Network Layer

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Network Layer

- Functionalities
  - forwarding
  - routing
  - connection setup
- Services
  - guaranteed delivery
  - guaranteed delivery with bounded delay
  - in-order packet delivery
  - guaranteed maximum jitter

Virtual-Circuit and Datagram Networks

- Virtual-Circuit: provides a connection-oriented service
  - a path
  - VC numbers
  - entries in the forwarding table corresponding to each VC
- Datagram Networks: connectionless service
  - routers forwards packets based on destination address range or following prefix matching rule

Inside a Router

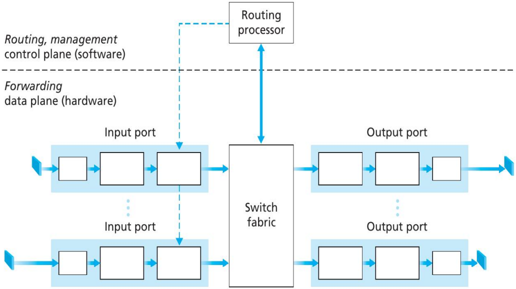


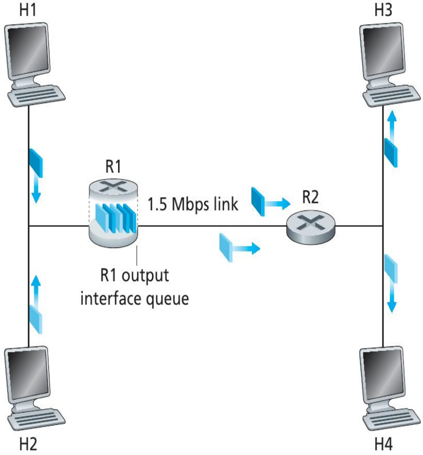
Figure 4.6 ♦ Router architecture

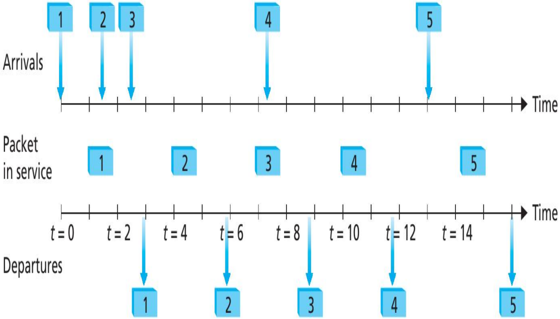
- Switching via memory
- Switching via bus
- Switching via interconnection of network

Scheduling and Policing

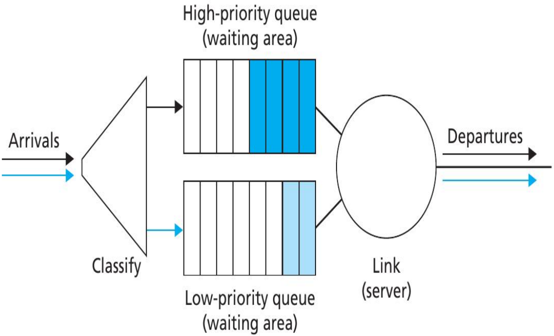
- Scheduling
  - FIFO
  - Priority Queue
  - Weighted Fair Queuing (WFQ)
- Policing
  - Leaky bucket

FIFO or FCFS

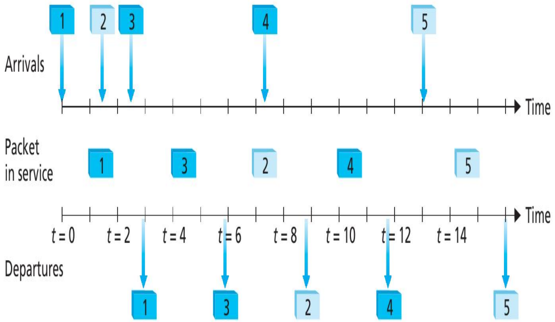



Arrivals
1
2
3
4
5
Time
Packet in service
1
2
3
4
5
Time
t = 0
t = 2
t = 4
t = 6
t = 8
t = 10
t = 12
t = 14
Departures
1
2
3
4
5

Priority Queuing

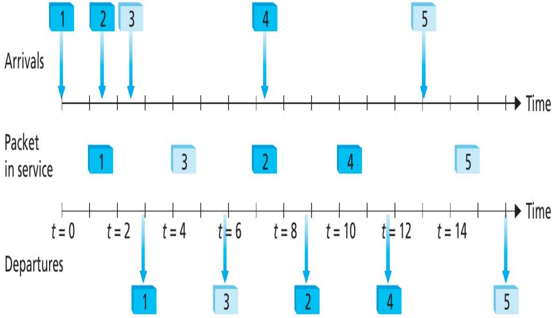


Priority Queuing



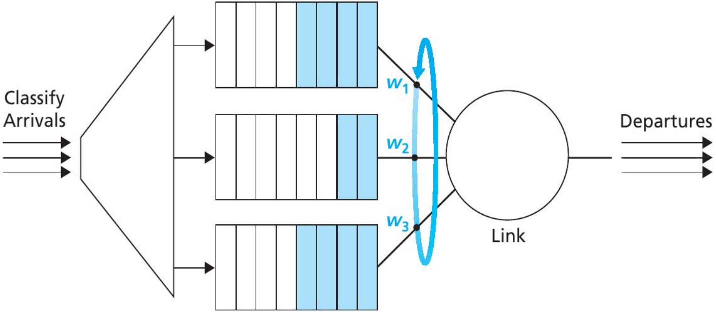
Round Robin

- Round robin queuing discipline
- No strict priority, schedule different queues in a round robin manner.
- Work-conserving round robin discipline



Robin.jpeg

Weighted Fair Queuing



- Bandwidth - R packets per second
- Class i will get a fraction of BW eqaul to $\frac{w_i}{\sum_j w_j}$

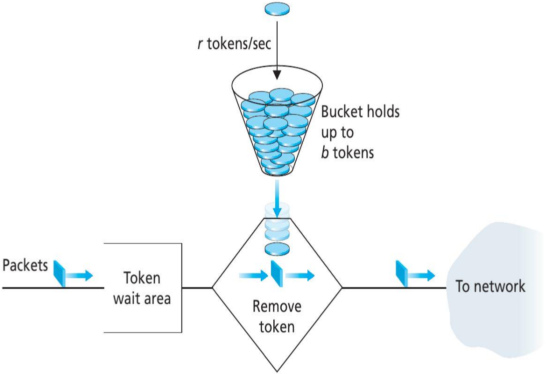
Policing: Leaky Bucket

- Restrictons:
  - average rate
  - peak rate
  - burst size

Policing: Leaky Bucket

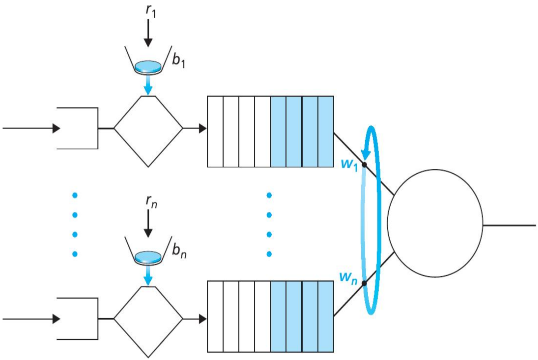
- Restrictons:
  - average rate
  - peak rate
  - burst size
- Leaky bucket:
  - a leaky bucket contains a maximum of b tokens
  - tokens are added to the bucket at rate r tokens per second
  - To transmit a packet, first remove token from the bucket and then transmit.

Leaky Bucket



- Maximum number of packets in an interval of t seconds: $rt + b$.

Leaky Bucket with WFQ



Maximum delay

- Consider flow 1: Its BW is $R\frac{w_1}{\sum w_j}$

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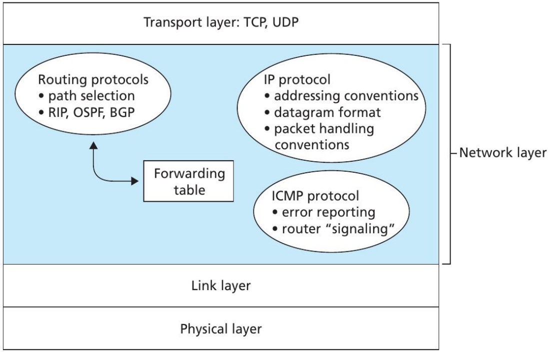
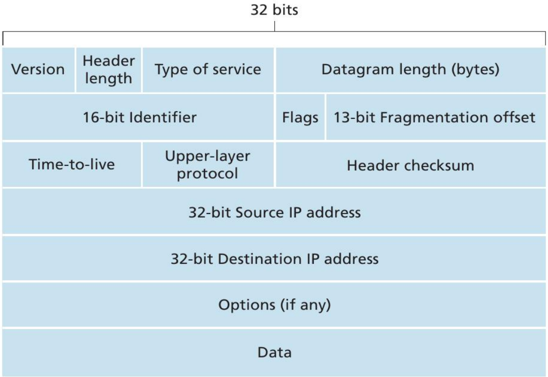
- A burst of b_1 packets have arrived.
- Last packet will be served with in d_{max}
- $d_{max} = \frac{b_1}{R\frac{w_1}{\sum w_j}}$

Internet Protocol



- IPv4 and IPv6

IPv4 Datagram



IPv4 Datagram

- Header checksum
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  - TCP already has checksum, why do datagrams need checksum?

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- Options
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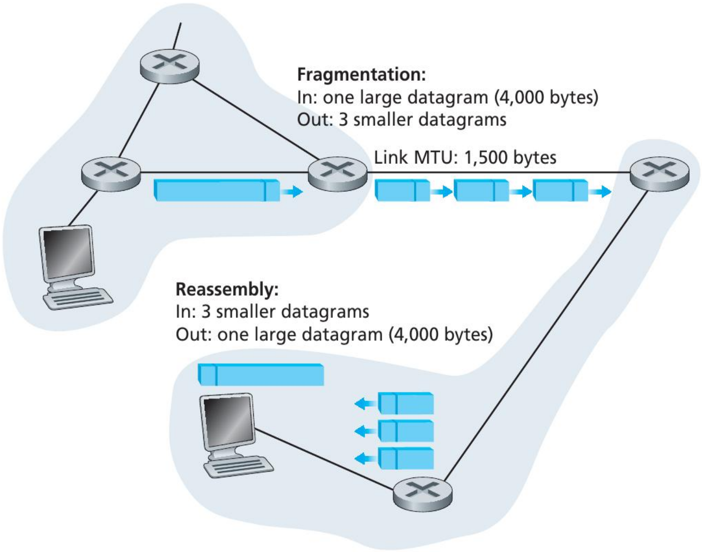
  - not used in general
  - Packet header is variable based on options used
- Data: Typically TCP/UDP segment.

Fragmentation

- Datagrams are often larger than MTU
- Fragmentation: Splitting a larger datagram into smaller frames suitable for transmission
- Link-layer in the end system reassembles the fragments and forwards to network layer.
- Datagram fields:
  - identification: all fragments of a datagram have same identification number.
  - flag: indicates whether it is last fragment or not
  - fragmentation offset: specifies the location of the fragment in the datagram

Fragmentation



Fragmentation

Fragment	Bytes	ID	Offset	Flag
1st fragment	1,480 bytes in the data field of the IP datagram	identification = 777	offset = 0 (meaning the data should be inserted beginning at byte 0)	flag = 1 (meaning there is more)
2nd fragment	1,480 bytes of data	identification = 777	offset = 185 (meaning the data should be inserted beginning at byte 1,480. Note that $185 \cdot 8 = 1{,}480$)	flag = 1 (meaning there is more)
3rd fragment	1,020 bytes (= 3,980–1,480–1,480) of data	identification = 777	offset = 370 (meaning the data should be inserted beginning at byte 2,960. Note that $370 \cdot 8 = 2{,}960$)	flag = 0 (meaning this is the last fragment)

IPv4 Addressing

- Who should be IP addressed?

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- Interface: The boundary between host and physical link.

IPv4 Addressing

- Who should be IP addressed?
    - Hosts?
    - Routers?
- Hosts are connected to internet through a link.
- Interface: The boundary between host and physical link.
- It is the interface that will be IP addressed.

IP Address

- IP address is 32-bit long
- It is represented in dotted-decimal notation. Example, the address

  11000001 00100000 11011000 00001001

  will be represented by 193.32.216.9
- About 4 billion addresses available
- Who assigns IP addresses?

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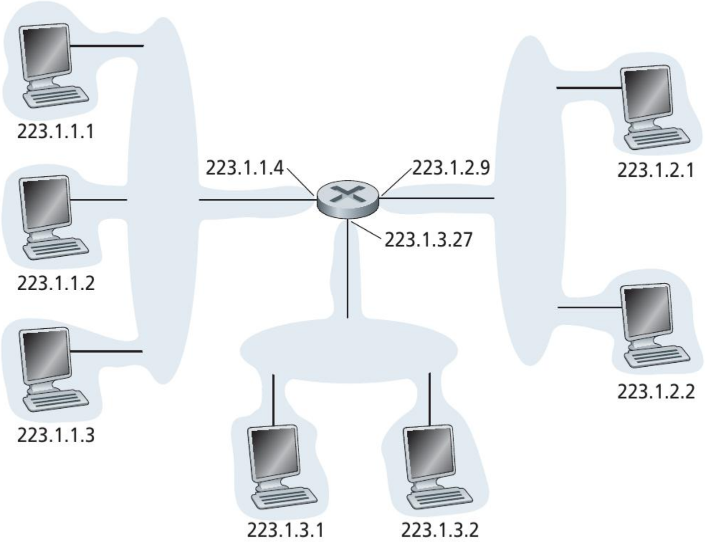
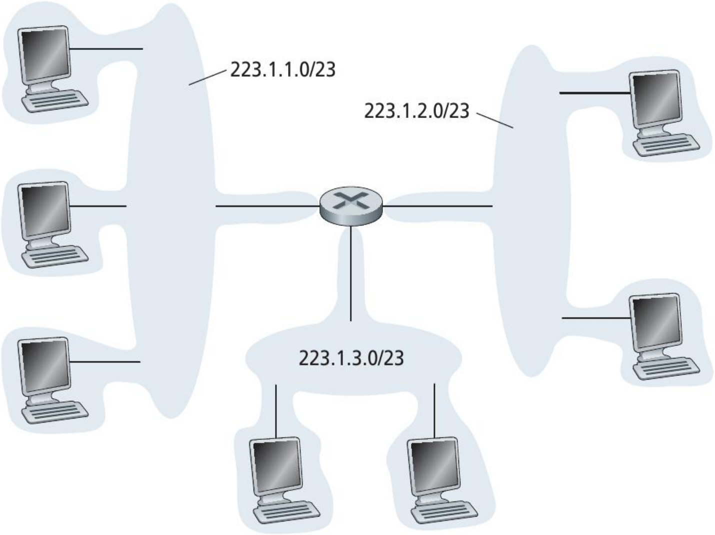
- How to assign IP addresses?
- Subnet: Detach each interface from its host or router, creating islands of isolated networks. Each of these isolated networks is called a subnet.

Subnet


223.1.1.1
223.1.1.2
223.1.1.3
223.1.1.4
223.1.2.9
223.1.3.27
223.1.2.1
223.1.2.2
223.1.3.1
223.1.3.2

Subnet



IP Addressing

- The internet's addressing strategy is known as Classless Interdomain Routing (CIDR)
- IP broadcast address: 255.255.255.255
- Classful addressing:
    - Class A: a.b.c.d/8
    - Class B: a.b.c.d/16
    - Class C: a.b.c.d/24
- CIDR: a.b.c.d/x

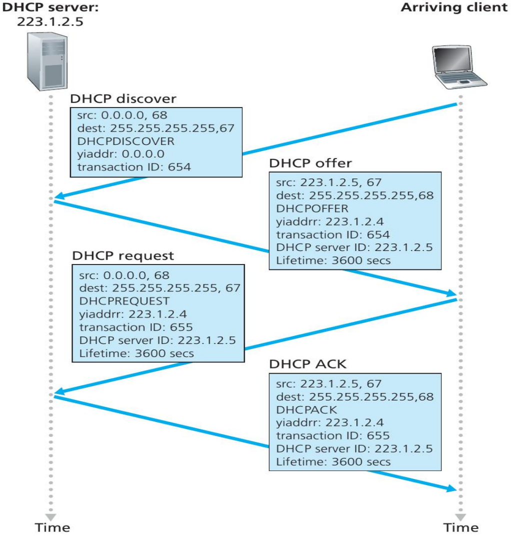
Obtaining a Block of Addresses

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

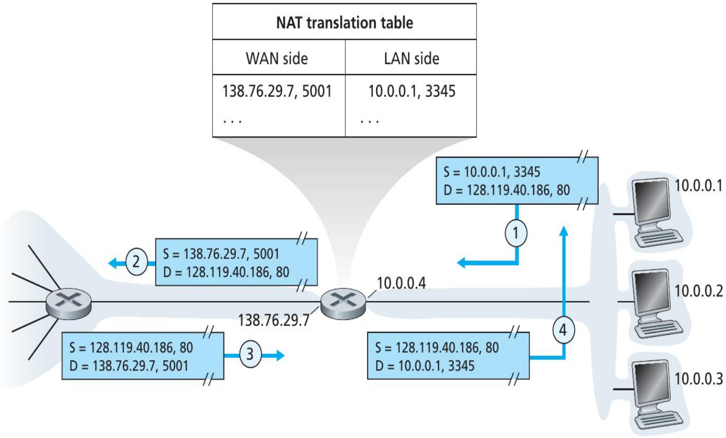
Dynamic Host Configuration Protocol

- Allows hosts to obtain IP address automatically
- Also known as plug and play protocol
- Client-server protocol
- Each server may have DHCP server. If a subnet does not have DHCP server, it will have DHCP relay agent that knows the address of DHCP server.

DHCP


DHCP server:
223.1.2.5
Arriving client
DHCP discover
src: 0.0.0.0, 68
dest: 255.255.255.255,67
DHCPDISCOVER
yiaddr: 0.0.0.0
transaction ID: 654
DHCP offer
src: 223.1.2.5, 67
dest: 255.255.255.255,68
DHCPOFFER
yiaddrr: 223.1.2.4
transaction ID: 654
DHCP server ID: 223.1.2.5
Lifetime: 3600 secs
DHCP request
src: 0.0.0.0, 68
dest: 255.255.255.255, 67
DHCPREQUEST
yiaddrr: 223.1.2.4
transaction ID: 655
DHCP server ID: 223.1.2.5
Lifetime: 3600 secs
DHCP ACK
src: 223.1.2.5, 67
dest: 255.255.255.255,68
DHCPACK
yiaddrr: 223.1.2.4
transaction ID: 655
DHCP server ID: 223.1.2.5
Lifetime: 3600 secs
Time
Time

Network Address Translation (NAT)



Internet Control Message Protocol (ICMP)

- Typically used for error reporting. Example: "Destination network unreachable"
- Can be used for congestion control
- ICMP messages have:
  - type and code field
  - header and the first 8 bytes of IP datagram that caused the ICMP message

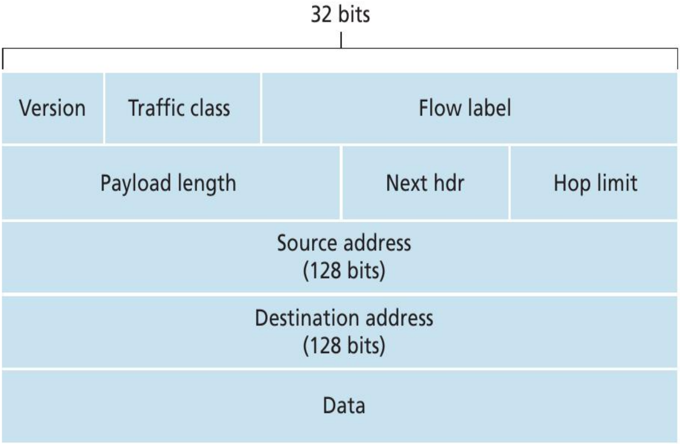
ICMP

ICMP Type	Code	Description
0	0	echo reply (to ping)
3	0	destination network unreachable
3	1	destination host unreachable
3	2	destination protocol unreachable
3	3	destination port unreachable
3	6	destination network unknown
3	7	destination host unknown
4	0	source quench (congestion control)
8	0	echo request
9	0	router advertisement
10	0	router discovery
11	0	TTL expired
12	0	IP header bad

IPv6

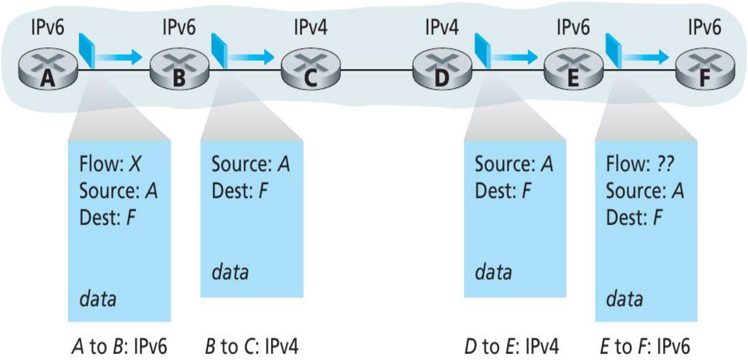
- Internet Engineering Task Force (IETF) developed IPv6
- Expanded addressing capabilities: 128 bits
- A streamlined 40-byte header: fixed length header
- Flow labeling and priority:
  - labeling of packets belonging to particular flows
  - ICMP packets can be given high priority than IP datagrams.
- No fragmentation and reassembly at router
- No checksum computation, and no options field.

IPv6 Datagram

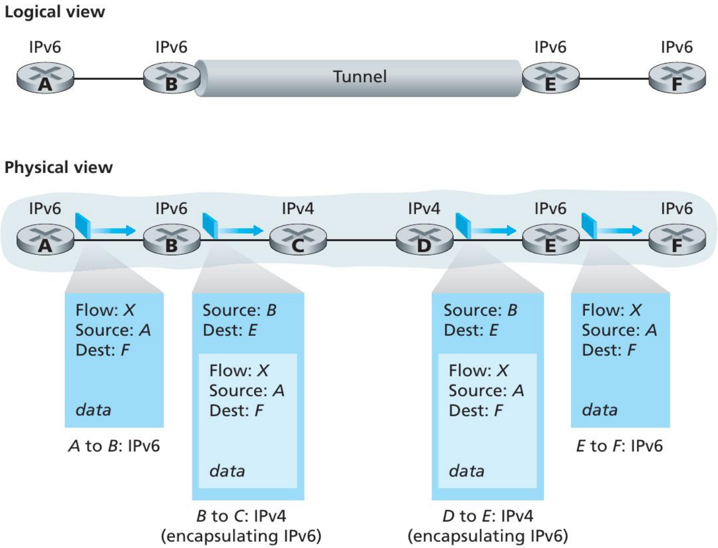


- IPv4 to IPv6
  - Dual-Stack approach
  - Tunneling

Dual-Stack Approach

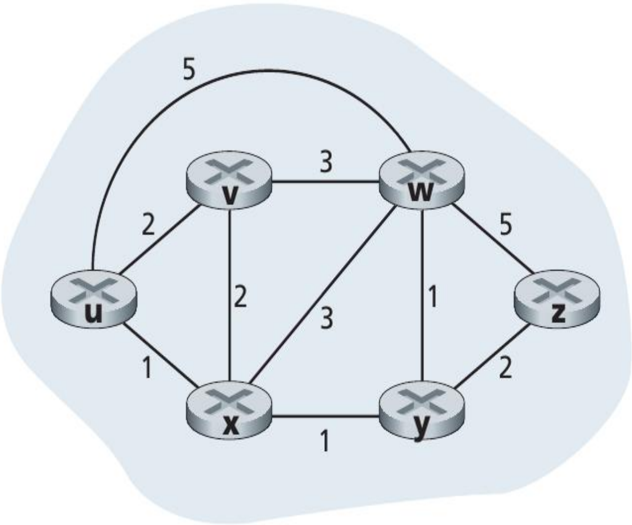


Tunneling


Logical view
IPv6
IPv6
IPv6
IPv6
A
B
Tunnel
E
F
Physical view
IPv6
IPv6
IPv4
IPv4
IPv6
IPv6
A
B
C
D
E
F
Flow: X
Source: A
Dest: F
data
A to B: IPv6
Source: B
Dest: E
Flow: X
Source: A
Dest: F
data
B to C: IPv4
(encapsulating IPv6)
Source: B
Dest: E
Flow: X
Source: A
Dest: F
data
D to E: IPv4
(encapsulating IPv6)
Flow: X
Source: A
Dest: F
data
E to F: IPv6

Routing

Notation



Notation

- We represent a network by an undirected graph $G = (N, E)$
- N is the set of Nodes (routers)
- E is the set of edges connecting nodes (links)
- $c(x, y)$ is the cost of the edge between x and y.
- Cost of a path $(x_1, \ldots, x_p)$ is sum of costs of edges along the path: $c(x_1, x_2) + \cdots + c(x_{p-1}, x_p)$
- We aim to find paths with least cost.

Classification

- Global vs Decentralized:
  - Global routing algorithm: requires global information about links and costs at every router. Also known as Link-State algorithm
  - Decentralized routing algorithm: no node has complete information
- Static vs Dynamic routing
- Load-sensitive vs Load-insensitive routing

Link-State Routing Algorithm

- We study Dijkstra's algorithm
- $D(v)$: cost of the least cost path from source to destination v as of this iteration
- $p(v)$: previous node along the current least cost path from the source to v
- N' : subset of N. If $v \in N$, then least cost path to v from source is definitely known.

LS Algorithm

```
Initialization:
  N' = {u}
  for all nodes v
    if v is a neighbor of u
      then D(v) = c(u,v)
    else D(v) = ∞

Loop
  find w not in N' such that D(w) is a minimum
  add w to N'
  update D(v) for each neighbor v of w and not in N':
        D(v) = min( D(v), D(w) + c(w,v) )
  /* new cost to v is either old cost to v or known
   least path cost to w plus cost from w to v */
until N'= N
```

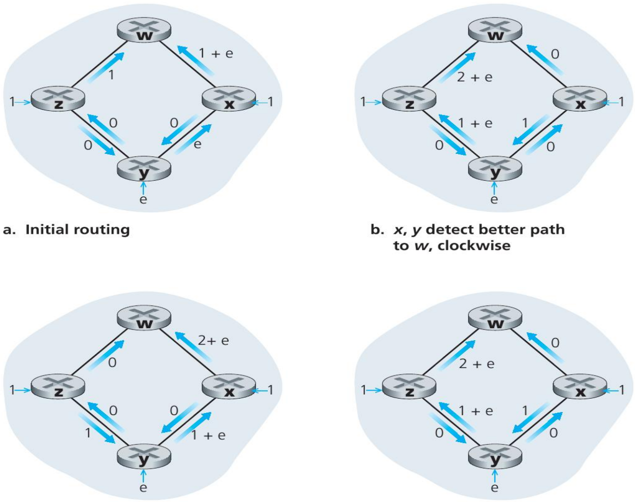
LS Routing Algorithm: Example

step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5	uxyvwz					

LS Routing: Pathology

- Congestion-sensitive routing
- Link-costs are equal to the load carried on the link.
- Link costs are not symmetric: $c(u, v) \neq c(v, u)$
- $c(u, v) = c(v, u)$, if load on the link in both directions is same

LS Routing: Pathology



a. Initial routing

b. ***x, y*** **detect better path to** ***w*****, clockwise**

c. ***x, y, z*** **detect better path to** ***w*****, counterclockwise**

d. ***x, y, z*****, detect better path to** ***w*****, clockwise**

Distance-Vector (DV) Routing Algorithm

- Decentralized,asynchronous
- Iterative process
- $d_x(y)$ denotes cost of least cost path from x to y
- Bellman-Ford equation

$$d_x(y) = \min_v\{c(x, v) + d_v(y)\},$$

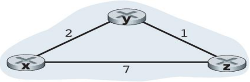
  v is a neighbor of x.
- Each node x maintains the following routing information:
  - For each neighbor v, the cost $c(x, v)$
  - Node x's distance vector, $\mathbf{D}_x = [D_x(y) : y \in N]$
  - Distance vectors of each of its neighbors $\mathbf{D}_v$

DV Algorithm

At each node, *x*:

```
Initialization:
   for all destinations y in N:
      D_x(y) = c(x,y)   /* if y is not a neighbor then c(x,y) = ∞ */
   for each neighbor w
      D_w(y) = ? for all destinations y in N
   for each neighbor w
      send distance vector D_x = [D_x(y): y in N] to w

loop
   wait (until I see a link cost change to some neighbor w or
         until I receive a distance vector from some neighbor w)

   for each y in N:
      D_x(y) = min_v{c(x,v) + D_v(y)}

   if D_x(y) changed for any destination y
      send distance vector D_x = [D_x(y): y in N] to all neighbors

forever
```

DV Example



Node x table

from \ cost to	x	y	z
x	0	2	7
y	∞	∞	∞
z	∞	∞	∞

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	7	1	0

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

Node y table

from \ cost to	x	y	z
x	∞	∞	∞
y	2	0	1
z	∞	∞	∞

from \ cost to	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

Node z table

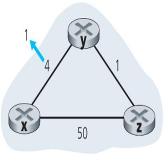
from \ cost to	x	y	z
x	∞	∞	∞
y	∞	∞	∞
z	7	1	0

from \ cost to	x	y	z
x	0	2	7
y	2	0	1
z	3	1	0

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

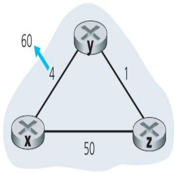
Time

DV Algorithm: Link Cost Changes



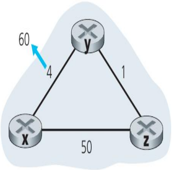
- Focus on distance tables entries of y and z to x
- At t_0, cost has changed to 1 from 4. y updates its table with $D_y(x) = 1$ and informs z
- At t_1, z receives update from y and updates its table $D_z(x) = 2$
- At t_2, y receives update from z and no changes in table.

DV Algorithm: Link Cost Changes



- Before link cost changes:
  $D_y(x) = 4, D_y(z) = 1, D_z(y) = 1, D_z(x) = 5$

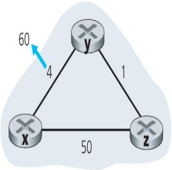
DV Algorithm: Link Cost Changes



- Before link cost changes:
  $D_y(x) = 4, D_y(z) = 1, D_z(y) = 1, D_z(x) = 5$
- At t_0, cost has changed to 60 from 4. y updates its table with

$$D_y(x) = min\{c(y,x) + D_x(x), c(y,z) + D_z(x)\} \tag{1}$$

DV Algorithm: Link Cost Changes



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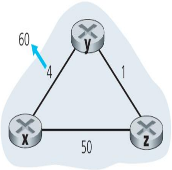
- At t_0, cost has changed to 60 from 4. y updates its table with

$$D_y(x) = min\{c(y,x) + D_x(x), c(y,z) + D_z(x)\} \qquad (1)$$

- $D_y(x) = min\{60 + 0, 1 + 5\} = 6$

DV Algorithm: Link Cost Changes

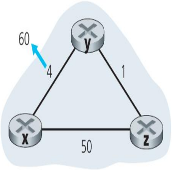


- Before link cost changes:
  $D_y(x) = 4, D_y(z) = 1, D_z(y) = 1, D_z(x) = 5$
- At t_0, cost has changed to 60 from 4. y updates its table with

$$D_y(x) = min\{c(y,x) + D_x(x), c(y,z) + D_z(x)\} \tag{1}$$

- $D_y(x) = min\{60 + 0, 1 + 5\} = 6$
- At t_1, z receives update from y and updates its table
  $D_z(x) = min\{50 + 0, 1 + 6\} = 7$

DV Algorithm: Link Cost Changes



- Before link cost changes:
  $D_y(x) = 4, D_y(z) = 1, D_z(y) = 1, D_z(x) = 5$
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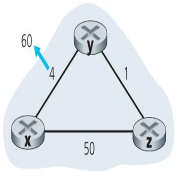
$$D_y(x) = min\{c(y,x) + D_x(x), c(y,z) + D_z(x)\} \qquad (1)$$

- $D_y(x) = min\{60 + 0, 1 + 5\} = 6$
- At t_1, z receives update from y and updates its table
  $D_z(x) = min\{50 + 0, 1 + 6\} = 7$
- At t_2, y receives update from z and updates table as
  $D_y(x) = 8$. and this process repeats.

DV Algorithm: Link Cost Changes



- Before link cost changes:
  $D_y(x) = 4, D_y(z) = 1, D_z(y) = 1, D_z(x) = 5$
- At t_0, cost has changed to 60 from 4. y updates its table with

$$D_y(x) = min\{c(y,x) + D_x(x), c(y,z) + D_z(x)\} \qquad (1)$$

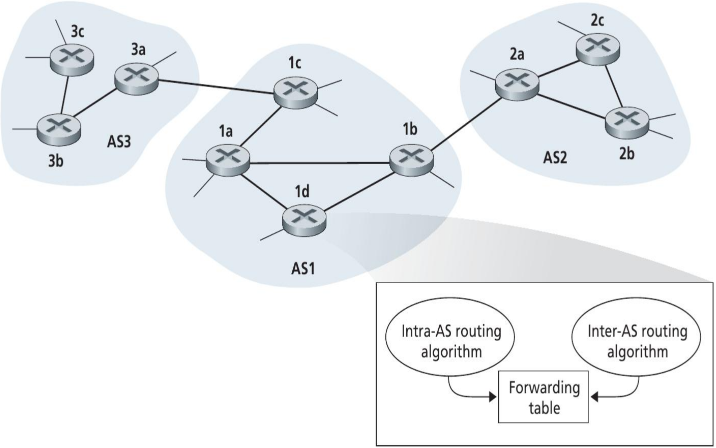
- $D_y(x) = min\{60 + 0, 1 + 5\} = 6$
- At t_1, z receives update from y and updates its table
  $D_z(x) = min\{50 + 0, 1 + 6\} = 7$
- At t_2, y receives update from z and updates table as
  $D_y(x) = 8$. and this process repeats.
- Count-to-infinity!

Poisoned Reverse

- If z routes through y, z will inform y that $D_z(x) = \infty$
- y cannot route to x via z as there is no path!
- When $c(x, y) = 60$, y updates its table with $D_y(x) = 60$!
- After receiving an update z routes to x via direct path and updates its table with $D_z(x) = 50$
- After receiving update from z, y recomputes route to x via z and informs z with $D_y(x) = \infty$ (infact it is 51!)

- Scale: number of routers in internet is very large. Which algorithm to use?
- Administrative autonomy: an organization should be able to run and administer its network as it wishes.
- These problems can be solved by organizing routers into autonomous systems (AS)
- Each AS will have a gateway router

Hierarchical routing



- Hot-potato routing

Routing in Internet

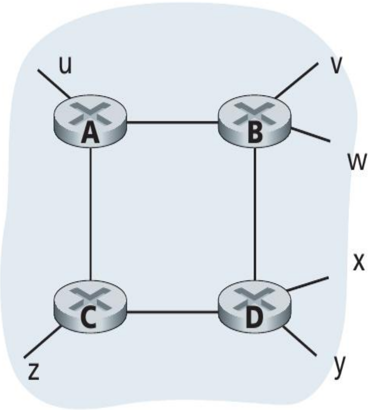
- Intra-AS routing
  - Routing information protocol (RIP): based on DV algorithm
  - Open shortest path first (OSPF): based on LS algorithm
- Inter-AS routing
  - Border Gateway Protocol (BGP)

BGP (Section 4.6.3) is left for self study! Its part of our CCN course

Routing Information Protocol

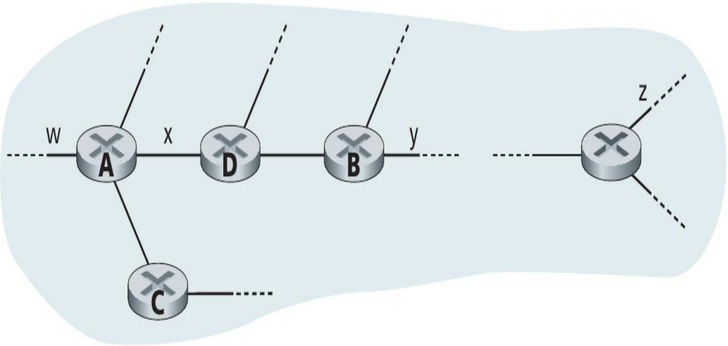
- In RIP, a hop means a subnet
- Cost of a path from source router to destination subnet is the number of hops (subnets) along the path including the destination subnet
- The maximum cost of a path is limited to 15
- RIP uses distance vector algorithm: the routers need to exchange distance vectors or routing updates every 30 seconds
- The RIP response messages or RIP advertisements can contain a list up to 25 destination subnets within the AS.

Example at A



Destination	Hops
u	1
v	2
w	2
x	3
y	3
z	2

A portion of AS



Routing Table at D

Destination Subnet	Next Router	Number of Hops to Destination
w	A	2
y	B	2
z	B	7
x	–	1
....	....	....

Advertisement from A

Destination Subnet	Next Router	Number of Hops to Destination
z	C	4
w	—	1
x	—	1
....	....	....

Updated Routing Table at D

Destination Subnet	Next Router	Number of Hops to Destination
w	A	2
y	B	2
z	A	5
....	....	....

If a router does not hear from its neighbor once every 180 seconds, that neighbor is considered dead. The router propagates about this information to its neighboring routers that are alive!

Open Shortest Path First

- OSPF uses Dijkstra's shortest-path algorihtm
- Choice of link cost is left to the administrator.
- A router broadcasts routing information to all other routers in the AS.
- A router broadcasts link's state whenever there is a change and periodically every 30 seconds.
- OSPF provides features such as security, multiple same-cost paths
- RIP and OSPF are in wide use: regional ISPs use RIP, top-tier ISPs use OSPF.