Lecture 8:
Routing

CS/ECE 438: Communication Networks

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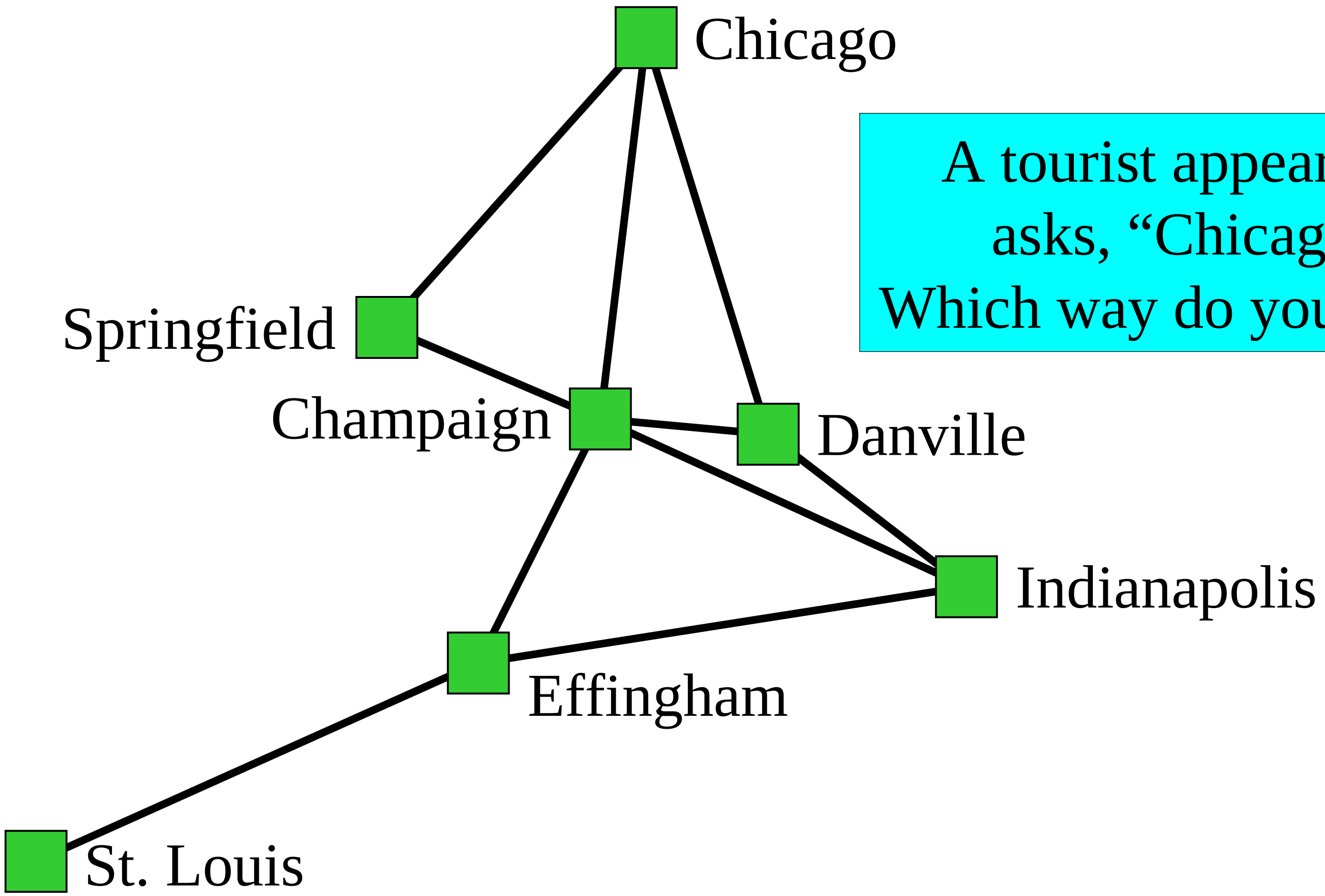
Routing



A tourist appears and asks, “Chicago?”
Which way do you point?

Routing

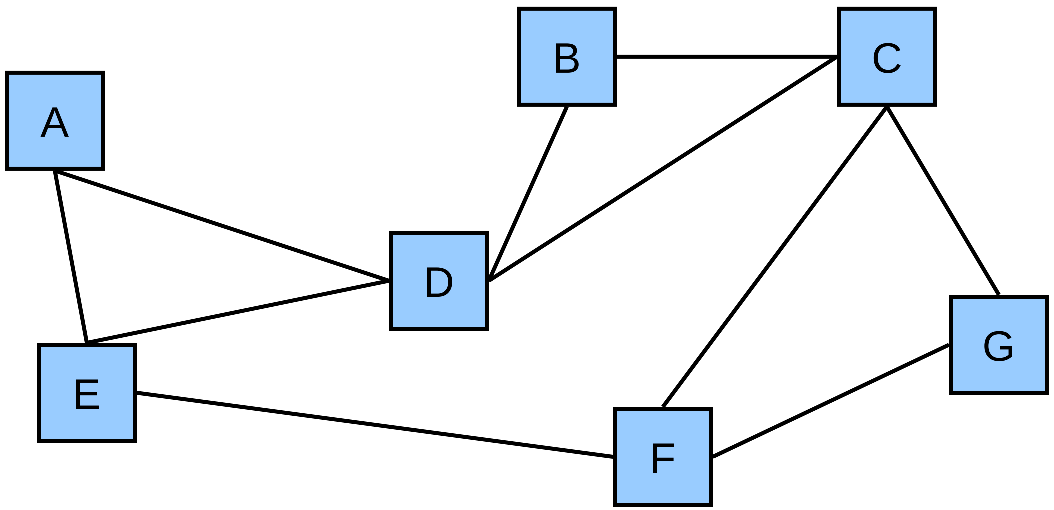
- Definition
  - The task of constructing and maintaining forwarding information (in hosts or routers)
- Goals
  - Capture the notion of “best” routes
  - Propagate changes effectively
  - Require limited information exchange
- Conceptually
  - A network can be represented as a graph where each host/router is a node and each physical connection is a link

Routing

- Factors
  - Network topology can change
  - Traffic conditions can change
- Design elements
  - Performance criteria
  - Decision time and place
  - Information source
- Goals
  - Correctness
  - Simplicity
  - Robustness
  - Fairness
  - High throughput
  - Low end-to-end latency

Routing: Ideal Approach

- Maintain information about each link
- Calculate fastest path between each directed pair



For each direction, maintain:

•Bandwidth

•Latency

•Queueing delay

Routing: Ideal Approach

- Problems
  - Unbounded amount of information
  - Queueing delay can change rapidly
  - Graph connectivity can change rapidly
- Solution
  - Dynamic
    - Periodically recalculate routes
  - Distributed
    - No single point of failure
    - Reduced computation per node
  - Abstract Metric
    - “Distance” may combine many factors
    - Use heuristics

Routing Overview

- Algorithms
  - Static shortest path algorithms
    - Bellman-Ford
      - Based on local iterations
    - Dijkstra's algorithm
      - Build tree from source
  - Distributed, dynamic routing algorithms
    - Distance vector routing
      - Distributed Bellman-Ford
    - Link state routing
      - Implement Dijkstra's algorithm at each node

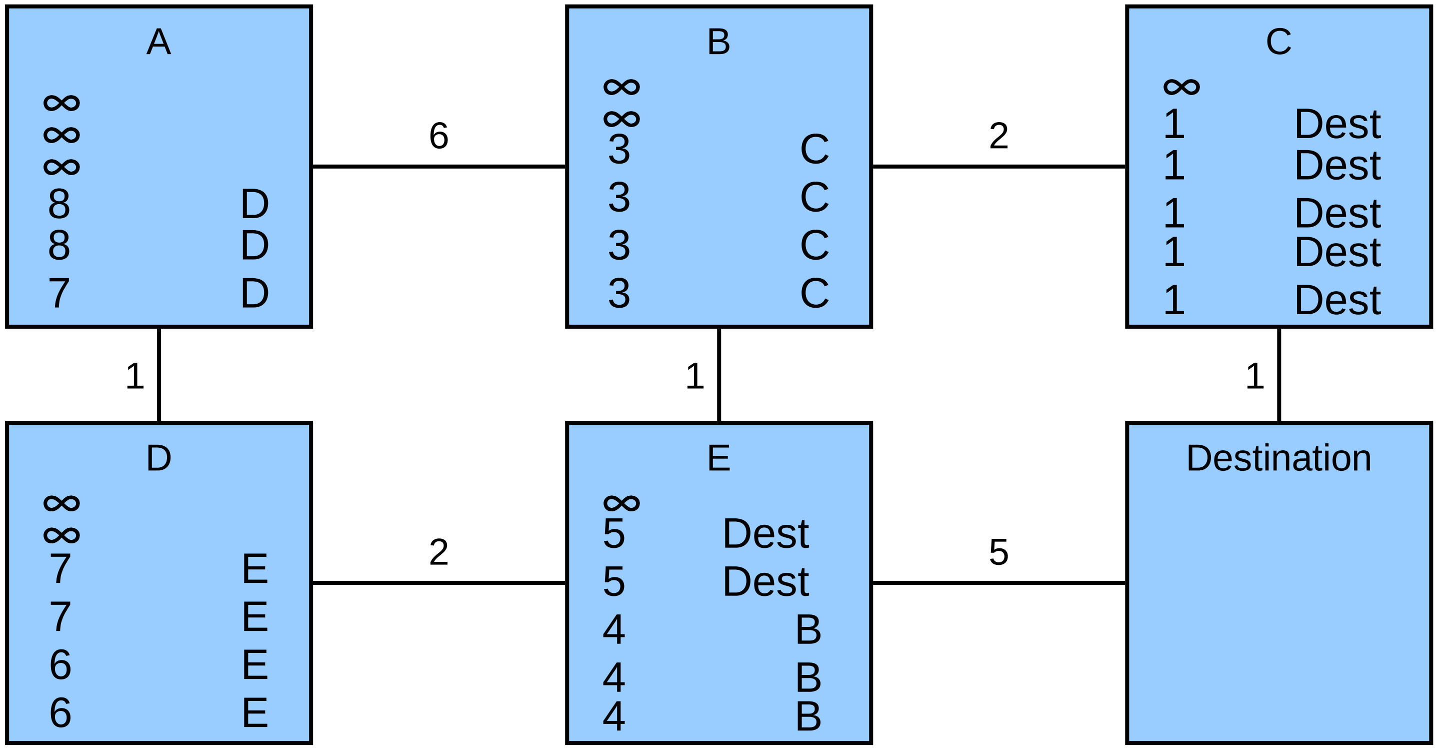
Bellman-Ford Algorithm

- Concept
  - Static centralized algorithm
- Given
  - Directed graph with edge costs and destination node
- Finds
  - Least cost path from each node to destination
- Multiple nodes
  - To find shortest paths for multiple destination nodes, run entire Bellman-Ford algorithm once per destination

Bellman-Ford Algorithm

- Based on repetition of iterations
  - For every node A and every neighbor B of A
    - Is the cost of the path (A $\rightarrow$ B $\rightarrow$ $\rightarrow$ $\rightarrow$ destination) smaller than the currently known cost from A to destination?
    - If YES
      - Make B the successor node for A
      - Update cost from A to destination
  - Can run iterations synchronously or all at once

Bellman-Ford Algorithm



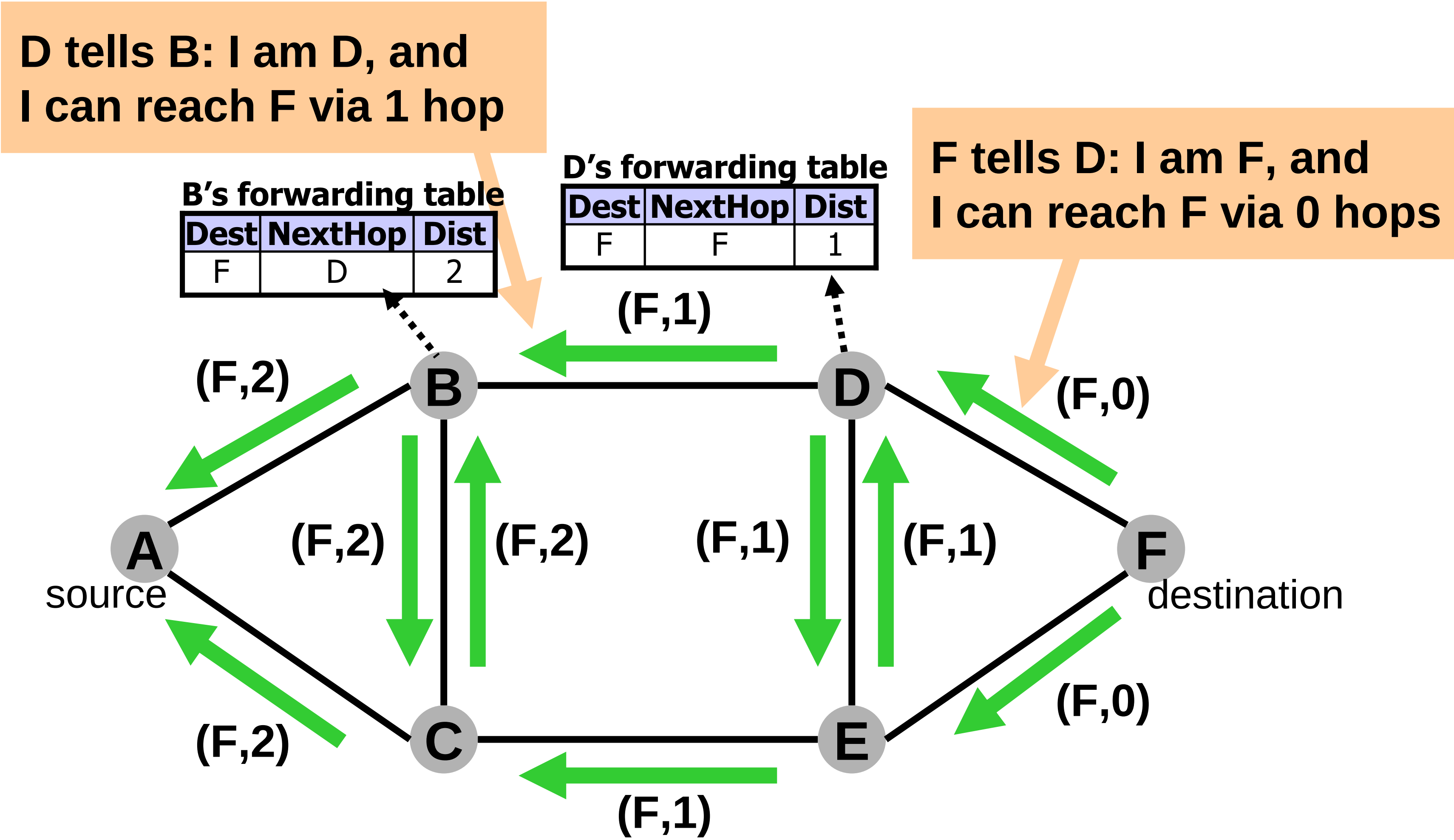
Distance Vector Routing

- Distributed dynamic version of Bellman-Ford
- Each node maintains a table of
  - <destination, distance, successor>
- Information acquisition
  - Assume nodes initially know cost to immediate neighbor
  - Nodes send <destination, distance> vectors to all immediate neighbors
    - Periodically – seconds, minutes
    - Whenever vector changes – triggered update

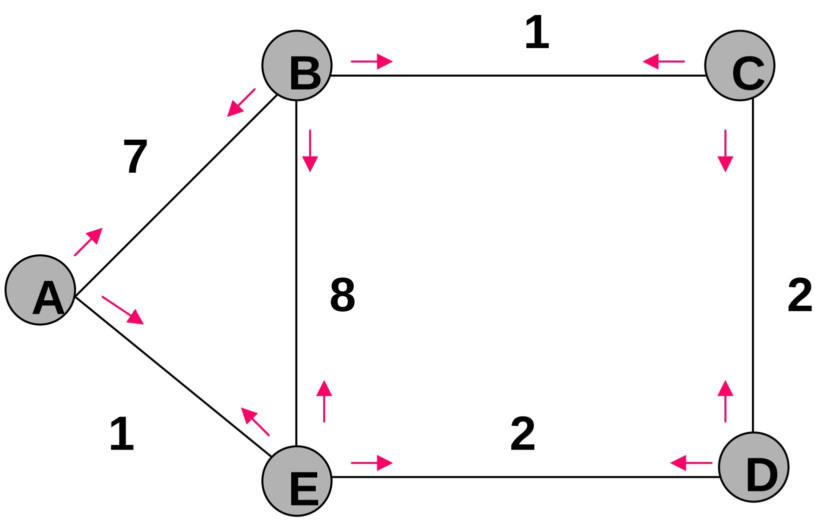
Distance Vector Routing

- When a route changes
  - Local failure detection
    - Control message not acknowledged
    - Timeout on periodic route update
  - Current route disappears
  - Newly advertised route is shorter than previous route
- Used in
  - Original ARPANET (until 1979)
  - Early Internet: Routing Information Protocol (RIP)
  - Early versions of DECnet and Novell IPX

Distance vector: update propagation

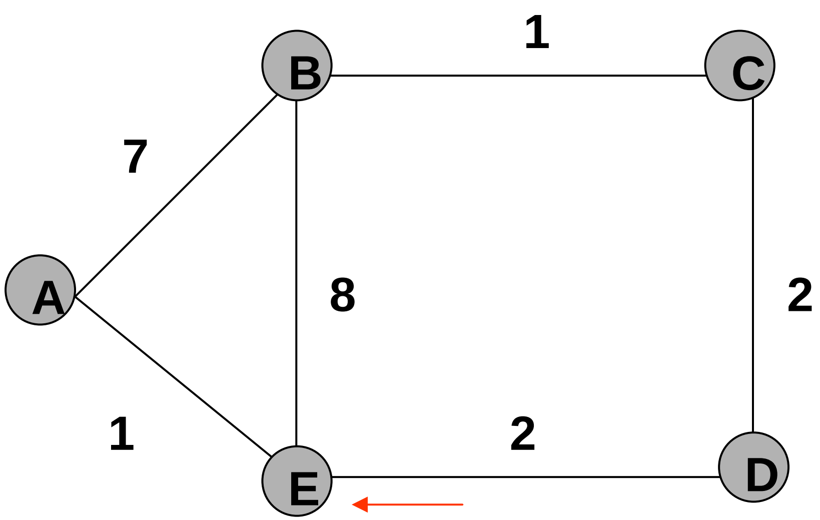


Example - Initial Distances



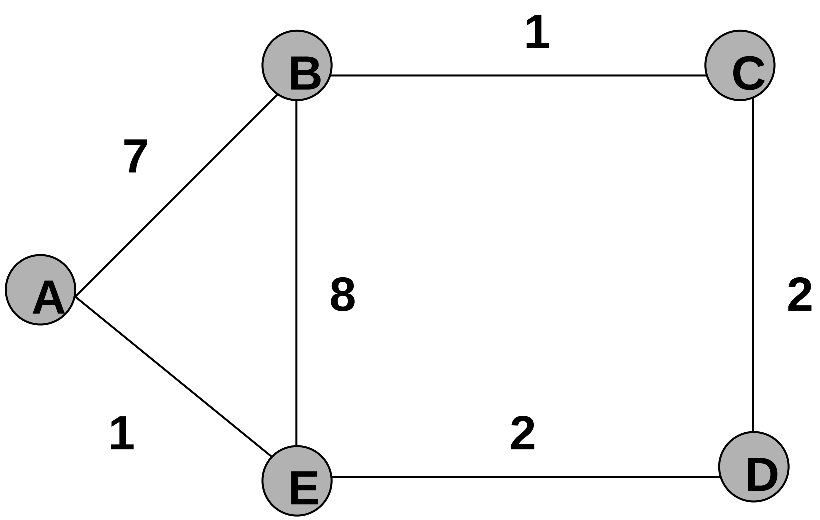
Info at node	Distance to node A	B	C	D	E
A	0	7	~	~	1
B	7	0	1	~	8
C	~	1	0	2	~
D	~	~	2	0	2
E	1	8	~	2	0

E Receives D's Routes



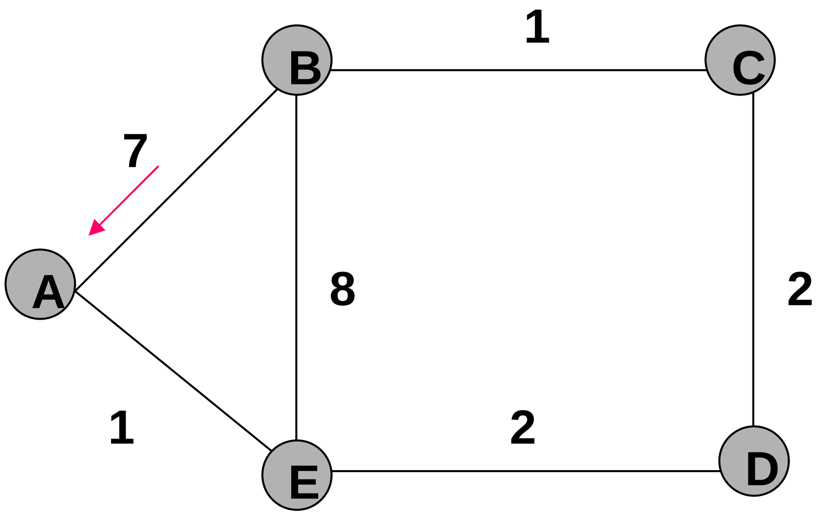
Info at node	Distance to node A	B	C	D	E
A	0	7	~	~	1
B	7	0	1	~	8
C	~	1	0	2	~
D	~	~	2	0	2
E	1	8	~	2	0

E Updates Cost to C



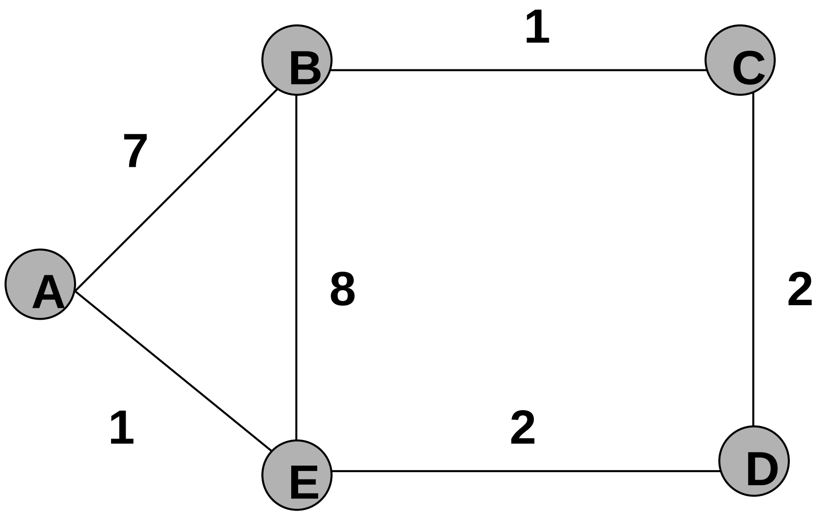
Info at node	Distance to node: A	B	C	D	E
A	0	7	~	~	1
B	7	0	1	~	8
C	~	1	0	2	~
D	~	~	2	0	2
E	1	8	4	2	0

A Receives B's Routes



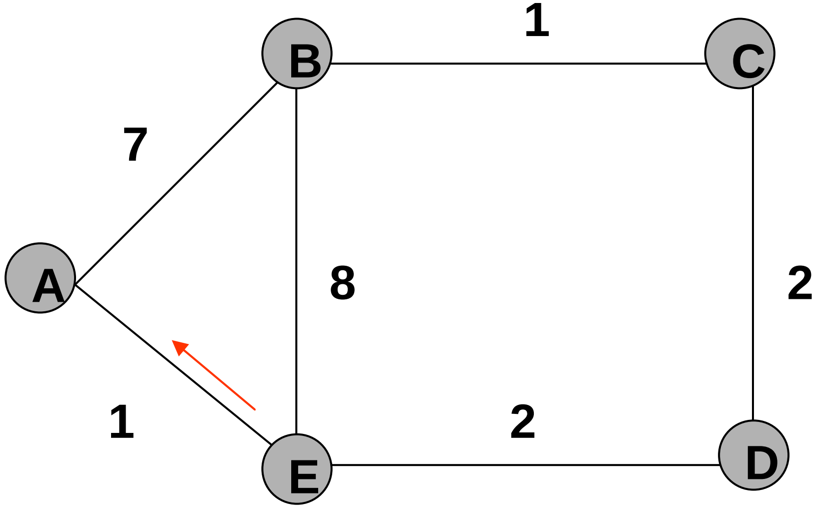
Info at node	Distance to node A	B	C	D	E
A	0	7	~	~	1
B	7	0	1	~	8
C	~	1	0	2	~
D	~	~	2	0	2
E	1	8	4	2	0

A Updates Cost to C



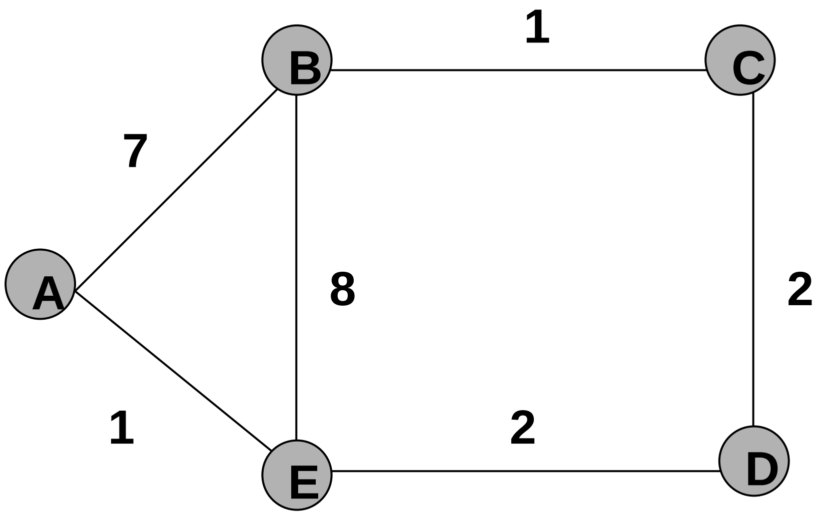
Info at node	Distance to node A	B	C	D	E
A	0	7	8	~	1
B	7	0	1	~	8
C	~	1	0	2	~
D	~	~	2	0	2
E	1	8	4	2	0

A Receives E's Routes



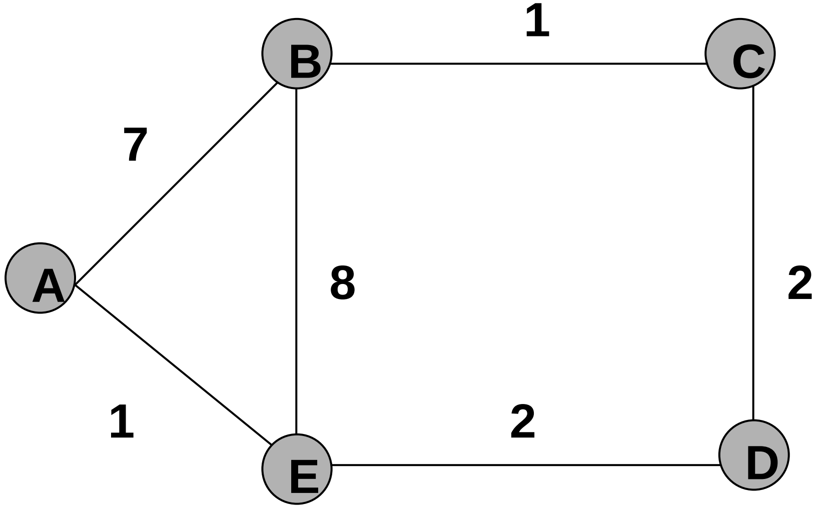
Info at node	Distance to node A	B	C	D	E
A	0	7	8	~	1
B	7	0	1	~	8
C	~	1	0	2	~
D	~	~	2	0	2
E	1	8	4	2	0

A Updates Cost to C and D



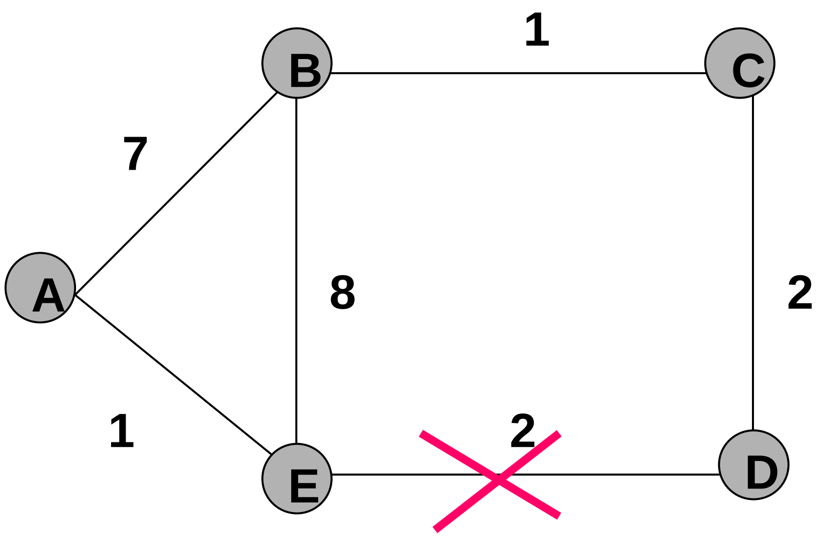
Info at node	Distance to node A	B	C	D	E
A	0	7	5	3	1
B	7	0	1	~	8
C	~	1	0	2	~
D	~	~	2	0	2
E	1	8	4	2	0

Final Distances



Info at node	Distance to node A	B	C	D	E
A	0	6	5	3	1
B	6	0	1	3	5
C	5	1	0	2	4
D	3	3	2	0	2
E	1	5	4	2	0

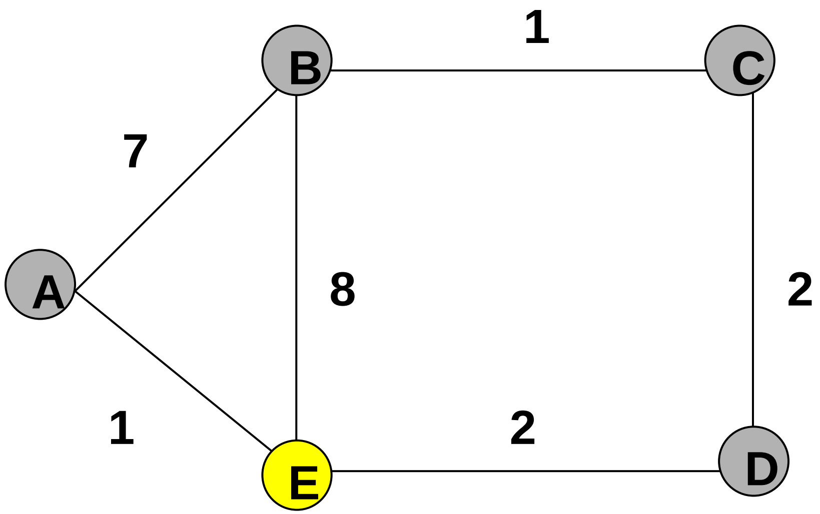
Final Distances After Link Failure



Info at node	A	B	C	D	E
A	0	7	8	10	1
B	7	0	1	3	8
C	8	1	0	2	9
D	10	3	2	0	11
E	1	8	9	11	0

Distance to node

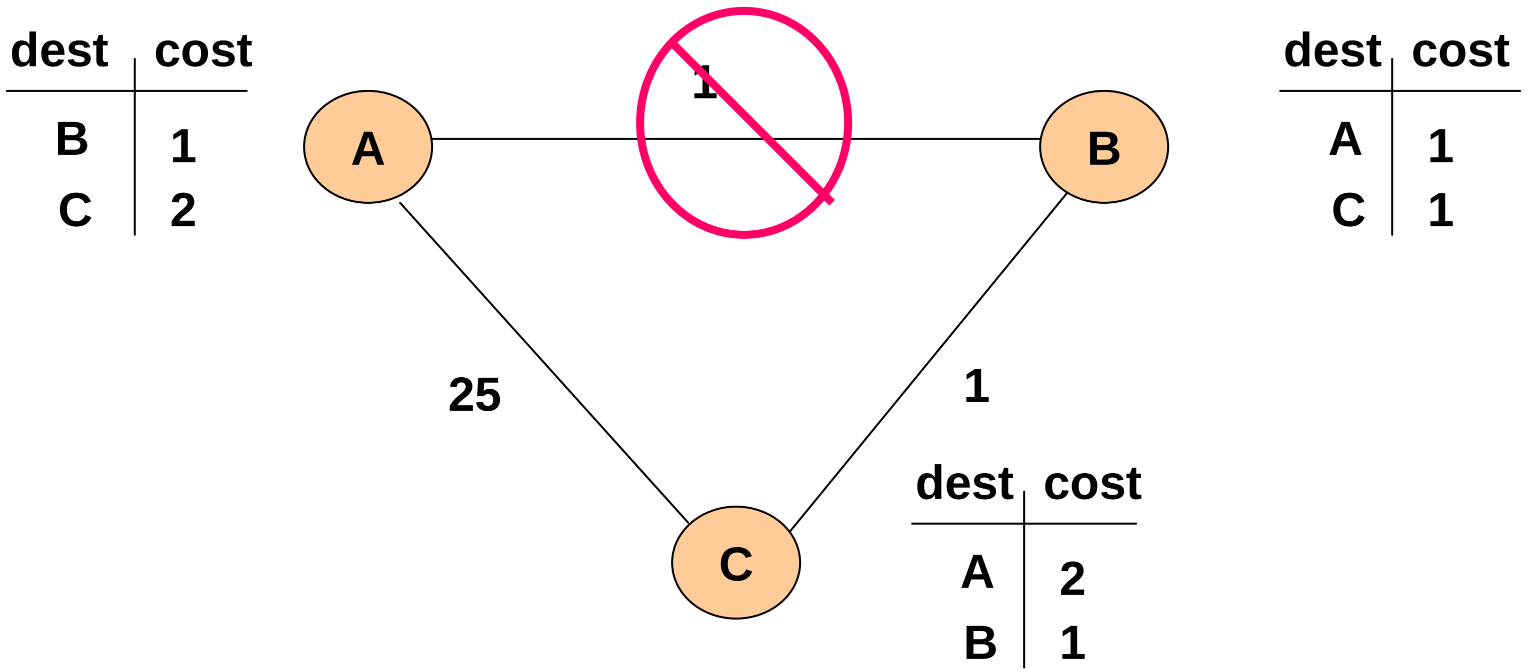
View From a Node



E's routing table

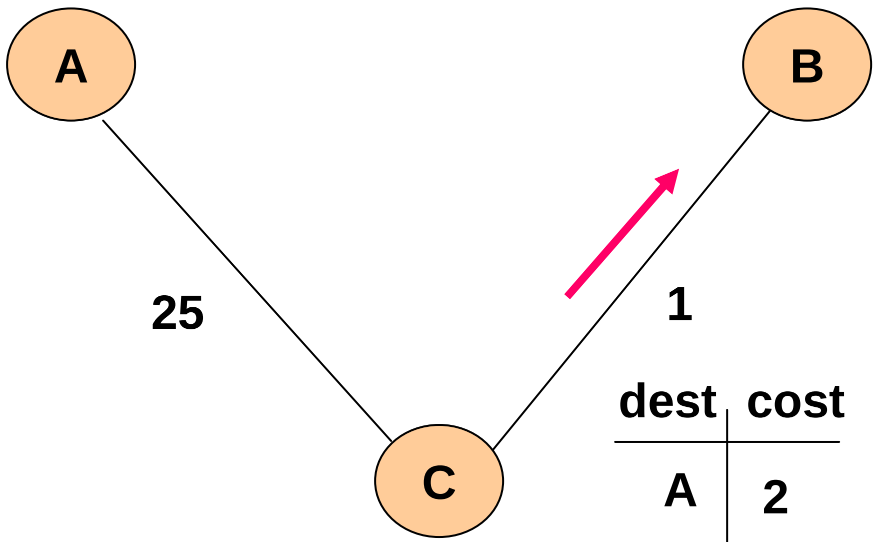
	Next hop		
dest	A	B	D
A	1	14	5
B	7	8	5
C	6	9	4
D	4	11	2

Count-to-infinity Problem



C Sends Routes to B

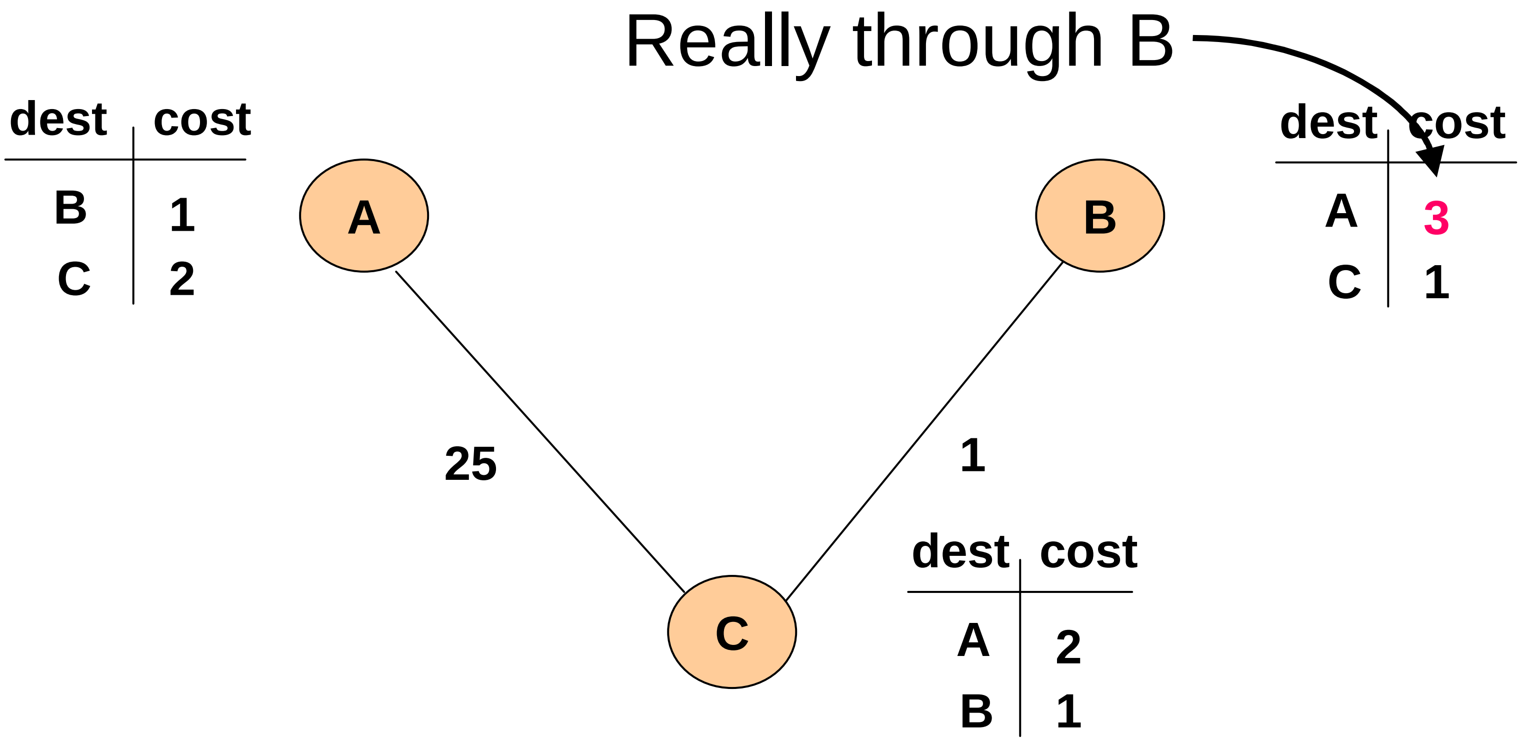
dest	cost
B	1
C	2



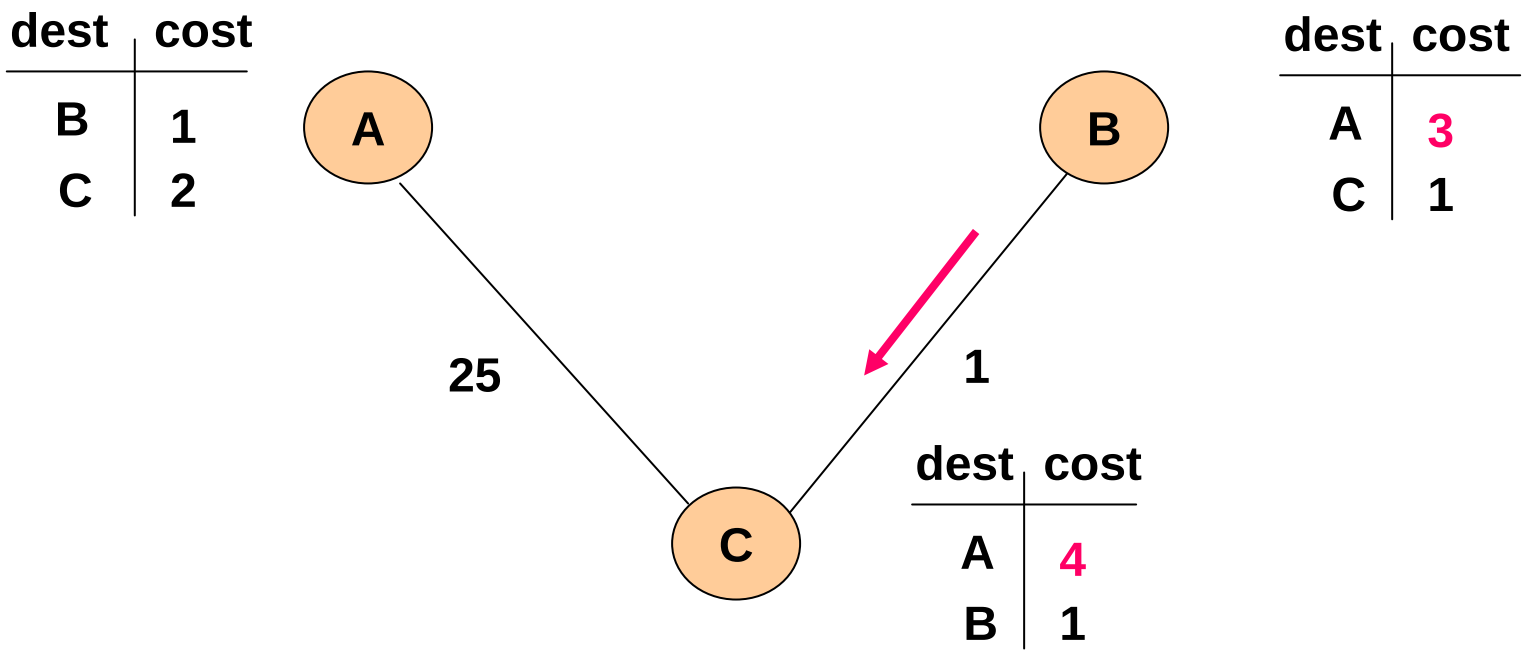
dest	cost
A	~
C	1

dest	cost
A	2
B	1

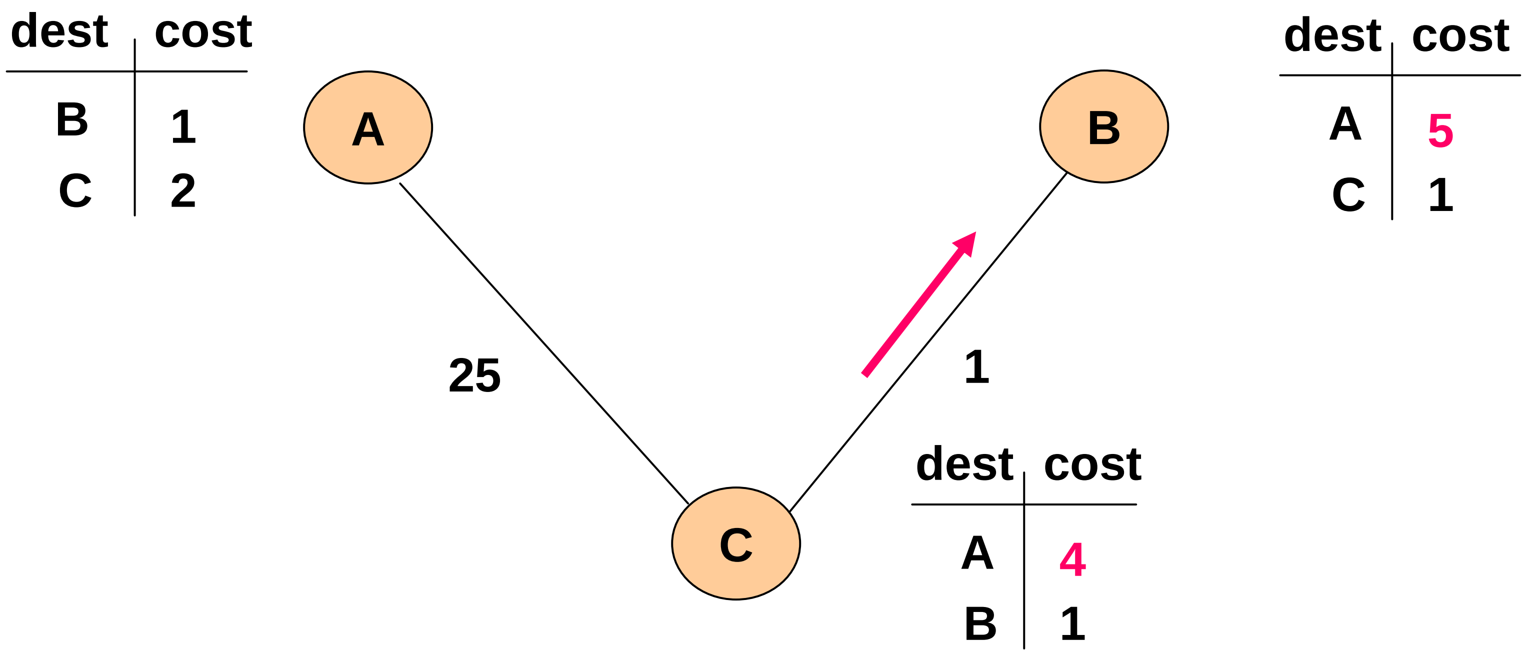
B Updates Distance to A



B Sends Routes to C



C Sends Routes to B



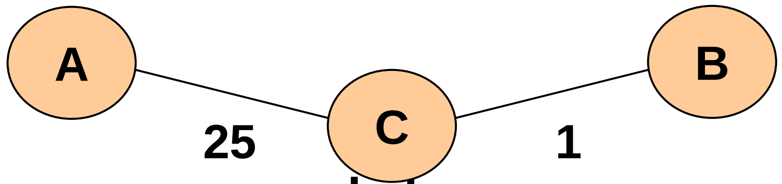
Distance Vector Routing

- Problem
  - Node **X** notices that its link to **Y** is broken
  - Other nodes believe that the route through **X** is still good
  - Mutual deception!

How Are These Loops Caused?

- Observation 1:
  - B's metric increases
- Observation 2:
  - C picks B as next hop to A
  - But, the implicit path from C to A includes itself!

Solution 1: Holddowns

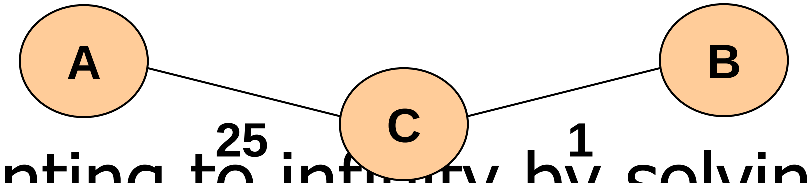


- If metric increases, delay propagating information
  - in our example, B delays advertising route
  - C eventually thinks B’s route is gone, picks its own route
  - B then selects C as next hop
- Adversely affects convergence

Heuristics for breaking loops

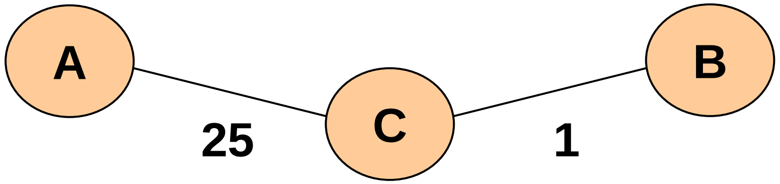
- Set infinity to 16
  - Small limit allows fast completion of "counting to infinity"
  - Limits the size of the network
- Split horizon
  - Avoid counting to infinity by solving "mutual deception" problem
- Split horizon with poisoned reverse
  - "Poison" the routes sent to you by your neighbors
- Sequence numbers on delay estimates

Split Horizon



- Avoid counting to infinity by solving “mutual deception” problem
- Distance Vector with split horizon:
  - when sending an update to node **X**, do not include destinations that you would route through **X**
  - If **X** thinks route is not through you, no effect
  - If **X** thinks route is through you, **X** will timeout route

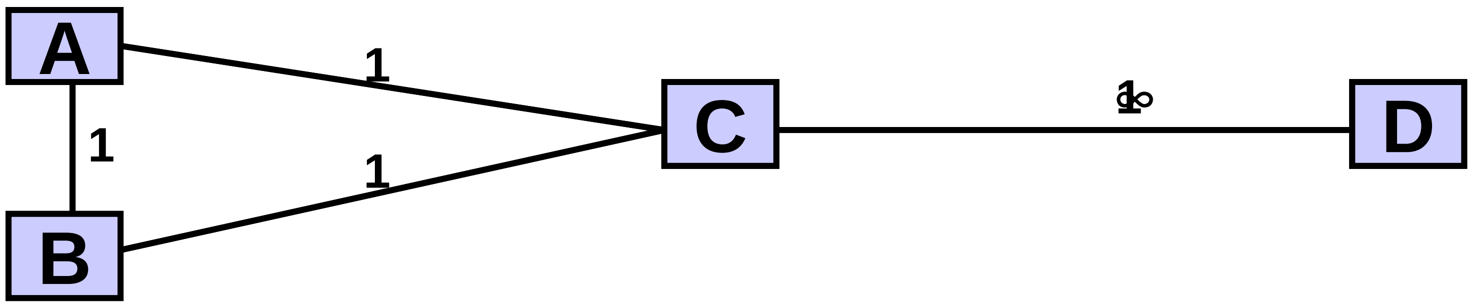
Split Horizon and Poisoned Reverse



- Distance Vector with Split Horizon and Poisoned Reverse:
  - When sending update to node **X**, include destinations that you would route through **X** with distance set to infinity
  - Don’t need to wait for **X** to timeout
- Problem:
  - Router on edge of Internet would need to include infinity route for all outside destinations on Internet!

Split Horizon

- Split Horizon (with or without poisoned reverse) may still allow some routing loops and counting to infinity
  - guarantees no 2-node loops
  - can still be fooled by 3-node (or larger) loops
- Consider link failure from **C** to **D**



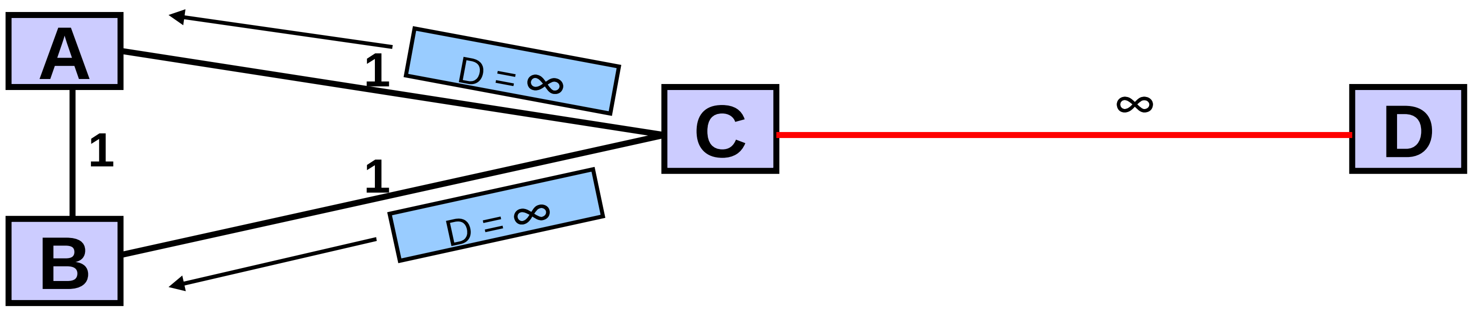
Split Horizon

- Initial routing table entries for route to **D**:

  A 2 via **C**

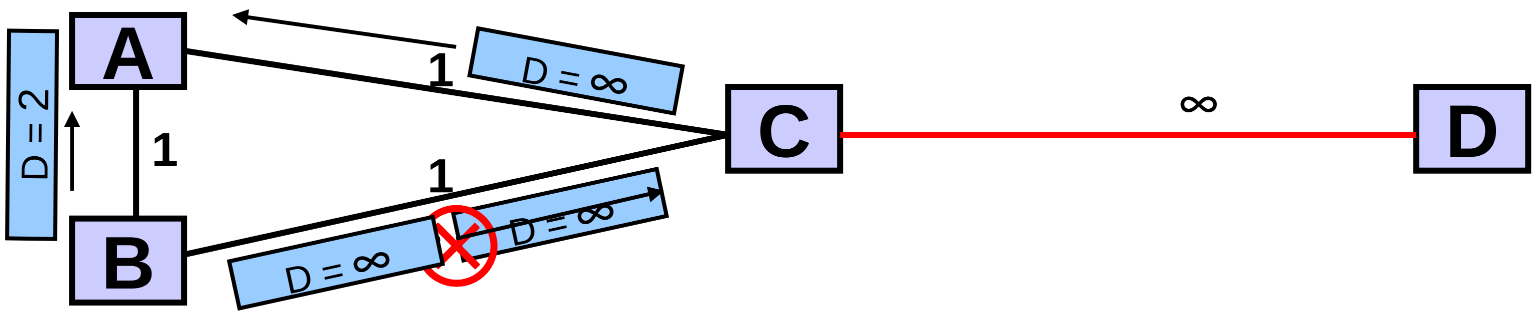
  B 2 via **C**

  C 1
- **C** notices link failure and changes to infinity
- Now **C** sends updates to **A** and **B**:
  - to **A**: infinity
  - to **B**: infinity



Split Horizon

- Suppose update to **B** is lost
- New tables:
  - **A** unreachable
  - **B** 2 via **C**
  - **C** unreachable
- Now **B** sends its periodic routing update:
  - to **C**: infinity (poisoned reverse)
  - to **A**: 2



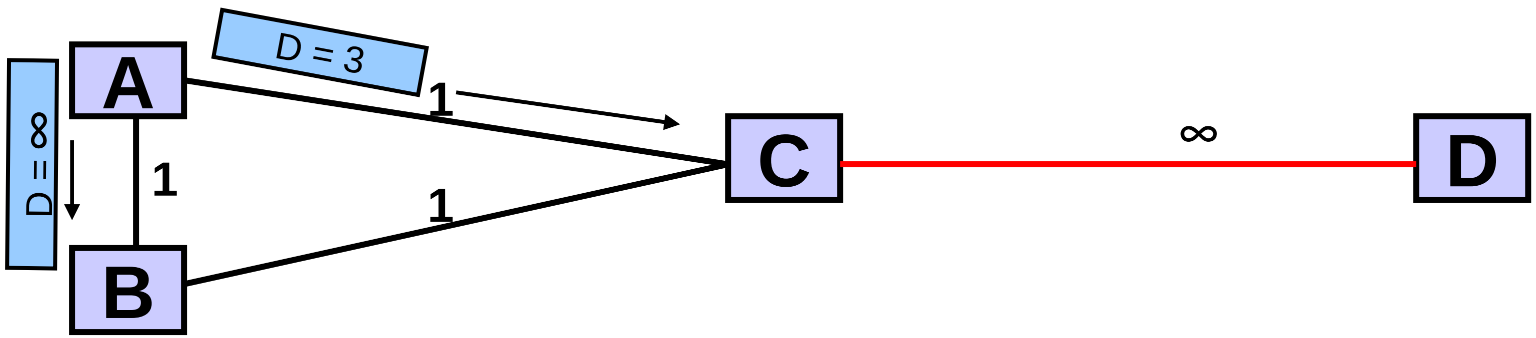
Split Horizon

- New tables for route to **D**:

  A 3 via **B**

  B 2 via **C**

  C unreachable
- Finally A sends its periodic routing update:
  - to **B**: infinity (poisoned reverse)
  - to **C**: 3



Split Horizon

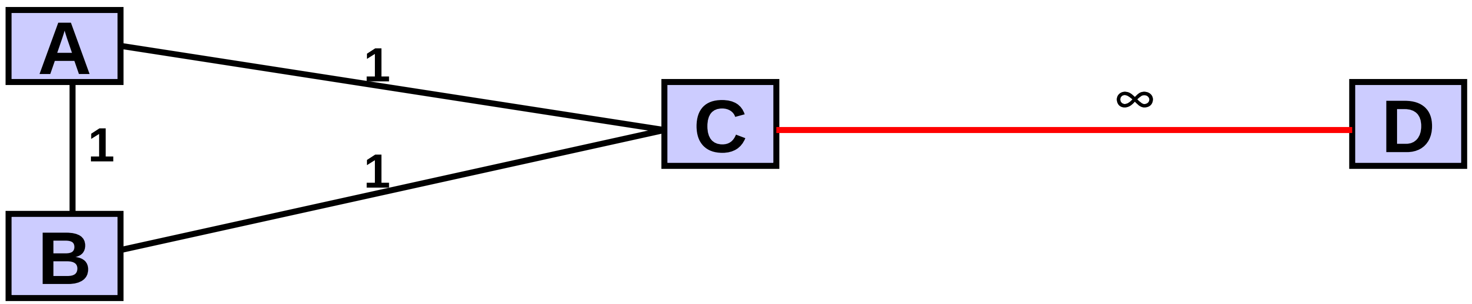
- New tables for route to **D**:

  A 3 via **B**

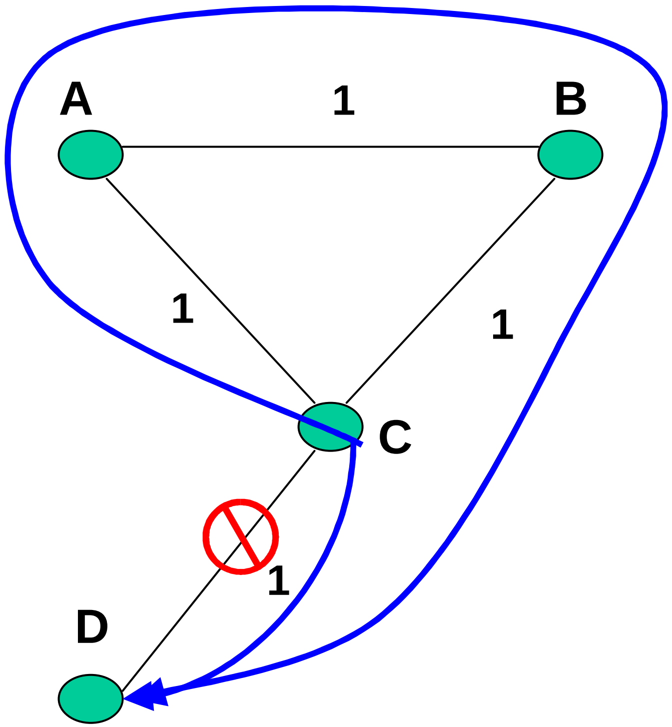
  B 2 via **C**

  C 4 via **A**

- A, B and C will still continue to count to infinity



Example Where Split Horizon Fails



- Link breaks
  - C marks D as unreachable and reports that to A and B.
- Suppose A learns it first.
  - A now thinks best path to D is through B.
  - A reports a route of cost=3 to C.
- C thinks D is reachable through A at cost 4 and reports that to B.
- B reports a cost 5 to A who reports new cost to C.
- etc...

Avoiding Counting to Infinity

- Select loop-free paths
- One way of doing this:
  - Each route advertisement carries entire path
  - If a router sees itself in path, it rejects the route
- BGP does it this way
- Space proportional to diameter

Loop Freedom at Every Instant

- Does keeping paths avoid all loops?
  - No! Transient loops are still possible
  - Why? Because path information may be stale
- Only way to fix this
  - Ensure that you have up-to-date information by explicitly querying

Distance Vector in Practice

- RIP and RIP2
  - uses split-horizon/poison reverse
- BGP/IDRP
  - propagates entire path
  - path also used for affecting policies
- AODV
  - “on-demand” distance vector protocol for wireless networks
  - Only maintain distance vectors along paths to destinations that you need to reach

Distance Vector Routing

- Problem
  - Information propagates slowly
    - One period per hop for new routes
    - Count to infinity to detect lost routes

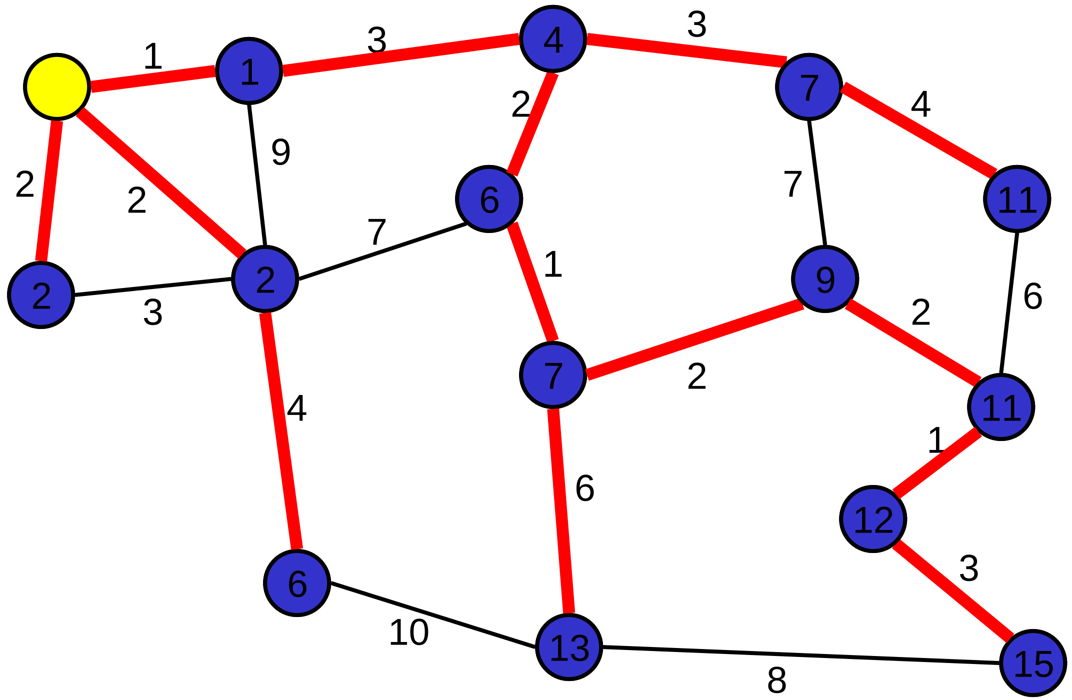
Dijkstra’s Algorithm

- Given
  - Directed graph with edge weights (distances)
- Calculate
  - Shortest paths from one node to all others

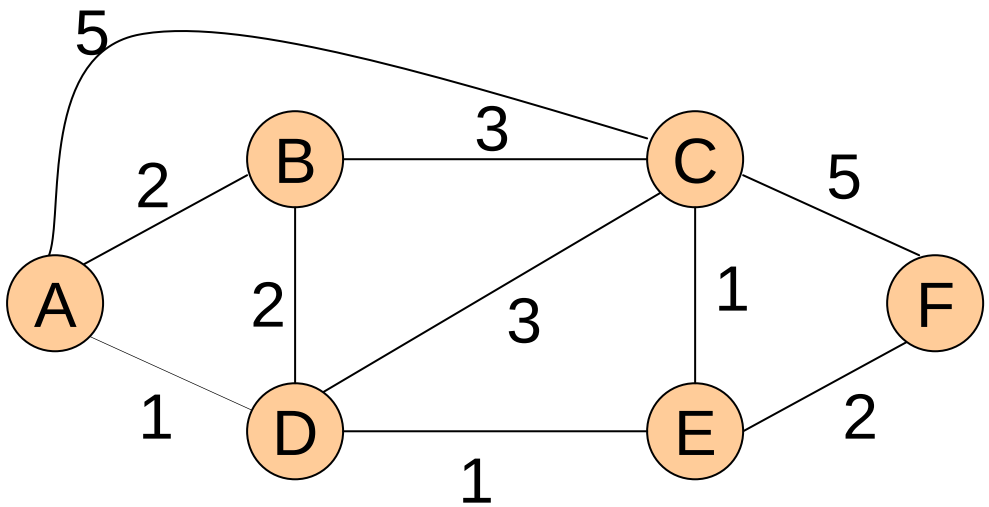
Dijkstra's Algorithm

- Greedily grow set C of confirmed least cost paths
- Initially C = {source}
- Loop N-1 times
  - Determine the node M outside C that is closest to the source
  - Add M to C and update costs for each node P outside C
    - Is the path (source → → … → M → P) better than the previously known path for (source → P)?
    - If YES
      - Update cost to reach P

Dijkstra's Algorithm

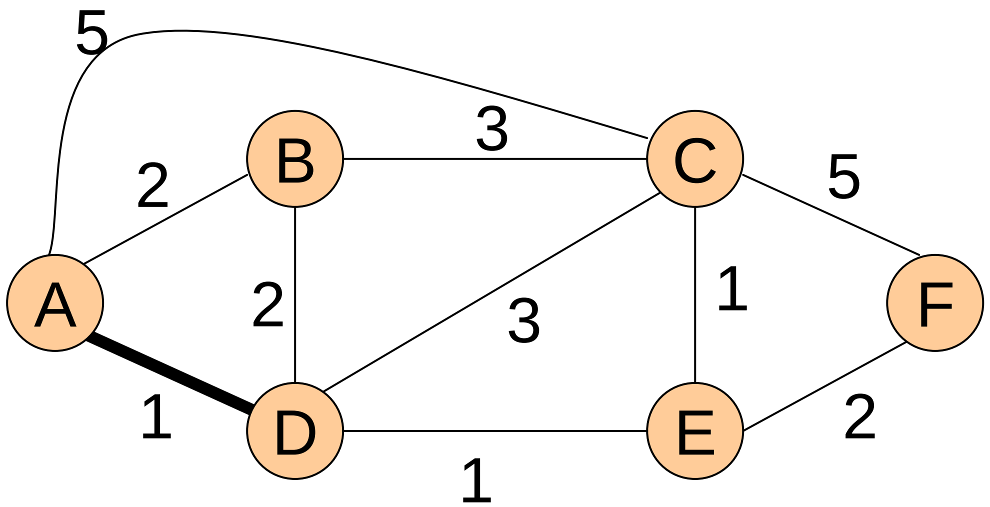


Example



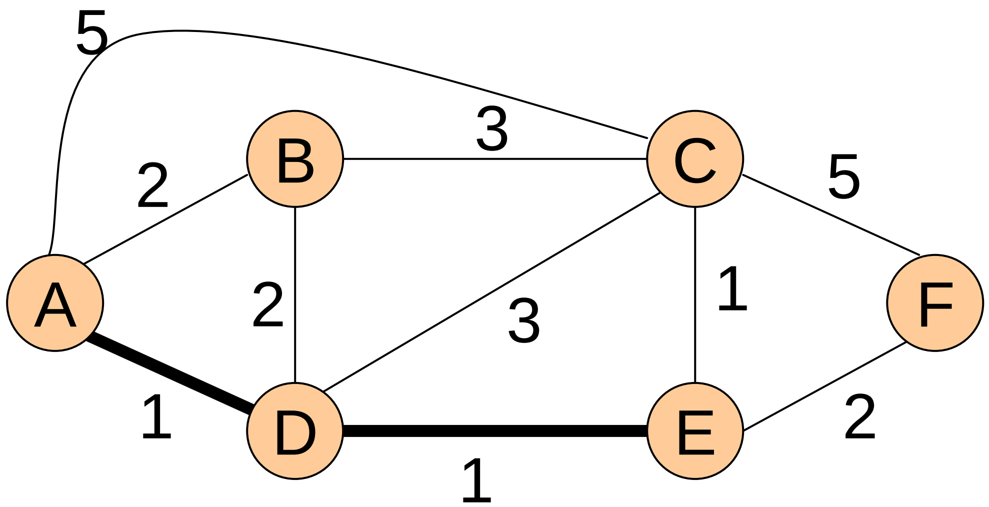
		B	C	D	E	F
step	SPT	D(b), P(b)	D(c), P(c)	D(d), P(d)	D(e), P(e)	D(f), P(f)
0	A	2, A	5, A	1, A	~	~

Example



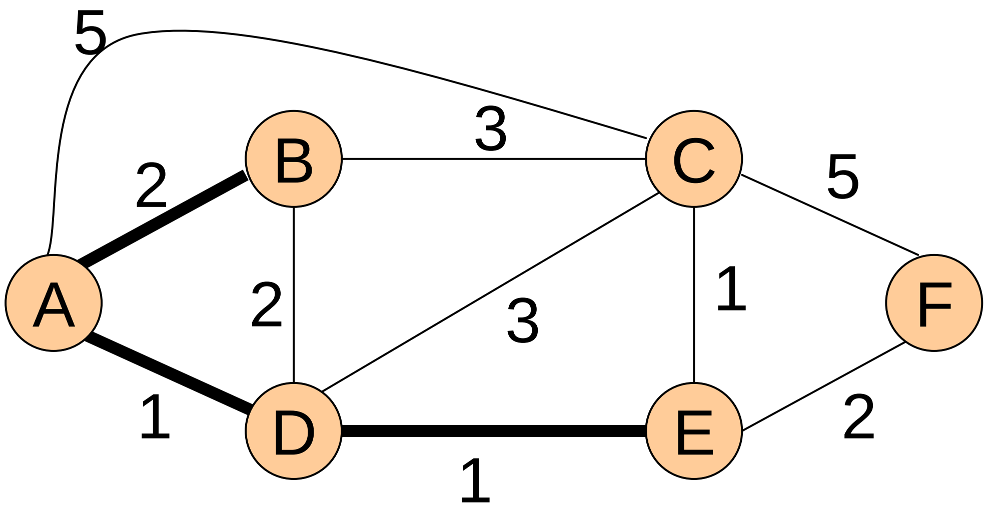
		B	C	D	E	F
step	SPT	D(b), P(b)	D(c), P(c)	D(d), P(d)	D(e), P(e)	D(f), P(f)
0	A	2, A	5, A	**1, A**	~	~
1	AD	2, A	4, D		2, D	~

Example



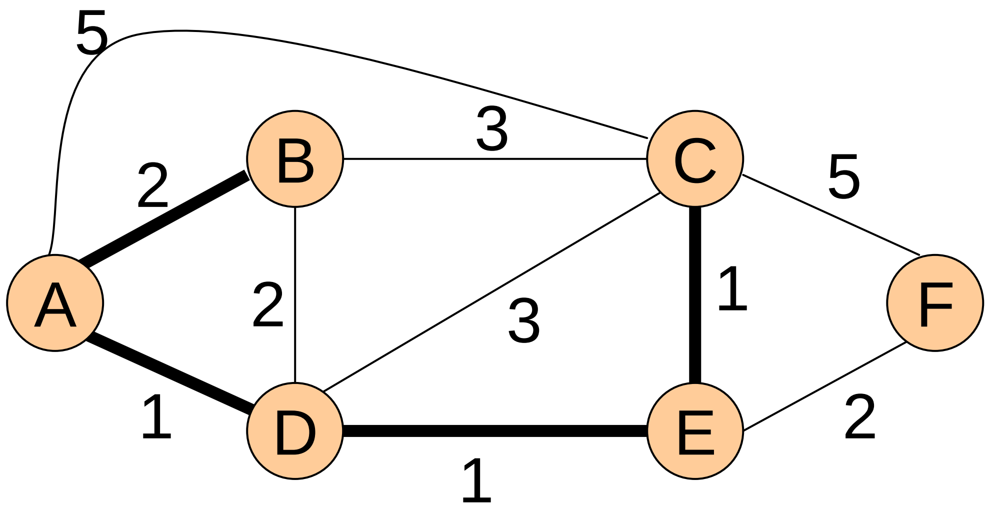
		B	C	D	E	F
step	SPT	D(b), P(b)	D(c), P(c)	D(d), P(d)	D(e), P(e)	D(f), P(f)
0	A	2, A	5, A	**1, A**	~	~
1	AD	2, A	4, D		**2, D**	~
2	ADE	2, A	3, E			4, E

Example



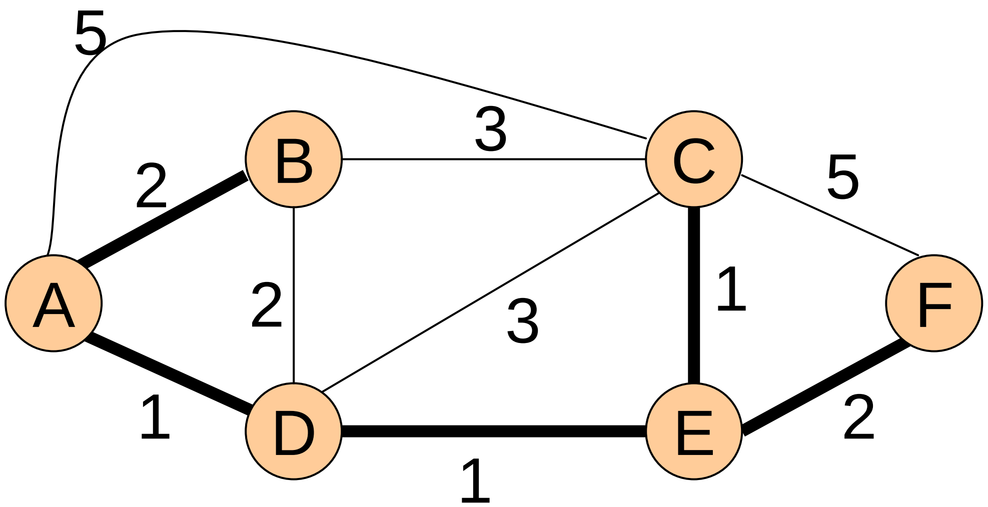
		B	C	D	E	F
step	SPT	D(b), P(b)	D(c), P(c)	D(d), P(d)	D(e), P(e)	D(f), P(f)
0	A	2, A	5, A	**1, A**	~	~
1	AD	2, A	4, D		**2, D**	~
2	ADE	**2, A**	3, E			4, E
3	ADEB		3, E			4, E

Example



		B	C	D	E	F
step	SPT	D(b), P(b)	D(c), P(c)	D(d), P(d)	D(e), P(e)	D(f), P(f)
0	A	2, A	5, A	**1, A**	~	~
1	AD	2, A	4, D		**2, D**	~
2	ADE	**2, A**	3, E			4, E
3	ADEB		**3, E**			4, E
4	ADEBC					4, E

Example



	B	C	D	E	F
step	SPT	D(b), P(b)	D(c), P(c)	D(d), P(d)	D(e), P(e)	D(f), P(f)

step	SPT	D(b), P(b) (B)	D(c), P(c) (C)	D(d), P(d) (D)	D(e), P(e) (E)	D(f), P(f) (F)
0	A	2, A	5, A	**1, A**	~	~
1	AD	2, A	4, D		**2, D**	~
2	ADE	**2, A**	3, E			4, E
3	ADEB		**3, E**			4, E
4	ADEBC					**4, E**

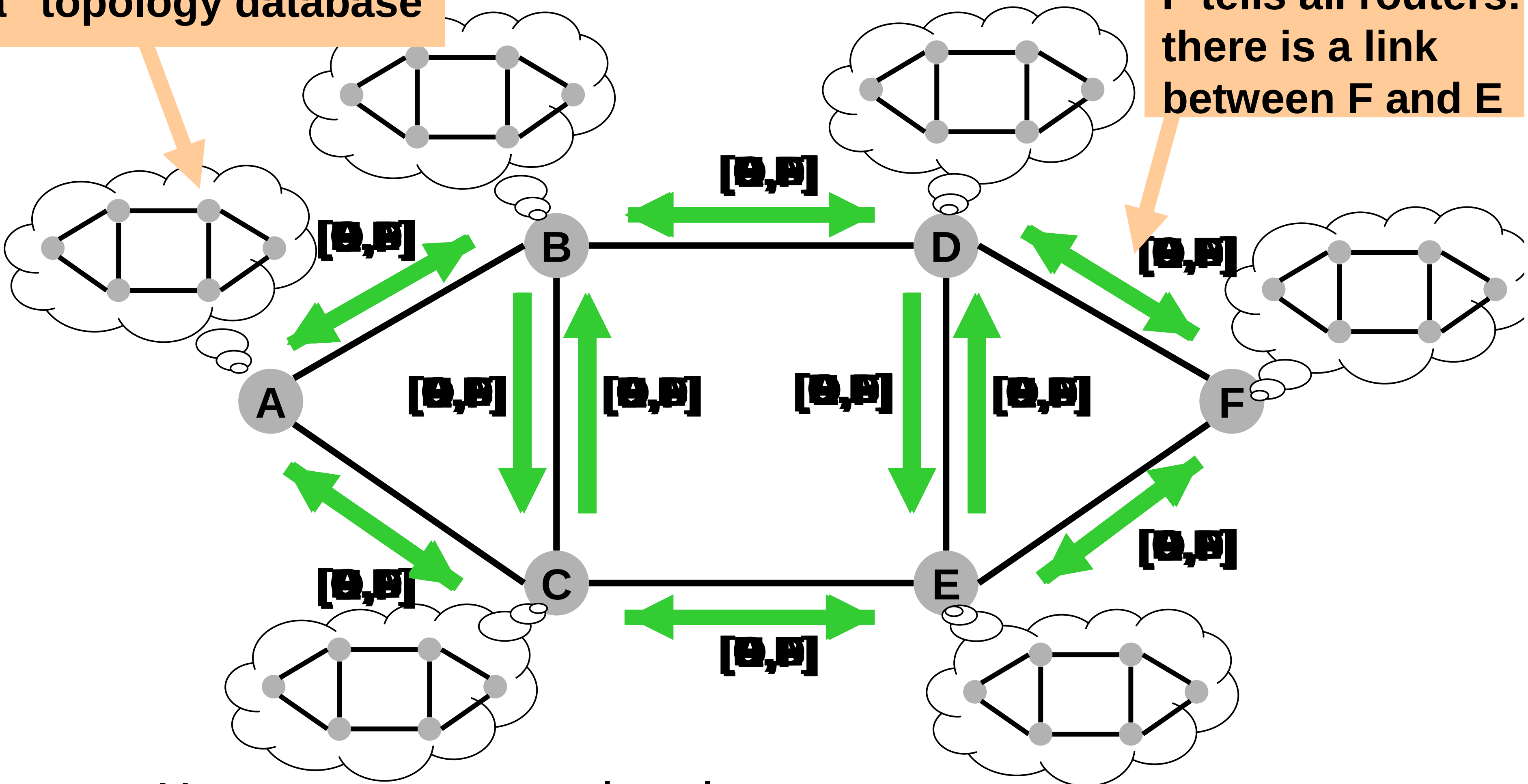
Link State Routing

- Strategy
  - Send all nodes information about directly connected links
  - Status of links is flooded in link state packets (LSPs)
- Each LSP carries
  - ID of node that created the LSP
  - Vector of <neighbor, cost of link to neighbor> pairs for the node that created the LSP
  - Sequence number
  - Time-to-live (TTL)
- Each node maintains a list of (ideally all) LSP's and runs Dijkstra's algorithm on the list

Link state: update propagation

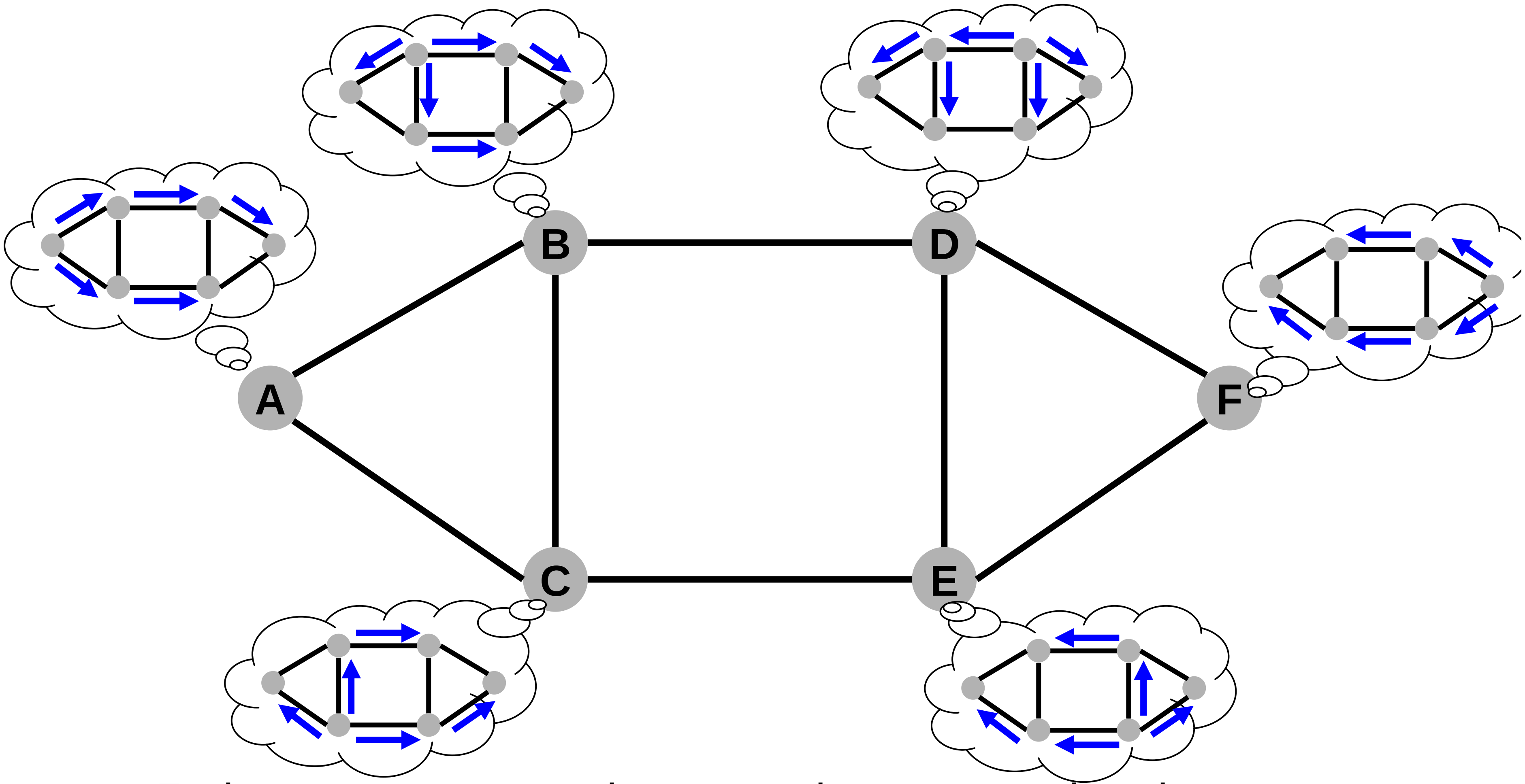
Each node maintains a "topology database"

F tells all routers: there is a link between F and E



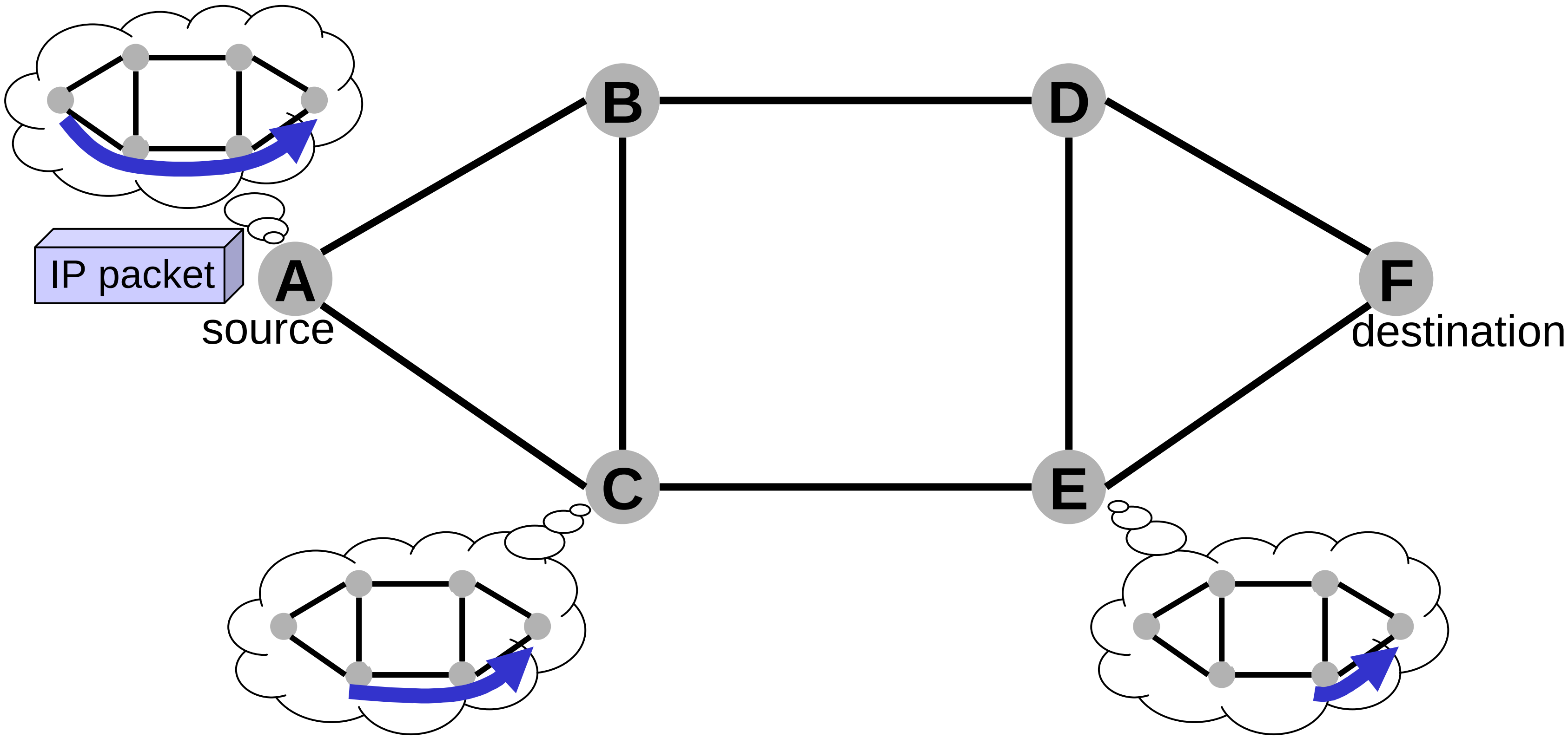
- How to prevent update loops:
- How to bring up new node:

Link state: route computation



- Each router computes shortest path tree, rooted at that router
- Determines next-hop to each dest, publish to forwarding table
- Operators can assign link costs to control path selection

Link-state: packet forwarding



- Downsides of link-state:
  - Lesser control on policy (certain routes can't be filtered), more cpu
  - Increased visibility (bad for privacy, but good for diagnostics)

Link State Routing

- LSP must be delivered to all nodes
- Information acquisition via reliable flooding
  - Create local LSP periodically with increasing sequence number
  - Send local LSP to all immediate neighbors
  - Forward LSP (if it has a new sequence number than previously received) out on all other links
- Why not just use TCP between every pair of routers?

Basic Steps

- Each node assumed to know state of links to its neighbors
- Step 1: Each node broadcasts its state to all other nodes
- Step 2: Each node locally computes shortest paths to all other nodes from global state

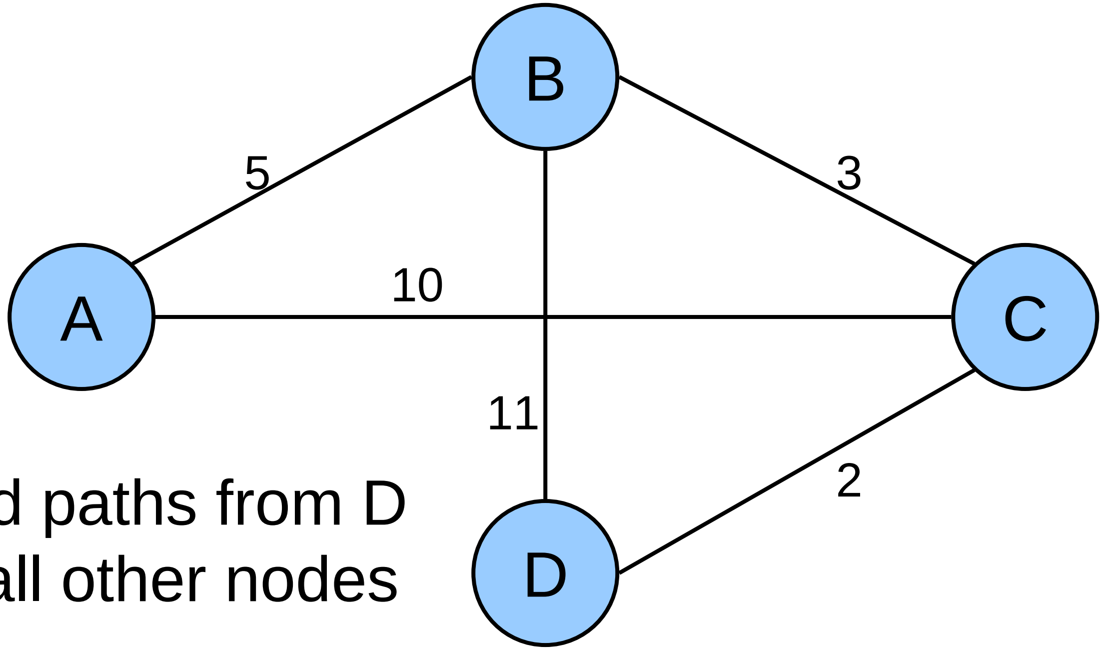
Reliable Flooding

- When i receives LSP from j:
  - If LSP is the most recent LSP from j that i has seen so far
    - i saves it in database and forwards a copy on all links except link LSP was received on
  - Otherwise, discard LSP

Link State Routing

- At each router, perform a forward search algorithm (variation of Dijkstra's)
- Router maintains two lists
  - Confirmed (nodes I know the shortest paths to)
  - Tentative (nodes that are adjacent to Confirmed nodes)
- Each list contains triplets
  - <destination, cost, nexthop>

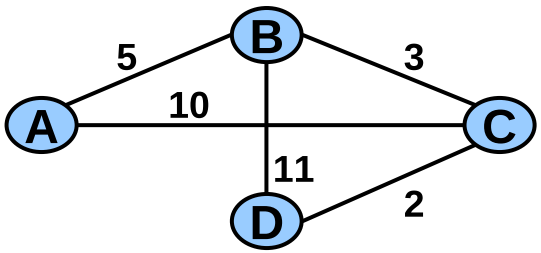
Link State Routing



Find paths from D
to all other nodes

Link State Routing

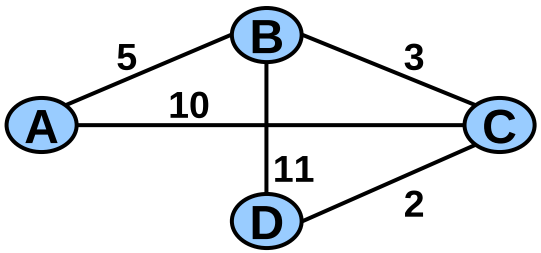
Step	Confirmed	Tentative
1.		
2.		
3.		
4.		



Step	Confirmed	Tentative
5		
6		
7		

Link State Routing

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)

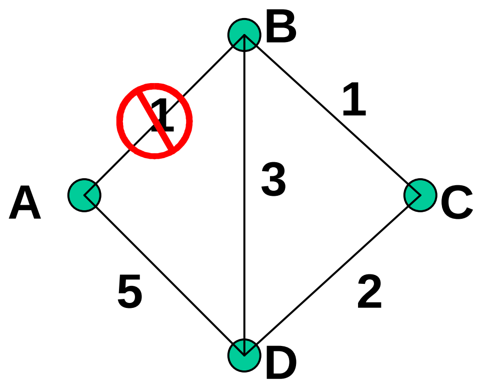


Step	Confirmed	Tentative
5	(D,0,-) (C,2,C) (B,5,C)	(A,12,C)
6	(D,0,-) (C,2,C) (B,5,C)	(A,10,C)
7	(D,0,-) (C,2,C) (B,5,C) (A,10,C)	

Link State Characteristics

- With consistent LSDBs, all nodes compute consistent loop-free paths
- Limited by Dijkstra computation overhead, space requirements
- Can still have transient loops

Packet from C->A
may loop around BDC

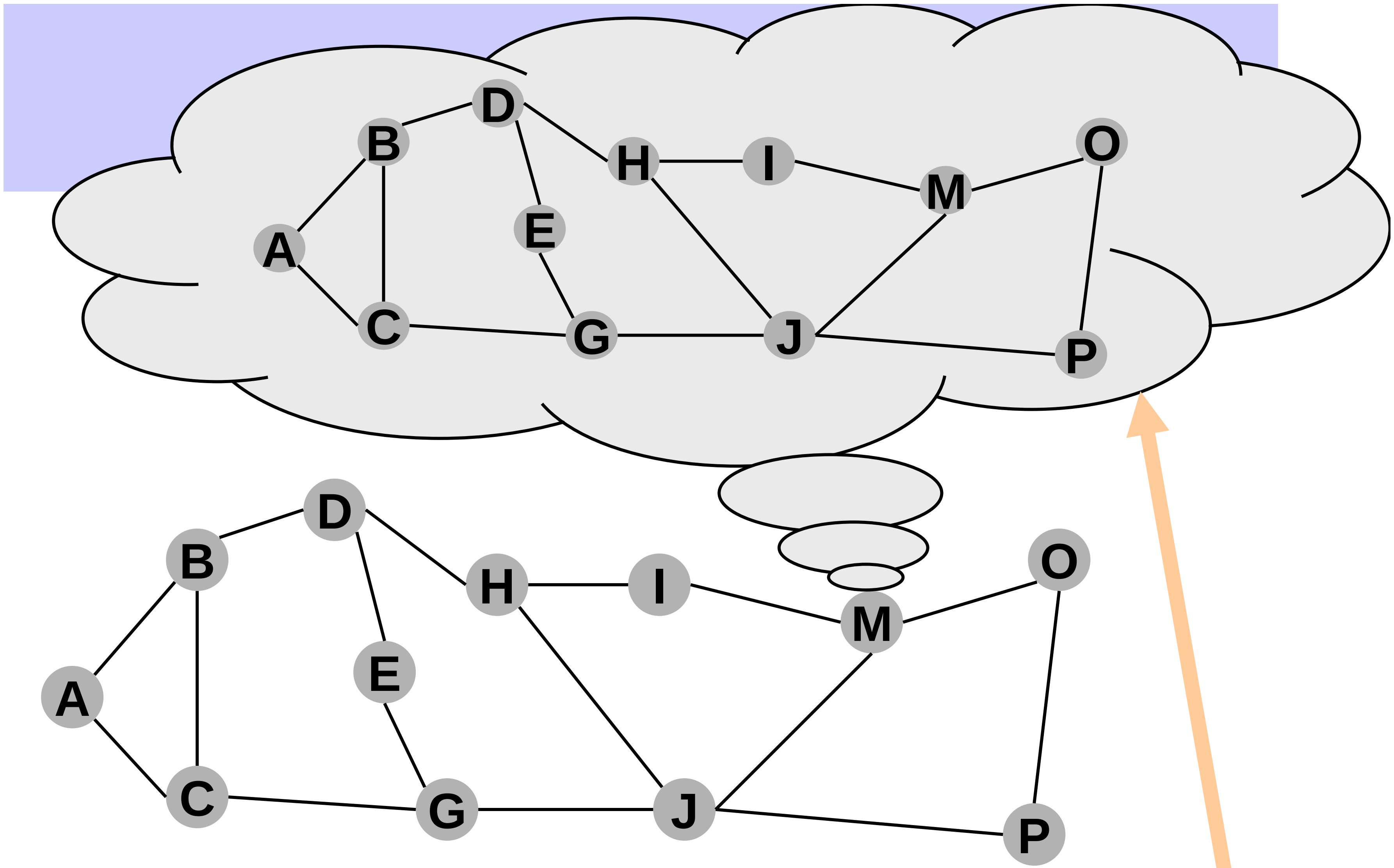


Link State Routing

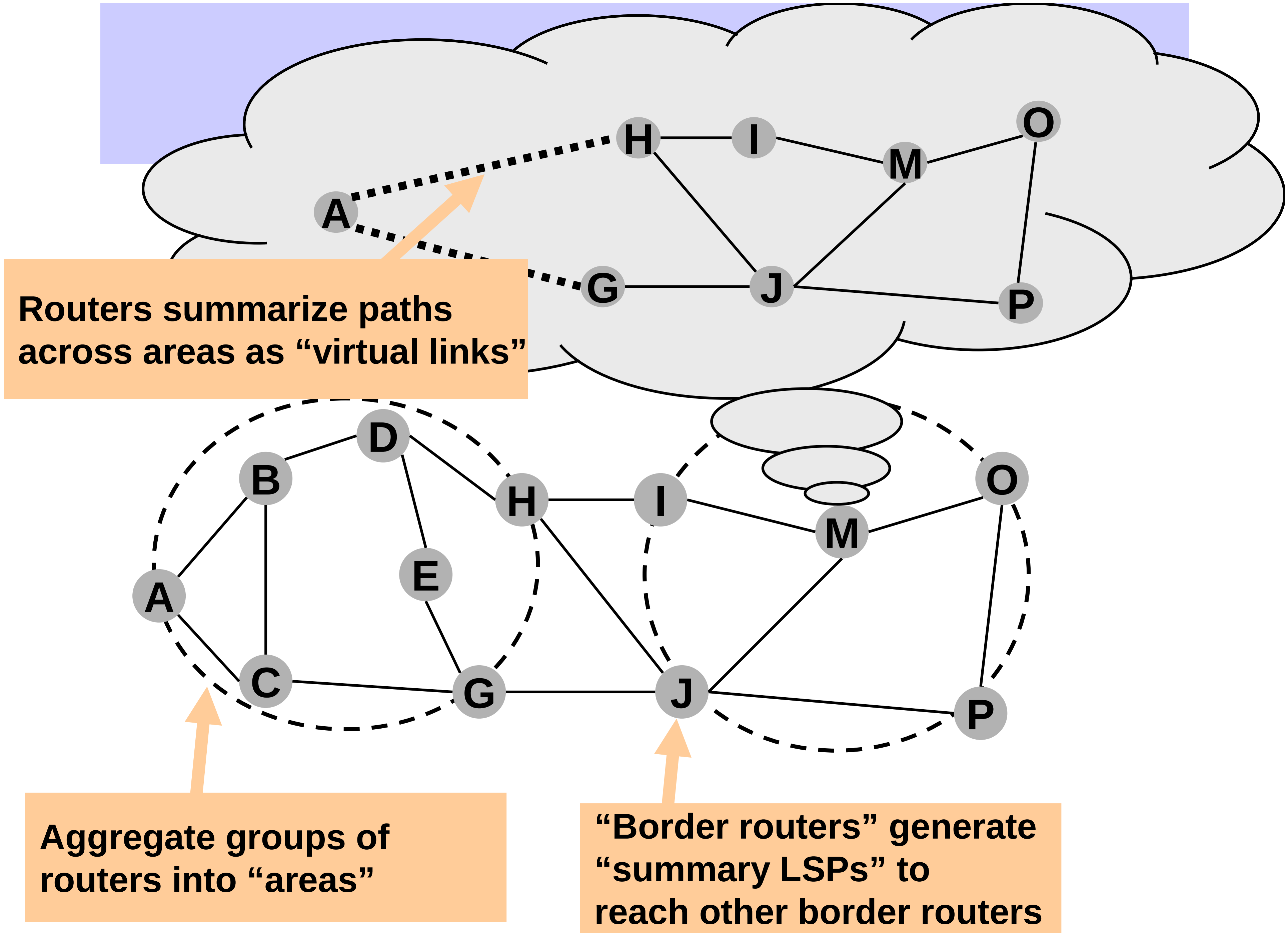
- Advertise routes to “IP prefixes” (blocks of IP addresses)
- Intermediate System-Intermediate System (IS-IS)
  - Designed for DECnet
  - Adopted by ISO for connectionless network layer protocol (CNLP)
  - Used in NSFNET backbone
  - Used in some ISPs, some digital cellular systems
- Open shortest path first (OSPF)
  - Defined in RFC 5340
  - Used in some ISPs

OSPF

- Authentication of routing messages
  - Encrypted communication between routers
- Additional hierarchy
  - Domains are split into areas
  - Routers only need to know how to reach every node in a domain
  - Routers need to know how to get to the right area
  - Load balancing
    - Allows traffic to be distributed over multiple routes



In regular link-state, routers maintain map of entire topology



Routers summarize paths across areas as “virtual links”
A
H
I
M
O
G
J
P
A
B
C
D
E
G
H
I
J
M
O
P
Aggregate groups of routers into “areas”
“Border routers” generate “summary LSPs” to reach other border routers

Tradeoffs of hierarchical routing

- Advantages: scalability
  - Reduce size of link-state database
  - Isolate rest of network from changes/faults
- Disadvantages
  - Complexity
    - Extra configuration effort
    - Requires tight coupling with address assignment
  - Inefficiency
    - One link change may affect multiple path costs
    - Summarization hides shorter paths

LS vs. DV

- Distance Vector (DV)
  - Send everything you know to your neighbors
- Link State (LS)
  - Send info about your adjacent links to everyone
- Which one's better?
- Message exchange
  - LS: O(nE)
  - DV: O(nd) for d destinations, worst-case O(d*n!)
  - But per-node computation time less in DV

LS vs. DV

- LS typically used *within* ISPs because
  - Faster convergence (usually)
  - Simpler troubleshooting
- DV typically used *between* ISPs because
  - Can support more flexible policies
  - Can avoid exporting routes
  - Can hide private regions of topology

LS vs. DV: Robustness

- LS can broadcast incorrect/corrupted LSP
    - Localized problem
    - But across multiple destinations
- DV can advertise incorrect paths to all destinations
    - Incorrect calculation can spread to entire network
    - But only for that destination
- Soft-state vs. Hard-state approaches
    - – Should we periodically refresh? Or rely on routers to locally maintain their state correctly?

Traffic engineering with routing protocols

- Load balancing
  - Some hosts/networks/paths are more popular than others
  - Need to shift traffic to avoid overrunning capacity
    - Why is this a different problem from congestion control?
- Avoiding oscillations
  - What if metrics are a function of offered load?
  - Causes dependencies across paths

Challenge #1: Avoiding oscillations

- Choice of link cost defines traffic load
  - Low cost = high probability link belongs to SPT
  - Will attract traffic, which increases cost
- Main problem: convergence
  - Avoid oscillations
  - Achieve good network utilization

Metrics

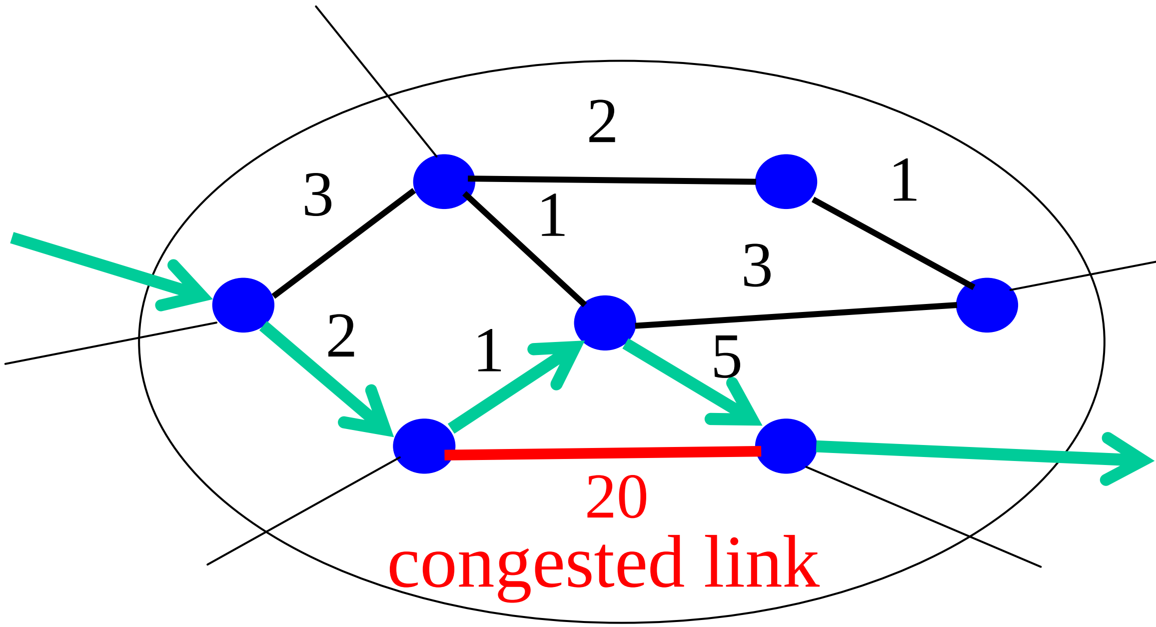
- Capture a general notion of distance
- A heuristic combination of
  - Distance
  - Bandwidth
  - Average traffic
  - Queue length
  - Measured delay

Metric Choices

- Fixed metrics (e.g., hop count)
  - Good only if links are homogeneous
  - Definitely not the case in the Internet
- Static metrics do not take into account
  - Link delay
  - Link capacity
  - Link load (hard to measure)
- But, can improve stability

Original ARPANET Algorithm

- Shortest-path routing based on link metrics
- Instantaneous queue length plus a constant
- Distance vector routing for shortest paths



Original ARPANET Algorithm

- Light load
  - Delay dominated by the constant part (transmission and propagation delay)
- Medium load
  - Queuing delay no longer negligable
  - Moderate traffic shifts to avoid congestion
- Heavy load
  - Very high metrics on congested links
  - Busy links look bad to all of the routers
  - All routers avoid the busy links
  - Routers may send packets on longer paths

Second ARPANET Algorithm (1979)

- Averaging of link metric over time
  - Old: Instantaneous delay fluctuates a lot
  - New: Averaging reduces the fluctuations
- Link-state protocol instead of DV
  - Old: DV led to loops
  - New: Flood metrics and let each router compute shortest paths
- Reduce frequency of updates
  - Old: Sending updates on each change is too much
  - New: Send updates if change passes a threshold

Problem #2: Load balancing

- Conventional static metrics:
  - Proportional to physical distance
  - Inversely proportional to link capacity

- Conventional dynamic metrics:
  - Tune weights based on the offered traffic
  - Network-wide optimization of link-weights
  - Directly minimizes metrics like maximum link utilization

Traffic engineering in IP networks

- Question: given traffic loads arriving at the network, how can we assign costs to links, to achieve desired balance of traffic across routers?

- Formulated as an optimization problem
  - Input parameters: network topology, input traffic matrix
  - Input constraints: minimize delay, maintain 70% average spare capacity on links
  - Compute: assignment of weights to links

Application to AT&T's backbone network

- Performance of the optimized weights
  - Search finds a good (approximate) solution within a few minutes
  - Much better than link capacity or physical distance
- How AT&T changes the link weights
  - Maintenance from Midnight to 6am ET
  - Predict effects of removing links from network
  - Reoptimize links to avoid congestion
  - Configure new weights before disabling equipment (costing-out)