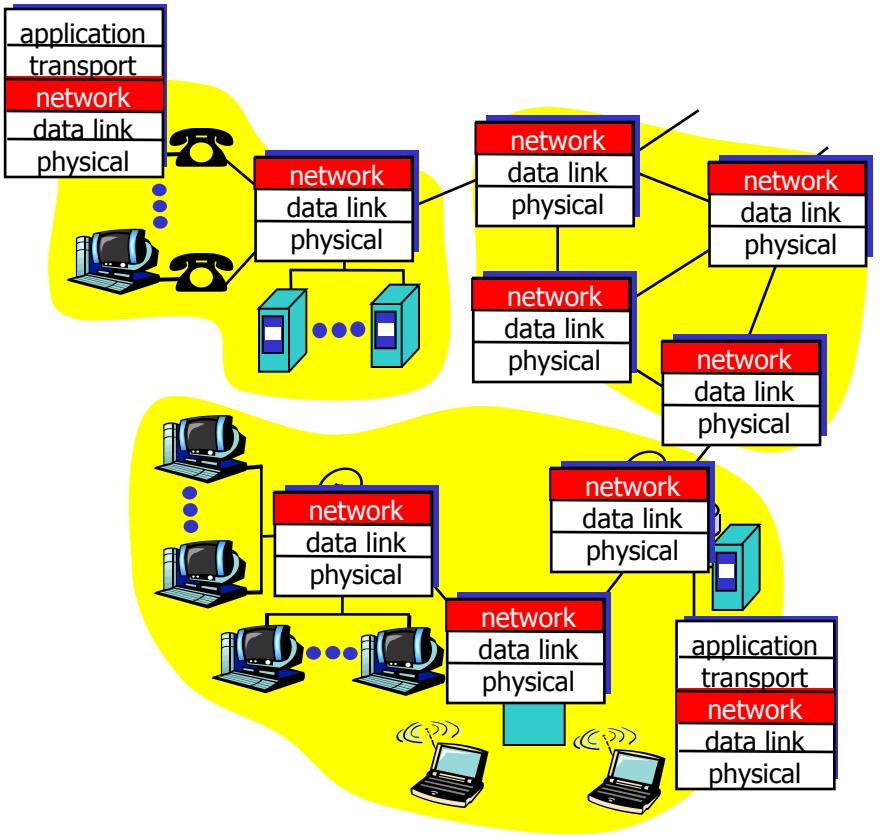
Network layer: Overview

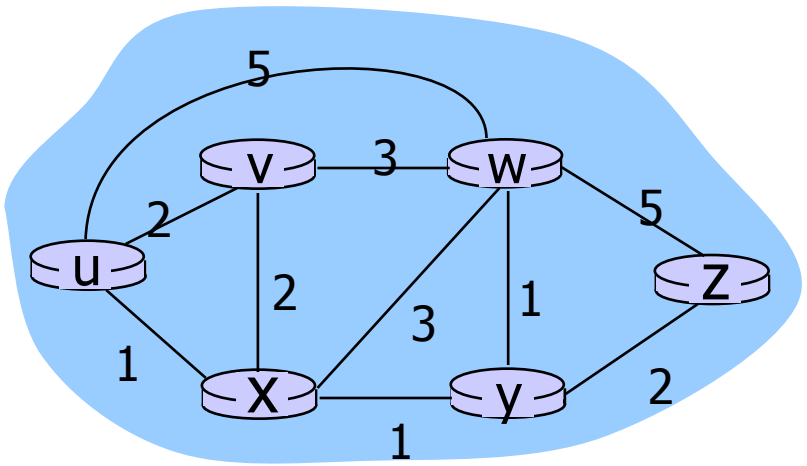
- Network layer functions
- Routing
- IP
- Forwarding

Network Layer Functions

- Transport packet from sending to receiving hosts (processes)
- Network layer protocols in *every* host, router
- Three important functions:
- *Addressing*
- *Path determination:* route taken by packets from source to dest. *Routing algorithms*
- *Switching/forwarding:* move packets from router's input to appropriate router output



Graph abstraction for routing



Graph: $G = (N,E)$

N = set of routers = { u, v, w, x, y, z }

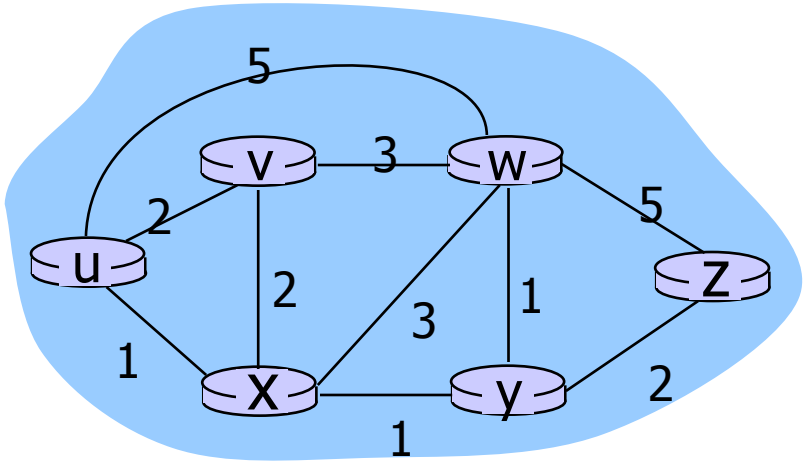
E = set of links ={ (u,v), (u,x), (v,x), (v,w), (x,w), (x,y), (w,y), (w,z), (y,z) }

Path: Sequence of meeting edges (routers)

Remark: Graph abstr. is useful in other network contexts

Example: P2P, where N is set of peers
and E is set of TCP connections

Graph abstraction: Costs



- $c(x,x')$ = cost of link (x,x')
  - e.g., $c(w,z) = 5$
- Cost can be always 1, or inversely related to bandwidth, or inversely related to congestion

Cost of path $(x_1,x_2,x_3,\ldots,x_p) = c(x_1,x_2)+c(x_2,x_3)+\ldots+c(x_{p-1},x_p)$

Question: What's the least-cost path between u and z?

Routing algorithm: Alg. that finds "good" path (typically: least cost path)

Routing algorithm classification

Global or decentralized information?

Global:

- All routers have complete topology, link cost info
- "Link state" algorithms

Decentralized:

- Router knows physically-connected neighbors, link costs to neighbors
- Iterative process of computation, exchange of info with neighbors
- "Distance vector" algorithms

Static or dynamic?

Static:

- Routes change slowly over time

Dynamic:

- Routes change more quickly
  - periodic update
  - in response to link cost changes

A link-state routing algorithm

Dijkstra's algorithm

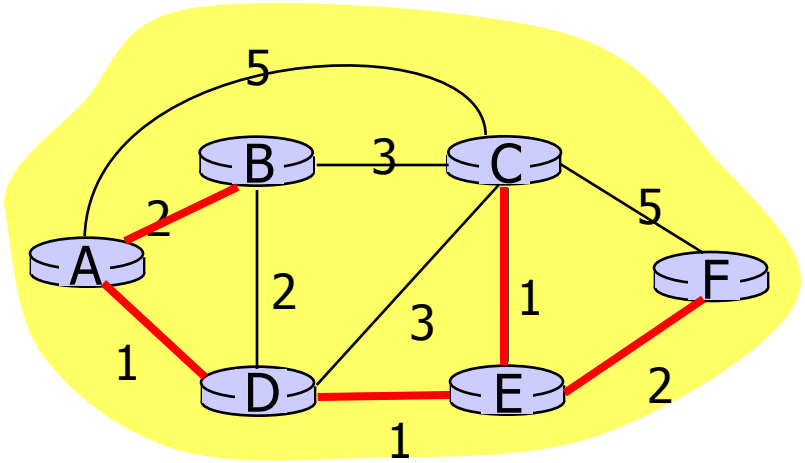
- Net topology, link costs known to all nodes
  - Accomplished via "link state broadcast"
  - All nodes have same info
- Computes least cost paths from one node ('source") to all other nodes
  - Gives routing table for that node
- Iterative: after k iterations, know least cost paths to k destinations

Notation:

- $c(i,j)$: Link cost from node i to j (infinite if not direct neighbors)
- $D(v)$: Current value of cost of path from source to v
- $p(v)$: Current predecessor of v along path from source to v
- N': Set of nodes whose least cost path known

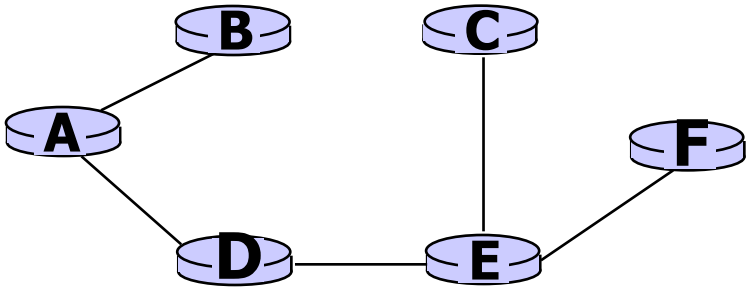
Dijkstra's algorithm: Example

Step	start N'	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	infinity	infinity
1	AD	2,A	4,D		2,D	infinity
2	ADE	2,A	3,E			4,E
3	ADEB		3,E			4,E
4	ADEBC					4,E
5	ADEBCF					



Dijkstra's algorithm: Example (2)

Resulting shortest-path tree from A:



Resulting forwarding table in A:

destination	link
B	(A,B)
D	(A,D)
E	(A,D)
C	(A,D)
F	(A,D)

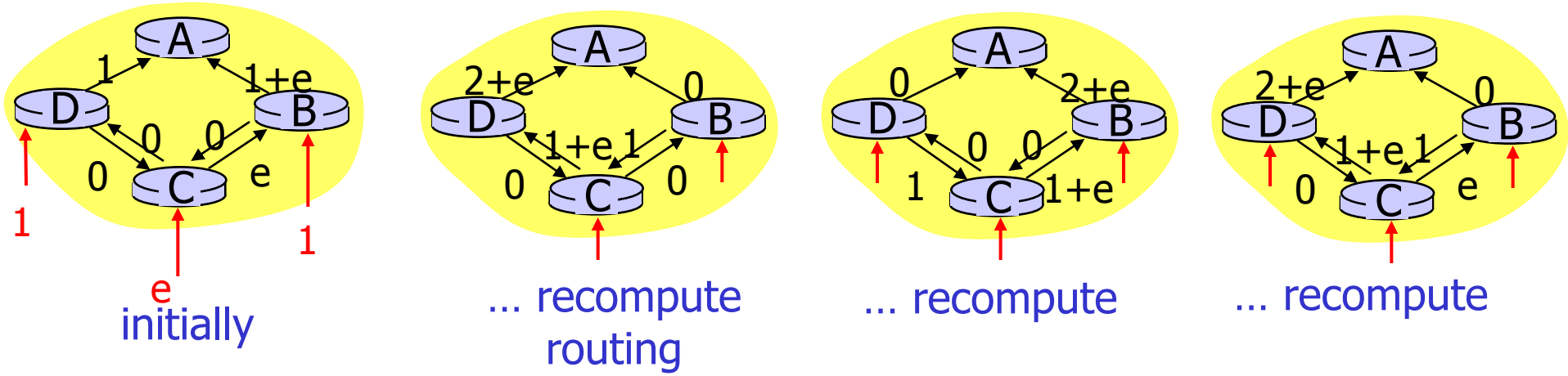
Dijkstra's algorithm: Discussion

Algorithm complexity: n nodes

- Each iteration: need to check all nodes, w, not in N'
- Depending on data structure: $O(n^2)$, $O(n \log n)$, …

Oscillations possible:

- E.g., link cost = amount of carried traffic
  - Fix: randomized update times



Distance vector algorithm

Bellman-Ford Equation (dynamic programming)

Define

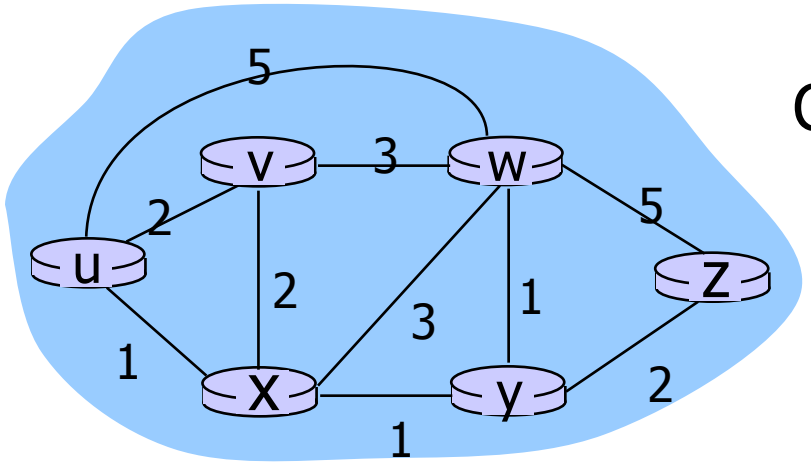
$d_x(y)$:= cost of least-cost path from x to y

Then

$$d_x(y) = \min_v\{c(x,v) + d_v(y)\}$$

where $\min$ is taken over all neighbors v of x

Bellman-Ford: Example



Clearly, $d_v(z) = 5$, $d_x(z) = 3$, $d_w(z) = 3$

Bellman-Ford equation says:

$$
\begin{aligned}
d_u(z) = \min_v\{\ & c(u,v) + d_v(z), \\
& c(u,x) + d_x(z), \\
& c(u,w) + d_w(z)\ \} \\
= \min\{&2 + 5, \\
&1 + 3, \\
&5 + 3\}\ = 4
\end{aligned}
$$

Node that yields minimum is next hop in shortest path ➜ forwarding table

Distance vector algorithm (2)

- $D_x(y)$ = estimate of least cost from x to y
- Node x knows cost to each neighbor v: $c(x,v)$
- Node x maintains its *distance vector* $\mathbf{D}_x = [D_x(y): y \in \mathrm{N}]$
- Node x also maintains its neighbors' distance vectors
  - For each neighbor v, x maintains $\mathbf{D}_v = [D_v(y): y \in \mathrm{N}]$

Distance vector algorithm (3)

Basic idea:

- Each node periodically sends its own distance vector estimate to neighbors
- When a node x receives new DV estimate from neighbor, it updates its own DV using B-F equation:

$$D_x(y) \leftarrow \min_v\{c(x,v) + D_v(y)\} \quad \text{for each node } y \in N$$

- Under "natural" conditions the estimates of $D_x(y)$ converge to the actual least cost $d_x(y)$

$D_x(y) = \min\{c(x,y) + D_y(y), c(x,z) + D_z(y)\}$
$= \min\{2+0 , 7+1\} = 2$

$D_x(z) = \min\{c(x,y) + D_y(z), c(x,z) + D_z(z)\}$
$= \min\{2+1 , 7+0\} = 3$

node x

from \ cost to	x	y	z
x	0	2	7
y	∞	∞	∞
z	∞	∞	∞

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	7	1	0

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

node y

from \ cost to	x	y	z
x	∞	∞	∞
y	2	0	1
z	∞	∞	∞

from \ cost to	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0

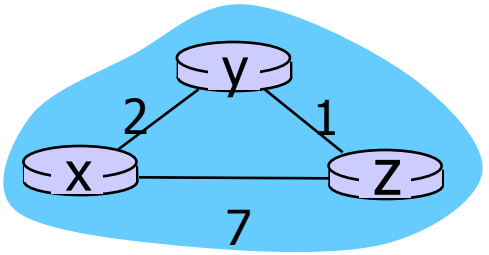
from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

node z

from \ cost to	x	y	z
x	∞	∞	∞
y	∞	∞	∞
z	7	1	0

from \ cost to	x	y	z
x	0	2	7
y	2	0	1
z	3	1	0

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0



time

Distance vector algorithm (4)

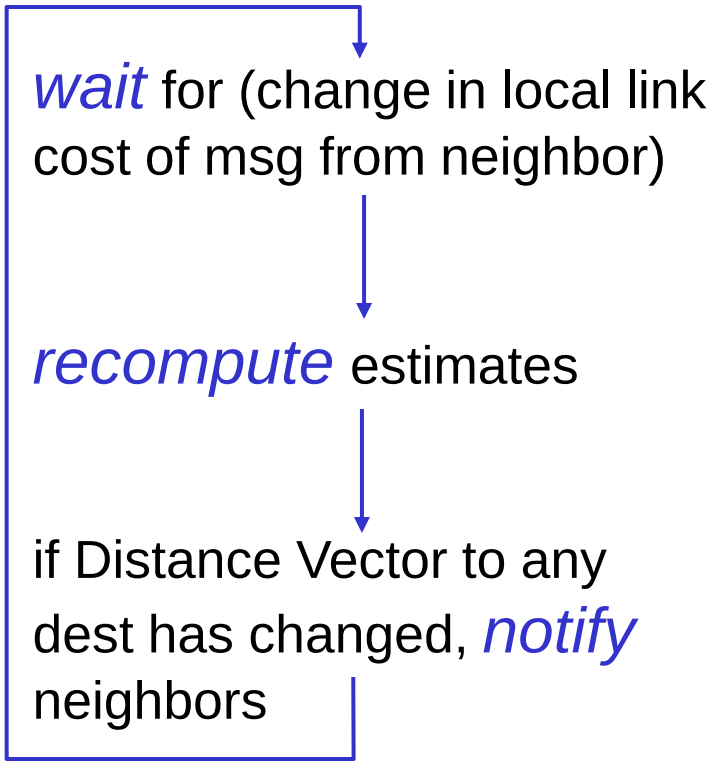
Iterative, asynchronous:

- Each local iteration caused by:
  - Local link cost change
  - DV update message from neighbor

Distributed:

- Each node notifies neighbors *only* when its Distance Vector changes
  - Neighbors then notify their neighbors if necessary

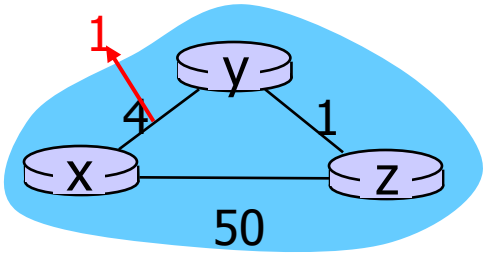
Each node:



Distance vector (DV): Link cost changes

Link cost changes:

- Node detects local link cost change
- Updates routing info, recalculates distance vector
- If DV changes, notify neighbors

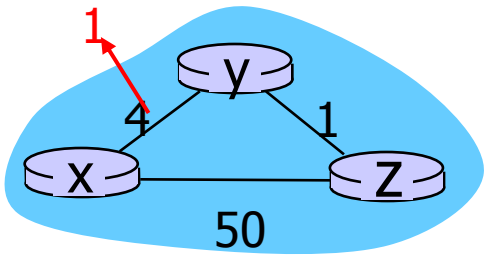


"Good news travels fast"

At time t_0, y detects the link-cost change, updates its DV, and informs its neighbors.

At time t_1, z receives the update from y and updates its table. It computes a new least cost to x and sends its neighbors its DV.

At time t_2, y receives z's update and updates its distance table. y's least costs do not change and hence y does *not* send any message to z.



node y table

from	cost to x	cost to y	cost to z
x			
y	~~4~~ 1	0	1
z	5	1	0

from	cost to x	cost to y	cost to z
x			
y	1	0	1
z	5	1	0

from	cost to x	cost to y	cost to z
x			
y	1	0	1
z	2	1	0

node z table

from	cost to x	cost to y	cost to z
x			
y	4	0	1
z	5	1	0

from	cost to x	cost to y	cost to z
x			
y	1	0	1
z	~~5~~ 2	1	0

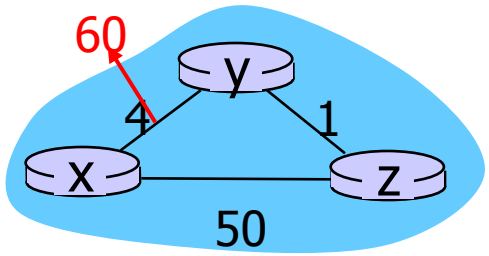
from	cost to x	cost to y	cost to z
x			
y	1	0	1
z	2	1	0

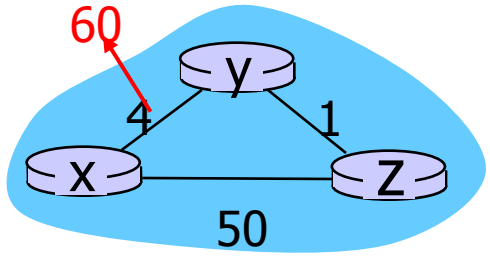
time

Distance vector: Link cost changes (2.)

Link cost changes:

- Good news travels fast
- Bad news travels slow





$D_y(x) = \min\{c(y,x) + D_x(x),\ c(y,z) + D_z(x)\}$
$= \min\{60 + 0\ ,\ 1 + 5\} = 6$

$D_y(x) = \min\{c(y,x) + D_x(x),$
$c(y,z) + D_z(x)\}$
$= \min\{60 + 0\ ,\ 1 + 7\} = 8$

node y table

cost to

from	x	y	z
x			
y	~~4~~ 6	0	1
z	5	1	0

cost to

from	x	y	z
x			
y	6	0	1
z	5	1	0

cost to

from	x	y	z
x			
y	~~6~~ 8	0	1
z	7	1	0

node z table

cost to

from	x	y	z
x			
y	4	0	1
z	5	1	0

cost to

from	x	y	z
x			
y	6	0	1
z	~~5~~ 7	1	0

cost to

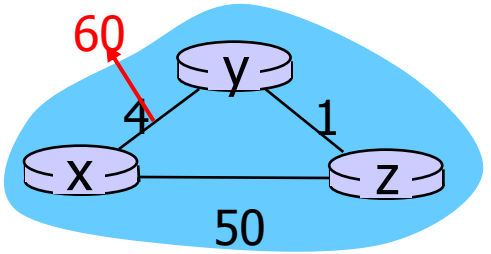
from	x	y	z
x			
y	6	0	1
z	7	1	0

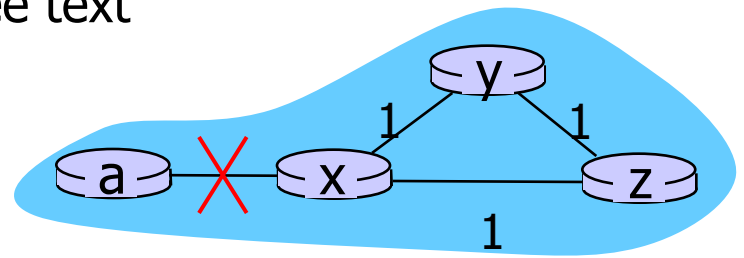
time

Distance vector: Link cost changes (3.)

Link cost changes:

- Good news travels fast
- Bad news travels slow - "count to infinity" problem!
  - 44 iterations before algorithm stabilizes: see text
- What happens here?





Poisoned reverse:

- If Z routes through Y to get to X :
  - Z tells Y its (Z's) distance to X is infinite (so Y won't route to X via Z)
- Will this completely solve count to infinity problem?

Comparison of LS and DV algorithms

Message complexity

-
-

Speed of Convergence

-
-

Robustness: What happens if router malfunctions?

LS:

-
-

DV:

-
-

Internet routing

So far – idealization

- All routers identical
- Network "flat"

… *not* true in practice

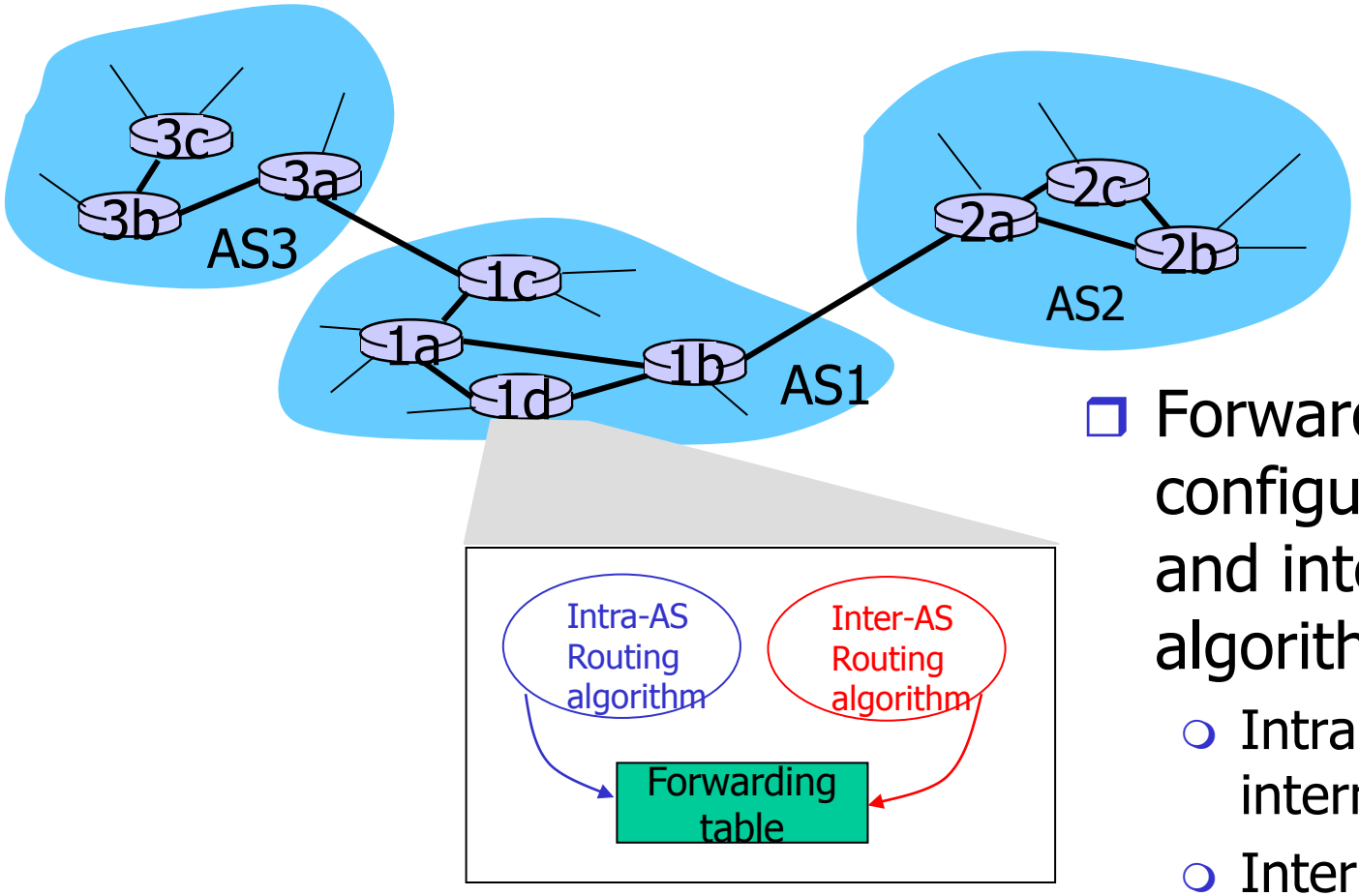
Scale: With 850 million destinations:

- Can't store all dest's in routing tables!
- Routing table exchange would swamp links!

Administrative autonomy

- Internet = network of networks
- Each network admin may want to control routing in its own network
- Aggregate routers into regions, **"autonomous systems" (AS)**
- Routers in same AS run same routing protocol
  - "Intra-AS" routing protocol
  - Routers in different AS can run different intra-AS routing protocol

Interconnected ASes



- Forwarding table is configured by both intra- and inter-AS routing algorithm
  - Intra-AS sets entries for internal dests
  - Inter-AS & Intra-AS set entries for external dests

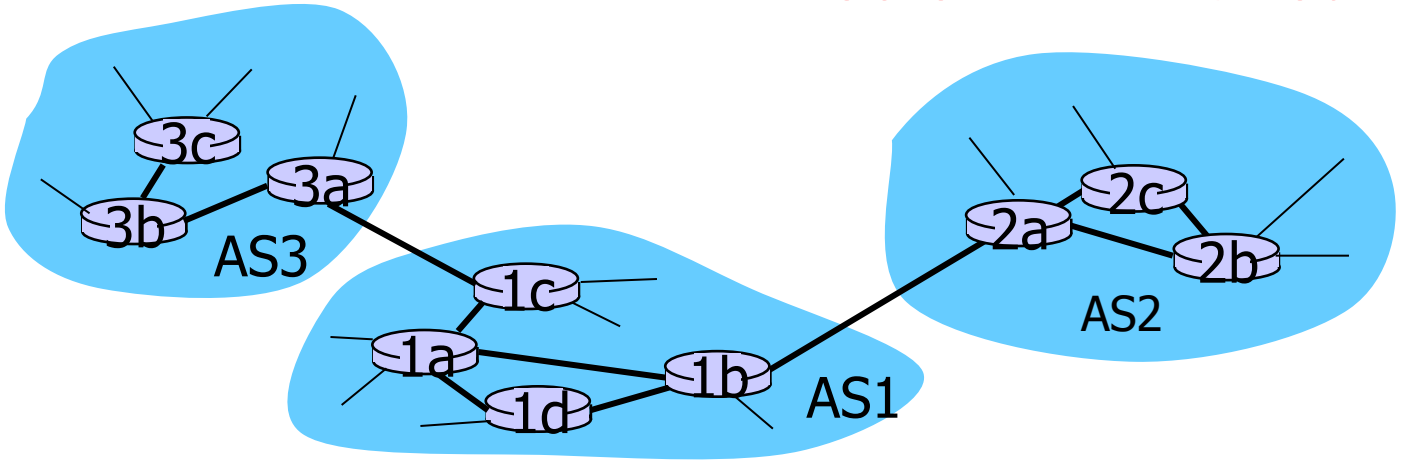
Inter-AS Tasks

- Suppose router in AS1 receives datagram for dest outside of AS1
  - Router should forward packet towards an AS-border router, but which one?

AS1 needs …

1. … to learn which dests are reachable through AS2 and which through AS3
2. … to propagate this reachability info to all routers in AS1

Job of inter-AS routing!



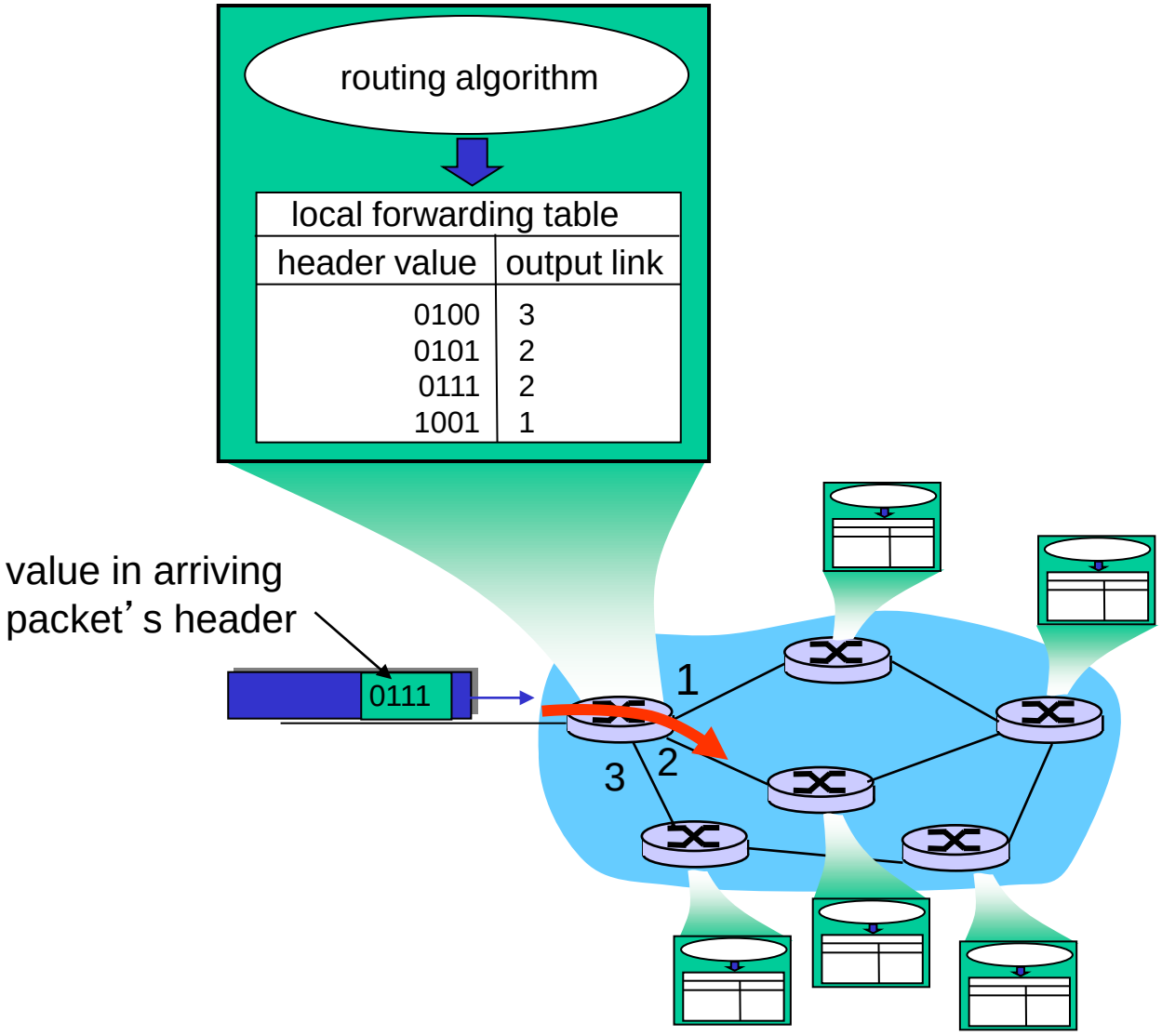
Intra-AS routing

- Also known as Interior Gateway Protocols (IGP)
- Most common Intra-AS routing protocols:
  - RIP: Routing Information Protocol
    - Distance vector protocol (based on Bellman-Ford)
    - Routers periodically exchange reachability info with their neighbors
    - Distance metric: hop count
    - Advantage: Simple, minimal communication overhead
    - Disadvantage: Long convergence times, loop detection

Intra-AS routing protocols

- OSPF: Open Shortest Path First
  - Link state protocol (based on Dijkstra)
  - Routers periodically **flood** immediate reachability information to all other routers
  - Distance metric: administrative weight
  - Advantage: fast convergence
  - Disadvantage: complexity and communication overhead
- ISIS: Intermediate-System-to-Intermediate-System (ISO 10589) (link state)
- IGRP: Interior Gateway Routing Protocol (Cisco proprietary) (distance vector)
- EIGRP: Enhanced Interior Gateway Routing Protocol (Cisco proprietary) (enhanced distance vector)

Interplay between routing and forwarding

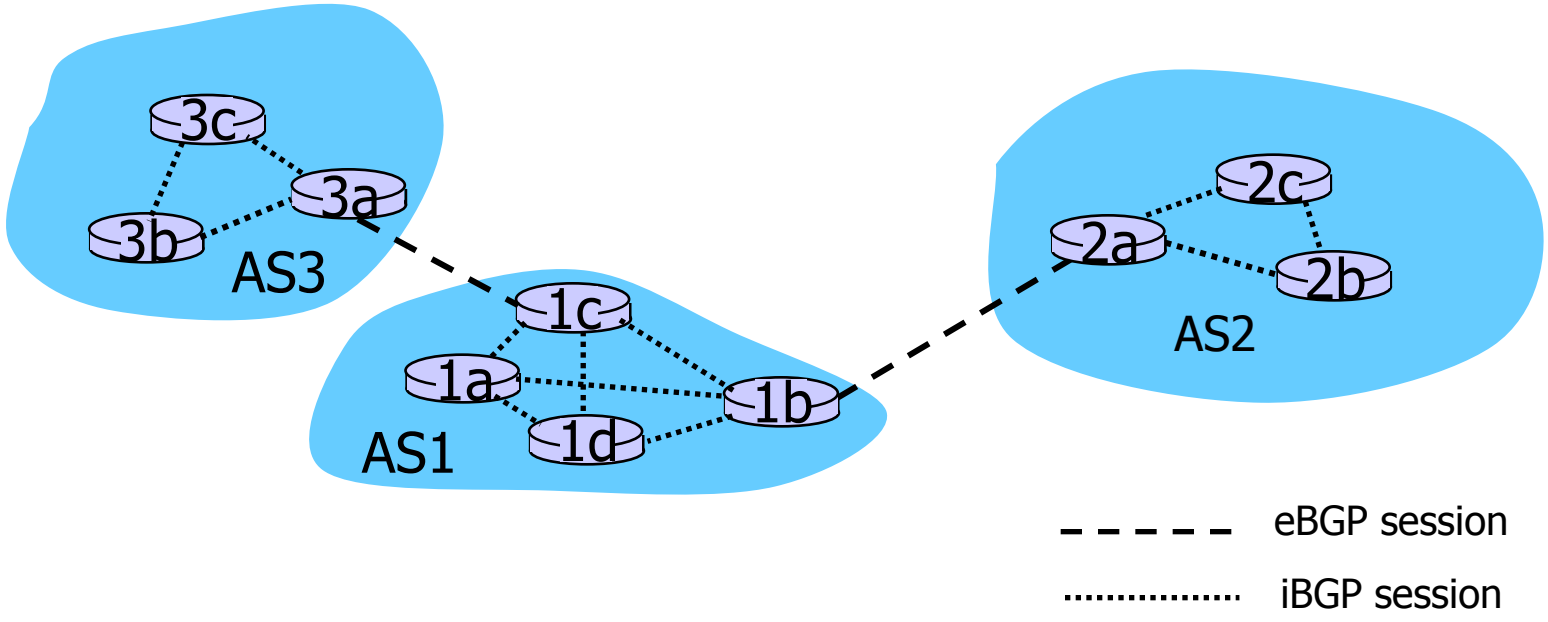


Internet Inter-AS routing: BGP

- *The* de facto standard: Border Gateway Protocol (BGP)
- BGP provides each AS a means to:
  1. Obtain subnet reachability information from neighboring ASs
  2. Propagate reachability information to all routers in the AS
  3. Determine "good" routes to subnets based on reachability information and routing policy.
- Allows a subnet to advertise its existence to rest of the Internet: *"I am here"*
- Issues:
  - Which routing algorithm?
  - How are routes advertised?
  - How to implement routing policies?

BGP Basics

- Pairs of routers (BGP peers) exchange routing info over semi-permanent TCP connections: BGP sessions
- Note that BGP sessions do not correspond to physical links.
- When AS2 advertises a prefix to AS1, AS2 is *promising* it will forward any datagrams destined to that prefix towards the prefix.
  - AS2 can aggregate prefixes in its advertisement



BGP is a path vector protocol

- Distance vector algorithm with extra information
  - Two important attributes:
    - AS-PATH: contains all ASs along the way: AS 67 AS 17
    - NEXT-HOP: Indicates the specific internal-AS router to next-hop AS.
  - Path can be used to make routing decisions, e.g., to avoid loops
  - Pure distance vector does not enable policies
  - Link state does not scale and exposes policies
- When advertising a prefix, advert includes BGP attributes
  - Prefix + other attributes = "route"
- When gateway router receives route advertisement, uses ingress filters to accept/decline
  - Can make decision based on ASes on path, e.g., to avoid loops

BGP messages

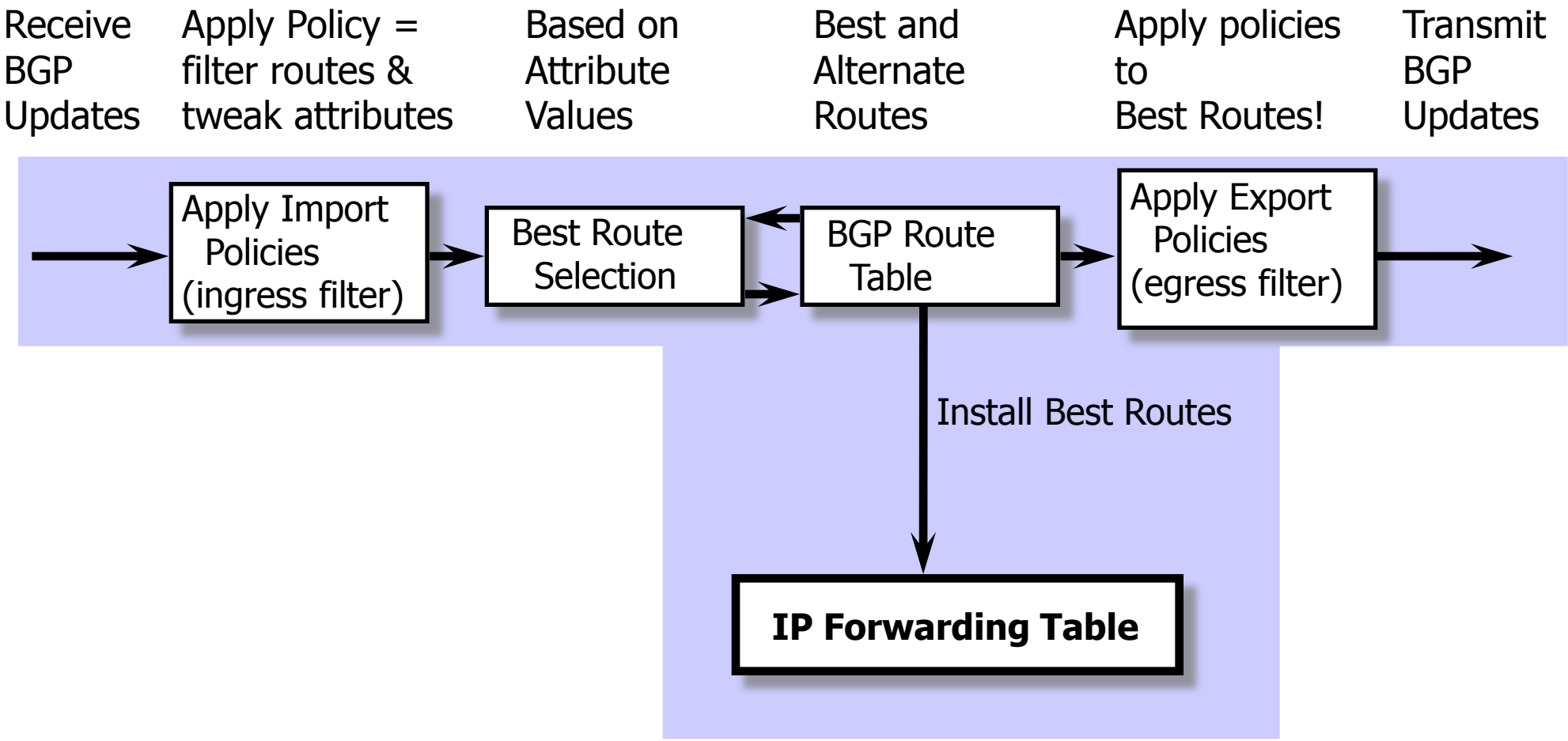
Peers exchange BGP messages using TCP

- OPEN:
  - Opens TCP conn. to peer
  - Authenticates sender
- UPDATE:
  - Advertises new routes (or withdraws old)
- KEEPALIVE:
  - Keeps conn alive in absence of UPDATES, ACKs OPEN request
- NOTIFICATION:
  - Reports errors in previous msg; closes a connection

Process:

- Initialization: Open ⇨ Updates for all routes
- Ongoing: Updates for changed routes

BGP route processing



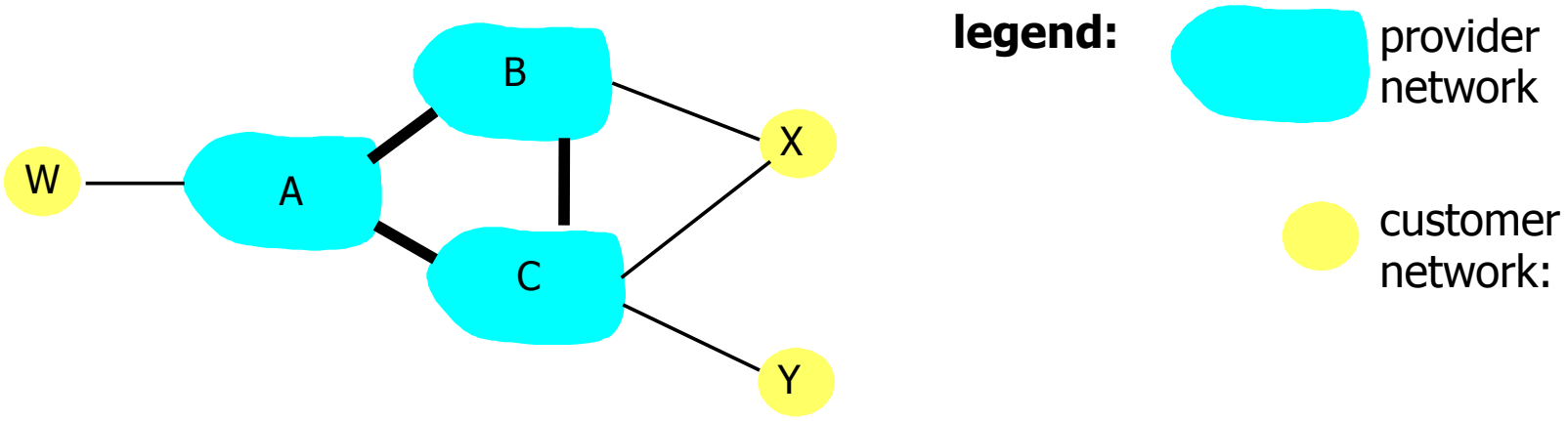
Routing policy

- Reflects goals of network provider
  - Which routes to accept from other ASes
  - How to manipulate the accepted routes
  - How to propagate routes through network
  - How to manipulate routes
    before they leave the AS
  - Which routes to send to another AS

Routing policy: Examples

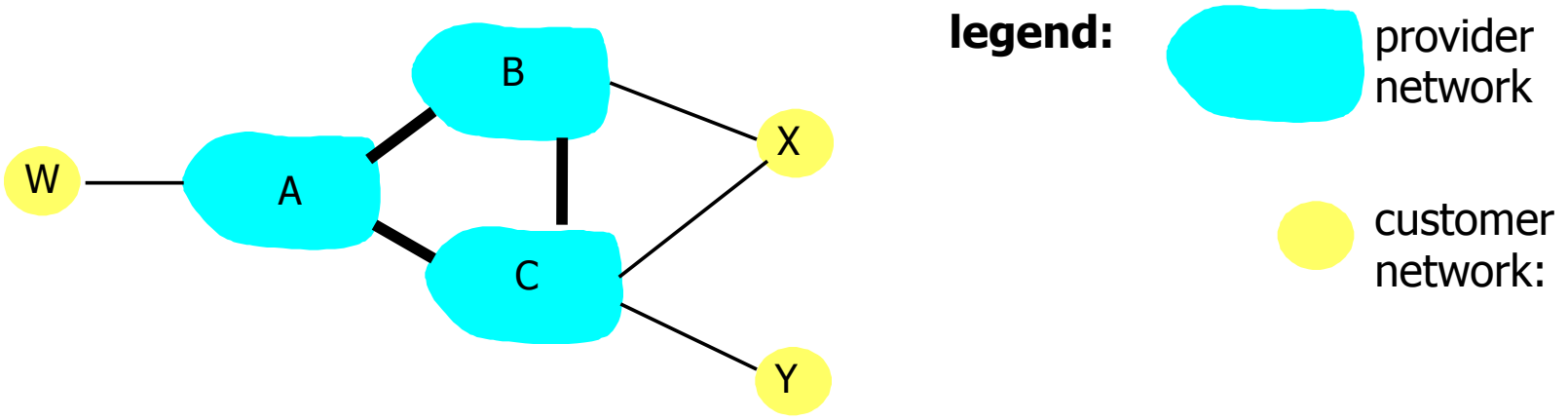
- Honor business relationships
  (E.g., customers get full-table; peers only customer prefixes)
  (E.g., prefer customer routes over peer routes over upstream routes)
- Allow customers a choice of route
  (E.g., on customer request do not export prefix to AS x, etc.)
- Enable customer traffic engineering
  (E.g., prepend x times to all peers or to specified AS)
- Enable DDoS defense for customers
  (E.g., blackholing by rewriting the next hop)
- …

BGP routing policy



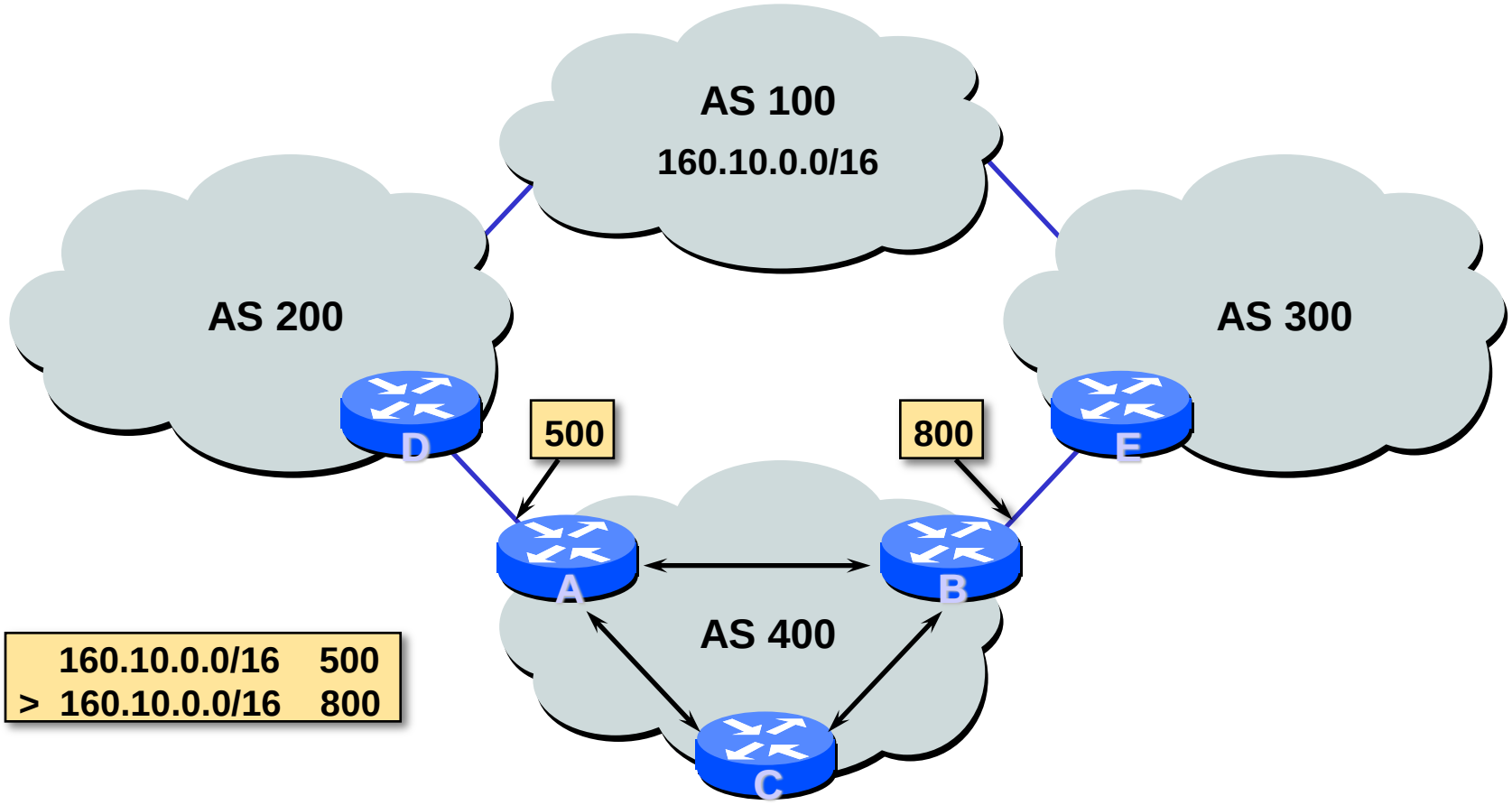
- A,B,C are provider networks
- X,W,Y are customer (of provider networks)
- X is dual-homed: attached to two networks
  - X does not want to route from B via X to C
  - .. so X will not advertise to B a route to C

BGP routing policy (2.)



- A advertises to B the path AW
- B advertises to X the path BAW
- Should B advertise to C the path BAW?
  - No way! B gets no "revenue" for routing CBAW since neither W nor C are B's customers
  - B wants to force C to route to w via A
  - B wants to route *only* to/from its customers!

Local preference attribute



- Path with highest local preference wins
- Allows providers to prefer routes

BGP route selection

- Router learn > 1 route to some prefix
- Router must select best route.
- Elimination rules:
  1. Local preference value attribute: policy decision
  2. Shortest AS-PATH
  3. Best MED (multi-exit-discriminator)
  4. Closest NEXT-HOP router: hot potato routing
  5. Additional criteria
  6. IP address of peer

Different types of ASs

- Providers: Offer connectivity to direct customer
  offer transit to other ISPs
- Customers: Buy connectivity from providers
- Peers: Exchange customers traffic at no cost
- Siblings: others

	Own Routes	Customer's Routes	Sibling's Route	Provider's Route	Peer's Route
Exporting to a Provider	×	×	×		
Exporting to a Customer	×	×	×	×	×
Exporting to a Peer	×	×	×		

OSPF (Open Shortest Path First)

- "Open": Specification publicly available
- Uses the Link State algorithm
  - State: per router info about itself and attached networks
  - OSPF advertisements: propagates state
  - Link state database: state of all routers
  - Topology map: derived from link state database

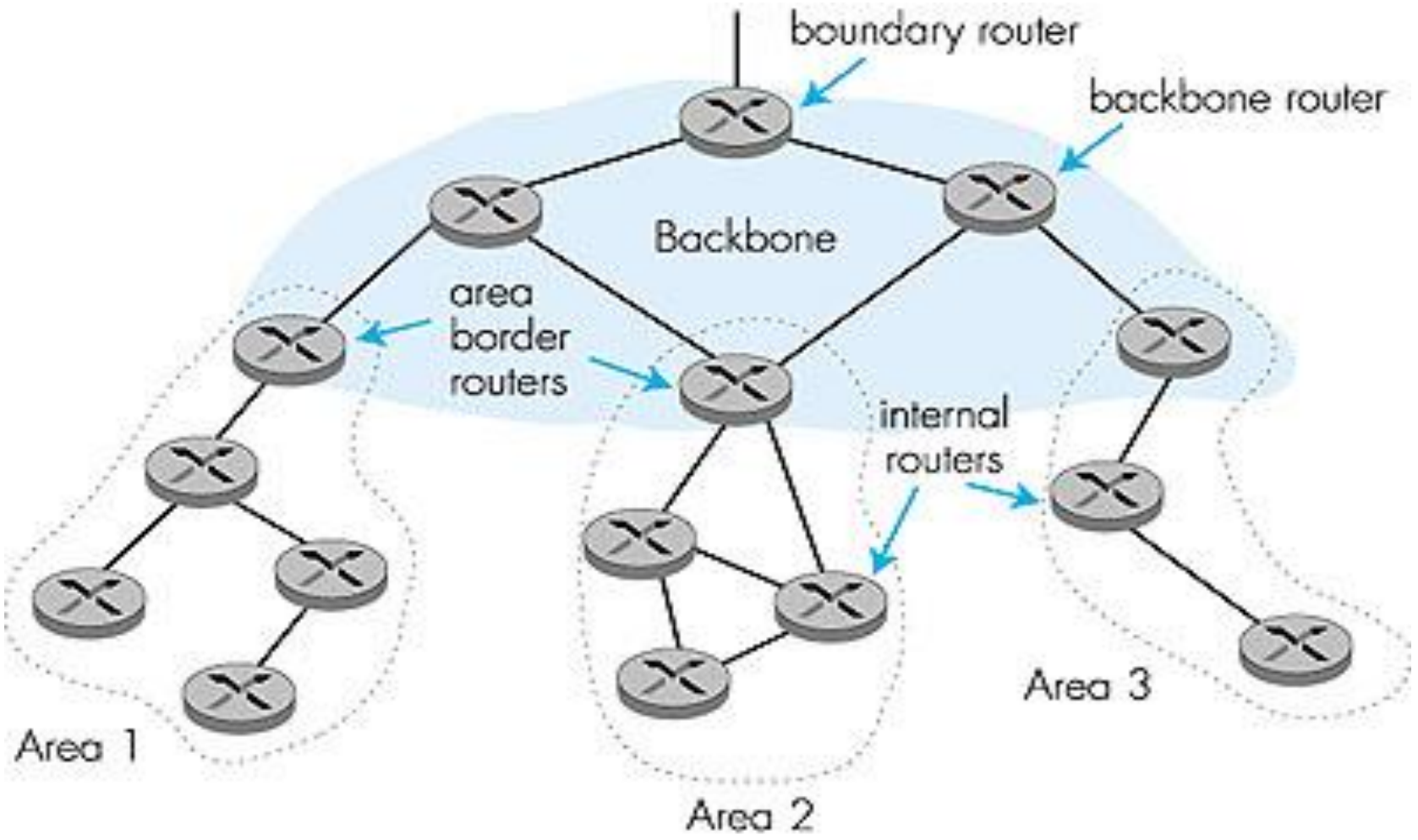
OSPFv2: Components

- Who is my neighbor?
  - Hello Protocol
- With whom I want to talk? (LAN!!!)
  - Designated router/Backup designated router concept
- What info am I missing?
  - Database synchronization
- How do I distribute info?
  - Advertisements disseminated to entire Autonomous System (via reliable flooding)
  - OSPF messages directly over IP (rather than TCP or UDP)
- Route computation
  - From link state database with Dijkstra's algorithm
  - Supports equal-cost path routing

OSPF "advanced" features

- Security: All OSPF messages are authenticated (to prevent malicious intrusion)
- Multiple same-cost paths allowed
- For each link, multiple cost metrics for different TOS (eg, satellite link cost set "low" for best effort; high for real time)
- Integrated uni- and multicast support:
  - Multicast OSPF (MOSPF) uses same topology data base as OSPF
- Hierarchical OSPF in large domains

Hierarchical OSPF



Hierarchical OSPF (2.)

- Two-level hierarchy: Local area and backbone.
  - Link-state advertisements only in respective areas.
  - Nodes in each area have detailed area topology; only know direction (shortest path) to networks in other areas.
- Area Border routers "summarize" distances to networks in the area and advertise them to other Area Border routers.
- Backbone routers: Run an OSPF routing algorithm limited to the backbone.
- Boundary routers: Connect to other ASs.

Why different Intra- and Inter-AS routing?

Policy:

- Inter-AS: Admin wants control over how its traffic routed, who routes through its net.
- Intra-AS: Single admin, so no policy decisions needed

Scale:

- Hierarchical routing saves table size, reduced update traffic

Performance:

- Intra-AS: Can focus on performance
- Inter-AS: Policy may dominate over performance

We need BOTH!