Recap: Finding best paths

No one notion of "best"

Finesse the issue using link costs

Goal becomes finding least cost or shortest path

Distance vector is one way to do it

- Exchange a vector of known destinations and cost
- Suffers count to infinity–heuristics help but are not foolproof

Link-State Routing

Link-State Routing

- Second broad class of routing algorithms
  - More computation than DV but better dynamics
- Widely used in practice
  - Used in Internet/ARPANET from 1979
  - Modern networks use OSPF (L3) and IS-IS (L2)

Link-State Setting

Same distributed setting as for distance vector:

1. Nodes know only the cost to their neighbors; not topology
2. Nodes can talk only to their neighbors using messages
3. All nodes run the same algorithm concurrently
4. Nodes/links may fail, messages may be lost

Link-State Algorithm

Proceeds in two phases:

1. Nodes flood topology with link state packets
   - Each node learns full topology
2. Each node computes its own forwarding table
   - By running Dijkstra (or equivalent)

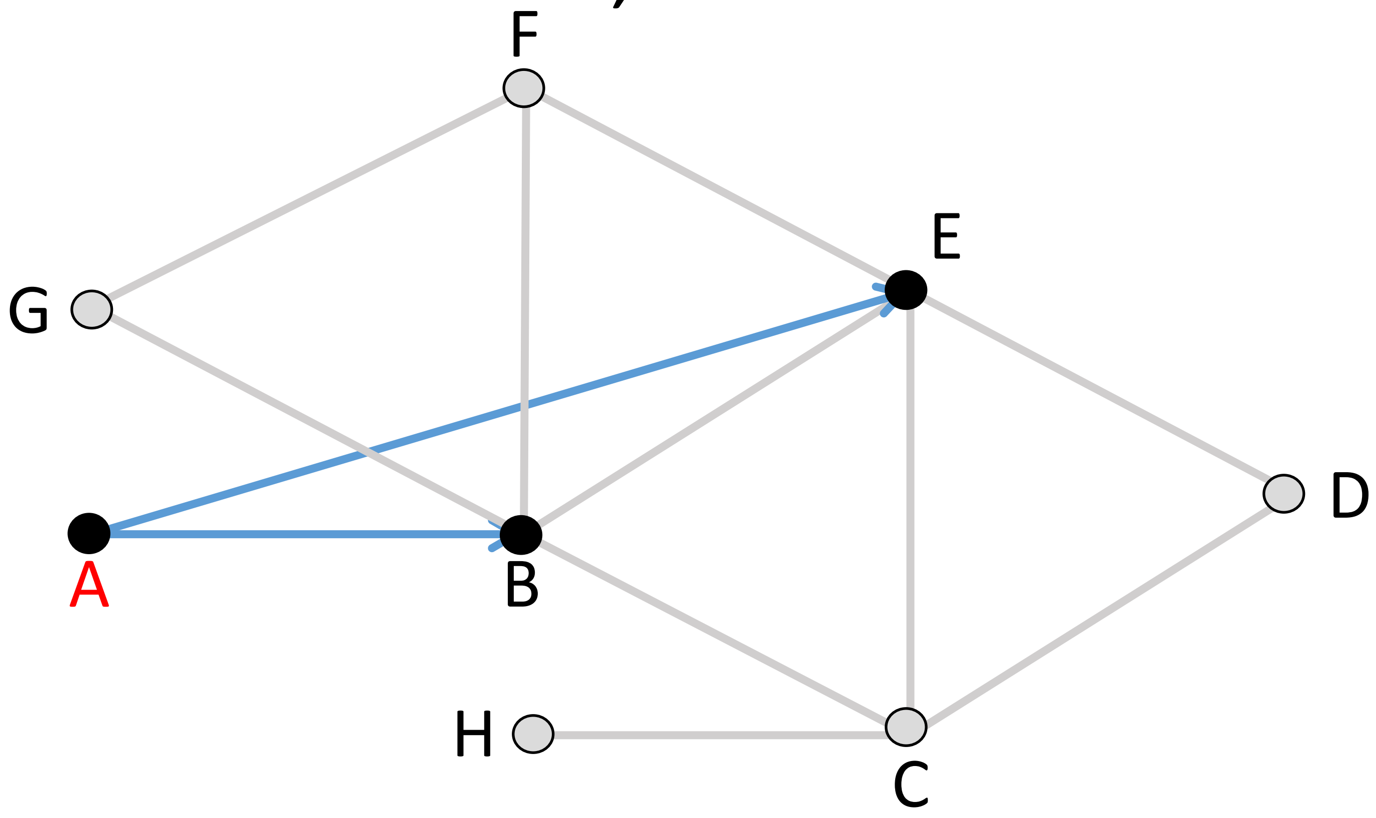
Part 1: Flooding

Flooding

- Rule used at each node:
  - Sends an incoming message on to all other neighbors
  - Remember the message so that it is only flood once

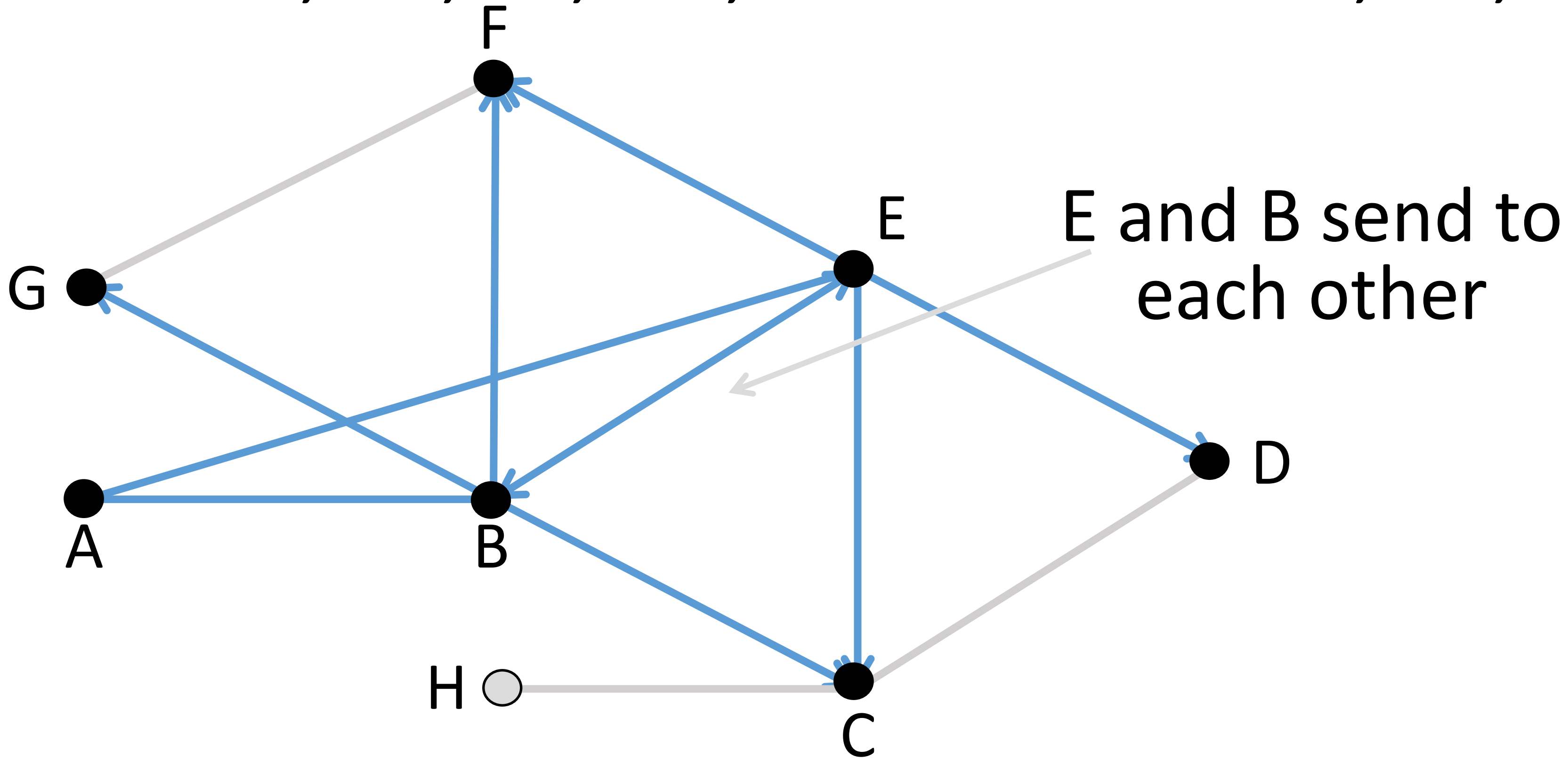
Flooding (2)

- Consider a flood from A; first reaches B via AB, E via AE



Flooding (3)

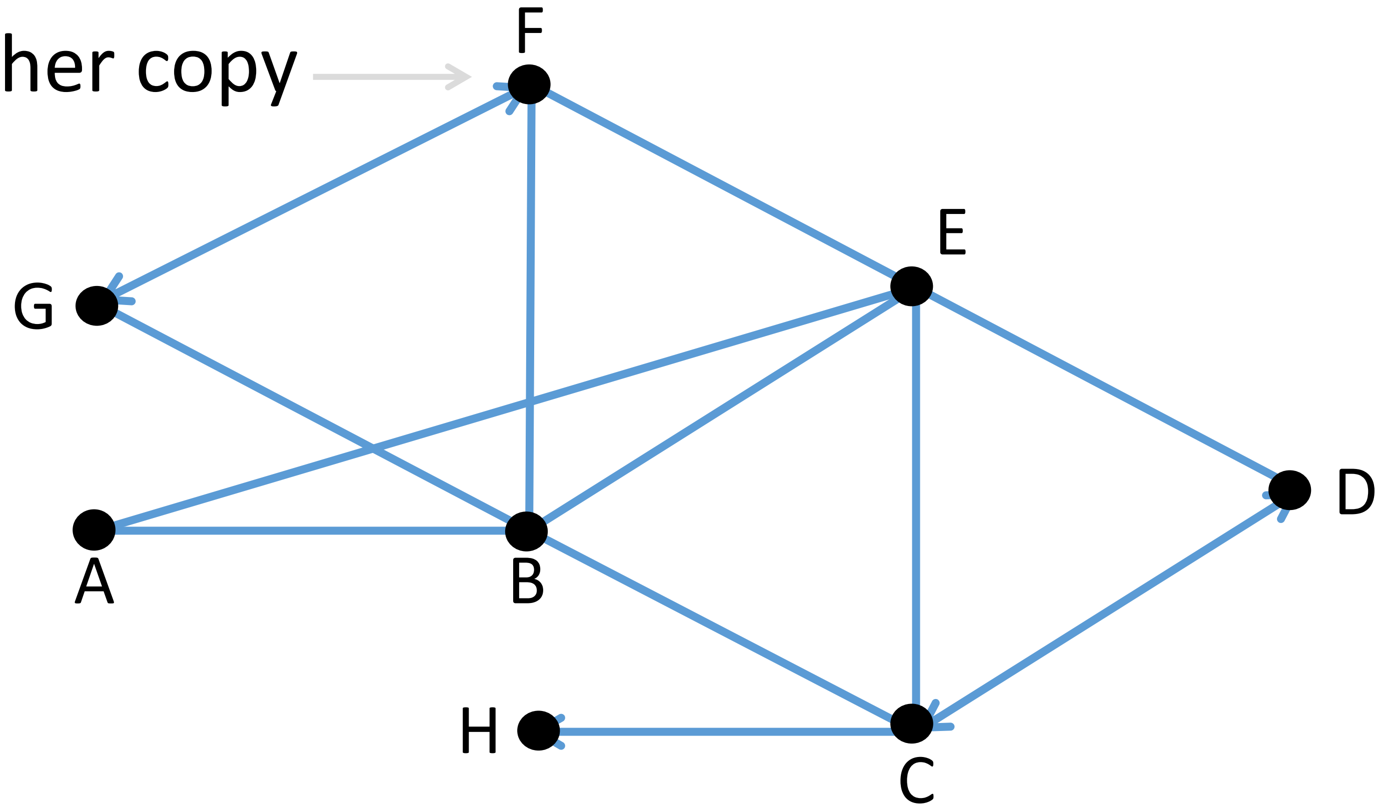
- Next B floods BC, BE, BF, BG, and E floods EB, EC, ED, EF



Flooding (4)

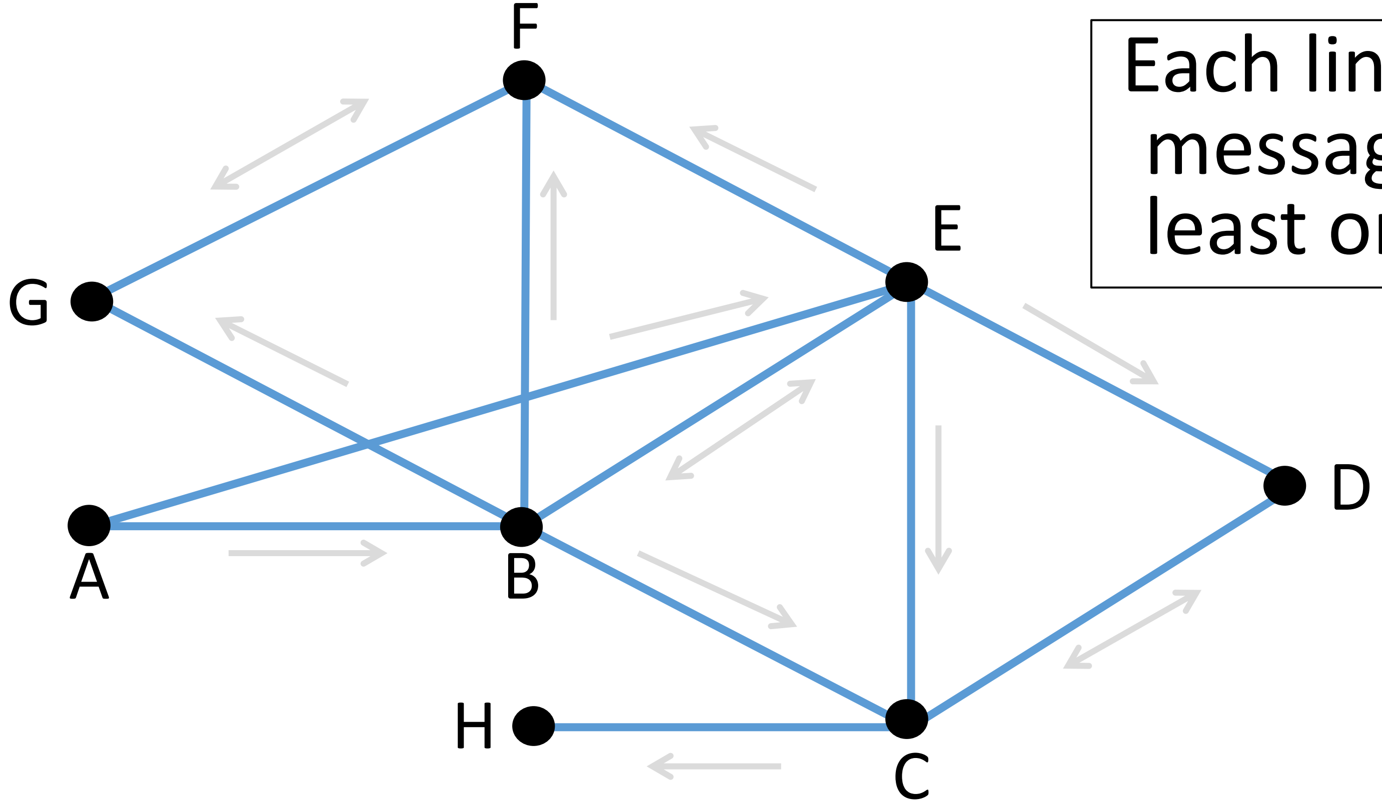
- C floods CD, CH; D floods DC; F floods FG; G floods GF

F gets another copy



Flooding (5)

- H has no-one to flood … and we're done



Each link carries the message, and in at least one direction

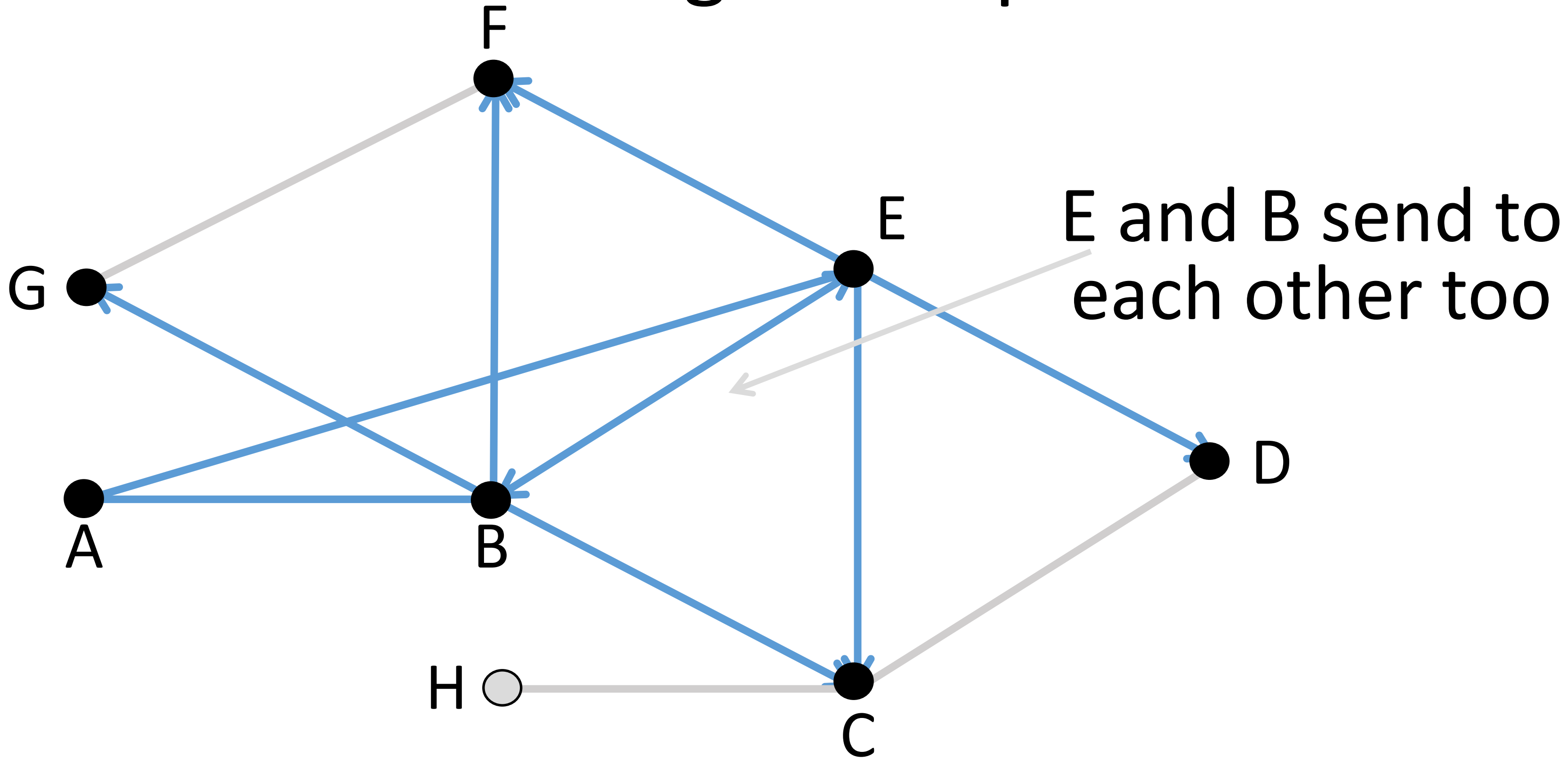
Flooding Details

- Remember message (to stop flood) using source and sequence number
  - So next message (with higher sequence) will go through
- To make flooding reliable, use ARQ
  - So receiver acknowledges, and sender resends if needed

Problem?

Flooding Problem

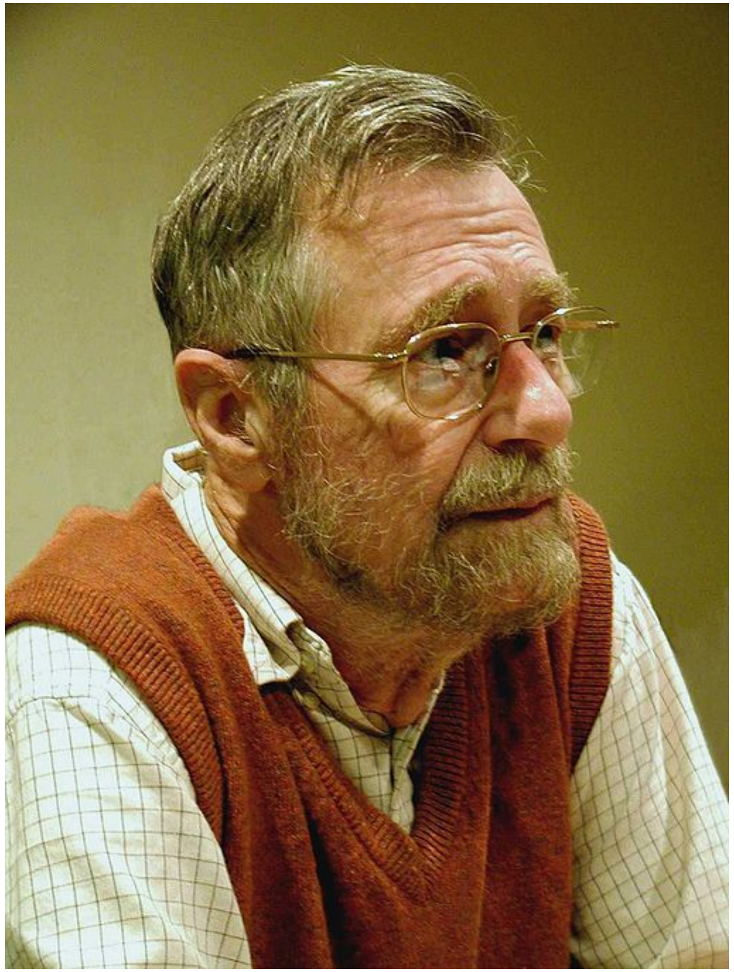
- F receives the same message multiple times



Part 2: Dijkstra’s Algorithm

Edsger W. Dijkstra (1930-2002)

- Famous computer scientist
  - Programming languages
  - Distributed algorithms
  - Program verification
- Dijkstra's algorithm, 1969
  - Single-source shortest paths, given network with non-negative link costs



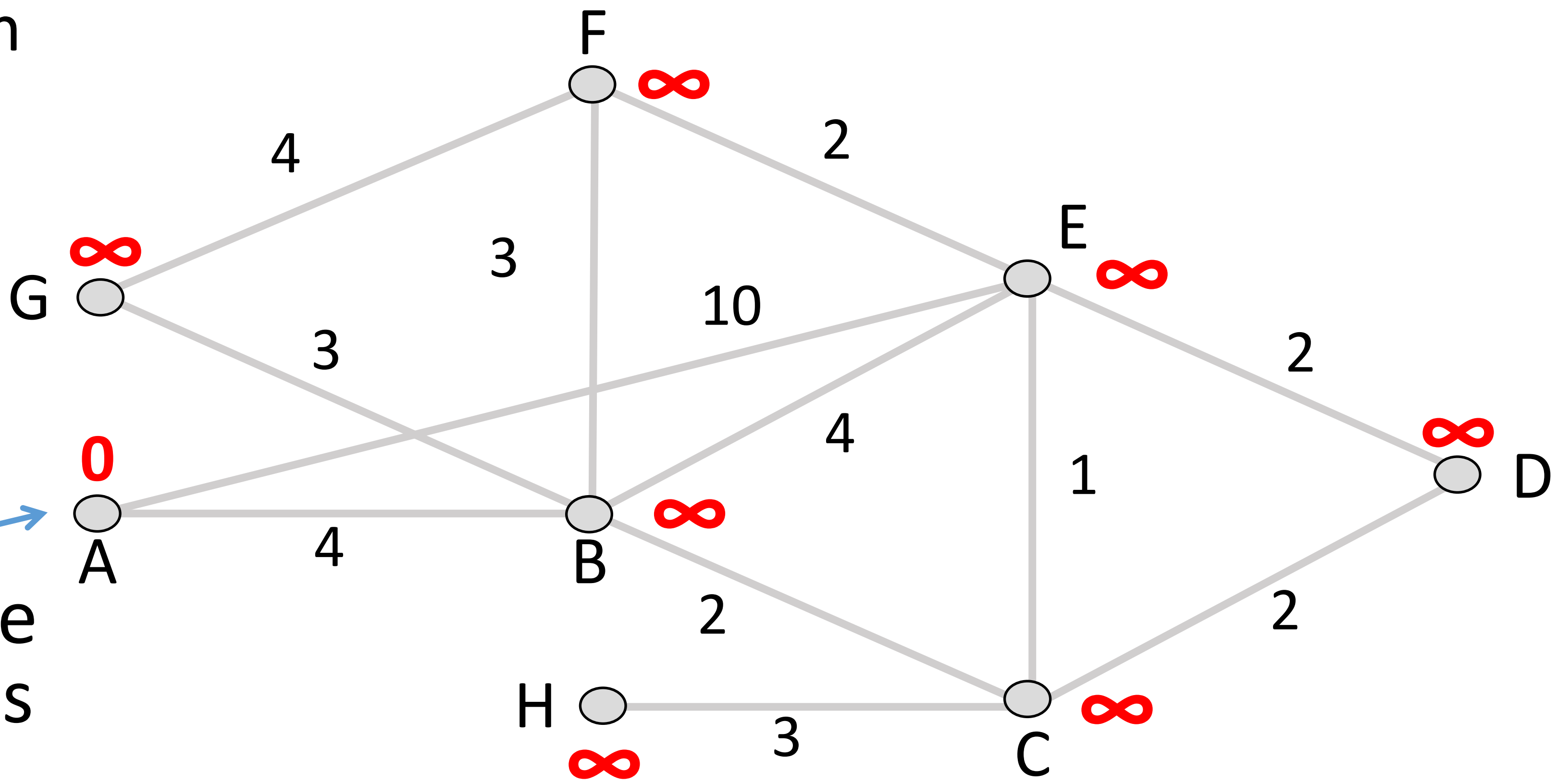
Dijkstra's Algorithm

Algorithm:

- Mark all nodes tentative, set distances from source to 0 (zero) for source, and ∞ (infinity) for all other nodes
- While tentative nodes remain:
    - Extract N, a node with lowest distance
    - Add link to N to the shortest path tree
    - Relax the distances of neighbors of N by lowering any better distance estimates

Dijkstra's Algorithm (2)

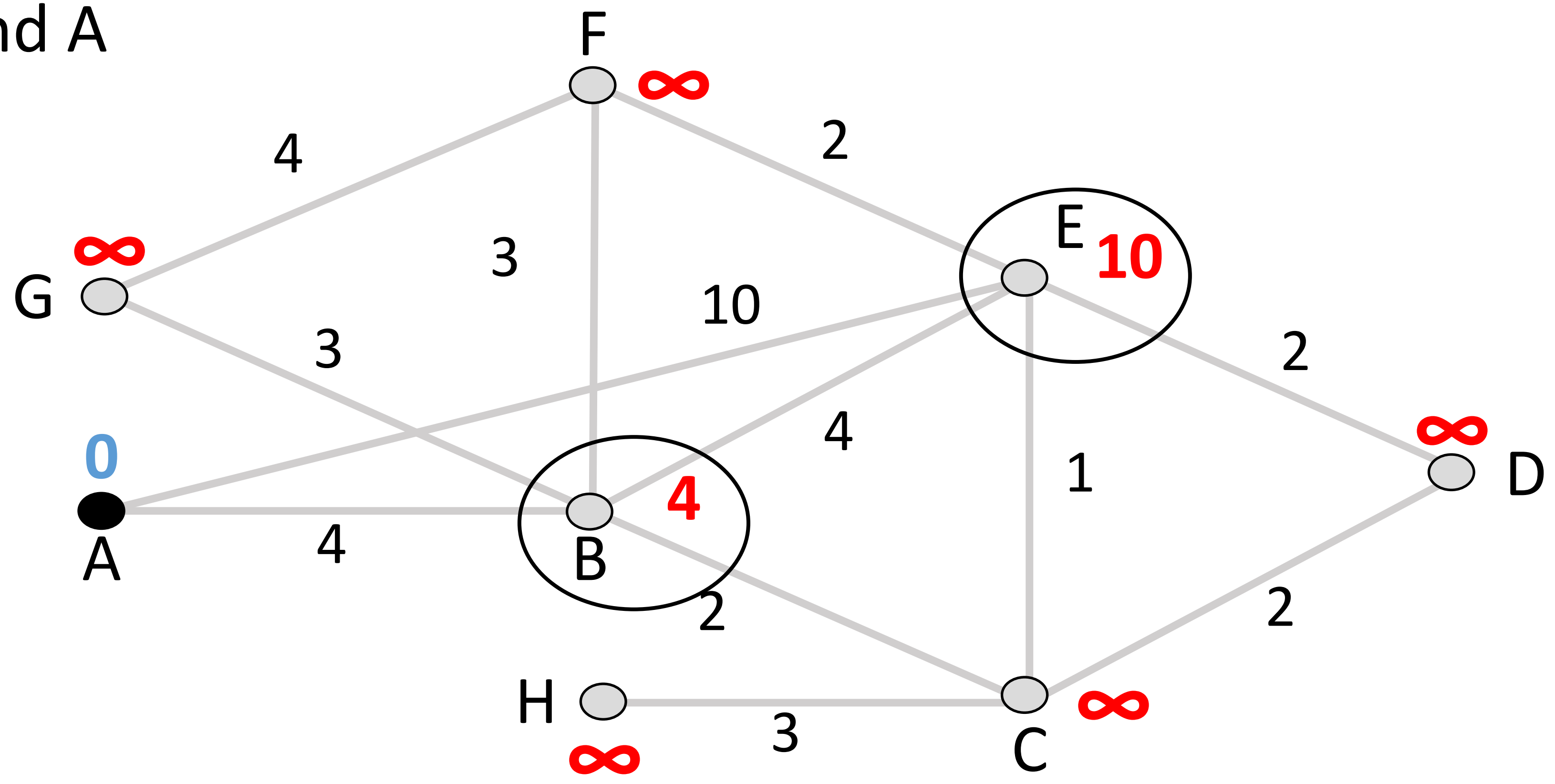
- Initialization



We'll compute shortest paths from A

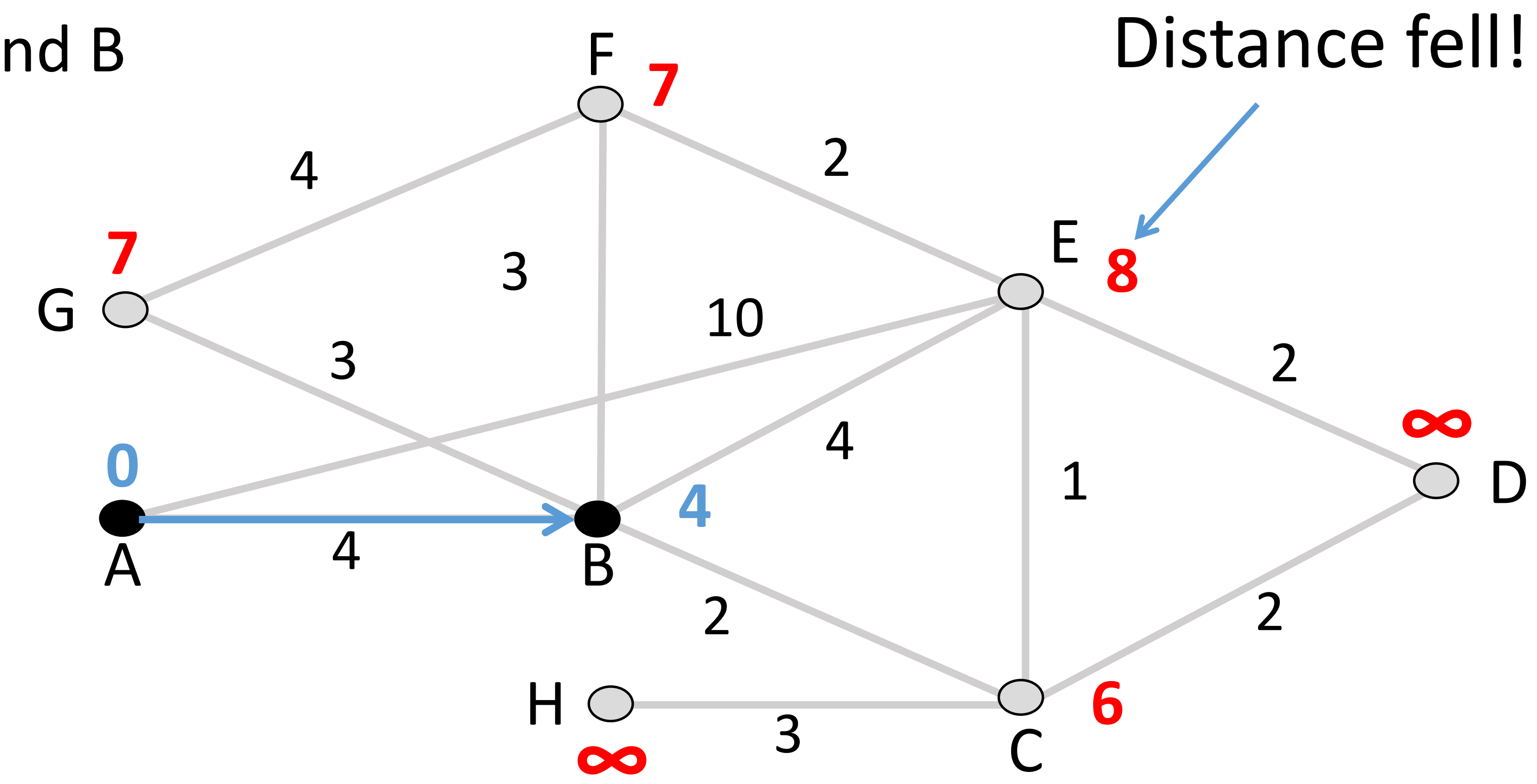
Dijkstra's Algorithm (3)

- Relax around A



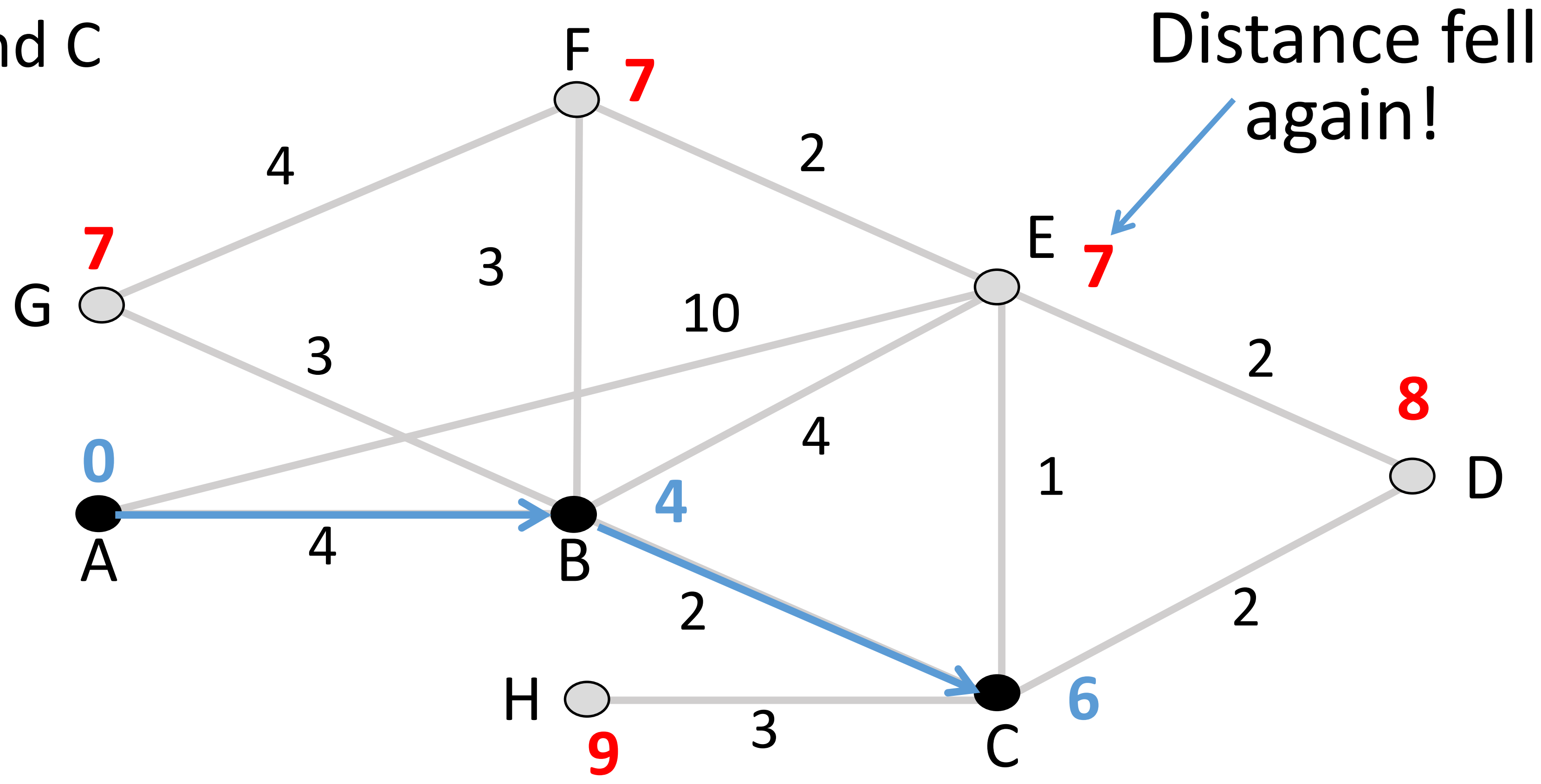
Dijkstra's Algorithm (4)

- Relax around B



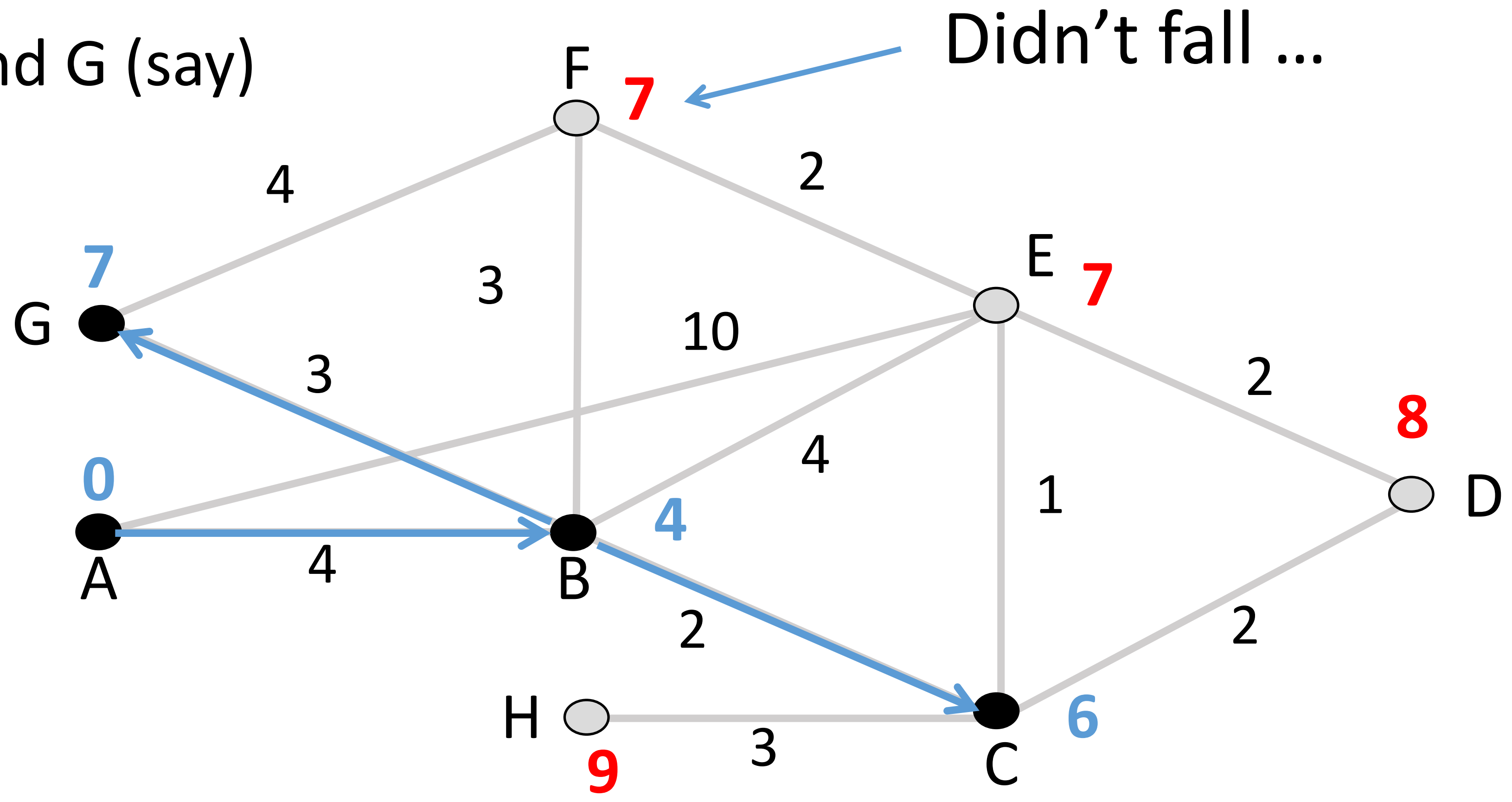
Dijkstra’s Algorithm (5)

- Relax around C



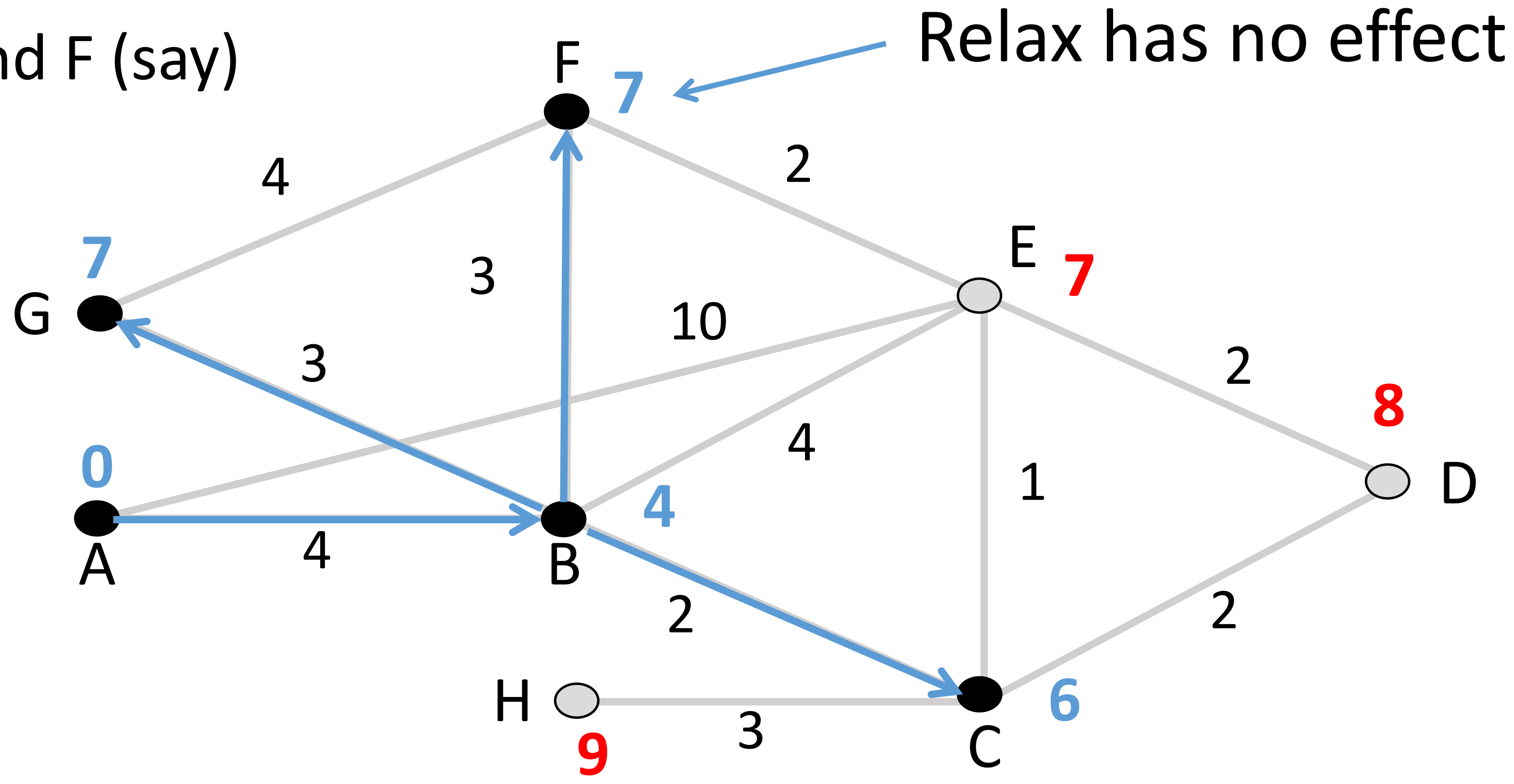
Dijkstra's Algorithm (6)

- Relax around G (say)



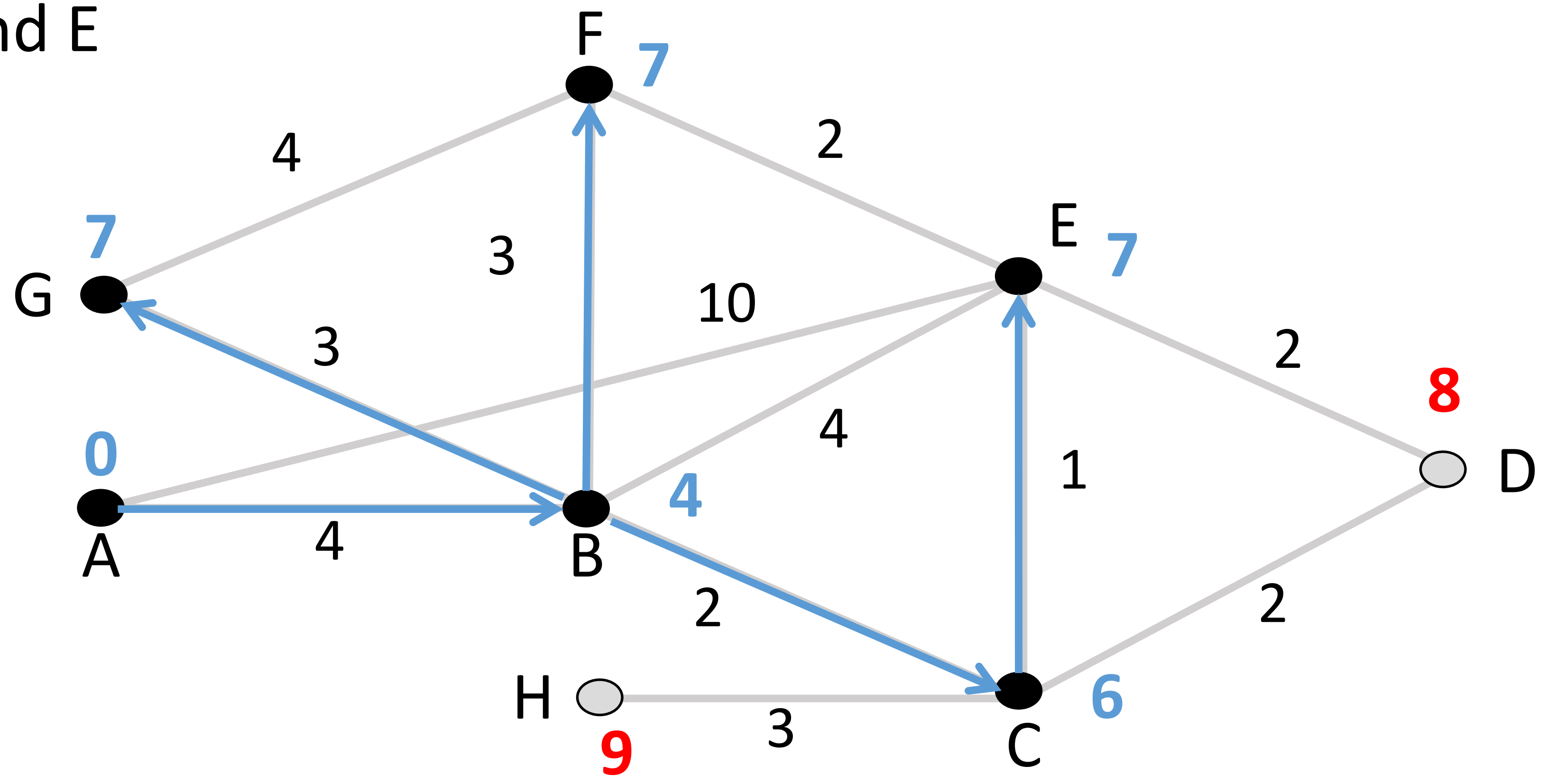
Dijkstra's Algorithm (7)

- Relax around F (say)



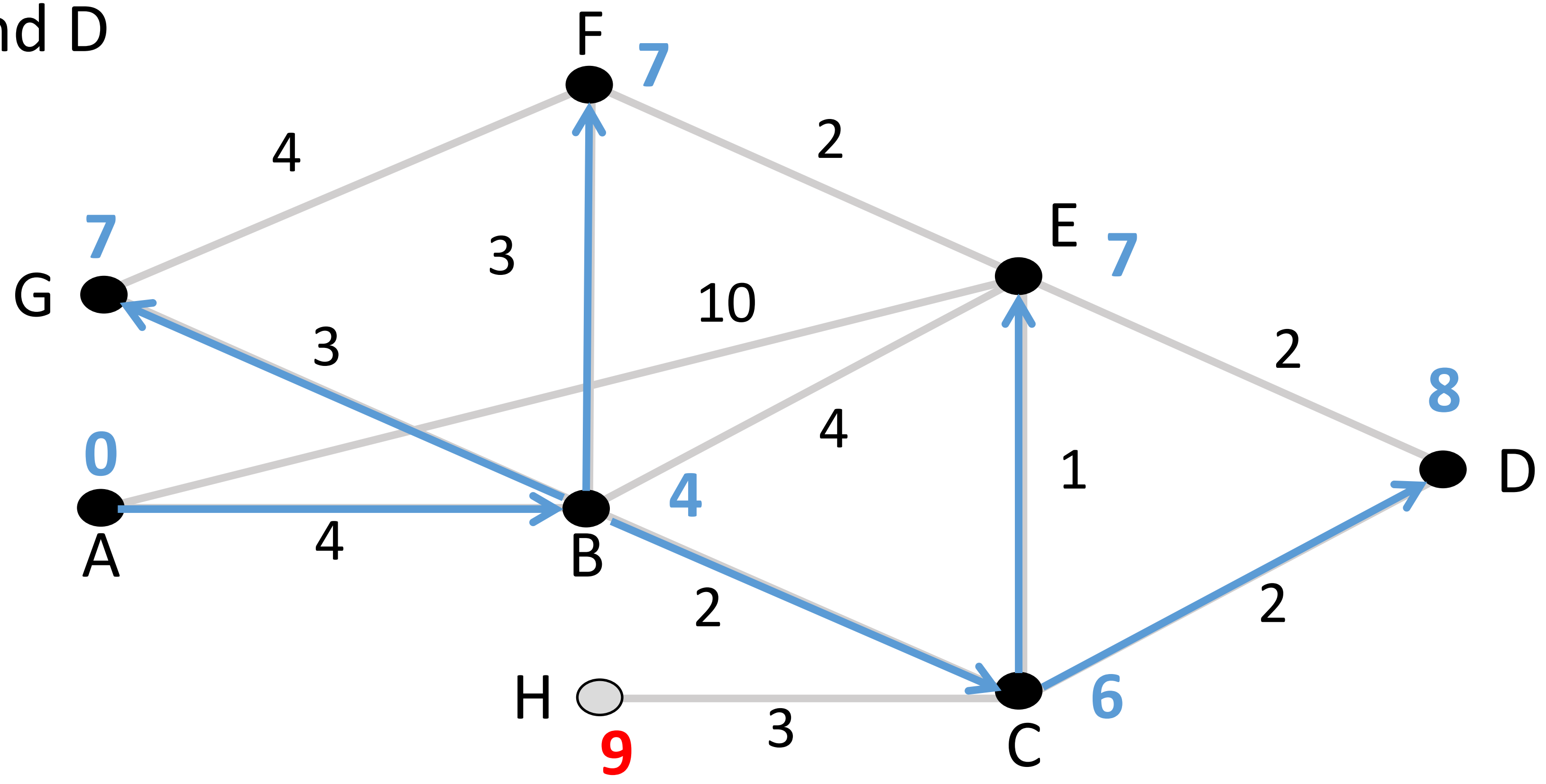
Dijkstra's Algorithm (8)

- Relax around E



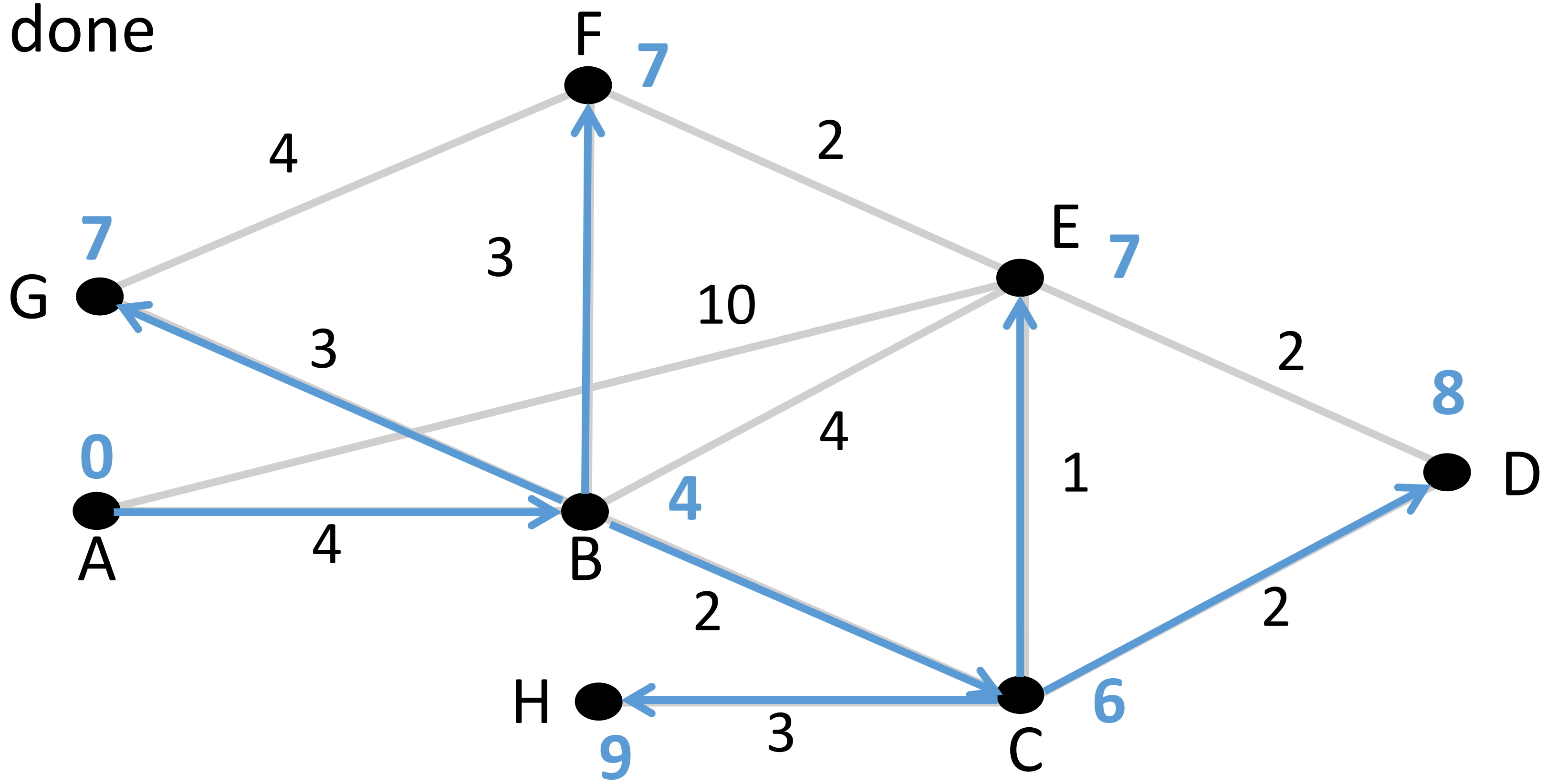
Dijkstra's Algorithm (9)

- Relax around D



Dijkstra's Algorithm (10)

- Finally, H … done



Dijkstra Comments

- Finds shortest paths in order of increasing distance from source
  - Leverages optimality property
- Runtime depends on cost of extracting min-cost node
  - Superlinear in network size (grows fast)
  - Using Fibonacci Heaps the complexity is $O(|E|+|V|\log|V|)$
- Gives complete source/sink tree
  - More than needed for forwarding!
  - But requires complete topology

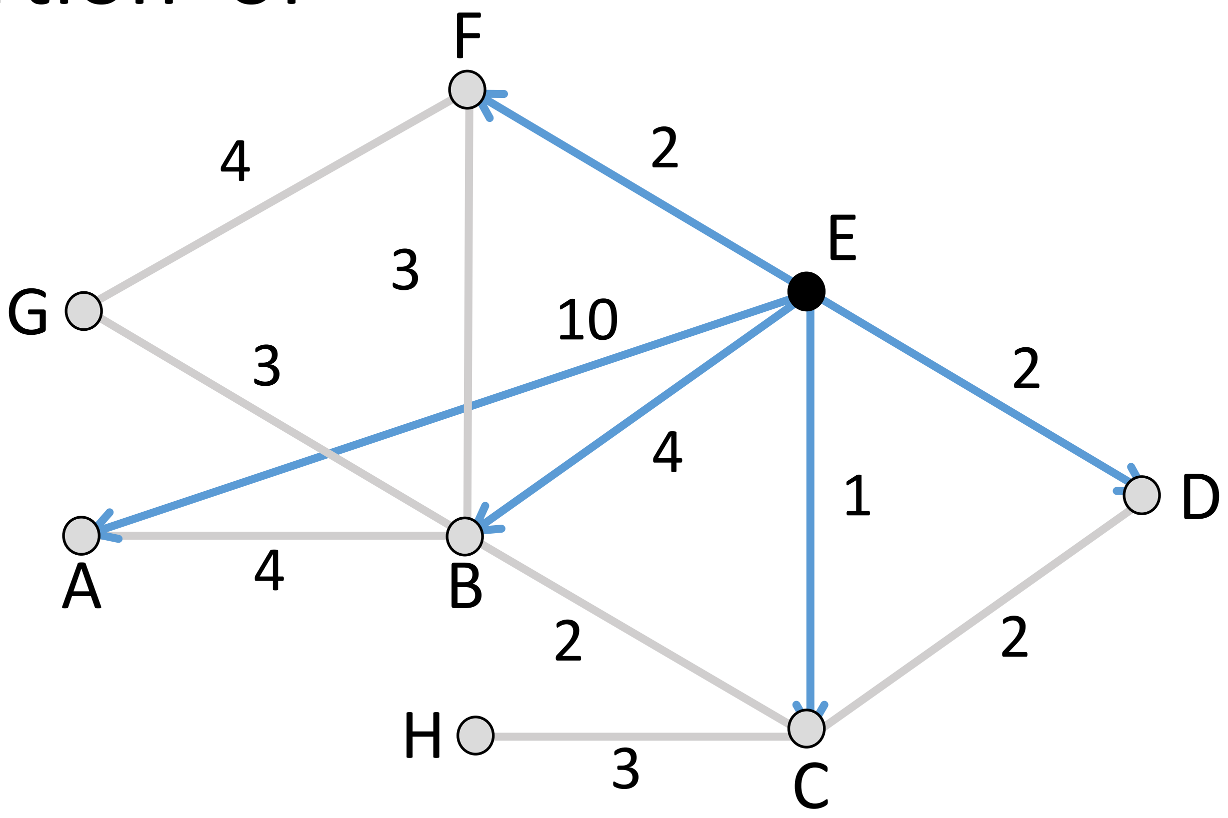
Bringing it all together…

Phase 1: Topology Dissemination

- Each node floods link state packet (LSP) that describes their portion of the topology

Node E's LSP flooded to A, B, C, D, and F

Seq. #	
A	10
B	4
C	1
D	2
F	2

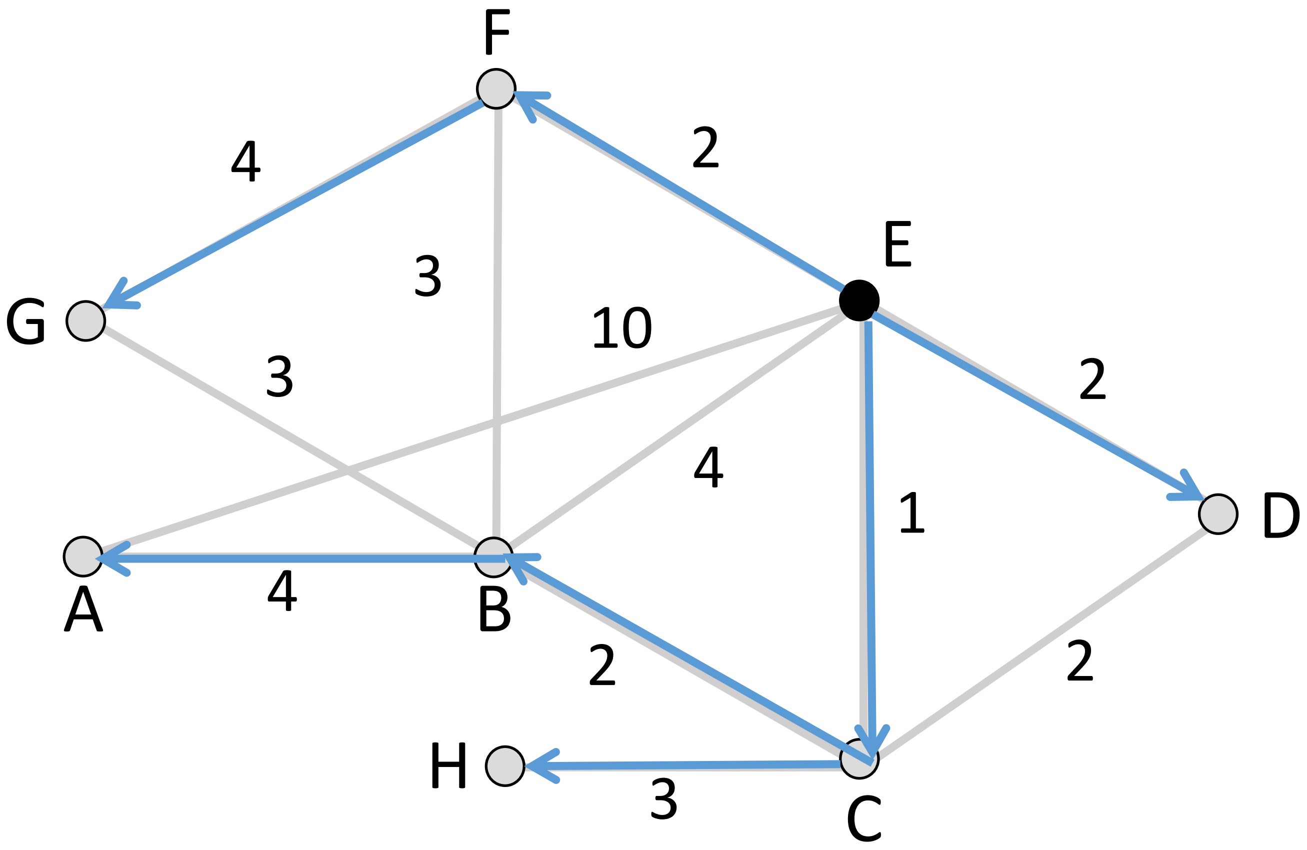


Phase 2: Route Computation

- Each node has full topology
  - By combining all LSPs
- Each node simply runs Dijkstra
  - Replicated computation, but finds required routes directly
  - Compile forwarding table from sink/source tree
  - That's it folks!

Forwarding Table

Source Tree for E (from Dijkstra)



E's Forwarding Table

To	Next
A	C
B	C
C	C
D	D
E	--
F	F
G	F
H	C

Handling Changes

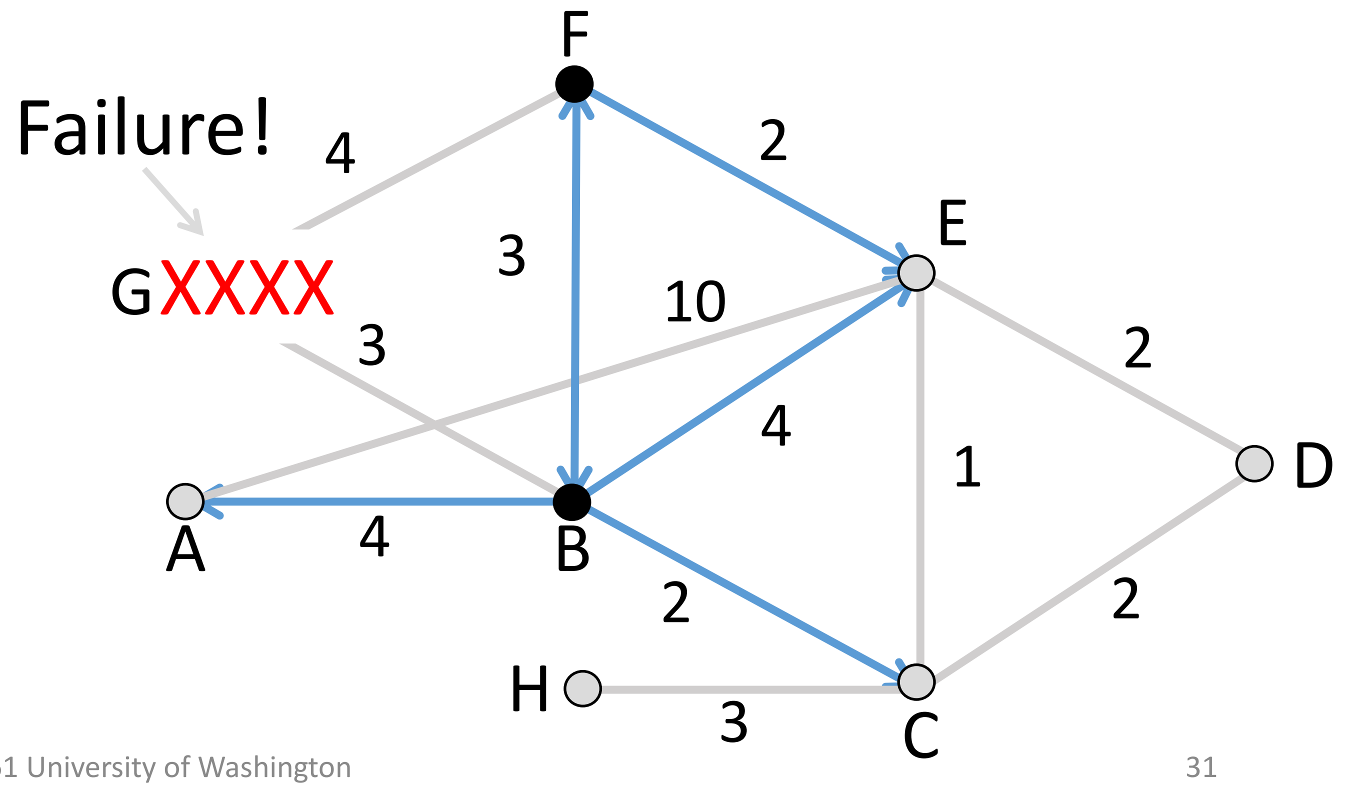
- On change, flood updated LSPs, re-compute routes
  - E.g., nodes adjacent to failed link or node initiate

B's LSP

Seq. #	
A	4
C	2
E	4
F	3
G	∞

F's LSP

Seq. #	
B	3
E	2
G	∞



Handling Changes (2)

- Link failure
  - Both nodes notice, send updated LSPs
  - Link is removed from topology
- Node failure
  - All neighbors notice a link has failed
  - Failed node can’t update its own LSP
  - But it is OK: all links to node removed

Handling Changes (3)

- Addition of a link or node
  - Add LSP of new node to topology
  - Old LSPs are updated with new link

- Additions are the easy case …

Link-State Complications

- Things that can go wrong:
  - Seq. number reaches max, or is corrupted
  - Node crashes and loses seq. number
  - Network partitions then heals
- Strategy:
  - Include age on LSPs and forget old information that is not refreshed
- Much of the complexity is due to handling corner cases

DV/LS Comparison

Goal	Distance Vector	Link-State
Correctness	Distributed Bellman-Ford	Replicated Dijkstra
Efficient paths	Approx. with shortest paths	Approx. with shortest paths
Fair paths	Approx. with shortest paths	Approx. with shortest paths
Fast convergence	Slow – many exchanges	Fast – flood and compute
Scalability	Excellent – storage/compute	Moderate – storage/compute

IS-IS and OSPF Protocols

- Widely used in large enterprise and ISP networks
  - IS-IS = Intermediate System to Intermediate System
  - OSPF = Open Shortest Path First
- Link-state protocol with many added features
  - E.g., “Areas” for scalability

Equal-Cost Multi-Path Routing

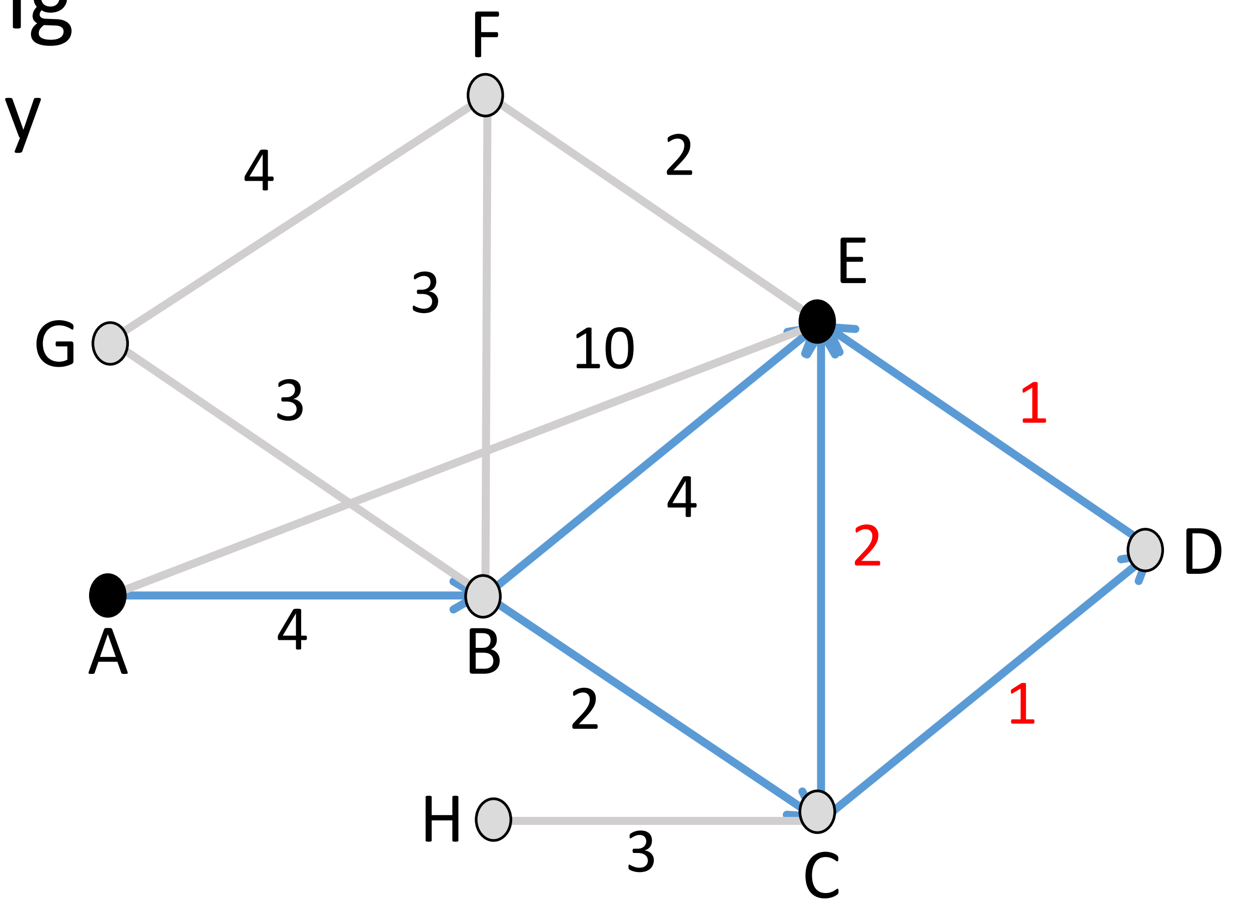
Multipath Routing

- Allow multiple routing paths from node to destination be used at once
  - Topology has them for redundancy
  - Using them can improve performance
- Questions:
  - How do we find multiple paths?
  - How do we send traffic along them?

Equal-Cost Multipath Routes

- One form of multipath routing
  - Extends shortest path model by keeping set if there are ties

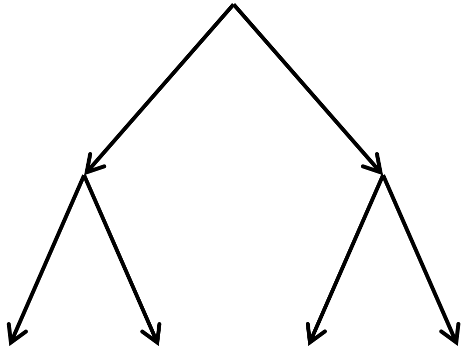
- Consider A→E
  - ABE = 4 + 4 = 8
  - ABCE = 4 + 2 + 2 = 8
  - ABCDE = 4 + 2 + 1 + 1 = 8
  - Use them all!



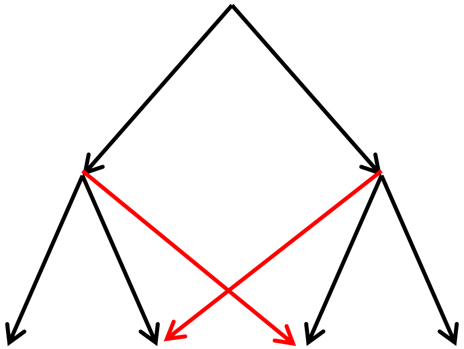
Source "Trees"

- With ECMP, source/sink "tree" is a directed acyclic graph (DAG)
  - Each node has set of next hops
  - Still a compact representation

Tree



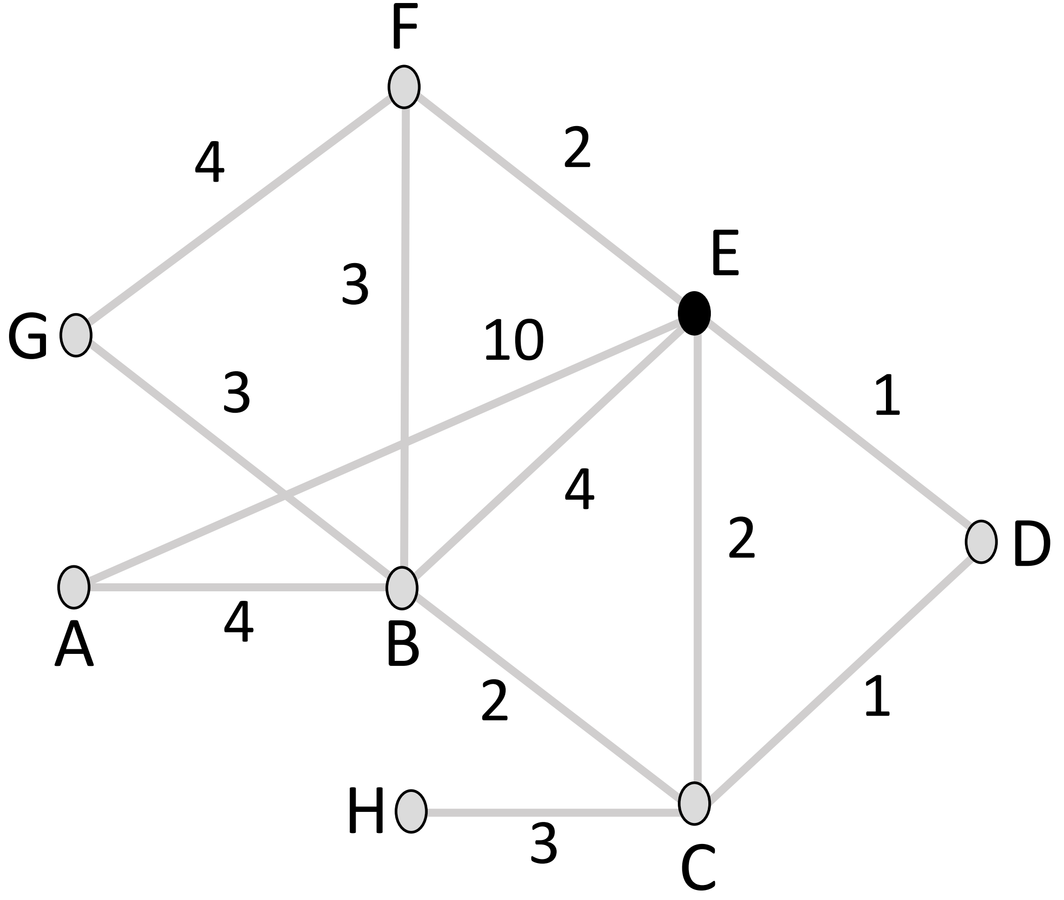
DAG



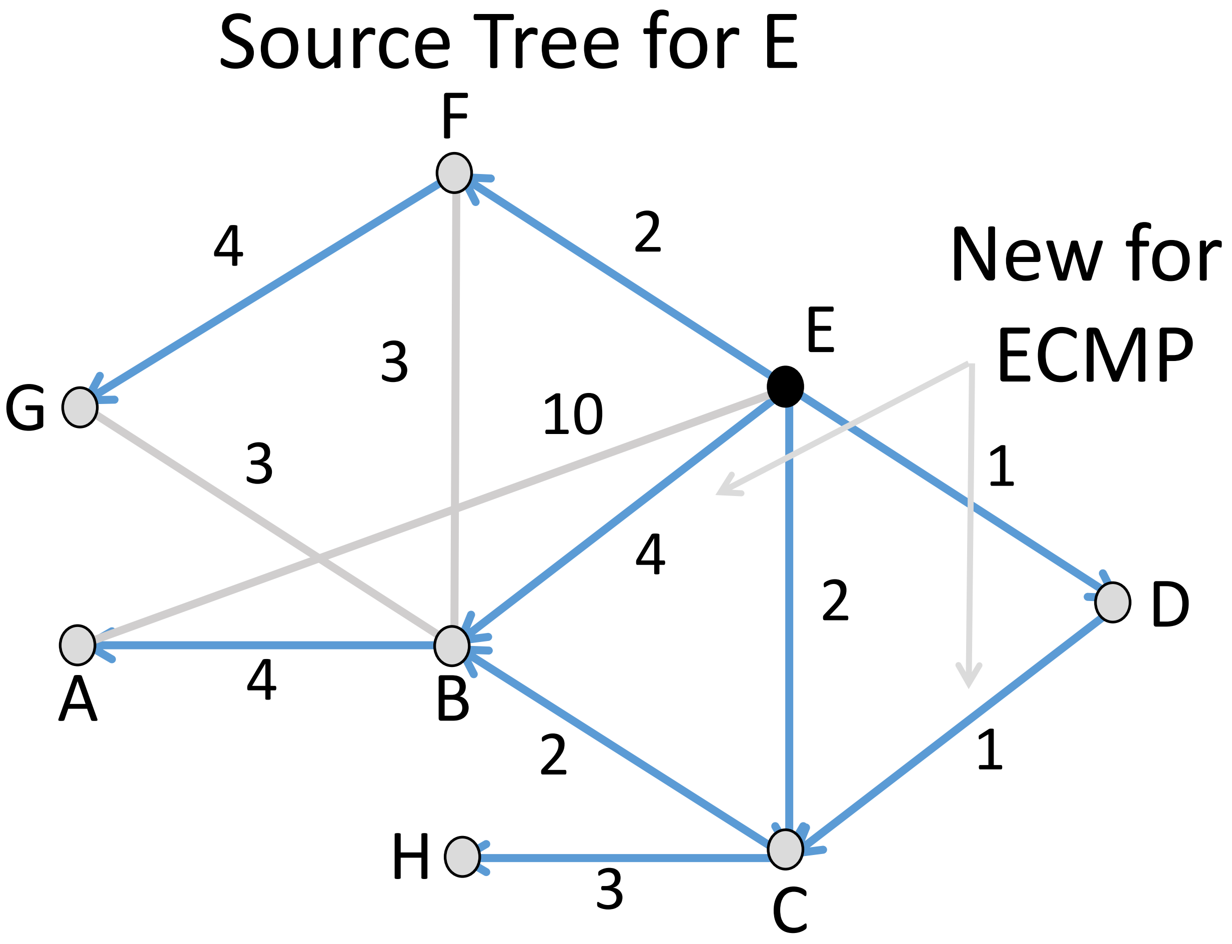
Source "Trees" (2)

- Find the source "tree" for E
  - Procedure is Dijkstra, simply remember set of next hops
  - Compile forwarding table similarly, may have set of next hops

- Straightforward to extend DV too
  - Just remember set of neighbors



Source “Trees” (3)



→

E’s Forwarding Table

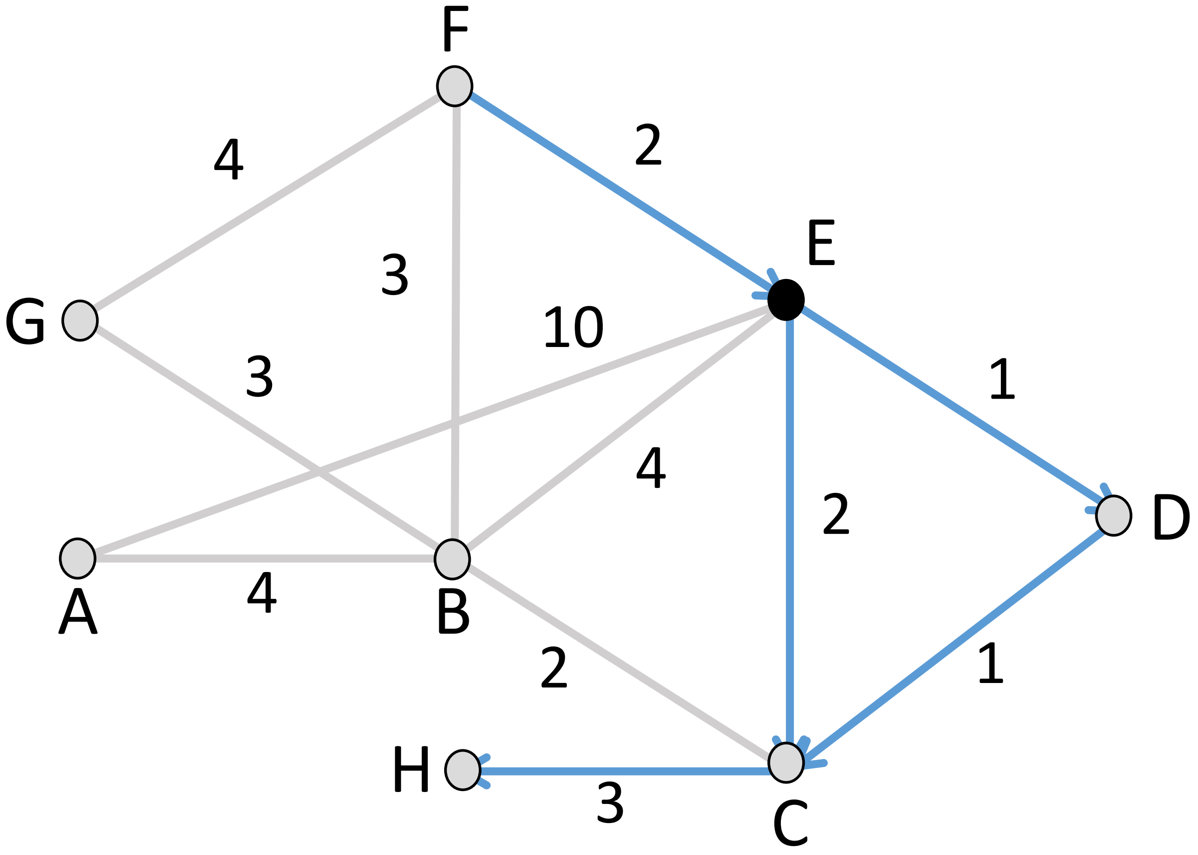
Node	Next hops
A	B, C, D
B	B, C, D
C	C, D
D	D
E	--
F	F
G	F
H	C, D

Forwarding with ECMP

- Could randomly pick a next hop for each packet based on destination
  - Balances load, but adds jitter
- Try sending packets from a flow on the same path
  - Flow identified using 5-tuple
  - Map flow identifier to single next hop
  - No jitter within flow, but less balanced

Forwarding with ECMP (2)

Multipath routes from F/E to C/H



E's Forwarding Choices

Flow	Possible next hops	Example choice
F → H	C, D	D
F → C	C, D	D
E → H	C, D	C
E → C	C, D	C

Use both paths to get to one destination