Network Layer: Routing Protocols

Computer Networking: A Top-Down Approach
9th edition
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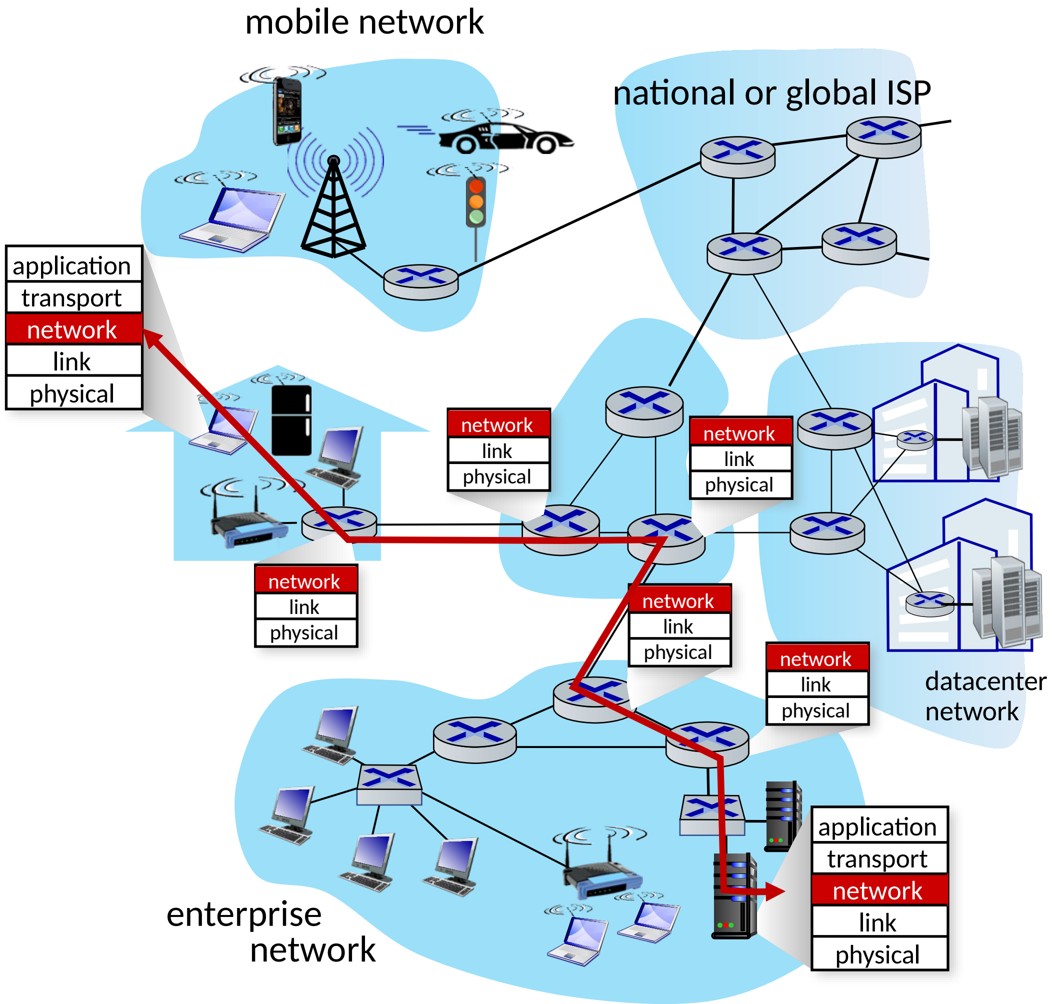
Pearson, 2025

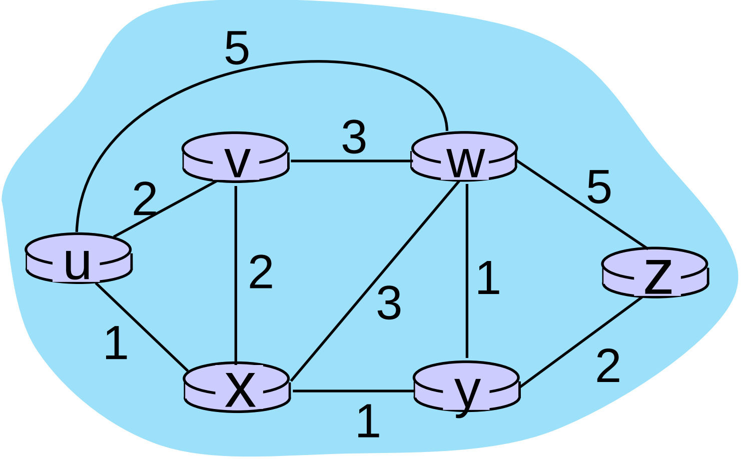
Routing protocols

Routing protocol goal: determine "good" paths (equivalently, routes), from sending hosts to receiving host, through network of routers

- path: sequence of routers packets traverse from given initial source host to final destination host
- "good": least "cost", "fastest", "least congested"
- routing: a "top-10" networking challenge!



Graph abstraction: link costs



$c_{a,b}$: cost of *direct* link connecting *a* and *b*

e.g., $c_{w,z} = 5$, $c_{u,z} = \infty$

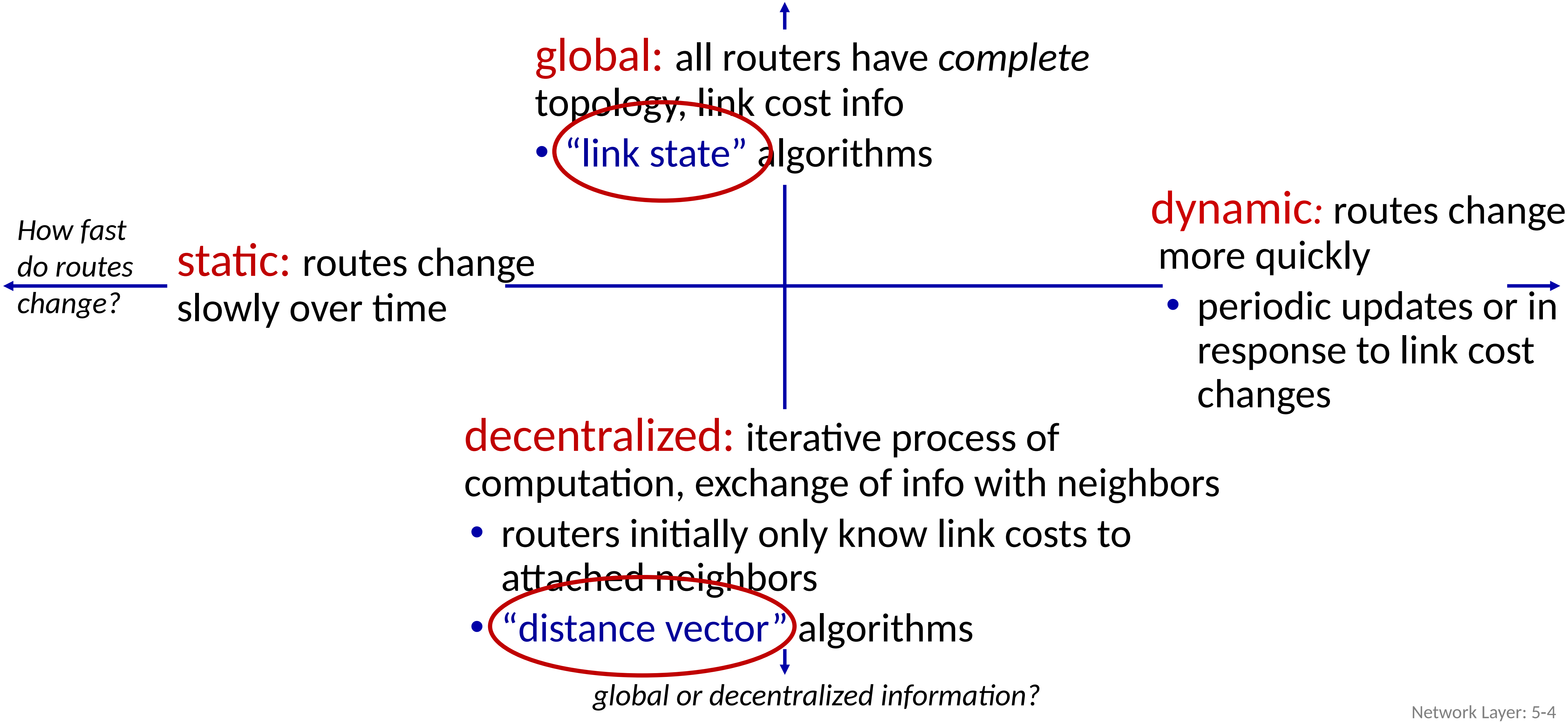
cost defined by network operator: could always be 1, or inversely related to bandwidth, or inversely related to congestion

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)* }

Routing algorithm classification



global: all routers have *complete* topology, link cost info

- "link state" algorithms

How fast do routes change?

static: routes change slowly over time

dynamic: routes change more quickly

- periodic updates or in response to link cost changes

decentralized: iterative process of computation, exchange of info with neighbors

- routers initially only know link costs to attached neighbors
- "distance vector" algorithms

global or decentralized information?

Network layer: “control plane” roadmap

- introduction
- routing protocols
  - link state
  - distance vector
- intra-ISP routing: OSPF
- routing among ISPs: BGP
- SDN control plane
- Internet Control Message Protocol

- network management, configuration
  - SNMP
  - NETCONF/YANG

Dijkstra’s link-state routing algorithm

- centralized: network 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 *forwarding table* for that node
- iterative: after *k* iterations, know least cost path to *k* destinations

notation

- $c_{x,y}$: direct link cost from node *x* to *y*; = ∞ if not direct neighbors
- *D(v)*: *current* estimate of cost of least-cost-path from source to destination *v*
- *p(v)*: predecessor node along path from source to *v*
- *N'*: set of nodes whose least-cost-path *definitively* known

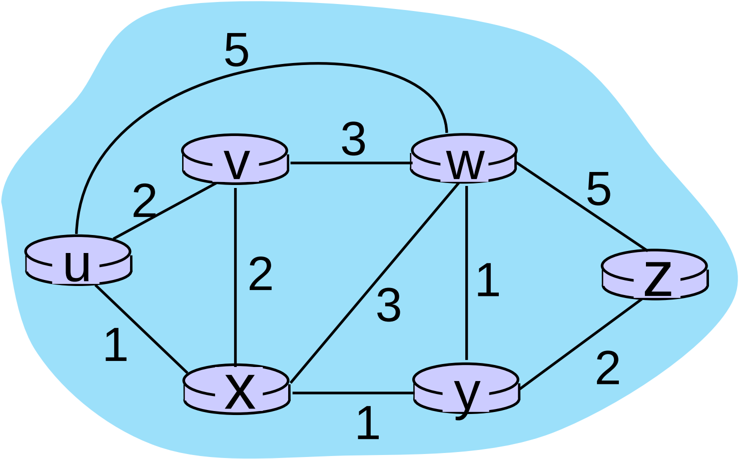
Dijkstra’s link-state routing algorithm

```
Initialization:
  $N' = \{u\}$                      /* compute least cost path from u to all other nodes */
  for all nodes $v$
    if $v$ adjacent to $u$          /* $u$ initially knows direct-path-cost only to direct neighbors */
      then $D(v) = c_{u,v}$         /* but may not be minimum cost! */
    else $D(v) = \infty$

Loop
  find $w$ not in $N'$ such that $D(w)$ is a minimum
  add $w$ to $N'$
  update $D(v)$ for all $v$ adjacent to $w$ and not in $N'$ :
    $D(v) = \min(D(v), D(w) + c_{w,v})$
  /* new least-path-cost to $v$ is either old least-cost-path to $v$ or known
  least-cost-path to $w$ plus direct-cost from $w$ to $v$ */
until all nodes in $N'$
```

Dijkstra’s algorithm: an example

		v	w	x	y	z
Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1						
2						
3						
4						
5						

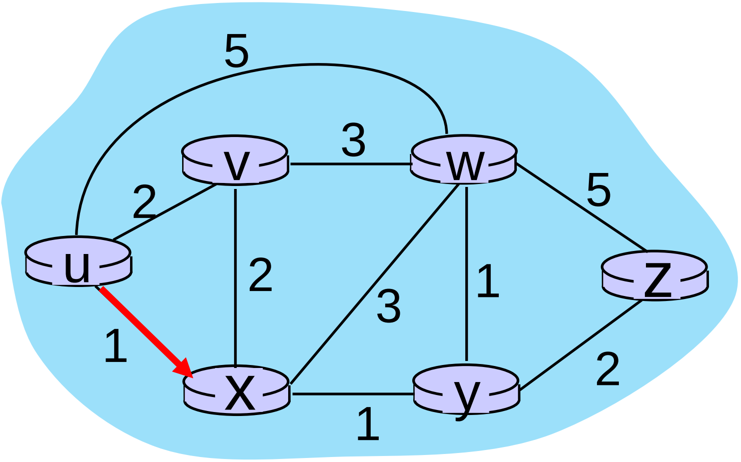


Initialization (step 0):

For all *a*: if *a* adjacent to *u* then *D(a)* = $c_{u,a}$

Dijkstra’s algorithm: an example

		v	w	x	y	z
Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux					
2						
3						
4						
5						



```
*Loop*
    find $a$ not in $N'$ such that $D(a)$ is a minimum
    add $a$ to $N'$
```

Dijkstra's algorithm: an example

		v	w	x	y	z
Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
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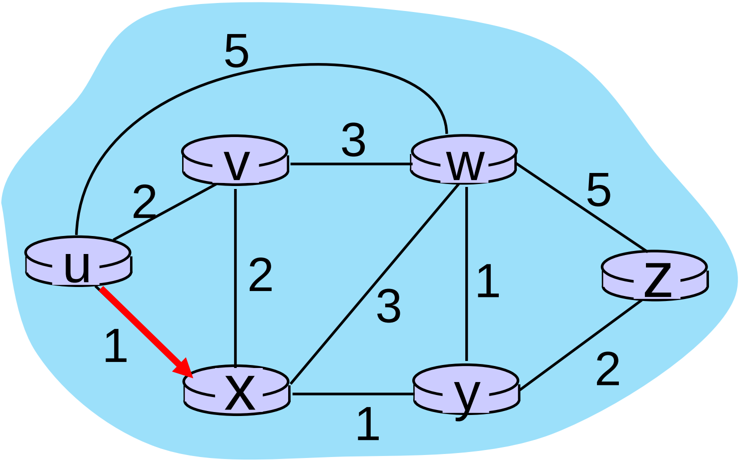
1	ux	2,u	4,x		2,x	∞
2						
3						
4						
5						



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Loop
    find a not in N' such that D(a) is a minimum
    add a to N'
  update D(b) for all b adjacent to a and not in N' :
      D(b) = min ( D(b), D(a) + c_{a,b} )
```

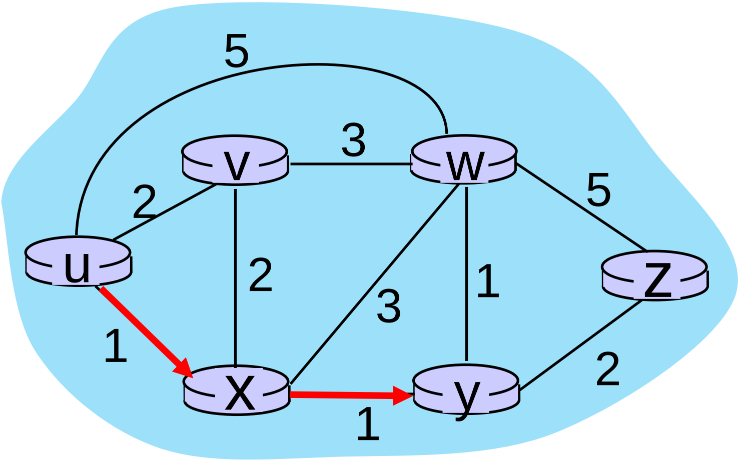
$D(v) = \min(D(v), D(x) + c_{x,v}) = \min(2, 1+2) = 2$

$D(w) = \min(D(w), D(x) + c_{x,w}) = \min(5, 1+3) = 4$

$D(y) = \min(D(y), D(x) + c_{x,y}) = \min(inf, 1+1) = 2$

Dijkstra’s algorithm: an example

		v	w	x	y	z
Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy					
3						
4						
5						



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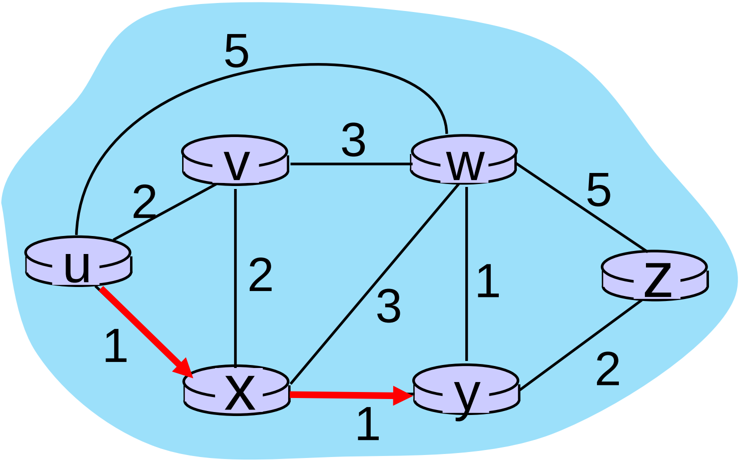
2	uxy	2,u	3,y			4,y
3						
4						
5						



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$D(w) = \min (D(w), D(y) + c_{y,w}) = \min (4, 2+1) = 3$

$D(z) = \min (D(z), D(y) + c_{y,z}) = \min(\text{inf},2+2) = 4$

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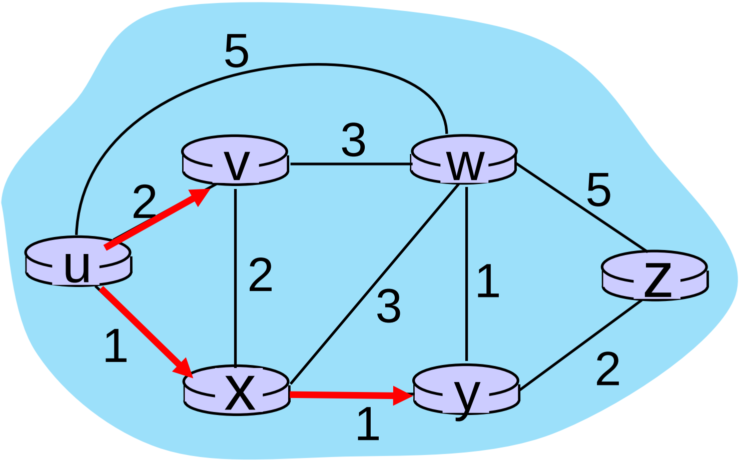

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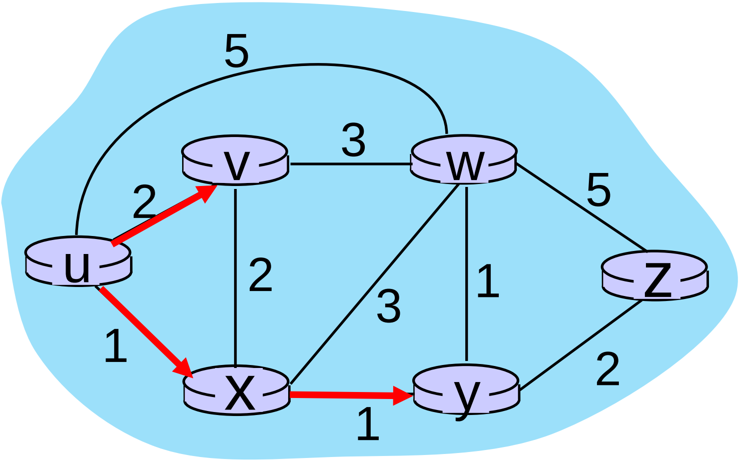
3	uxyv		3,y			4,y
4						
5						



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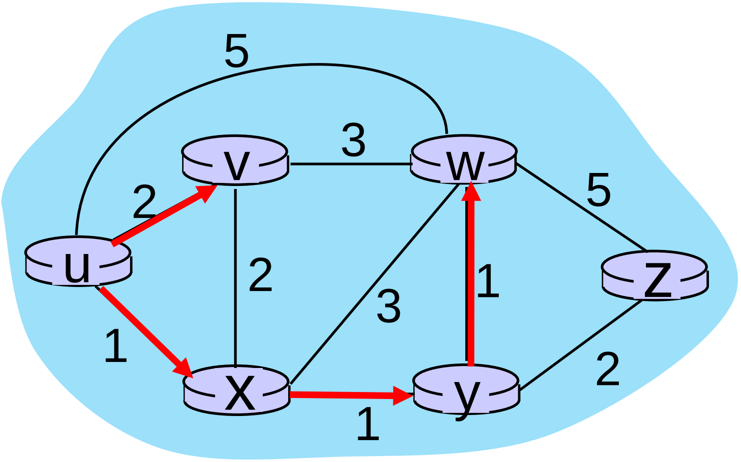

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Dijkstra's algorithm: an example

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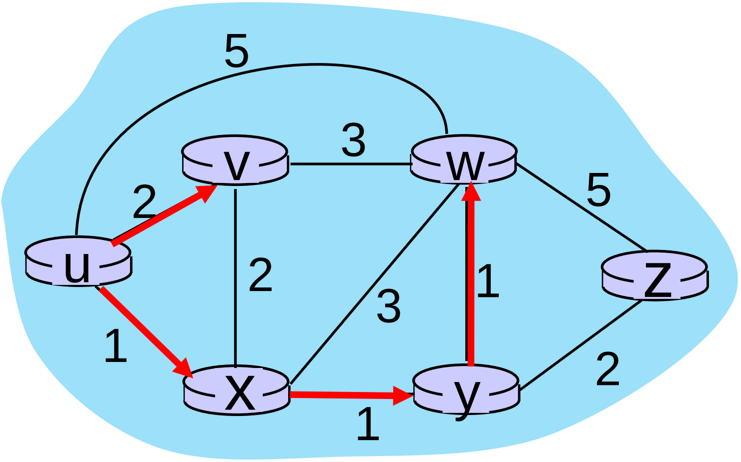
5						



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4	uxyvw					4,y
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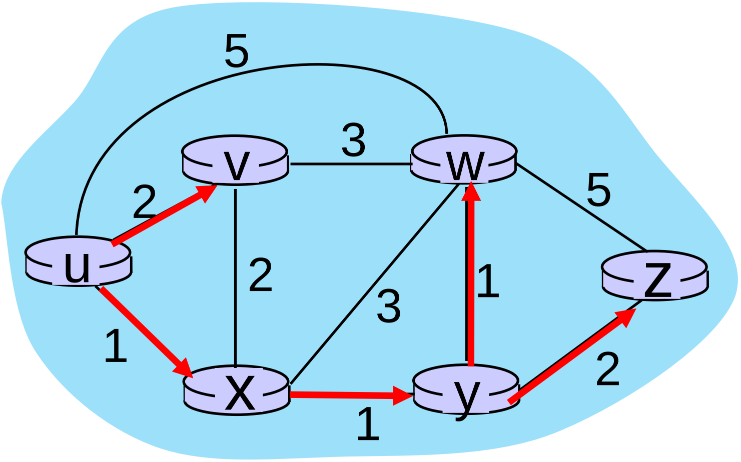

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2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
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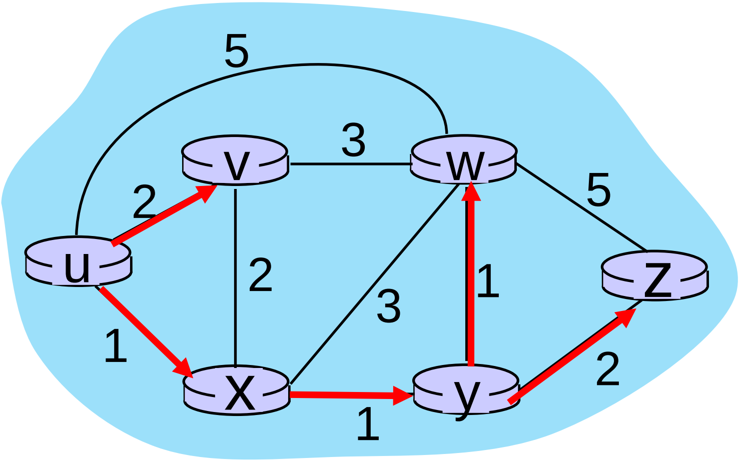

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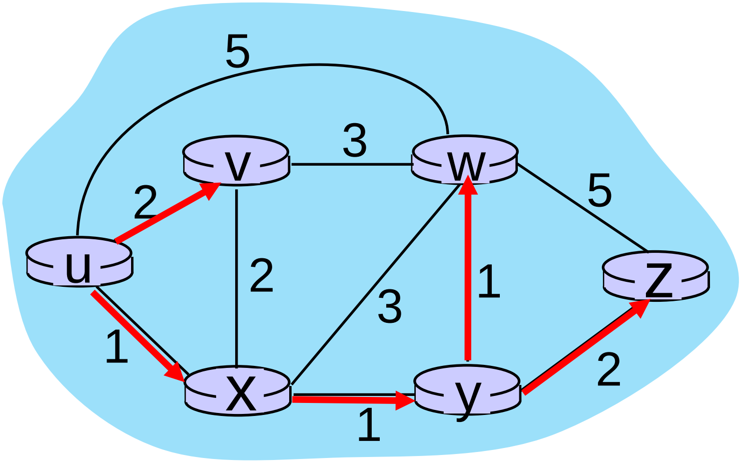
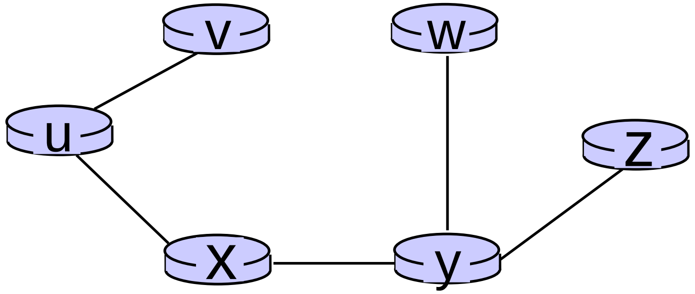
Dijkstra’s algorithm: an example



resulting least-cost-path tree from u:



resulting forwarding table in u:

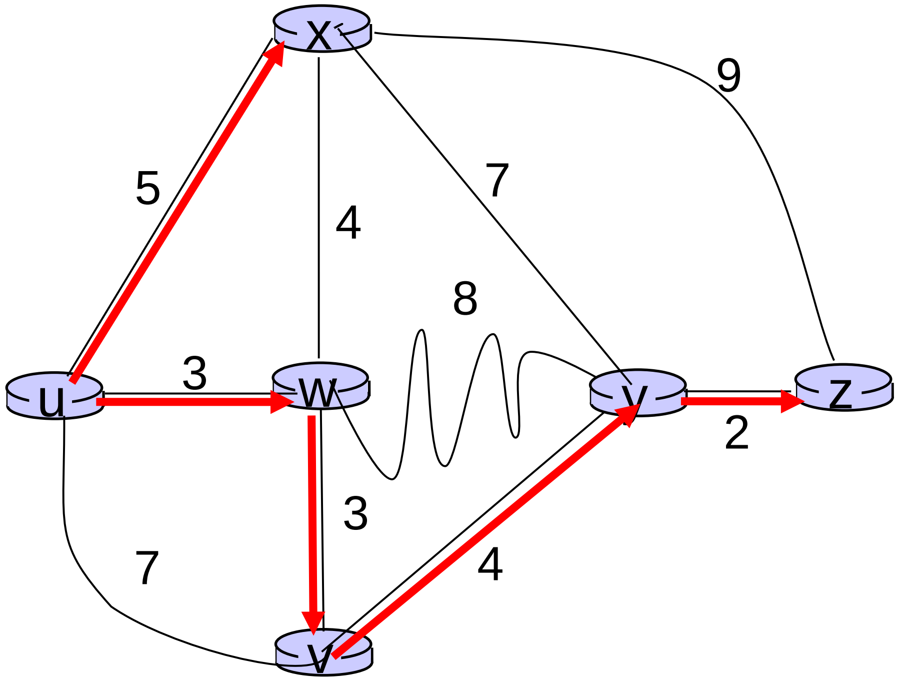
destination	outgoing link
v	(u,v)
x	(u,x)
y	(u,x)
w	(u,x)
x	(u,x)

route from *u* to *v* directly

route from u to all other destinations via *x*

Dijkstra’s algorithm: another example

		v	w	x	y	z
Step	*N'*	*D(v), p(v)*	*D(w), p(w)*	*D(x), p(x)*	*D(y), p(y)*	*D(z), p(z)*
0	u	7,u	3,u	5,u	∞	∞
1	uw	6,w		5,u	11,w	∞
2	uwx	6,w			11,w	14,x
3	uwxv				10,v	14,x
4	uwxvy					12,y
5	uwxvyz					



notes:

- construct least-cost-path tree by tracing predecessor nodes
- ties can exist (can be broken arbitrarily)

Dijkstra's algorithm: discussion

algorithm complexity: *n* nodes

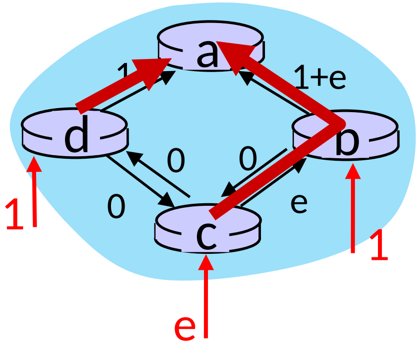
- each of *n* iteration: need to check all nodes, *w*, not in *N*
- *n*(*n*+1)/2 comparisons: O(n^2) complexity
- more efficient implementations possible: O(*n*log*n*)

message complexity:

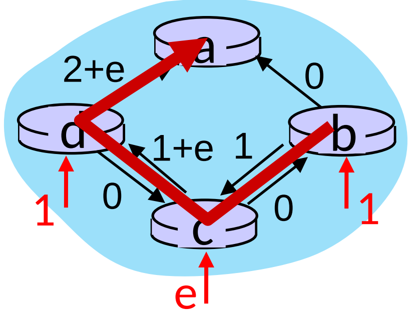
- each router must *broadcast* its link state information to other *n* routers
- efficient (and interesting!) broadcast algorithms: O(*n*) link crossings to disseminate a broadcast message from one source
- each router's message crosses O(*n*) links: overall message complexity: O(n^2)

Dijkstra’s algorithm: oscillations possible

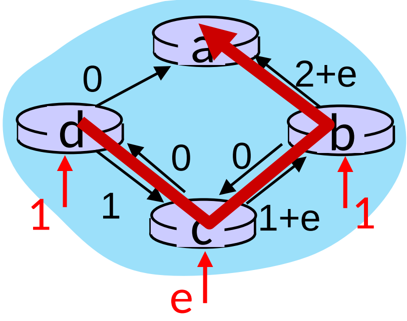
- when link costs depend on traffic volume, route oscillations possible
- sample scenario:
  - routing to destination a, traffic entering at d, c, e with rates 1, e (<1), 1
  - link costs are directional, and volume-dependent



initially



given these costs, find new routing…. resulting in new costs



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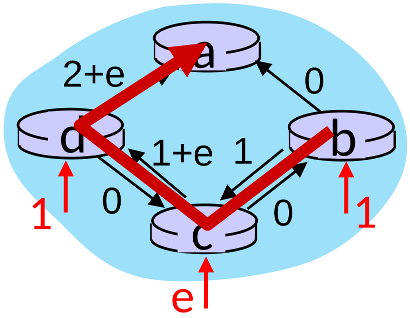

given these costs, find new routing…. resulting in new costs

Network layer: “control plane” roadmap

- introduction
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  - link state
  - distance vector
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Distance vector algorithm

Based on *Bellman-Ford* (BF) equation (dynamic programming):

Bellman-Ford equation

Let $D_x(y)$: cost of least-cost path from x to y.

Then:

$$D_x(y) = \min_v \{ c_{x,v} + D_v(y) \}$$

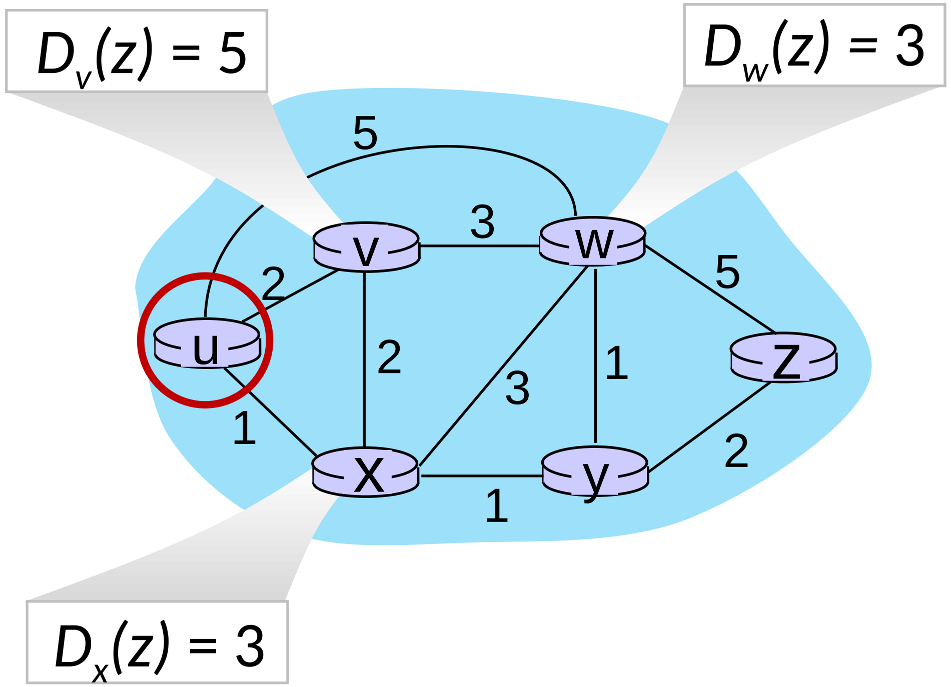
v’s estimated least-cost-path cost to y

min taken over all neighbors v of x

direct cost of link from x to v

Bellman-Ford Example

Suppose that *u*'s neighboring nodes, *x*,*v*,*w*, know that for destination *z*:



Bellman-Ford equation says:

$$\boxed{D_u(z)} = \min \{ c_{u,v} + D_v(z), \boxed{c_{u,x} + D_x(z)}, c_{u,w} + D_w(z) \}$$

$$= \min \{2 + 5, 1 + 3, 5 + 3\} \boxed{= 4}$$

*node achieving minimum (x) is **next hop** on estimated least-cost path to destination (z)*

Distance vector algorithm

key idea:

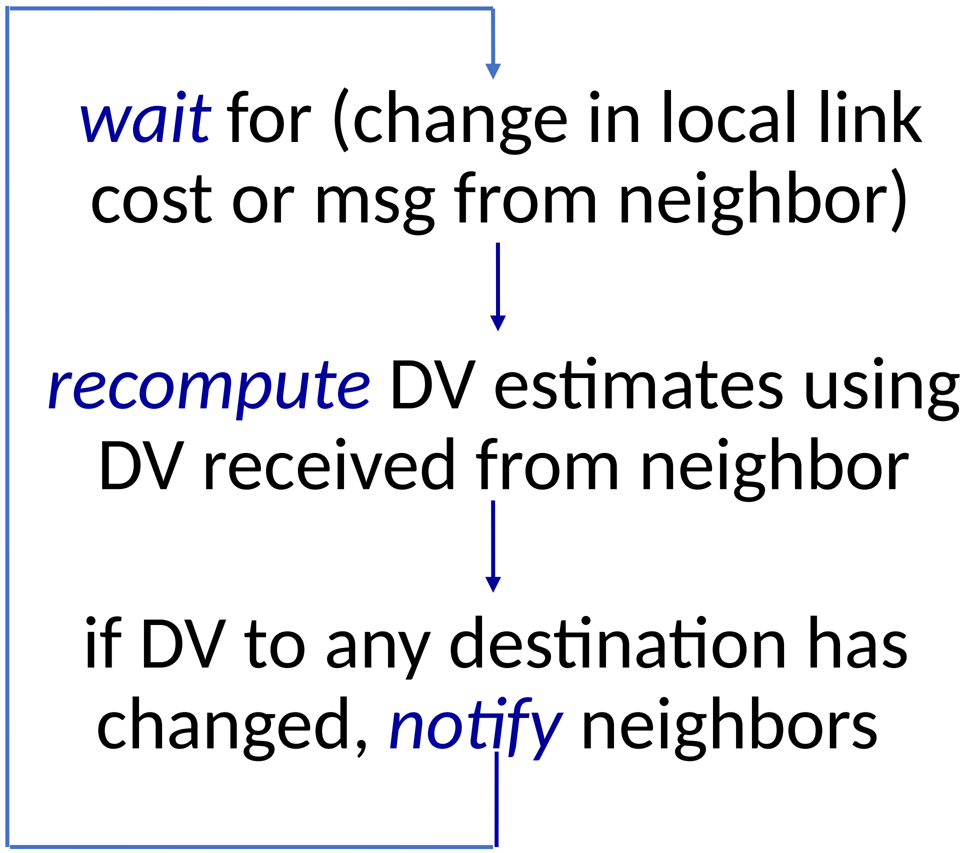
- from time-to-time, each node sends its own distance vector estimate to neighbors
- when *x* receives new DV estimate from any neighbor, it updates its own DV using B-F equation:

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

- under minor, natural conditions, the estimate $D_x(y)$ *converge to the actual least cost* $\mathrm{d}_x(\mathrm{y})$

Distance vector algorithm:

each node:



wait for (change in local link cost or msg from neighbor)

recompute DV estimates using DV received from neighbor

if DV to any destination has changed, *notify* neighbors

iterative, asynchronous: each local iteration caused by:

- local link cost change
- DV update message from neighbor

distributed, self-stopping: each node notifies neighbors *only* when its DV changes

- neighbors then notify their neighbors – *only if necessary*
- no notification received, no actions taken!

Distance vector: example

DV in a:

$D_a(a)=0$

$D_a(b) = 8$

$D_a(c) = \infty$

$D_a(d) = 1$

$D_a(e) = \infty$

$D_a(f) = \infty$

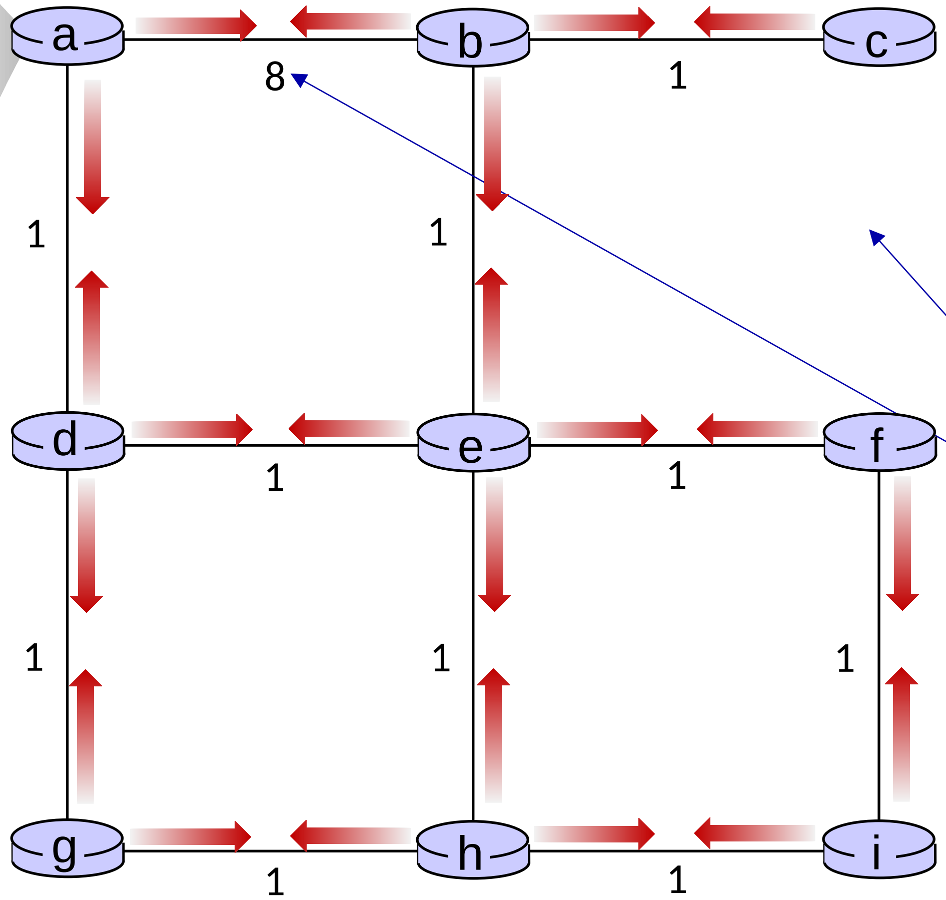
$D_a(g) = \infty$

$D_a(h) = \infty$

$D_a(i) = \infty$

t=0

- All nodes have distance estimates to nearest neighbors (only)
- All nodes send their local distance vector to their neighbors



A few asymmetries:

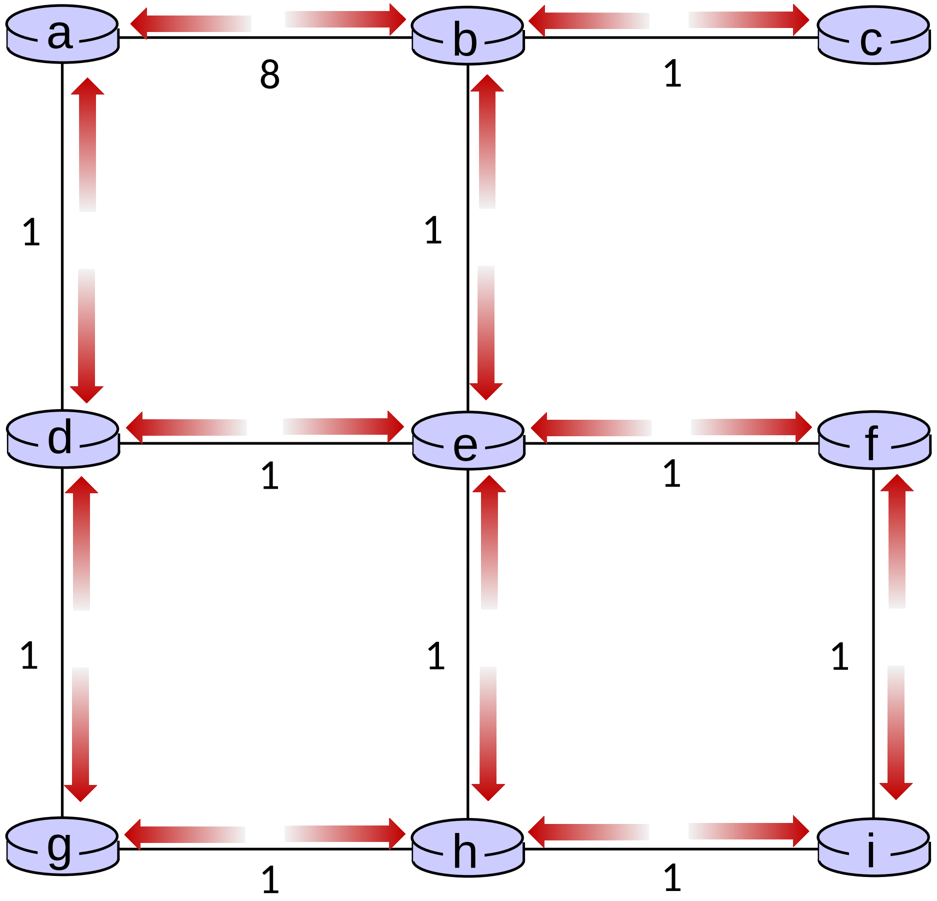
- missing link
- larger cost

Distance vector example: iteration

t=1

All nodes:

- receive distance vectors from neighbors
- compute their new local distance vector
- send their new local distance vector to neighbors



Distance vector example: iteration

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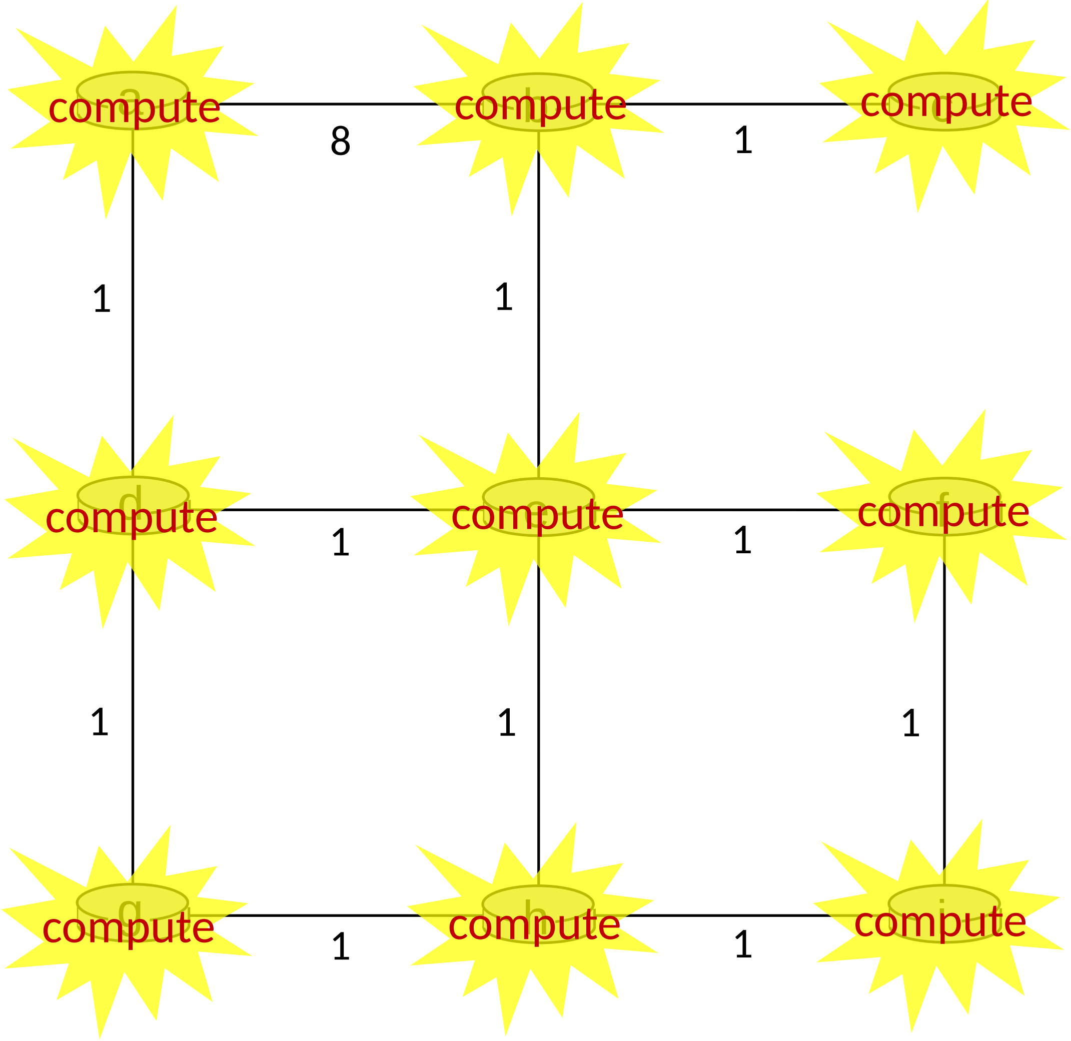

Distance vector example: iteration

t=1

All nodes:

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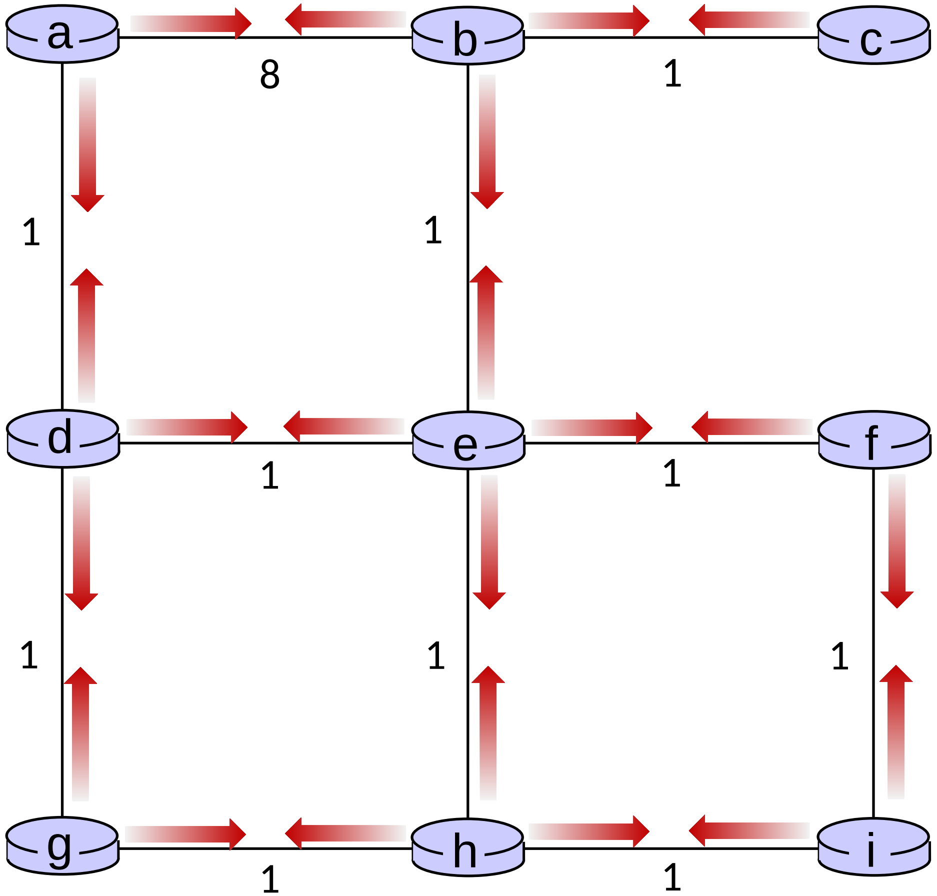
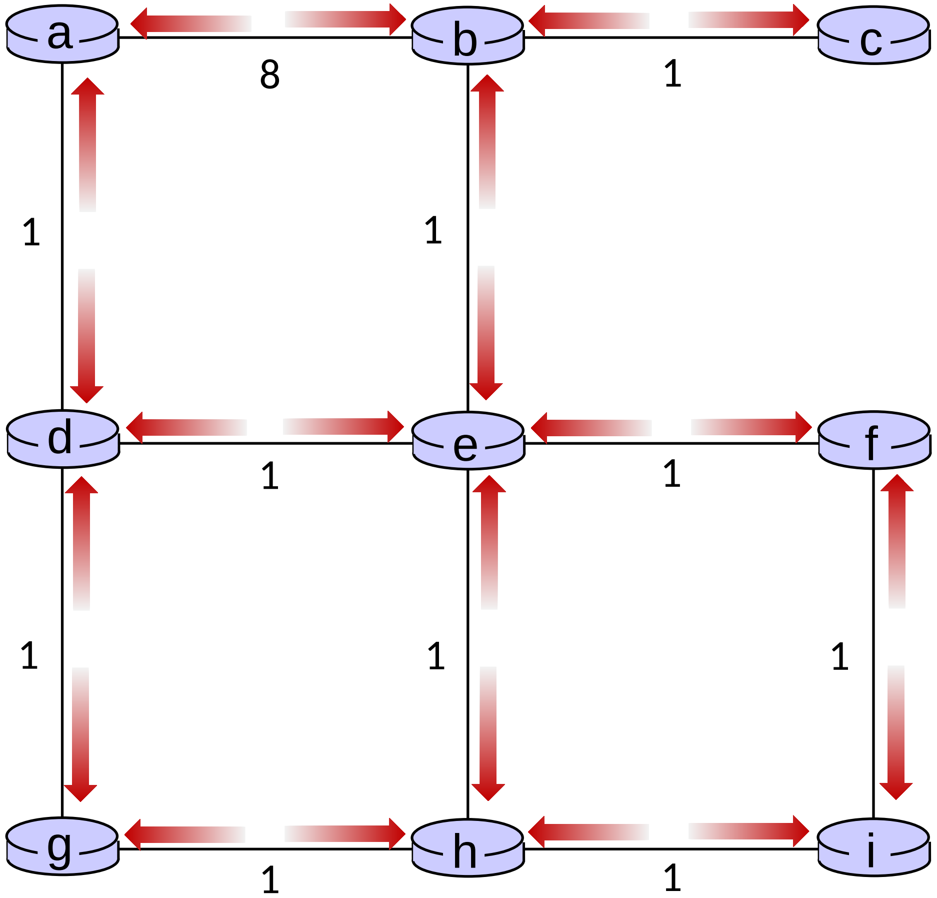


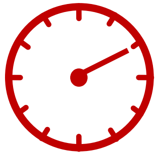
Distance vector example: iteration

t=2

All nodes:
- receive distance vectors from neighbors
- compute their new local distance vector
- send their new local distance vector to neighbors



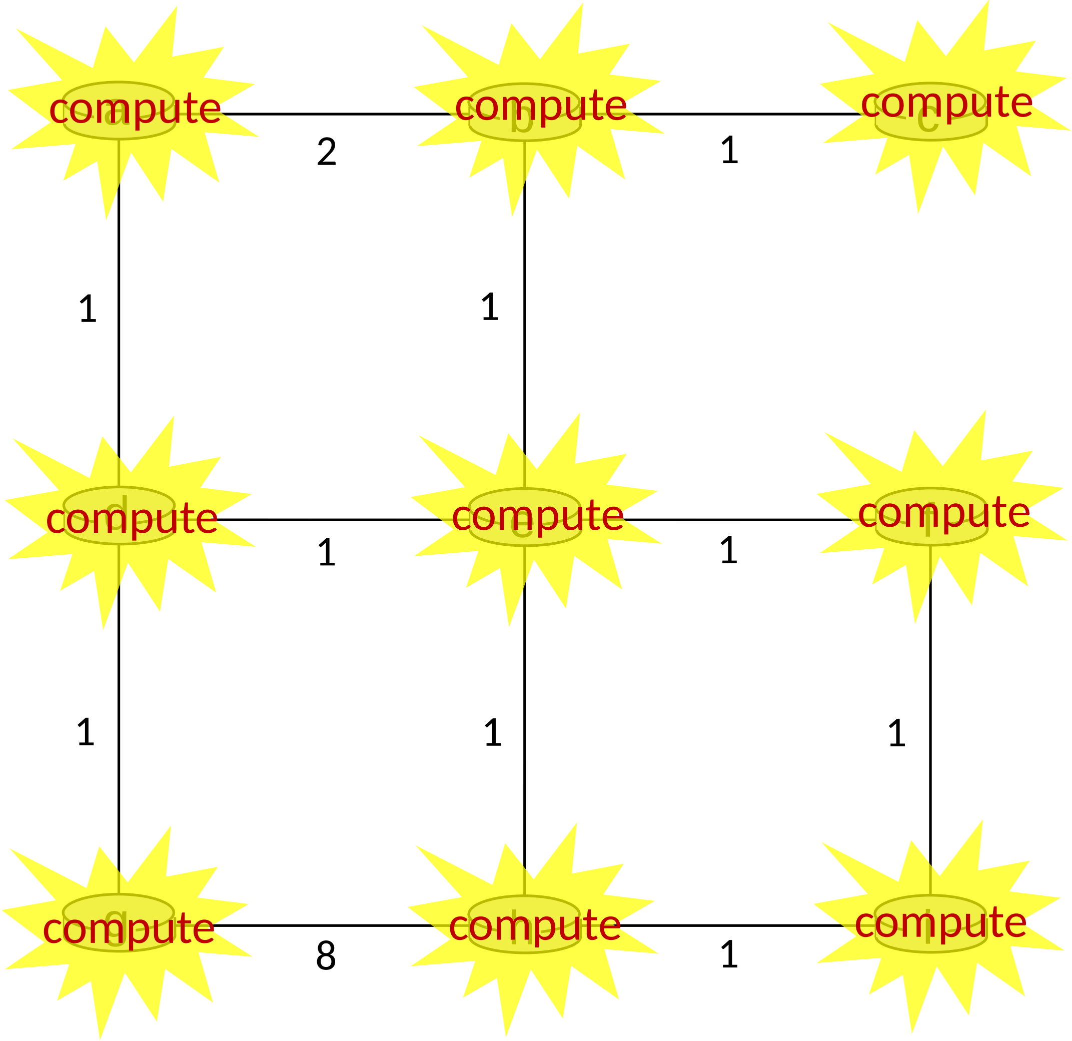
Distance vector example: iteration



t=2

All nodes:

- receive distance vectors from neighbors
- compute their new local distance vector
- send their new local distance vector to neighbors



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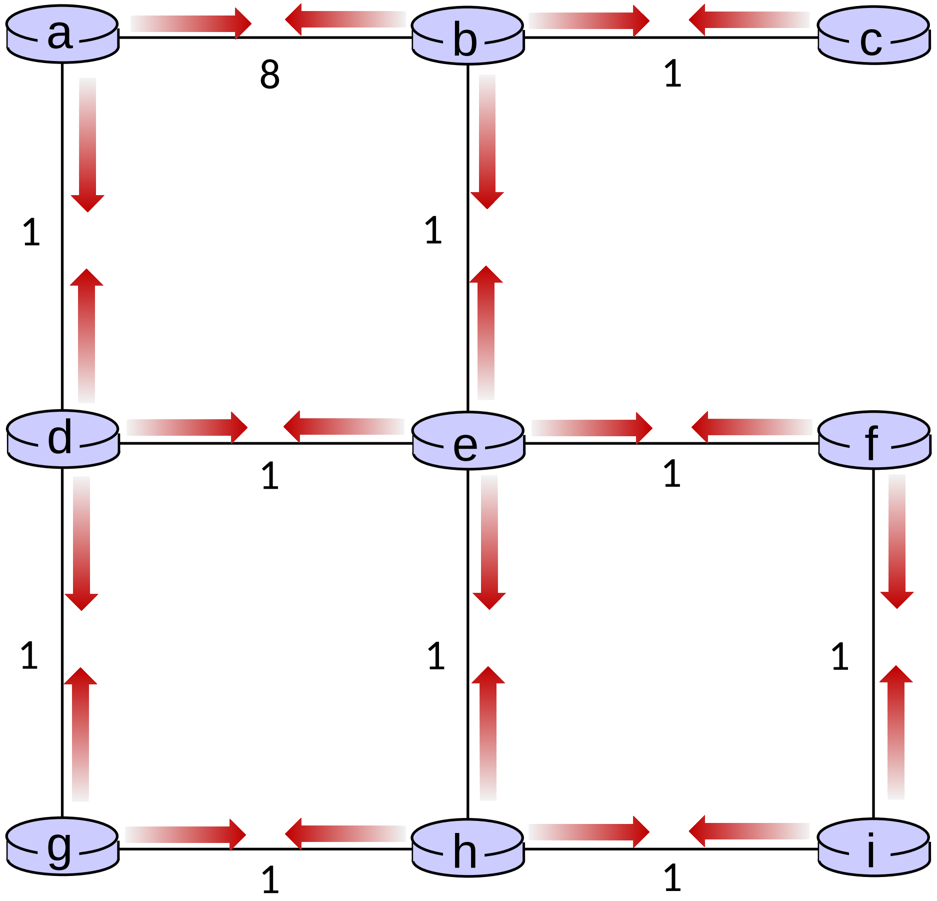


Distance vector: state information diffusion

Iterative communication, computation steps diffuses information through network:

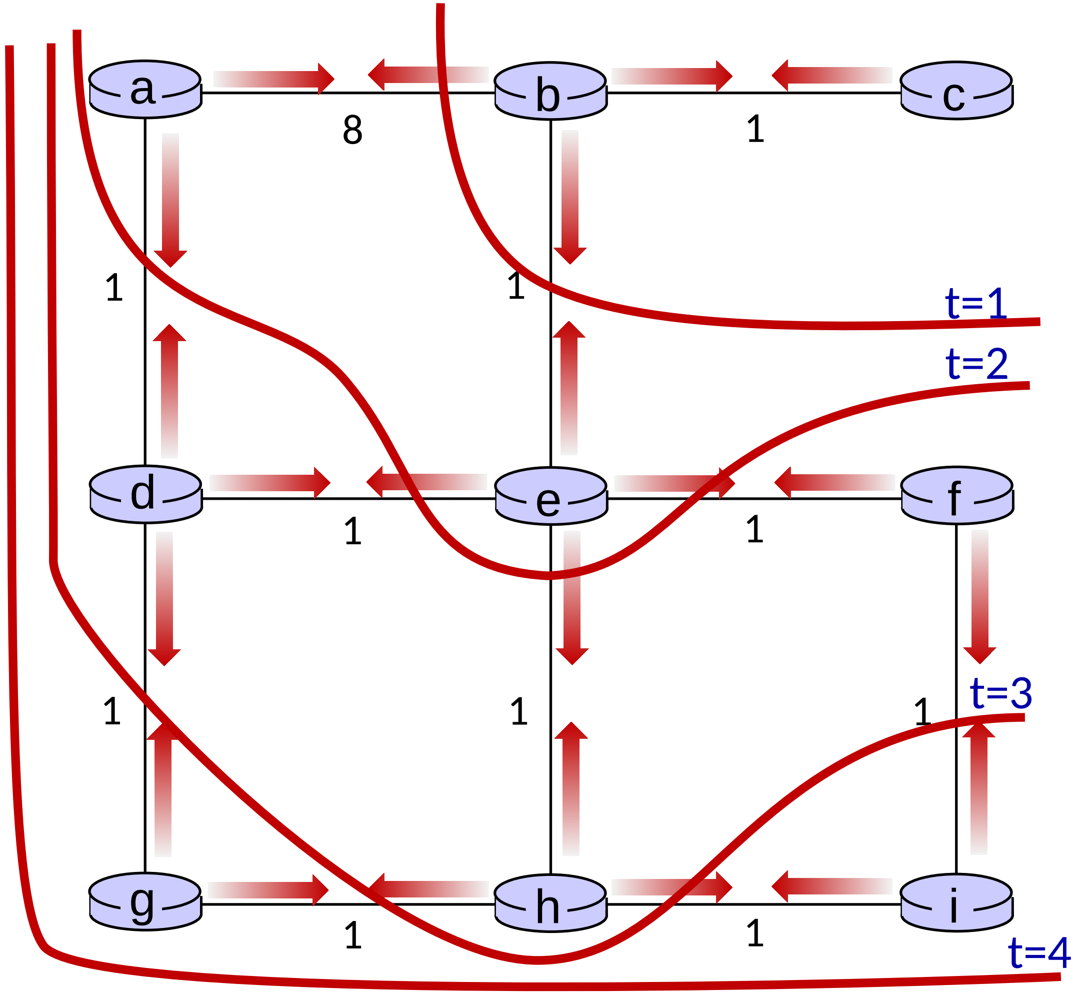
t=0 c's state at t=0 is at c only

t=1 c's state at t=0 has propagated to b, and may influence distance vector computations up to **1** hop away, i.e., at b

t=2 c's state at t=0 may now influence distance vector computations up to **2** hops away, i.e., at b and now at a, e as well

t=3 c's state at t=0 may influence distance vector computations up to **3** hops away, i.e., at d, f, h

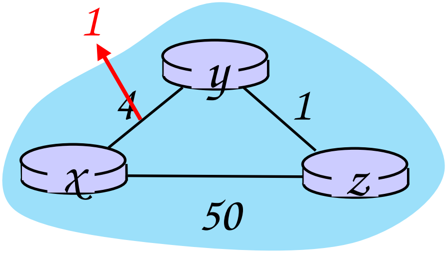
t=4 c's state at t=0 may influence distance vector computations up to **4** hops away, i.e., at g, i



Distance vector: link cost changes

link cost changes:

- node detects local link cost change
- updates routing info, recalculates local DV
- if DV changes, notify neighbors



“good news travels fast”

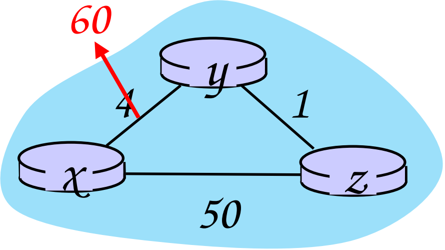
t_0 : *y* detects link-cost change, updates its DV, informs its neighbors.

t_1 : *z* receives update from *y*, updates its DV, computes new least cost to *x* , sends its neighbors its DV.

t_2 : *y* receives *z*’s update, updates its DV. *y*’s least costs do *not* change, so *y* does *not* send a message to *z*.

Distance vector: link cost changes

link cost changes:



- node detects local link cost change
- "bad news travels slow" – count-to-infinity problem:
  - *y* sees direct link to *x* has new cost 60, but z has said it has a path at cost of 5. So *y* computes "my new cost to x will be 6, via z); notifies *z* of new cost of 6 to *x*.
  - *z* learns that path to *x* via *y* has new cost 6, so *z* computes "my new cost to *x* will be 7 via y), notifies *y* of new cost of 7 to *x*.
  - *y* learns that path to *x* via *z* has new cost 7, so *y* computes "my new cost to *x* will be 8 via y), notifies *z* of new cost of 8 to *x*.
  - *z* learns that path to *x* via *y* has new cost 8, so *z* computes "my new cost to *x* will be 9 via y), notifies *y* of new cost of 9 to *x*.

    …
- see text for solutions. *Distributed algorithms are tricky!*

Comparison of LS and DV algorithms

message complexity

LS: *n* routers, O(n^2) messages sent

DV: exchange between neighbors; convergence time varies

speed of convergence

LS: O(n^2) algorithm, O(n^2) messages

- may have oscillations

DV: convergence time varies

- may have routing loops
- count-to-infinity problem

robustness: what happens if router malfunctions, or is compromised?

LS:

- router can advertise incorrect *link* cost
- each router computes only its *own* table

DV:

- DV router can advertise incorrect *path* cost ("I have a *really* low-cost path to everywhere"): *black-holing*
- each router's DV is used by others: error propagate thru network

Making routing scalable

our routing study thus far - idealized

- all routers identical
- network "flat"

… not true in practice

scale: billions of destinations:

- can't store all destinations in routing tables!
- routing table exchange would swamp links!

administrative autonomy:

- Internet: a network of networks
- each network admin may want to control routing in its own network

Internet approach to scalable routing

aggregate routers into regions known as "autonomous systems" (AS) (a.k.a. "domains")

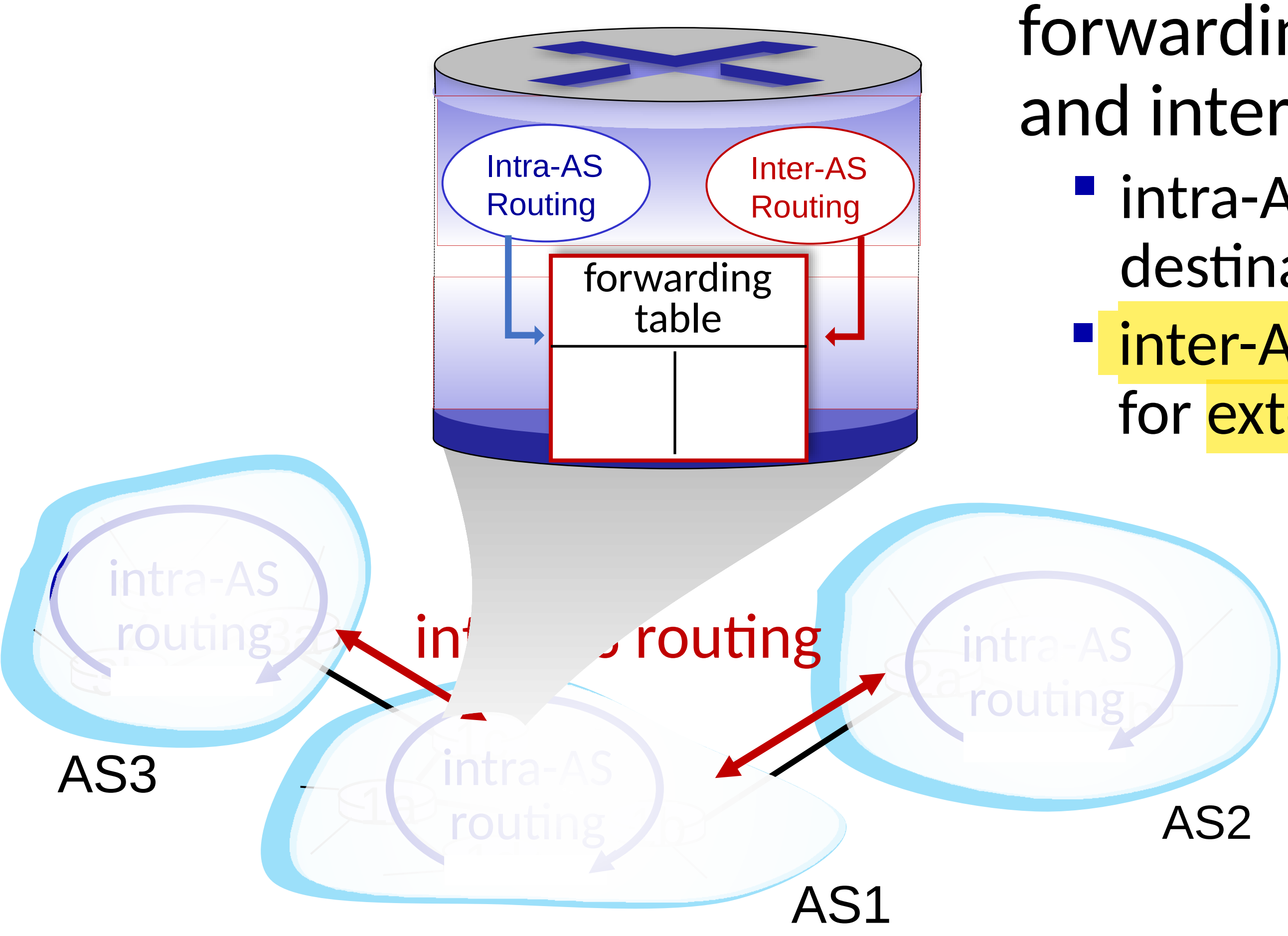
intra-AS (aka "intra-domain"): routing among routers *within same AS ("network")*

- all routers in AS must run same intra-domain protocol
- routers in different AS can run different intra-domain routing protocols
- gateway router: at "edge" of its own AS, has link(s) to router(s) in other AS'es

inter-AS (aka "inter-domain"): routing *among* AS'es

- gateways perform inter-domain routing (as well as intra-domain routing)

Interconnected ASes



forwarding table configured by intra- and inter-AS routing algorithms

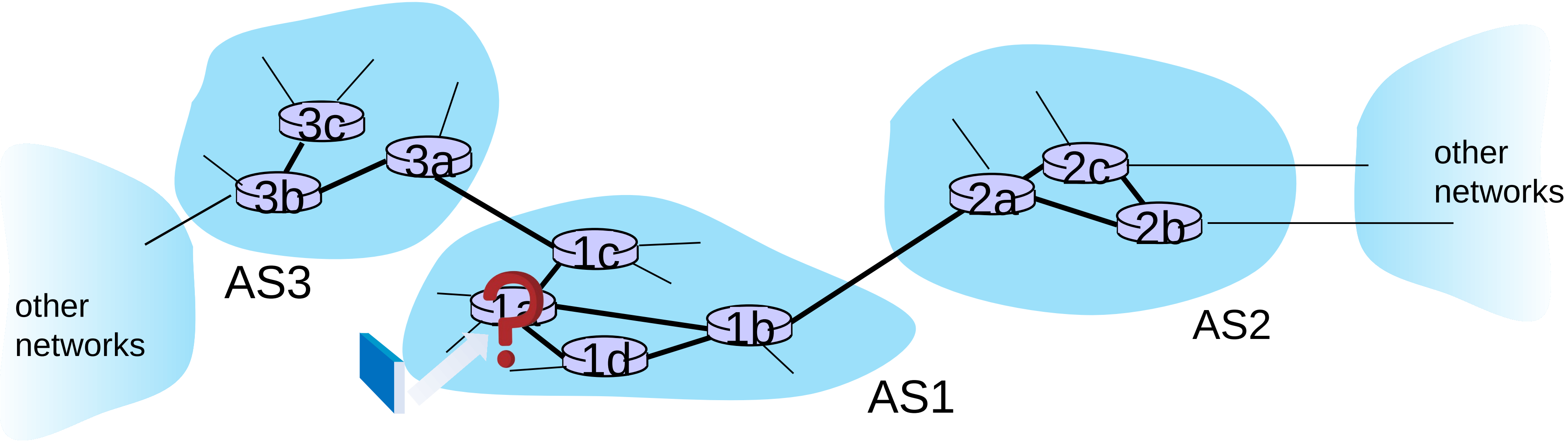
- intra-AS routing determine entries for destinations within AS
- inter-AS & intra-AS determine entries for external destinations

Inter-AS routing: a role in intradomain forwarding

- suppose router in AS1 receives datagram destined outside of AS1:
  - router should forward packet to gateway router in AS1, but which one?

AS1 inter-domain routing must:

1. learn which destinations reachable through AS2, which through AS3
2. propagate this reachability info to all routers in AS1



Intra-AS routing: routing within an AS

most common intra-AS routing protocols:

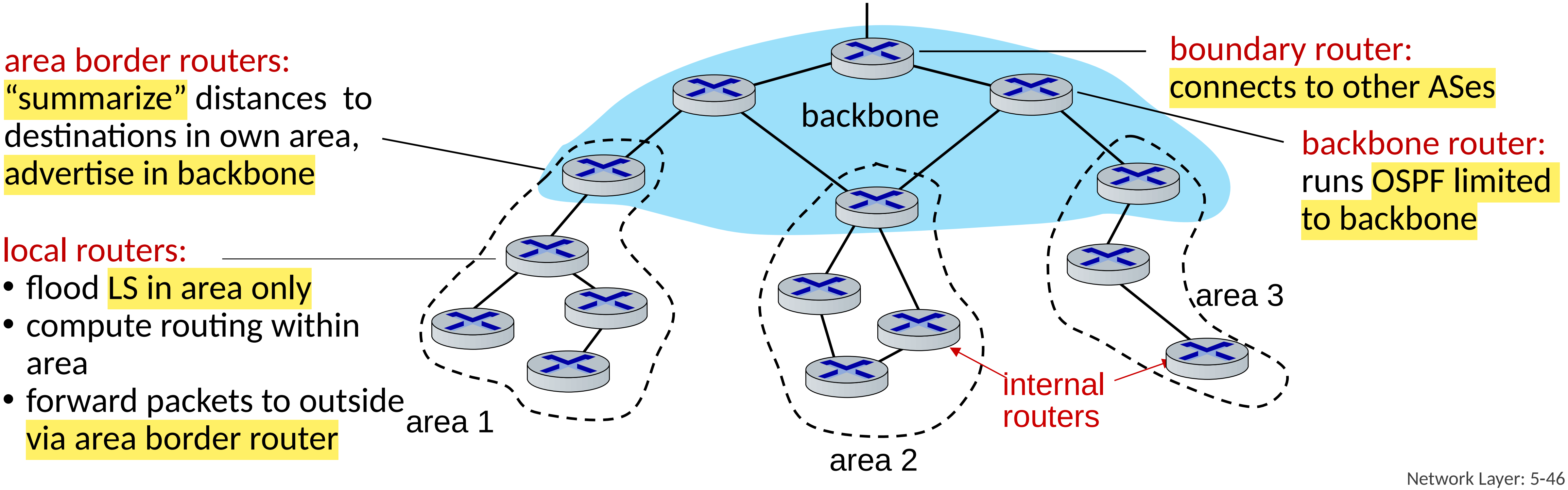
- RIP: Routing Information Protocol [RFC 1723]
  - classic DV: DVs exchanged every 30 secs
  - no longer widely used
- EIGRP: Enhanced Interior Gateway Routing Protocol
  - DV based
  - formerly Cisco-proprietary for decades (became open in 2013 [RFC 7868])
- OSPF: Open Shortest Path First [RFC 2328]
  - link-state routing
  - IS-IS protocol (ISO standard, not RFC standard) essentially same as OSPF

OSPF (Open Shortest Path First) routing

- "open": publicly available
- classic link-state
  - each router floods OSPF link-state advertisements (directly over IP rather than using TCP/UDP) to all other routers in entire AS
  - multiple link costs metrics possible: bandwidth, delay
  - each router has full topology, uses Dijkstra's algorithm to compute forwarding table
- *security:* all OSPF messages authenticated (to prevent malicious intrusion)

Hierarchical OSPF

- two-level hierarchy: local area, backbone.
  - link-state advertisements flooded only in area, or backbone
  - each node has detailed area topology; only knows direction to reach other destinations



area border routers:
"summarize" distances to destinations in own area, advertise in backbone

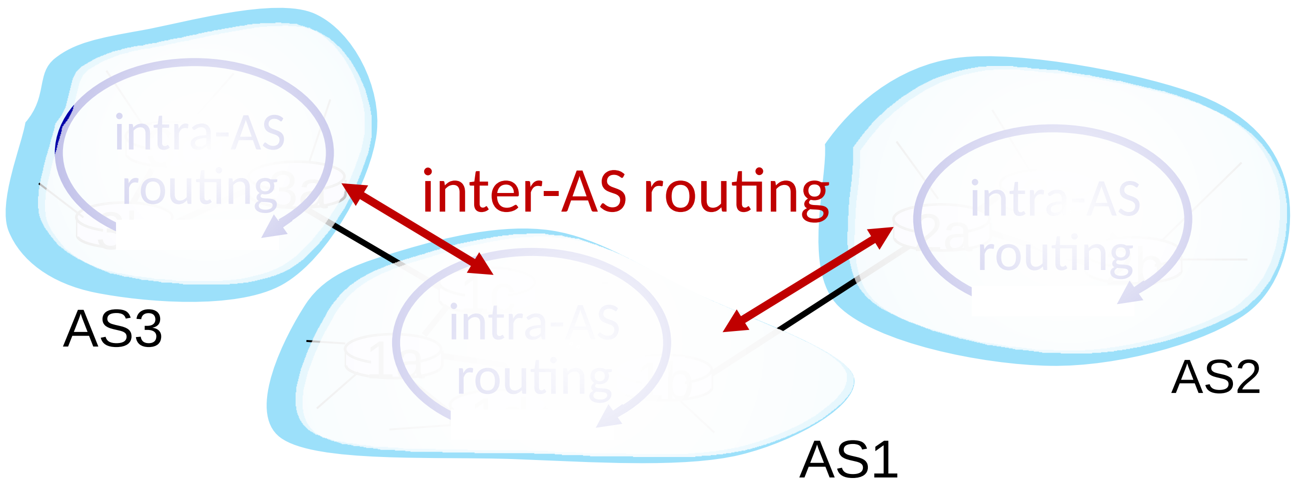
local routers:
- flood LS in area only
- compute routing within area
- forward packets to outside via area border router

boundary router:
connects to other ASes

backbone router:
runs OSPF limited to backbone

internal routers

Interconnected ASes



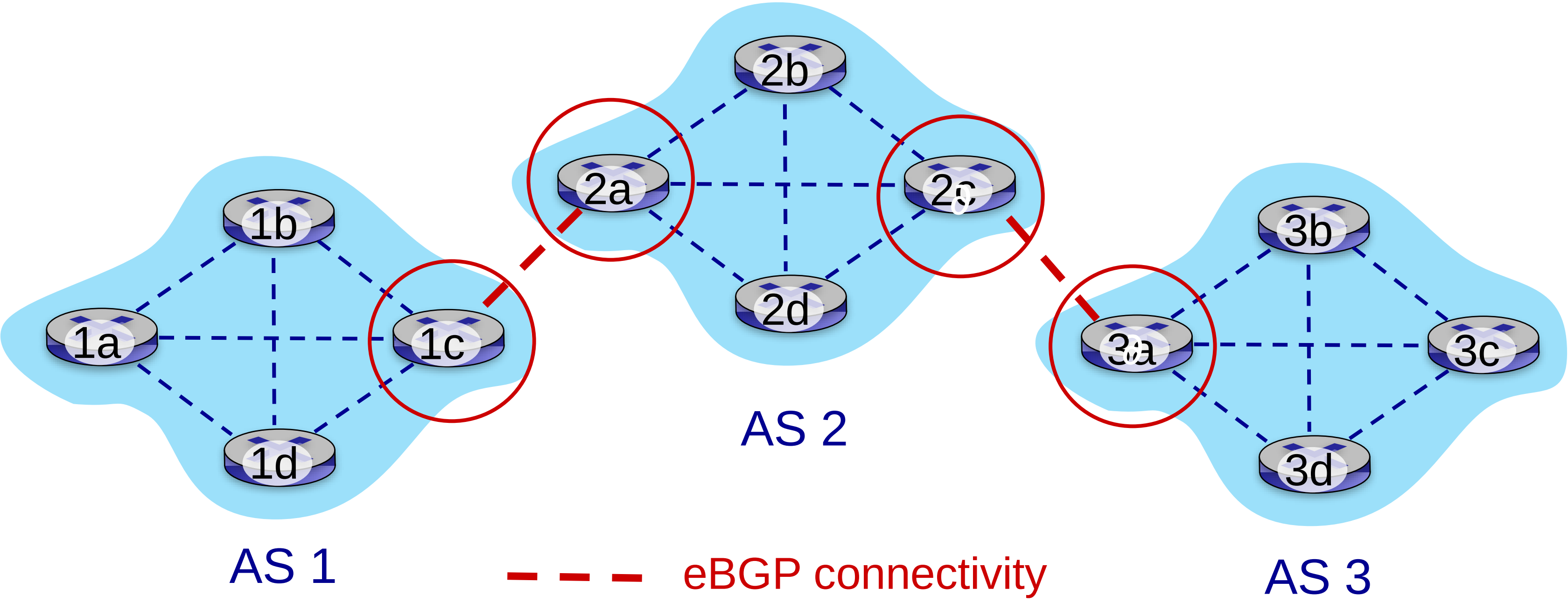
✓ intra-AS (aka "intra-domain"): routing among routers *within same AS ("network")*

➡ inter-AS (aka "inter-domain"): routing *among* AS'es

Internet inter-AS routing: BGP

- BGP (Border Gateway Protocol): *the* de facto inter-domain routing protocol
  - "glue that holds the Internet together"
- allows subnet to advertise its existence, and the destinations it can reach, to rest of Internet: *"I am here, here is who I can reach, and how"*
- BGP provides each AS a means to:
  - obtain destination network reachability info from neighboring ASes (eBGP)
  - determine routes to other networks based on reachability information and *policy*
  - propagate reachability information to all AS-internal routers (iBGP)
  - advertise (to neighboring networks) destination reachability info

eBGP, iBGP connections



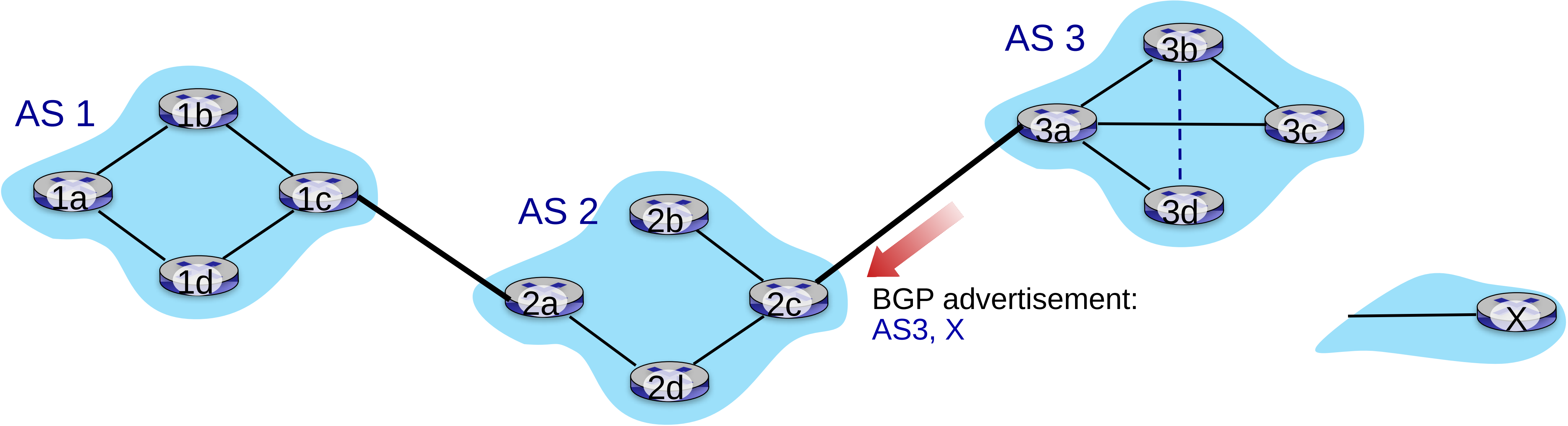
▬ ▬ ▬ eBGP connectivity

- - - - - - logical iBGP connectivity

gateway routers run both eBGP and iBGP protocols

BGP basics

- BGP session: two BGP routers ("peers") exchange BGP messages over semi-permanent TCP connection:
  - advertising *paths* to different destination network prefixes (BGP is a "path vector" protocol)
- when AS3 gateway 3a advertises path AS3,X to AS2 gateway 2c:
  - AS3 *promises* to AS2 it will forward datagrams towards X



BGP advertisement:
AS3, X

Why different Intra-, Inter-AS routing ?

policy:

- inter-AS: admin wants control over how its traffic routed, who routes through its network
- intra-AS: single admin, so policy less of an issue

scale:

- hierarchical routing saves table size, reduced update traffic

performance:

- intra-AS: can focus on performance
- inter-AS: policy dominates over performance