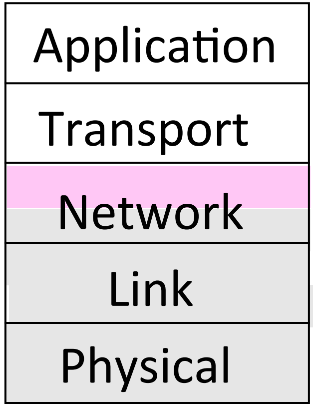
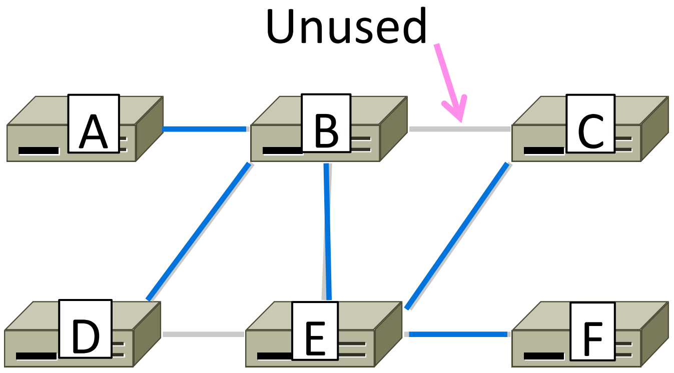
Where we are in the Course

- More fun in the Network Layer!
  - We've covered packet forwarding
  - Now we'll learn about <u>routing</u>

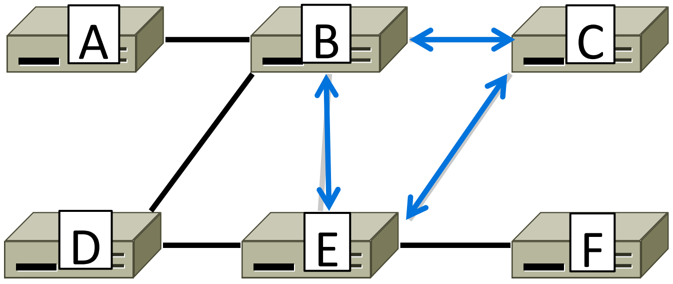


Improving on the Spanning Tree

- Spanning tree provides basic connectivity
  - e.g., some path B→C



- Routing uses all links to find “best” paths
  - e.g., use BC, BE, and CE



Perspective on Bandwidth Allocation

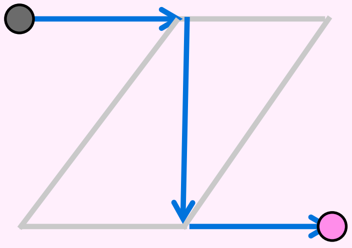
- Routing allocates network bandwidth adapting to failures; other mechanisms used at other timescales

Mechanism	Timescale / Adaptation
Load-sensitive routing	Seconds / Traffic hotspots
Routing	Minutes / Equipment failures
Traffic Engineering	Hours / Network load
Provisioning	Months / Network customers

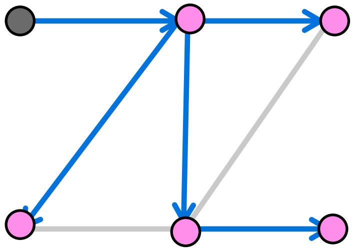
Delivery Models

- Different routing used for different delivery models

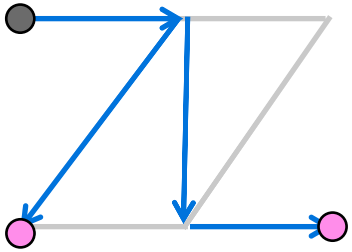
Unicast
(§5.2)



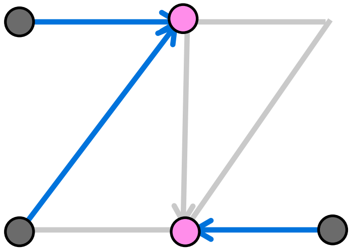
Broadcast
(§5.2.7)



Multicast
(§5.2.8)



Anycast
(§5.2.9)



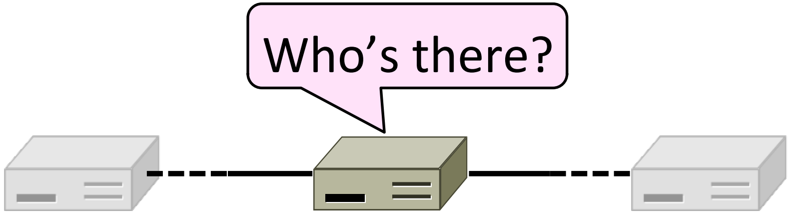
Goals of Routing Algorithms

- We want several properties of any routing scheme:

Property	Meaning
Correctness	Finds paths that work
Efficient paths	Uses network bandwidth well
Fair paths	Doesn't starve any nodes
Fast convergence	Recovers quickly after changes
Scalability	Works well as network grows large

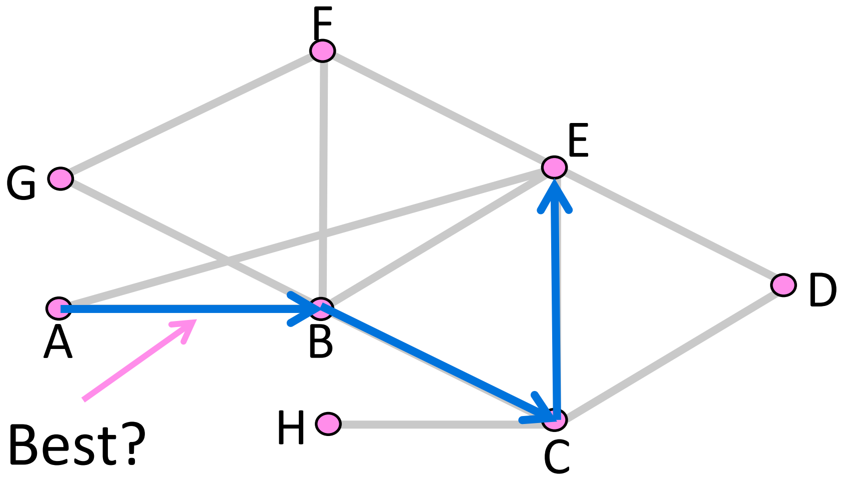
Rules of Routing Algorithms

- Decentralized, distributed setting
  - All nodes are alike; no controller
  - Nodes only know what they learn by exchanging messages with neighbors
  - Nodes operate concurrently
  - May be node/link/message failures



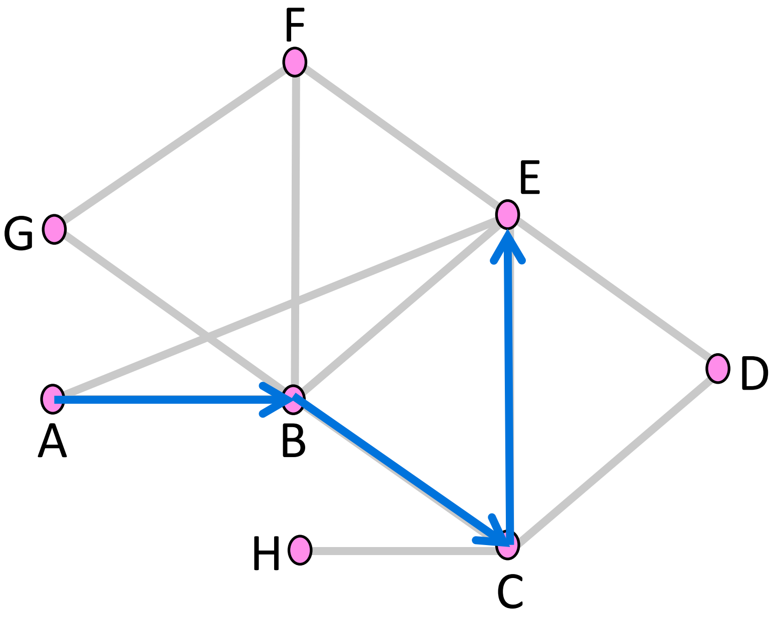
Topic

- Defining "best" paths with link costs
  - These are shortest path routes



What are “Best” paths anyhow?

- Many possibilities:
  - Latency, avoid circuitous paths
  - Bandwidth, avoid slow links
  - Money, avoid expensive links
  - Hops, to reduce switching
- But only consider topology
  - Ignore workload, e.g., hotspots



Shortest Paths

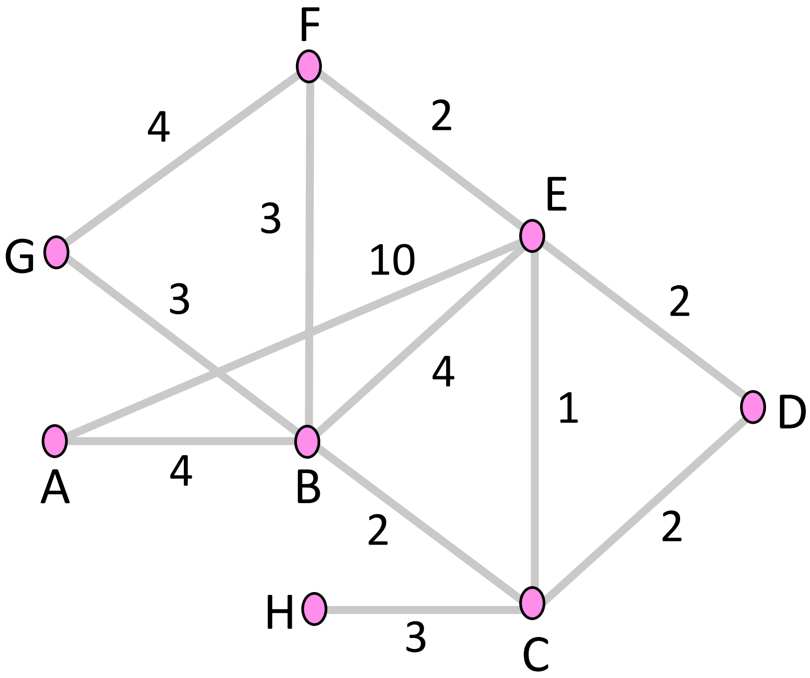
We'll approximate "best" by a cost function that captures the factors

- Often call lowest "shortest"

1. Assign each link a cost (distance)
2. Define best path between each pair of nodes as the path that has the lowest total cost (or is shortest)
3. Pick randomly to any break ties

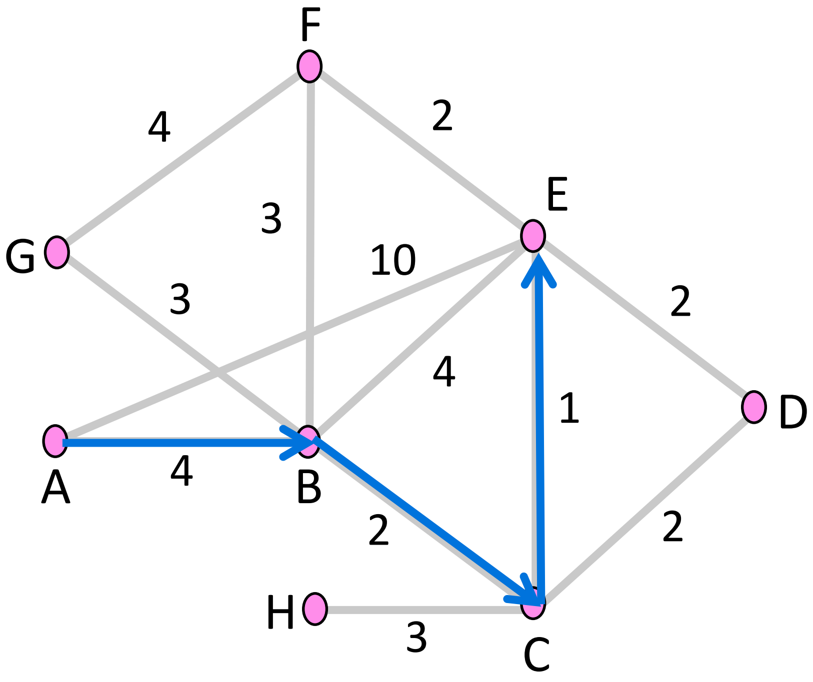
Shortest Paths (2)

- Find the shortest path A → E
- All links are bidirectional, with equal costs in each direction
  - Can extend model to unequal costs if needed



Shortest Paths (3)

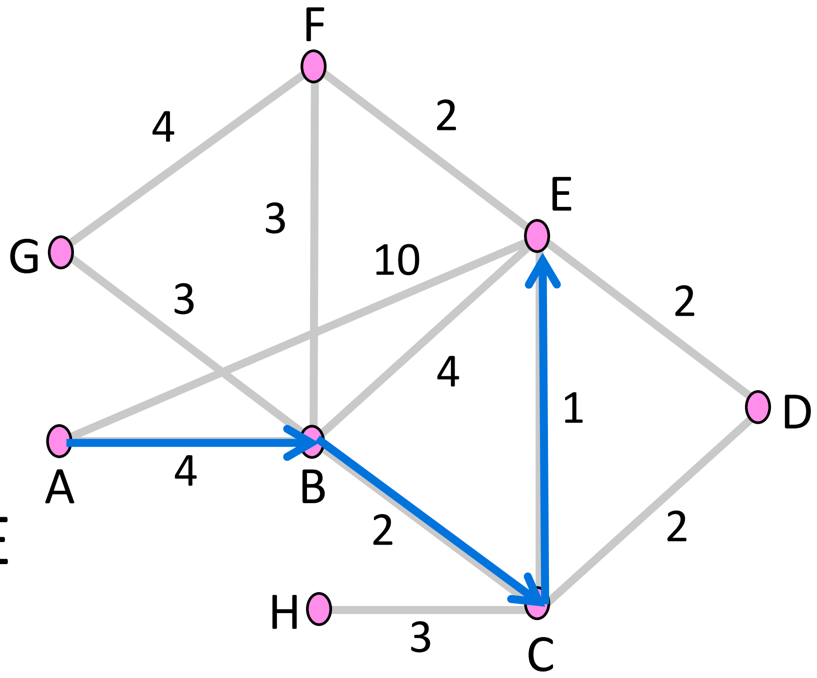
- ABCE is a shortest path
- dist(ABCE) = 4 + 2 + 1 = 7
- This is less than:
  - dist(ABE) = 8
  - dist(ABFE) = 9
  - dist(AE) = 10
  - dist(ABCDE) = 10



Shortest Paths (4)

- Optimality property:
  - Subpaths of shortest paths are also shortest paths
- ABCE is a shortest path

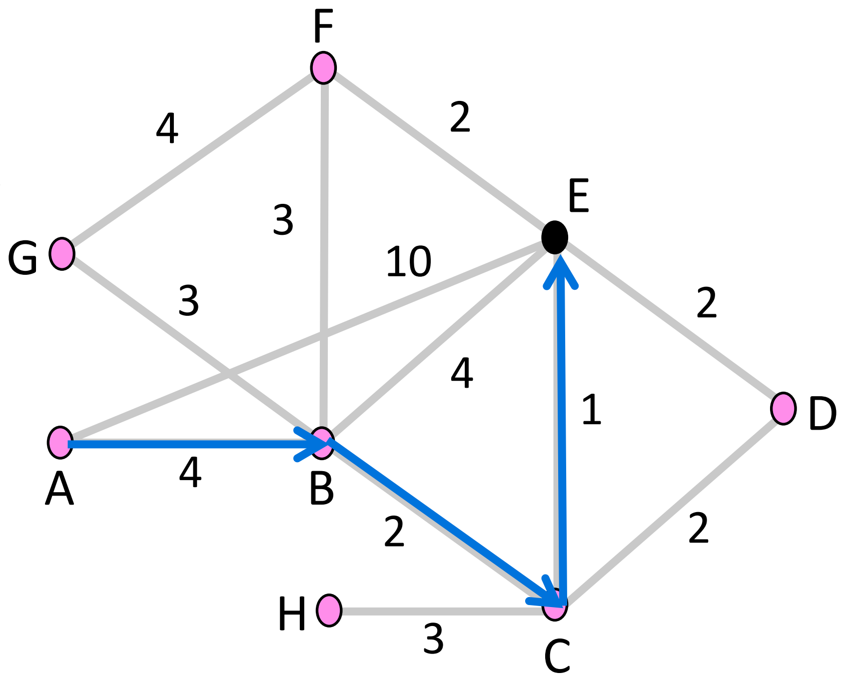
  →So are ABC, AB, BCE, BC, CE



Sink Trees

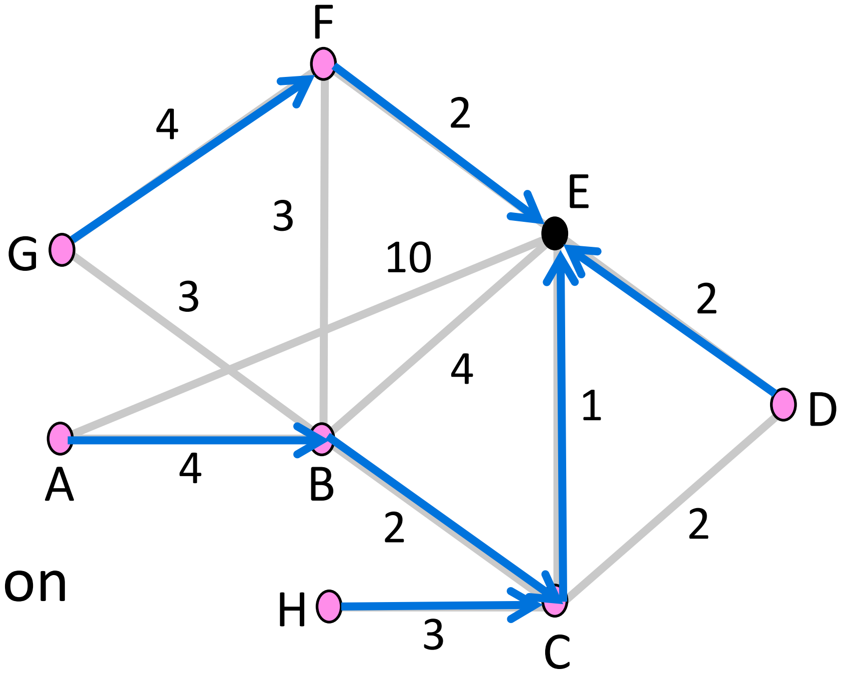
- Sink tree for a destination is the union of all shortest paths towards the destination
  - Similarly source tree

- Find the sink tree for E



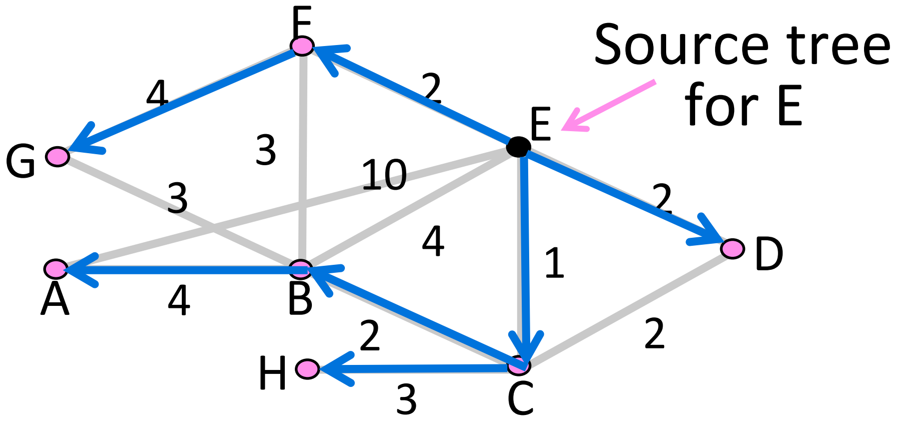
Sink Trees (2)

- Implications:
  - Only need to use destination to follow shortest paths
  - Each node only need to send to the next hop
- <u>Forwarding table </u>at a node
  - Lists next hop for each destination
  - Routing table may know more



Topic

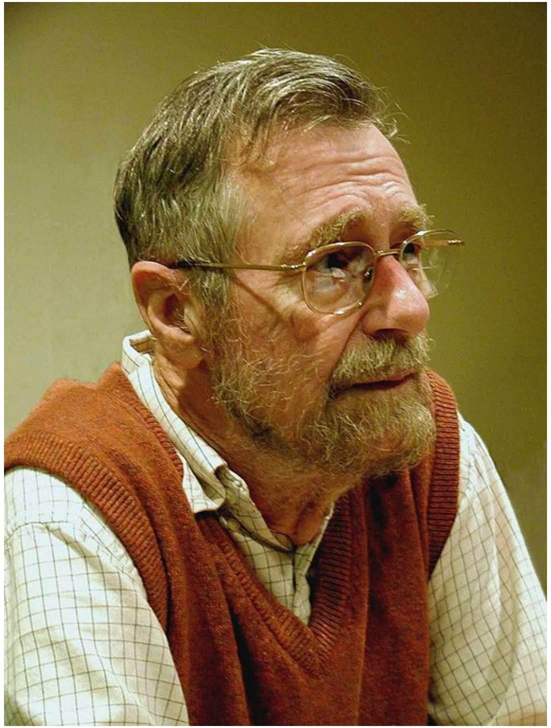
- How to compute shortest paths given the network topology
  - With Dijkstra's algorithm



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



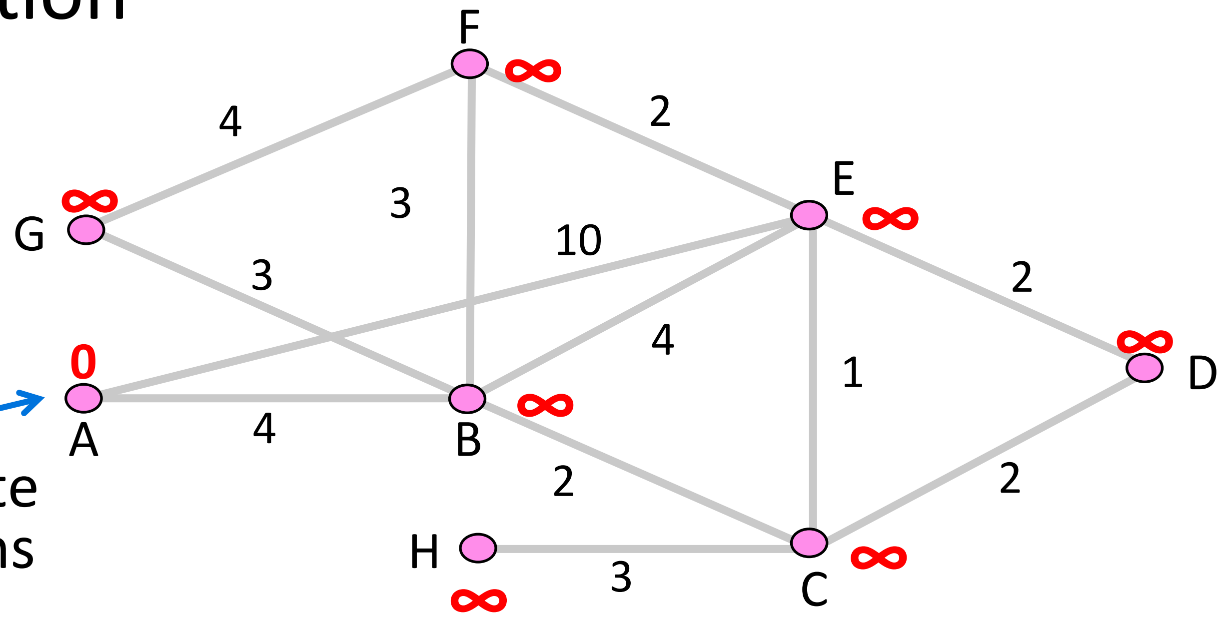
Dijkstra's Algorithm

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)

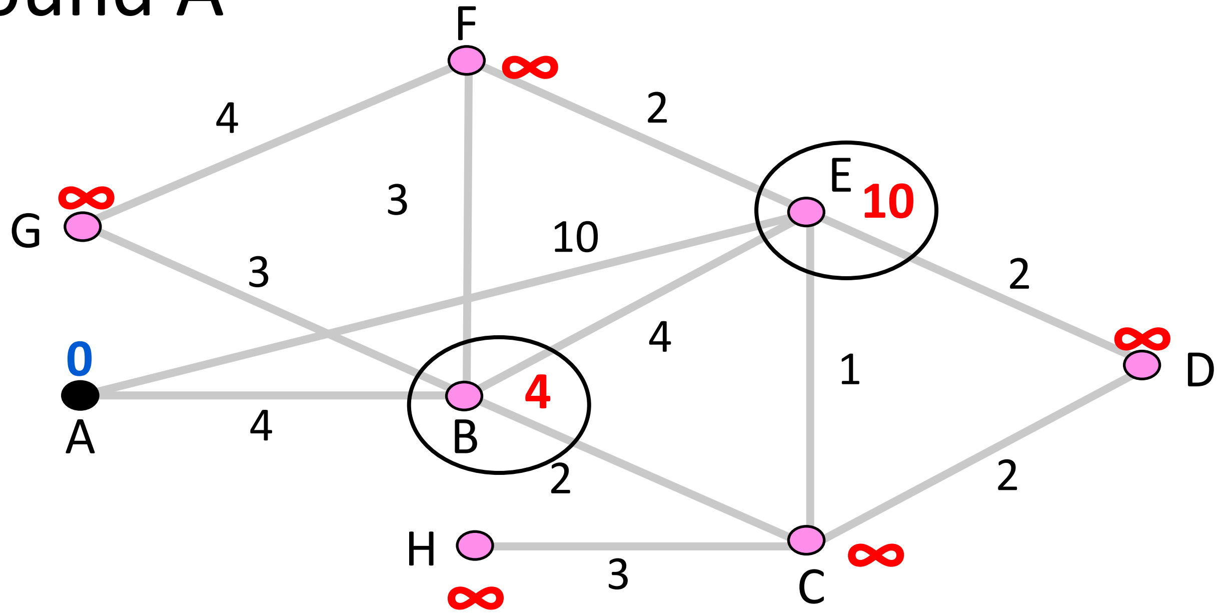
- Initialization



We'll compute shortest paths from A

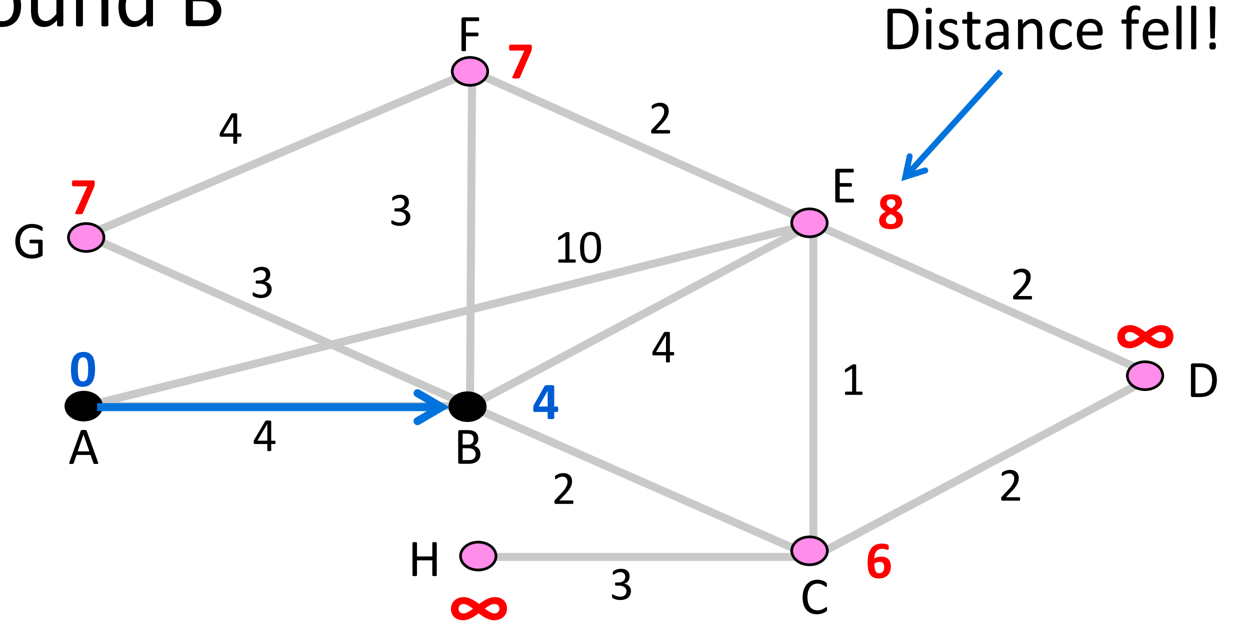
Dijkstra's Algorithm (3)

- Relax around A



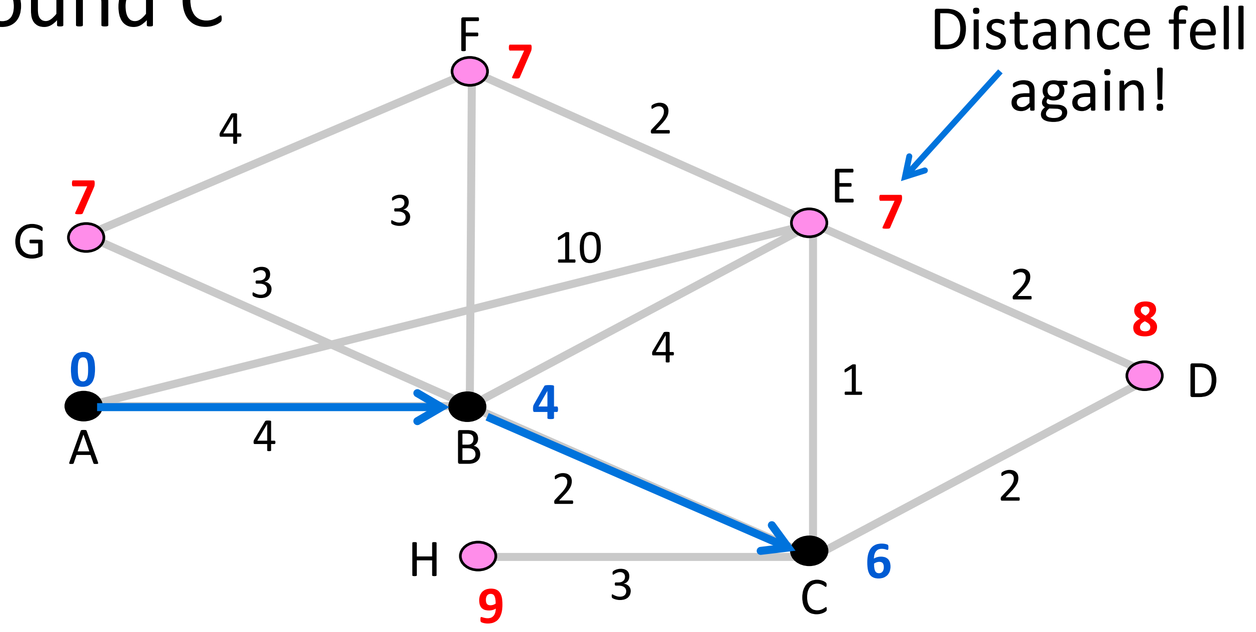
Dijkstra's Algorithm (4)

- Relax around B



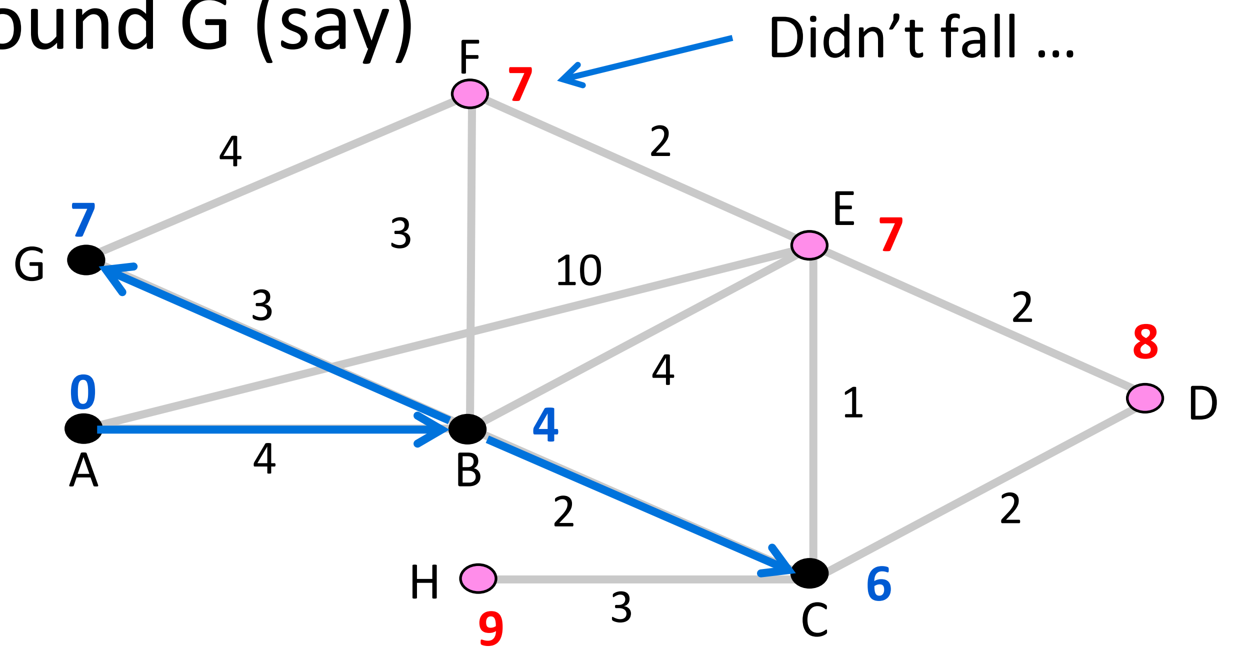
Dijkstra's Algorithm (5)

- Relax around C



Dijkstra's Algorithm (6)

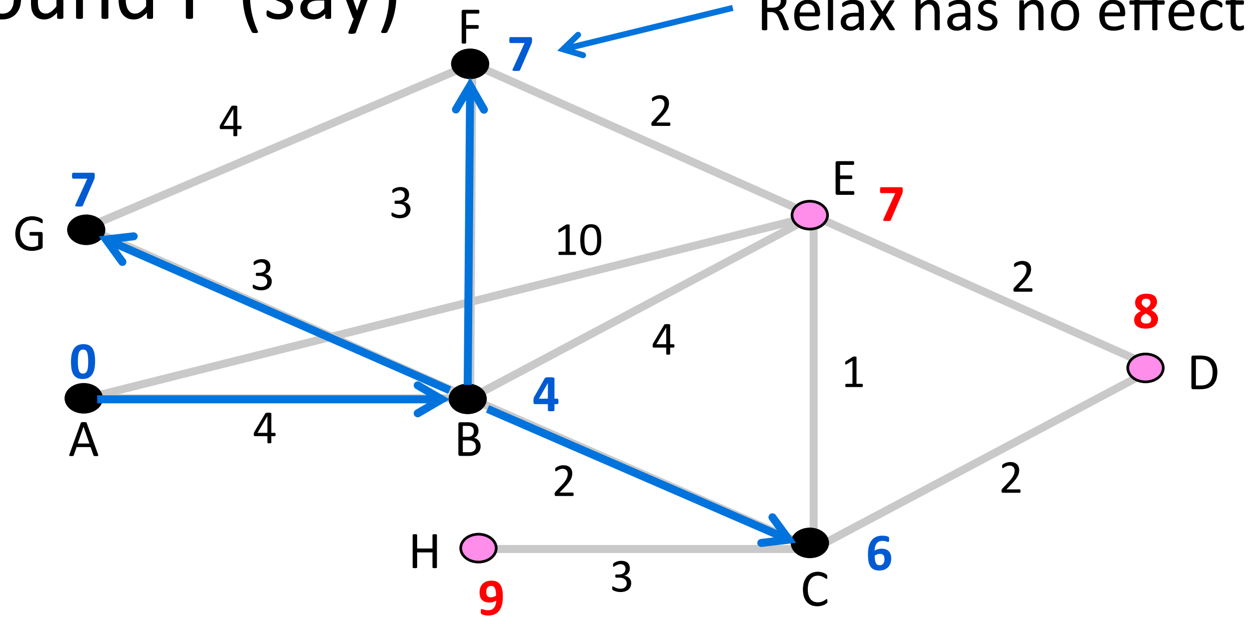
- Relax around G (say)



Dijkstra's Algorithm (7)

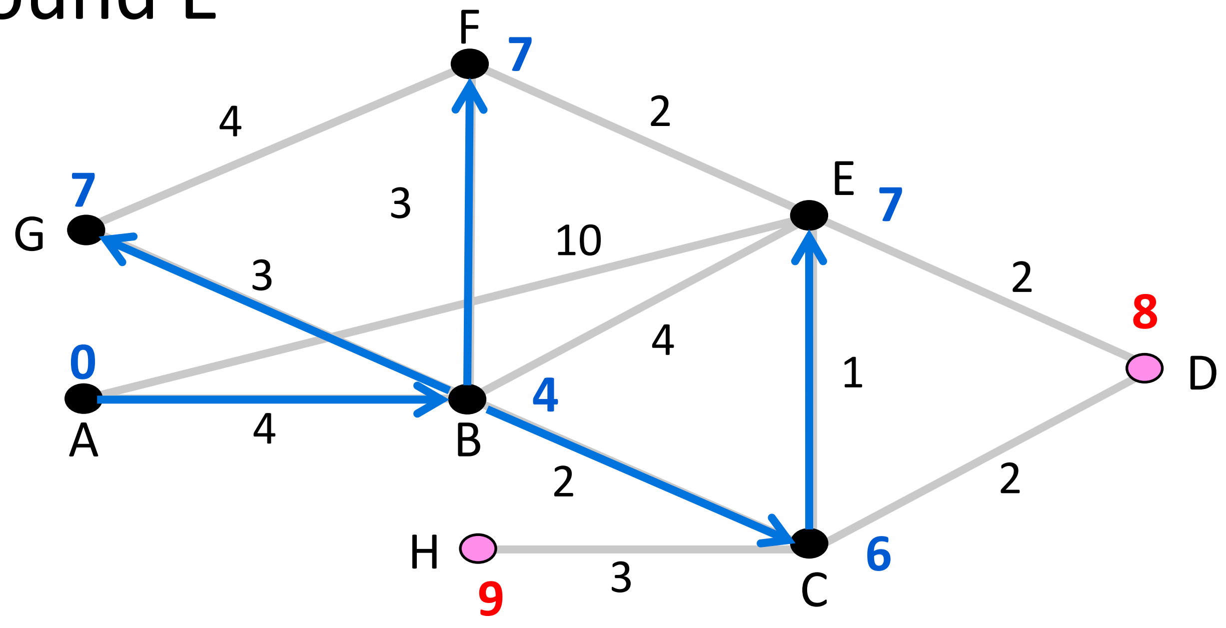
- Relax around F (say)

Relax has no effect



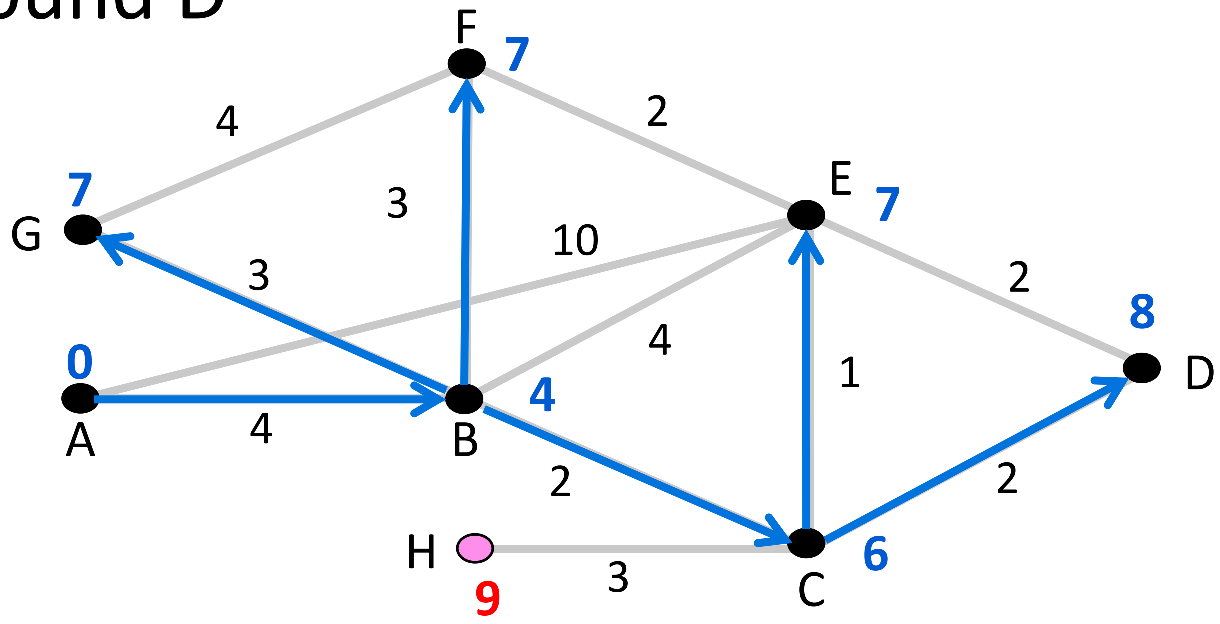
Dijkstra's Algorithm (8)

- Relax around E



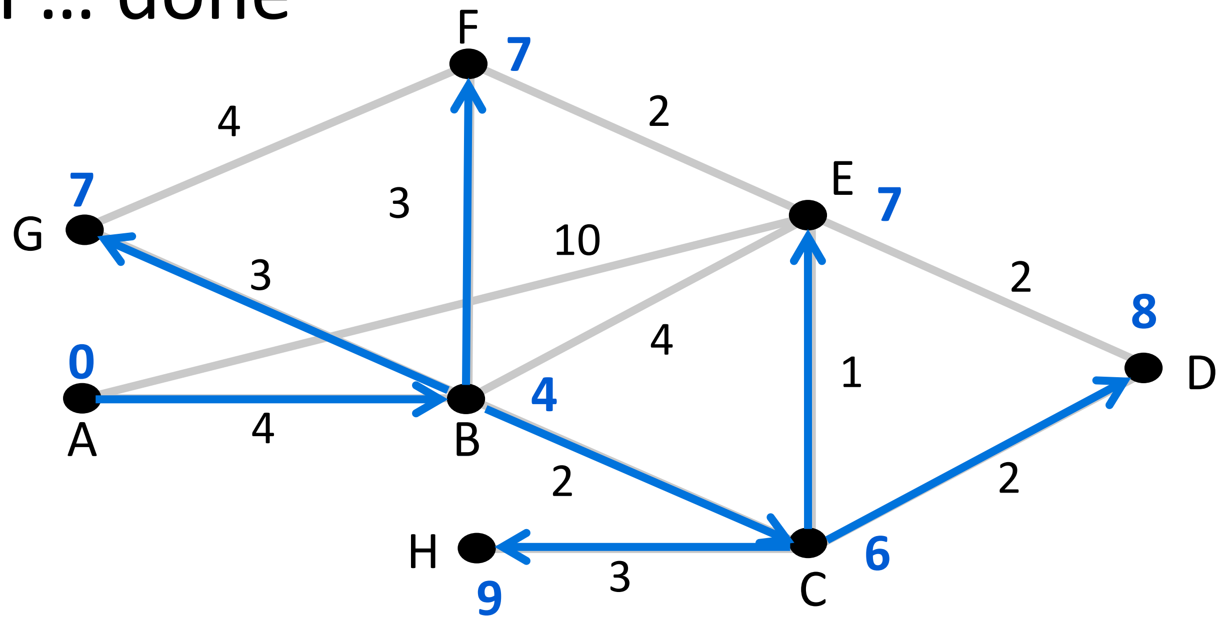
Dijkstra's Algorithm (9)

- Relax around D



Dijkstra's Algorithm (10)

- Finally, H … done

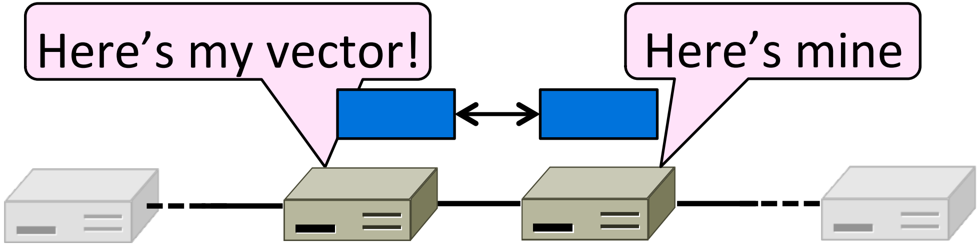


Dijkstra Comments

- Finds shortest paths in order of increasing distance from source
  - Leverages optimality property
- Runtime depends on efficiency of extracting min-cost node
  - Superlinear in network size (grows fast)
- Gives complete source/sink tree
  - More than needed for forwarding!
  - But requires complete topology

Topic

- How to compute shortest paths in a distributed network
  - The Distance Vector (DV) approach



Distance Vector Routing

- Simple, early routing approach
  - Used in ARPANET, and RIP
- One of two main approaches to routing
  - Distributed version of Bellman-Ford
  - Works, but very slow convergence after some failures
- Link-state algorithms are now typically used in practice
  - More involved, better behavior

Distance Vector Setting

Each node computes its forwarding table in a distributed setting:

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

Distance Vector Algorithm

Each node maintains a vector of distances (and next hops) to all destinations

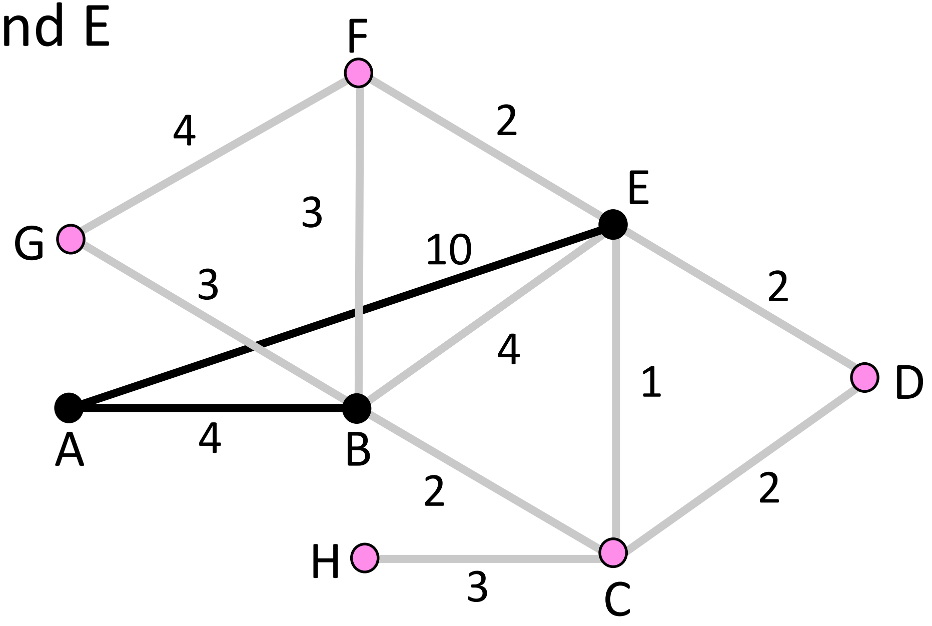
1. Initialize vector with 0 (zero) cost to self, ∞ (infinity) to other destinations
2. Periodically send vector to neighbors
3. Update vector for each destination by selecting the shortest distance heard, after adding cost of neighbor link
   - Use the best neighbor for forwarding

Distance Vector (2)

- Consider from the point of view of node A
  - Can only talk to nodes B and E

Initial vector

To	Cost
A	0
B	∞
C	∞
D	∞
E	∞
F	∞
G	∞
H	∞



Distance Vector (3)

- First exchange with B, E; learn best 1-hop routes

To	B says	E says
A	∞	∞
B	0	∞
C	∞	∞
D	∞	∞
E	∞	0
F	∞	∞
G	∞	∞
H	∞	∞

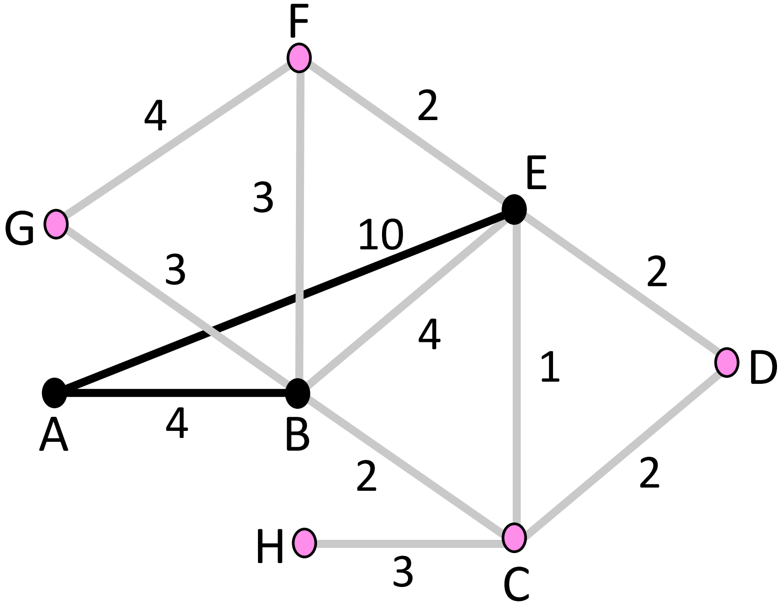
→

B +4	E +10
∞	∞
4	∞
∞	∞
∞	∞
∞	10
∞	∞
∞	∞
∞	∞

→

A's Cost	A's Next
0	--
4	B
∞	--
∞	--
10	E
∞	--
∞	--
∞	--

Learned better route



Distance Vector (4)

- Second exchange; learn best 2-hop routes

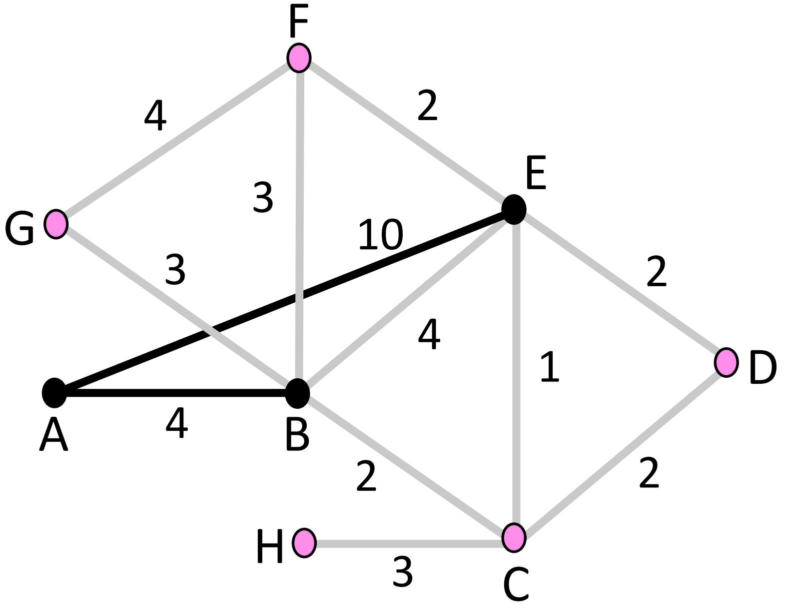
To	B says	E says
A	4	10
B	0	4
C	2	1
D	∞	2
E	4	0
F	3	2
G	3	∞
H	∞	∞

→

B +4	E +10
8	20
4	14
6	11
∞	12
8	10
7	12
7	∞
∞	∞

→

A's Cost	A's Next
0	--
4	B
6	B
12	E
8	B
7	B
7	B
∞	--



Distance Vector (4)

- Third exchange; learn best 3-hop routes

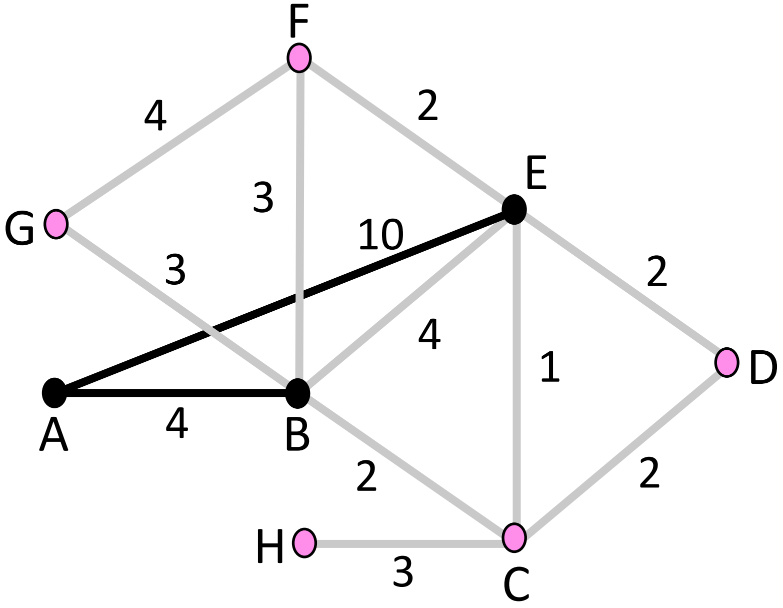
To	B says	E says
A	4	8
B	0	3
C	2	1
D	4	2
E	3	0
F	3	2
G	3	6
H	5	4

→

B +4	E +10
8	18
4	13
6	11
8	12
7	10
7	12
7	16
9	14

→

A's Cost	A's Next
0	--
4	B
6	B
8	B
7	B
7	B
7	B
9	B



Distance Vector (5)

- Subsequent exchanges; converged

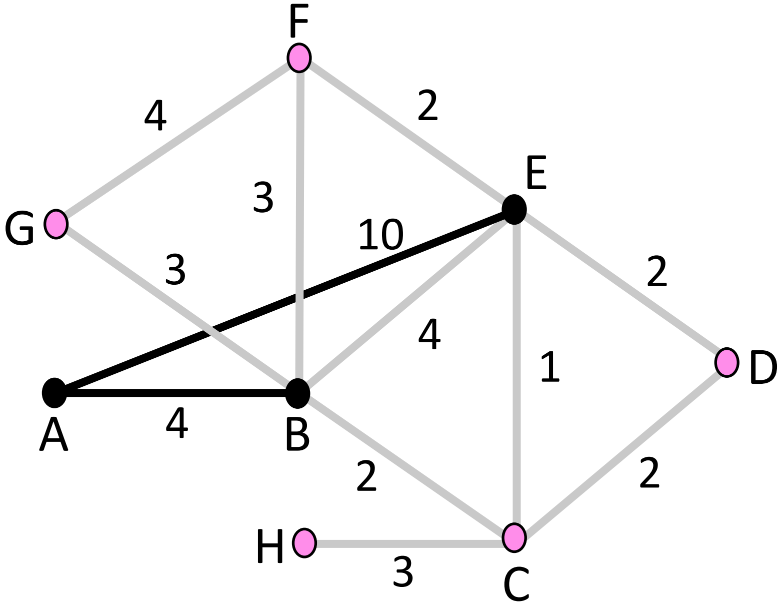
To	B says	E says
A	4	7
B	0	3
C	2	1
D	4	2
E	3	0
F	3	2
G	3	6
H	5	4

→

B +4	E +10
8	17
4	13
6	11
8	12
7	10
7	12
7	16
9	14

→

A's Cost	A's Next
0	--
4	B
6	B
8	B
8	B
7	B
7	B
9	B



Distance Vector Dynamics

- Adding routes:
  - News travels one hop per exchange
- Removing routes
  - When a node fails, no more exchanges, other nodes forget
- But partitions (unreachable nodes in divided network) are a problem
  - "Count to infinity" scenario

DV Dynamics (2)

- Good news travels quickly, bad news slowly (inferred)

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

Desired convergence

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
		⋮			

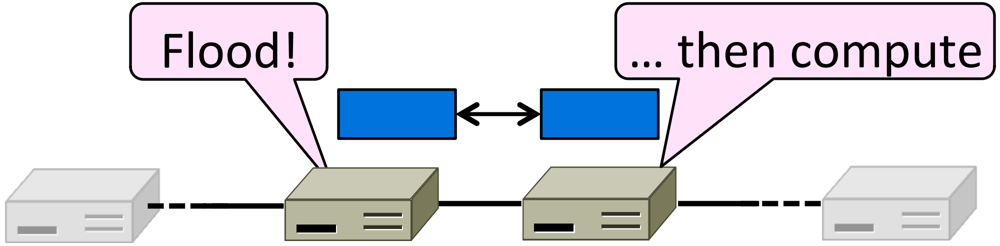
"Count to infinity" scenario

DV Dynamics (3)

- Various heuristics to address
  - e.g., “Split horizon, poison reverse” (Don’t send route back to where you learned it from.)
- But none are very effective
  - Link state now favored in practice
  - Except when very resource-limited

Topic

- How to compute shortest paths in a distributed network
  - The Link-State (LS) approach



Link-State Routing

- One of two approaches to routing
  - Trades more computation than distance vector for better dynamics
- Widely used in practice
  - Used in Internet/ARPANET from 1979
  - Modern networks use OSPF and IS-IS

Link-State Setting

Nodes compute their forwarding table in the same distributed setting as for distance vector:

1. Nodes know only the cost to their neighbors; not the 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:

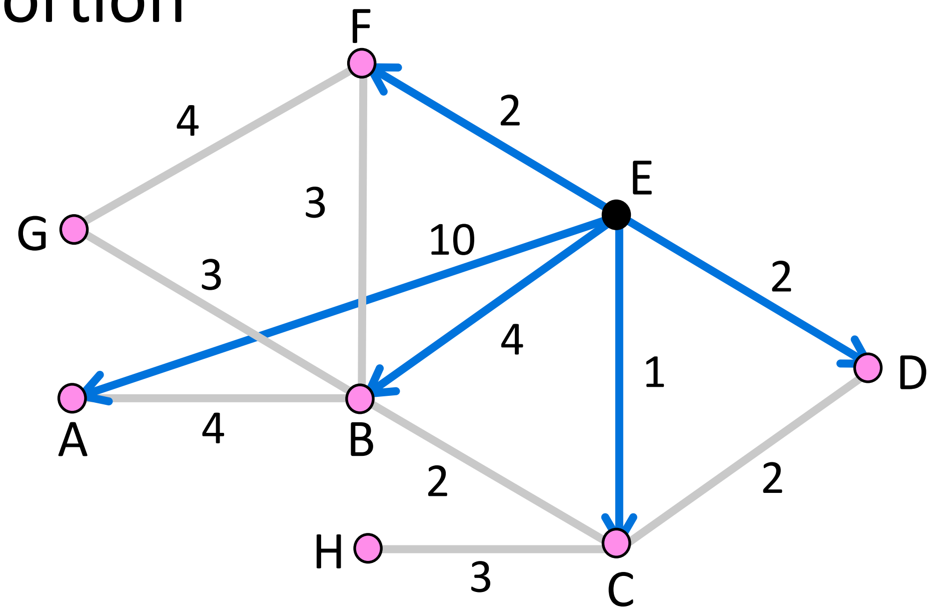
1. Nodes <u>flood</u> topology in the form of link state packets
   - Each node learns full topology
2. Each node computes its own forwarding table
   - By running Dijkstra (or equivalent)

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

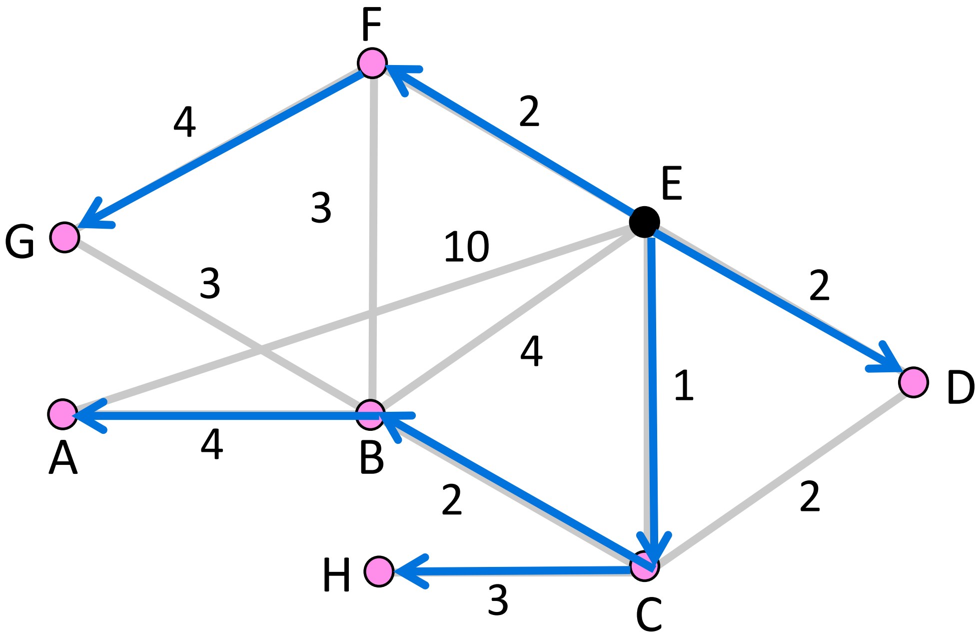


Phase 2: Route Computation

- Each node has full topology
  - By combining all LSPs
- Each node simply runs Dijkstra
  - Some 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, and re-compute routes
  - E.g., nodes adjacent to failed link or node initiate

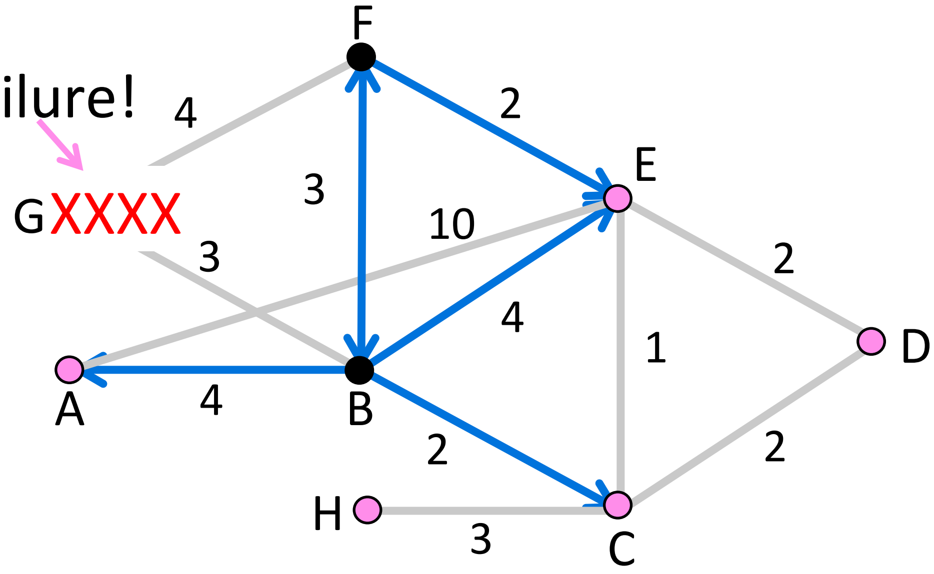
B's LSP

Seq. #	
A	4
C	2
E	4
F	3
G	∞

F's LSP

Seq. #	
B	3
E	2
G	∞

Failure!



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 (as usual!)

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

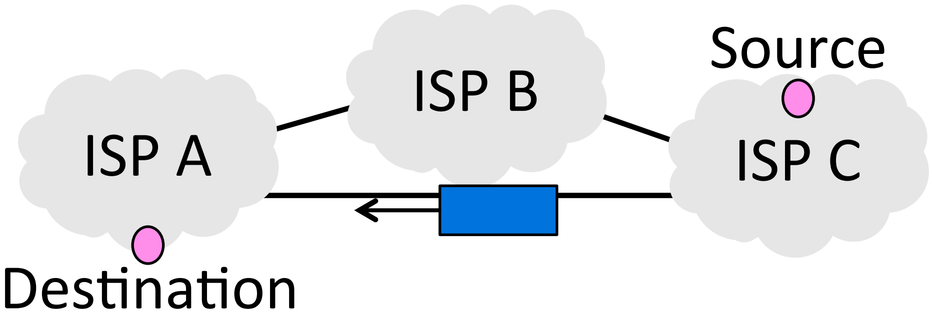
IS-IS and OSPF Protocols

- 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

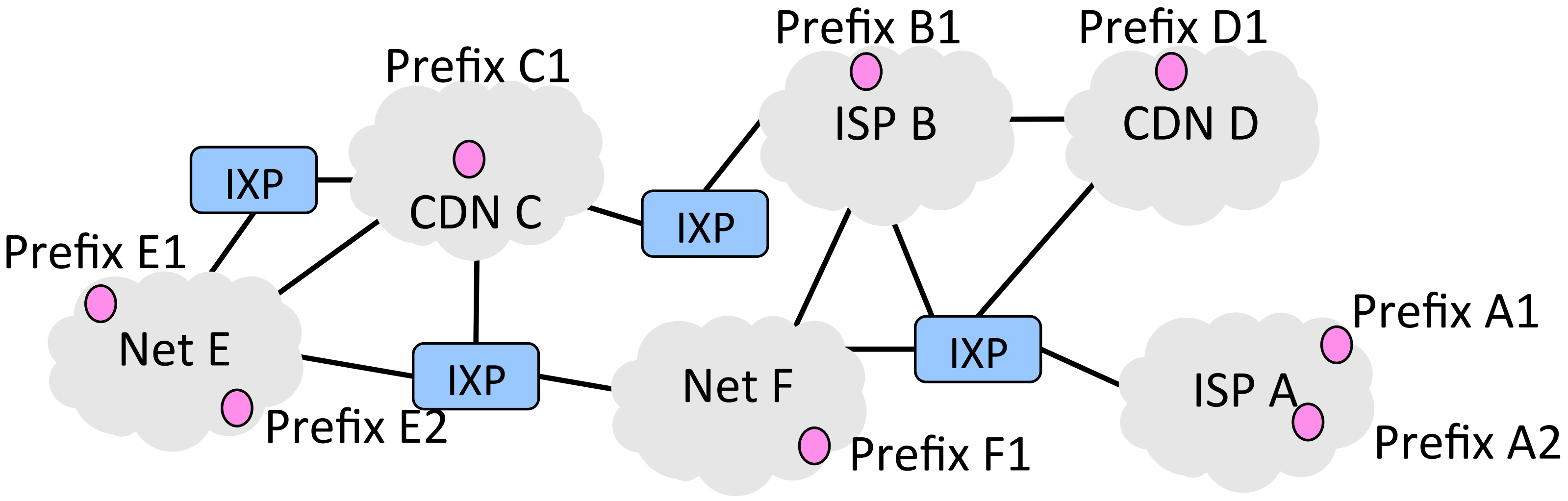
Topic

- How to route with multiple parties, each with their own routing policies
  - This is Internet-wide BGP routing



Structure of the Internet

- Networks (ISPs, CDNs, etc.) group hosts as IP prefixes
- Networks are richly interconnected, often using IXPs



Internet-wide Routing Issues

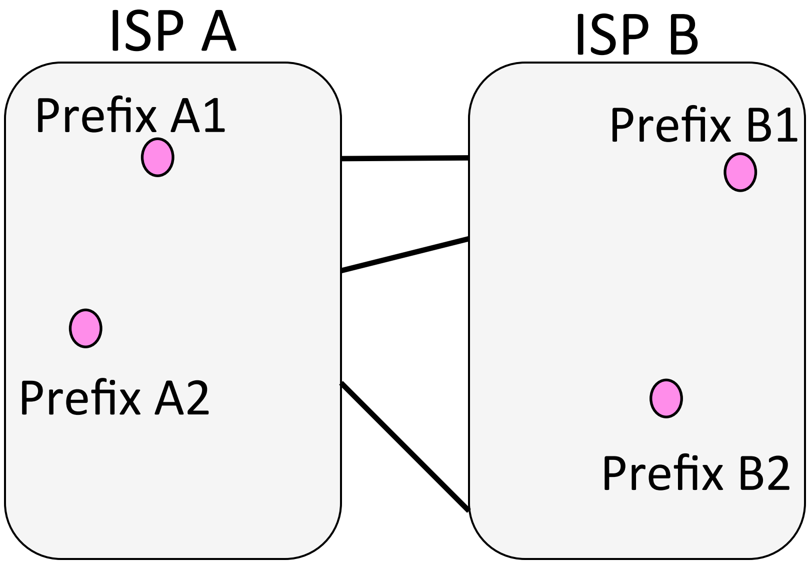
- Two problems beyond routing within an individual network

1. Scaling to very large networks
   - Techniques of IP prefixes, hierarchy, prefix aggregation
2. Incorporating policy decisions
   - Letting different parties choose their routes to suit their own needs

Yikes!

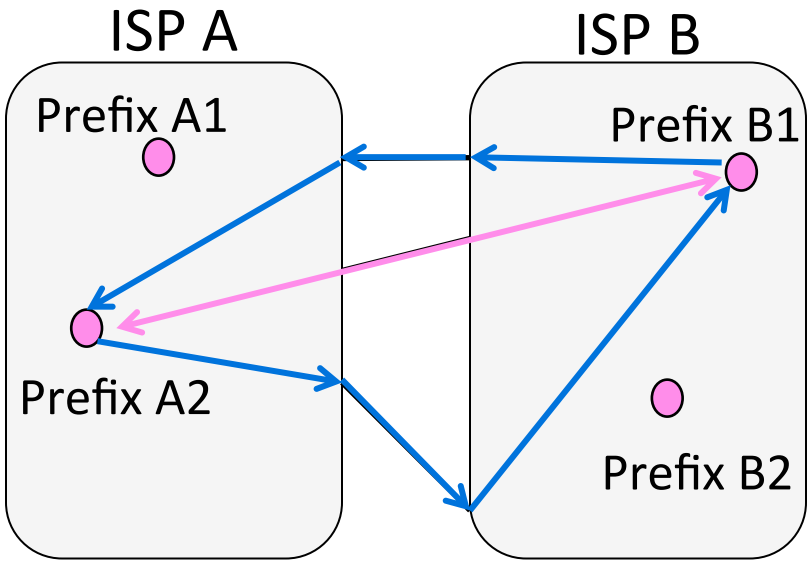
Effects of Independent Parties

- Each party selects routes to suit its own interests
  - e.g, shortest path in ISP
- What path will be chosen for A2→B1 and B1→A2?
  - What is the best path?



Effects of Independent Parties (2)

- Selected paths are longer than overall shortest path
  - And symmetric too!
- This is a consequence of independent goals and decisions, not hierarchy

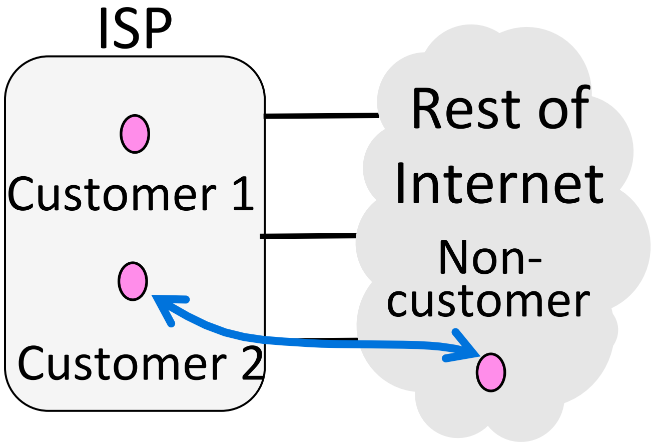


Routing Policies

- Capture the goals of different parties – could be anything
  - E.g., Internet2 only carries non-commercial traffic
- Common policies we'll look at:
  - ISPs give TRANSIT service to customers
  - ISPs give PEER service to each other

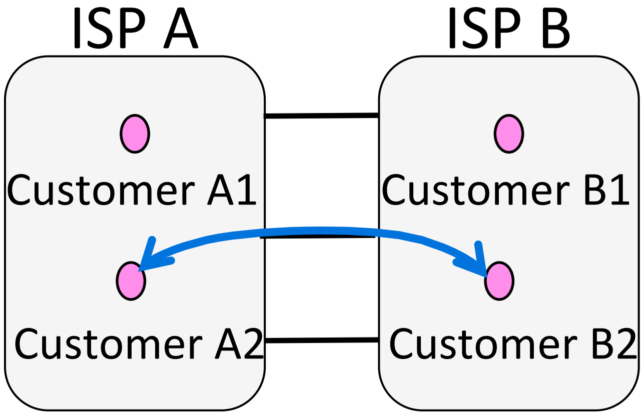
Routing Policies – Transit

- One party (customer) gets TRANSIT service from another party (ISP)
  - ISP accepts traffic for customer from the rest of Internet
  - ISP sends traffic from customer to the rest of Internet
  - Customer pays ISP for the privilege



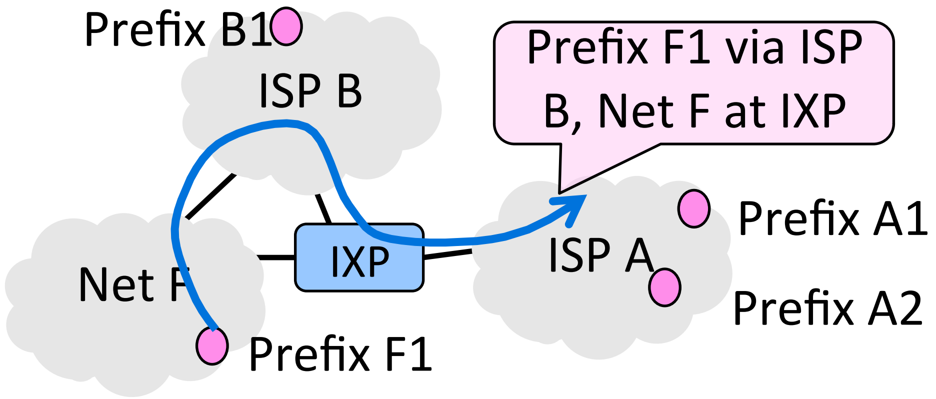
Routing Policies – Peer

- Both party (ISPs in example) get PEER service from each other
  - Each ISP accepts traffic from the other ISP only for their customers
  - ISPs do not carry traffic to the rest of the Internet for each other
  - ISPs don't pay each other



Routing with BGP (Border Gateway Protocol)

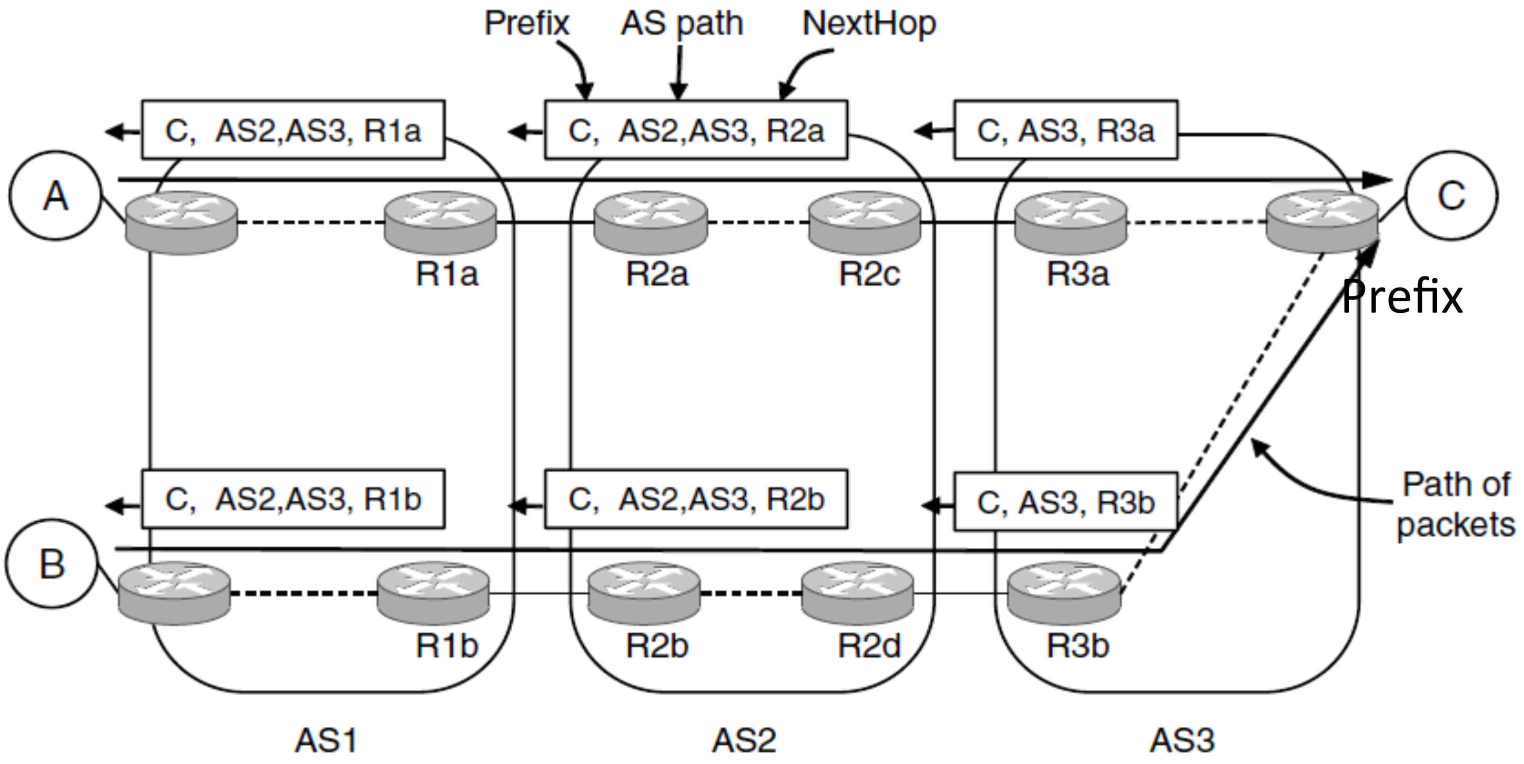
- BGP is the <u>interdomain</u> routing protocol used in the Internet
  - Path vector, a kind of distance vector



Routing with BGP (2)

- Different parties like ISPs are called AS (Autonomous Systems)
- Border routers of ASes announce BGP routes to each other
- Route announcements contain an IP prefix, path vector, next hop
  - Path vector is list of ASes on the way to the prefix; list is to find loops
- Route announcements move in the opposite direction to traffic

Routing with BGP (3)



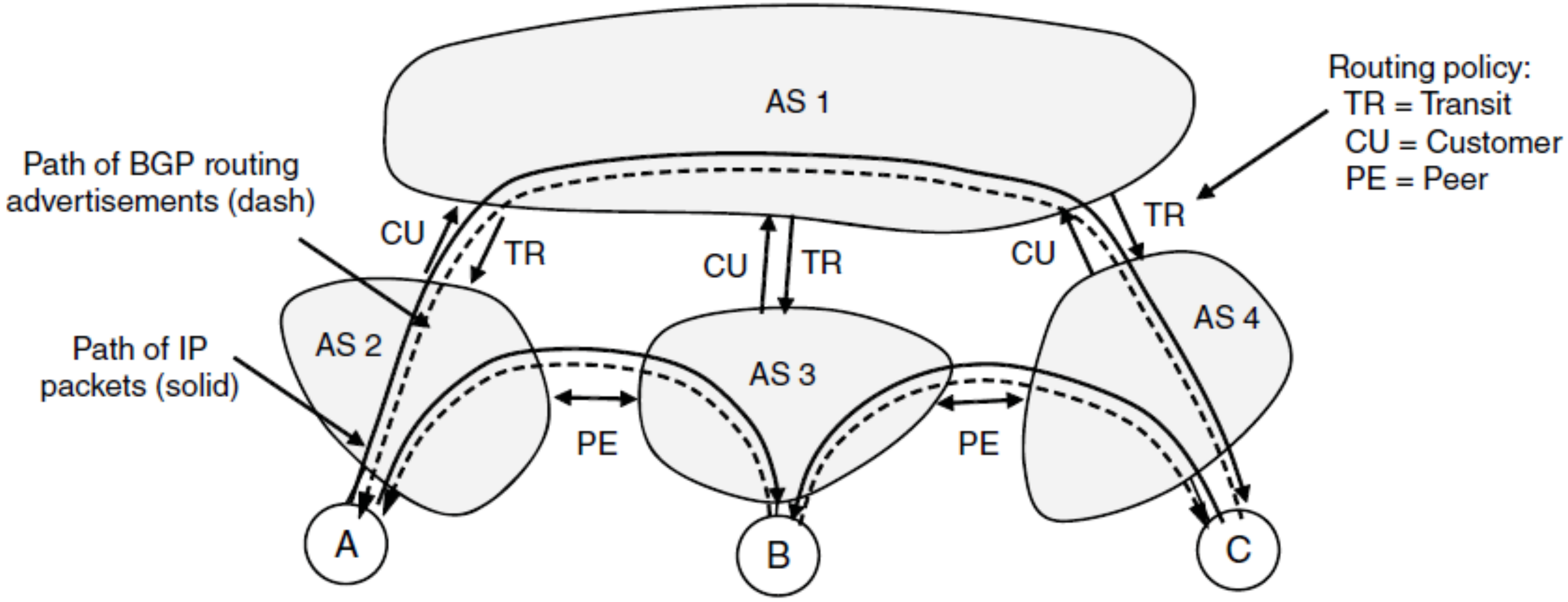
Routing with BGP (4)

Policy is implemented in two ways:

1. Border routers of ISP announce paths only to other parties who may use those paths
   - Filter out paths others can't use
2. Border routers of ISP select the best path of the ones they hear in any, non-shortest way

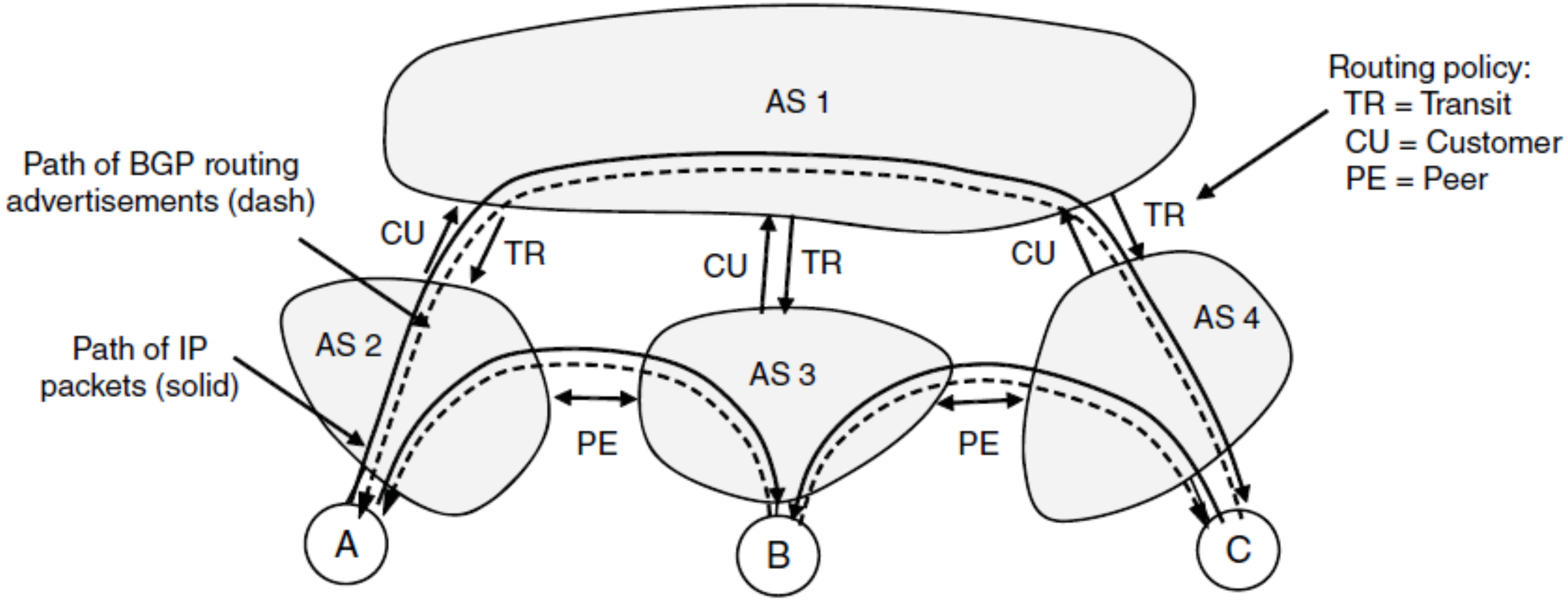
Routing with BGP (5)

- TRANSIT: AS1 says [B, (AS1, AS3)], [C, (AS1, AS4)] to AS2



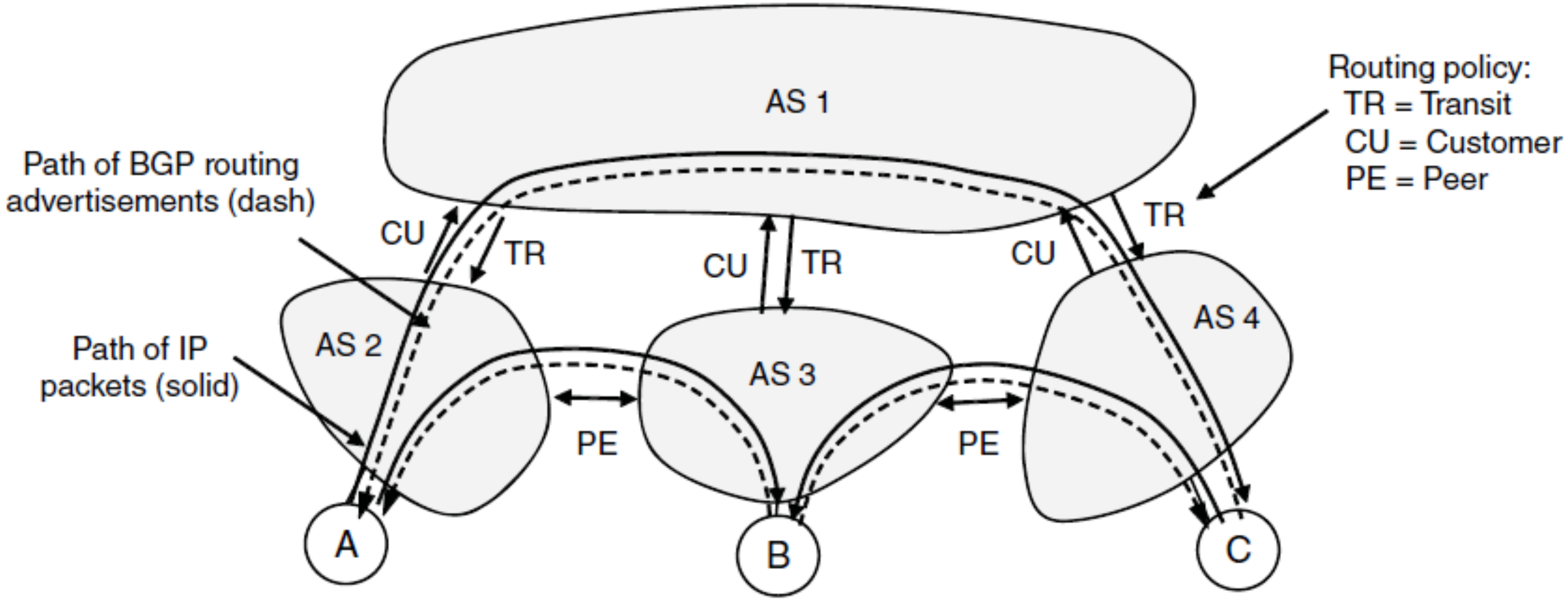
Routing with BGP (6)

- CUSTOMER (other side of TRANSIT): AS2 says [A, (AS2)] to AS1



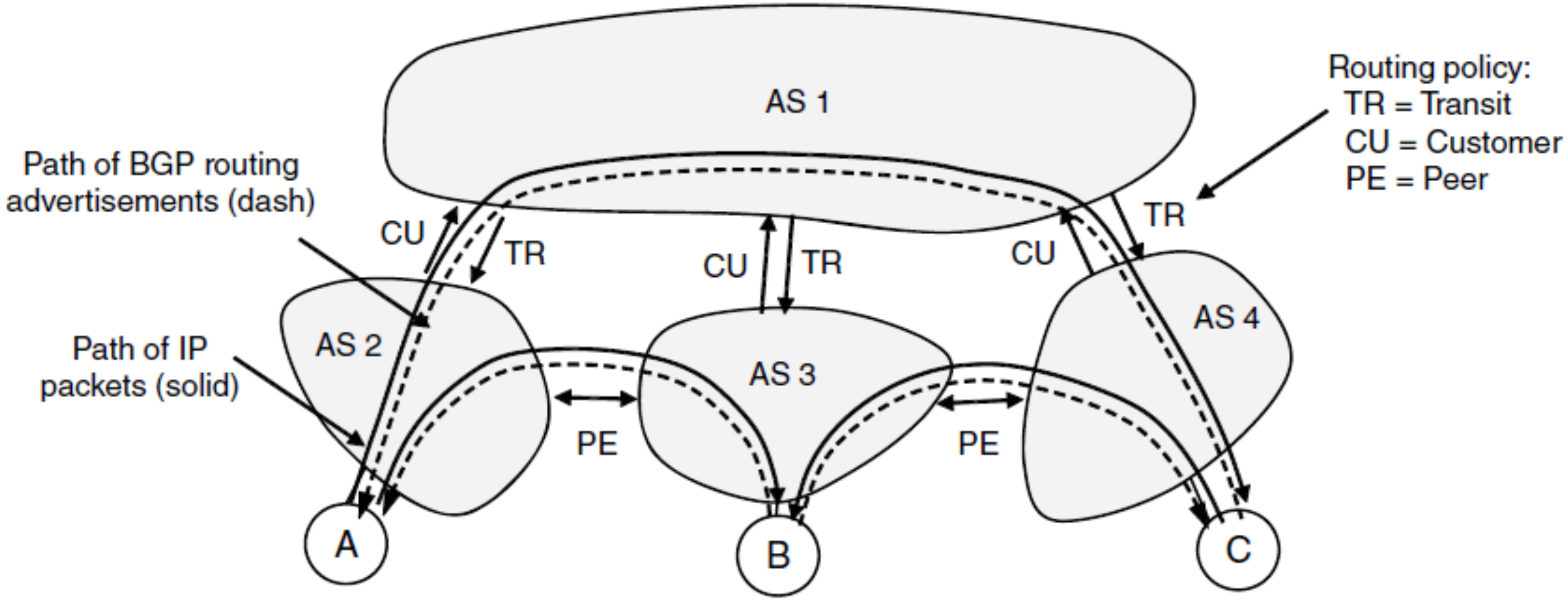
Routing with BGP (7)

- PEER: AS2 says [A, (AS2)] to AS3, AS3 says [B, (AS3)] to AS2



Routing with BGP (8)

- AS2 hears two routes to B (via AS1, AS3) and chooses AS3 (Free!)



BGP Thoughts

- Much more beyond basics to explore!
- Policy is a substantial factor
  - Can we even be independent decisions will be sensible overall?
- Other important factors:
  - Convergence effects
  - How well it scales
  - Integration with intradomain routing
  - And more …