Inter-Domain Routing

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Acknowledgements

- Some pictures used in this presentation were obtained from the Internet
- The instructor used the following references
  - Larry L. Peterson and Bruce S. Davie, Computer Networks: A Systems Approach, 5th Edition, Elsevier, 2011
  - Andrew S. Tanenbaum, Computer Networks, 5th Edition, Prentice-Hall, 2010
  - James F. Kurose and Keith W. Ross, Computer Networking: A Top-Down Approach, 5th Ed., Addison Wesley, 2009
  - Larry L. Peterson's (http://www.cs.princeton.edu/~llp/) Computer Networks class web site

Routing vs. Routing

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

Forwarding Table vs. Routing Table

- Forwarding table
  - Used when a packet is being forwarded and must contain enough information to accomplish the forwarding function
  - A row in the forwarding table contains the mapping from a network number to an outgoing interface and some MAC information, such as Ethernet Address of the next hop
- Routing table
  - Built by the routing algorithm as a precursor to build the forwarding table
  - Generally contains mapping from network numbers to next hops

Forwarding Table vs. Routing Table: Example

- Example rows from (a) routing and (b) forwarding tables

(a)

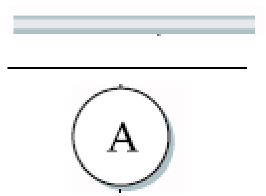
Prefix/Length	Next Hop
18/8	171.69.245.10

(b)

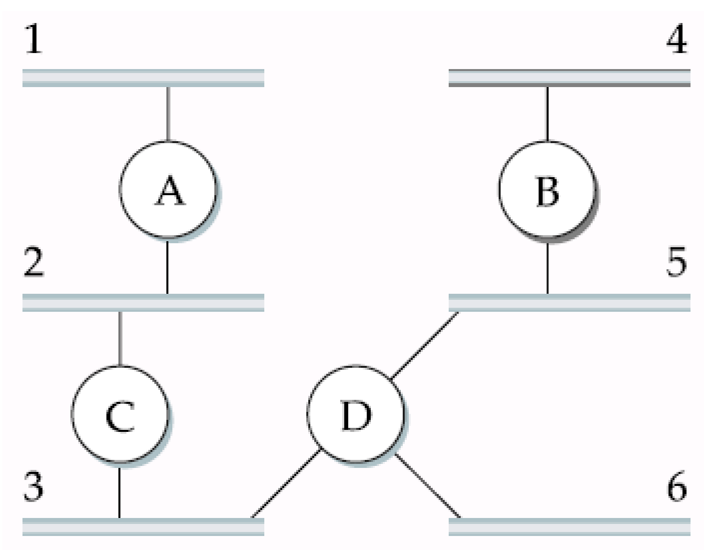
Prefix/Length	Interface	MAC Address
18/8	if0	8:0:2b:e4:b:1:2

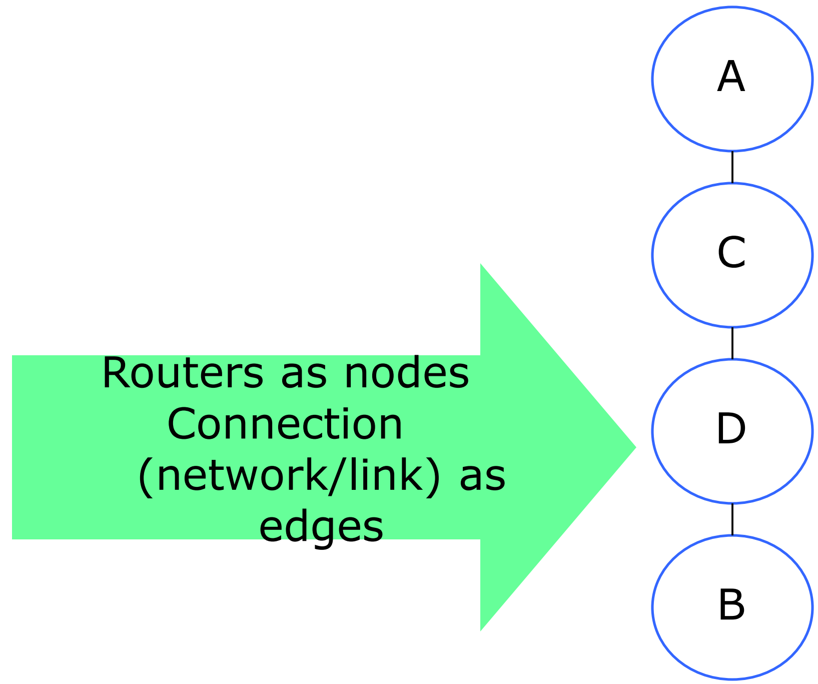
Modeling Internetworks as Graph for Routing

Legends:



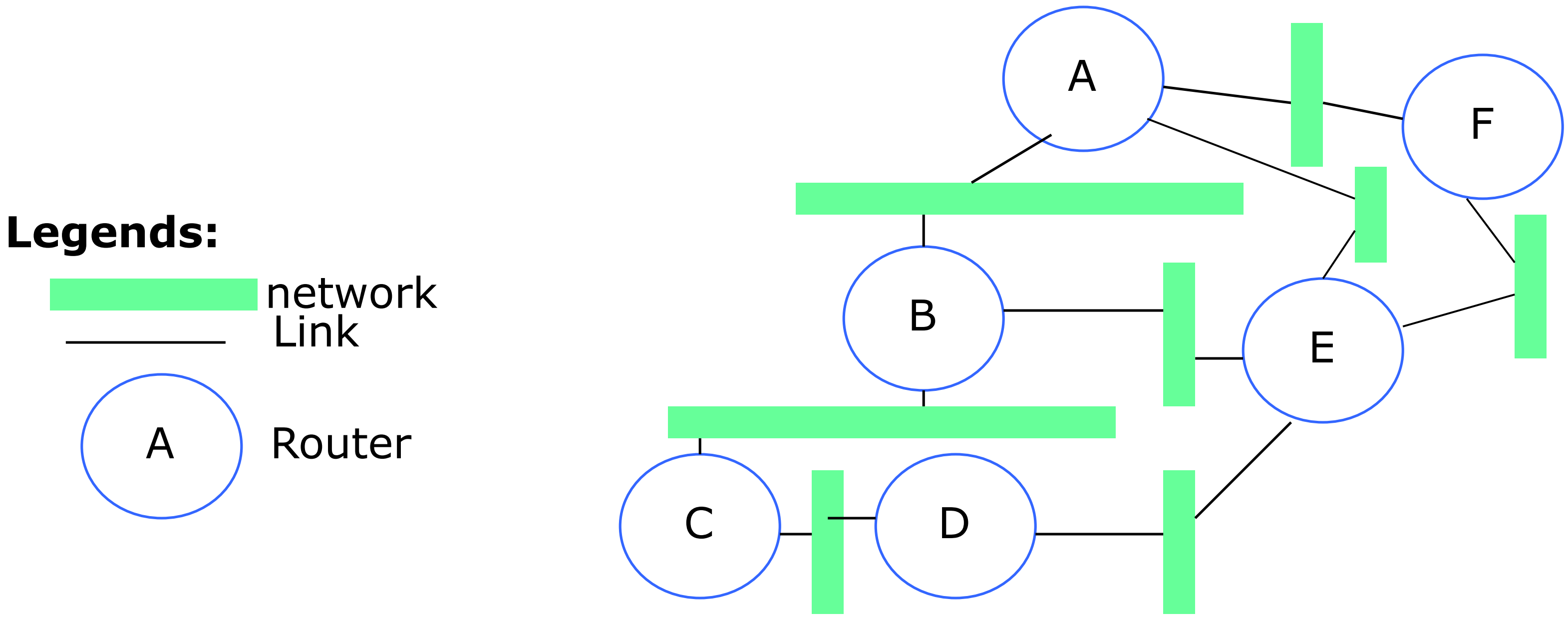
network
link
router





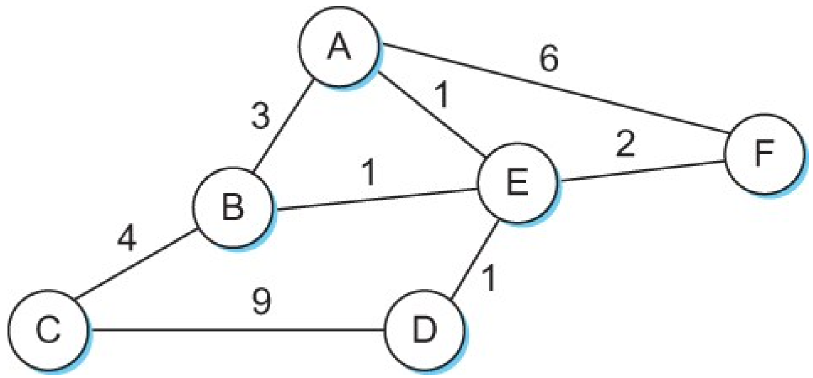
Exercise L12-1

- Use routers as nodes, connections between routers as edges, please construct the graph of the internet shown below



Routing

- Model Network as a Graph



- Routing problem
  - To find the lowest-cost path between any two nodes
  - where the cost of a path equals the sum of the costs of all the edges that make up the path

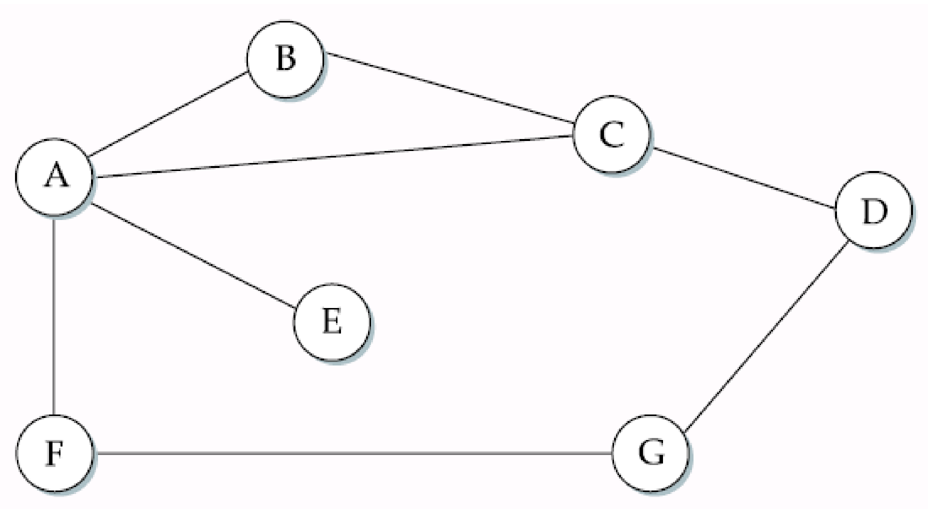
Routing

- Calculate all shortest paths and load them into some nonvolatile storage on each node
  - Such a static approach has several shortcomings
    - It does not deal with node or link failures
    - It does not consider the addition of new nodes or links
    - It implies that edge costs cannot change
- What is the solution?
  - Need a distributed and dynamic protocol
    - Two main classes of protocols
      - Distance Vector
      - Link State

Distance Vector

- Each node constructs a one dimensional array (a vector) containing the “distances” (costs) to all other nodes and distributes that vector to its immediate neighbors
- Starting assumption is that each node knows the cost of the link to each of its directly connected neighbors

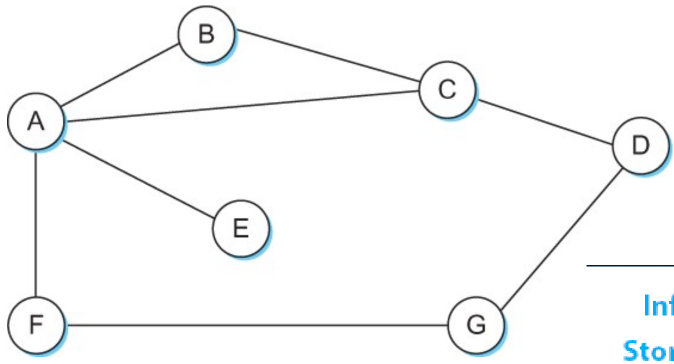
Distance From a Node to Other Nodes



- What is the (shortest) distance from A to B?
- What is the (shortest) distance from A to C?
- What is the (shortest) distance from A to D?

Distance Vector: Example

- Initial distances stored at each node (*global view*)

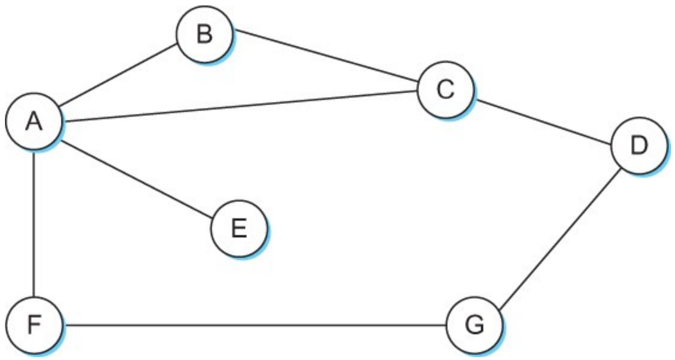


Information Stored at Node	Distance to Reach Node						
	A	B	C	D	E	F	G
A	0	1	1	∞	1	1	∞
B	1	0	1	∞	∞	∞	∞
C	1	1	0	1	∞	∞	∞
D	∞	∞	1	0	∞	∞	1
E	1	∞	∞	∞	0	∞	∞
F	1	∞	∞	∞	∞	0	1
G	∞	∞	∞	1	∞	1	0

- No node has this global view!

Distance Vector: Example of Initial Routing Table

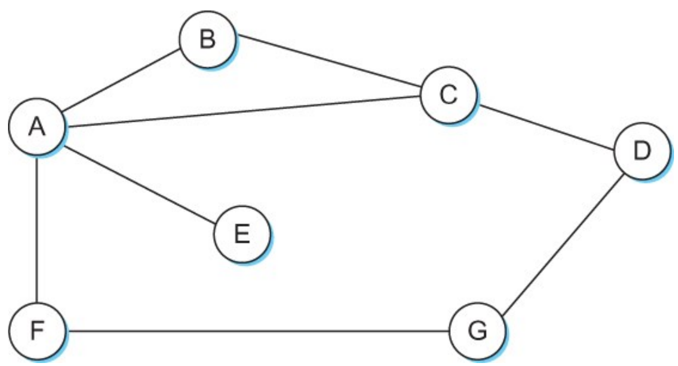
- Initial routing table at node A



Destination	Cost	NextHop
B	1	B
C	1	C
D	∞	—
E	1	E
F	1	F
G	∞	—

Distance Vector: Example of Final Routing Table

- Final routing table at node A

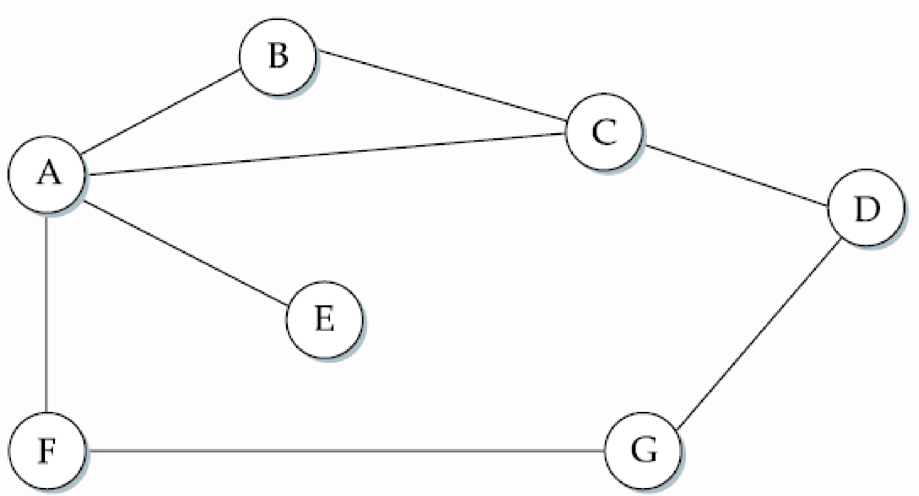


Distance vector: distances from A to the other nodes

Destination	Cost	NextHop
B	1	B
C	1	C
D	2	C
E	1	E
F	1	F
G	2	F

Exercise L12-2

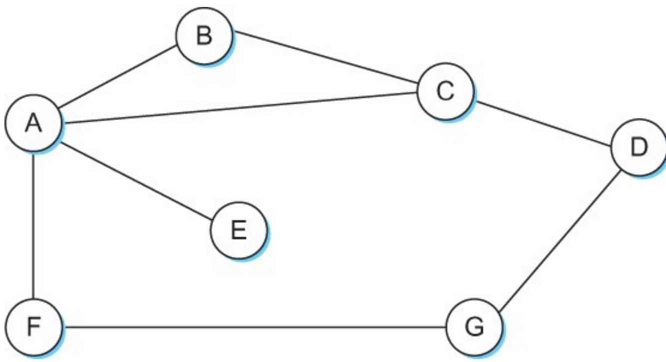
- Given an internetwork below, construct the *initial* routing table for the distance vector routing algorithm at *router C* (by filling the provided table below)



Destination	Cost	Next Hop
A		
B		
D		
E		
F		
G		

Distance Vector: Example

- Final distances stored at each node (*global view*)

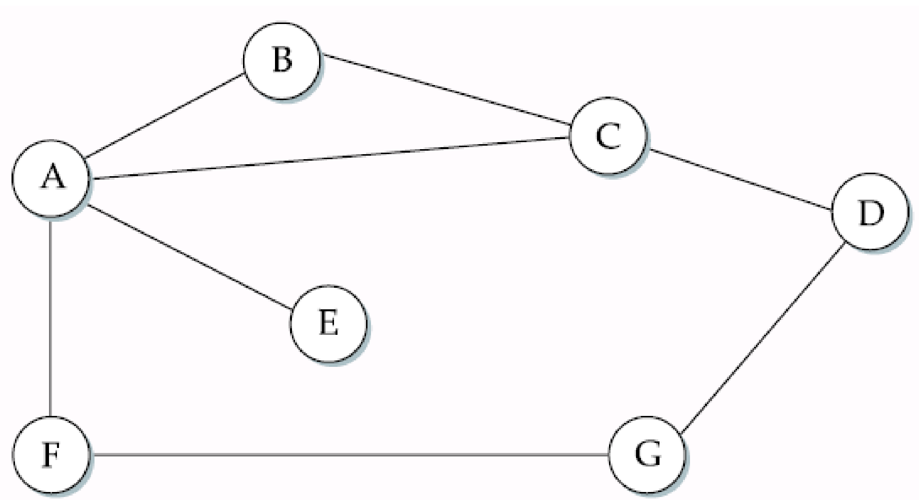


Information Stored at Node	Distance to Reach Node						
	A	B	C	D	E	F	G
A	0	1	1	2	1	1	2
B	1	0	1	2	2	2	3
C	1	1	0	1	2	2	2
D	2	2	1	0	3	2	1
E	1	2	2	3	0	2	3
F	1	2	2	2	2	0	1
G	2	3	2	1	3	1	0

- No node has this global view!

Exercise L12-3

- Given an internetwork below, construct the *final* routing table for the distance vector routing algorithm at *router C* (by filling the provided table below)



Destination	Cost	Next Hop
A		
B		
D		
E		
F		
G		

Distance Vector Routing Algorithm

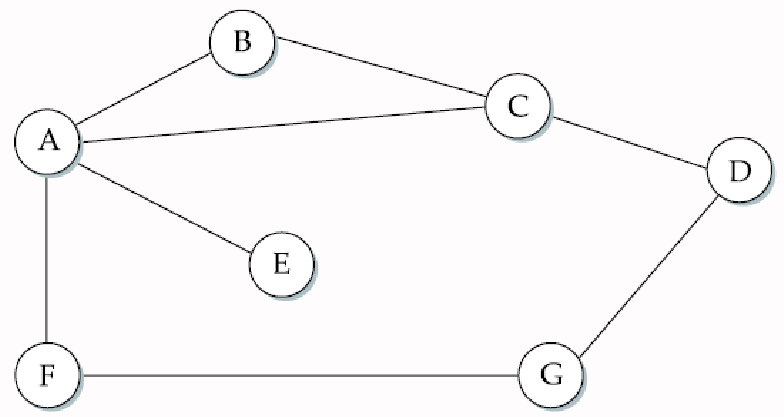
- Sometimes called as *Bellman-Ford* algorithm
- Main idea
  - Every T seconds each router sends its table to its neighbor each router then updates its table based on the new information
- Problems
  - Fast response to good news, but slow response to bad news
  - Also too many messages to update

Distance Vector Routing Algorithm: More Details

- Each node maintains a routing table consisting of a set of triples
  - (Destination, Cost, NextHop)
- Exchange updates directly connected neighbors
  - periodically (on the order of several seconds)
  - whenever table changes (called *triggered update*)
- Each update is a list of pairs:
  - (Destination, Cost): from sending router to destination
  - Update local table if receive a "better" route
    - smaller cost
    - came from next-hop
- Refresh existing routes; delete if they time out

Table Update

- Example: Exchange updates between A and C



- Then A sends an update to C

Destination	Cost
B	1
C	1
D	∞
E	1
F	1
G	∞

C's initial routing table

Destination	Cost	Next Hop
A	1	A
B	1	B
D	1	D
E	∞	-
F	∞	-
G	∞	-

C's updated routing table

Destination	Cost	Next Hop
A	1	A
B	1	B
D	1	D
E	2	A
F	2	A
G	∞	-

Table Update from A at C

Destination	Cost
B	1
C	1
D	∞
E	1
F	1
G	∞

+ 1 =

Destination	Cost	Next Hop
B	2	A
C	2	A
D	∞	A
E	2	A
F	2	A
G	∞	A

Destination	Cost	Next Hop
A	1	A
B	1	B
D	1	D
E	∞	-
F	∞	-
G	∞	-

Destination	Cost	Next Hop
A	1	A
B	1	B
D	1	D
E	2	A
F	2	A
G	∞	-

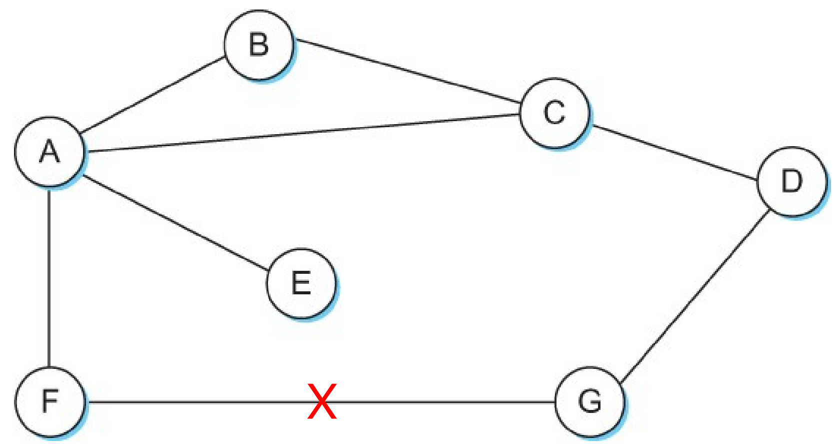
Convergence

- Process of getting consistent routing information to all the nodes
- Desired results: routing tables converges to a stable *global* table (no more changes upon receiving updates from neighbors)

Information Stored at Node	Distance to Reach Node						
	A	B	C	D	E	F	G
A	0	1	1	2	1	1	2
B	1	0	1	2	2	2	3
C	1	1	0	1	2	2	2
D	2	2	1	0	3	2	1
E	1	2	2	3	0	2	3
F	1	2	2	2	2	0	1
G	2	3	2	1	3	1	0

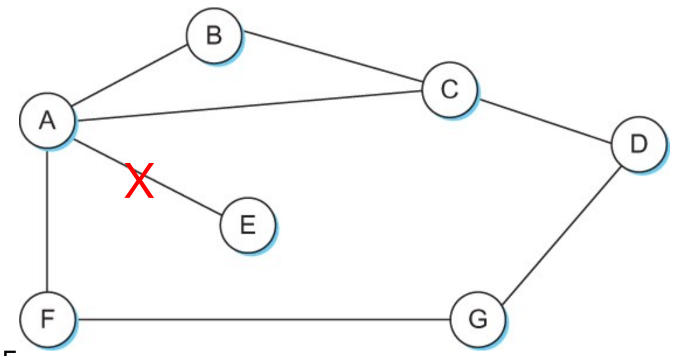
Link Failure: Example

- When a node detects a link failure
  - F detects that link to G has failed
  - F sets distance to G to infinity and sends update to A
  - A sets distance to G to infinity since it uses F to reach G
  - A receives periodic update from C with 2-hop path to G
  - A sets distance to G to 3 and sends update to F
  - F decides it can reach G in 4 hops via A



Count-to-infinity Problem

- Slightly different circumstances can prevent the network from *stabilizing*
  - Suppose the link from A to E goes down
  - In the next round of updates, A advertises a distance of infinity to E, but B and C advertise a distance of 2 to E
  - Depending on the exact timing of events, the following might happen
    - Node B, upon hearing that E can be reached in 2 hops from C, concludes that it can reach E in 3 hops and advertises this to A
    - Node A concludes that it can reach E in 4 hops and advertises this to C
    - Node C concludes that it can reach E in 5 hops; and so on.
    - This cycle stops only when the distances reach some number that is large enough to be considered infinite
    - *called* **count-to-infinity problem**



Count-to-infinity Problem: Solutions

- Use some relatively small number as an approximation of infinity
- For example, the maximum number of hops to get across a certain network is never going to be more than 16
  - Set infinity to 16
  - Stabilize fast, but not working for larger networks
- One technique to improve the time to stabilize routing is called *split horizon*

Split Horizon

- When a node sends a routing update to its neighbors, it does *not* send those routes it learned from each neighbor *back* to that neighbor
- For example, if B has the route (E, 2, A) in its table, then it knows it must have learned this route from A, and so whenever B sends a routing update to A, it does not include the route (E, 2) in that update

Split Horizon with Poison Reverse

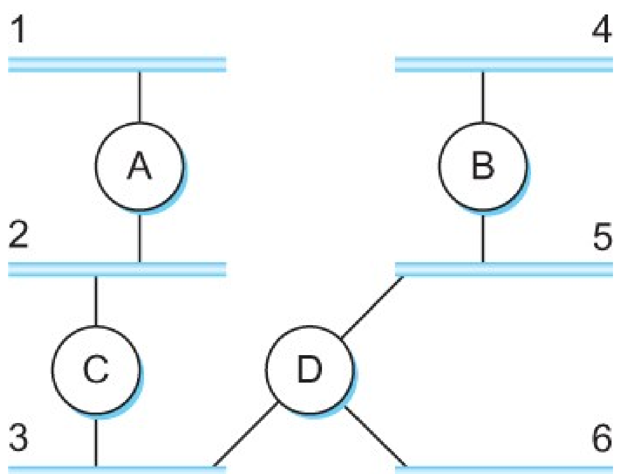
- In a stronger version of split horizon, called *split horizon with poison reverse*
  - B actually sends that back route to A, but it puts negative information in the route to ensure that A will not eventually use B to get to E
  - For example, B sends the route (E, ∞) to A

Routing Information Protocol

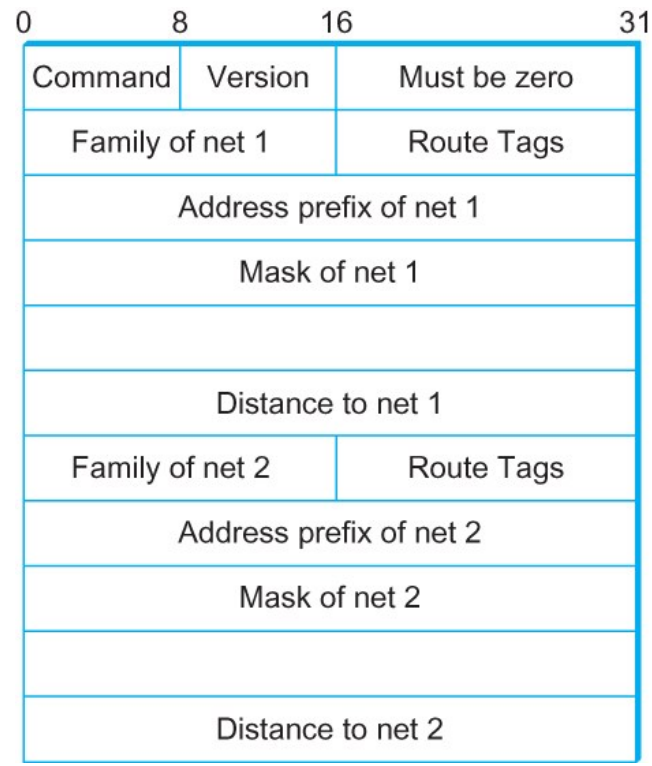
- Routing Information Protocol (RIP)
  - Initially distributed along with BSD Unix
  - Widely used
- Straightforward implementation of distance-vector routing

Routing Information Protocol (RIP)

- Distance: cost (# of routers) of reach a network
  - C → A
    - Network 2 at cost 0; 3 at cost 0
    - Network 5 at cost 1, 4 at 2



Example Network



RIPv2 Packet Format

Link State Routing

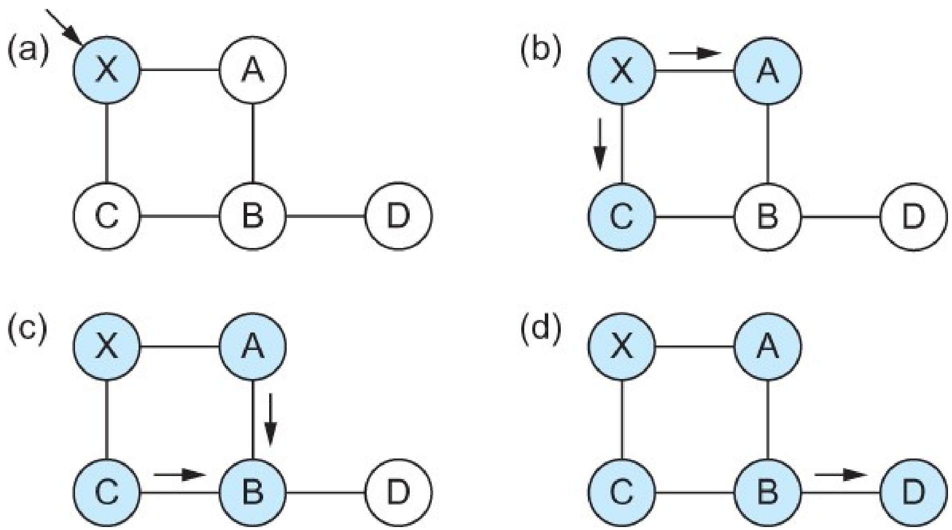
- Strategy: Send to all nodes (not just neighbors) information about directly connected links (not entire routing table).
- Link State Packet (LSP)
  - id of the node that created the LSP
  - cost of link to each directly connected neighbor
  - sequence number (SEQNO)
  - time-to-live (TTL) for this 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

Link State Routing

- Reliable flooding triggered by
  - Timer
  - Topology or link cost change
- increment SEQNO
  - start SEQNO at 0 when reboot
  - SEQNO does not wrap
    - e.g., 64 bits
  - decrement TTL of each stored LSP
- discard when TTL=0

Link State Routing: Example

- Reliable Flooding



- Flooding of link-state packets. (a) LSP arrives at node X; (b) X floods LSP to A and C; (c) A and C flood LSP to B (but not X); (d) flooding is complete

Shortest Path Routing Algorithm

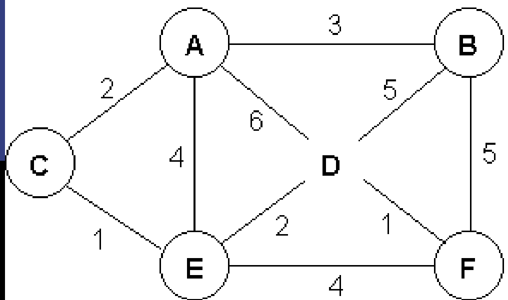
- Dijkstra's Algorithm
  - Assume non-negative link weights
  - N: set of nodes in the graph
  - l(i, j): the non-negative cost associated with the edge between nodes i, j $\in$N and l(i, j) = $\propto$ if no edge connects i and j
  - Let s $\in$N be the starting node which executes the algorithm to find shortest paths to all other nodes in N
  - Two variables used by the algorithm
    - M: set of nodes incorporated so far by the algorithm
    - C(n) : the cost of the path from s to each node n

Shortest Path Routing Algorithm

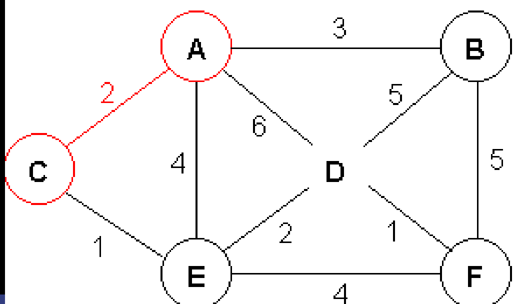
- Dijkstra's Algorithm - Assume non-negative link weights

```
M = {s}
  For each n in N - {s}
     C(n) = l(s, n)
  while ( N ≠ M)
    M = M ∪ {w} such that C(w) is the minimum
                                 for all w in (N-M)
    For each n in (N-M)
            C(n) = MIN (C(n), C(w) + l(w, n))
```

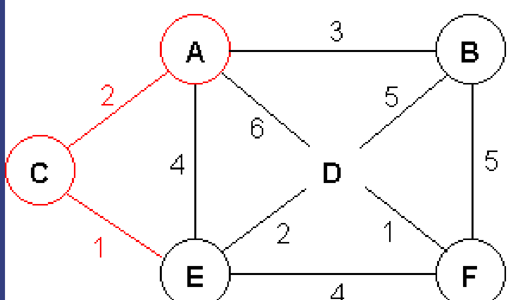
Dijkstra’s shortest path algorithm



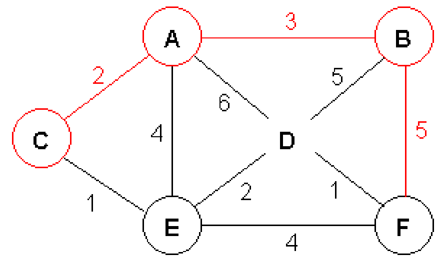
Step	Costs B	C	D	E	F	visited?



Step	Costs B	C	D	E	F	visited?
Init	3	2	6	4	-	C

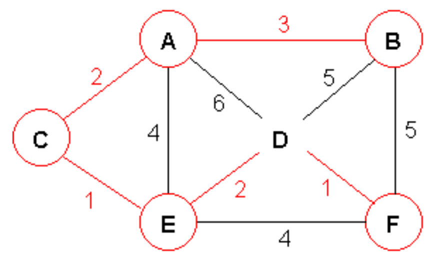


Step	Costs B	C	D	E	F	visited?
Init	3	2	6	4	-	C
1	3	2	6	3	-	



Step	Costs B	C	D	E	F	visited?
Init	3	2	6	4	-	C
1	3	2	6	3	-	B
2	3	2	6	3	8	

. . . . . .

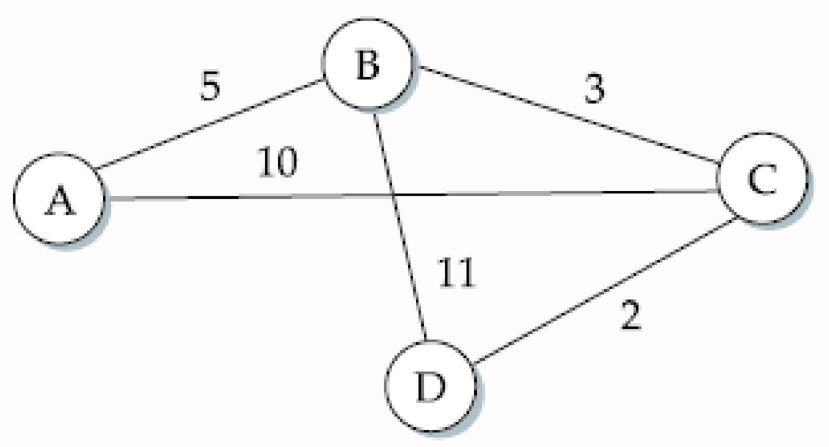


Step	Costs B	C	D	E	F	visited?
Init	3	2	6	4	-	C
1	3	2	6	3	-	B
2	3	2	6	3	8	E
3	3	2	5	3	7	D
4	3	2	5	3	6	F

Jens Brodowski, Animation of Dijkstra’s shortest path algorithm, Available: http://www.animal.ahrgr.de/showAnimationDetails.php3?lang=en&anim=15

Exercise L12-4

- Following the example illustrated and using the Dijkstra's shortest path algorithm, find the shortest path to all the other nodes from node D and show steps



Shortest Path Routing Algorithm

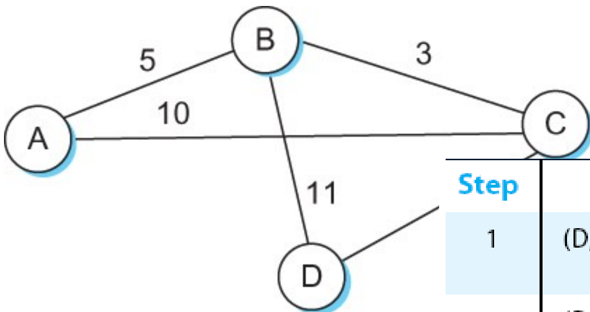
- In practice, each switch computes its routing table directly from the LSPs it has collected using a realization of Dijkstra's algorithm called the *forward search algorithm*
- Specifically each switch maintains two lists, known as **Tentative** and **Confirmed**
- Each of these lists contains a set of entries of the form (Destination, Cost, NextHop)

Shortest Path Routing Algorithm in Linked State Routing

- Each router runs the algorithm
  - Initialize the **Confirmed** list with an entry for myself; this entry has a cost of 0
  - For the node just added to the **Confirmed** list in the previous step, call it node **Next**, select its LSP
  - For each neighbor (Neighbor) of **Next**, calculate the cost (Cost) to reach this Neighbor as the sum of the cost from myself to Next and from Next to Neighbor
    - If Neighbor is currently on neither the **Confirmed** nor the **Tentative** list, then add (Neighbor, Cost, Nexthop) to the **Tentative** list, where Nexthop is the direction I go to reach Next
    - If Neighbor is currently on the **Tentative** list, and the Cost is less than the currently listed cost for the Neighbor, then replace the current entry with (Neighbor, Cost, Nexthop) where Nexthop is the direction I go to reach Next
  - If the **Tentative** list is empty, stop. Otherwise, pick the entry from the **Tentative** list with the lowest cost, move it to the **Confirmed** list, and return to Step 2.

Shortest Path Routing: Example

- Forward search algorithm: building routing table in D from received LSP's



Step	Confirmed	Tentative	Comments
1	(D,0,–)		Since D is the only new member of the confirmed list, look at its LSP.
2	(D,0,–)	(B,11,B) (C,2,C)	D's LSP says we can reach B through B at cost 11, which is better than anything else on either list, so put it on Tentative list; same for C.
3	(D,0,–) (C,2,C)	(B,11,B)	Put lowest-cost member of Tentative (C) onto Confirmed list. Next, examine LSP of newly confirmed member (C).
4	(D,0,–) (C,2,C)	(B,5,C) (A,12,C)	Cost to reach B through C is 5, so replace (B,11,B). C's LSP tells us that we can reach A at cost 12.
5	(D,0,–) (C,2,C) (B,5,C)	(A,12,C)	Move lowest-cost member of Tentative (B) to Confirmed, then look at its LSP.
6	(D,0,–) (C,2,C) (B,5,C)	(A,10,C)	Since we can reach A at cost 5 through B, replace the Tentative entry.
7	(D,0,–) (C,2,C) (B,5,C) (A,10,C)		Move lowest-cost member of Tentative (A) to Confirmed, and we are all done.

Link State in Practice

- Open Shortest Path First Protocol (OSPF)
  - “Open” → open, non-proprietary standard, created under the auspices of the IETF
  - “SPF” → Shortest Path First, alternative name of link-state routing
- Implementation of Link-State Routing with added features
  - Authenticating of routing messages
    - Due to the fact too often some misconfigured hosts decide they can reach every host in the universe at a cost of 0
  - Additional hierarchy
    - Partition domain into areas → increase scalability
  - Load balancing
    - Allows multiple routes to the same place to be assigned the same cost → cause traffic to be distributed evenly over those routes

Open Shortest Path First Protocol

OSPF Header Format

0	8	16	31
Version	Type	Message length	
SourceAddr			
AreaId			
Checksum		Authentication type	
Authentication			

OSPF Link State Advertisement

LS Age			Options	Type=1
Link-state ID				
Advertising router				
LS sequence number				
LS checksum			Length	
0	Flags	0	Number of links	
Link ID				
Link data				
Link type		Num_TOS	Metric	
Optional TOS information				
More links				

Type	Packet name	Protocol function
1	Hello	Discover/maintain neighbors
2	Database Description	Summarize database contents
3	Link State Request	Database download
4	Link State Update	Database update
5	Link State Ack	Flooding acknowledgment

Metrics

- Original ARPANET metric
  - measures number of packets enqueued on each link
  - took neither latency or bandwidth into consideration
- New ARPANET metric
  - stamp each incoming packet with its arrival time (AT)
  - record departure time (DT)
  - when link-level ACK arrives, compute
- Delay = (DT - AT) + Transmit + Latency
  - if timeout, reset DT to departure time for retransmission
  - link cost = average delay over some time period
- Fine Tuning
  - compressed dynamic range
  - replaced Delay with link utilization

Summary

- Distance Vector
  - Algorithm
  - Routing Information Protocol (RIP)
- Link State
  - Algorithm
  - Open Shortest Path First Protocol (OSPF)
- Metrics
  - How to measure link cost?