NETWORK PROTOCOLS

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NETWORK LAYER (CONTROL PLANE) ***AND*** NETWORK LAYER PROTOCOLS

LECTURE (6) PART A

2204 - 2025

11 November

Our goal

In this lecture will talk about the following:

- **understand the principles behind the network control plane:**
  - traditional routing algorithms
  - SDN controllers
  - network management, configuration

- **Instantiation, implementation in the Internet:**
  - OSPF, BGP
  - OpenFlow, ODL and ONOS controllers
  - Internet Control Message Protocol: ICMP
  - SNMP, YANG/NETCONF

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

Network-layer functions

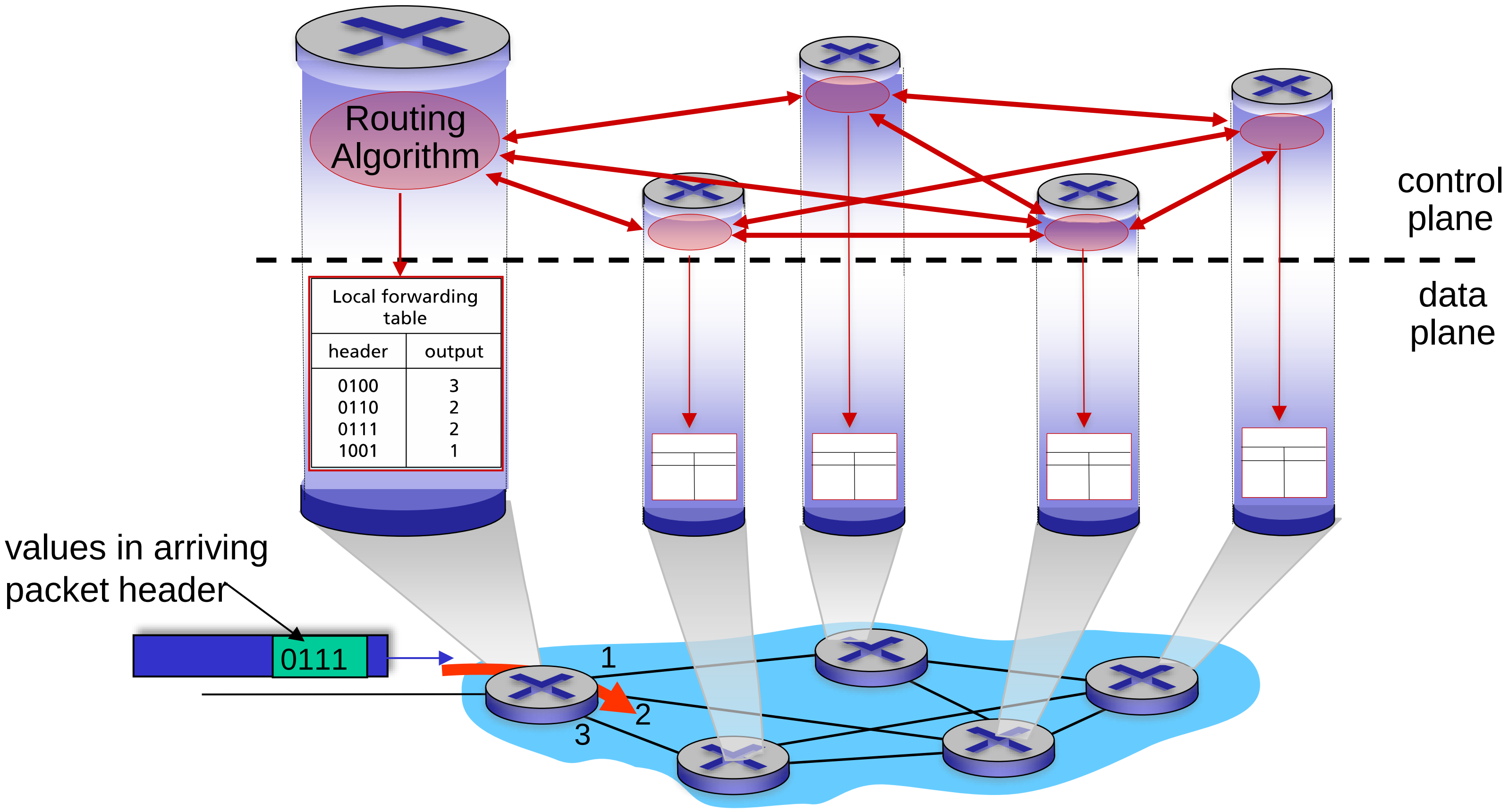
- forwarding: move packets from router's input to appropriate router output — *data plane*
  - routing: determine route taken by packets from source to destination — *control plane*

Two approaches to structuring network control plane:

- per-router control (traditional)
- logically centralized control (software defined networking)

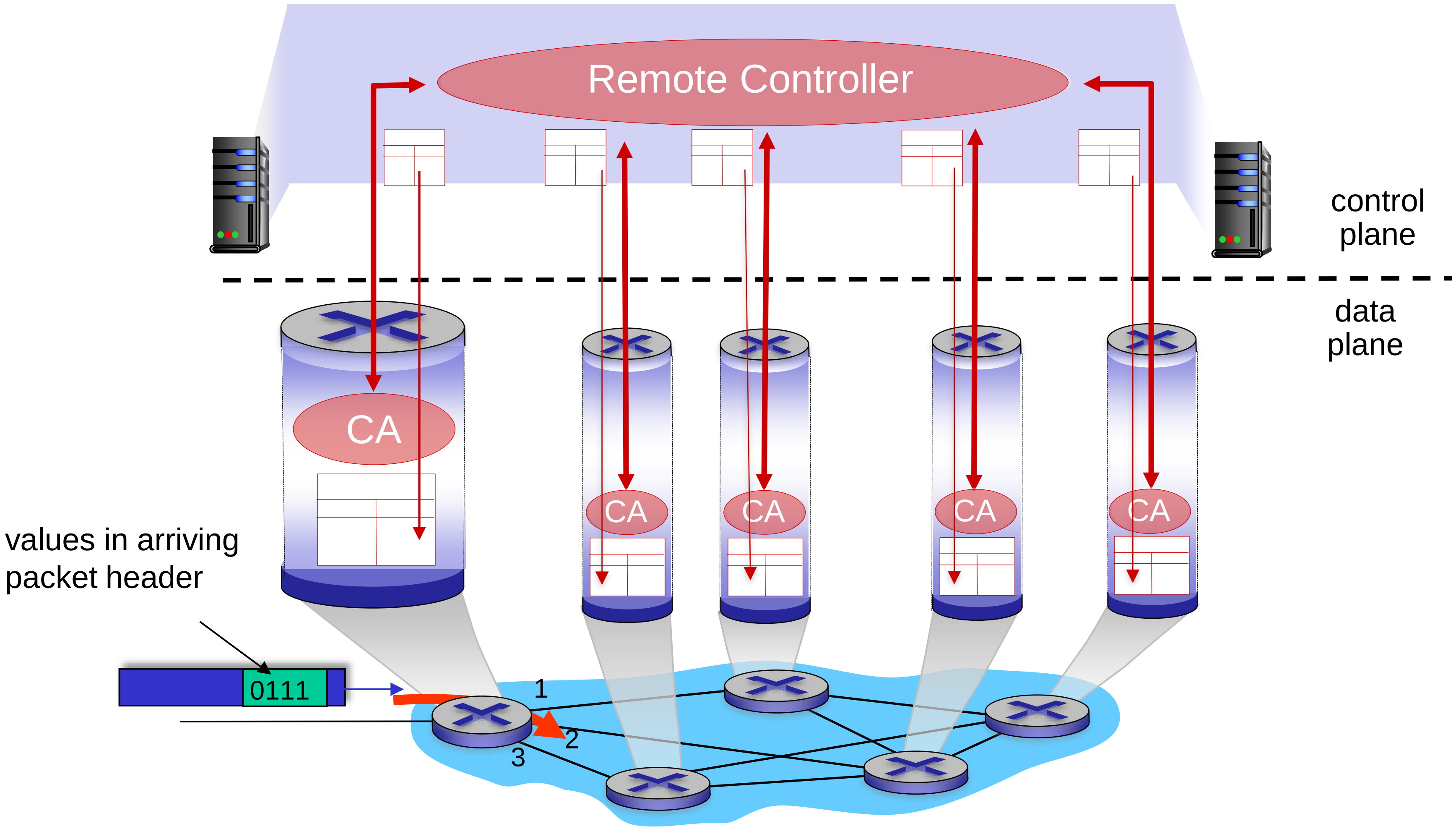
Per-router control plane

Individual routing algorithm components *in each and every router* interact in the control plane

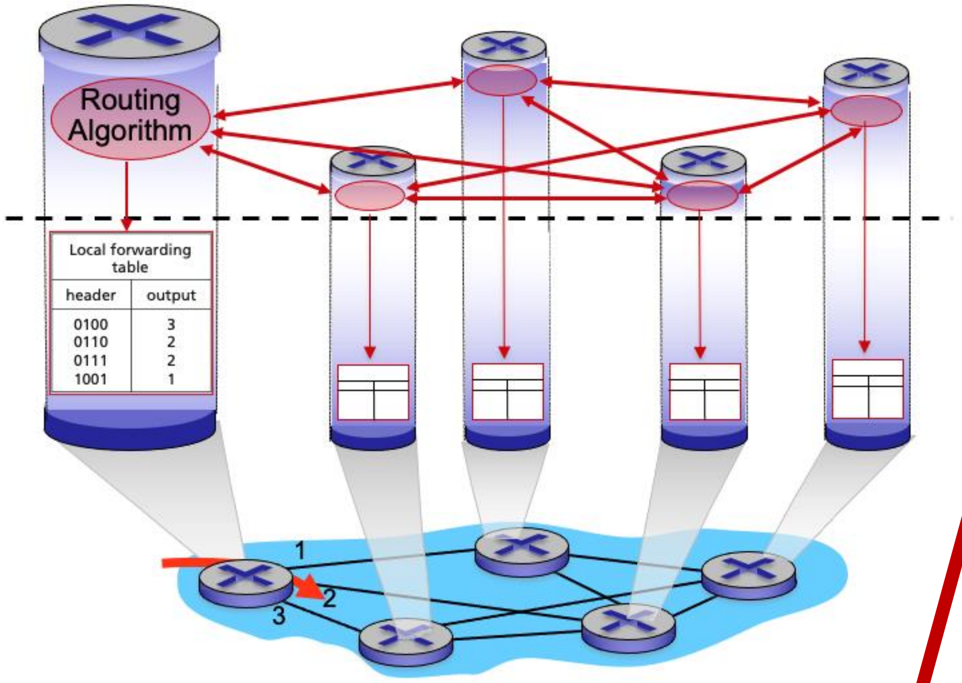


Software-Defined Networking (SDN) control plane

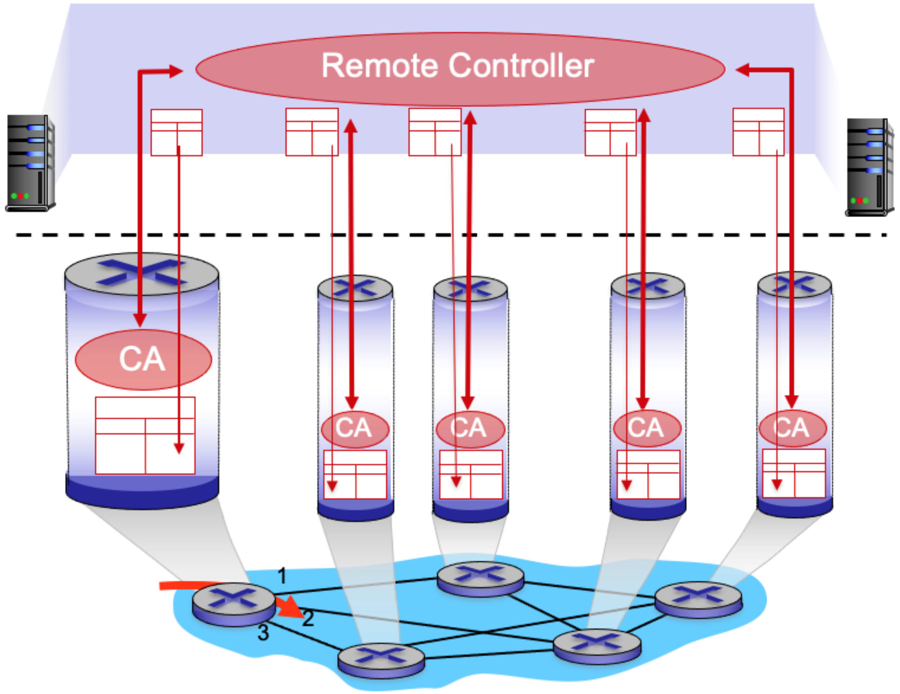
Remote controller computes, installs forwarding tables in routers



Per-router control plane



SDN control plane



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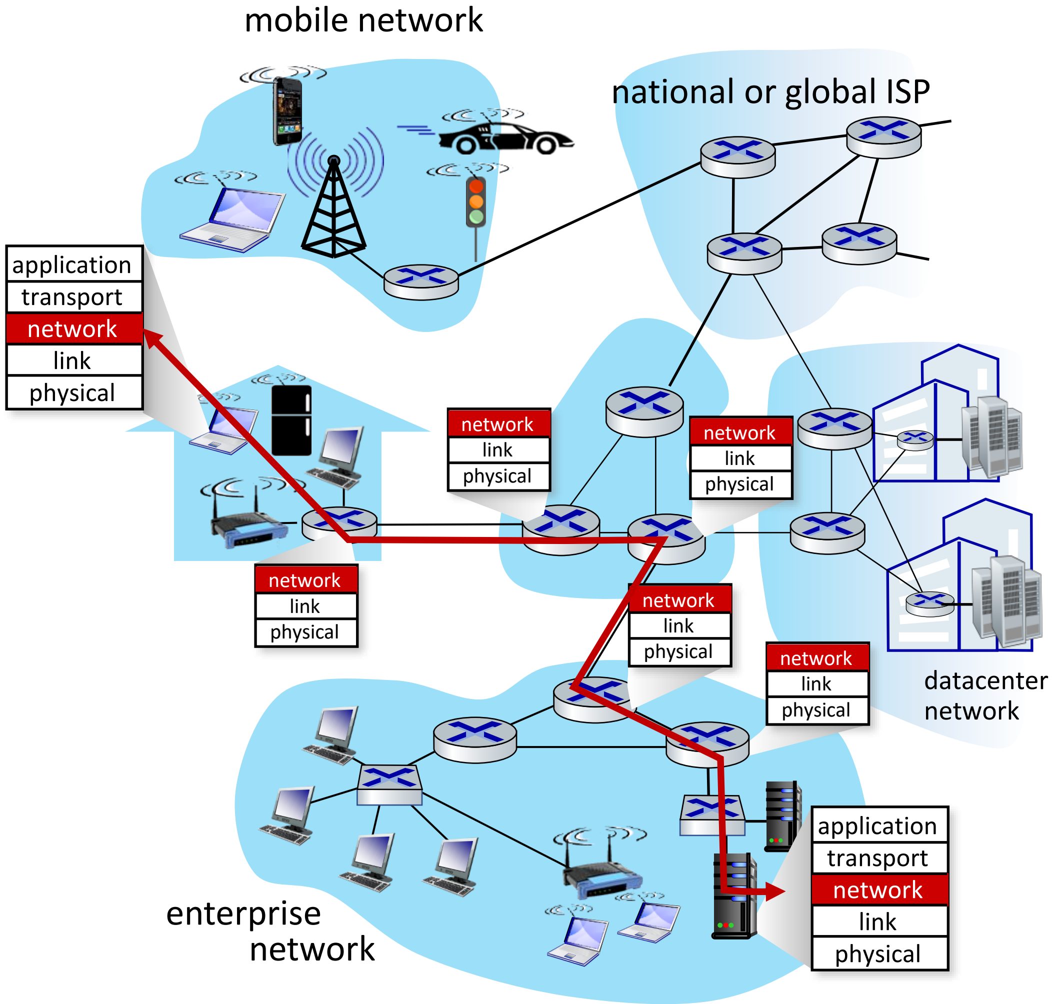
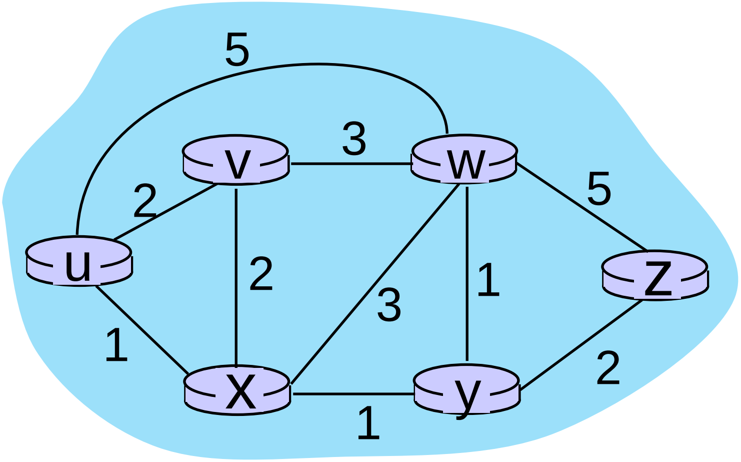
Routing protocols

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

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?

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

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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*; $= \infty$ 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

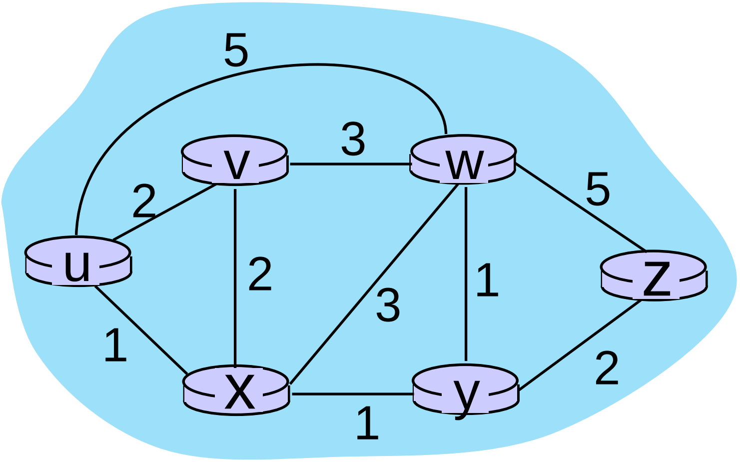
Dijkstra's link-state routing algorithm

```
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) = ∞

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

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

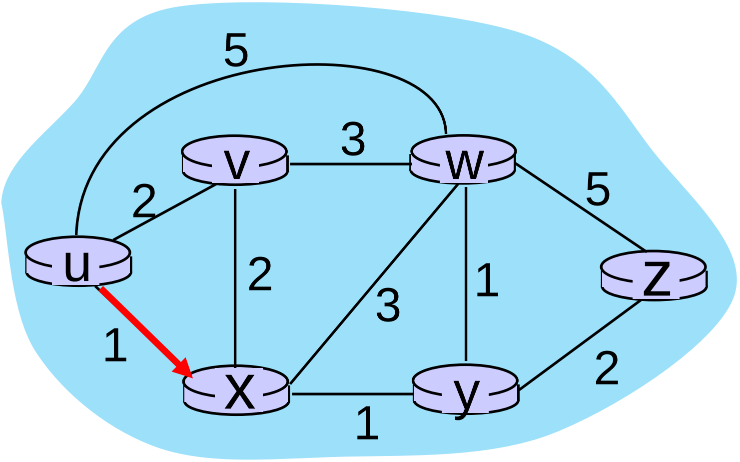


Initialization (step 0):

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

Dijkstra's algorithm: an example

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



8 *Loop*

9 find *a* not in *N'* such that *D(a)* is a minimum

10 add *a* to *N'*

Dijkstra's algorithm: an example

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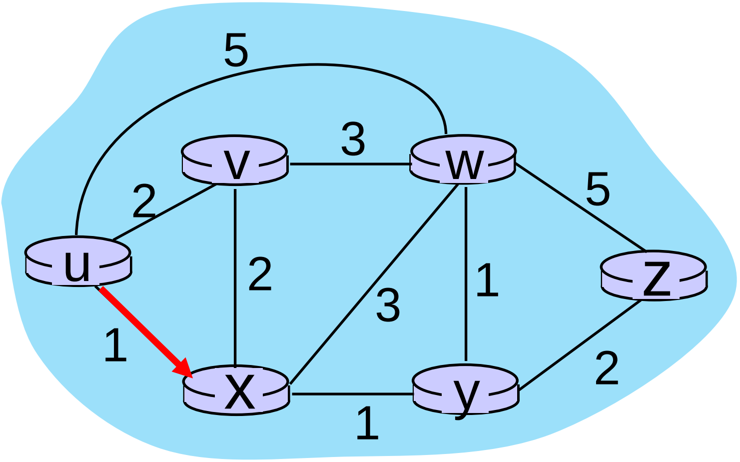
5						



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11 update *D(b)* for all *b* adjacent to *a* and not in *N'* :

$D(b) = \min(D(b), D(a) + c_{a,b})$

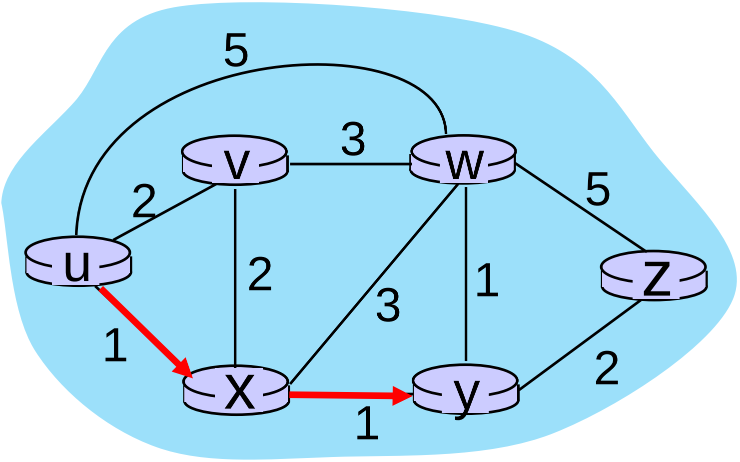
$D(v) = \min(D(v), D(x) + c_{x,v}) = \min(2, 1+2) = 2$

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

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

Dijkstra's algorithm: an example

Step	N'	v D(v),p(v)	w D(w),p(w)	x D(x),p(x)	y D(y),p(y)	z 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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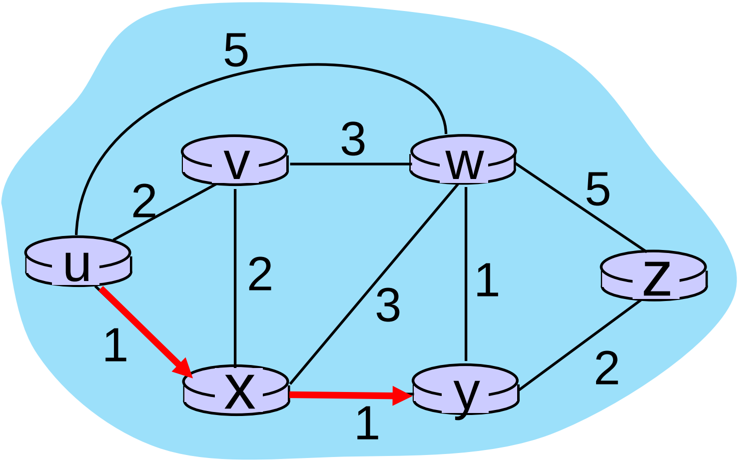
4						
5						



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$$D(b) = \min (D(b), D(a) + c_{a,b})$$

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

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

Dijkstra's algorithm: an example

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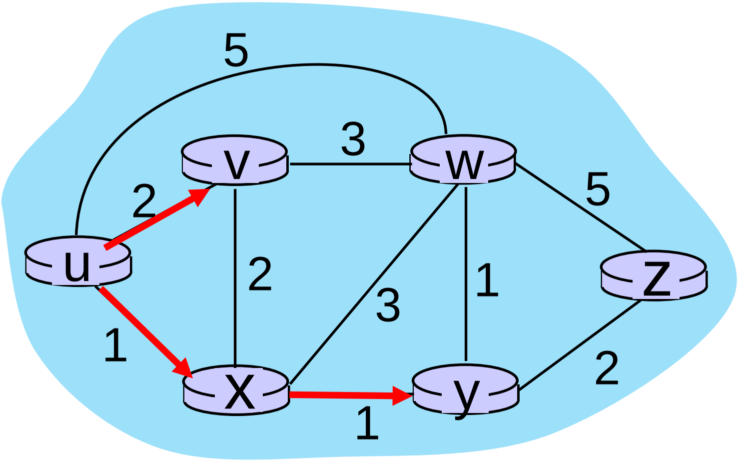
4						
5						



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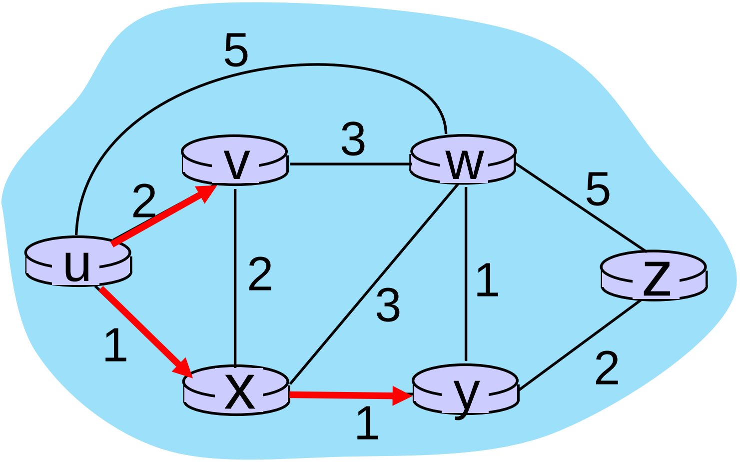

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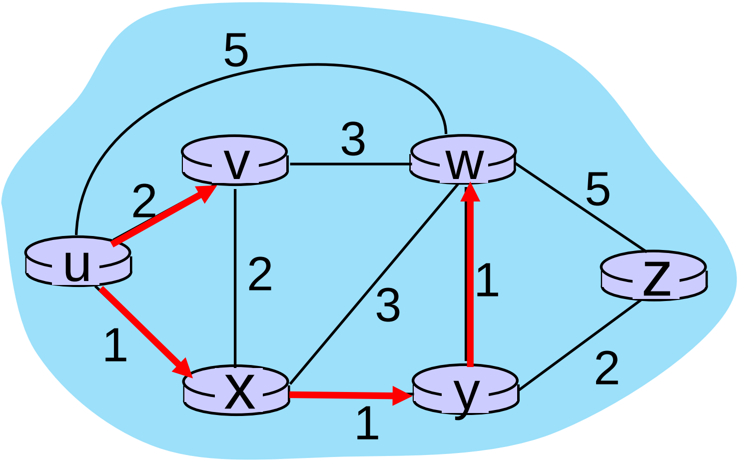

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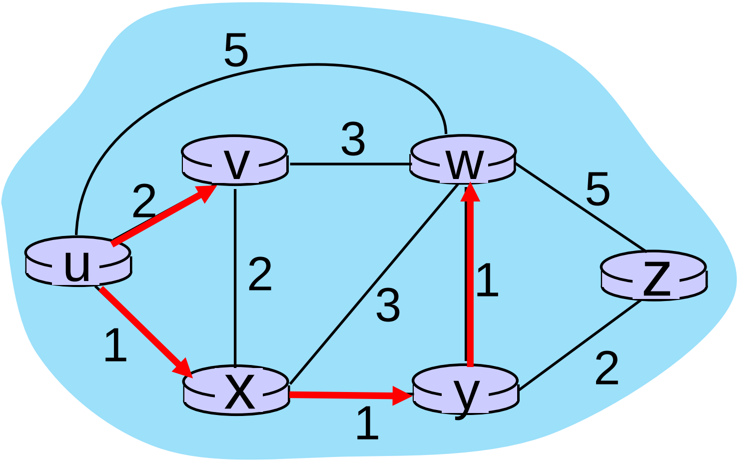

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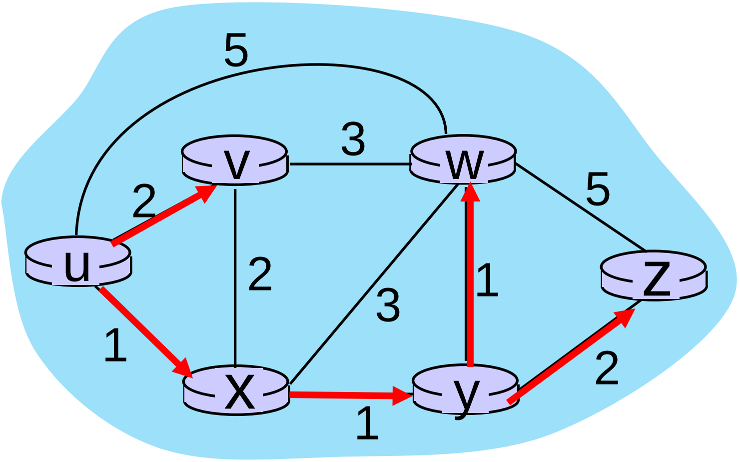

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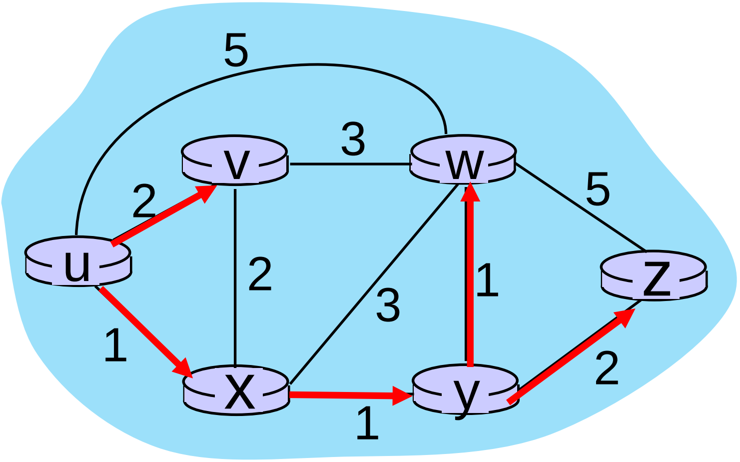

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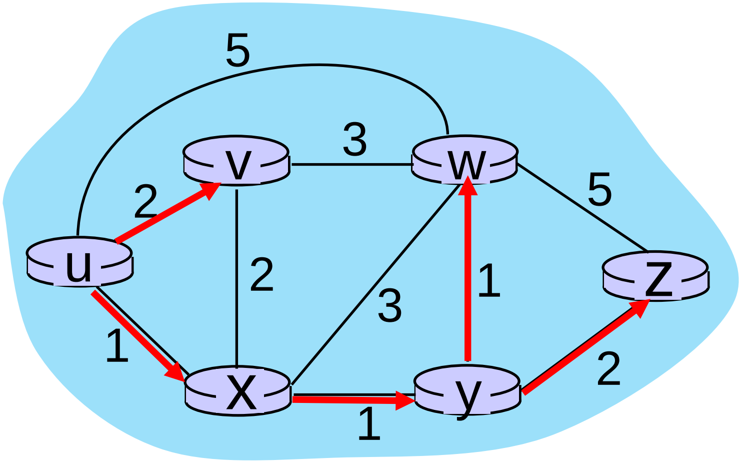
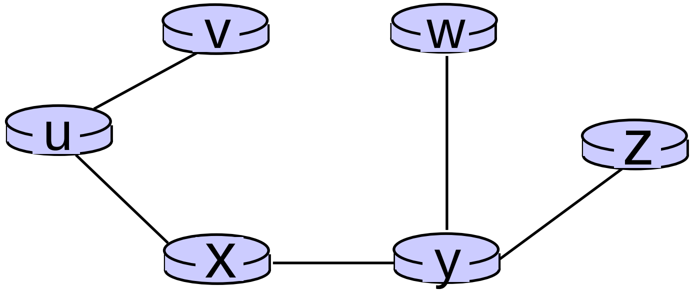


resulting least-cost-path tree from u:



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

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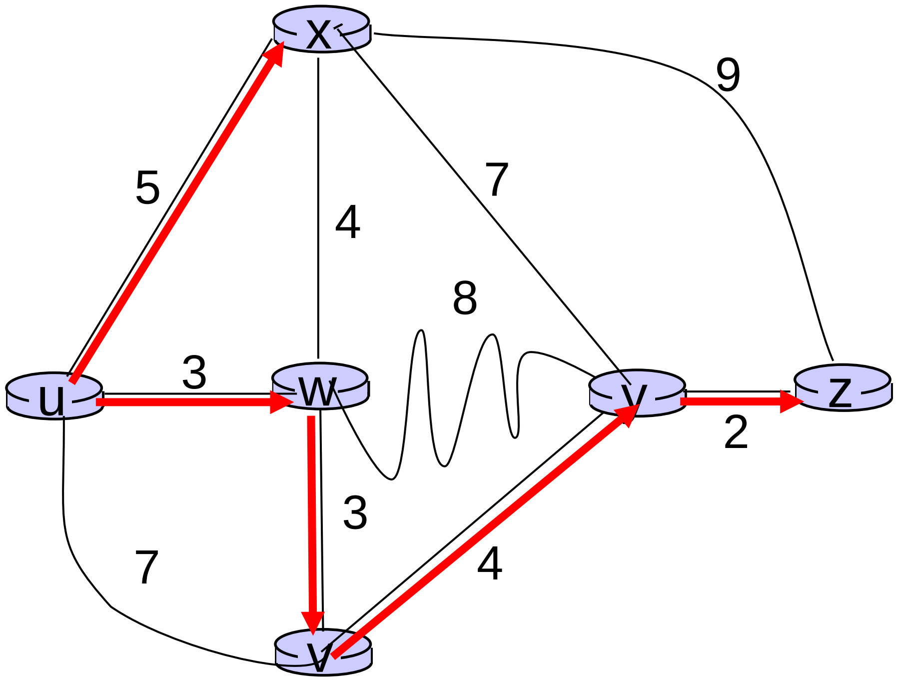
0	u	7,u	3,u	5,u	∞	∞
1	uw	6,w		5,u	11,w	∞
2	uwx	6,w			11,w	14,x
3	uwxv				10,v	14,x
4	uwxvy					12,y
5	uwxvyz					



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

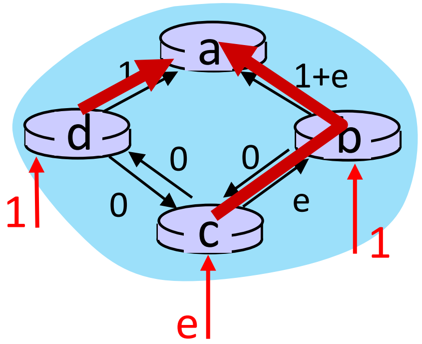
- each of *n* iteration: need to check all nodes, *w*, not in *N*
- $n(n+1)/2$ comparisons: $O(n^2)$ complexity
- more efficient implementations possible: $O(n\log n)$

message complexity:

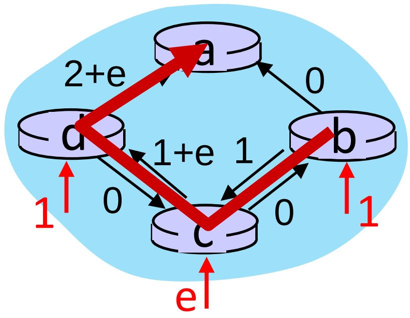
- each router must *broadcast* its link state information to other *n* routers
- efficient (and interesting!) broadcast algorithms: $O(n)$ link crossings to disseminate a broadcast message from one source
- each router's message crosses $O(n)$ links: overall message complexity: $O(n^2)$

Dijkstra's algorithm: oscillations possible

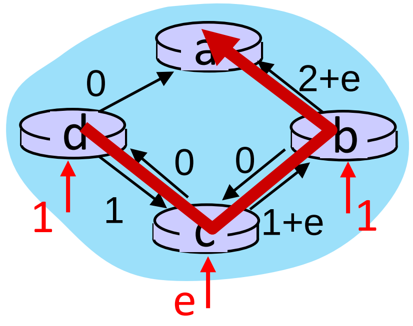
- when link costs depend on traffic volume, route oscillations possible
- sample scenario:
  - routing to destination a, traffic entering at d, c, e with rates 1, e (<1), 1
  - link costs are directional, and volume-dependent



initially



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



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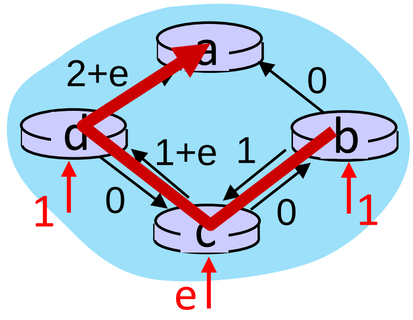

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Distance vector algorithm

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:

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

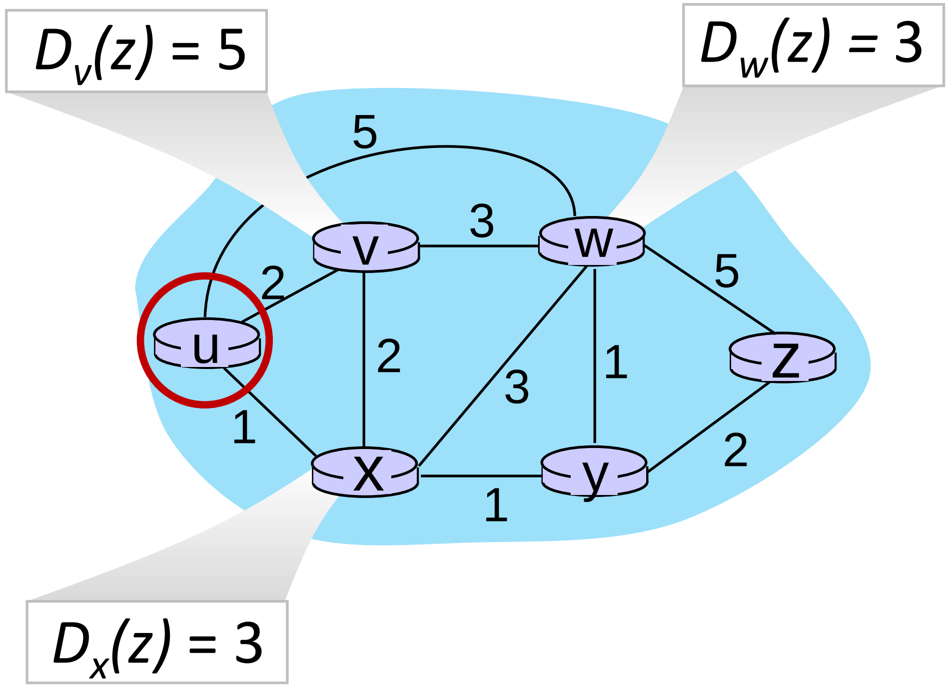
v's estimated least-cost-path cost to *y*

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:

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

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

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* $d_x(y)$

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

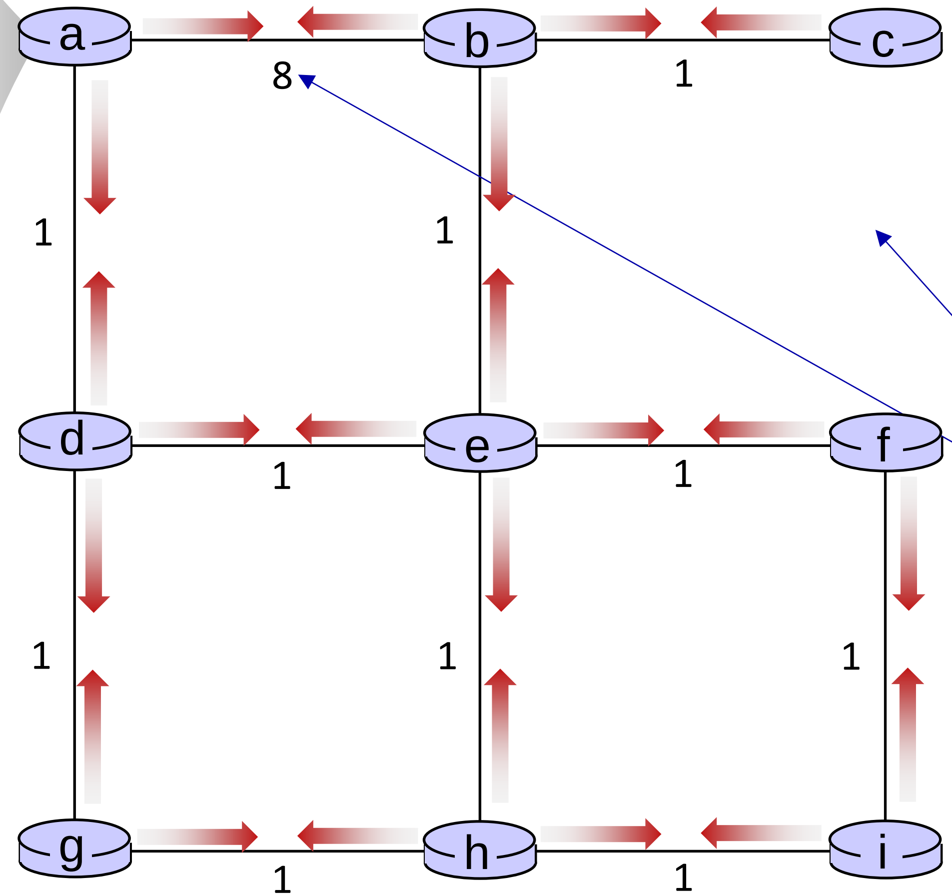
- neighbors then notify their neighbors – *only if necessary*
- no notification received, no actions taken!

Distance vector: example

t=0

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

DV in a:
$D_a(a)=0$
$D_a(b) = 8$
$D_a(c) = \infty$
$D_a(d) = 1$
$D_a(e) = \infty$
$D_a(f) = \infty$
$D_a(g) = \infty$
$D_a(h) = \infty$
$D_a(i) = \infty$

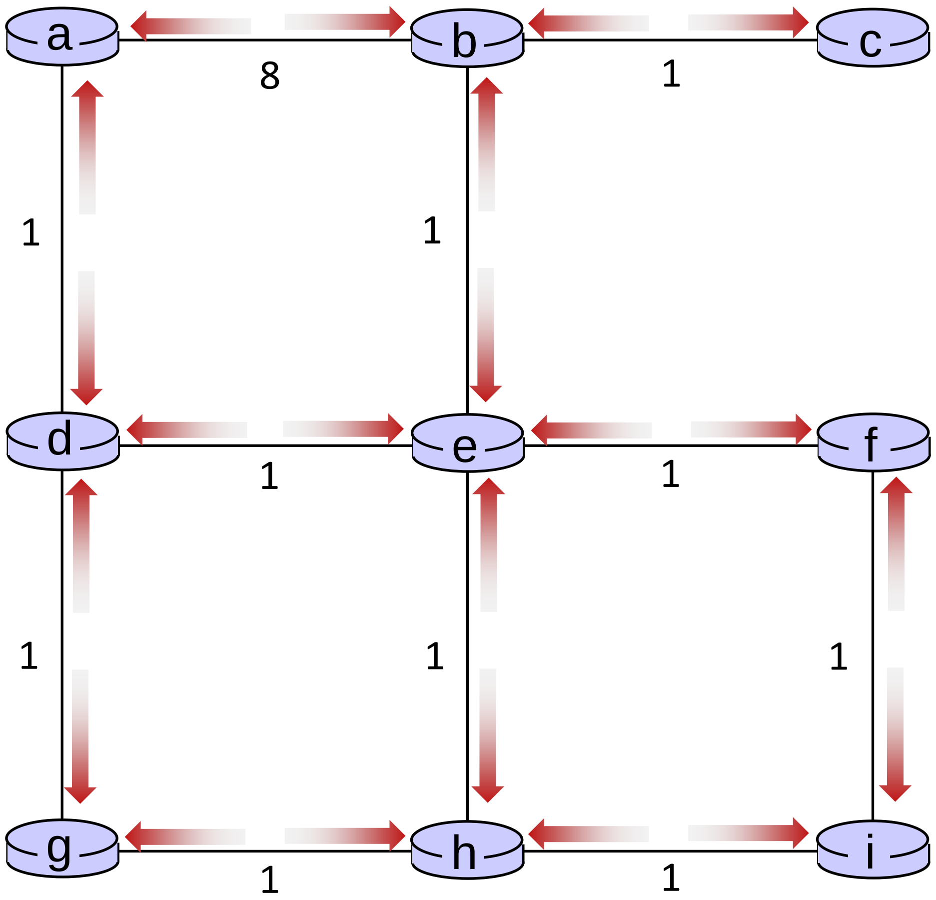


A few asymmetries:
- missing link
- larger cost

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

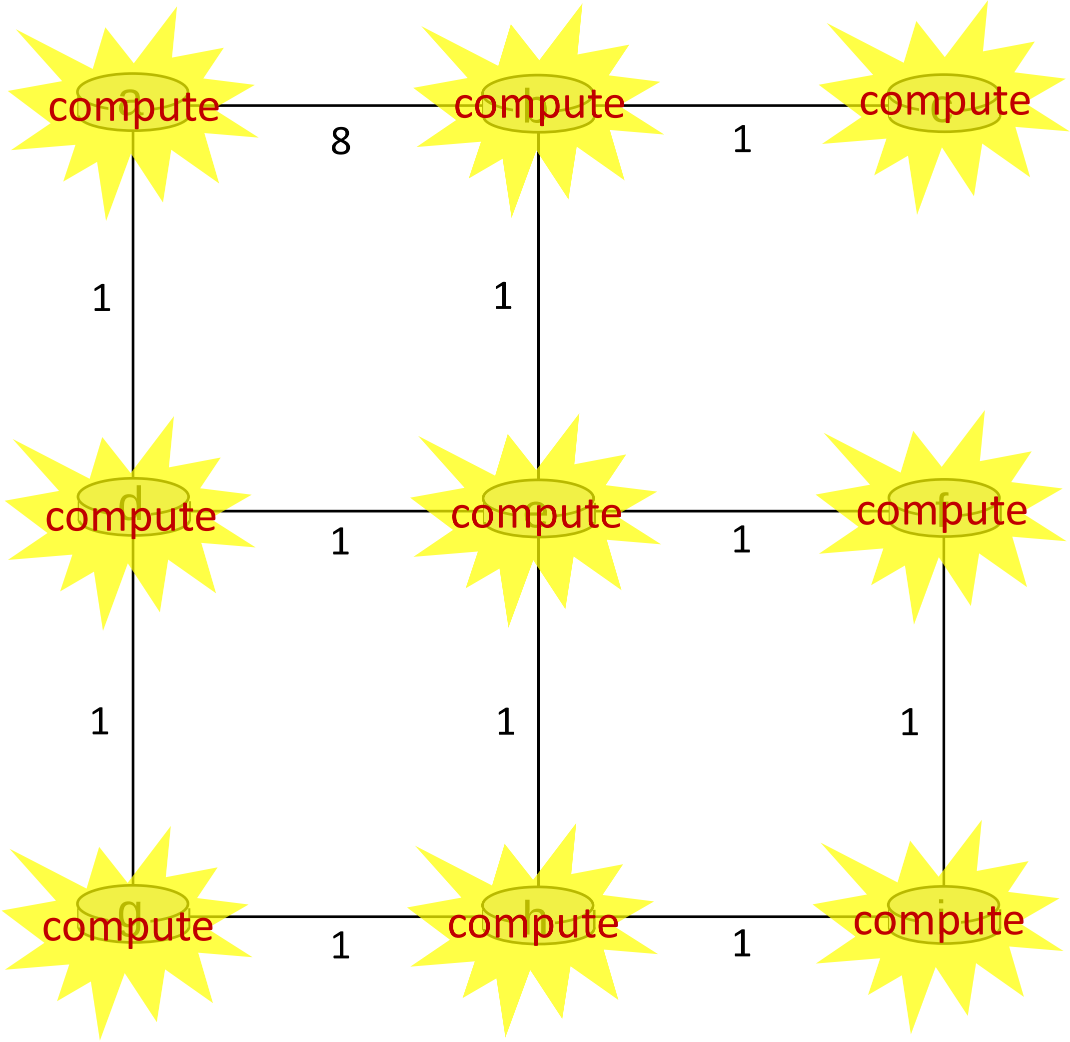


Distance vector example: iteration


t=1

All nodes:

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

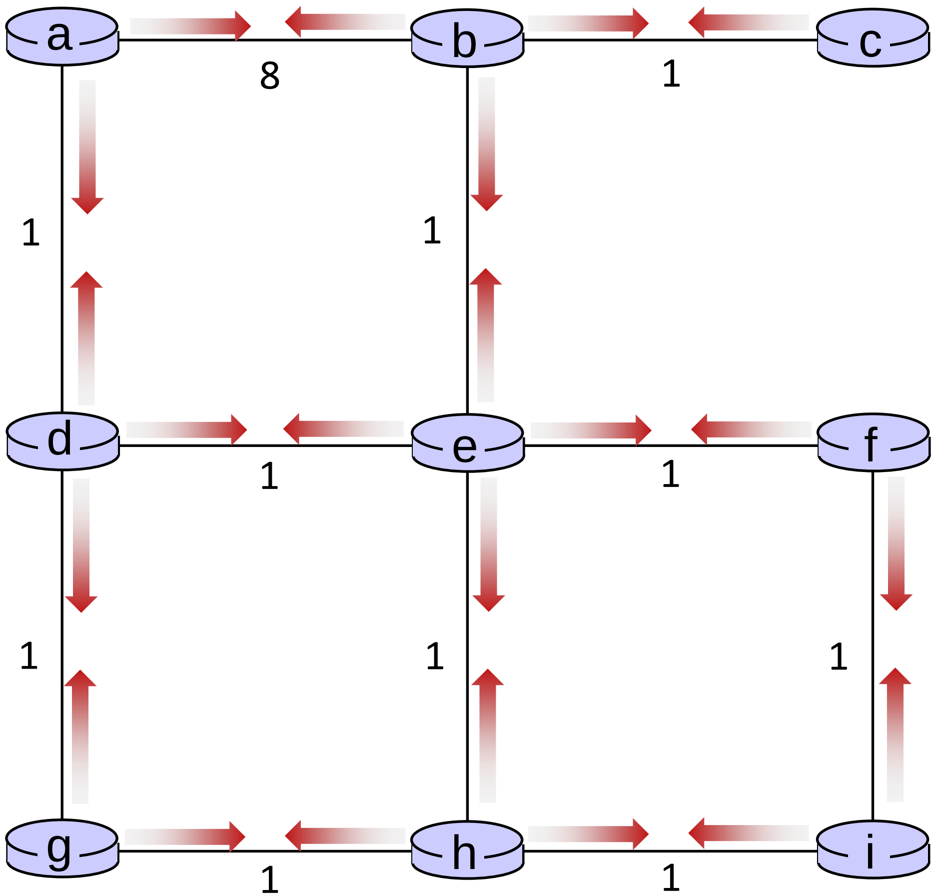


Distance vector example: iteration

t=1

All nodes:

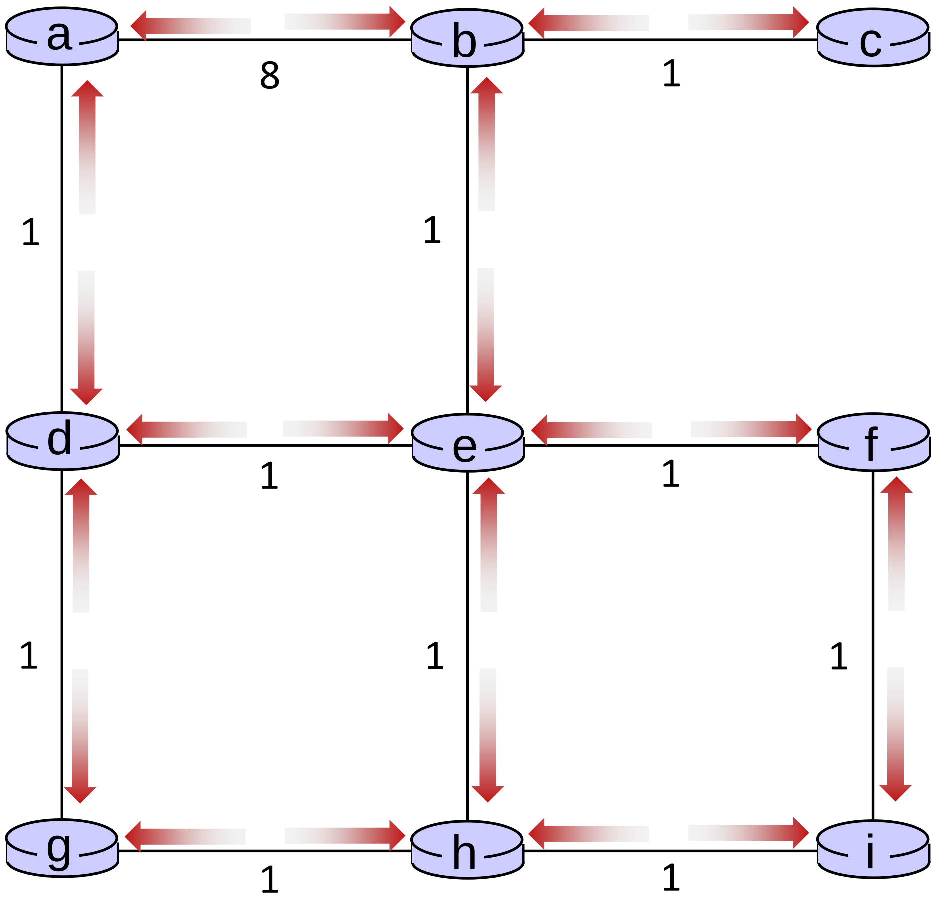
- receive distance vectors from neighbors
- compute their new local distance vector
- send their new local distance vector to neighbors



Distance vector example: iteration

t=2

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

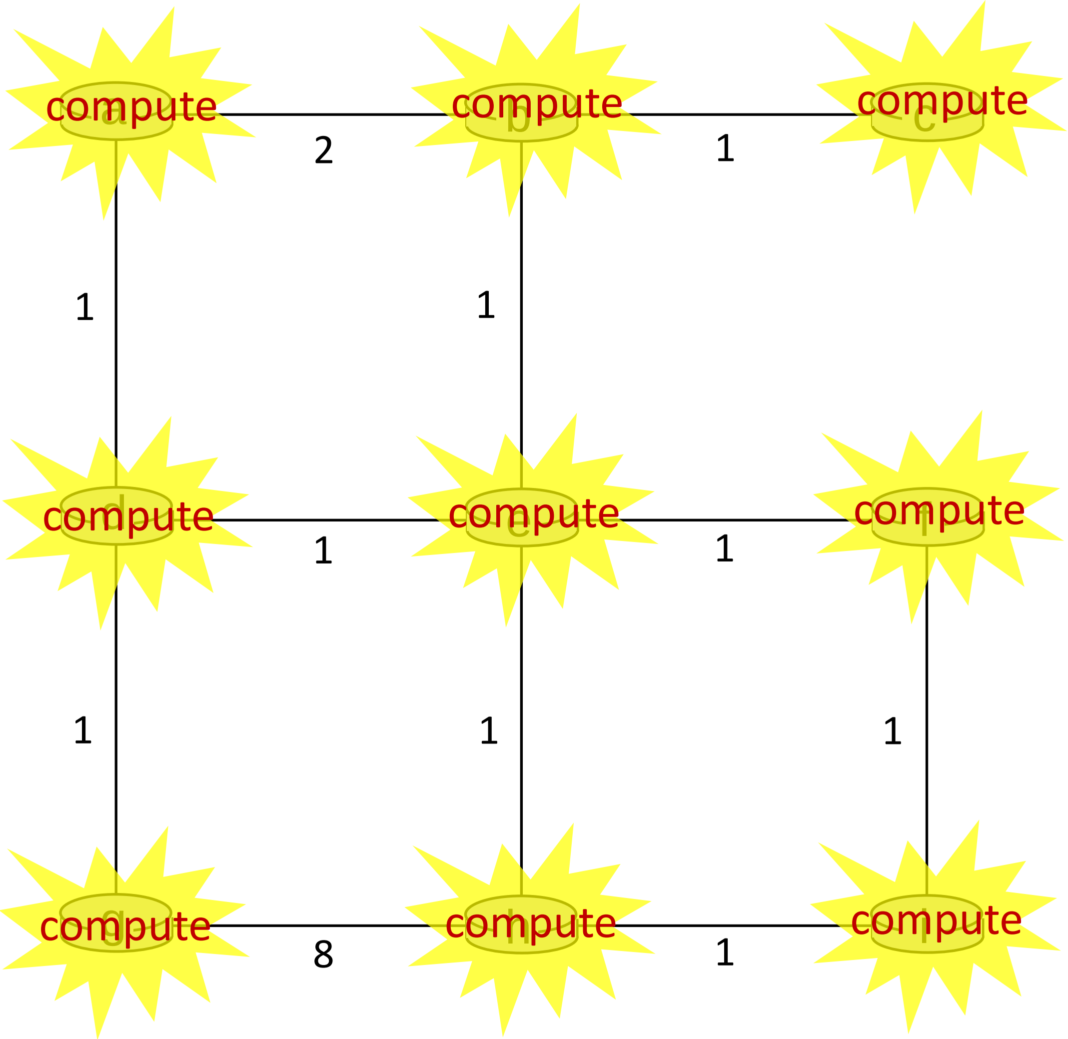


Distance vector example: iteration

t=2

All nodes:

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

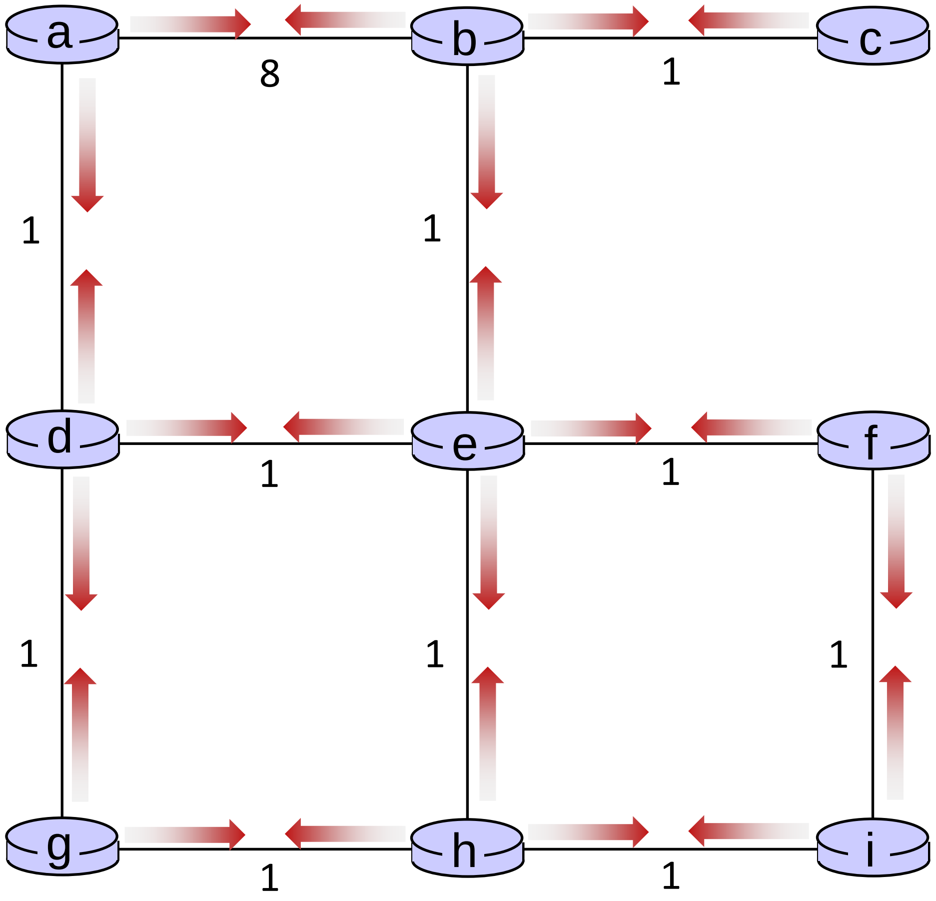


Distance vector example: iteration

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

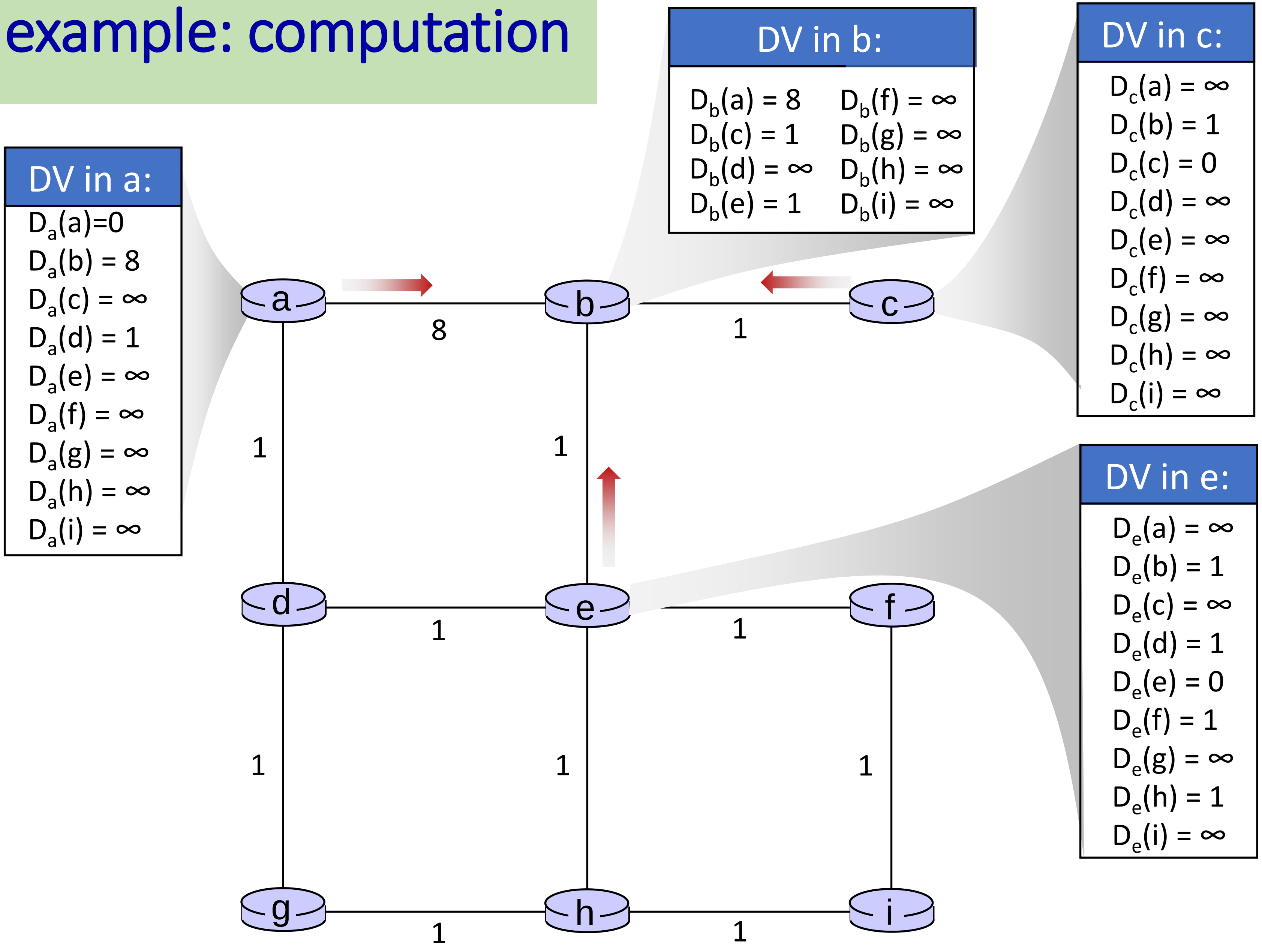
…. and so on

Let’s next take a look at the iterative *computations* at nodes

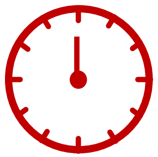
Distance vector example: computation

t=1

- b receives DVs from a, c, e



Distance vector example: computation

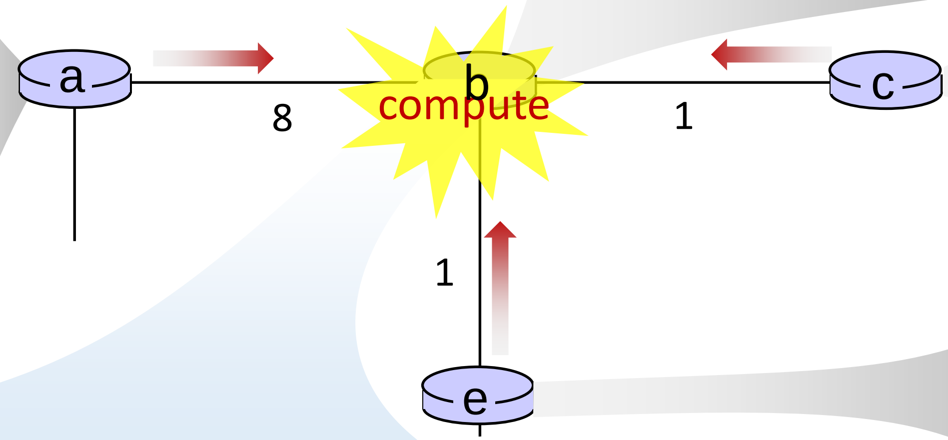


t=1

- b receives DVs from a, c, e, computes:

DV in a:

$D_a(a)=0$
$D_a(b) = 8$
$D_a(c) = \infty$
$D_a(d) = 1$
$D_a(e) = \infty$
$D_a(f) = \infty$
$D_a(g) = \infty$
$D_a(h) = \infty$
$D_a(i) = \infty$



DV in b:

$D_b(a) = 8$	$D_b(f) = \infty$
$D_b(c) = 1$	$D_b(g) = \infty$
$D_b(d) = \infty$	$D_b(h) = \infty$
$D_b(e) = 1$	$D_b(i) = \infty$

DV in c:

$D_c(a) = \infty$
$D_c(b) = 1$
$D_c(c) = 0$
$D_c(d) = \infty$
$D_c(e) = \infty$
$D_c(f) = \infty$
$D_c(g) = \infty$
$D_c(h) = \infty$
$D_c(i) = \infty$

DV in e:

$D_e(a) = \infty$
$D_e(b) = 1$
$D_e(c) = \infty$
$D_e(d) = 1$
$D_e(e) = 0$
$D_e(f) = 1$
$D_e(g) = \infty$
$D_e(h) = 1$
$D_e(i) = \infty$

$D_b(a) = \min\{c_{b,a}+D_a(a),\ c_{b,c}+D_c(a),\ c_{b,e}+D_e(a)\} = \min\{8,\infty,\infty\} = 8$

$D_b(c) = \min\{c_{b,a}+D_a(c),\ c_{b,c}+D_c(c),\ c_{b,e}+D_e(c)\} = \min\{\infty,1,\infty\} = 1$

$D_b(d) = \min\{c_{b,a}+D_a(d),\ c_{b,c}+D_c(d),\ c_{b,e}+D_e(d)\} = \min\{9,2,\infty\} = 2$

$D_b(e) = \min\{c_{b,a}+D_a(e),\ c_{b,c}+D_c(e),\ c_{b,e}+D_e(e)\} = \min\{\infty,\infty,1\} = 1$

$D_b(f) = \min\{c_{b,a}+D_a(f),\ c_{b,c}+D_c(f),\ c_{b,e}+D_e(f)\} = \min\{\infty,\infty,2\} = 2$

$D_b(g) = \min\{c_{b,a}+D_a(g),\ c_{b,c}+D_c(g),\ c_{b,e}+D_e(g)\} = \min\{\infty, \infty, \infty\} = \infty$

$D_b(h) = \min\{c_{b,a}+D_a(h),\ c_{b,c}+D_c(h),\ c_{b,e}+D_e(h)\} = \min\{\infty, \infty, 2\} = 2$

$D_b(i) = \min\{c_{b,a}+D_a(i),\ c_{b,c}+D_c(i),\ c_{b,e}+D_e(i)\} = \min\{\infty, \infty, \infty\} = \infty$

DV in b:

$D_b(a) = 8$	$D_b(f) =2$
$D_b(c) = 1$	$D_b(g) = \infty$
$D_b(d) = 2$	$D_b(h) = 2$
$D_b(e) = 1$	$D_b(i) = \infty$

Distance vector example: computation

t=1

- c receives DVs from b

DV in a:

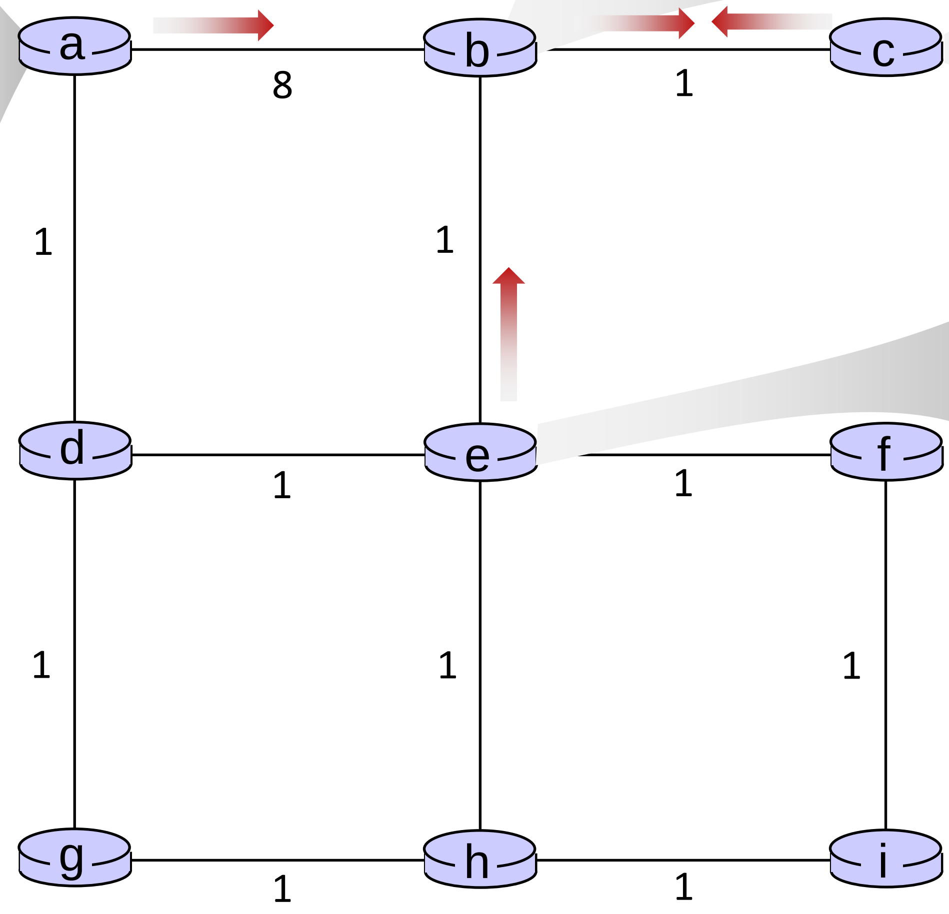
$D_a(a)=0$
$D_a(b) = 8$
$D_a(c) = \infty$
$D_a(d) = 1$
$D_a(e) = \infty$
$D_a(f) = \infty$
$D_a(g) = \infty$
$D_a(h) = \infty$
$D_a(i) = \infty$

DV in b:

$D_b(a) = 8$	$D_b(f) = \infty$
$D_b(c) = 1$	$D_b(g) = \infty$
$D_b(d) = \infty$	$D_b(h) = \infty$
$D_b(e) = 1$	$D_b(i) = \infty$

DV in c:

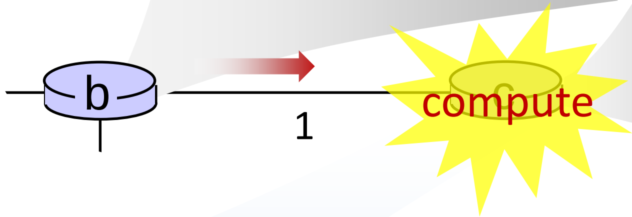
$D_c(a) = \infty$
$D_c(b) = 1$
$D_c(c) = 0$
$D_c(d) = \infty$
$D_c(e) = \infty$
$D_c(f) = \infty$
$D_c(g) = \infty$
$D_c(h) = \infty$
$D_c(i) = \infty$



DV in e:

$D_e(a) = \infty$
$D_e(b) = 1$
$D_e(c) = \infty$
$D_e(d) = 1$
$D_e(e) = 0$
$D_e(f) = 1$
$D_e(g) = \infty$
$D_e(h) = 1$
$D_e(i) = \infty$

Distance vector example: computation



DV in b:

$D_b(a) = 8$ $D_b(f) = \infty$
$D_b(c) = 1$ $D_b(g) = \infty$
$D_b(d) = \infty$ $D_b(h) = \infty$
$D_b(e) = 1$ $D_b(i) = \infty$

DV in c:

$D_c(a) = \infty$
$D_c(b) = 1$
$D_c(c) = 0$
$D_c(d) = \infty$
$D_c(e) = \infty$
$D_c(f) = \infty$
$D_c(g) = \infty$
$D_c(h) = \infty$
$D_c(i) = \infty$

t=1

- c receives DVs from b computes:

$D_c(a) = \min\{c_{c,b}+D_b(a)\} = 1 + 8 = 9$

$D_c(b) = \min\{c_{c,b}+D_b(b)\} = 1 + 0 = 1$

$D_c(d) = \min\{c_{c,b}+D_b(d)\} = 1+ \infty = \infty$

$D_c(e) = \min\{c_{c,b}+D_b(e)\} = 1 + 1 = 2$

$D_c(f) = \min\{c_{c,b}+D_b(f)\} = 1+ \infty = \infty$

$D_c(g) = \min\{c_{c,b}+D_b(g)\} = 1+ \infty = \infty$

$D_c(h) = \min\{c_{bc,b}+D_b(h)\} = 1+ \infty = \infty$

$D_c(i) = \min\{c_{c,b}+D_b(i)\} = 1+ \infty = \infty$

DV in c:

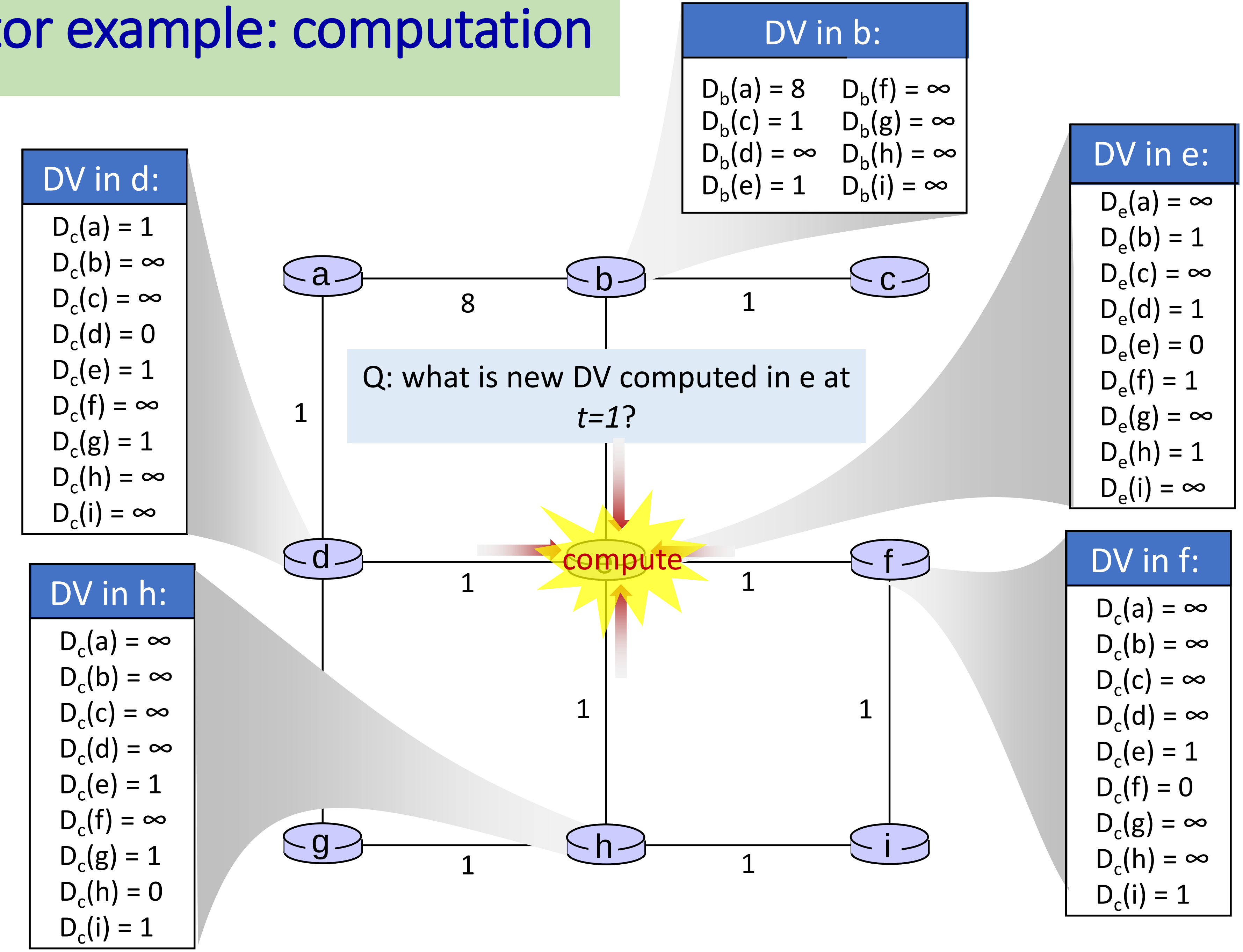
$D_c(a) = 9$
$D_c(b) = 1$
$D_c(c) = 0$
$D_c(d) = 2$
$D_c(e) = \infty$
$D_c(f) = \infty$
$D_c(g) = \infty$
$D_c(h) = \infty$
$D_c(i) = \infty$

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

Distance vector example: computation

t=1

- e receives DVs from b, d, f, h



Distance vector: state information diffusion

Iterative communication, computation steps diffuses information through network:

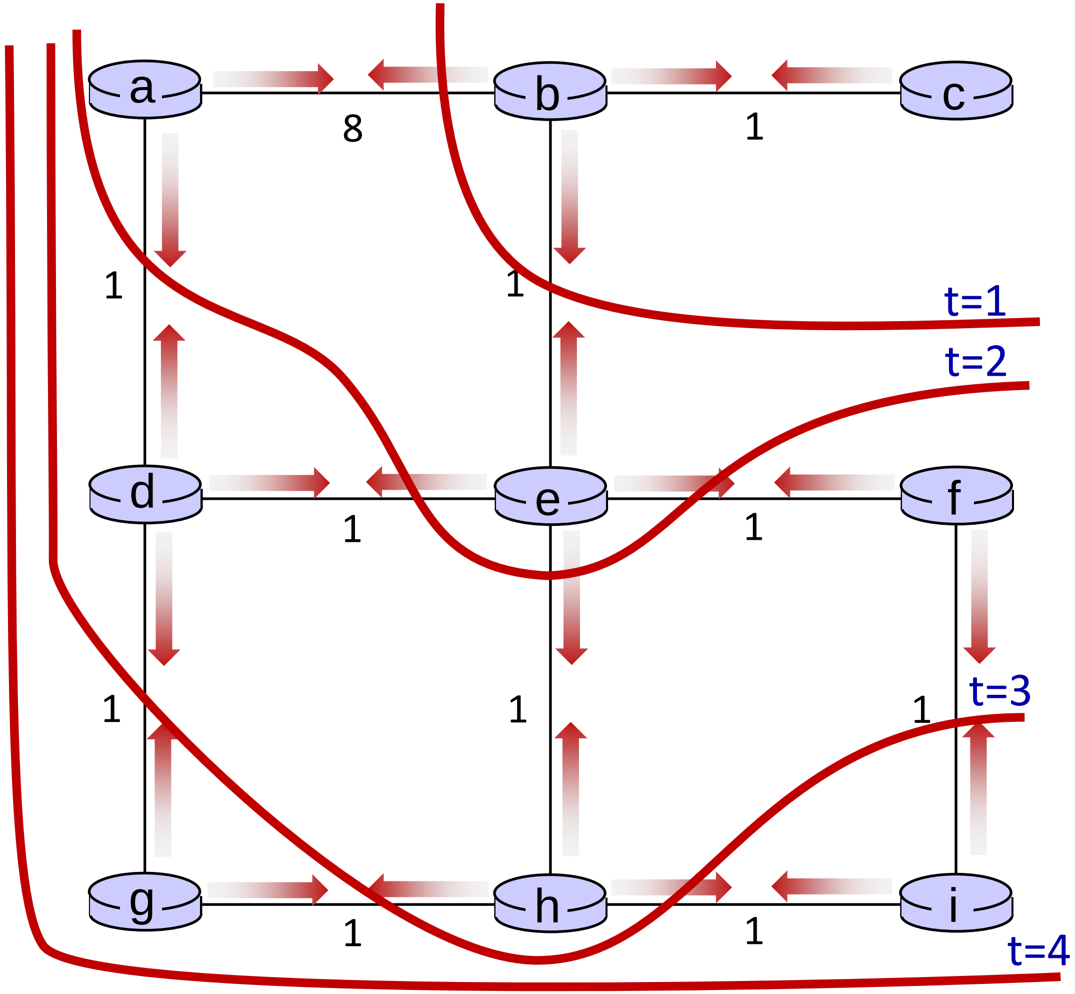
t=0 c's state at t=0 is at c only

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

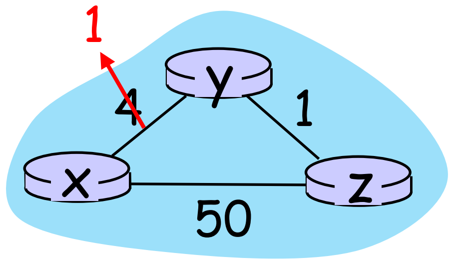
t=2 c's state at t=0 may now influence distance vector computations up to **2** hops away, i.e., at b and now at a, e as well

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.

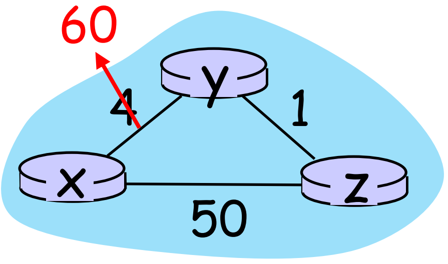
t_2 : *y* receives *z*'s update, updates its DV. *y*'s least costs do *not* change, so *y* does *not* send a message to *z*.

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

Network layer: "control plane" roadmap

- introduction
- routing protocols
- intra-ISP routing: OSPF
- routing among ISPs: BGP
- SDN control plane
- Internet Control Message Protocol
- network management, configuration
  - SNMP
  - NETCONF/YANG

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")

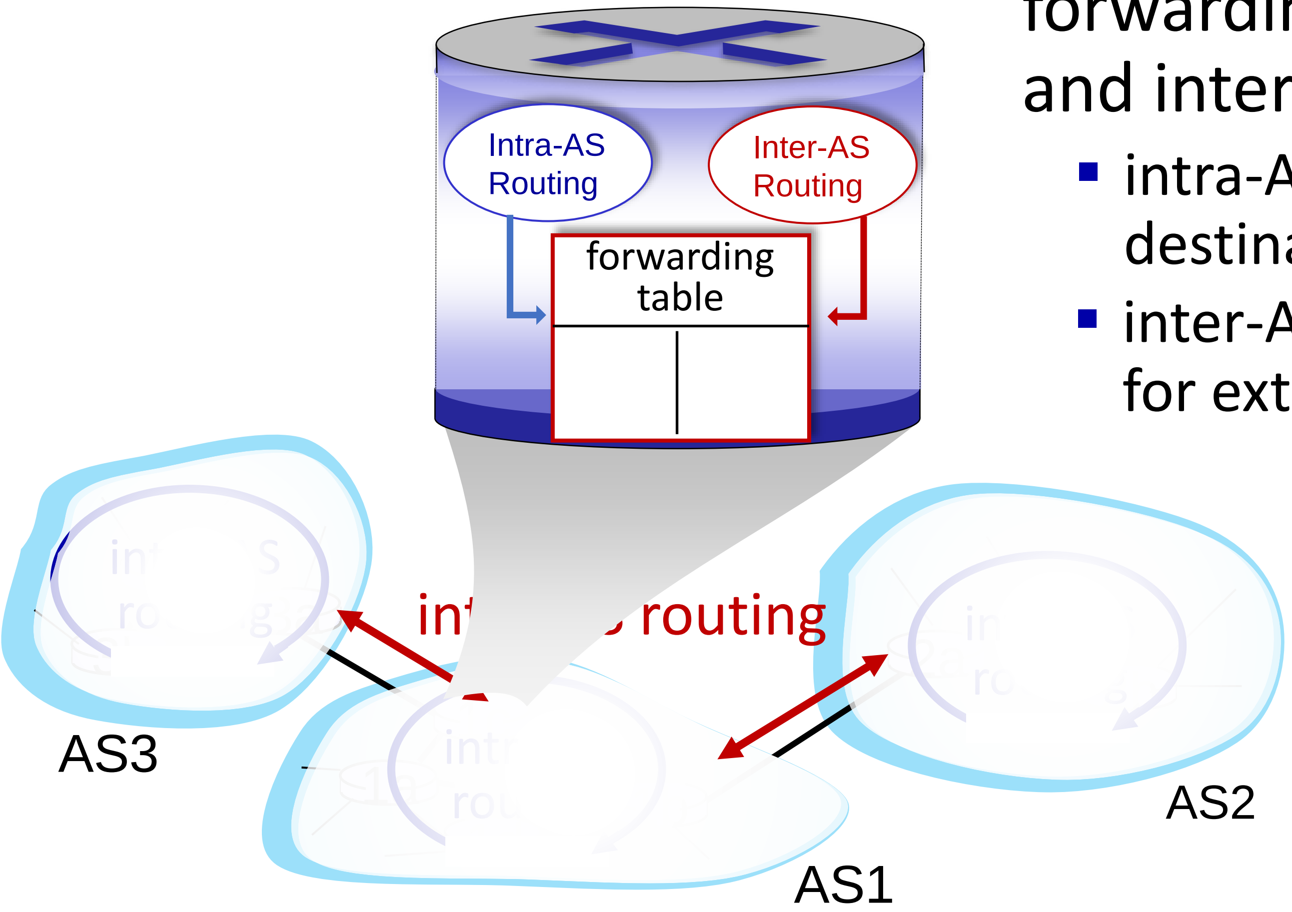
intra-AS (aka "intra-domain"): routing among routers *within same AS ("network")*

- 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

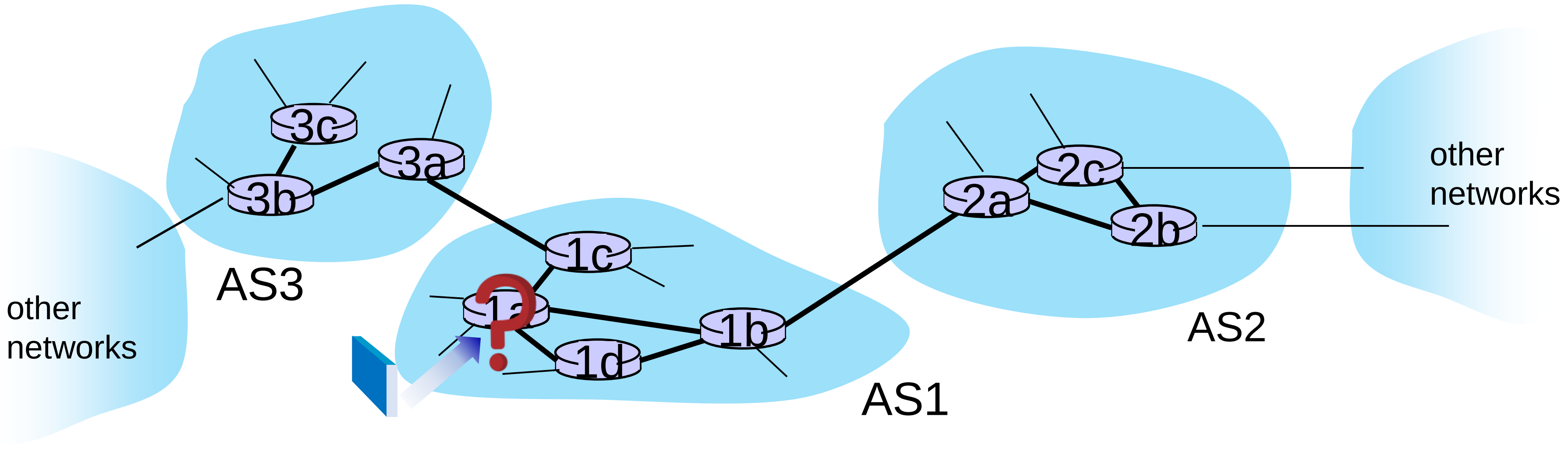
- intra-AS routing determine entries for destinations within AS
- inter-AS & intra-AS determine entries for external destinations

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

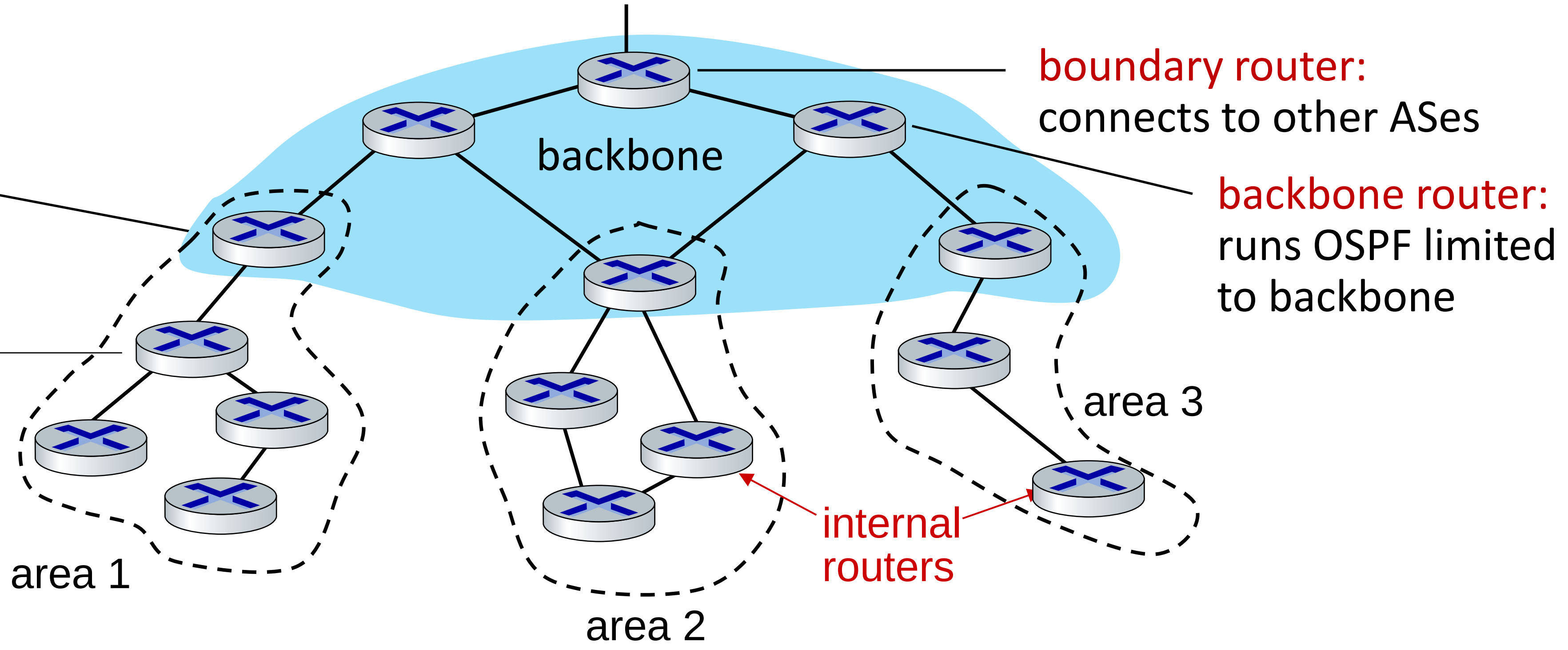
- "open": publicly available
- classic link-state
  - each router floods OSPF link-state advertisements (directly over IP rather than using TCP/UDP) to all other routers in entire AS
  - multiple link costs metrics possible: bandwidth, delay
  - each router has full topology, uses Dijkstra's algorithm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



Acknowledgment

- **These lecture slides are based on:**

1) **Chapter 5 (P 407-429)** from the book "Computer Networking: A Top-Down Approach, Eighth Edition, Global Edition" by (James F. Kurose and Keith W. Ross's).

END OF LECTURE

END OF LECTURE (6) PART A

Keep connected with the classroom

lmzcbsf

THANK YOU FOR YOUR ATTENTION