CSCI-1680 - Computer Networks

Network Layer: Intra-domain Routing

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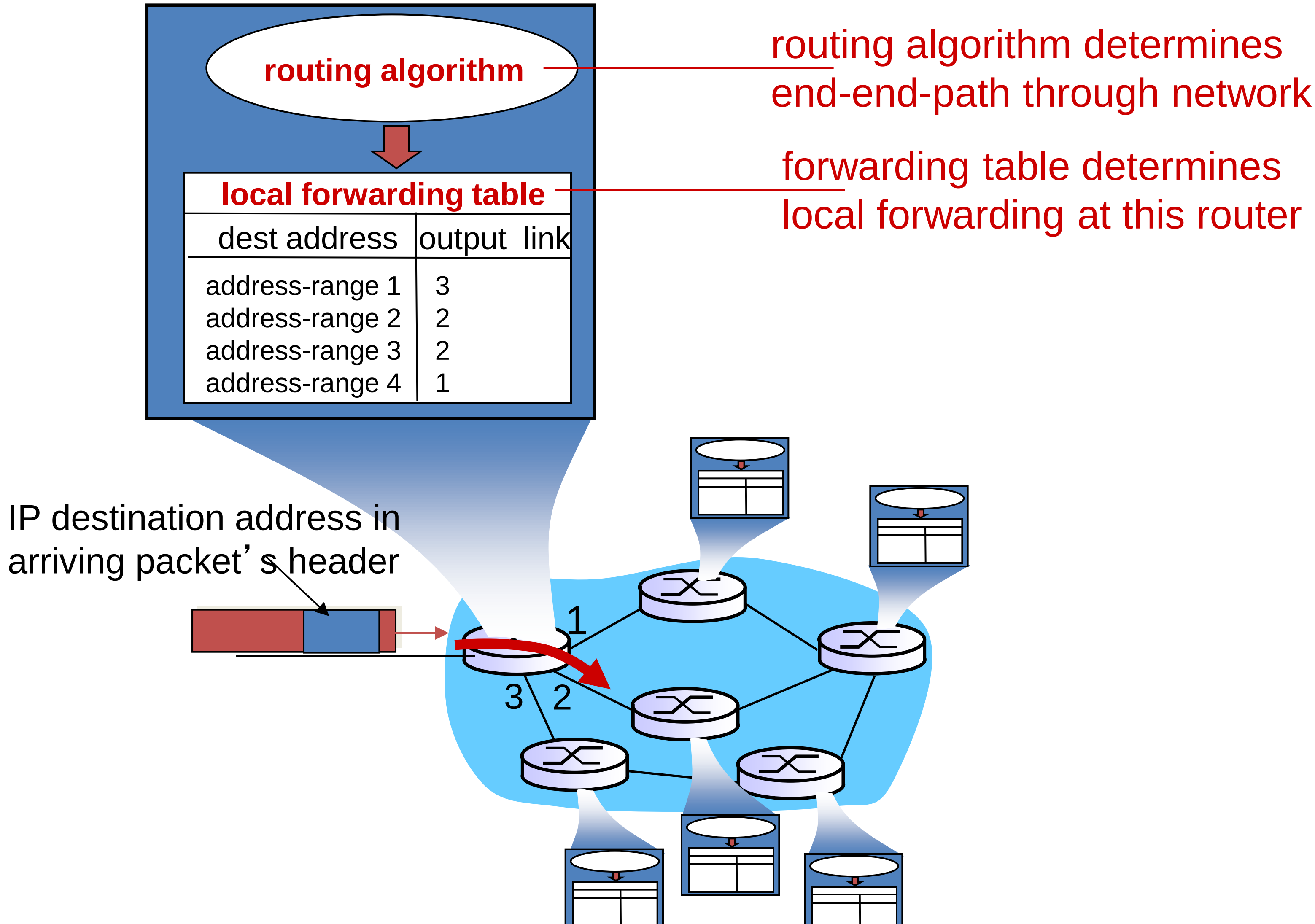
Based partly on lecture notes by David Mazières, Phil Levis, John Jannotti, Peterson & Davie, Rodrigo Fonseca

Today

- Intra-Domain Routing
- Next class: Inter-Domain Routing

Interplay between routing, forwarding



Slide from: “Computer Networking: A Top Down Approach” - 6th edition

Routing

- **Routing is the process of updating forwarding tables**
  - Routers exchange messages about routers or networks they can reach
  - Goal: find optimal route for every destination
  - … or maybe a good route, or *any* route (depending on scale)
- **Challenges**
  - Dynamic topology
  - Decentralized
  - Scale

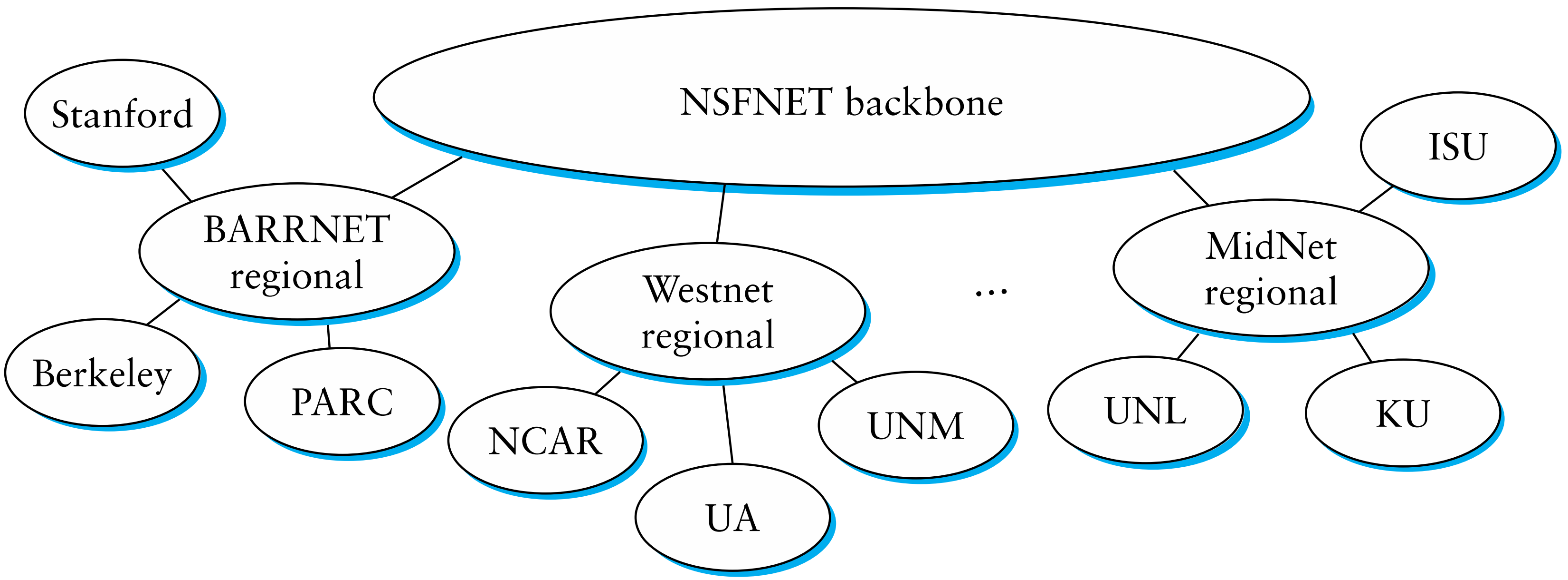
Scaling Issues

- **Every router must be able to forward based on *any* destination IP address**
  - Given address, it needs to know next hop
  - Naïve: one entry per address
  - There would be 10^8 entries!
- **Solutions**
  - Hierarchy (many examples)
  - Address aggregation
    - Address allocation is very important (should mirror topology)
  - Default routes

IP Connectivity

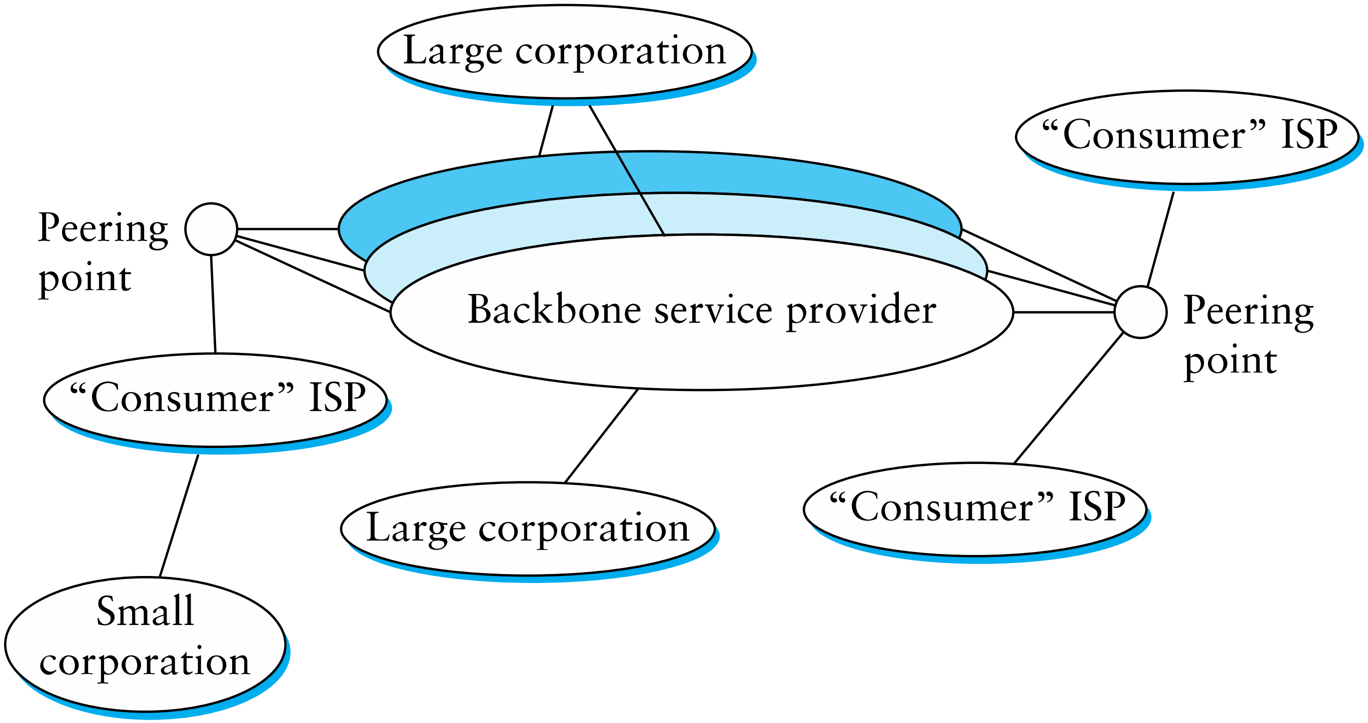
- **For each destination address, must either:**
  - Have prefix mapped to next hop in forwarding table
  - Know “smarter router” – default for unknown prefixes
- **Route using longest prefix match, default is prefix 0.0.0.0/0**
- **Core routers know everything – no default**
- **Manage using notion of *Autonomous System* (AS)**

Internet structure, 1990



- **Several independent organizations**
- **Hierarchical structure with single backbone**

Internet structure, today



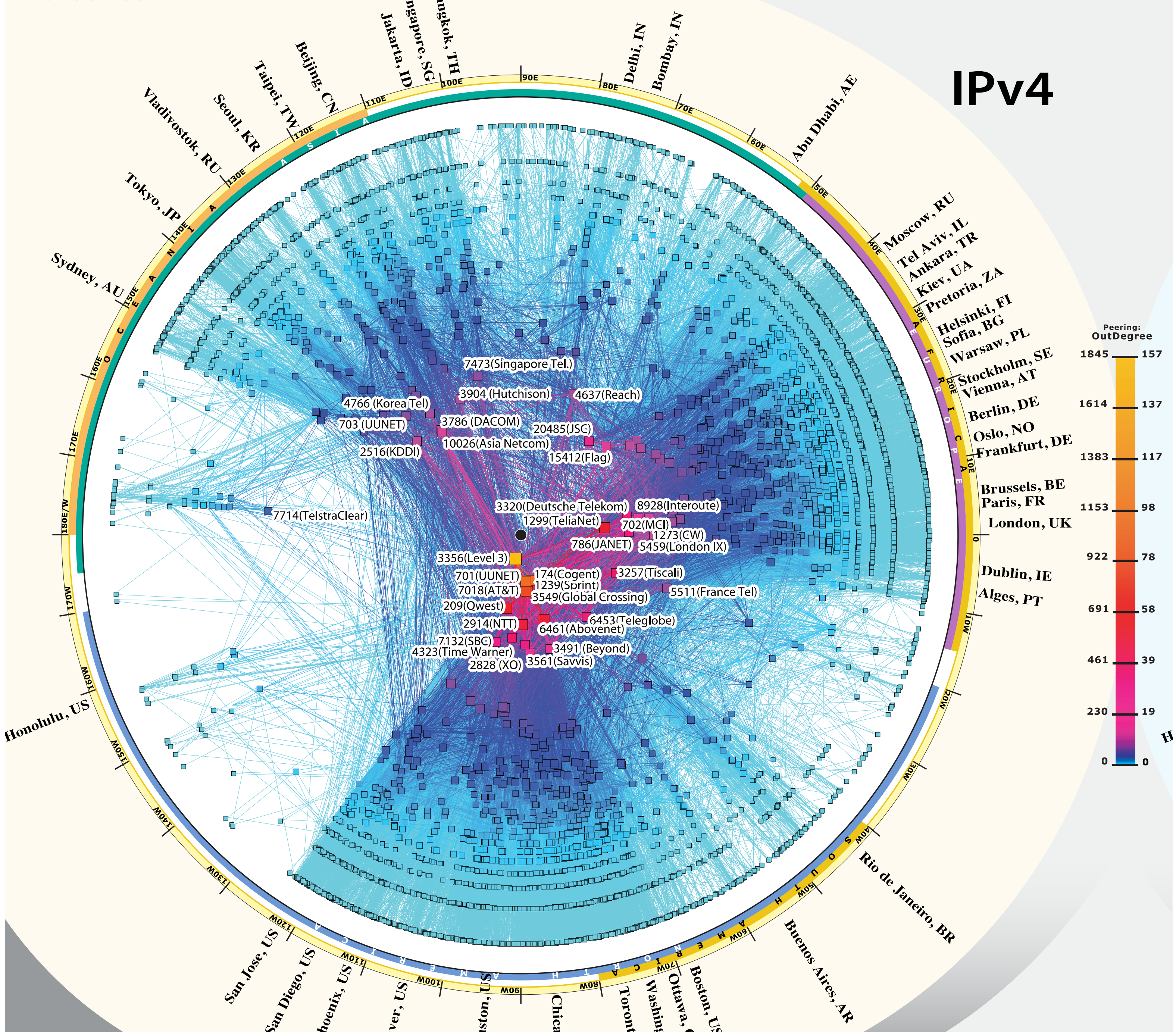
- **Multiple backbones, more arbitrary structure**

Autonomous Systems

- **Correspond to an administrative domain**
  - AS’s reflect organization of the Internet
  - E.g., Brown, large company, etc.
  - Identified by a 16-bit number
- **Goals**
  - AS’s choose their own local routing algorithm
  - AS’s want to set policies about non-local routing
  - AS’s need not reveal internal topology of their network

AS-level INTERNET GRAPH

IPv4

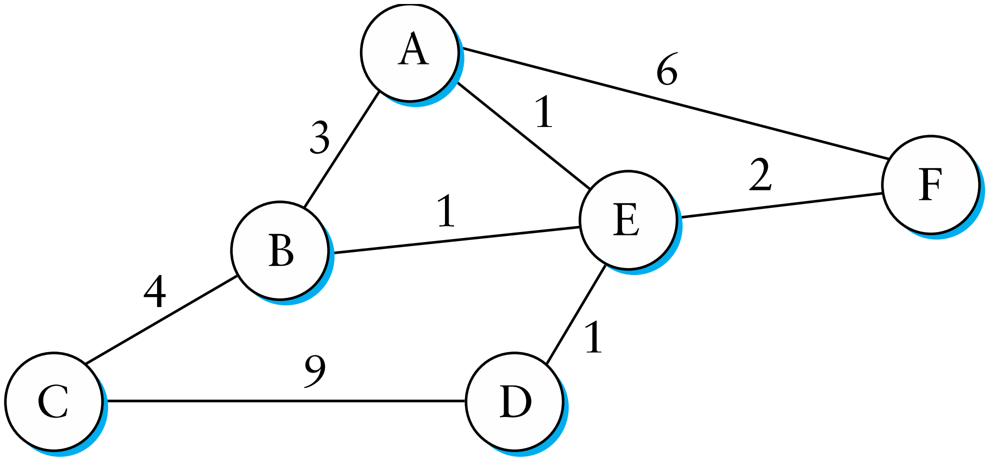


Inter and Intra-domain routing

- **Routing organized in two levels**
- **Intra-domain routing**
  - Complete knowledge, strive for *optimal* paths
  - Scale to ~100 networks
  - Today
- **Inter-domain routing**
  - Aggregated knowledge, scale to Internet
  - Dominated by *policy*
    - E.g., route through X, unless X is unavailable, then route through Y. Never route traffic from X to Y.
  - Policies reflect business agreements, can get complex
  - Next lecture

Intra-Domain Routing

Network as a graph



- **Nodes are routers**
- **Assign *cost* to each edge**
  - Can be based on latency, b/w, queue length, …
- **Problem: find lowest-cost path between nodes**
  - Each node individually computes routes

Basic Algorithms

- **Two classes of intra-domain routing algorithms**
- **Distance Vector**
  - Requires only local state
  - Harder to debug
  - Can suffer from loops
- **Link State**
  - Each node has global view of the network
  - Simpler to debug
  - Requires global state

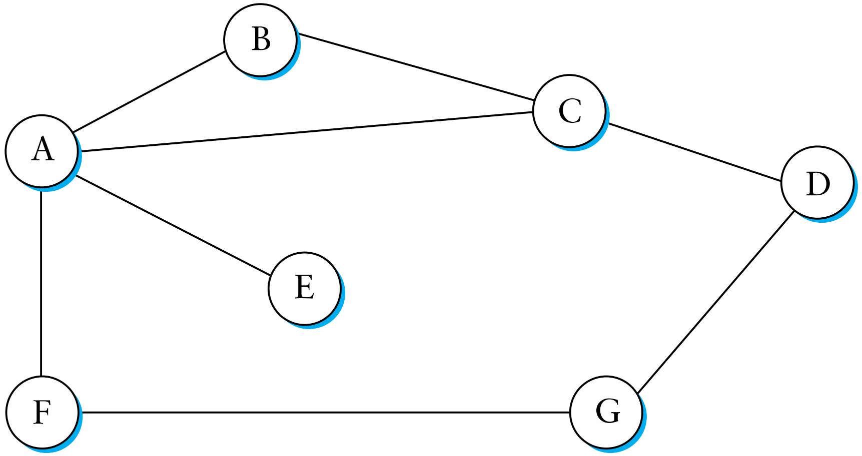
Distance Vector

- **Local routing algorithm**
- **Each node maintains a set of triples**
  - *<Destination, Cost, NextHop>*
- **Exchange updates with neighbors**
  - Periodically (seconds to minutes)
  - Whenever table changes (*triggered* update)
- **Each update is a list of pairs**
  - *<Destination, Cost>*
- **Update local table if receive a "better" route**
  - Smaller cost
- **Refresh existing routes, delete if time out**

Calculating the best path

- **Bellman-Ford equation**
- **Let:**
  - $D_a(b)$ denote the current best distance from a to b
  - $c(a,b)$ denote the cost of a link from a to b
- **Then $D_x(y) = \min_z(c(x,z) + D_z(y))$**
- **Routing messages contain D**
- **D is any additive metric**
  - e.g, number of hops, queue length, delay
  - log can convert multiplicative metric into an additive one (e.g., probability of failure)

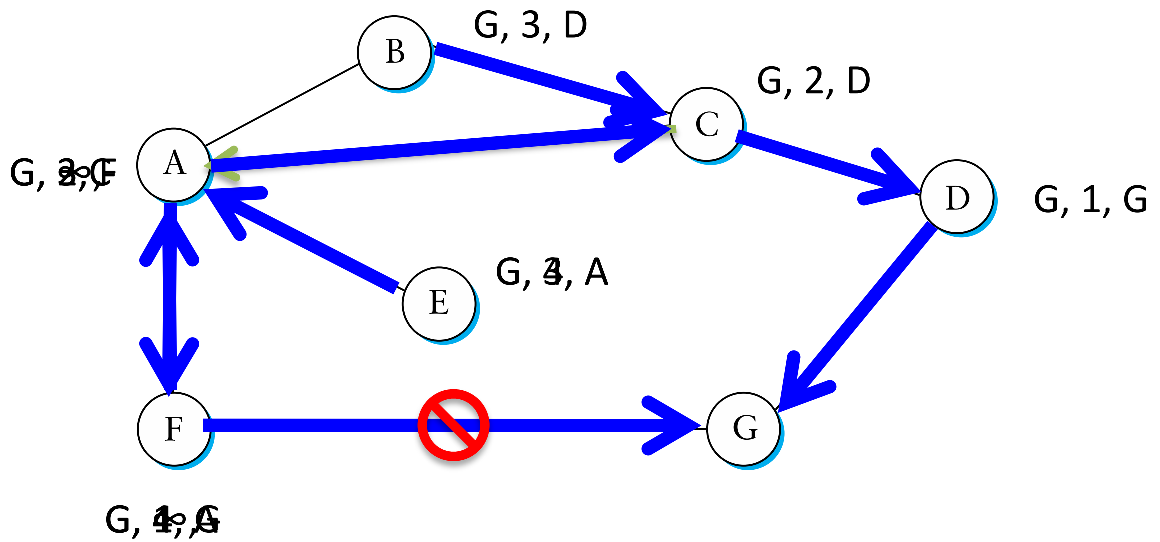
DV Example



B's routing table

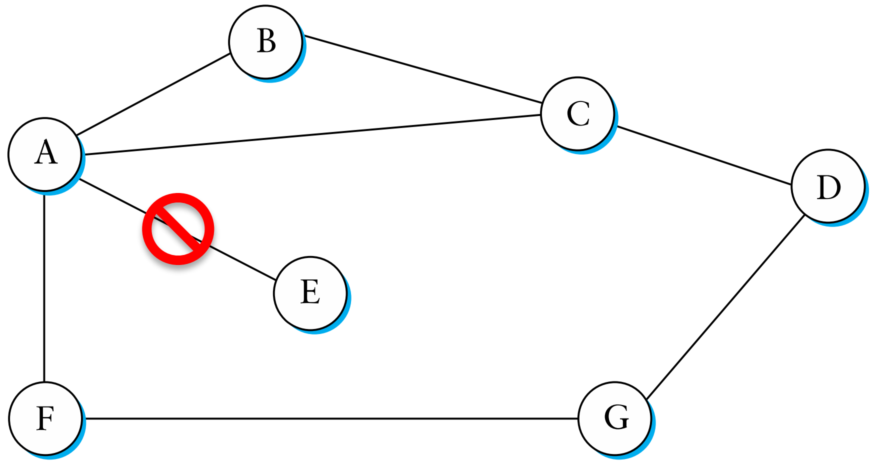
Destination	Cost	Next Hop
A	1	A
C	1	C
D	2	C
E	2	A
F	2	A
G	3	A

Adapting to Failures



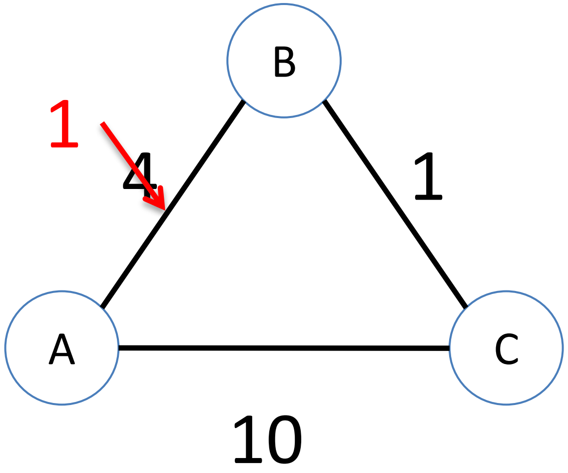
- F-G fails
- F sets distance to G to infinity, propagates
- A sets distance to G to infinity
- A receives periodic update from C with 2-hop path to G
- A sets distance to G to 3 and propagates
- F sets distance to G to 4, through A

Count-to-Infinity



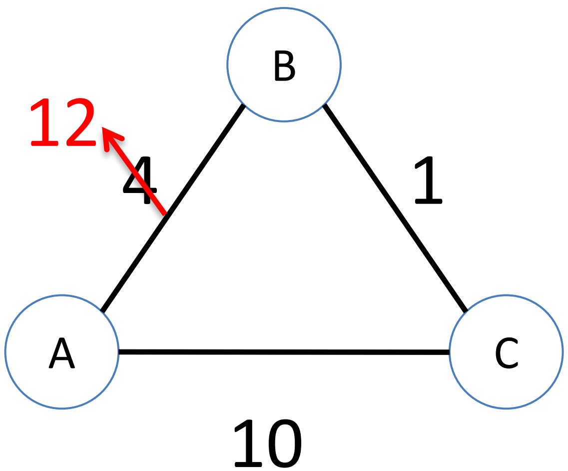
- **Link from A to E fails**
- **A advertises distance of infinity to E**
- **B and C advertise a distance of 2 to E**
- **B decides it can reach E in 3 hops through C**
- **A decides it can reach E in 4 hops through B**
- **C decides it can reach E in 5 hops through A, …**
- **When does this stop?**

Good news travels fast



- A decrease in link cost has to be fresh information
- Network converges at most in O(diameter) steps

Bad news travels slowly



- An increase in cost may cause confusion with old information, may form loops
- Consider routes to A
- Initially, B:A,4,A; C:A,5,B
- Then B:A,12,A, selects C as next hop -> B:A,6,C
- C -> A,7,B; B -> A,8,C; C -> A,9,B; B -> A,10,C;
- C finally chooses C:A,10,A, and B -> A,11,C!

How to avoid loops

- **IP TTL field prevents a packet from living forever**
  - Does not *repair* a loop
- **Simple approach: consider a small cost *n* (e.g., 16) to be infinity**
  - After *n* rounds decide node is unavailable
  - But rounds can be long, this takes time
- **Problem: distance vector based only on local information**

Better loop avoidance

- **Split Horizon**
  - When sending updates to node A, don't include routes you learned from A
  - Prevents B and C from sending cost 2 to A
- **Split Horizon with Poison Reverse**
  - Rather than not advertising routes learned from A, explicitly include cost of ∞.
  - Faster to break out of loops, but increases advertisement sizes

Warning

- **Split horizon/split horizon with poison reverse only help between two nodes**
  - Can still get loop with three nodes involved
  - Might need to delay advertising routes after changes, but affects convergence time

Other approaches

- **DSDV: destination sequenced distance vector**
  - Uses a ‘version’ number per destination message
  - Avoids loops by preventing nodes from using old information from descendents
  - But, you can only update when new version comes from root
- **Path Vector: (BGP)**
  - Replace ‘distance’ with ‘path’
  - Avoids loops with extra cost

Link State Routing

- **Strategy:**
  - send to all nodes information about directly connected neighbors
- **Link State Packet (LSP)**
  - ID of the node that created the LSP
  - Cost of link to each directly connected neighbor
  - Sequence number (SEQNO)
  - TTL

Reliable Flooding

- **Store most recent LSP from each node**
  - Ignore earlier versions of the same LSP
- **Forward LSP to all nodes but the one that sent it**
- **Generate new LSP periodically**
  - Increment SEQNO
- **Start at SEQNO=0 when reboot**
  - If you hear your own packet with SEQNO=n, set your next SEQNO to n+1
- **Decrement TTL of each stored LSP**
  - Discard when TTL=0

A Link-State Routing Algorithm

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**

Dijsktra’s Algorithm

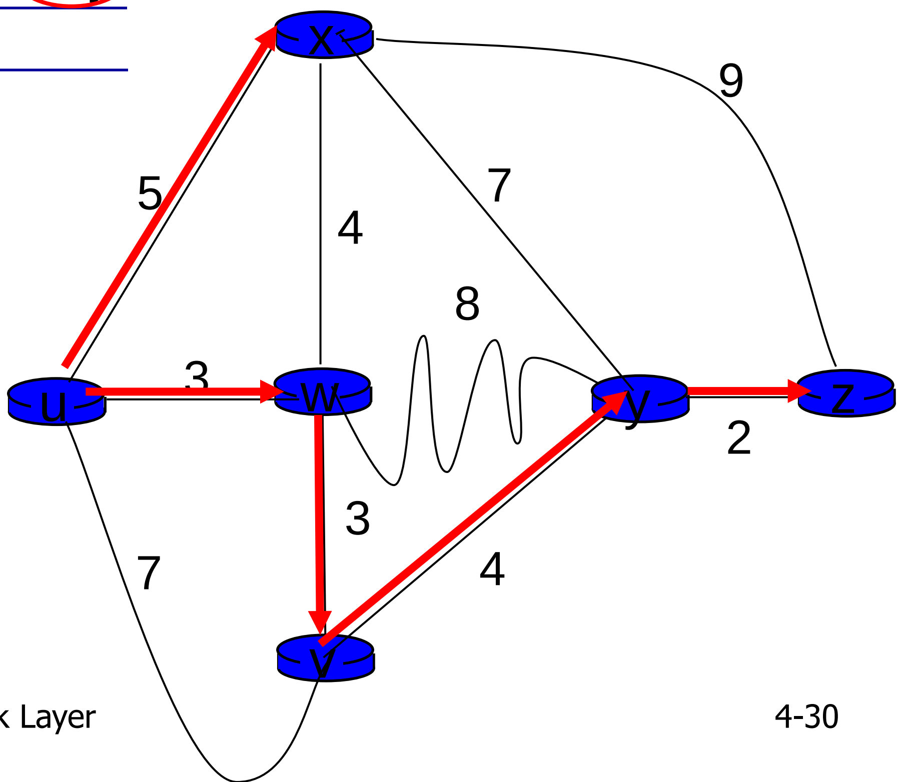
```
Initialization:
  N' = {u}
  for all nodes v
    if v adjacent to u
        then D(v) = c(u,v)
    else D(v) = ∞

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					

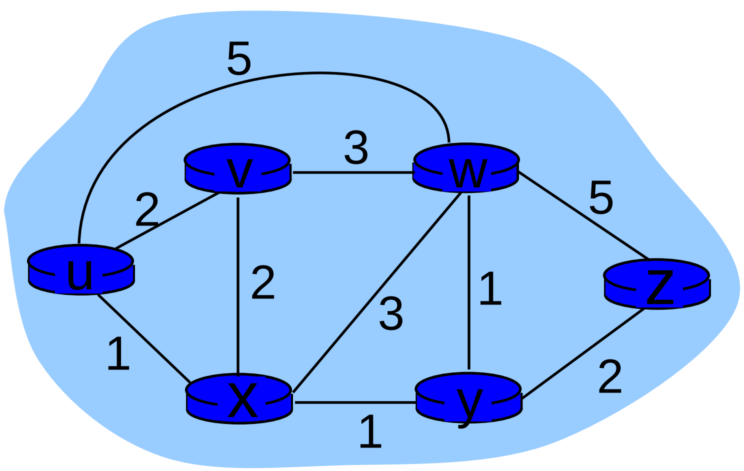
notes:

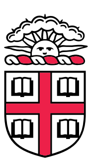
- construct shortest path tree by tracing predecessor nodes
- ties can exist (can be broken arbitrarily)



Dijkstra's algorithm: another example

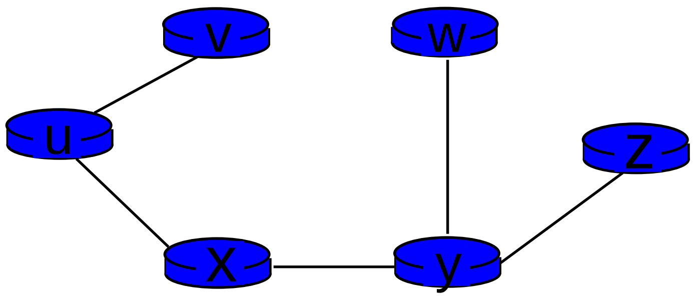
Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5	uxyvwz					





Dijkstra's algorithm: example (2)

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)

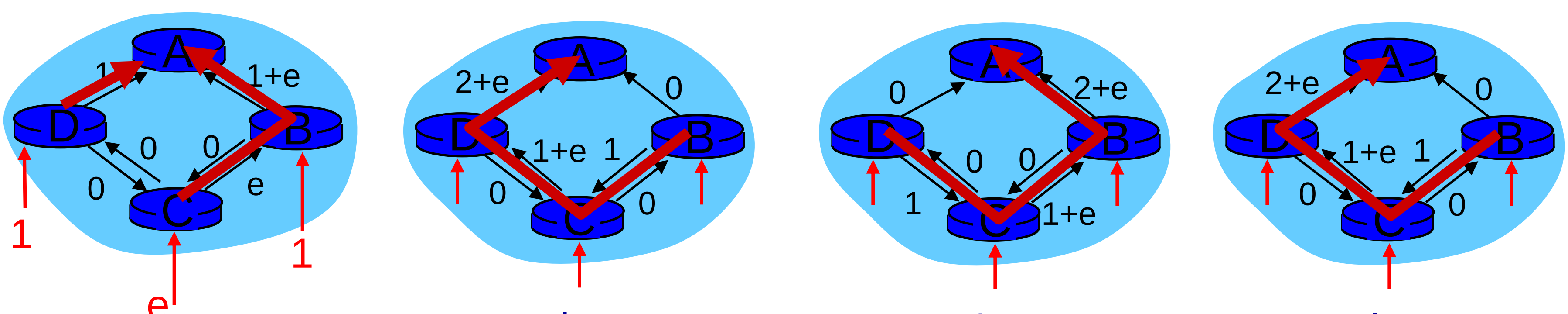
Dijkstra's algorithm, discussion

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

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

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

Distance Vector vs. Link State

- **# of messages (per node)**
  - DV: O(d), where d is degree of node
  - LS: O(nd) for n nodes in system
- **Computation**
  - DV: convergence time varies (e.g., count-to-infinity)
  - LS: $O(n^2)$ with O(nd) messages
- **Robustness: what happens with malfunctioning router?**
  - DV: Nodes can advertise incorrect *path* cost
  - DV: Others can use the cost, propagates through network
  - LS: Nodes can advertise incorrect *link* cost

Metrics

- **Original ARPANET metric**
  - measures number of packets enqueued in each link
  - neither latency nor bandwidth in consideration
- **New ARPANET metric**
  - Stamp arrival time (AT) and departure time (DT)
  - When link-level ACK arrives, compute

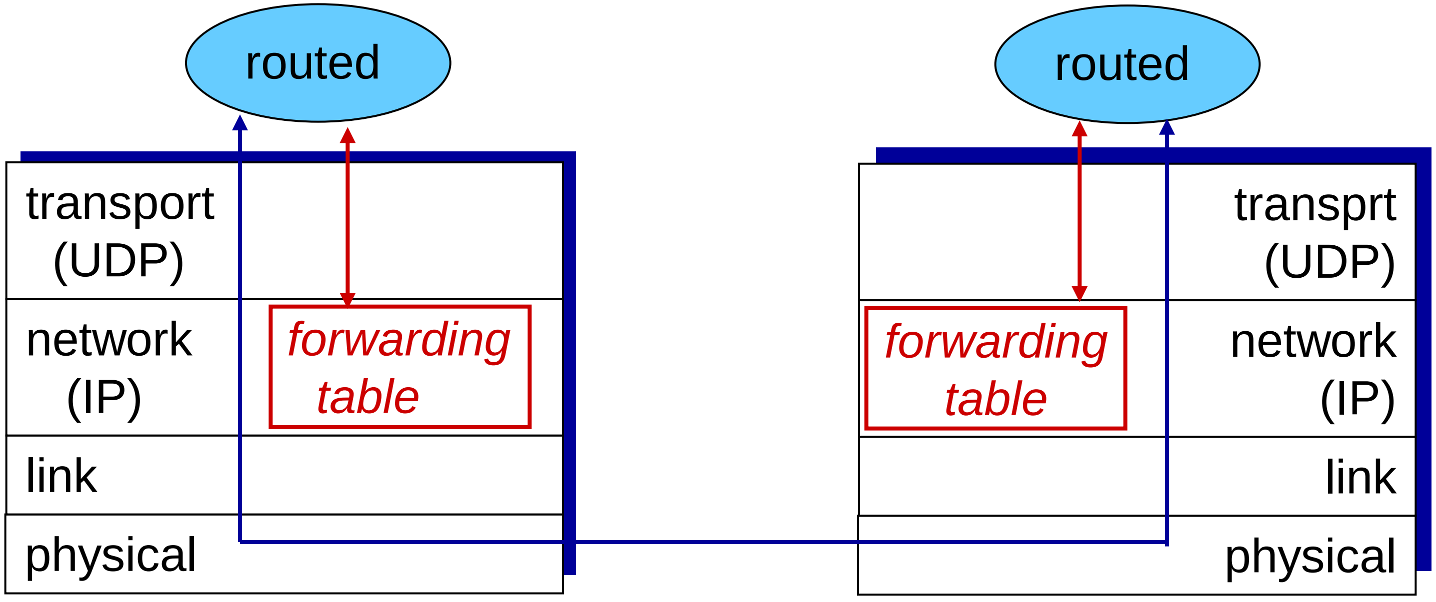
    Delay = (DT – AT) + Transmit + Latency
  - If timeout, reset DT to departure time for retransmission
  - Link cost = average delay over some time period
- **Fine Tuning**
  - Compressed dynamic range
  - Replaced Delay with link utilization
- **Today: commonly set manually to achieve specific goals**

Examples

- **RIPv2**
  - Fairly simple implementation of DV
  - RFC 2453 (38 pages)
- **OSPF (Open Shortest Path First)**
  - More complex link-state protocol
  - Adds notion of *areas* for scalability
  - RFC 2328 (244 pages)

RIP table processing

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



RIPv2

- **Runs on UDP port 520**
- **Link cost = 1**
- **Periodic updates every 30s, plus triggered updates**
- **Relies on count-to-infinity to resolve loops**
  - Maximum diameter 15 (∞ = 16)
  - Supports split horizon, poison reverse
- **Deletion**
  - If you receive an entry with metric = 16 OR
  - If a route times out

Packet format

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  command (1)  |  version (1)  |       must be zero (2)        |
+---------------+---------------+-------------------------------+
|                                                               |
~                         RIP Entry (20)                        ~
|                                                               |
+---------------+---------------+---------------+---------------+
```

RIPv2 Entry

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| address family identifier (2) |        Route Tag (2)          |
+-------------------------------+-------------------------------+
|                        IP address (4)                         |
+---------------------------------------------------------------+
|                        Subnet Mask (4)                        |
+---------------------------------------------------------------+
|                        Next Hop (4)                           |
+---------------------------------------------------------------+
|                        Metric (4)                             |
+---------------------------------------------------------------+
```

Route Tag field

- Allows RIP nodes to distinguish internal and external routes
- Must persist across announcements
- E.g., encode AS

Next Hop field

- **Allows one router to advertise routes for multiple routers on the same subnet**
- **Suppose only XR1 talks RIPv2:**

```
-----   -----   -----           -----   -----   -----
|IR1|   |IR2|   |IR3|           |XR1|   |XR2|   |XR3|
--+--   --+--   --+--           --+--   --+--   --+--
  |       |       |               |       |       |
--+-------+-------+---------------+-------+-------+--
  <-------------RIP-2------------->
```

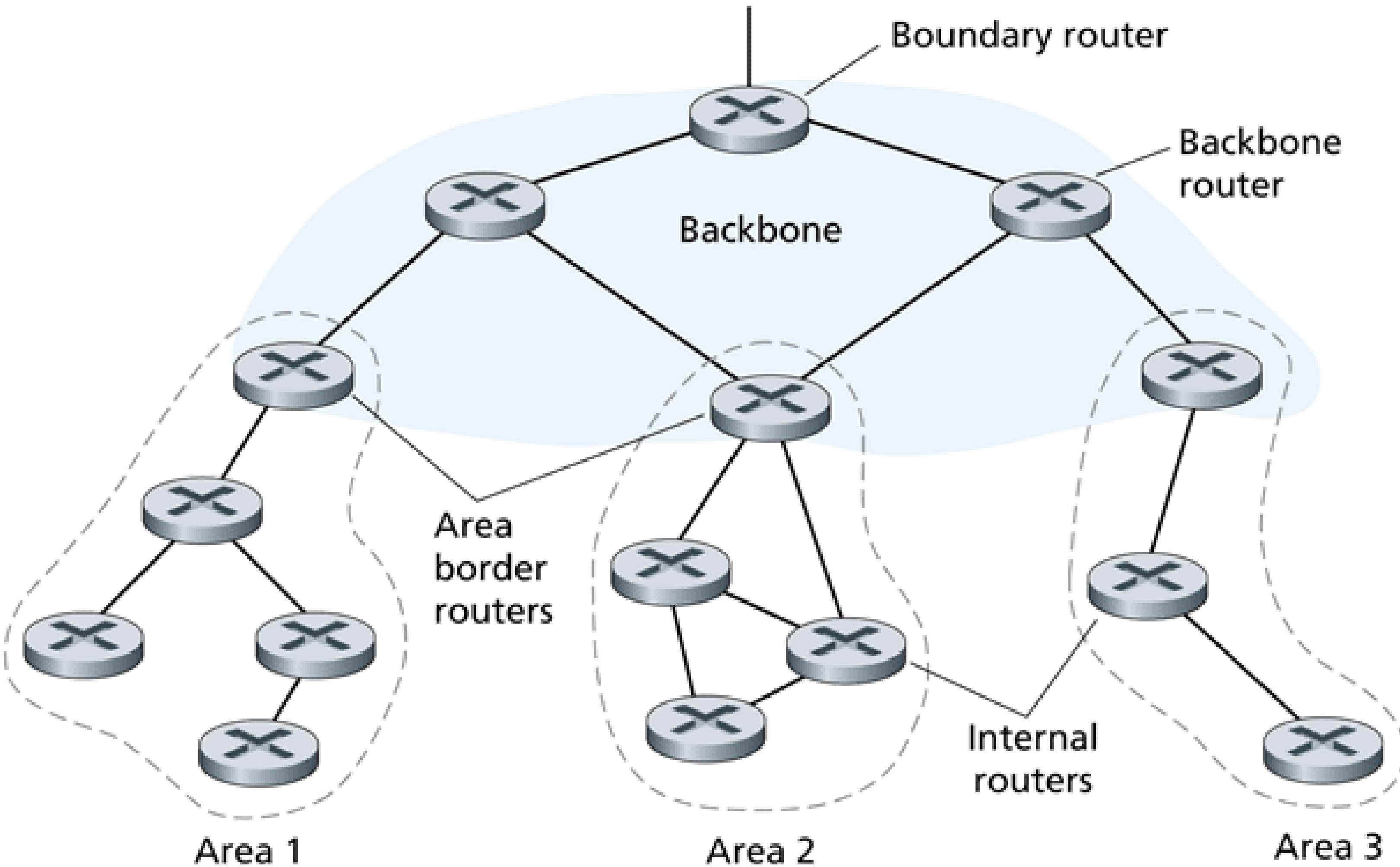
OSPFv2

- **Link state protocol**
- **Runs directly over IP (protocol 89)**
  - Has to provide its own reliability
- **All exchanges are authenticated**
- **Adds notion of *areas* for scalability**

OSPF Areas

- Area 0 is "backbone" area (includes all boundary routers)
- Traffic between two areas must always go through area 0
- Only need to know how to route exactly within area
- Otherwise, just route to the appropriate area
- Tradeoff: scalability versus optimal routes

OSPF Areas



Boundary router
Backbone router
Backbone
Area border routers
Internal routers
Area 1
Area 2
Area 3

Next Class

- **Inter-domain routing: how scale routing to the entire Internet**