

CSCI-1680

Network Layer:

Intra-domain Routing

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Today

- **Intra-Domain Routing**
- **Next class (next Thursday): Inter-Domain Routing**



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

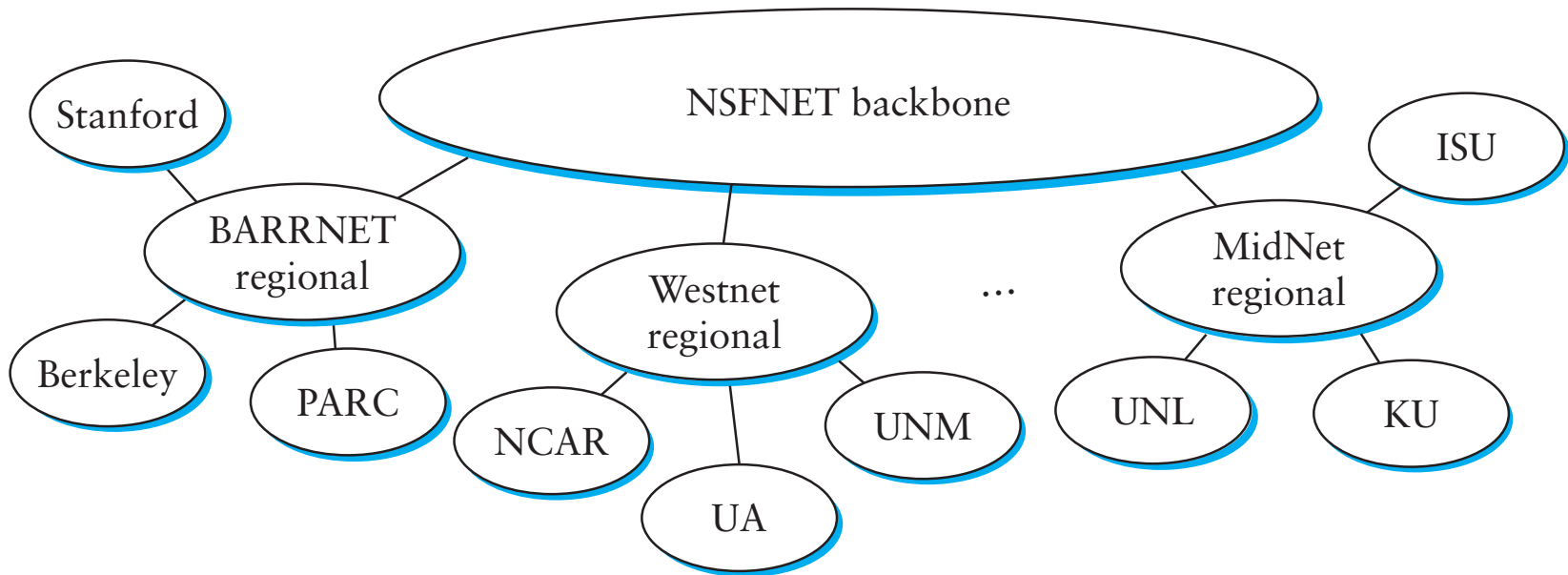


IP Connectivity

- **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)**



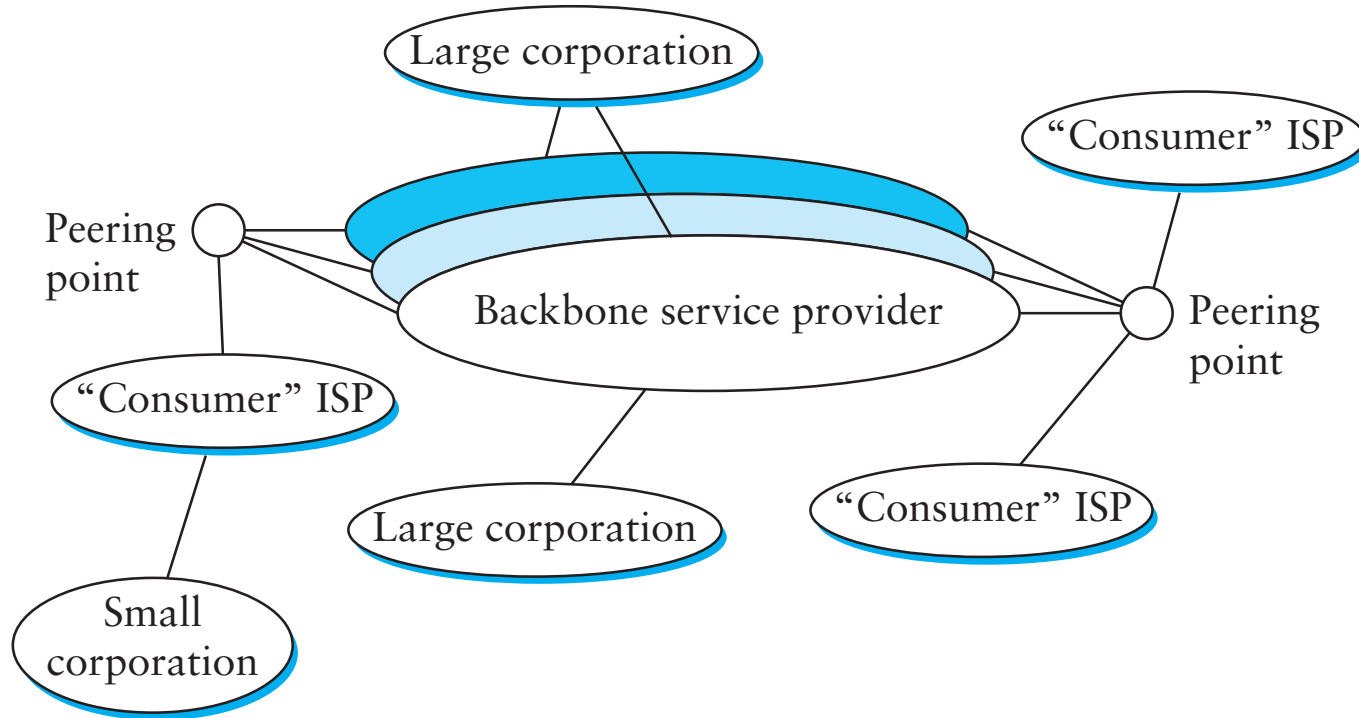
Internet structure, 1990



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



Internet structure, today



- **Multiple backbones, more arbitrary structure**

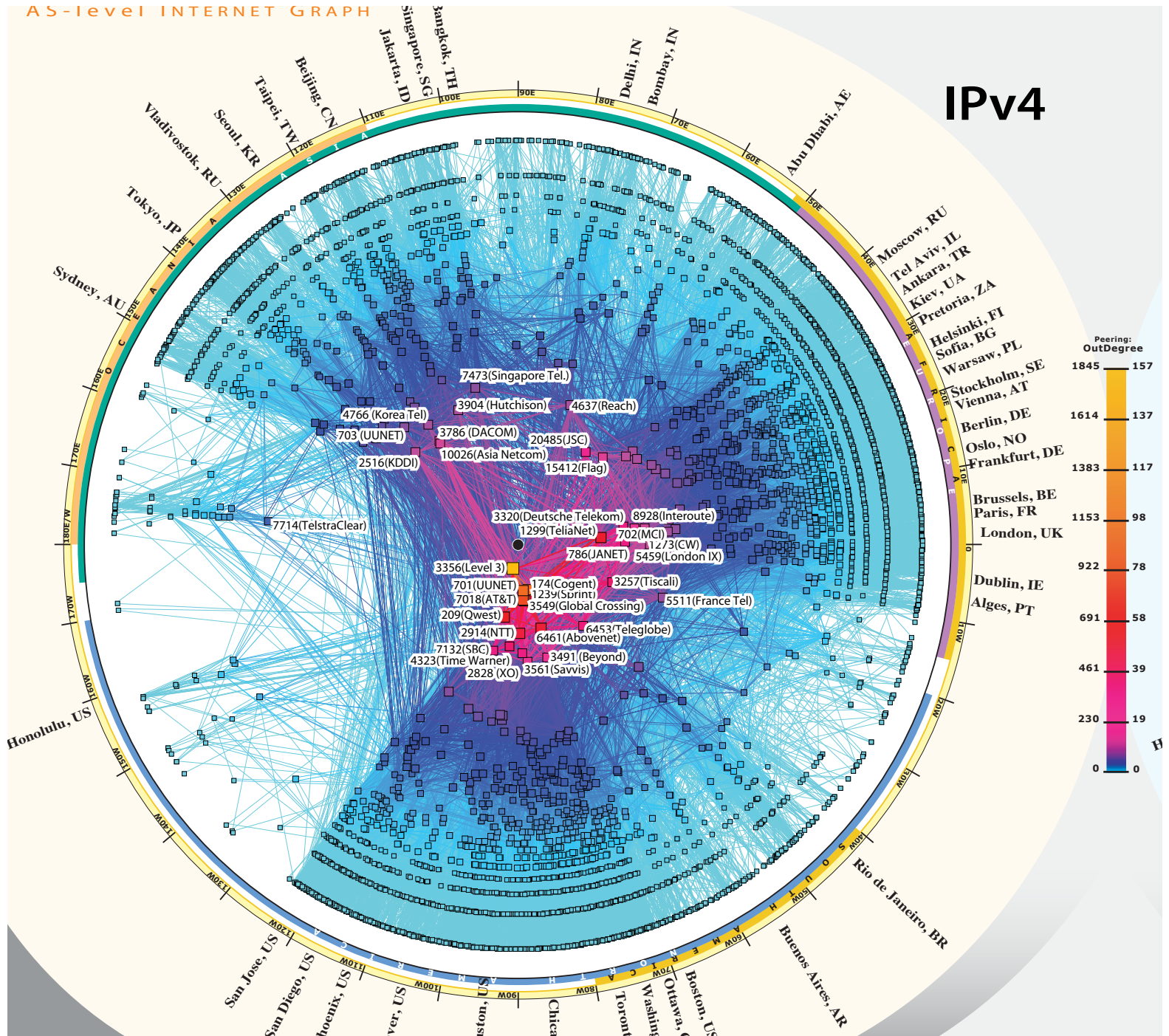


Autonomous Systems

- **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



IPv4



Inter and Intra-domain routing

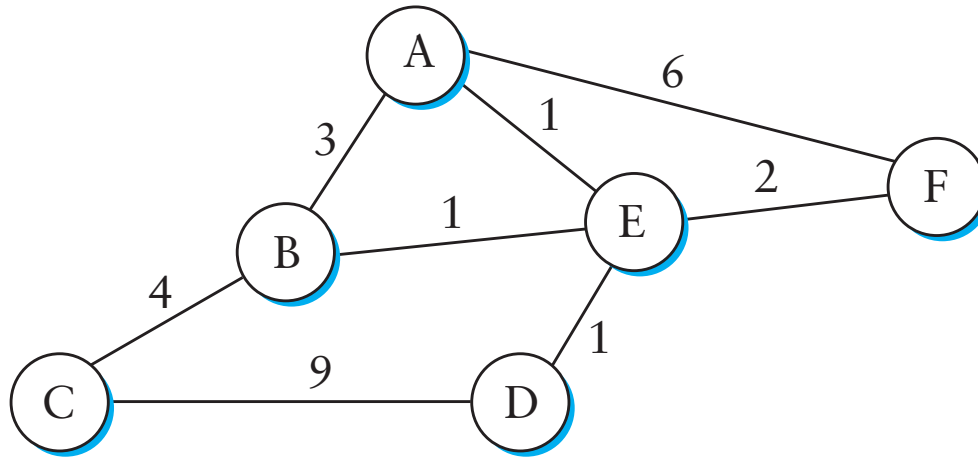
- **Routing organized in two levels**
- **Intra-domain routing**
 - Complete knowledge, strive for *optimal* paths
 - Scale to ~100 networks
 - Today
- **Inter-domain routing**
 - Aggregated knowledge, scale to Internet
 - Dominated by *policy*
 - E.g., route through X, unless X is unavailable, then 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 (Bellman-Ford SP Algorithm)**
 - Requires only local state
 - Harder to debug
 - Can suffer from loops
- **Link State (Dijkstra-Prim SP Algorithm)**
 - 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**
 - $\langle Destination, Cost, NextHop \rangle$
- **Exchange updates with neighbors**
 - Periodically (seconds to minutes)
 - Whenever table changes (*triggered* update)
- **Each update is a list of pairs**
 - $\langle Destination, Cost \rangle$
- **Update local table if receive a “better” route**
 - Smaller cost
- **Refresh existing routes, delete if time out**

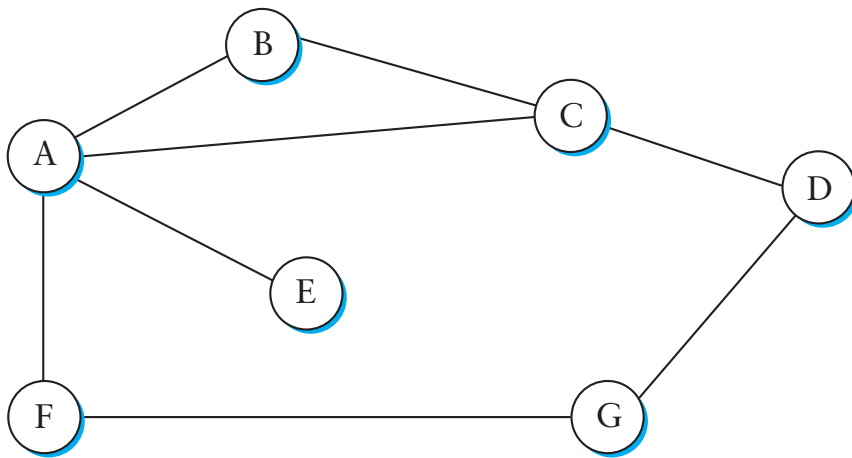


Calculating the best path

- **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

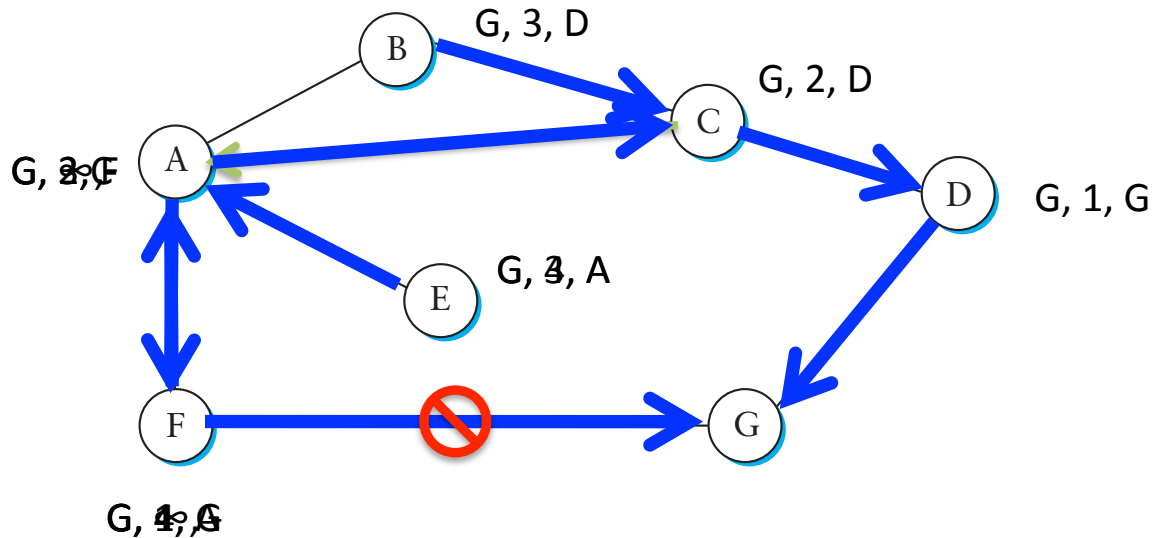


B's routing table

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



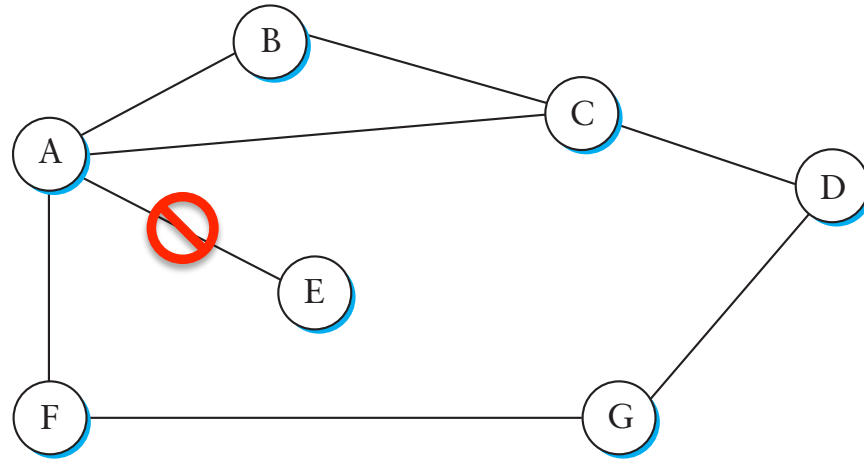
Adapting to Failures



- **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**



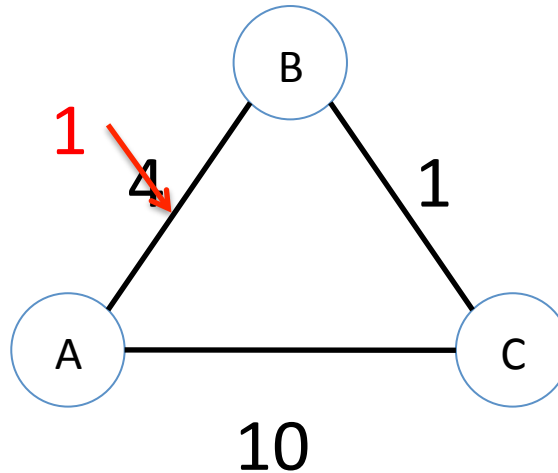
Count-to-Infinity



- **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?**



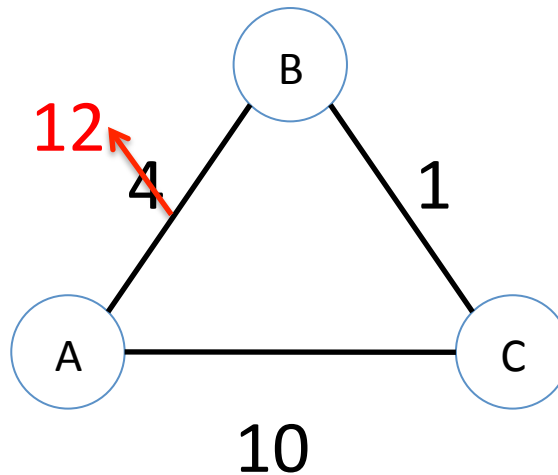
Good news travels fast



- A decrease in link cost has to be fresh information
- Network converges at most in $O(\text{diameter})$ 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 descendants
 - 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



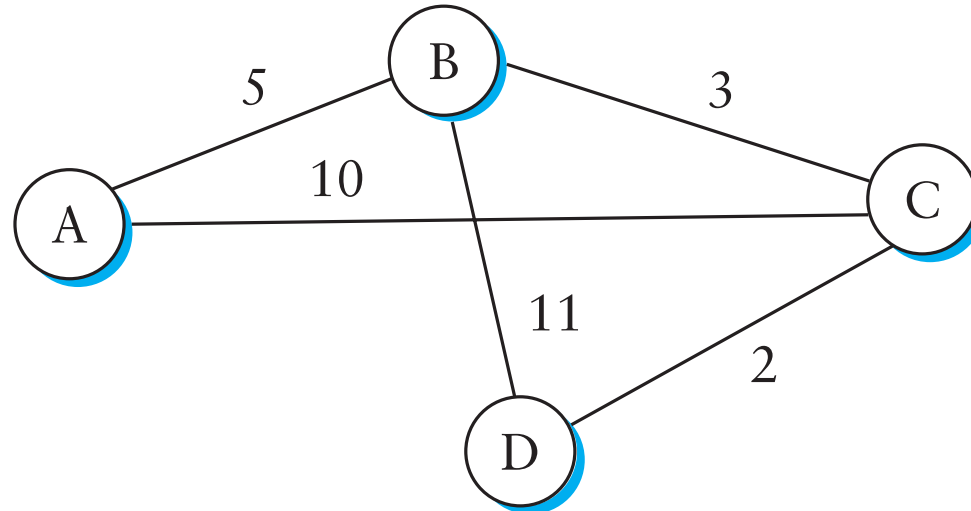
Calculating best path

- **Dijkstra's single-source shortest path algorithm**
 - Each node computes shortest paths from itself
- **Let:**
 - N denote set of nodes in the graph
 - $l(i,j)$ denote the non-negative link between i,j
 - ∞ if there is no direct link between i and j
 - $C(n)$ denote the cost of path from s to n
 - s denotes yourself (node computing paths)
- **Initialize variables**
 - $M = \{s\}$ (set of nodes incorporated thus far)
 - For each n in $N - \{s\}$, $C(n) = l(s,n)$
 - $\text{Next}(n) = n$ if $l(s,n) < \infty$, – otherwise



Dijkstra's Algorithm

- **While $N \neq M$**
 - Let $w \in (N-M)$ be the node with lowest $C(w)$
 - $M = M \cup \{w\}$
 - Foreach $n \in (N-M)$, if $C(w) + l(w,n) < C(n)$
then $C(n) = C(w) + l(w,n)$, $\text{Next}(n) = \text{Next}(w)$
- **Example: D: (D,0,-) (C,2,C) (B,5,C) (A,10,C)**



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
$$\text{Delay} = (\text{DT} - \text{AT}) + \text{Transmit} + \text{Latency}$$
 - 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)

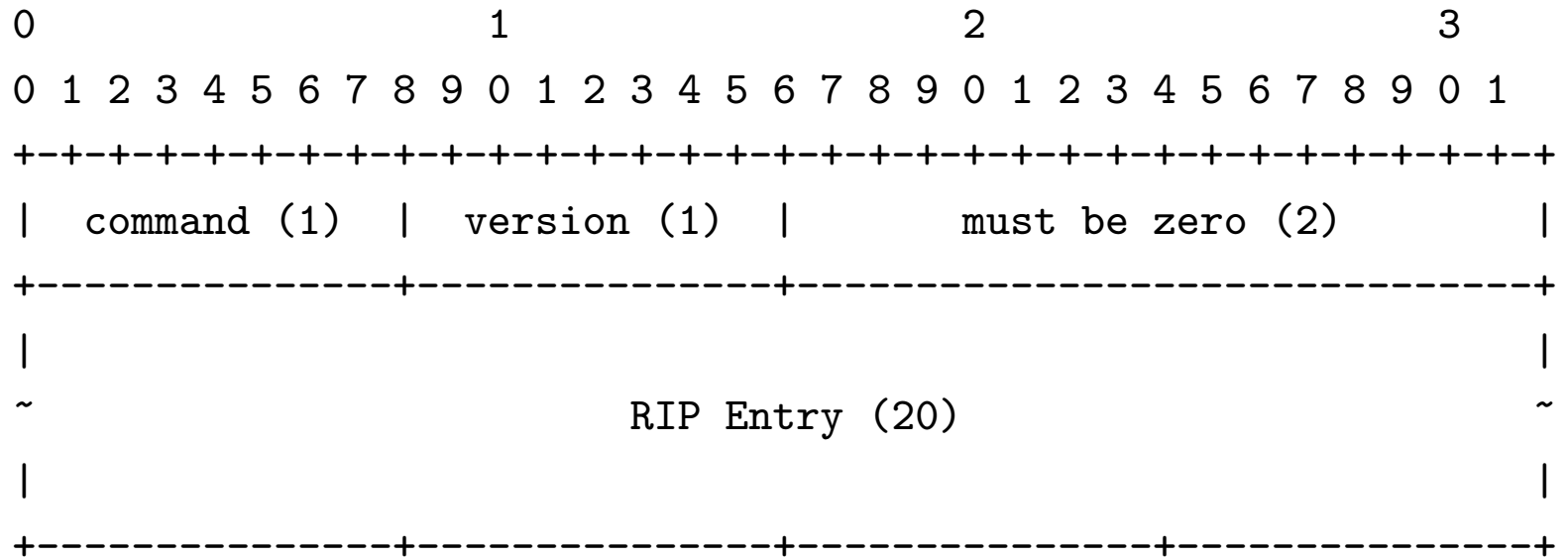


RIPv2

- **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 ($\infty = 16$)
 - Supports split horizon, poison reverse
- **Deletion**
 - If you receive an entry with metric = 16 OR
 - If a route times out



Packet format



Route Tag field

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



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**

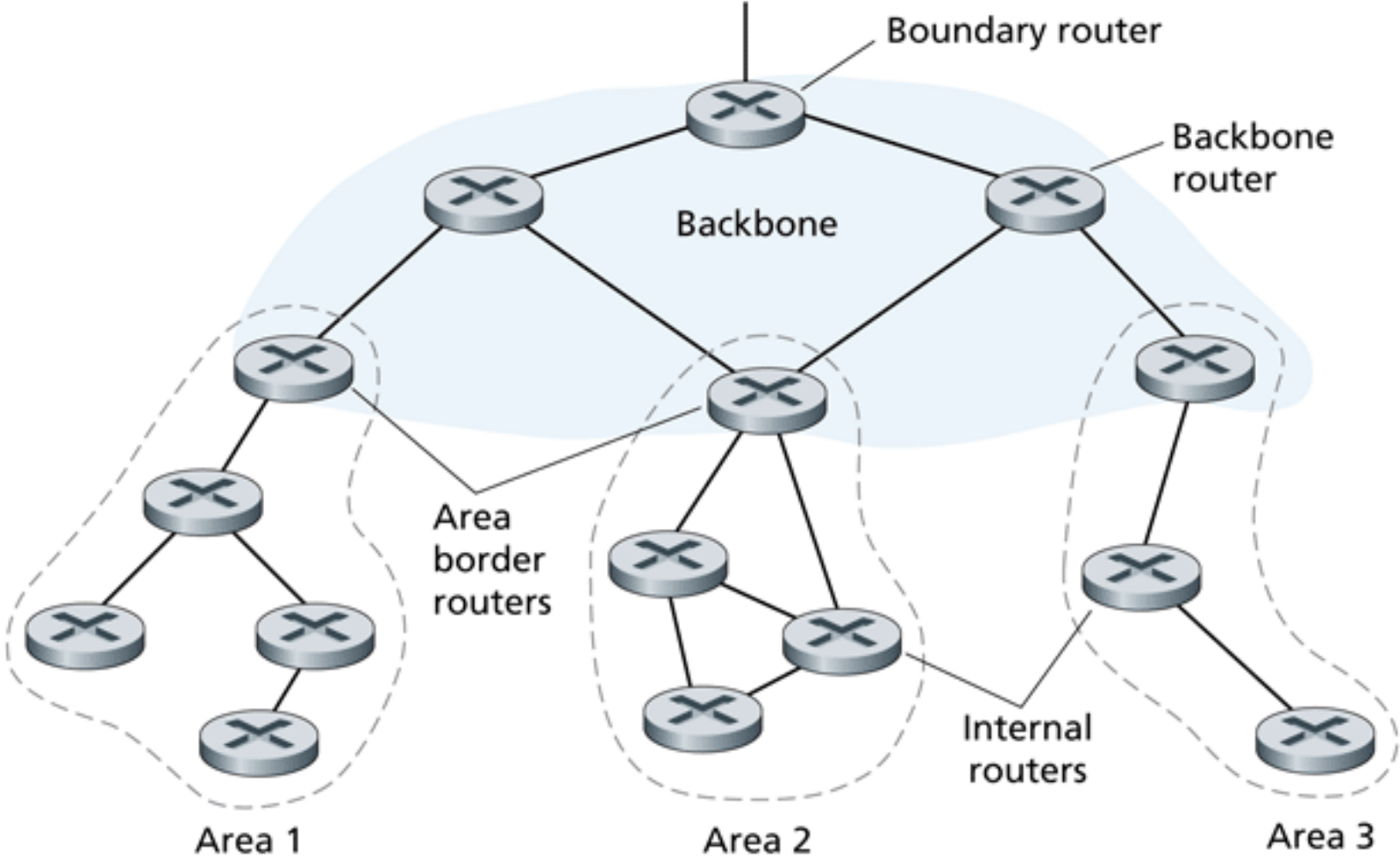


OSPF Areas

- **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



Next Class

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

