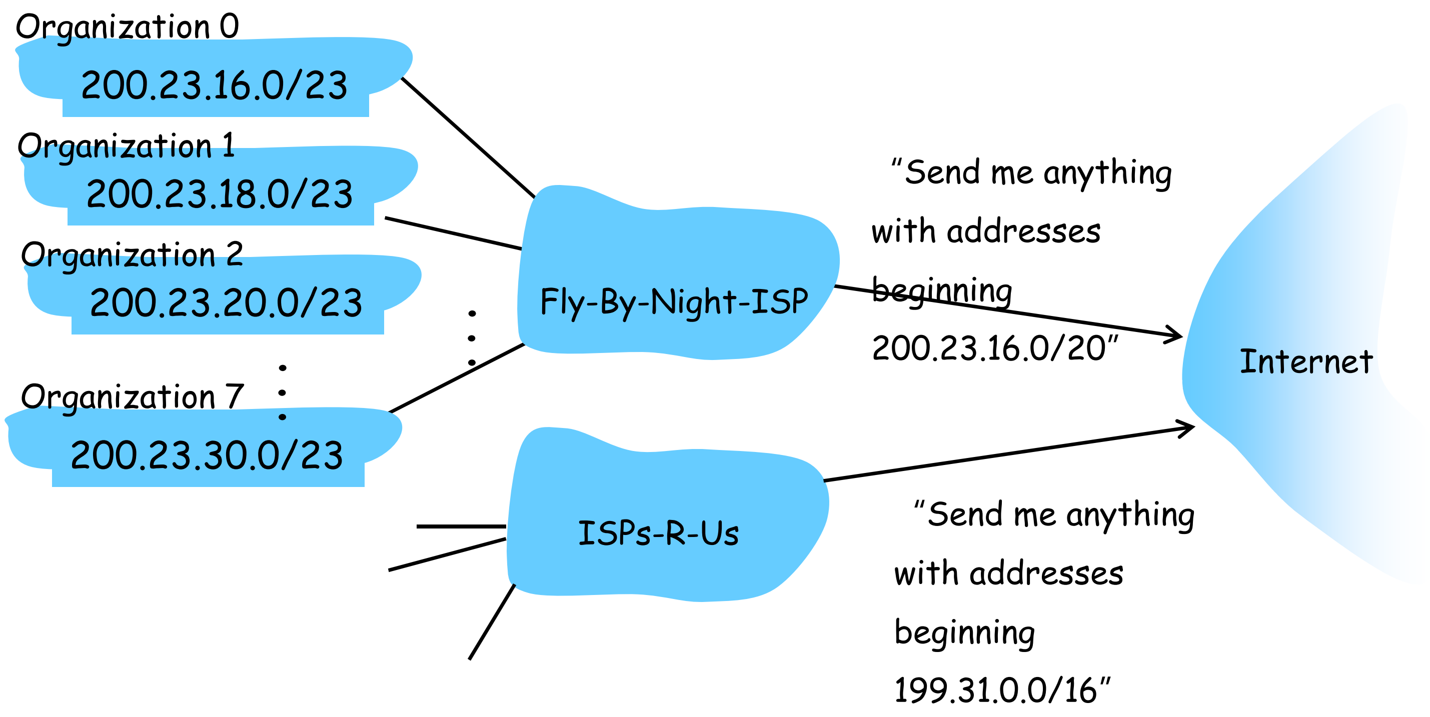
Q: how does *network* get subnet part of IP addr?

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

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	00010111	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

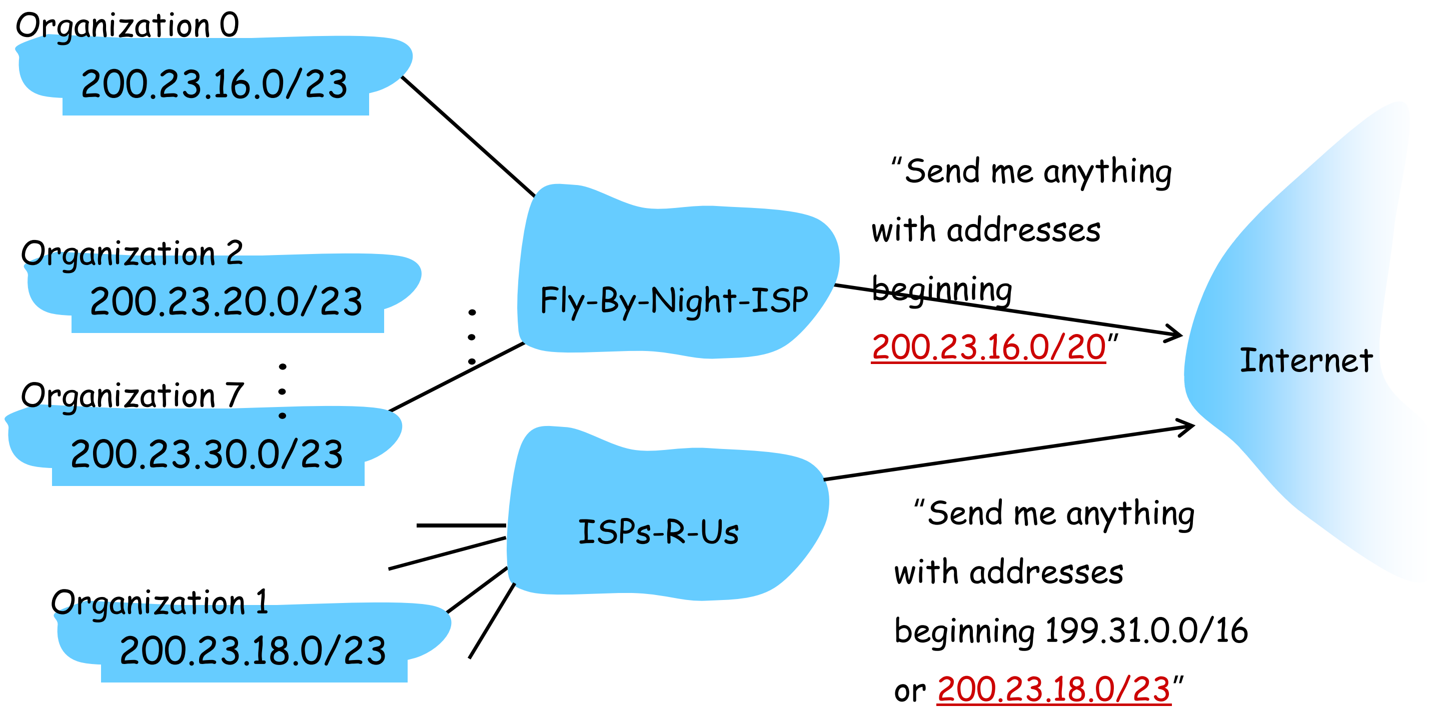
Hierarchical addressing: route aggregation

hierarchical addressing allows efficient advertisement of routing information:



Hierarchical addressing: more specific routes

ISPs-R-Us has a more specific route to Organization 1



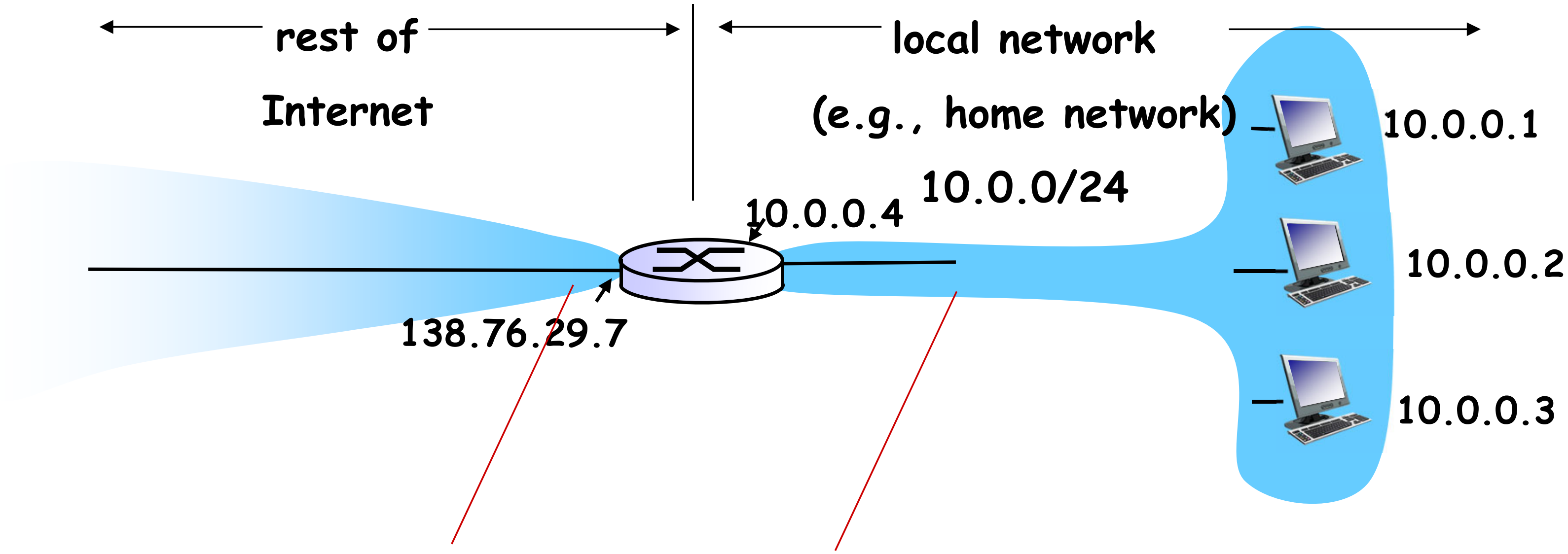
IP addressing: the last word...

Q: how does an ISP get block of addresses?

A: ICANN: Internet Corporation for Assigned Names and Numbers http://www.icann.org/

- allocates addresses
- manages DNS
- assigns domain names, resolves disputes

NAT: network address translation



all datagrams *leaving* local network have *same* single source NAT IP address: 138.76.29.7,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

motivation: local network uses just one IP address as far as outside world is concerned:

- range of addresses not needed from ISP: just one IP address for all devices
- can change addresses of devices in local network without notifying outside world
- can change ISP without changing addresses of devices in local network
- devices inside local net not explicitly addressable, visible by outside world (a security plus)

NAT: network address translation

- *implementation*: NAT router must:

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 addr

- *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 dest fields of every incoming datagram with corresponding (source IP address, port #) stored in NAT table

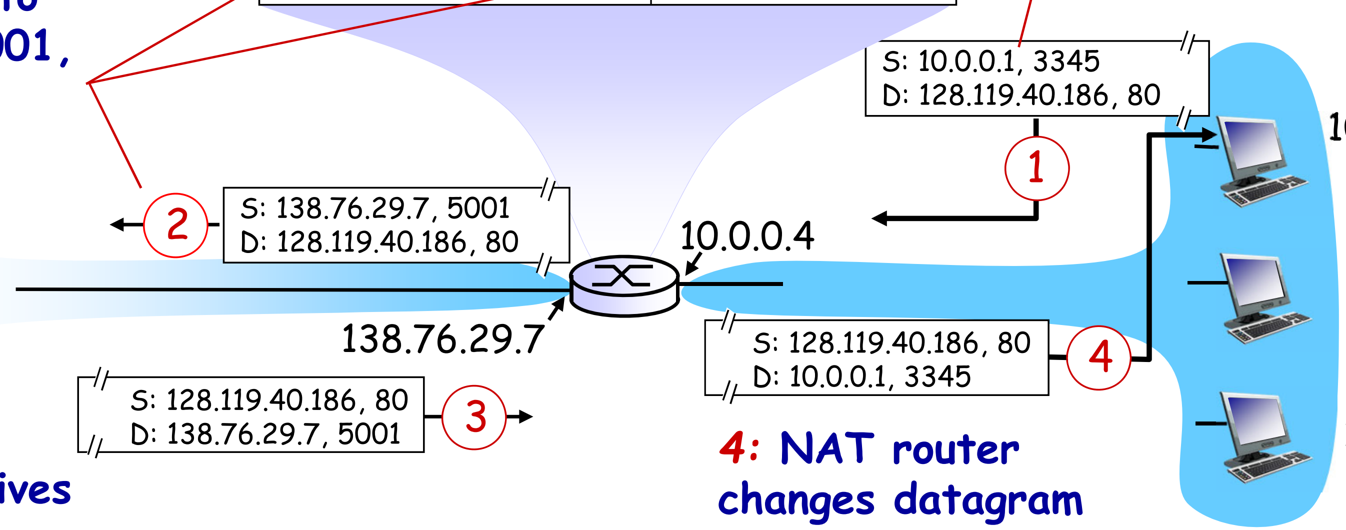
NAT: network address translation

NAT translation table

WAN side addr	LAN side addr
138.76.29.7, 5001	10.0.0.1, 3345
……	……

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

1: host 10.0.0.1 sends datagram to 128.119.40.186, 80



3: reply arrives dest. address: 138.76.29.7, 5001

4: NAT router changes datagram dest addr from 138.76.29.7, 5001 to 10.0.0.1, 3345

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

NAT: network address translation

- 16-bit port-number field:
  - 60,000 simultaneous connections with a single LAN-side address!
- NAT is controversial:
  - routers should only process up to layer 3
  - address shortage should be solved by IPv6
  - violates end-to-end argument
    - NAT possibility must be taken into account by app designers, e.g., P2P applications
  - NAT traversal: what if client wants to connect to server behind NAT?

Chapter 4: outline

4.1 Overview of Network layer
- data plane
- control plane

4.2 What's inside a router

4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- network address translation
- IPv6

4.4 Generalized Forward and SDN
- match
- action
- OpenFlow examples of match-plus-action in action

IPv6: motivation

- *initial motivation:* 32-bit address space soon to be completely allocated.
- additional motivation:
  - header format helps speed processing/forwarding
  - header changes to facilitate QoS

IPv6 datagram format:

- fixed-length 40 byte header
- no fragmentation allowed

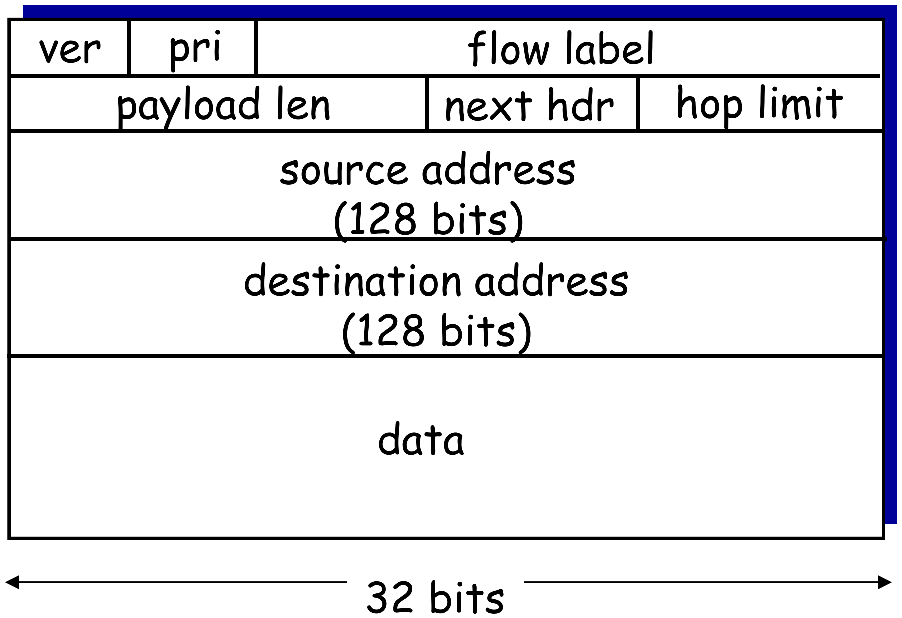
IPv6 datagram format

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

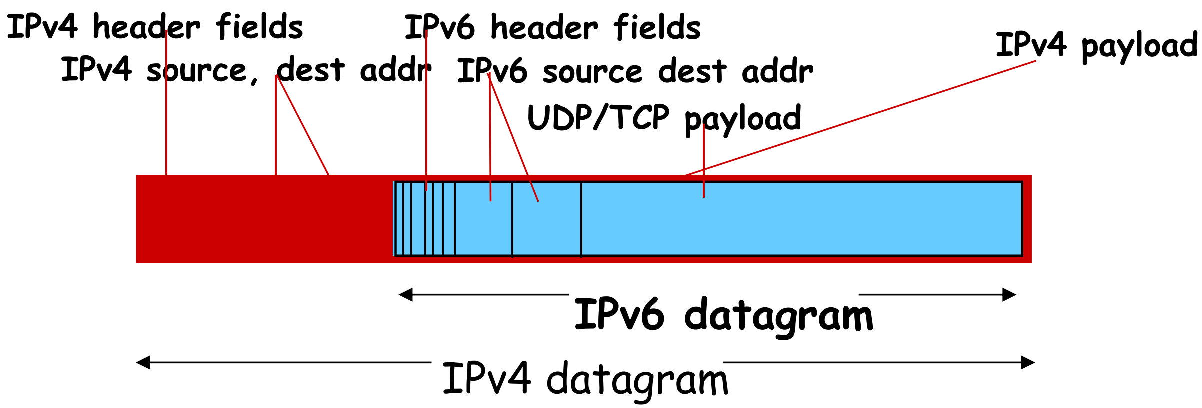


Other changes from IPv4

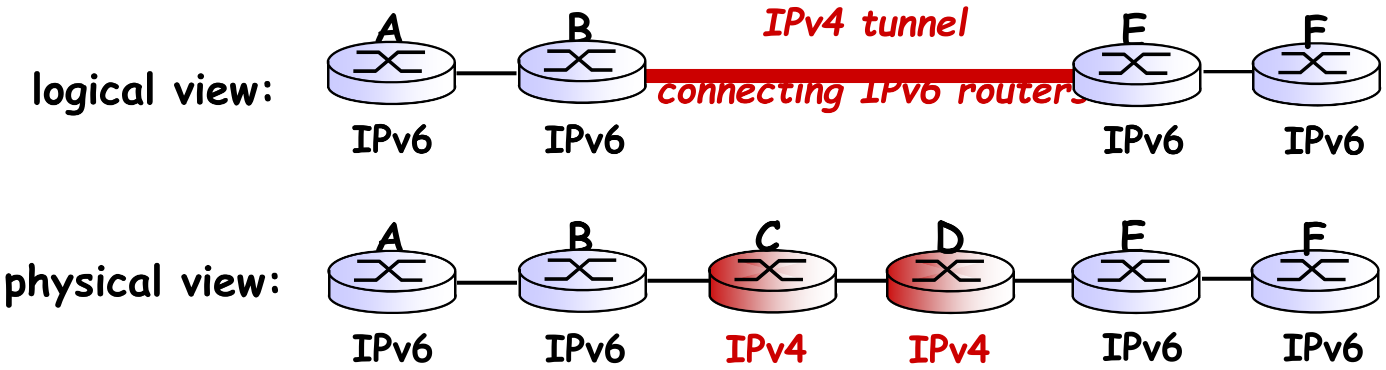
- *checksum:* removed entirely to reduce processing time at each hop
- *options:* allowed, but outside of header, indicated by "Next Header" field
- *ICMPv6:* new version of ICMP
  - additional message types, e.g. "Packet Too Big"
  - multicast group management functions

Transition from IPv4 to IPv6

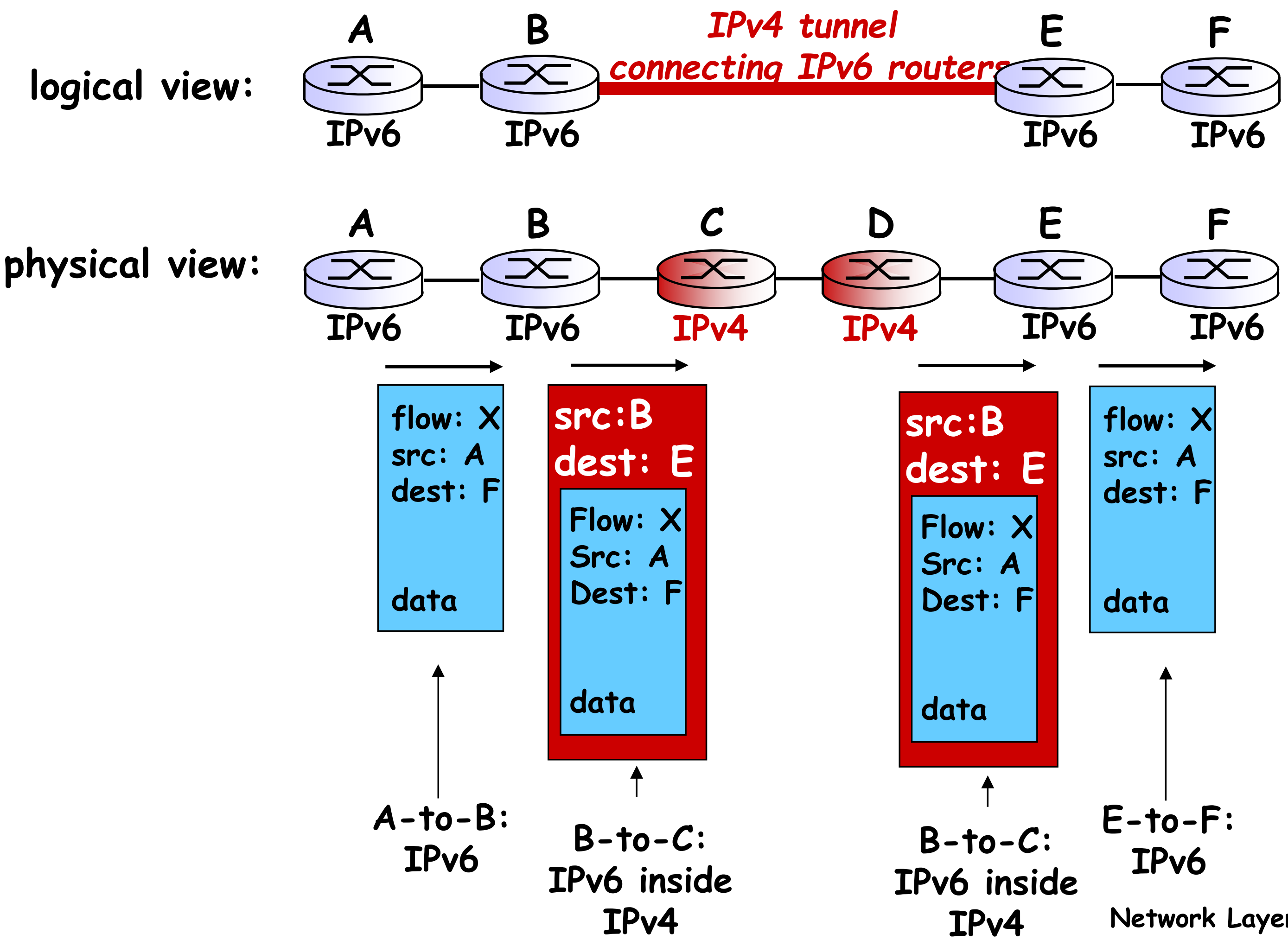
- not all routers can be upgraded simultaneously
  - no "flag days"
  - how will network operate with mixed IPv4 and IPv6 routers?
- *tunneling:* IPv6 datagram carried as *payload* in IPv4 datagram among IPv4 routers



Tunneling


IPv4 tunnel
connecting IPv6 routers
logical view:
physical view:
A
B
C
D
E
F
IPv6
IPv4

Tunneling


logical view:
A
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IPv6
IPv6
IPv6
IPv6
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A
B
C
D
E
F
IPv6
IPv6
IPv4
IPv4
IPv6
IPv6
flow: X
src: A
dest: F
data
src:B
dest: E
Flow: X
Src: A
Dest: F
data
src:B
dest: E
Flow: X
Src: A
Dest: F
data
flow: X
src: A
dest: F
data
A-to-B:
IPv6
B-to-C:
IPv6 inside
IPv4
B-to-C:
IPv6 inside
IPv4
E-to-F:
IPv6

IPv6: adoption

- Google: 8% of clients access services via IPv6
- NIST: 1/3 of all US government domains are IPv6 capable

- *Long (long!) time for deployment, use*
  - 20 years and counting!
  - think of application-level changes in last 20 years: WWW, Facebook, streaming media, Skype, …
  - *Why?*

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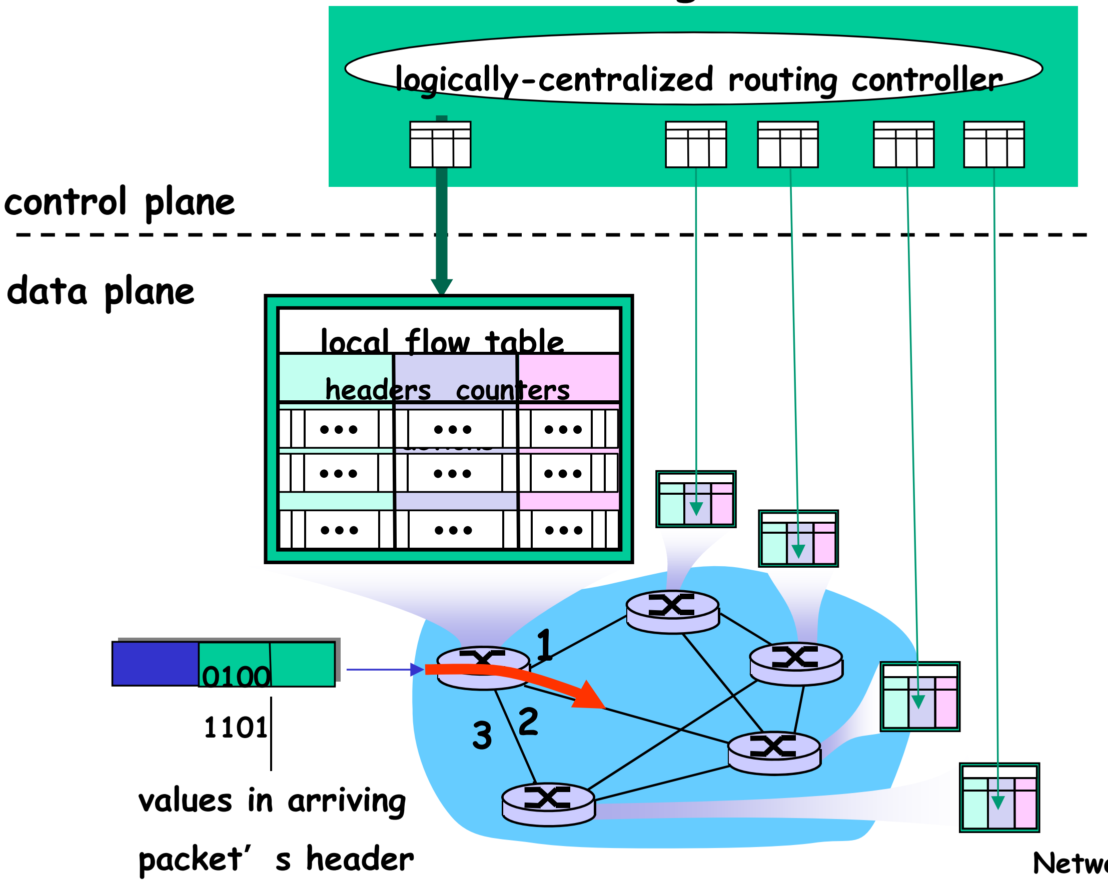
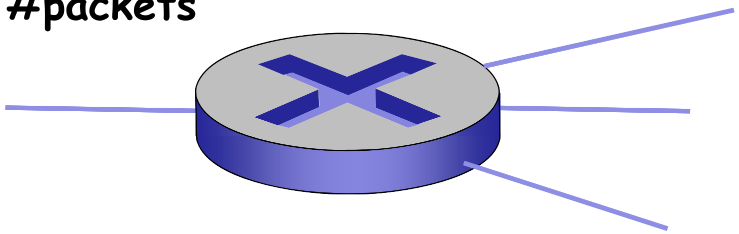
Generalized Forwarding and SDN

Each router contains a *flow table* that is computed and distributed by a *logically centralized* routing controller



OpenFlow data plane abstraction

- *flow*: defined by header fields
- generalized forwarding: simple packet-handling rules
  - *Pattern:* match 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 in a router (computed and distributed by controller) define router's match+action rules

OpenFlow data plane abstraction

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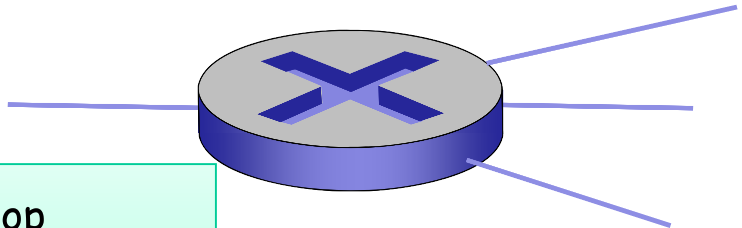
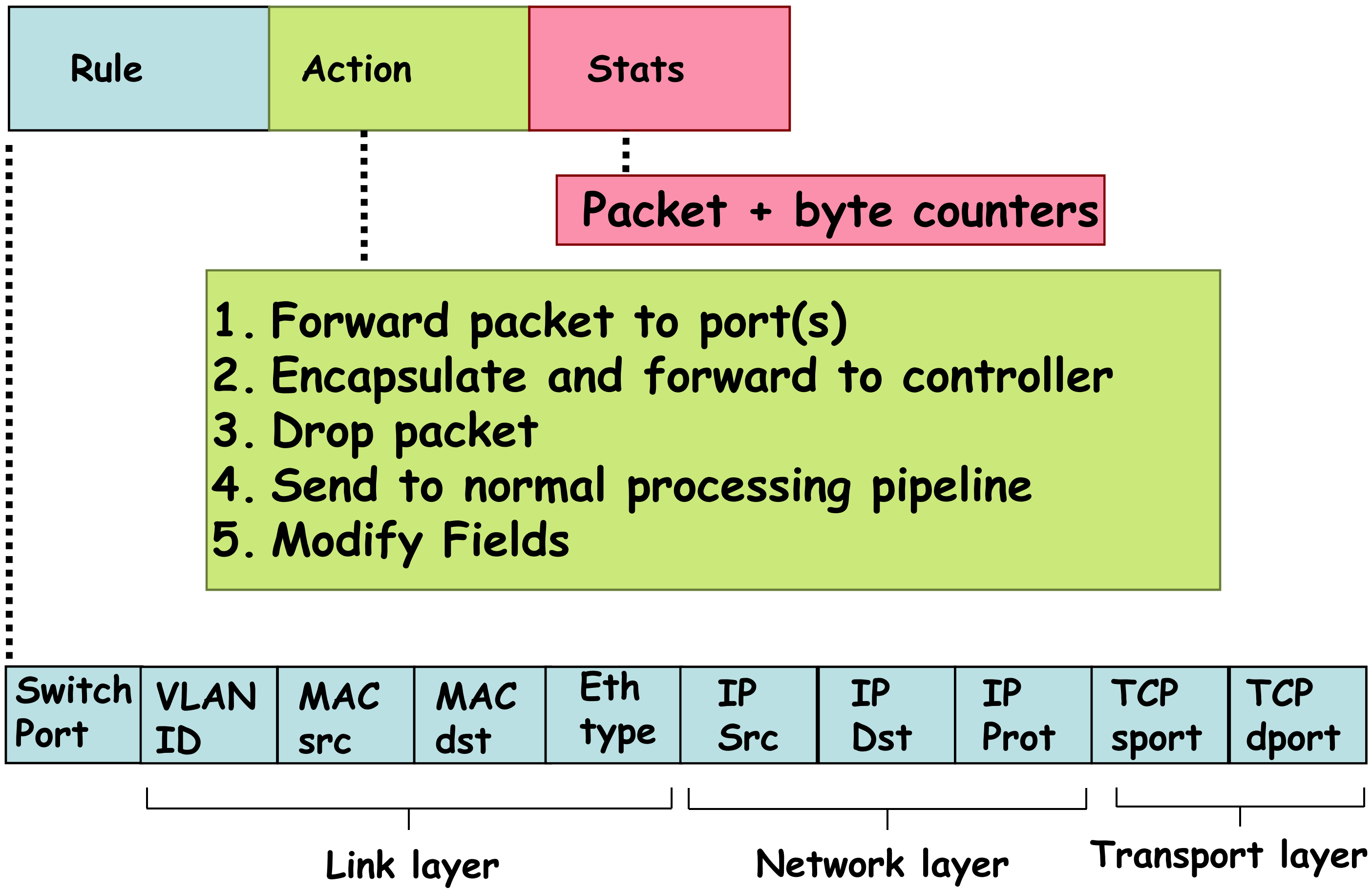


1. src=1.2.*.*, dest=3.4.5.* drop
2. src = *.*.*.*, dest=3.4.*.* forward(2)
3. src=10.1.2.3, dest=*.*.*.* send to controller

* : wildcard

OpenFlow: Flow Table Entries



Examples

Destination-based forwarding:

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	*	*	*	*	51.6.0.8	*	*	*	port6

IP datagrams destined to IP address 51.6.0.8 should be forwarded to router output port 6

Firewall:

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Forward
*	*	*	*	*	*	*	*	*	22	drop

do not forward (block) all datagrams destined to TCP port 22

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Forward
*	*	*	*	*	128.119.1.1	*	*	*	*	drop

do not forward (block) all datagrams sent by host 128.119.1.1

Examples

Destination-based layer 2 (switch) forwarding:

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	22:A7:23:11:E1:02	*	*	*	*	*	*	*	*	port3

layer 2 frames from MAC address 22:A7:23:11:E1:02 should be forwarded to output port 6

OpenFlow abstraction

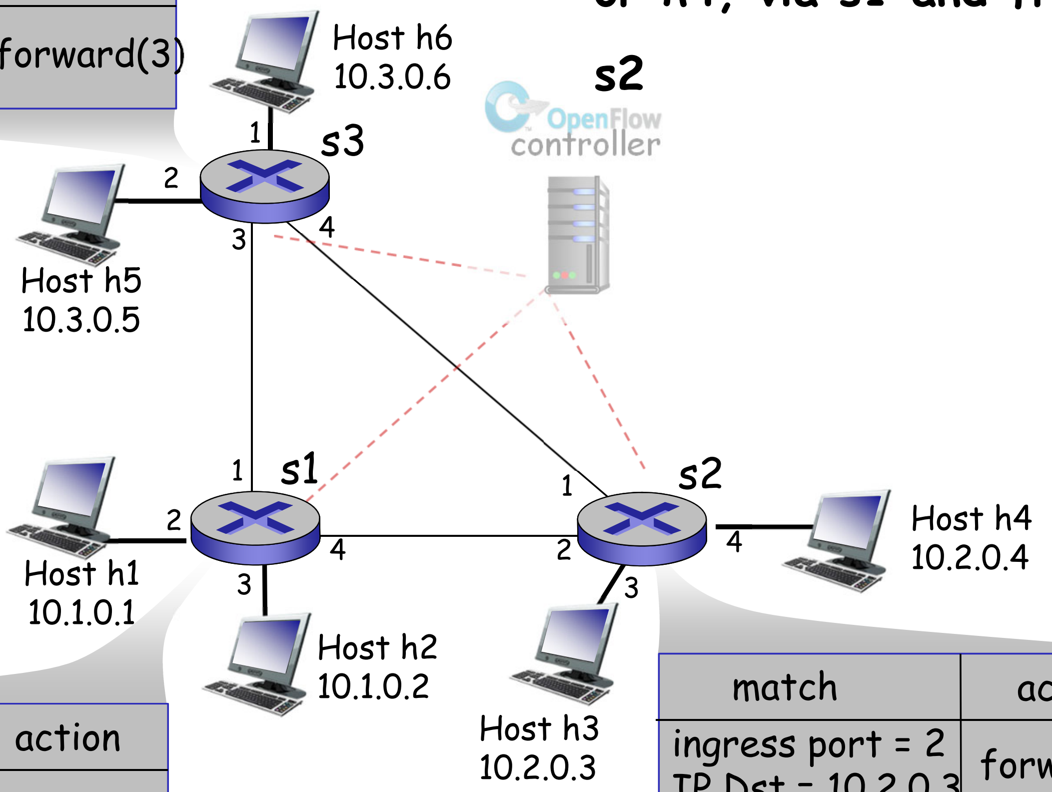
- *match+action:* unifies different kinds of devices

- Router
  - *match:* longest destination IP prefix
  - *action:* forward out a link
- Switch
  - *match:* destination MAC address
  - *action:* forward or flood
- Firewall
  - *match*: IP addresses and TCP/UDP port numbers
  - *action:* permit or deny
- NAT
  - *match:* IP address and port
  - *action:* rewrite address and port

OpenFlow example

Example: **datagrams from hosts h5 and h6 should be sent to h3 or h4, via s1 and from there to s2**

match	action
IP Src = 10.3.*.* IP Dst = 10.2.*.*	forward(3)



match	action
ingress port = 1 IP Src = 10.3.*.* IP Dst = 10.2.*.*	forward(4)

match	action
ingress port = 2 IP Dst = 10.2.0.3	forward(3)
ingress port = 2 IP Dst = 10.2.0.4	forward(4)

Chapter 4: *done!*

4.1 Overview of Network layer: data plane and control plane

4.2 What' s inside a router

4.3 IP: Internet Protocol

- datagram format
- fragmentation
- IPv4 addressing
- NAT
- IPv6

4.4 Generalized Forward and SDN

- match plus action
- OpenFlow example

Question: how do forwarding tables (destination-based forwarding) or flow tables (generalized forwarding) computed?

Answer: by the control plane (next chapter)