Lecture 5

The Network Layer

(Computer Communication Networks)

CS 35201

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§5.0.0 Contents

The contents of this lecture have been composed from various resources including those listed at the reference section.

§5.1.0 Glossaries

ABR	Area Border Router 44
AS	Autonomous System 23
BGP	Boarder Gateway Protocol 23, 44, 71
DDoS	Distributed Denial of Service Attack 64
DoS	Denial of Service Attack 64
DV	Distance Vector 44
GSM	Global System for Mobile communication 52
IETF	Internet Engineering Task Force 82
IGP	Interior Gateway Protocol 44
IGRP	Interior Gateway Routing Protocol 42
IP	Internet Protocol 12, 20, 53, 71, 74, 76, 78, 79, 82, 83
IS-IS	Intermediate System to Intermediate System 42
ISP	Internet Service Provider 65
LS	Link State 44
LSP	LinK State Packet 34–36, 39, 41
MPLS	Multi-protocol Label Switching 71, 82, 83
OSPF	Open Shortest Path First 23, 42, 44, 71
PPP	Point-to-Point Protocol 82
RIP	Routing Information Protocol 42
RPF	Router Protocol Filtering 47
RTT	Round Trip Time 35
TCP	Transport Control Protocol 6, 79, 82
TTL	Time-To-Live 35
UDP	User Data Protocol 6, 79
VPN	Virtual Private Network 52

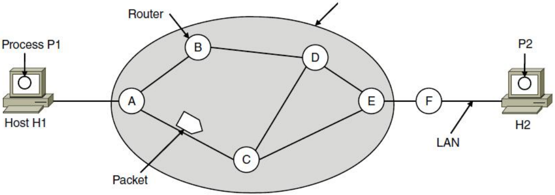
Part I

Overview

§5.2.0 Network Layer Design Issues

1. Store-and-forward packet switching
2. Facilitating getting data from a source to a destination
3. Data link layer move frames only one hop
4. Must know the topology of network and available paths
5. Load balancing $\Rightarrow$ traffic management
6. Services provided to transport layer
7. Implementation of
   - Connection-oriented services
   - Connectionless services
8. Comparison of virtual-circuit and datagram networks

§5.2.1 Store-and-Forward Packet Switching



- Packet Delivery Model
  - A global addressing scheme is needed
- Service Model
  - Connection-less (datagram-based) hat supports
    - Connection-orient transport protocol ⇒ Transport Control Protocol (TCP)
    - Connection-less transport protocol ⇒ User Data Protocol (UDP)
- Best-effort delivery (unreliable service)
  - packets are lost
  - packets are delivered out of order
  - duplicate copies of a packet are delivered
  - packets can be delayed for a long time

§5.2.2 Services Provided to the Transport Layer

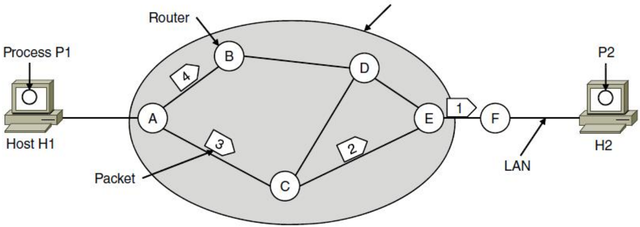
- Services are generally independent of router technology
- Transport layer is shielded from number, type, topology of routers
- Network addresses available to transport layer use uniform numbering plan

Two Implementation Techniques

1. Virtual circuits:
   - The complete route is set up in advance
2. Datagrams
   - Each is routed independently
   - Route is determined on the fly
     - They hop from router to router

§5.2.3 Implementation of Connectionless Service

Routing within a datagram network



A's table (initially)

A	⊠
B	B
C	C
D	B
E	C
F	C

Dest. Line

A's table (later)

A	⊠
B	B
C	C
D	B
E	D
F	D

C's table

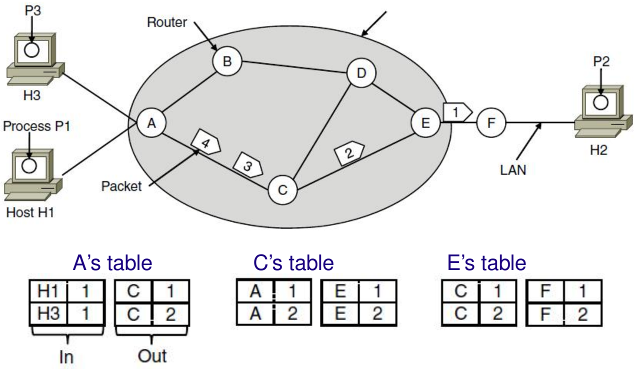
A	A
B	A
C	⊠
D	E
E	E
F	E

E's table

A	C
B	D
C	C
D	D
E	⊠
F	F

§5.2.4 Implementation of Connection-Oriented Service

Routing within a virtual-circuit network



Two connections:

H3-A-C-E-F-H2 ⇒ 1A1C1E1F1 ⇒ label switching

H1-A-C-E-F-H2 ⇒ 1A2C1E1F1   2 circuits/channels between A and C

§5.2.5 Virtual-Circuit vs. Datagram Networks

Issue	Datagram network	Virtual-circuit network
Circuit setup	Not needed	Required
Addressing	Each packet contains the full source and destination address	Each packet contains a short VC number
State information	Routers do not hold state information about connections	Each VC requires router table space per connection
Routing	Each packet is routed independently	Route chosen when VC is set up; all packets follow it
Effect of router failures	None, except for packets lost during the crash	All VCs that passed through the failed router are terminated
Quality of service	Difficult	Easy if enough resources can be allocated in advance for each VC
Congestion control	Difficult	Easy if enough resources can be allocated in advance for each VC

Part II

Routing, Forwarding, Flooding

§5.3.0 Routing I

- Routing tables carry
  - Internet Protocol (IP) addresses to get to distant networks
  - IP addresses to get to local hosts
- Lookup table is used for incoming IP packets
- If the network is not present, the packet is forwarded to a default router with more extensive table
- Each router only has to keep track of other networks and local hosts, not network pairs, reducing table size

Forwarding versus Routing

- **Forwarding:** selects an output port based on destination address and routing table
- **Routing:** process by which routing table is built

§5.3.0 Routing II

- Process of finding a path from a Src to a Dst
- Issues
  - What route should you take?
  - Does a shorter route exist?
  - What if a link along the route goes down?
  - What if you are on a mobile wireless link?

- A routing protocol sets up a routing table in routers switch controllers
- A node makes a local choice depending on global topology
  - This is a fundamental problem
- Other problems
  - How to make correct local decisions?
    - Each router must know something about global states
      inherently large ⇓
      dynamic ⇓
      hard to collect ⇓
  - Routing protocol must intelligently deduce relevant information

§5.3.1 Routing Objectives

- Minimize routing table space for
  - fast look up
  - less to exchange
- Minimize the number and frequency of messages
- Avoid black holes, loops and oscillations
- Use optimal paths
- Factors:
  - Static: topology
  - Dynamic: load

§5.3.2 Low Cost Routing

- Two major approaches
  - Distance Vector: Bellman-Ford Algorithm
    - Each router sends a vector of distances to its neighbors
    - Global information to local neighbors
  - Link State: Dijkstra -Ford Algorithm
    - Each router sends a vector of distances to all nodes
    - Local neighbor information to global nodes
    - $\Rightarrow$ Internet approach
- Both assume router knows
  - address of each neighbor
  - cost of reaching each neighbor
- Both allow a router to determine global routing information by talking to its neighbors

§5.4.0 Routing Algorithms

1. Optimality principle
2. Shortest path algorithm
3. Flooding
4. Distance vector routing
5. Link state routing
6. Routing in ad hoc networks
7. Broadcast routing
8. Multicast routing
9. Anycast routing
10. Routing for mobile hosts
11. Routing in ad hoc networks

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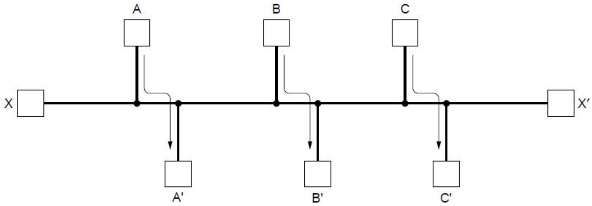
§5.4.1 Fairness vs. Efficiency

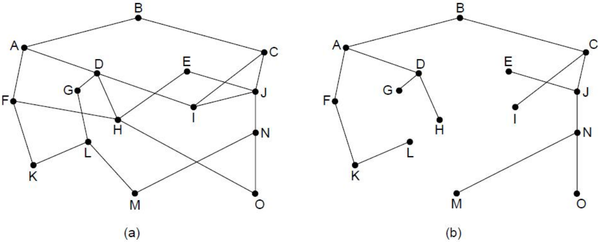
100% efficient, but unfair *Why?*



- X to X' is restricted (blocked) by other connections
- Routing is topology-sensitive

§5.4.2 The Optimality Principle

- Routers should cooperate to find the best routes between all pairs of stations
- All optimal routes from station A to other stations in the network, jointly constitute a sink tree

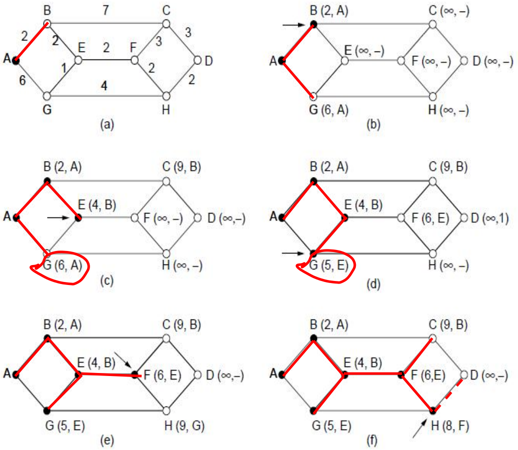


- Routers have to collaborate to build the sink tree for each source station

§5.4.3 Shortest Path Algorithm

Dijkstra's Algorithm

- Labels on the arcs represent the cost (e.g., distance, delay,, etc.)
- It select a newly reachable node at the lowest cost $O(N)$
  - Creates an edge of the tree



- The first five steps used to find the shortest path from A to D. The arrows indicate the working node

§5.5.0 Flooding I

- Forward an incoming packet across every outgoing line
  - Except the one it came in through
- Problem: how to avoid cycling? ⇒ drowning by packets?

Anti-cycling

1. Use a hop counter ⇒ IP does that
   - After a packet has been forwarded across N routers, it is discarded
   - How to find the right hop count? ⇒ network diameter
2. Be sure to forward a packet only once ⇒ avoid directed cycles
   - This requires sequence numbers per source router
   - Each router keeps track of the last sequence number per source router
   - Not scalable
3. Flood selectively
   - Only in the direction that makes sense
   - Requires some knowledge of network topology

§5.5.0 Flooding II

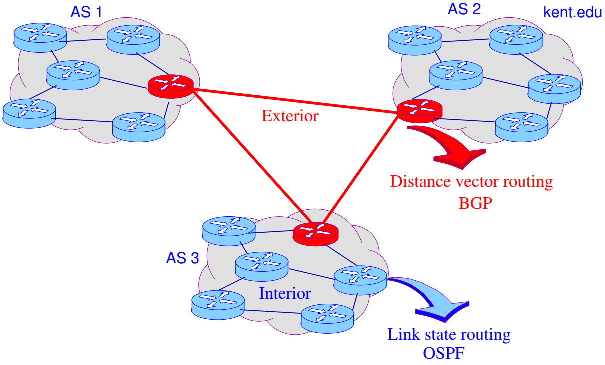
- Flooding always chooses the shortest path *Why?*
  - Because all path are explored in parallel
  - The overhead grows significantly $\Downarrow$
- Flooding makes sense only when robustness is needed
- Flooding is useful (natural) in wireless networks *Why?*
  - Broadcasting:
    - A message transmitted by a station is received by all other stations in the range
- These protocols are static
  - They do not take the current network load into account
- Dynamic Protocols $\Rightarrow$ Later

1. Distance Vector Routing $\Rightarrow$ Bellman-Ford Algorithm
2. Link State Routing $\Rightarrow$ Dijkstra Algorithm

Part III

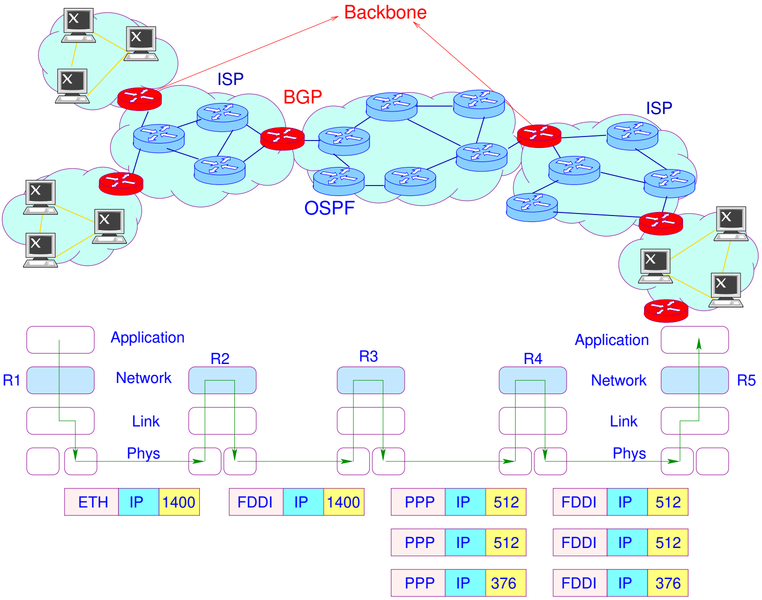
Internet Infrastructure

§5.6.0 Internet Infrastructure



- Within Autonomous Systems (ASs)
  ⇒ use Link Sate (Open Shortest Path First (OSPF))
- Between ASs ⇒ use Distance Vector (Boarder Gateway Protocol (BGP))

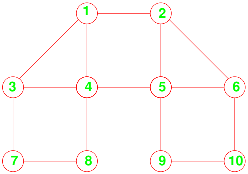
§5.7.0 Internet Routing



§5.7.1 Distance Vector Routing I

1. A node receives distance vectors (cost) from neighbors
   - Nodes tell neighbors the best way to get to other nodes
2. The node updates its distance (cost) to the destinations
3. The node advertises this information to its neighbors

- Features
  - Distributed algorithm
  - Adapts to traffic changes and failures



Routing table for Node 4

Dst	Next hop	Dst	Next hop
1	1	7	3
2	5	8	8
3	3	9	5
5	5	10	5
6	5		

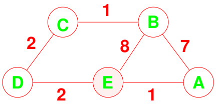
Why Does it Work?

- Each node knows its cost to its neighbors
- This information is spread to its neighbors
- Subsequent dissemination spreads the truth one hop at a time
- Eventually, the information is incorporated into routing tables

§5.7.1 Distance Vector Routing II

Distance Vector Routing Algorithm (Bellman-Ford)

- Iterative
  - Continues until no nodes exchange information
  - Self-terminating $\Rightarrow$ no stopping mechanism
- Asynchronous $\Rightarrow$ no lock step
- Distributed
  - Each node communicates only with its neighbors to find new routes



		via	
Src E	**A**	**B**	**D**
Dst A	1	14*	5*
B	7*	8	5
C	6*	9	4
D	4*	11	2

* loop

- For node E — d(X,Y,Z) means distance from X to Y via Z
  - d(E,A,A)=EA(1) or d(E,A,B)=EBCDEA(14*) or d(E,A,D) = EDEA (5*)
  - d(E,B,A)=EAEDCB(7*) or d(E,B,B)=EB(8) or d(E,B,D) = EDCB(5)
  - d(E,C,A)=EAEDC(6*) or d(E,C,B)=EBC(9) or d(E,C,D)=EDC(4)
  - d(E,D,A)=EAED(4*) or d(E,D,B)=EBCD(11) or d(E,D,D)=ED(2)
- Why loops $\Rightarrow$ sometimes lower cost $\Rightarrow$ EAED (4) $<$ EBCD(11)

§5.7.1 Distance Vector Routing III

Distance Vector ⇒ Routing Table

Src E		via A	via B	via D
Dst	A	1	14	5
	B	7	8	5
	C	6	9	4
	D	4	11	2

Routing table for E

Src E		Cost
Dst	A	1
	B	5
	C	4
	D	2

E shares this table wit its neighbots

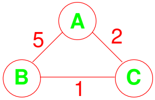
- Routing table is updated if least cost path to any destination has changed

Distance Vector Algorithm (Bellman Ford)

For all nodes, X

1. Initialization: For all adjacent node Y,
   - d(X,Y) = ∞
2. For all destination Z,
   - Advertise Min d(Z,Y) to each neighbor

§5.7.2 Distance Vector Example I



Exchange tables (distance vectors)

A	B	C
B	5	∞
C	∞	2

B	A	C
A	5	∞
C	∞	1

C	A	B
A	2	∞
B	∞	1

A finds BC=1, CB=1 ⇒ B finds CA=2, AC=2 ⇒ C finds AB=5, BA=5

A	B	C
B	5	*3*
C	6	*2*

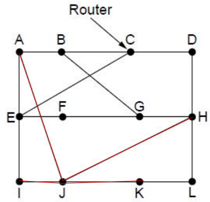
B	A	C
A	5	*3*
C	7	*1*

C	A	B
A	*2*	6
B	7	*1*

➥ *Until no new shortest route found*

§5.7.2 Distance Vector Example II

⇒ Consider node J and its neighbors A, I, H, K



(a)

To	A	I	H	K	New estimated delay from J	Line
A	0	24	20	21	8	A
B	12	36	31	28	20	A
C	25	18	19	36	28	I
D	40	27	8	24	20	H
E	14	7	30	22	17	I
F	23	20	19	40	30	I
G	18	31	6	31	18	H
H	17	20	0	19	12	H
I	21	0	14	22	10	I
J	9	11	7	10	0	–
K	24	22	22	0	6	K
L	29	33	9	9	15	K
	JA delay is 8	JI delay is 10	JH delay is 12	JK delay is 6	New routing table for J	

Vectors received from J's four neighbors

(b)

(a) A network

Link cost =1

(b) J receives input from A, I, H, K, and calculate a new routing table for J.

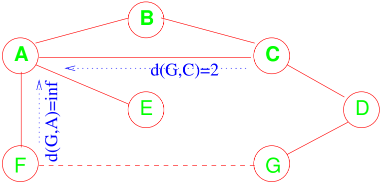
⇒ DV is expensive ⇒ $O(n^3)$ ⇒ Too slow to converge

Why?

§5.7.3 Routing Process in Practice

No Failure

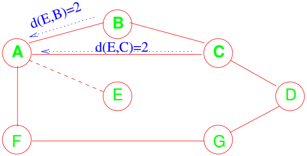
1. F detects that the link to G has failed $\Rightarrow$ d(G,F) = ∞
2. F advertise d(G,F) = ∞ A find d(G,F) = ∞
3. A advertise d(G,A) = ∞
4. A also receives d(G,C) = 2
5. A now advertise d(G,C) = 3
6. F knows d(A,G) = 4



§5.7.4 DV: Count to Infinity Problem I

Link A to E Fails

1. A detects that link to E is failed ⇒ d(E,A) = ∞
   - B, C, D, G, F have not received this information yet
   - C and F tell A that d(E,B) =2 and d(E,C)=2
2. A advertises d(E,A) = ∞
3. A receives d(E,B) =2 and d(E,C)=2
4. B finds and advertises d(E,C) =3
5. A finds and advertises d(E,C) =4
6. C finds and advertises d(E,A) =5
7. A finds and advertises d(E,C) =6 ⇒ this goes on



- A wrongly calculate a new distance to E from inaccurate information received by B and C
- What do you observe?
  - E has only one link to the rest ⇒ deg(E) =1

§5.7.4 DV: Count to Infinity Problem II

Another Scenario (count to infinity

- A suddenly goes down
- When A is down C claims it is away from A by 2 hops via B
  - C propagates this information
  - B and D add 1 to their distance to A $\Rightarrow$ 3
- C finds from B it can reach A in 3 hops, it calculates its distance (4)

Initial build up

A	B	C	D	E	
	•	•	•	•	Initially
	1	•	•	•	After 1 exchange
	1	2	•	•	After 2 exchanges
	1	2	3	•	After 3 exchanges
	1	2	3	4	After 4 exchanges

(a)

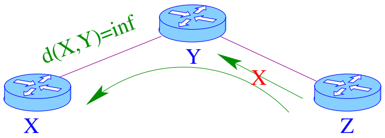
count to infinity propagation

A	B	C	D	E	
	1	2	3	4	Initially
	3	2	3	4	After 1 exchange
	3	4	3	4	After 2 exchanges
	5	4	5	4	After 3 exchanges
	5	6	5	6	After 4 exchanges
	7	6	7	6	After 5 exchanges
	7	8	7	8	After 6 exchanges
		⋮			
	•	•	•	•	

(b)

§5.7.4 A Few Partial Solutions

- Use a relatively small number instead of ∞
  - Diameter of the network
- Split horizon
  - If Z route through Y to get to X
    - Y is an entry in X's routing table
  - Z does not advertise its route to X via Y
    - Y has a lower cost to X than Z



- Split horizon with poison reverse
  - If Z routes through Y to get X
  - It tells Y, d(X,Z) =∞

§5.8.0 Link State Routing I

- Distance vector routing was used in the ARPANET until 1979
- Then it was replaced by Link State Routing
  - Broadcast information to the entire network
  - Let each router calculate its own sink tree
    - Minimum spanning tree
- Broadcast info on the entire network topology to all routers
  - Let each router calculate a sink tree to the other routers

Each router does the following steps:

1. Finds out who its neighbors are and get their network addresses
2. Calculates the cost (time) for getting a packet to a neighbor
3. Constructs a LinK State Packet (LSP) telling all it has just learned
4. Sends LSP to all other routers (not just neighbors)
5. Runs Dijkstras algorithm locally

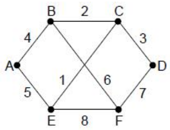
§5.8.0 Link State Routing II

Open Shortest Path First (OSPF)

- A Link State Routing
- Strategy: Send to all nodes (not just neighbors) information about
- directly connected links (not the entire routing table)
- LSP contains the:
  - id of the node that created the LSP
  - cost of link to each directly connected neighbor
  - sequence number (SEQNO)
  - Time-To-Live (TTL) for this packet
- Reliable Flooding:
  - store most recent LSP from each node
  - forward LSP to all nodes but one that sent it
  - generate new LSP periodically; increment SEQNO
  - start SEQNO at 0 when reboot
  - decrement TTL of each stored LSP; discard when TTL=0
- How to measure the delay?
  - Just send an ECHO packet through the interface and measure Round Trip Time (RTT)
- Do we take local load into account?
  - Queuing delay? We should

§5.8.0 Link State Routing III

- This could redirect traffic and cause load oscillations
  - Every node uses flooding to sends its LSP to all other routers



(a)

Link State Packets

A	B	C	D	E	F
Seq.	Seq.	Seq.	Seq.	Seq.	Seq.
Age	Age	Age	Age	Age	Age
B 4	A 4	B 2	C 3	A 5	B 6
E 5	C 2	D 3	F 7	C 1	D 7
	F 6	E 1		F 8	E 8

(b)

(a) A network. (b) The link state packets for this network

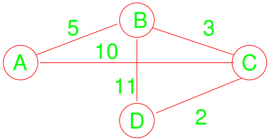
- The combination of Seq. and Age identify recycled LSP packets

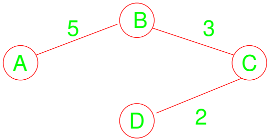
			Send flags			ACK flags			
Source	Seq.	Age	A	C	F	A	C	F	Data
A	21	60	0	1	1	1	0	0	
F	21	60	1	1	0	0	0	1	
E	21	59	0	1	0	1	0	1	
C	20	60	1	0	1	0	1	0	
D	21	59	1	0	0	0	1	1	

§5.8.1 LS Route Calculation (An Example)

Example 5.1 (Dijkstra's Shortest)

Step	Confirmed	Tentative
1.	(D,0,-)	
2.	(D,0,-)	(B,11,B) (C,2,C)
3.	(D,0,-) (C,2,C)	(B,11,B)
4.	(D,0,-) (C,2,C)	(B,5,C) (A,12,C)
5.	(D,0,-) (C,2,C) (B,5,C)	(A,12,C)
6.	(D,0,-) (C,2,C) (B,5,C)	(A,10,C)
7.	(D,0,-) (C,2,C) (B,5,C) (A,10,C)	





Spanning tree

§5.8.2 LS Route Calculation (in theory)

Dijkstra's shortest path algorithm

- Let N denotes the set of nodes in the graph
- $\ell(i, j)$ denotes non-negative cost (weight) for edge (i, j)
- $s \in N$ denotes the source
- M denotes the set of nodes incorporated so far
- $C(n)$ denotes cost of the path from s to node n

1. Initially $M = \{s\}$, the source
2. For each $n \in N - \{s\}$ calculate $C(n) = \ell(s, n)$
3. While $(N \neq M)$
   a. Find w such that $C(w)$ is minimum $\forall w \in N - M$
   b. $M = M \cup \{w\}$
   c. For each $n \in N - M$ update $C(n) = \min\{C(n), \underbrace{C(n) + \ell(w, n))}_{new\ route\ found}\}$

5.38

§5.8.3 Route Calculation (in practice) I

- It is a forward search algorithm
- Each router maintains two lists: Tentative and Confirmed
- Each list contains a set of triples: (Destination, Cost, NextHop)

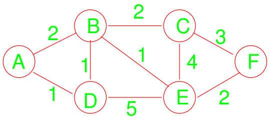
Dijkstra's Shortest Path Algorithm

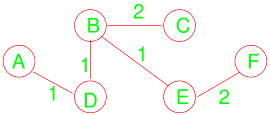
1. Initialized Confirmed with entry for me; cost = 0
2. For the node just added to Confirmed (call it Next) select its LSP
3. For each Neighbor of Next, calculate the Cost to reach this Neighbor as the sum of the cost from me to Next and from Next to Neighbor
   a. If Neighbor is currently in neither Confirmed or Tentative, add (Neighbor, Cost, NextHop) to Tentative, where NextHop is the direction to reach Next
   b. If Neighbor is currently in Tentative and Cost is less that current cost for Neighbor, then replace current entry with (Neighbor, Cost, NextHop), where NextHop is the direction to reach Next
   c. If Tentative is empty, stop. Otherwise, pick entry from Tentative with the lowest cost, move it to Confirmed, and return to step 2.

§5.8.3 Route Calculation (in practice) II

Example 5.2 (Dijkstra's Shortest)

Step	Confirmed	Tentative
1	(A, 0 , –)	(B, 2, B) (D, 1, D)
2	(A, 0 , –) (D, 1 , D)	(B, 2, B) (B, 2, D) (E, 6, D)
3	(A, 0 , –) (D, 1 , D) (B, 2 , D)	(E, 3, D) (C, 4, D)
4	(A, 0 , –) (D, 1 , D) (B, 2 , D) (E, 3 , D)	(C, 7, D) X (C, 4, D) (F, 5, D)
4	(A, 0 , –) (D, 1 , D) (B, 2 , D) (E, 3 , D) (C, 4, D)	(F, 5, D)
5	(A, 0 , –) (D, 1 , D) (B, 2 , D) (E, 3 , D) (C, 4, D) (F, 5, D)	





Spanning tree

§5.9.0 OSPF (Open Shortest Path First)

- Open : publicly available
- Recent Internet standard
- Supports load balancing
- Supports authentication
- Uses Link State algorithm
  - LSP packet dissemination
  - Topology map at each node
  - Route computation using Dijkstra's algorithm
- Advertisements carry one entry per neighbor router
- Advertisements disseminated via flooding

§5.9.1 Distance Vector vs. Link State

Metrics	Distance Vector Routing	Link State Routing
How	Global information (distances) shared with local neighbors	Local information shared with global network
Bandwidth	Less required due to local sharing, small packets, no flooding	More required due to flooding, sending large link state packets
Knowledge	Local knowledge, updates gathered from neighbors	Based on global knowledge, a router has knowledge about the entire network
Algorithm	Uses Bellman Ford Algorithm	Uses Dijkstra Algorithm
Complexity	$O(\mid V \mid \times \mid E \mid)$	$O(\mid E \mid + \mid V \mid \log \mid V \mid)$
Traffic	Less traffic generated	More traffic generated
Convergence	Slow	Fast
Count to ∞	Count to infinity problem	No Count to infinity problem
Looping	Persistent looping problem, could loop forever	No persistent looping problem, only transient loops
Use	Used in Routing Information Protocol (RIP) and Interior Gateway Routing Protocol (IGRP)	Used in OSPF and Intermediate System to Intermediate System (IS-IS) protocol

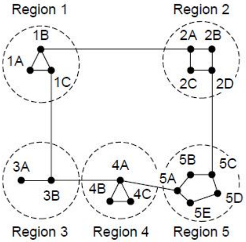
Part IV

Hierarchical Routing

§5.10.0 Hierarchical Routing I

- No routing algorithm discussed so far can scale
  - Link State (LS), BGP, Bellman Ford Algorithm, $O(|V| \times |E|)$
  - Distance Vector (DV), Interior Gateway Protocol (IGP), Dijkstra Algorithm, $O(|E| + |V| \log |V|)$, faster
  - All of them require each router to know about all others
- One solution is to go suboptimal
  1. Regions
  2. Inter Regions
  3. Intera Regions
- Two-level hierarchy: local area, backbone $\Rightarrow$ mostly geographic
  - Each node has detailed area topology; only knows direction (shortest path) to network in other areas
  - LS advertisements only in area
- Area Border Router (ABR): summarize distances to the network in own area
  - Advertise to other ABRs
- Backbone routers: run OSPF; routing limited to backbone
- Boundary routers: connect to other AS's

§5.10.0 Hierarchical Routing II



(a)

Full table for 1A

Dest.	Line	Hops
1A	–	–
1B	1B	1
1C	1C	1
2A	1B	2
2B	1B	3
2C	1B	3
2D	1B	4
3A	1C	3
3B	1C	2
4A	1C	3
4B	1C	4
4C	1C	4
5A	1C	4
5B	1C	5
5C	1B	5
5D	1C	6
5E	1C	5

(b)

Hierarchical table for 1A

Dest.	Line	Hops
1A	–	–
1B	1B	1
1C	1C	1
2	1B	2
3	1C	2
4	1C	3
5	1C	4

(c)

- No optimal routes any more, e.g., 1A $\Rightarrow$ 5C

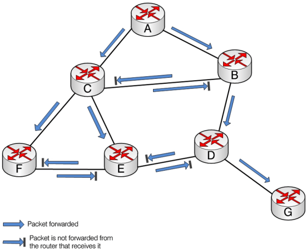
§5.11.0 Broadcast Routing I

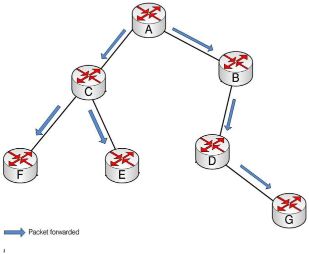
- We want to send a message to (almost) every host on the network
  - This means nearly a complete graph
- Options:
  1. Send the message to each host individually
     - Not really good *Why?*
       - ☆ $O(n)$
  2. Use flooding
     - Acceptable, provided that we can dam the flood
  3. Use multi-destination routing
     - A router checks the destinations, and splits the list when forwarding it across different output lines
     - The message must contain all the destinations
  4. Build a sink tree at the source and use that as your multicast route
     - The sink tree is a spanning tree (as in Dijkstra)
     - The routers need to know the trees

➥ *Reverse Path Forwarding*

§5.12.0 Reverse Path Forwarding (RPF) I

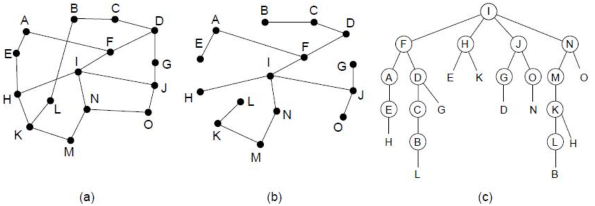
- A technique used in modern routers to ensure loop-free forwarding of multicast packets
  - Also to prevent IP address spoofing in unicast routing
- In standard unicast IP routing, a router forwards packets away from the source to make a spanning (lop free) tree
- In contrast, in Router Protocol Filtering (RPF), every router forwards a broadcast packet to every adjacent router item except the one where it received the packet router $\Rightarrow$ anti-looping
- Organizing tables based on the reverse path, from the receiver back to the root





§5.12.0 Reverse Path Forwarding (RPF) II

- Each router has a simple forwarding algorithm
- **If** multicast datagram received on incoming link on shortest path back to root,
  - **then** flood datagram onto all outgoing links
  - **else** ignore datagram
- Difference between sink tree and reverse path forwarding



(a) A network. (b) Uncast sink tree. (c) Reverse path forwarding

§5.13.0 Multicast Routing I

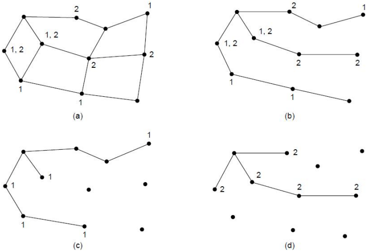
Question 5.1

Suppose that we want to send a message to only a subset of all the nodes in a network. How do we do that?

Answer:

- *We Construct a spanning tree (at each router) for the entire network.*
- *We prune paths to nodes that do not contain members for that group*

Two Multicasting Groups



(a) A network

(b) A spanning tree for the leftmost router

(c) A multicast tree for group 1

(d) A multicast tree for group 2

⇒ example: Chat groups

§5.13.0 Multicast Routing II

Question 5.2

What is the problem with the just presented solution ?

Answer: Scalability! We need to maintain a spanning tree per each broadcasting source

Part V

Mobile Networks

§5.14.0 Routing in Mobile Networks I

Question 5.3

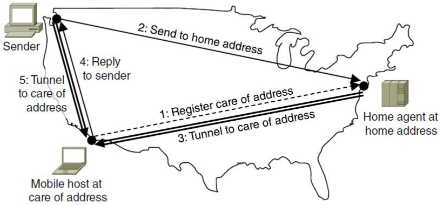
How one can forward packets to nodes that are constantly on the move?

Answer: *Use Home and Foreign agents* How?

1. The mobile hosts register with the foreign agents
2. The foreign agent contacts the mobile host's home agent and says:
   - One of your hosts is over here
3. When a packet is sent to a mobile host, it is routed to the host's home LAN
4. The home agent then forward the message to the foreign agent

- Similar to C/O in postal service
- Similar to Virtual Private Network (VPN)
- Similar protocol also used in Global System for Mobile communication (GSM) to track mobile users

§5.14.0 Routing in Mobile Networks II



- Tunneling: sending an IP packet in an IP packet

§5.15.0 Routing in Mobile Ad Hoc Networks

- Host Mobility + Wireless + Router Mobility
- No fixed infrastructure ⇒ battlefield
- Dynamically changing topology
- Traditional routing are impractical

➥ *Ad Hoc Distance Vector (AoDV)*

- It is an on-demand protocol :
  - Routes are set up only when required
- Represent the network as a graph
  - Two nodes are connected if they can communicate directly

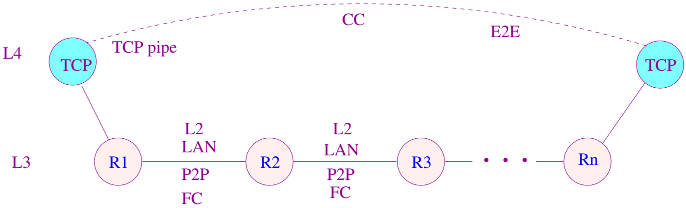
Part VI

Congestion Control

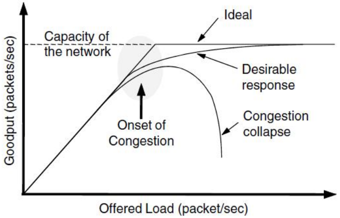
§5.16.0 Congestion Control I

- Traffic burstiness ⇒ high mean/var
- Lack of bandwidth
- Misconfiguration or slow routers
- Link failure
- Bottleneck
- Traffic oscillation due to re-routing
- Significant number of packet drops
- Flooding, flushing, DoS, DDoS,

⋮



§5.16.0 Congestion Control II



$$\rho = \frac{\lambda}{\mu} = \frac{arrival\ \ rate}{departure\ \ rate(capacity)} < 1$$

➥ $\boxed{\rho = 1 \text{ may result in congestion collapse}}$

Approaches to Congestion Control

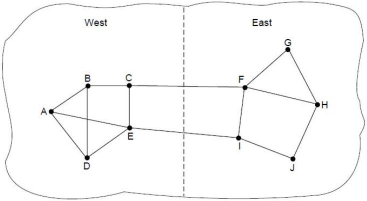
1. Network provisioning
2. Traffic aware routing
3. Admission control
4. Traffic shaping
5. Traffic throttling
6. Load shedding

§5.16.1 Network provisioning

- Resource provisioning
  - Throw resources at the problem
- May solve the problem, but not for long
  - Not scalable

§5.16.2 Traffic-Aware Routing

- Route based on the knowledge of traffic on links
  - May not be available ⇒ dynamic traffic
- Bridged network

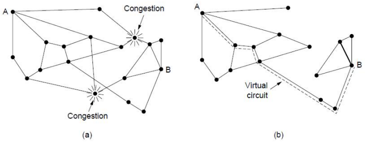


§5.16.3 Admission Control

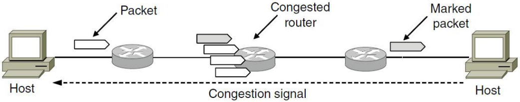
- When you set up a circuit, be sure that congestion can be avoided
- Refuse to set up a virtual circuit if close to congestion
- Similar to refusing an ftp request

§5.16.4 Traffic Throttling

1. Select alternative routes when a part in the network is getting overloaded

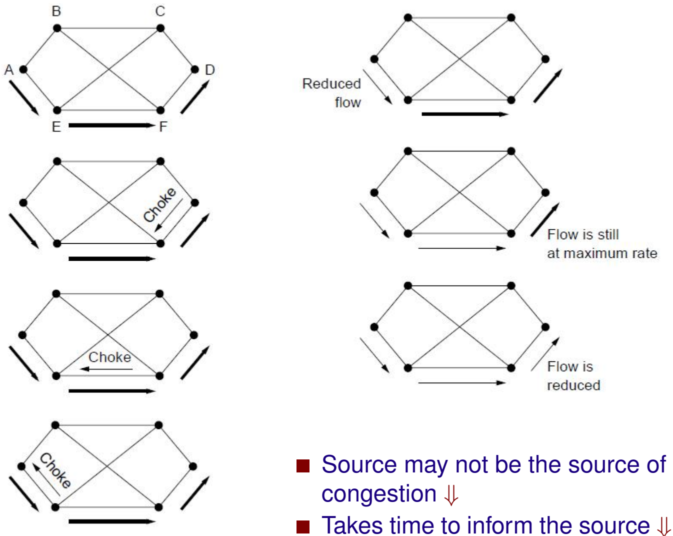


2. Explicit congestion notification



§5.16.5 Load Shedding I

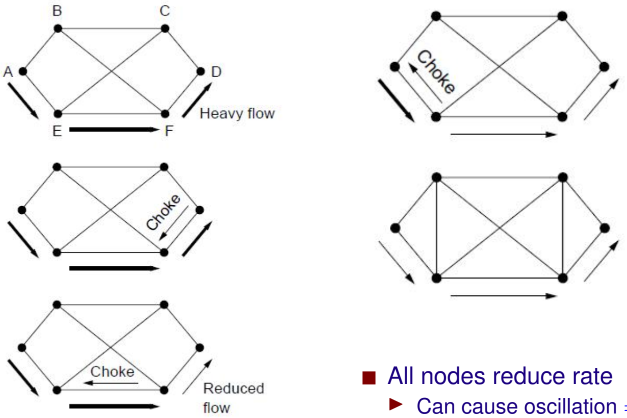
1 A choke packet is used that affects only the source



- Source may not be the source of congestion ⇓
- Takes time to inform the source ⇓
  - Congestion may disappear ⇒ unnecessary choke

§5.16.5 Load Shedding II

2 A choke packet that affects each hop it passes through



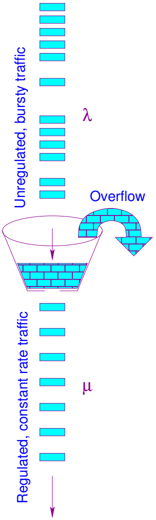
- All nodes reduce rate
  - Can cause oscillation ⇒

§5.16.6 Traffic Shaping

- Bursty traffic is one of the causes of congestion
  - User behavior
  - Fair (round robin) queuing
  - Cumulative Acknowledgements
  - Denial of Service Attack (DoS) and Distributed Denial of Service Attack (DDoS)

Leaky Bucket: Rate and jitter control

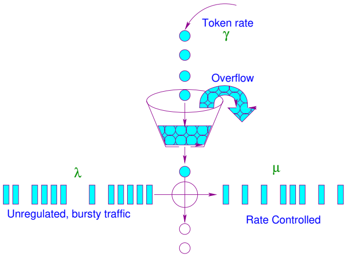
- Regulates/shape bursty traffic
  - Bursty traffic $\Rightarrow$ source of congestion
- Short bursts can be tolerated
  - If the bucket has enough room
- Long burst may overflow the bucket
  - Packets dropped
- What bucket size?
- Average arrival rate (λ) with high variance
- Constant departure rate (μ) with zero variance
- $\mu < \lambda$ when the bucket is full (overflowed)
  - Stable queues have $\mu > \lambda$



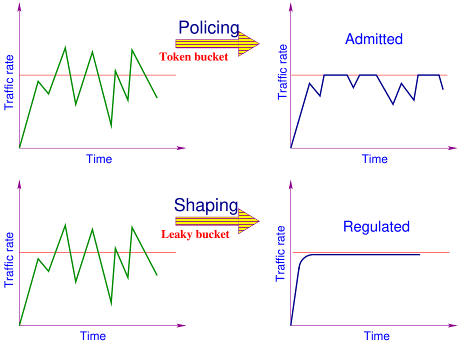
§5.16.7 Traffic Policing (Regulating)

Token Bucket: Rate control

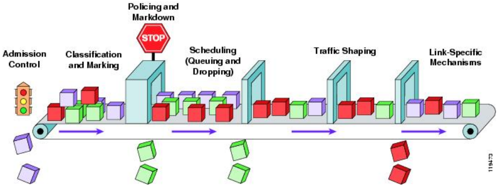
- Tokens are added at a constant rate (γ)
- An arriving packet facing an empty bucket cannot be forwarded
- Internet Service Providers (ISPs) use Token Bucket to allocate bandwidth to customers
  - Works like credit card limit
  - Controls rate but not burstiness
- How to control burstiness (jitter)?
  - Put a leaky bucket behind a token bucket (with a larger rate)
- Which one to control first? $\Rightarrow$ Rate or Shape?



§5.16.8 Traffic Management in Practice



Cisco Approach



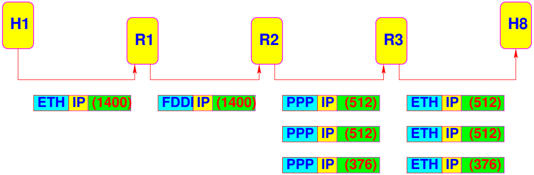
§5.17.0 Quality of Service

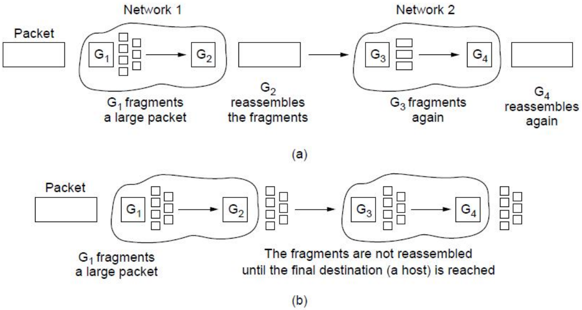
- The needs of each flow are determined by
  1. Reliability ⇒ loss rate
  2. Delay
  3. Jitter) delay variation
  4. Bandwidth
- How stringent the quality-of-service requirements are?

Application	Bandwidth	Delay	Jitter	Loss
Email	Low	Low	Low	Medium
File sharing	High	Low	Low	Medium
Web access	Medium	Medium	Low	Medium
Remote login	Low	Medium	Medium	Medium
Audio on demand	Low	Low	High	Low
Video on demand	High	Low	High	Low
Telephony	Low	High	High	Low
Videoconferencing	High	High	High	Low

- How do we set the network to make them all happy?

§5.18.0 Packet Fragmentation and Reassembly I





(a) Transparent fragmentation. (b) Non-transparent fragmentation

The Network Layer
Congestion Control
Quality of Service
Fragmentation and Reassembly

§5.18.0 Packet Fragmentation and Reassembly II

- Each network has a Max Transmission Unit (MTU)
- Strategy:
  - Fragment when necessary (Datagram $>$ MTU)
  - Try to avoid fragmentation at source host *Why?*
    - re-fragmentation is possible *How?*
  - Fragments are self-contained datagrams
  - Delay reassembly until destination host, *Why?*
  - Do not recover from lost fragments *Why?*

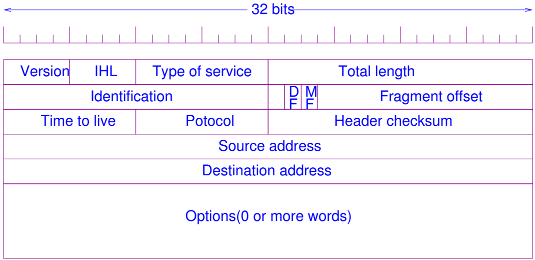
Part VII

IP Network Layer

§5.18.1 The Network Layer in the Internet

1. The IP Version 4 Protocol
2. IP Addresses
3. IP Version 6
4. Internet Control Protocols
5. Label Switching and Multi-protocol Label Switching (MPLS)
6. OSPF: An Interior Gateway Routing Protocol
7. BGP: The Exterior Gateway Routing Protocol
8. Internet Multicasting
9. Mobile IP

§5.18.2 IPv4

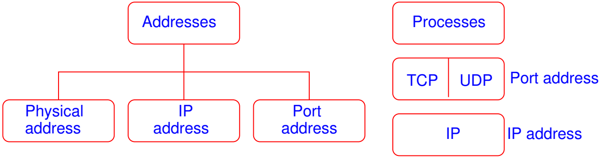


Some of the IP options

Option	Description
Security	Specifies how secret the datagram is
Strict source routing	Gives the complete path to be followed
Loose source routing	Gives a list of routers not to be missed
Record route	Makes each router append its IP address
Timestamp	Makes each router append its address and timestamp

§5.19.0 IP addresses

Address Structure

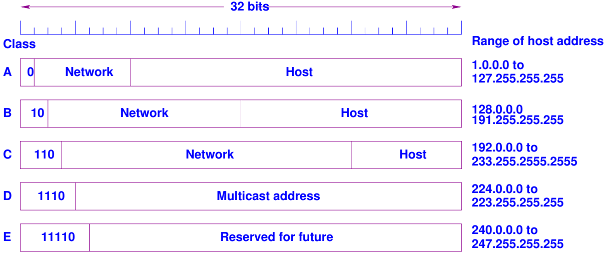


- Properties
  - Should be globally unique
  - Hierarchical: network + host
- Notation/Interpretation
  - Class-based
    - 10.3.2.4
    - 128.96.33.81
    - 192.12.69.77
  - Classless InterDomain Routing (CIDR) notation

§5.19.0 Class-based Addresses

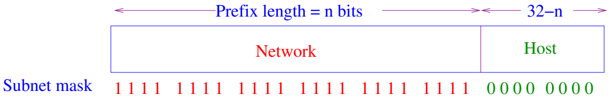
- An IP address contains 32 bits of data
- The leftmost four (4) bits determine its class ⇒ non uniformly

Class	Leftmost bits	Start addresses	Finish addresses
A	0xxx	0.0.0.0	127.255.255.255
B	10xx	128.0.0.0	191.255.255.255
C	110x	192.0.0.0	223.255.255.255
D	1110	224.0.0.0	239.255.255.255
E	1111	240.0.0.0	255.255.255.255



§5.19.0 Classless InterDomain Routing (CIDR) notation

- Variable Length Subnet Masking $\Rightarrow$ x.y.z.t/n



- 192.168.100.14/24 represents the IPv4 address 192.168.100.14 with subnet mask is 255.255.255.0 which has 24 leading 1-bits associated routing prefix, 192.168.100.0
- $n = 1 \Rightarrow$ 0 1000000 00000000 00000000 00000000 $\Rightarrow$ 128 class C
- $n = 6 \Rightarrow$ 0 1100000 00000000 00000000 00000000 $\Rightarrow$ 192 class C

/n	Mask	/n	Mask	/n	Mask	/n	Mask
/1	128.0.0.0	/9	255.128.0.0	/17	255.255.128.0	/25	255.255.255.128
/2	192.0.0.0	/10	255.192.0.0	/18	255.255.192.0	/26	255.255.255.192
/3	224.0.0.0	/11	255.224.0.0	/19	255.255.224.0	/27	255.255.255.224
/4	240.0.0.0	/12	255.240.0.0	/20	255.255.240.0	/28	255.255.255.240
/5	248.0.0.0	/13	255.248.0.0	/21	255.255.248.0	/29	255.255.255.248
/6	252.0.0.0	/14	255.252.0.0	/22	255.255.252.0	/30	255.255.255.252
/7	254.0.0.0	/15	255.254.0.0	/23	255.255.254.0	/31	255.255.255.254
/8	255.0.0.0	/16	255.255.0.0	/24	255.255.255.0	/32	255.255.255.255

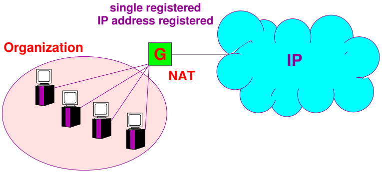
§5.19.0 Private Networks and Subnets

- IP has reserved certain networks for internal use

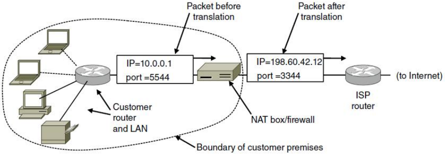
Network address	Default mask
10.0.0.0	255.0.0.0
172.16.0.0	255.240.0.0
192.168.0.0	255.255.0.0

§5.19.0 Network Access Translator (NAT)

- Many local computers with many local addresses, but one public, registered address for the entire organization



- Allows hosts within private (non-routable) addresses to talk to the global Internet.
- Replaces SrcAddr with G for outgoing
- Replaces DstAddr with correct host address
- Uses a translation table to convert G
- The table is a cache

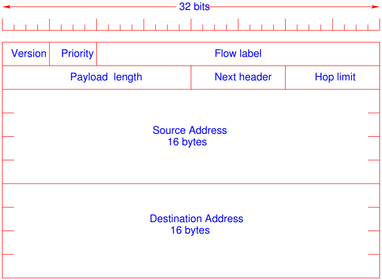


§5.19.1 IPv6 I

- IPv6 Goals
  - Supports billions of hosts (flat or class)
  - Reduces the size of the routing tables
  - Simplifies the protocol $\Rightarrow$ process packets faster
  - Provides better security/authentication/privacy
  - Supports more ToS, particularly for real-time data
  - Aids multicasting by allowing scopes to be specified
  - Supports roaming without changing address
  - Allows the protocol to evolve in the future
  - Permits old/new protocols to coexist
- Major Features
  - 128-bit addresses
  - Multicast
  - Real-time service
  - Authentication and security
  - Auto-configuration
  - End-to-end fragmentation
  - Protocol extensions

§5.19.1 IPv6 II

■ IPv6 Header



The IPv6 fixed header

- 40-byte header, fixed (required)
- Version field: 6 for IPv6 and 4 for IPv4
- Priority field: distinguishes flow controlled packets
  - 0-7: slowing down in the event of congestion
    0: less important; news:1, FTP:4, telnet:6, ..
  - 8-15 are for real-time traffic(audio, video)
- Payload length: # of bytes follow the header
- Next header: tells which of the (currently) six extension headers follows this one.
  If this header is IP header the next header could be TCP, UDP, etc.

§5.19.1 IPv6 III

- Hop limit: keeps packets from living forever
- Source/Destination: 16-byte addresses
  - Addresses with 80 0s are reserved for IPv4
  - Separate prefixes are assigned to different ISPs
- Extension header
  - fragmentation
  - source routing
  - authentication and security
  - other options

Extension Headers

Extension header	Description
Hop-by-hop options	Miscellaneous information for routers
Routing	Full or partial route to follow
Fragmentation	Management of datagram fragments
Authentication	Verification of the sender's identity
Encrypted payload	Information about encrypted contents
Destination options	Additional information for the destination

§5.19.1 IPv6 IV

- IPv6 Addresses
  - Notation: x:x:x:x:x:x:x:x (x = 16-bit hex number)

3	m	n	0	p	125–(m+n+o+p)
010	RegistryID	ProviderID	SubscriberID	SubnetID	InterfaceID

- The hop-by-hop extension header for large datagrams
  - jumbograms, beyond 65,535 bytes
  - No fragmentation

Next header	0	194	4
Jumbo payload length			

- The extension header for routing

Next header	Header extension length	Routing type	Segments left
Type-specific data			

§5.20.0 Label Switching I

- Routers establish connections
- Add a connection-ID to datagrams
  - Routers use the ID to choose outgoing interfaces
- Very closely to virtual circuits *How?*

Question 5.4

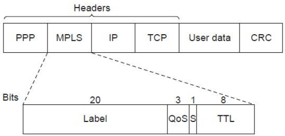
What is the difference between label switching and virtual circuit?

Answer:

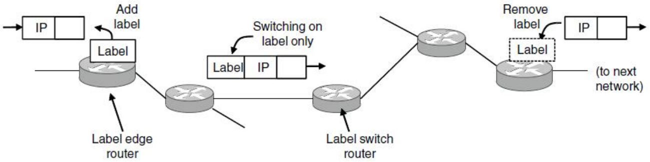
- *In VC, there is a setup phase for each connection*
- *In LS, routes are data (packet) driven*
  - *Label are created by routers at boot time*

- Internet Engineering Task Force (IETF) this under MultiProtocol Label Switching (MLPS)
- Transmitting a TCP segment using IP, MPLS, and Point-to-Point Protocol (PPP)

§5.20.0 Label Switching II



- Forwarding an IP packet through an MPLS network



§5.21.0 References

[Tanenbaum and Wetherall, 2011] Tanenbaum, A. S. and Wetherall, D. J. (2011).
Computer Networks: 5th Edition.
Prentice Hall PTR.

§5.22.0 Suggested Exercises From the Text I

3 Give three examples of protocol parameters that might be negotiated when a connection is set up.

6 Consider the network of Fig. 5-12(a). Distance vector routing is used, and the following vectors have just come in to router C: from B: (5, 0, 8, 12, 6, 2); from D: (16, 12, 6, 0, 9, 10); and from E: (7, 6, 3, 9, 0, 4). The cost of the links from C to B, D, and E, are 6, 3, and 5, respectively. What is C's new routing table? Give both the outgoing line to use and the cost.

7 If costs are recorded as 8-bit numbers in a 50-router network, and distance vectors are exchanged twice a second, how much bandwidth per (full-duplex) line is chewed up by the distributed routing algorithm? Assume that each router has three lines to other routers.

11 Looking at the network of Fig. 5-6, how many packets are generated by a broadcast from B, using
(a) reverse path forwarding?
(b) the sink tree?
Show your work.

18 A token bucket scheme is used for traffic shaping. A new token is put into the bucket every 5 μsec. Each token is good for one short packet, which contains 48 bytes of data. What is the maximum sustainable data rate?

19 A computer on a 6-Mbps network is regulated by a token bucket. The token bucket is filled at a rate of 1 Mbps. It is initially filled to capacity with 8 megabits. How long can the computer transmit at the full 6 Mbps?

21 A router can process 2 million packets/sec. The load offered to it is 1.5 million packets/ sec on average. If a route from source to destination contains 10 routers, how much time is spent being queued and serviced by the router? Hint; queuing delay at each node is $1/(\mu - \lambda)$

28 A network on the Internet has a subnet mask of 255.255.240.0. What is the maximum number of hosts it can handle?

30 A large number of consecutive IP addresses are available starting at 198.16.0.0. Suppose that four organizations, A, B, C, and D, request 4000, 2000, 4000, and 8000 addresses, respectively, and in that order. For each of these, give the first IP address assigned, the last IP address assigned, and the mask in the w.x.y.z/s notation.

§5.22.0 Suggested Exercises From the Text II

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Suggested Exercises From the Text

33 A router has the following (CIDR) entries in its routing table:

Address/mask	Next hop
135.46.56.0/22	Interface 0
135.46.60.0/22	Interface 1
192.53.40.0/23	Router 1
default	Router 2

For each of the following IP addresses, what does the router do if a packet with that address arrives?
(a) 135.46.63.10
(b) 135.46.57.14
(c) 135.46.52.2
(d) 192.53.40.7
(e) 192.53.56.7

38 In IP, the checksum covers only the header and not the data. Why do you suppose this design was chosen?

40 IPv6 uses 16-byte addresses. If a block of 1 million addresses is allocated every picosecond, how long will the addresses last?

41 The Protocol field used in the IPv4 header is not present in the fixed IPv6 header. Why not?

42 When the IPv6 protocol is introduced, does the ARP protocol have to be changed? If so, are the changes conceptual or technical?