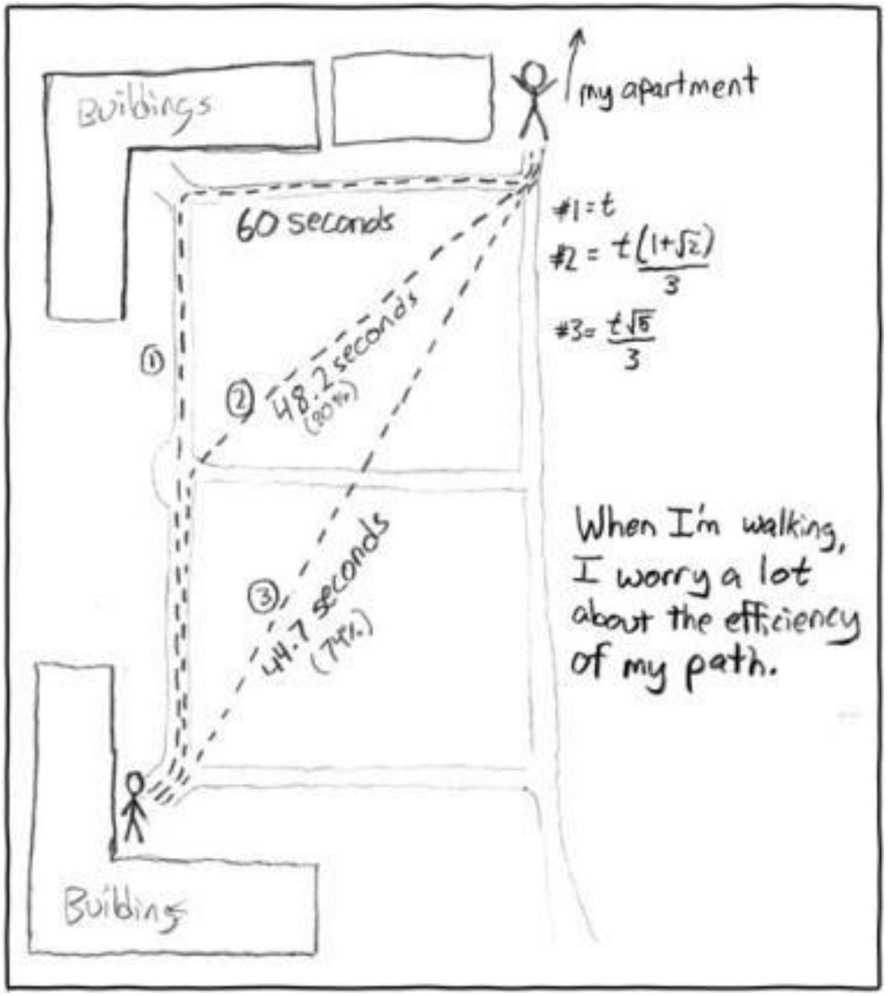
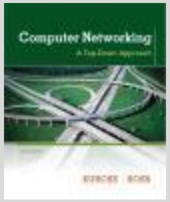
Intra-AS Routing



http://xkcd.com/85/

Computer Networking: A Top Down Approach
6th edition
Jim Kurose, Keith Ross
Addison-Wesley



Chapter 4: outline

4.1 Introduction

4.2 Virtual circuit and datagram networks

4.3 What's inside a router

4.4 IP: Internet Protocol

- Datagram format
- IPv4 addressing
- Network Address Translation (NAT)
- DHCP
- ICMP
- IPv6
- IPsec

4.5 Routing algorithms

- Distance vector
- Link state
- Hierarchical routing

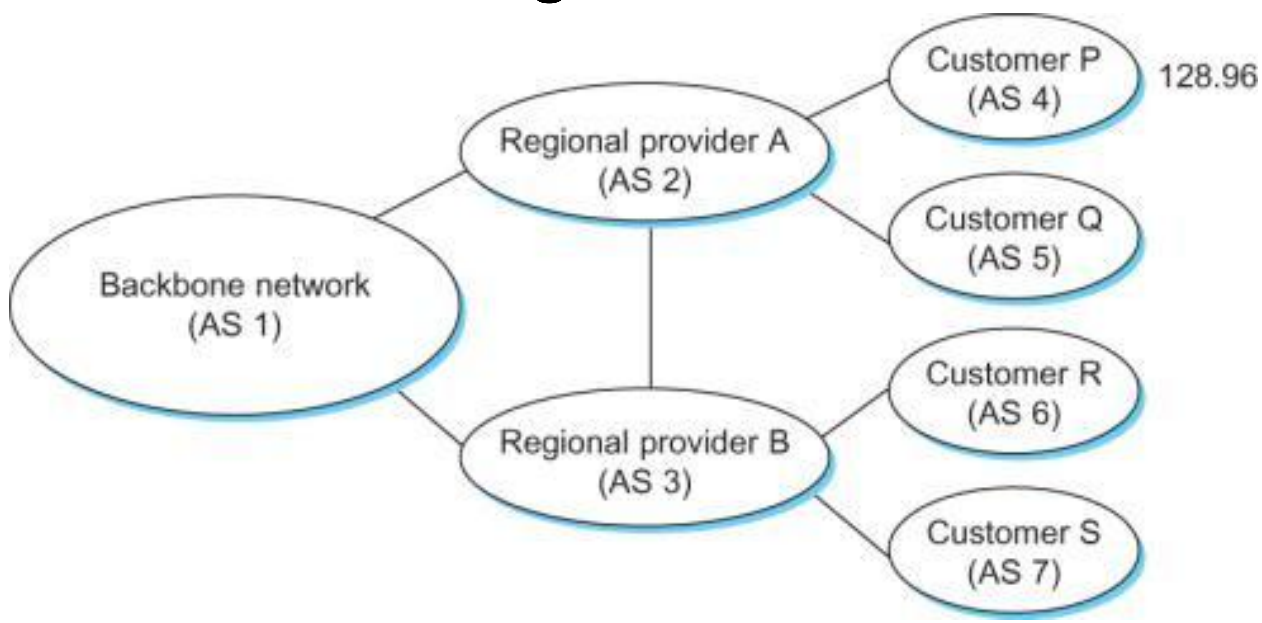
4.6 Routing in the Internet

- RIP
- OSPF
- BGP

4.7 Broadcast and multicast routing

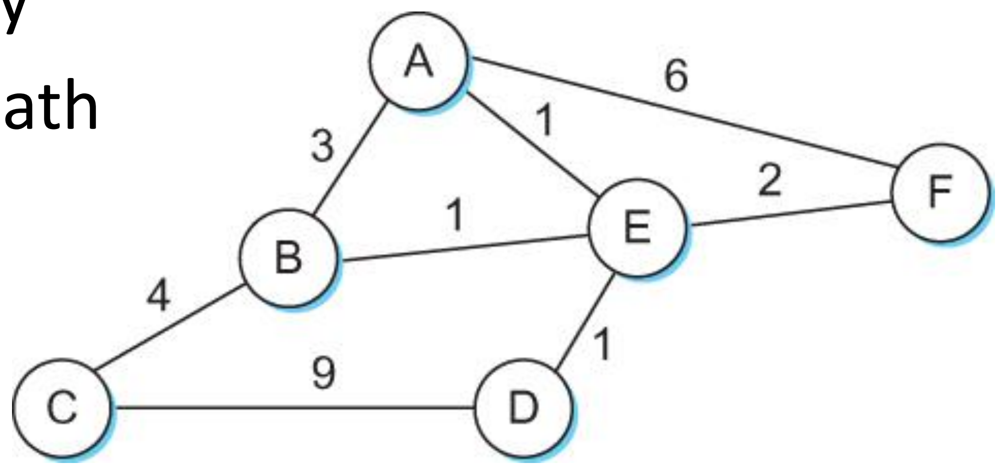
Autonomous System (AS)

- Autonomous System (AS)
  - Distinct region of admin control
  - Routers/links managed by a single institution
  - Each AS can decide how to route within their AS
  - Today: Intra-AS routing
  - Next time: Inter-AS routing



Network as a graph

- Nodes:
  - Hosts, switches, routers, networks
- Edges:
  - Network links
  - May have an associated cost
- Basic problems:
  - Learning the topology
  - Finding lowest cost path



Routing protocols

- Distributed algorithm
  - Running on many devices
  - No central authority
  - Must deal with changing topology
- Classes of routing algorithms:
  - Distance vector routing
  - Link state routing
  - Path vector (hierarchical) routing

Distance vector routing

- Each node maintains state
  - Cost of direct link to each of your neighbors
  - Least cost route known to all destinations
- Routers send periodic updates
  - Send neighbor your array
  - When you receive an update from your neighbor
    - Update array entries if new info provides shorter route
  - Converges quickly (if no topology changes)

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

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

node x table

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

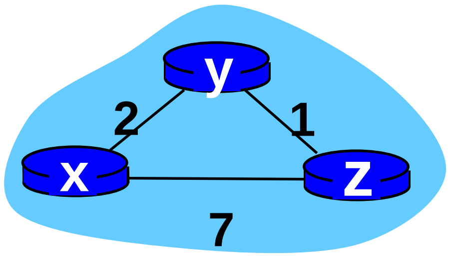
node y table

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

node z table

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

time



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z	∞	∞	∞

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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 table

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

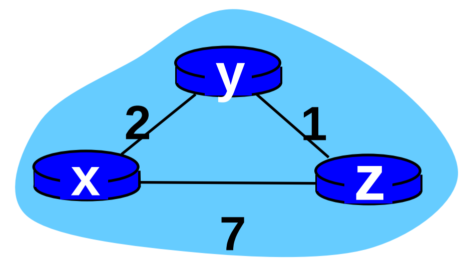
node z table

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 updates

- Periodic updates
  - Automatically send update every so often
  - Lets other nodes know you are alive
- Triggered updates

Wait for (change in local link cost or update from neighbor)

↓

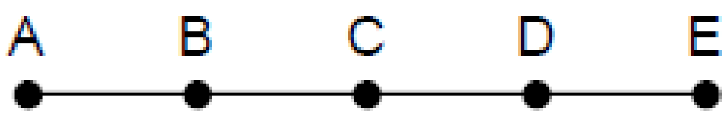
Recompute estimates

↓

If distance to any destination has changed, *notify* neighbors

Link cost change

- What if link added or cost reduced?
  - Update propagates from point of change
  - Network with longest path of N hops:
    - N exchanges, everyone knows of new/improved link
  - "Good news travels fast"



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

Link cost change

- What if link deleted or cost increased?
  - Problem: Neighbor has a path somewhere, but you don't know if it goes through you
- Count to infinity problem
  - "Bad news travels slow"

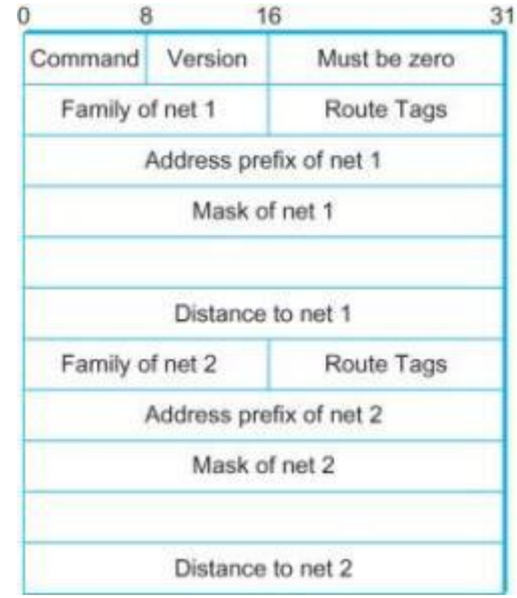
A	B	C	D	E	
•	•	•	•	•	
	1	2	3	4	Initially
	3	2	3	4	After 1 exchange
	3	4	3	4	After 2 exchanges
	5	4	5	4	After 3 exchanges
	5	6	5	6	After 4 exchanges
	7	6	7	6	After 5 exchanges
	7	8	7	8	After 6 exchanges
		⋮			
	•	•	•	•	

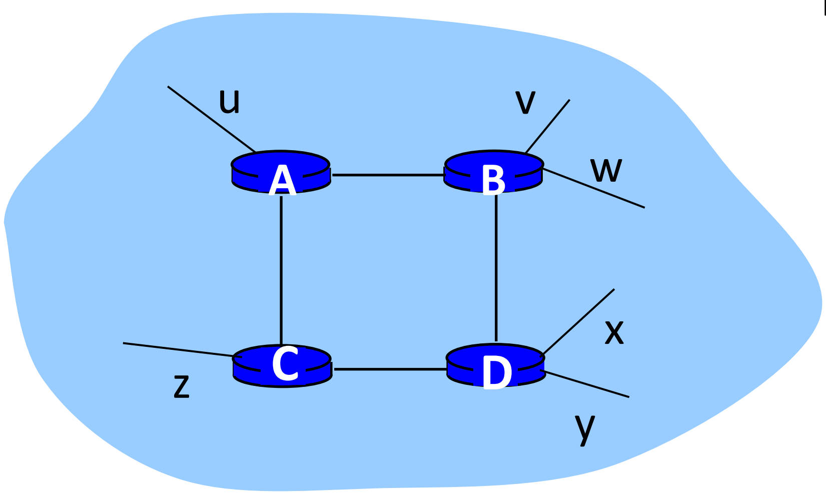
Count-to-infinity

- Various ways to "fix":
  - Use a small values for infinity, e.g. 16
    - Limits network size to 15 hops
  - Split horizon with poisoned reverse
    - Track where you learned the route
    - e.g. (E, 2, A), I learned a cost 2 route to E from A
    - When B updates A, sends (E, ∞)
    - Only works for two node routing loops
  - Holddown timer
    - Start a timer when a network becomes unreachable
    - Don't update until timer expires

RIP

- Routing Information Protocol (RIP)
  - Distance-vector protocol
  - Used in original ARPANET, in BSD
  - All links costs 1
  - Advertise every 30 seconds
  - Small networks, < 16 hops
  - Runs over UDP

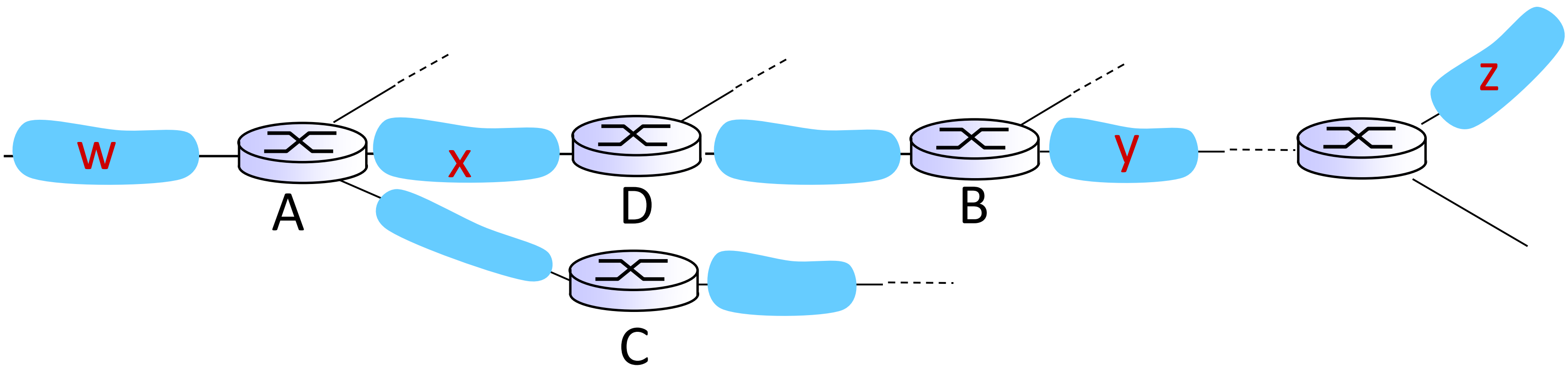




From router A to destination *subnets:*

subnet	hops
u	1
v	2
w	2
x	3
y	3
z	2

RIP: example



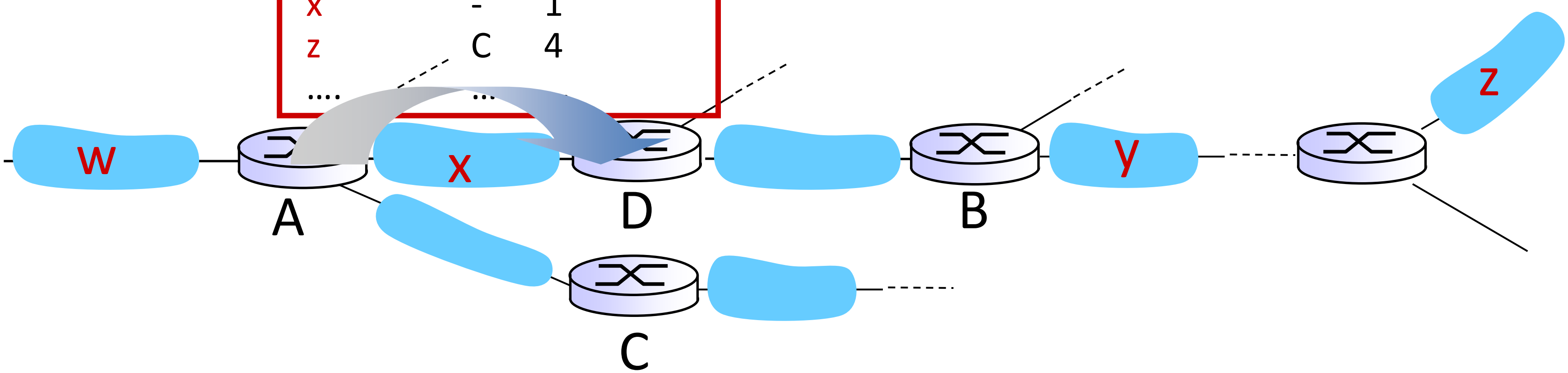
routing table in router D

destination subnet	next router	# hops to dest
w	A	2
y	B	2
z	B	7
x	--	1
….	….	….

RIP: example

A-to-D advertisement

dest	next	hops
w	-	1
x	-	1
z	C	4
….	…	



routing table in router D

destination subnet	next router	# hops to dest
w	A	2
y	B	2
z	~~B~~ A	~~7~~ 5
x	--	1
….	….	….

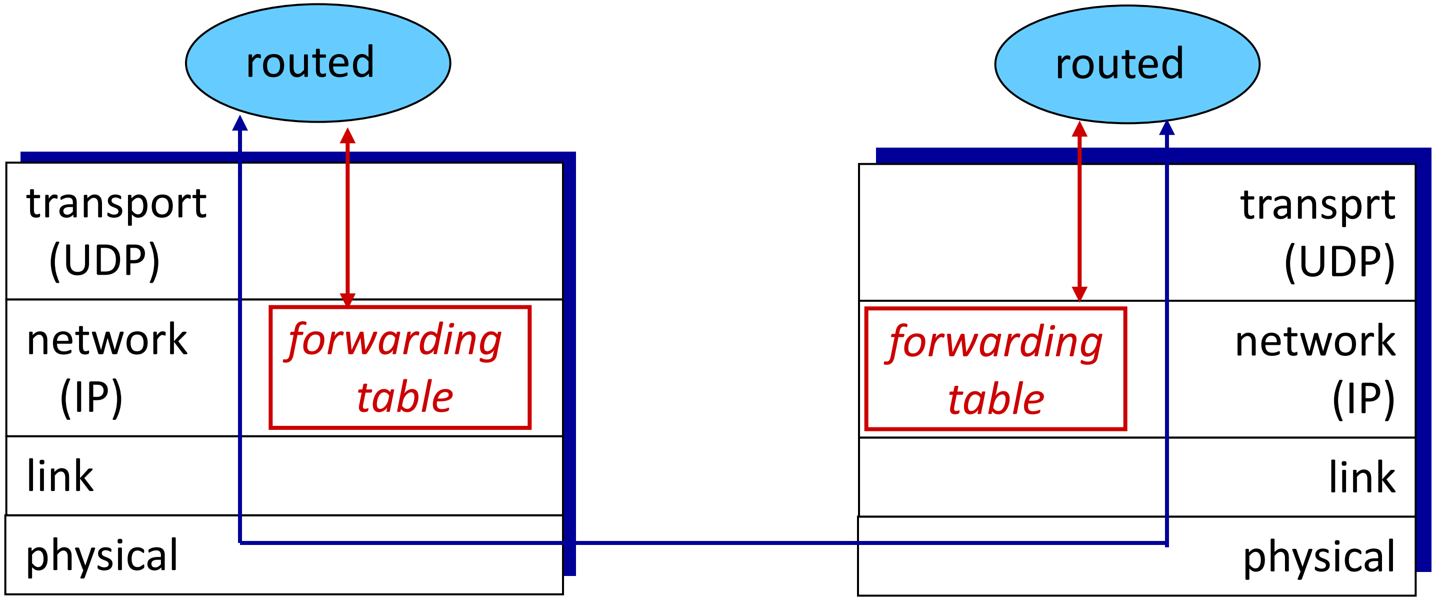
RIP: link failure, recovery

If no advertisement heard after 180 sec --> neighbor/link declared dead

- Routes via neighbor invalidated
- New advertisements sent to neighbors
- Neighbors in turn send out new advertisements (if tables changed)
- Link failure info quickly (?) propagates to entire net
- *Poison reverse* used to prevent ping-pong loops (infinite distance = 16 hops)

RIP table processing

- RIP routing tables managed by *application-level* process called route-d (daemon)
- Advertisements sent in UDP packets, periodically repeated

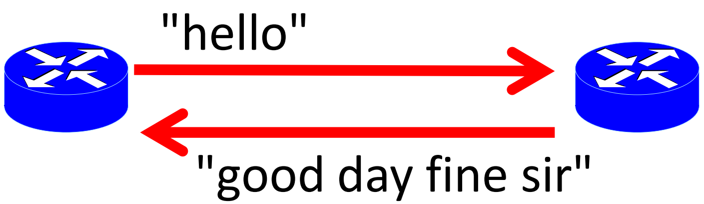


Link state routing

- Link state routing
  - Each router tracks its immediate links
    - Whether up or down
    - Cost of link
  - Each router broadcasts link state
    - Information disseminated to all nodes
    - Routers have global state from which to compute path
  - e.g. Open Shortest Path First (OSPF)

1. Learning about your neighbors

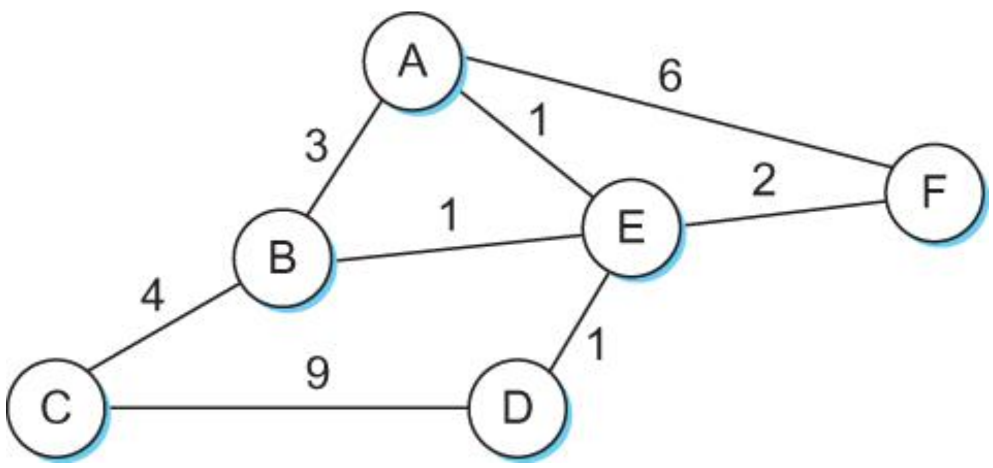
- Beaconing
  - Find out about your neighbors when you boot
  - Send periodic "hello" messages to each other
  - Detect a failure after several missed "hellos"



- Beacon frequency is tradeoff:
  - Detection speed
  - Bandwidth and CPU overhead
  - Likelihood of false detection

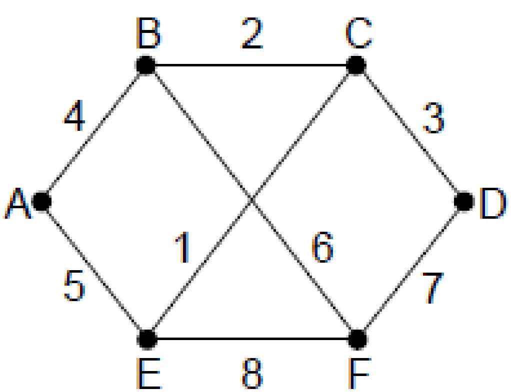
2. Setting link costs

- Assign a link cost for each outbound link
  - Manual configuration
  - Automatic
    - Inverse of link bandwidth
      - 1-Gbps cost 1
      - 100-Mbps cost 10
    - Measure latency by sending an ECHO packet



3. Building link state packets

- Package info into a Link State Packet (LSP)
  - Identity of sender
  - List of neighbors
  - Sequence number of packet
  - Age of packet

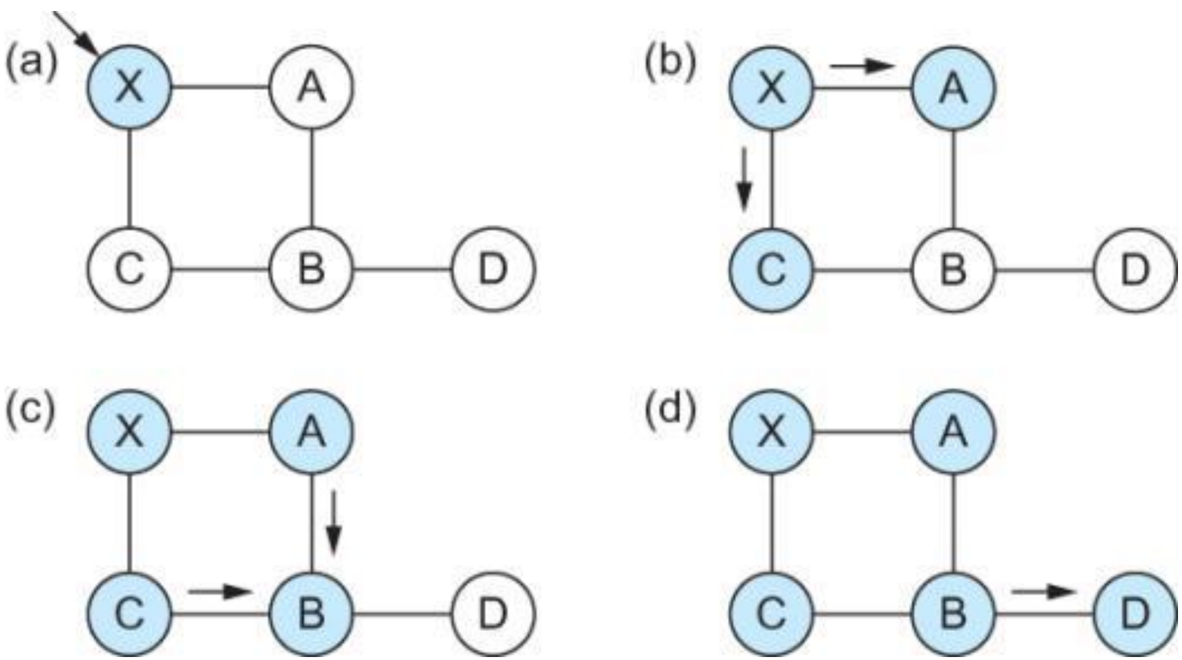


Link State Packets

A		B		C		D		E		F	
Seq.		Seq.		Seq.		Seq.		Seq.		Seq.	
Age		Age		Age		Age		Age		Age	
B	4	A	4	B	2	C	3	A	5	B	6
E	5	C	2	D	3	F	7	C	1	D	7
		F	6	E	1			F	8	E	8

4. Distributing link state

- Flooding
  - Send your LSP out on all links
  - Next node sends LSP onward using its links
    - Except for link it arrived on



a) LSP arrives at node X
b) X floods LSP to A and C
c) A and C flood LSP to B (but not X)
d) flooding complete

4. Distributing link state

- Making flooding reliable
  - Use acknowledgments and retransmissions between routers
  - Use sequence numbers
    - Discard info from packets older than your current info
  - Time-to-live TTL keeps LSP from being endlessly forwarded
- When to distribute?
  - Periodic timer
  - On detected change

5. Computing routes

- Router has accumulated full set of LSPs
  - Construct entire network graph
  - Shortest path from A to B?

Notation:

- c(x,y): Link cost from node x to y; ∞ if not direct neighbors
- D(v): Current value of cost of path from source to dest. v
- p(v): Predecessor node along path from source to v
- N': Set of nodes whose least cost path definitively known

Dijkstra's algorithm

- Net topology known to all nodes
  - All nodes have same info
- Computes least cost paths from some source node to all other nodes
  - Gives *forwarding table* for that node
- Iterative: after k iterations, know least cost path to k dest's

Dijkstra's algorithm

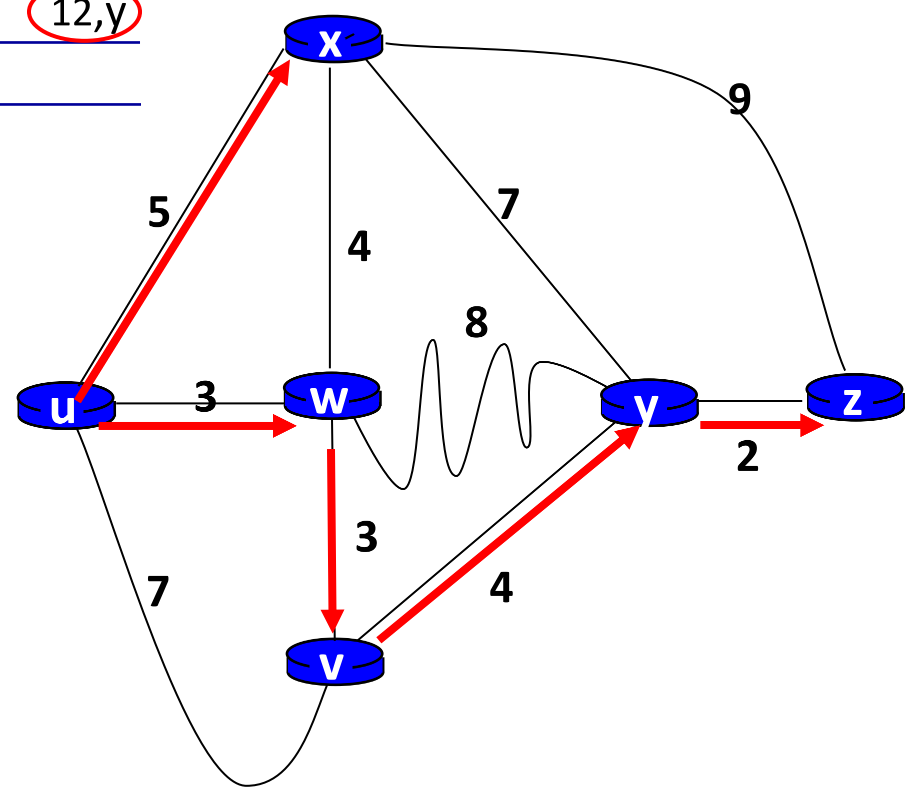
```
Initialization:
  N' = {u}
  for all nodes v
    if v adjacent to u
       then D(v) = c(u,v)
    else D(v) = ∞

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 cost to v is either old cost to v or known
   shortest path cost to w plus cost from w to v */
until all nodes in N'
```

Dijkstra's algorithm: example

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					

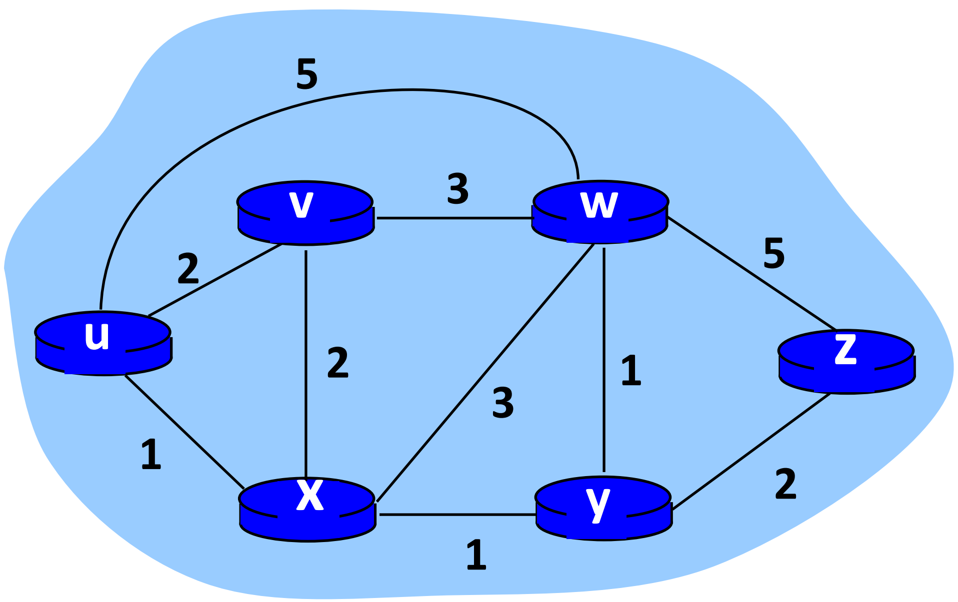
Notes:

- Construct shortest path tree by tracing predecessor nodes
- Ties can exist (can be broken arbitrarily)



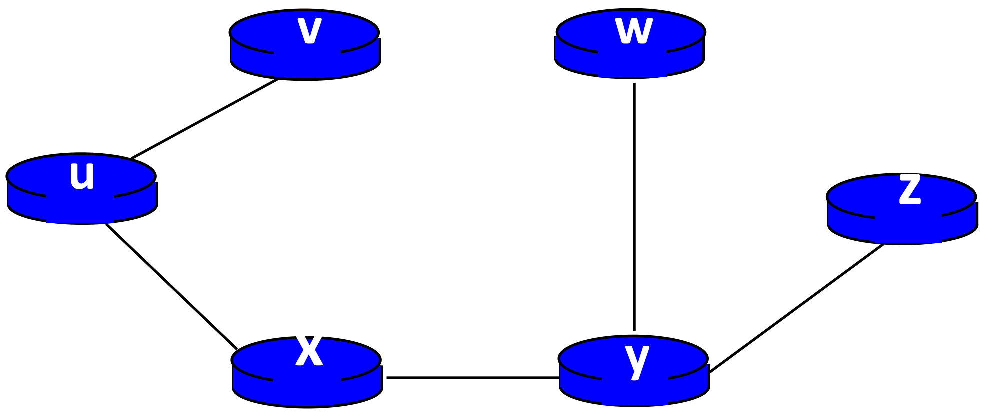
Dijkstra's algorithm: another example

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	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5	uxyvwz					



Dijkstra's algorithm: another example

Resulting shortest-path tree from u:



Resulting forwarding table in u:

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

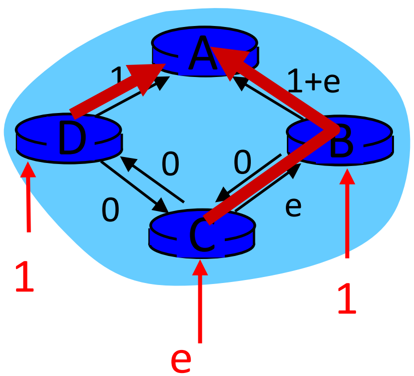
Dijkstra's algorithm: discussion

Algorithm complexity: n nodes

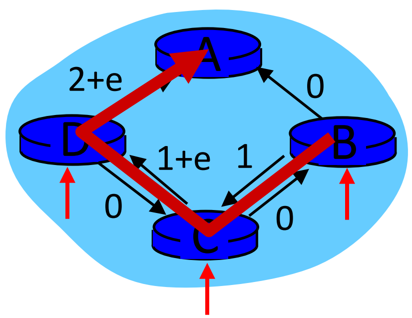
- Each iteration: need to check all nodes, w, not in N
- n(n+1)/2 comparisons: $O(n^2)$
- More efficient implementations possible: O(nlogn)

Oscillations possible:

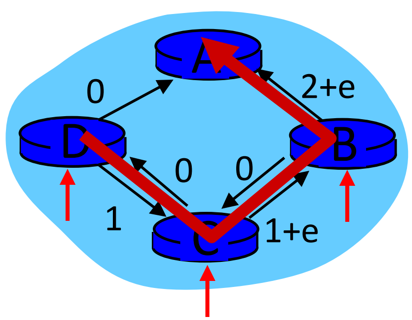
- e.g. support link cost equals amount of carried traffic:



Initially



Given these costs, find new routing…. Resulting in new costs



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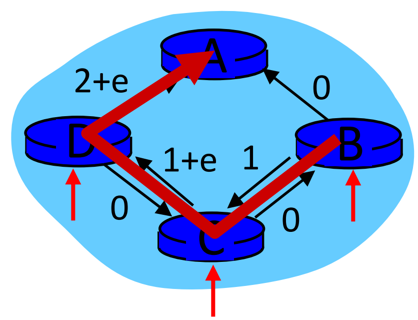
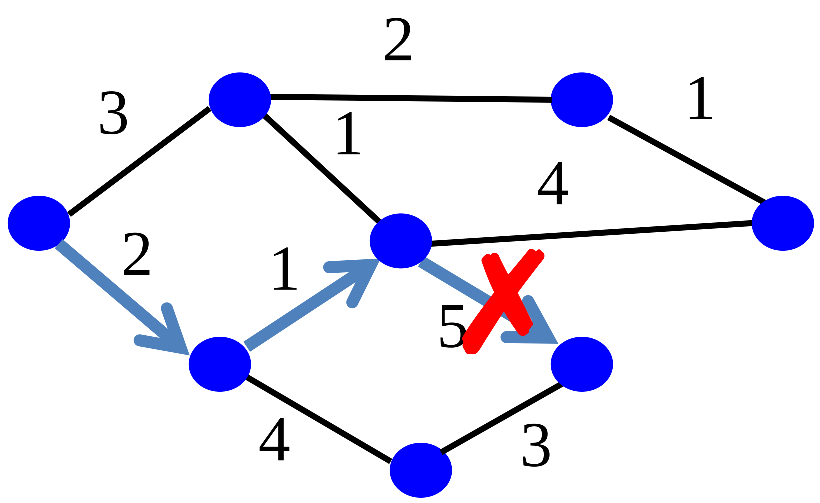


Given these costs, find new routing…. Resulting in new costs

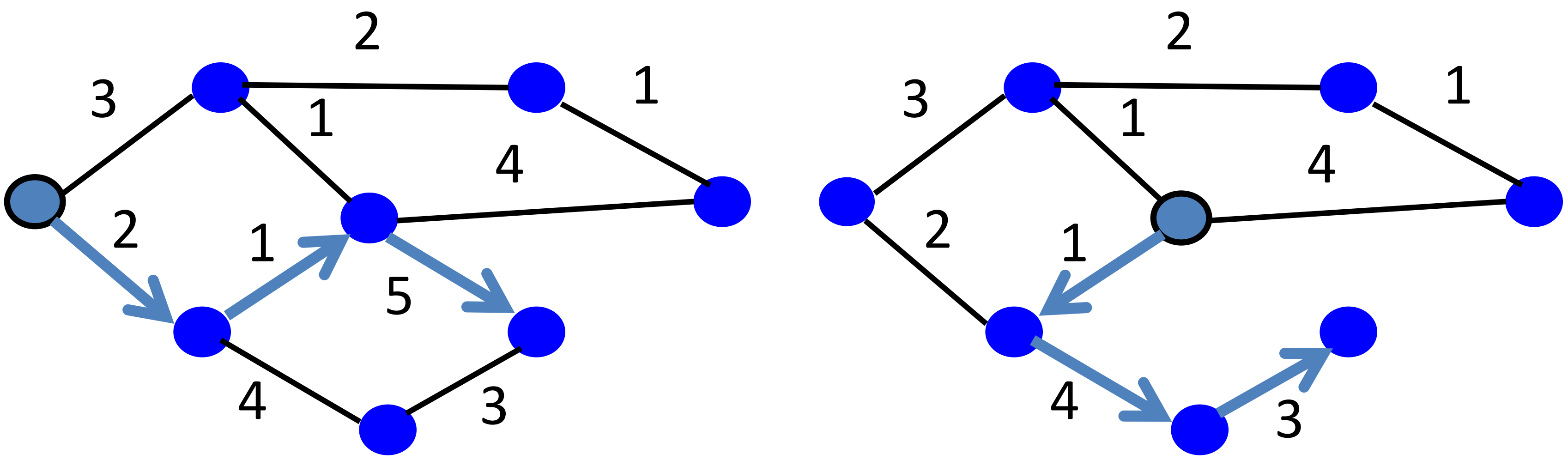
Transient disruptions

- Detection delay
  - Failures are not detected immediately
  - Router may forward packet into a "blackhole"
  - Chance depends on frequency of "hello" messages



Transient disruptions

- Inconsistent link-state
  - Some routers know about a failure, others don't
  - Shortest path no longer consistent
  - Can causes transient forwarding loops



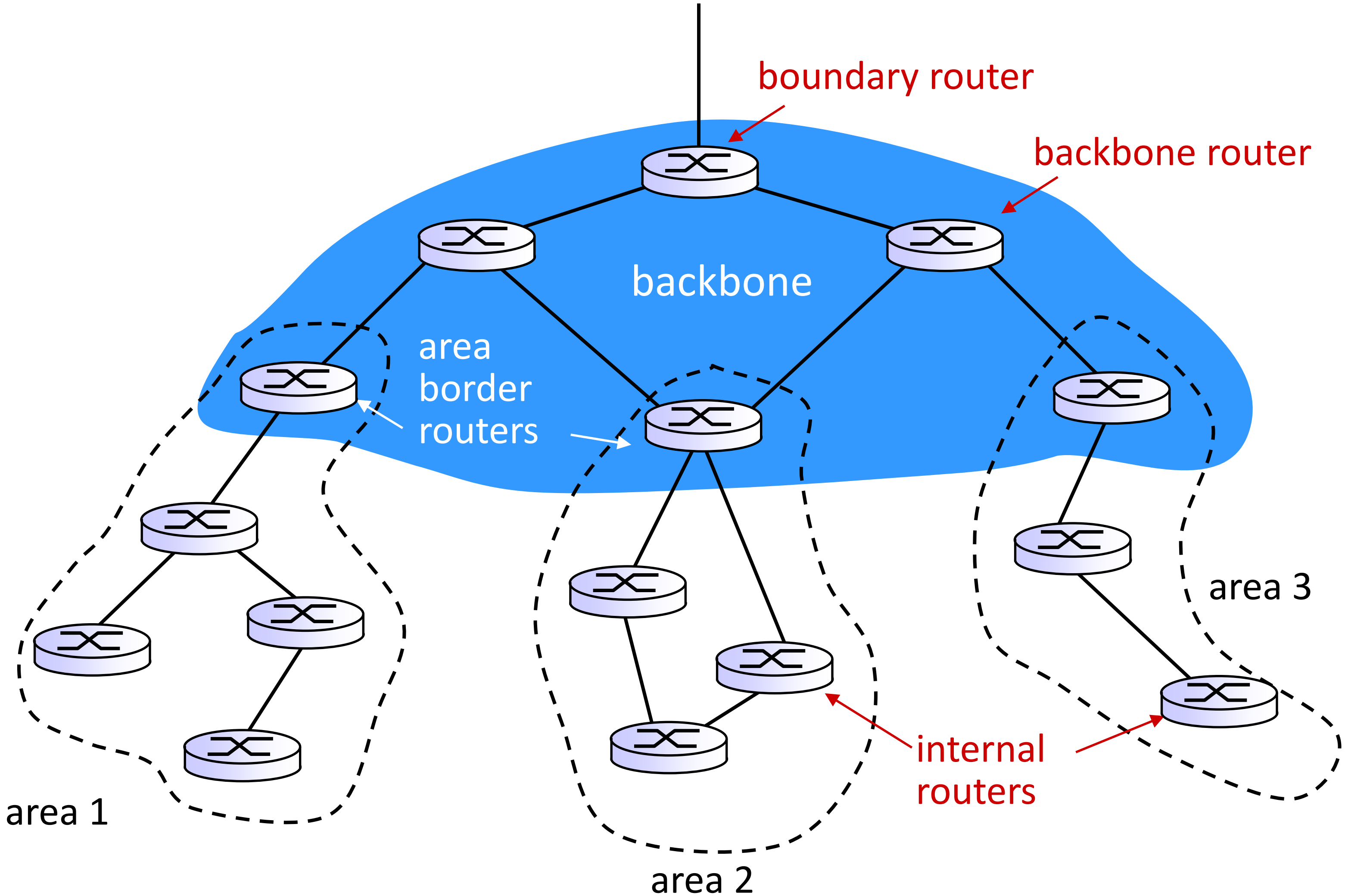
OSPF (Open Shortest Path First)

- Open: publicly available
- Uses link state algorithm
  - LS packet dissemination
  - Topology map at each node
  - Route computation: Dijkstra's algorithm
- OSPF advertisements:
  - One entry per neighbor
  - Flooded to entire AS
  - Carried in OSPF messages directly over IP
- IS-IS routing protocol
  - Nearly identical to OSPF

OSPF advanced features (not in RIP)

- Security: All OSPF messages authenticated
  - To prevent malicious attacks
- Multiple same-cost paths allowed
  - Only one path allowed in RIP
- Multiple link cost metrics for different TOS
  - e.g. satellite link cost set low for best effort ToS; high for real time ToS
- Integrated uni- and multicast support:
  - Multicast OSPF (MOSPF) uses same topology data base as OSPF
- Hierarchical OSPF in large domains

Hierarchical OSPF



Hierarchical OSPF

- *Two-level hierarchy:* local area, backbone
  - Link-state advertisements only in area
  - Each node has detailed area topology; only knows direction (shortest path) to nets in other areas
- *Area border routers:*
  - Summarize distances to nets in own area, advertise to other Area Border routers
- *Backbone routers:*
  - Run OSPF routing limited to backbone
- *Boundary routers:*
  - Connect to other AS's

Convergence delay

- Sources of delay:
  - Time to detect failure
  - Time to flood link-state info
  - Shortest path computation
  - Creating the forwarding table
- Before convergence:
  - Lost packets due to blackholes, TTL expiry
  - Looping packets
  - Out of order packets
  - Bad for Voice over IP, gaming, video

Reducing convergence delay

- Detect failures faster
  - Increase beacon frequency
  - Link-layer technologies that can detect failures
- Faster flooding
  - Flood immediately on a change
  - LSP sent with high-priority
- Faster computation
  - Faster processors in routers
  - Faster algorithms
    - e.g. incremental Dijkstra's
  - Faster forwarding table update
    - e.g. data structures supporting incremental updates

Distance vector vs. Link state

Distance vector	**Link state**
Knowledge of neighbors' distance to destinations	Knowledge of every router's links (entire network graph)
Router has O(# neighbors * # nodes)	Router has O(# edges)
Messages only between neighbors	Messages between all nodes
Trust a peer's routing computation	Trust a peer's info Do routing yourself
Bellman-Ford algorithm	Dijkstra's algorithm
<u>**Advantages:**</u> Less info has to be stored Lower computation overhead	<u>**Advantages:**</u> Fast to react to changes

Summary

- Intra-AS routing, two major types:
  - Distance vector
    - Router only know about its neighbors
    - RIP protocol
      - Original protocol on the ARPANET
      - Limited to networks < 16 hops
  - Link state
    - Full state of network known by each router
    - OSPF protocol
      - More advanced features: security, multiple paths, multiple cost metrics, routing areas