CSCI-1680
Network Layer:
Intra-domain Routing

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

Administrivia

- IP milestone meetings: Should meet with staff on/before October 6 (TOMORROW)
  - Sign up link via email
  - Can't find a time? Make a private post on Ed!

- IP Gearup II tonight (10/5) 5-7pm, CIT368
  - Implementation/debugging stuff; bring questions!

- HW1 due tonight; HW2 out after this class or next class

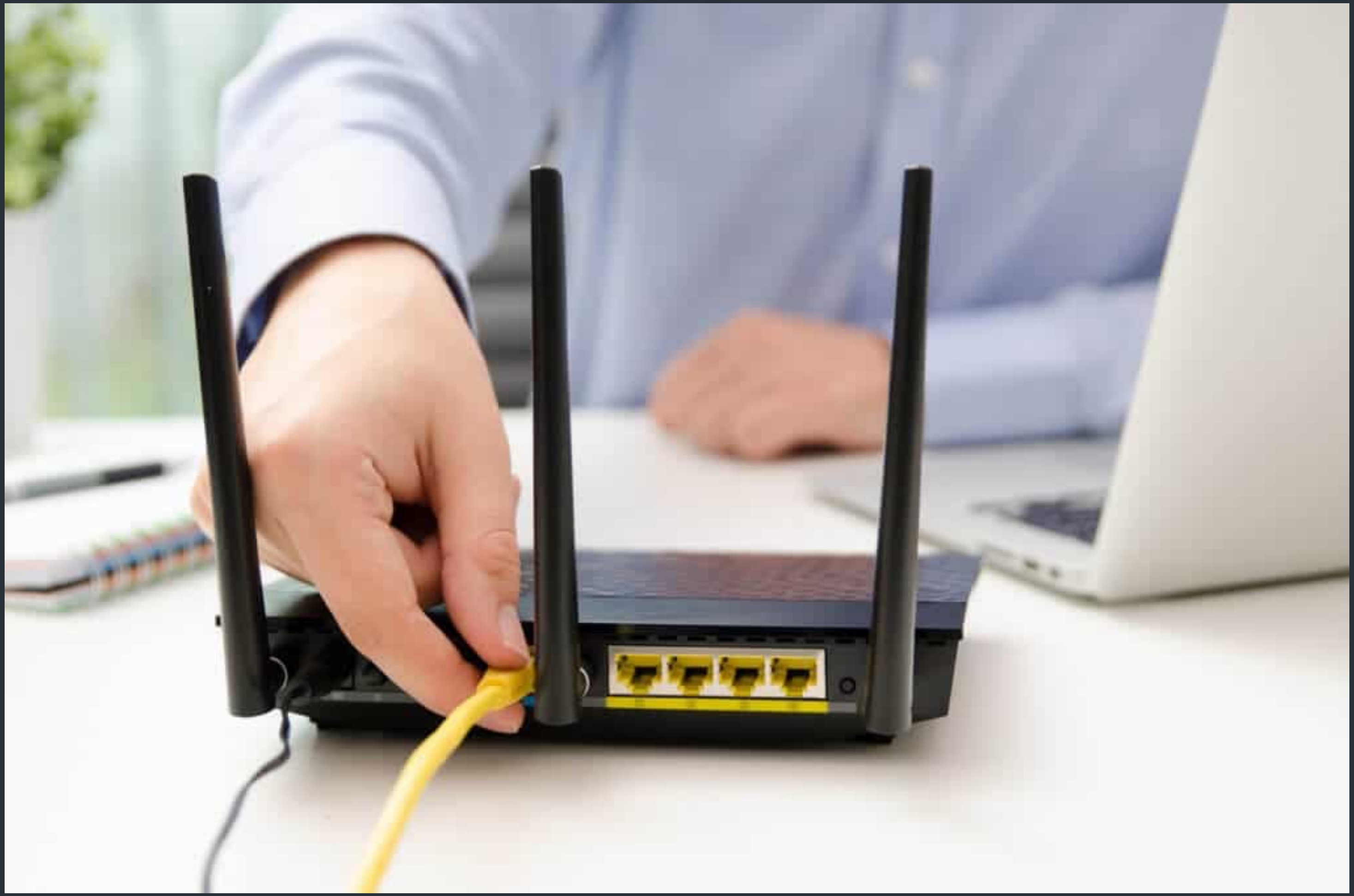
Today

Two things

- More on NAT
- Intro to routing, RIP

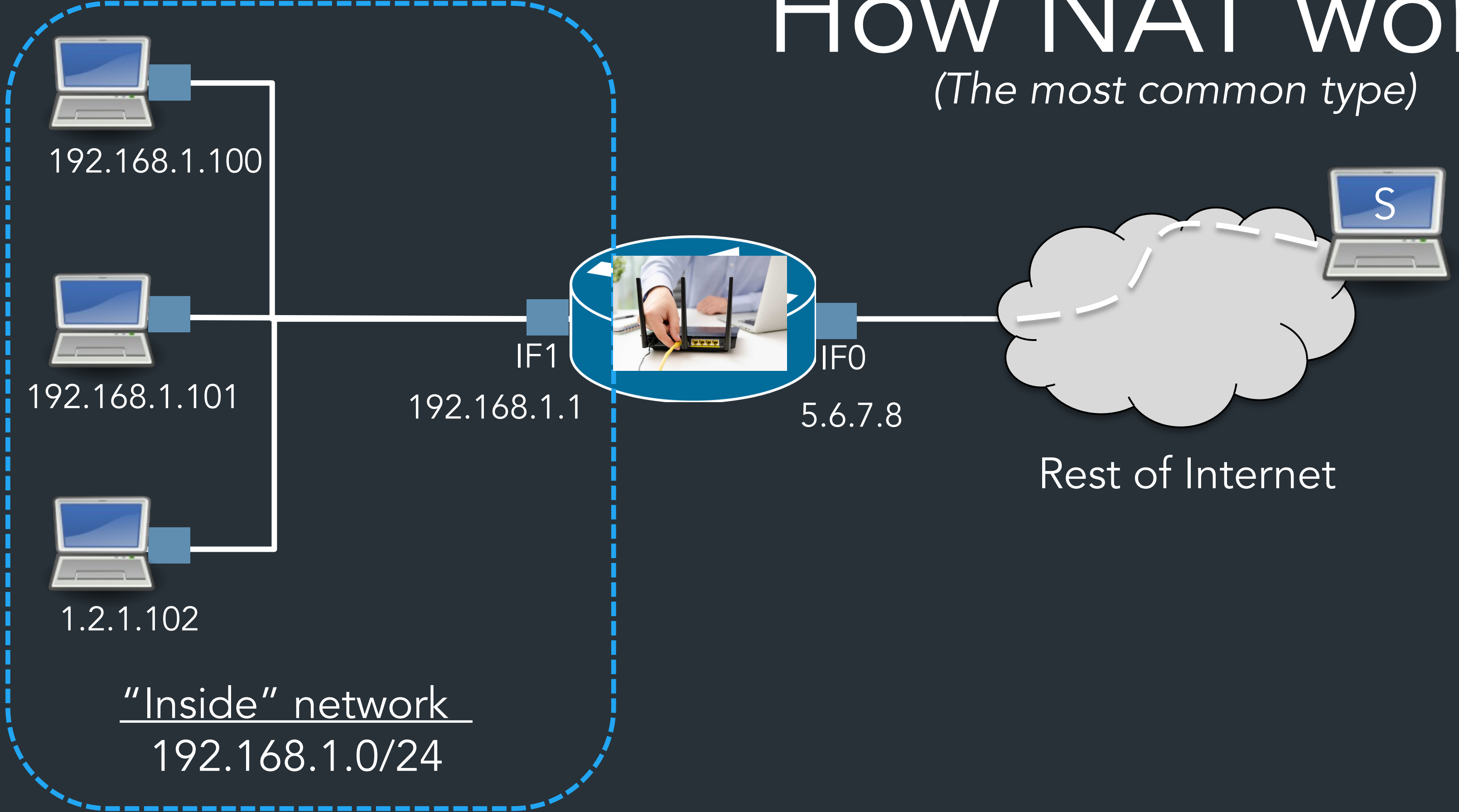
Network Address Translation (NAT)

Story time



How NAT works

(The most common type)



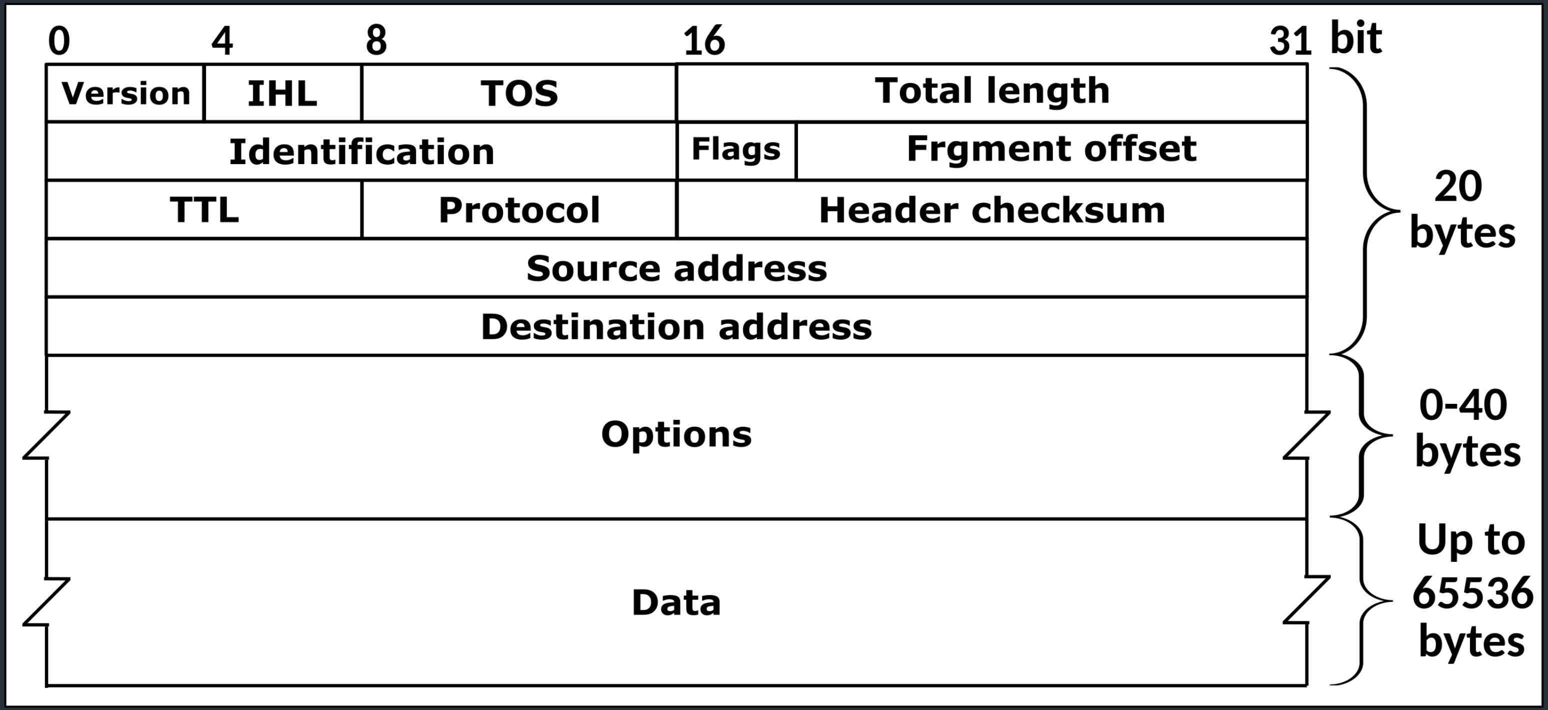
Goal: Share one IP among many hosts on a private network

Router *translates (modifies) packets from "inside" to use "outside" address*

=> Router needs to remember connection state

=> Router makes some (sketchy) assumptions about traffic

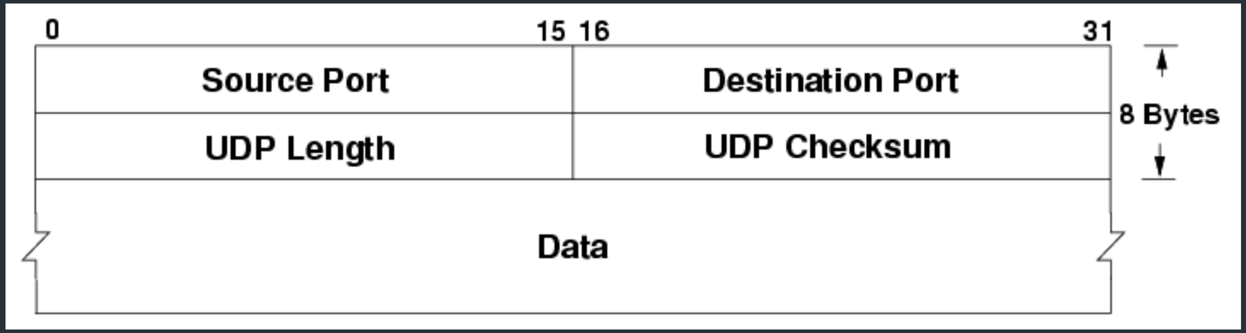
IP Header



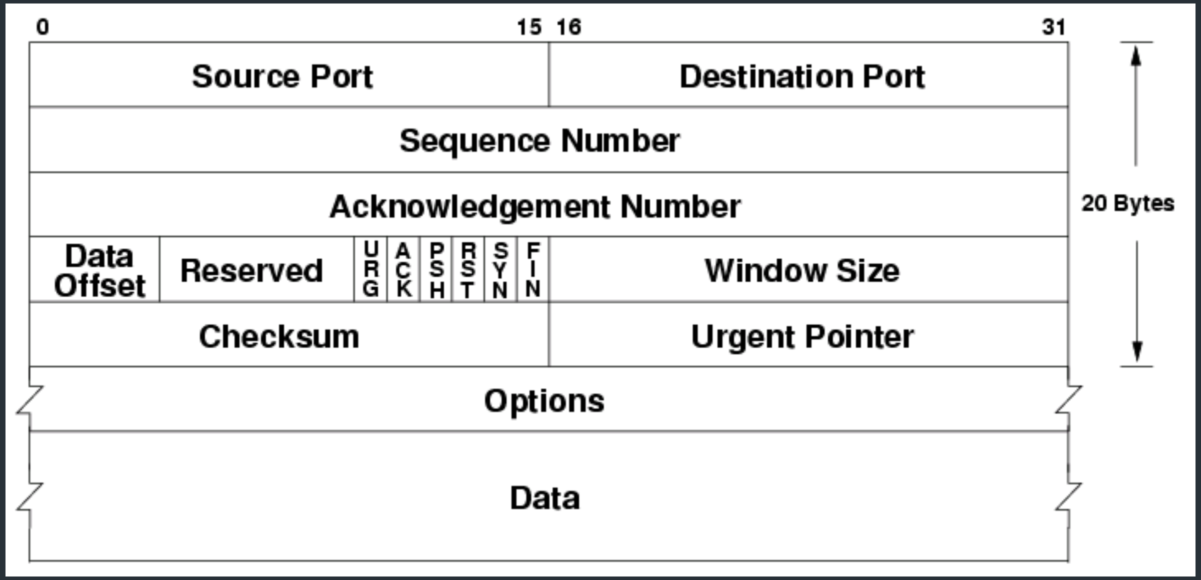
Where are the port numbers?????

… ports are actually part of the transport layer header!

UDP



TCP

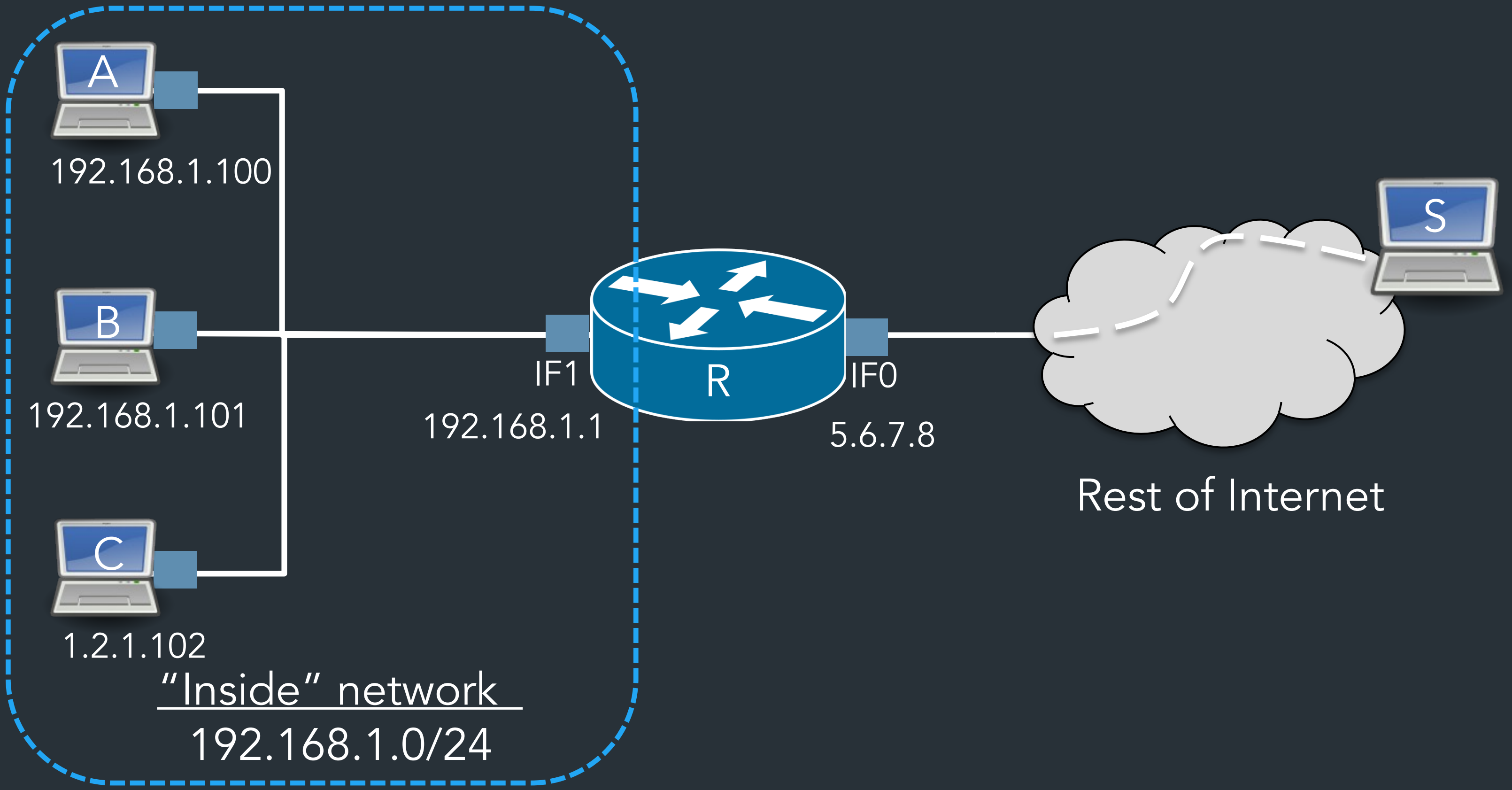


Problem?

⇒ Technically a violation of layering! Network layer shouldn't care about port numbers, but here it matters

⇒ NAT needs to know semantics of TCP/UDP (how connections start/end…

…but wait there's more…



What happens when outside host S wants to connect to inside host A?

Can't do it (at least without special setup)!
⇒ By default, R only knows how to translate packets for connections originating from INSIDE the network
⇒ Breaks end to end connectivity!!!

End to end connectivity, you say?

Breaking end-to-end connectivity?

Why is this bad?

NAT is used in just about every consumer network

- Generally: can't connect directly to an end host unless it connects to you first

- Need extra work for any protocols that need a direct connection between hosts

=> When do we need this?

Why is this bad?

NAT is used in just about every consumer network

- Generally: can't connect directly to an end host unless it connects to you first

- Need extra work for any protocols that need a direct connection between hosts

⇒ Protocols that aren't strictly client-server
⇒ Latency critical applications: voice/video calls, games

NAT Traversal

Various methods, depending on the type of NAT

Examples:

- Manual method: port forwarding
- ICE: Interactive Connectivity Establishment (RFC8445)
- STUN: Session Traversal Utilities for NAT (RFC5389)

One idea: connect to external server via UDP, it tells you the address/port

Routing

Challenges in moving packets

- Forwarding: given a packet, decide which interface to send the packet (based on IP destination)

- Routing: network-wide process of determining a packet's path through the network

  => How each router builds its forwarding table

Routing

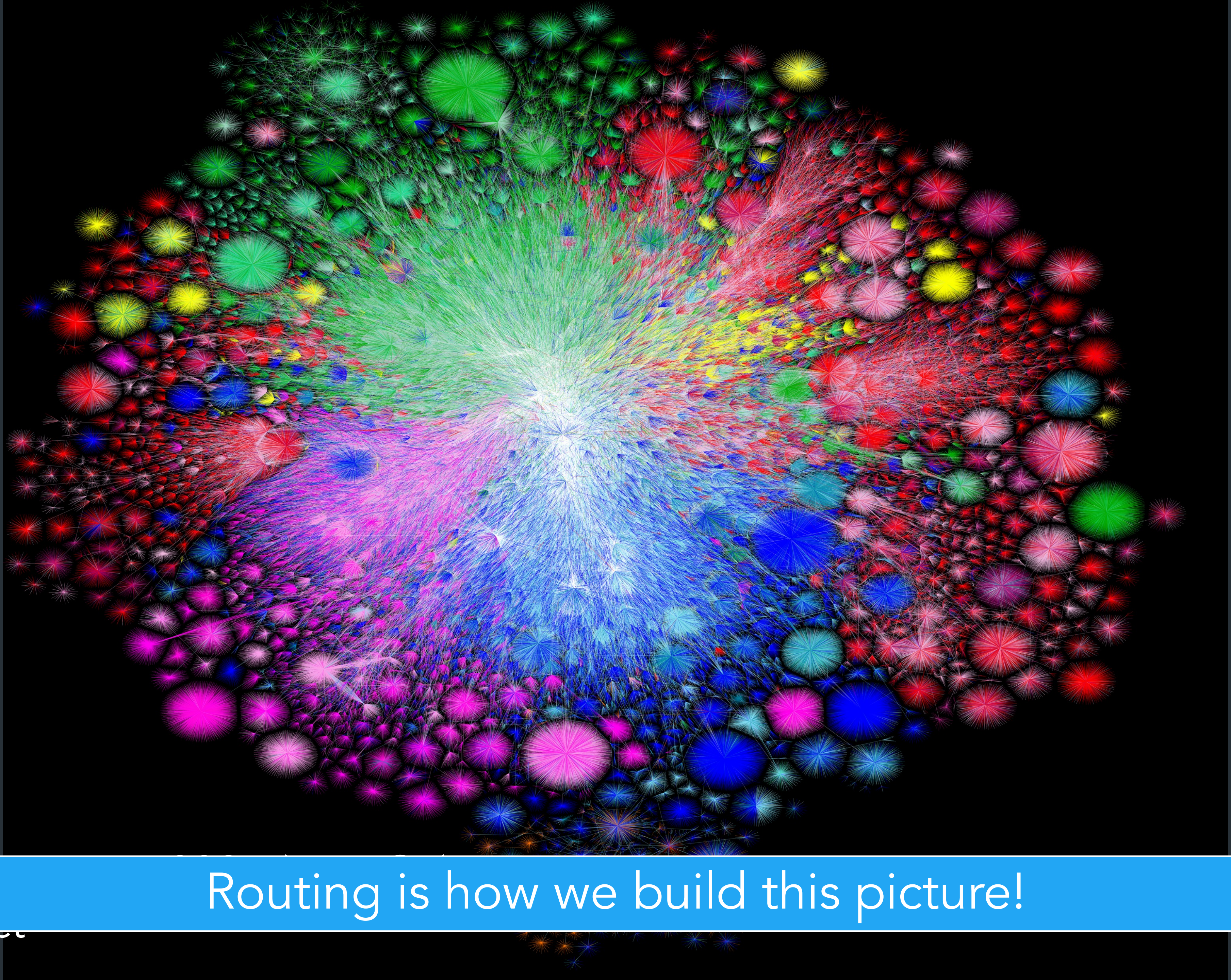
Routing is the process of updating forwarding tables

- Routers exchange messages about networks they can reach

Goal: find optimal route (or *any* route…) for every other destination

This is a hard problem

- Decentralized
- Topology always changing
- Scale!



Map of th
OPTE proj

Routing is how we build this picture!

How do we connect *everything*?

Relies on hierarchical nature of IP addressing

- Smaller routers don’t need to know everything, just another router that knows more

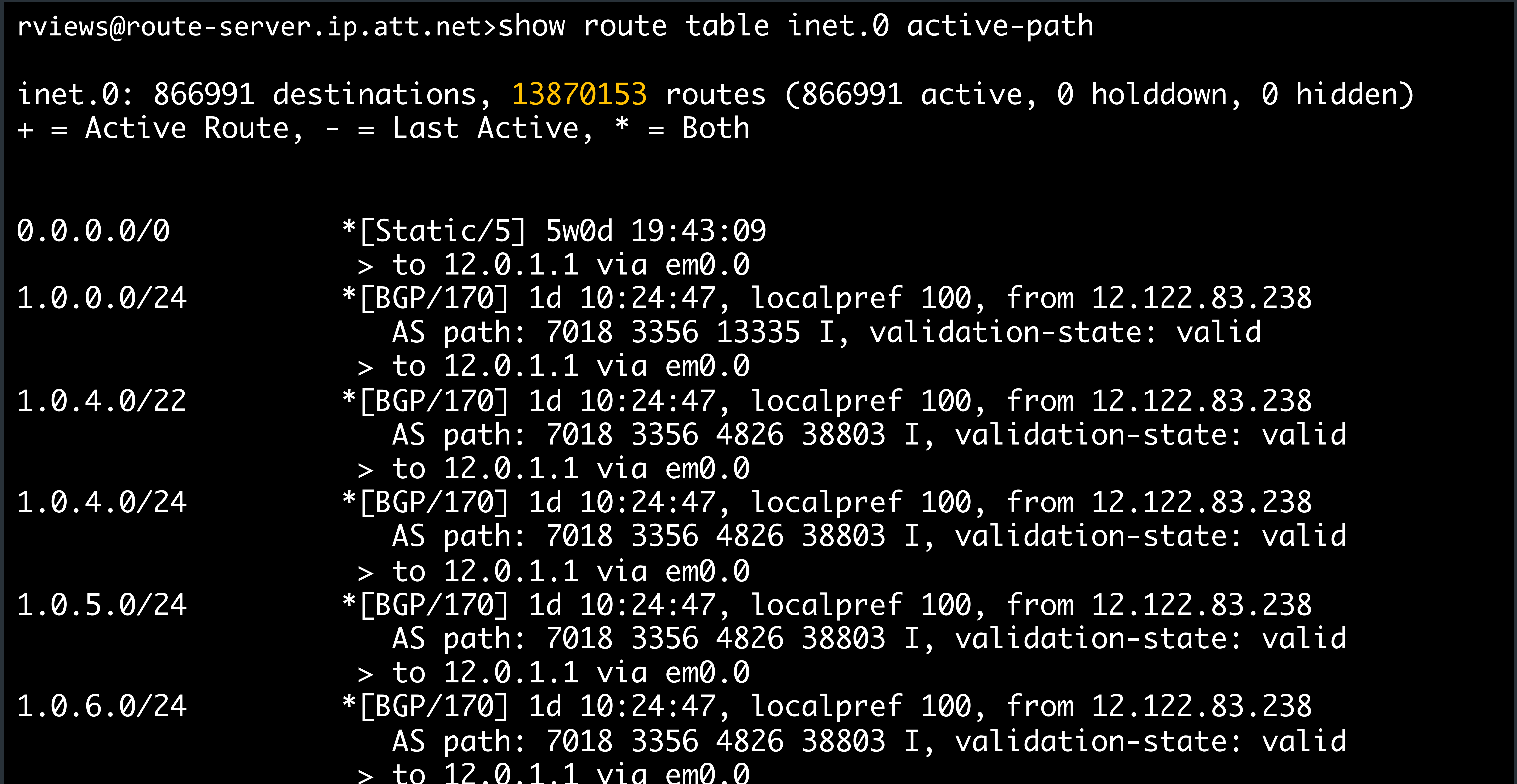
  ⇒ Has default route

- Core routers know everything => no default!

A forwarding table (my laptop)

```
deemer@ceres ~ % ip route
default via 10.3.128.1 dev wlp2s0
10.3.128.0/18 dev wlp2s0 proto dhcp scope link src 10.3.135.44 metric 3003
172.18.0.0/16 dev docker0 proto kernel scope link src 172.18.0.1
192.168.1.0/24 dev enp0s31f6 proto kernel scope link src 192.168.1.1
```

A large table



```
rviews@route-server.ip.att.net>show route table inet.0 active-path

inet.0: 866991 destinations, 13870153 routes (866991 active, 0 holddown, 0 hidden)
+ = Active Route, - = Last Active, * = Both


0.0.0.0/0          *[Static/5] 5w0d 19:43:09
                    > to 12.0.1.1 via em0.0
1.0.0.0/24         *[BGP/170] 1d 10:24:47, localpref 100, from 12.122.83.238
                      AS path: 7018 3356 13335 I, validation-state: valid
                    > to 12.0.1.1 via em0.0
1.0.4.0/22         *[BGP/170] 1d 10:24:47, localpref 100, from 12.122.83.238
                      AS path: 7018 3356 4826 38803 I, validation-state: valid
                    > to 12.0.1.1 via em0.0
1.0.4.0/24         *[BGP/170] 1d 10:24:47, localpref 100, from 12.122.83.238
                      AS path: 7018 3356 4826 38803 I, validation-state: valid
                    > to 12.0.1.1 via em0.0
1.0.5.0/24         *[BGP/170] 1d 10:24:47, localpref 100, from 12.122.83.238
                      AS path: 7018 3356 4826 38803 I, validation-state: valid
                    > to 12.0.1.1 via em0.0
1.0.6.0/24         *[BGP/170] 1d 10:24:47, localpref 100, from 12.122.83.238
                      AS path: 7018 3356 4826 38803 I, validation-state: valid
                    > to 12.0.1.1 via em0.0
```

Thinking about the scale

At this stage, we think about routing to *whole networks*, ie, some entity with some set of IP prefixes:

eg. Brown University @ 128.148.0.0/16, 138.16.0.0/16

We call each entity an Autonomous System (AS):
a single administrative domain that lives on the Internet

Routing is organized in two levels:

- Intra-domain (interior) routing: routing within an AS

- Inter-domain (exterior) routing: routing between ASes

Routing is organized in two levels:

- Intra-domain (interior) routing: routing within an AS

  => Full knowledge of the network inside the AS
  => One administrator, routing policy
  => Strive for optimal paths

^ We are here today

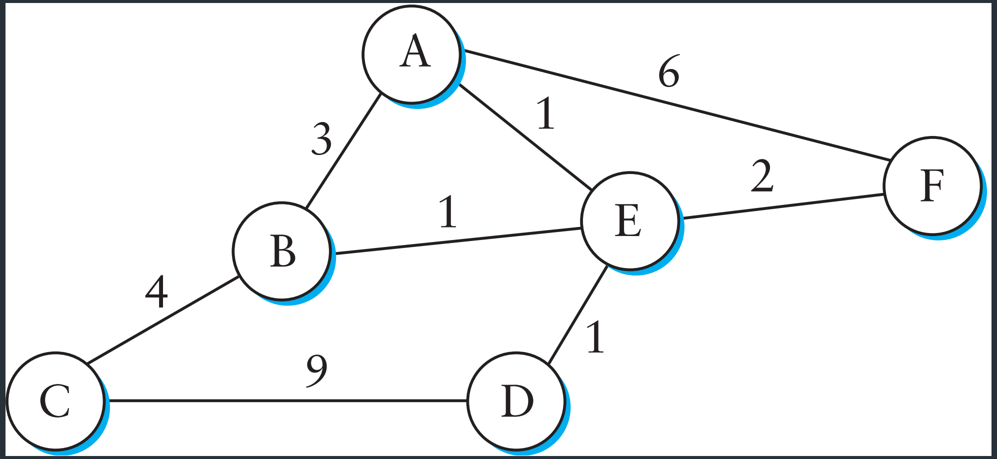
- Inter-domain (exterior) routing: routing between ASes

  => None of the above, decisions instead made by *policy* (later)

Intra-Domain (Interior) Routing

Typically, view network as a graph

- Nodes are routers
- Assign some *cost* to each edge
  - latency, b/w, queue length, …



Goal: find lowest-cost path between nodes

- Each node individually computes routes

Collect routes into a *routing table*, used to generate the forwarding table based on lowest-cost path

Two classes of intra-domain routing algorithms

- Distance Vector (Bellman-Ford shortest path algorithm)
  - Each node gets updates only from neighbors
  - Can suffer from loops

- Link State (Djikstra/Prim shortest path algorithm)
  - Each node has global view of the network
  - Requires global state

Distance Vector Routing

Dest.	Cost	Next Hop
A	3	S
B	4	T
C	5	S
D	6	U

- Each node maintains a routing table
- Exchange *updates* with neighbors about node's links:
  => List of <Destination, Cost> pairs
- When to send updates?
  - Periodically (seconds to minutes)
  - Whenever table changes (*triggered* update)
  - Time out an entry if no updates within some time interval

Distance Vector: Update rules

Say router R receives an update <D, c_D> from neighbor N at cost C_N

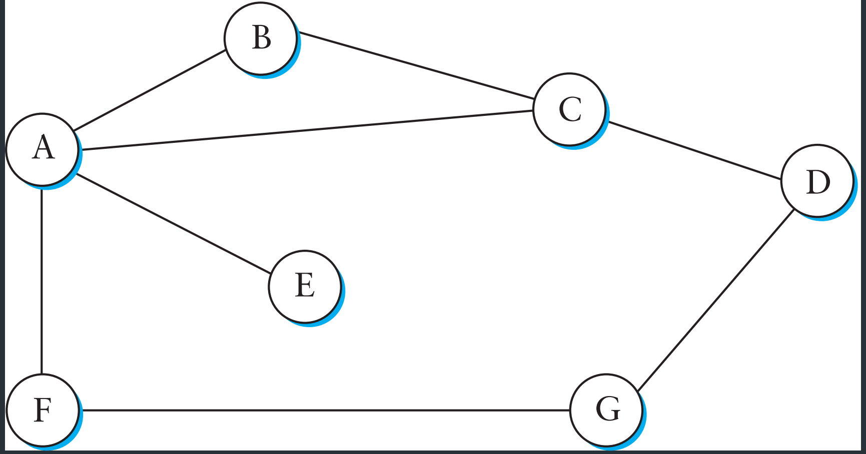
=> Know: R can reach D via N with cost $c = c_D + c_N$

How to update table?

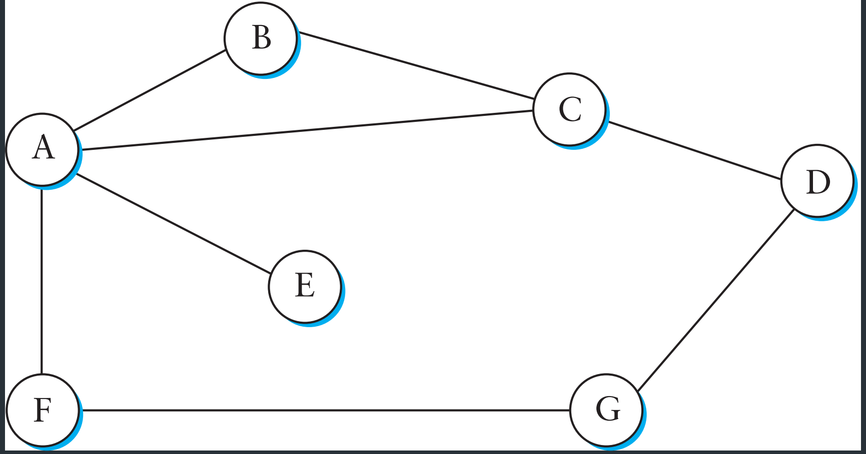
1. If D not in table, add <D, c, N> (New route!)
2. If table has entry <D, M, c_{old}>:
   - if $c < c_{old}$: update table to <D, c, M>. (Lower cost!)
   - if $c > c_{old}$ and M == N: update table to <D, c, N> (Cost increased!)
   - if $c > c_{old}$ and M != N: ignore (N is better)
   - if $c == c_{old}$ and M ==N: no change (No new info)

     (Just refresh timeout)

DV Example



DV Example



B's routing table

Dest.	Cost	Next Hop
(B)	(0)	(B)
A	1	A
C	1	C
D	2	C
E	2	A
F	2	A
G	3	A

Warmup

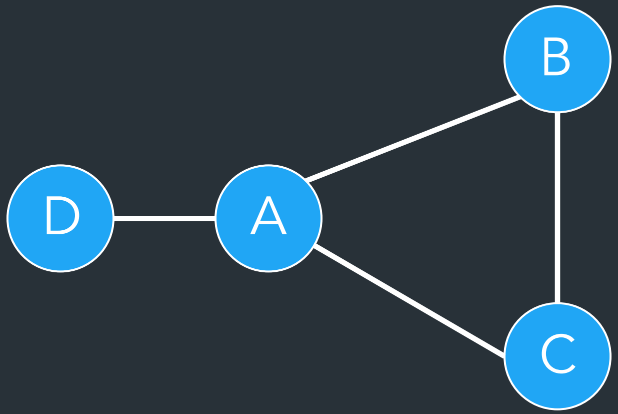
Suppose router R has the following table:

Dest.	Cost	Next Hop
A	3	S
B	4	T
C	5	S
D	6	U

What happens when it gets this update from router S?

Dest.	Cost
A	2
B	3
C	5
D	4
E	2

Dealing with Failures



- What happens when the D-A link fails?

=> "Count to Infinity" problem

How to avoid loops

- Does IP TTL help?
- 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

One way: Split Horizon

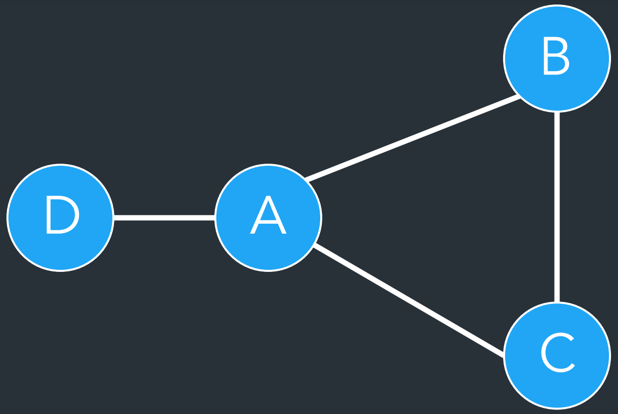
- When sending updates to node A, don’t include routes you learned from A
- Prevents B and C from sending cost 2 to A

Split Horizon + Poison Reverse

- Rather than not advertising routes learned from A, explicitly include cost of ∞.
- Faster to break out of loops, but increases advertisement sizes

Distance-vector updates

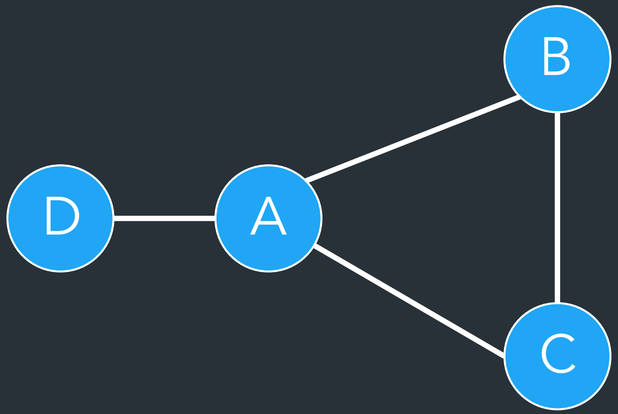
Even with split horizon + poison reverse, can still create loops with >2 nodes



What else can we do?

- Triggered updates: send update as soon as link state changes
- Hold down: delay using new routes for certain time, affects convergence time

Practice



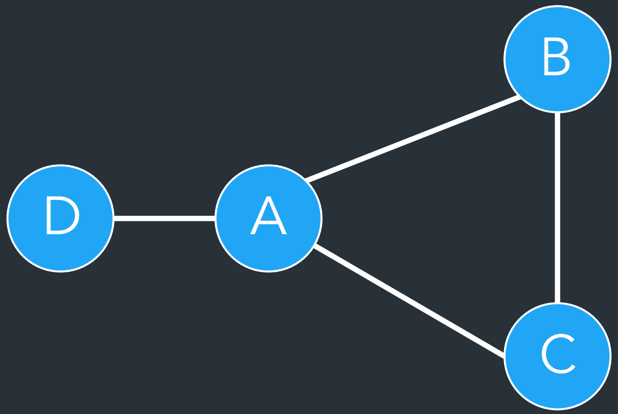
B's routing table

Dest.	Cost	Next Hop
A	1	A
C	1	C
D	2	A

Routers A,B,C,D use RIP. When B sends a periodic update to A, what does it send…

- When using standard RIP?
- When using split horizon + poison reverse?

Dealing with failures



- What happens when the D-A link fails?

Link State Routing

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

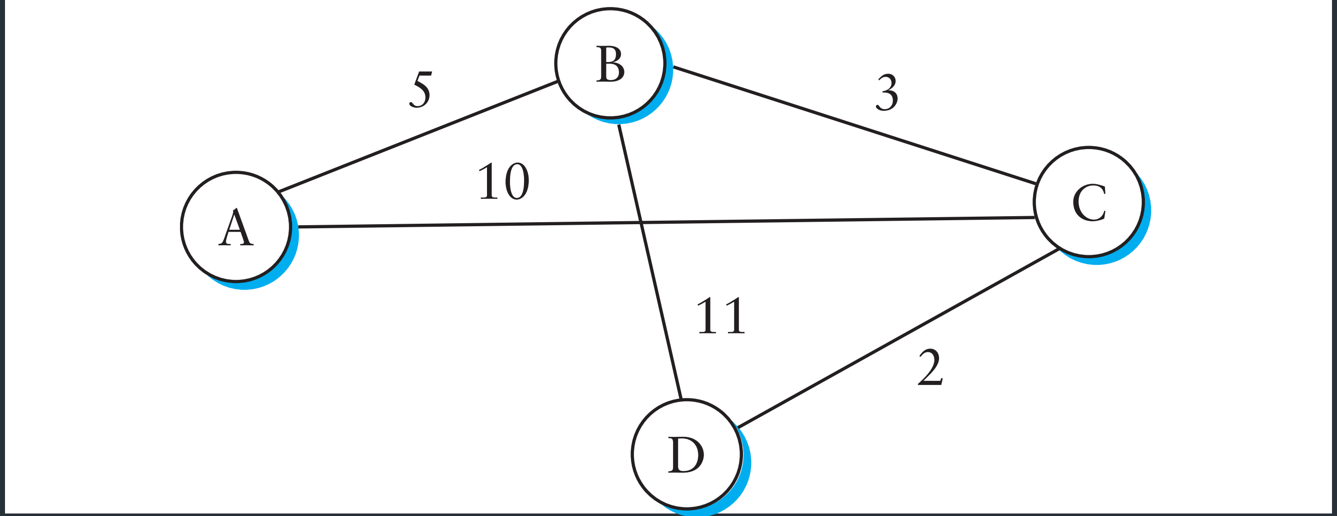
- Store most recent LSP from each node
  - Ignore earlier versions of the same LSP
- Forward LSP to all nodes but the one that sent it
- Generate new LSP periodically
  - Increment SEQNO
- Start at SEQNO=0 when reboot
  - If you hear your own packet with SEQNO=n, set your next SEQNO to n+1
- Decrement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

Calculating best path

- Djikstra’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
  - s denotes yourself (node computing paths)
  - C(n) denote the cost of path from s to n
- Initialize variables
  - M = {s} (set of nodes incorporated thus far)
  - For each n in N-{s}, C(n) = l(s,n)
  - Next(n) = n if l(s,n) < ∞, – otherwise

Djikstra'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 $C(n) = C(w) + l(w,n)$, $Next(n) = Next(w)$
- 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, which 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)
- ISIS (Intermediate System to Intermediate System)
  - OSI standard (210 pages)
  - Link-state protocol (similar to OSPF)
  - Does not depend on IP

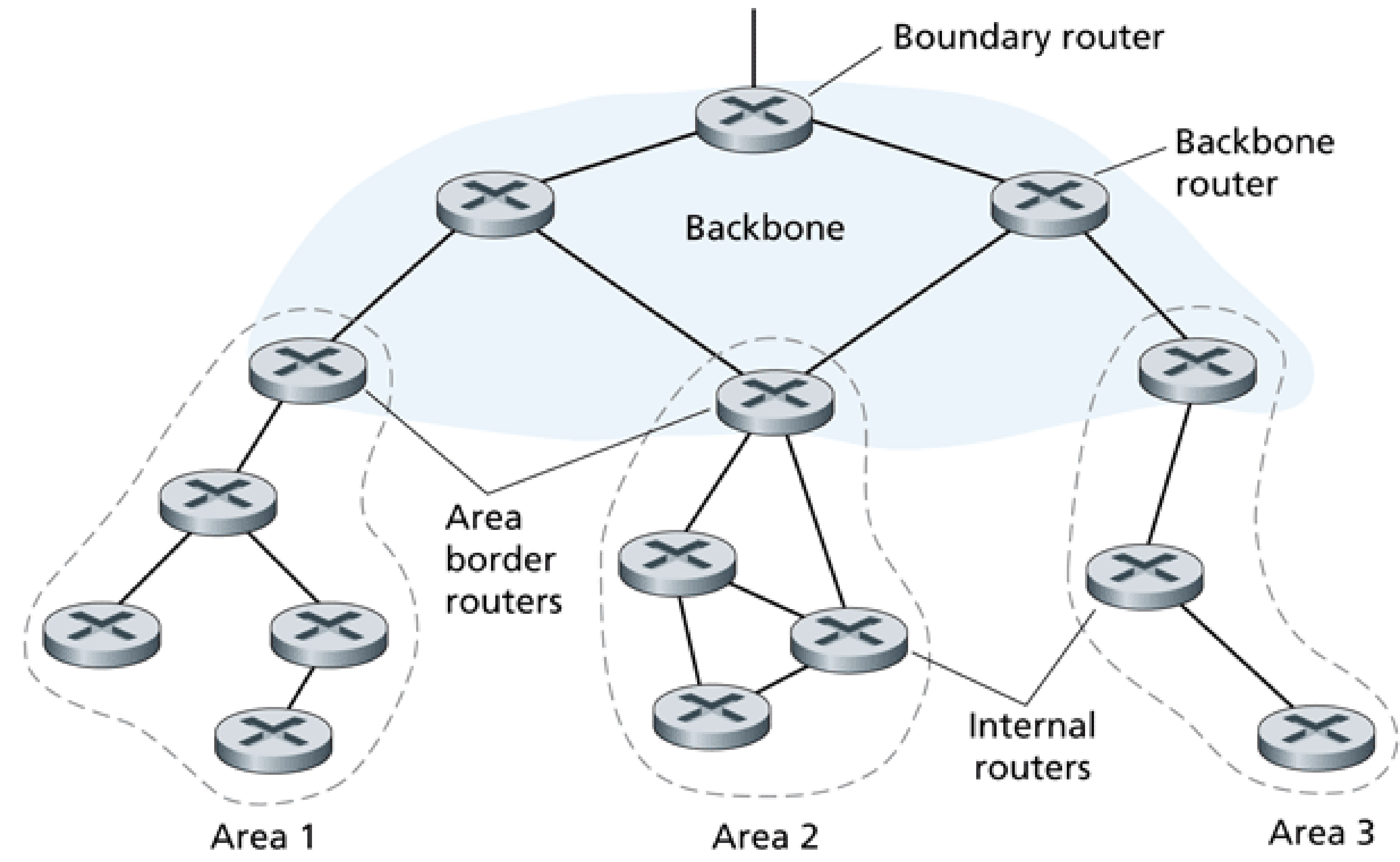
OSPFv2

- Link state protocol
- Runs directly over IP (protocol 89)
  - Must 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

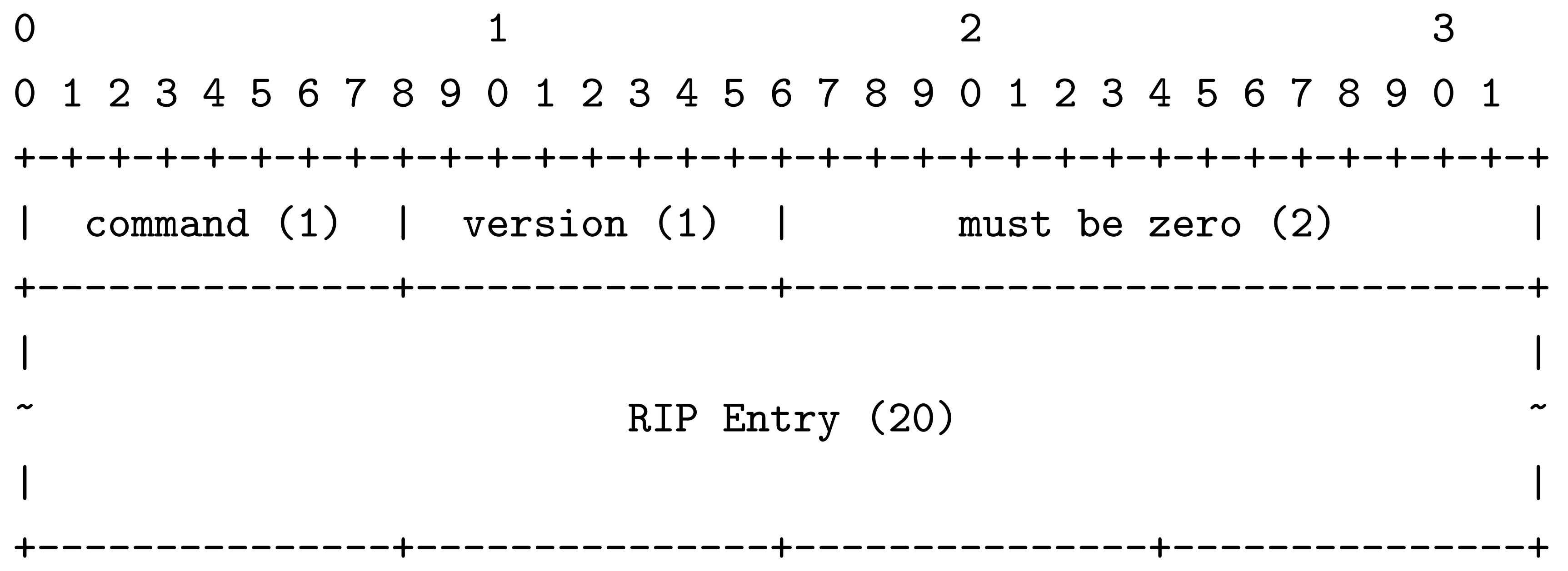
OSPF Areas


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

RIPv2

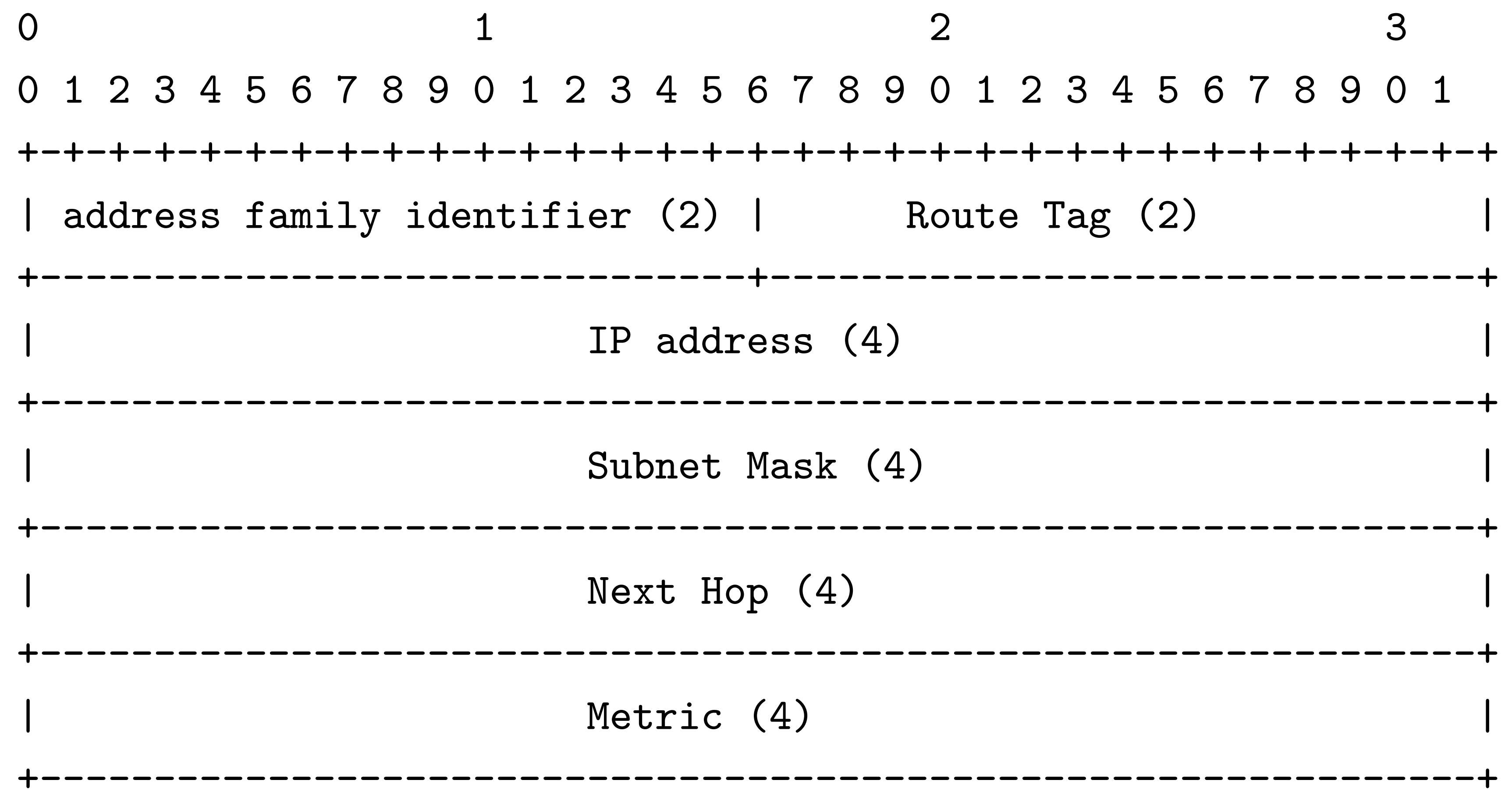
- Runs on UDP port 520
  - (IP assignment: directly in IP, protocol 200)
- Link cost = 1
- Periodic updates every 30s, plus triggered updates
- Relies on count-to-infinity to resolve loops
  - Maximum diameter 15 (∞ = 16)
  - Supports split horizon, poison reverse
- Deletion
  - If you receive an entry with metric = 16 from parent 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



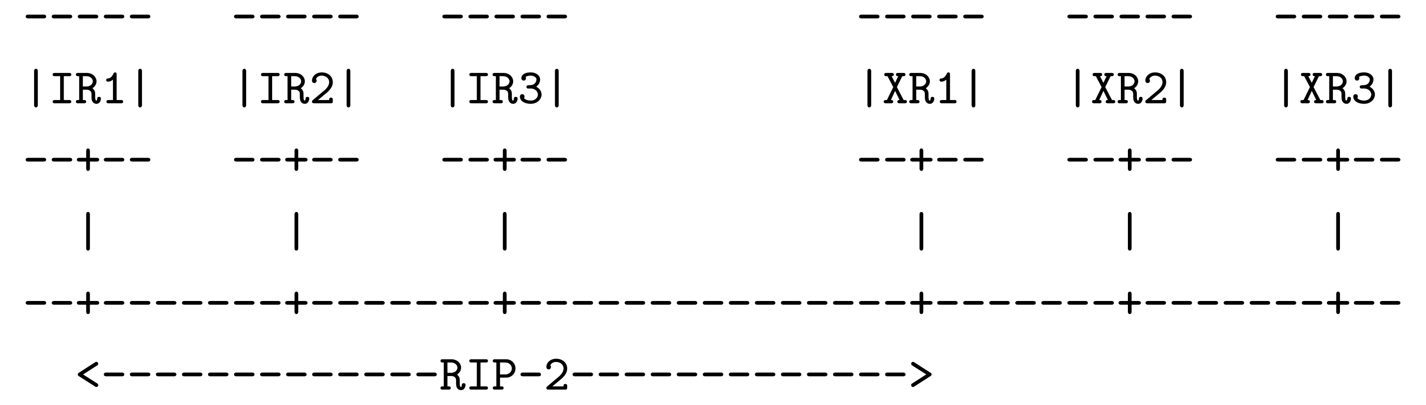
```
0                   1                   2                   3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| address family identifier (2) |      Route Tag (2)            |
+-------------------------------+-------------------------------+
|                        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

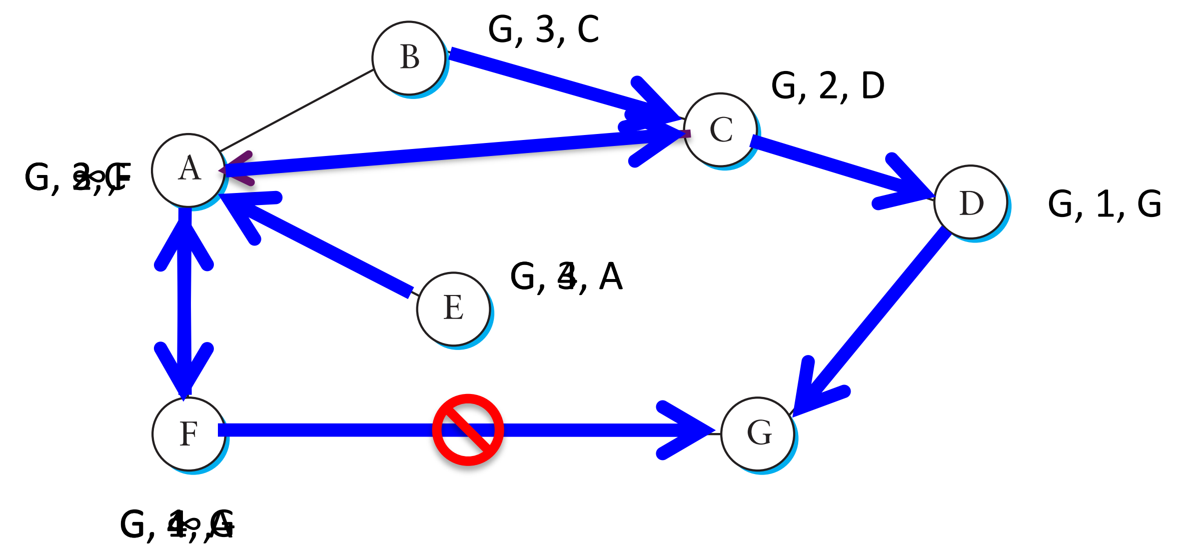
Next Hop field

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



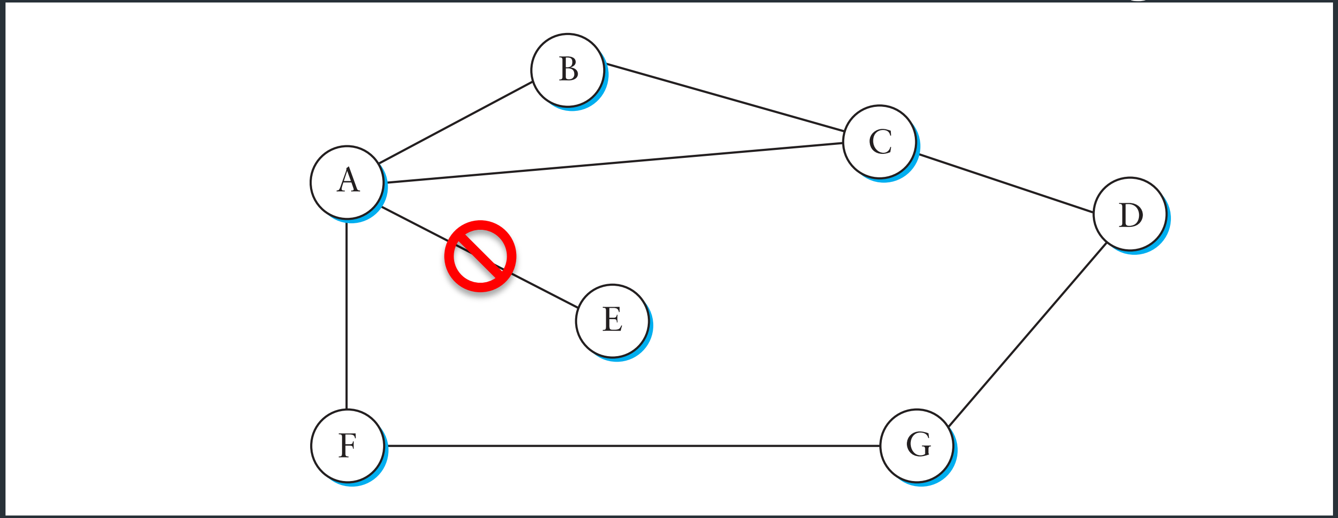
```
-----   -----   -----           -----   -----   -----
|IR1|   |IR2|   |IR3|           |XR1|   |XR2|   |XR3|
--+--   --+--   --+--           --+--   --+--   --+--
  |       |       |               |       |       |
--+-------+-------+---------------+-------+-------+--
  <-------------RIP-2------------->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

Adapting to Failures



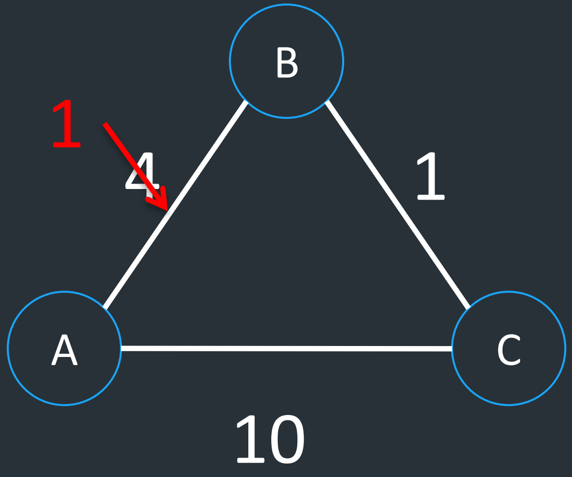
- F-G fails
- F sets distance to G to infinity, propagates
- A sets distance to G to infinity
- A receives periodic update from C with 2-hop path to G
- A sets distance to G to 3 and propagates
- F sets distance to G to 4, through A

Count-to-Infinity



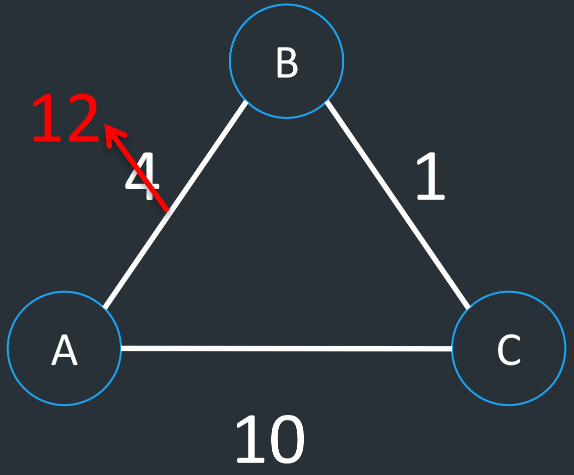
- Link from A to E fails
- A advertises distance of infinity to E
- B and C advertise a distance of 2 to E
- B decides it can reach E in 3 hops through C
- A decides it can reach E in 4 hops through B
- C decides it can reach E in 5 hops through A, …
- When does this stop?

Good news travels fast



- A decrease in link cost must 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!

Next Class

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

IP Connectivity

For each destination address, a router must either:

- Have matching prefix in its forwarding table
- Know a “smarter router”, ie default route for unknown prefixes

- Core routers know everything => no default route!
- Manage using notion of *Autonomous System* (AS)

Scaling Issues

Problem: Every router must be able to forward based on *any* destination IP address

- Map destination address => next hop
- Could we have one entry per IP? No!

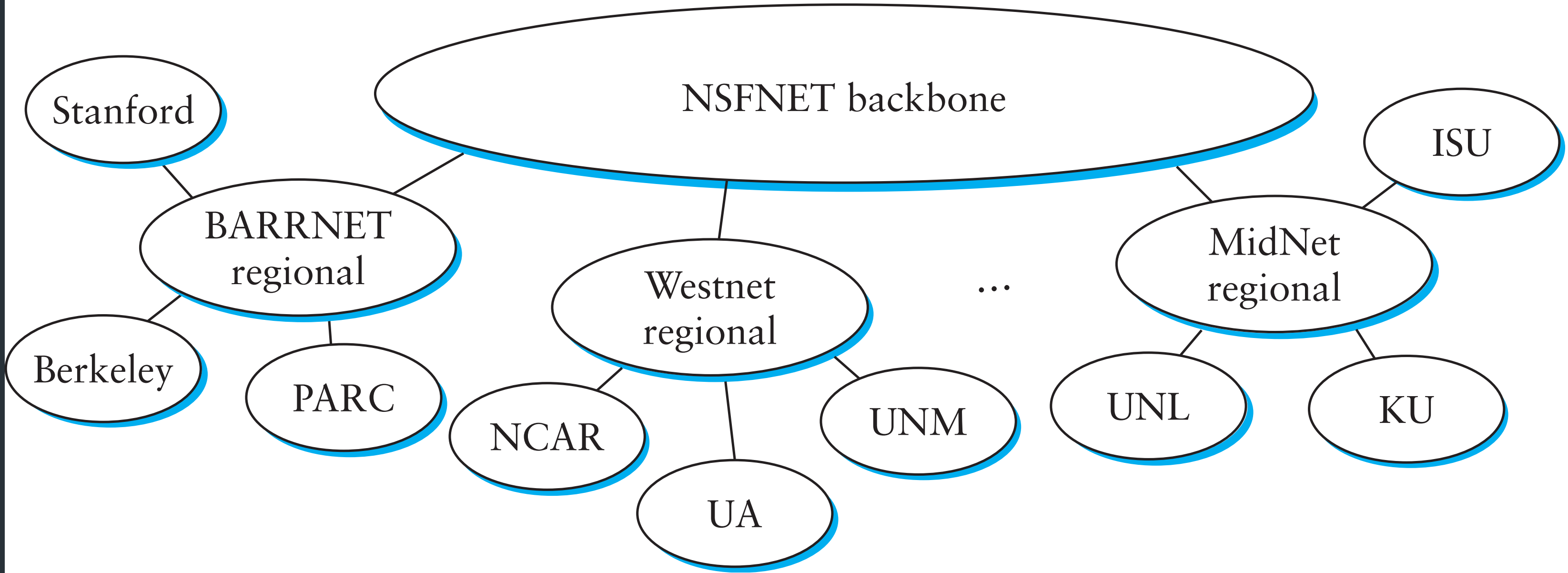
Solutions

- Leverage hierarchy in network topology
- Address aggregation
  - Address allocation is very important (should mirror topology)
- Default routes

Autonomous Systems (ASes)

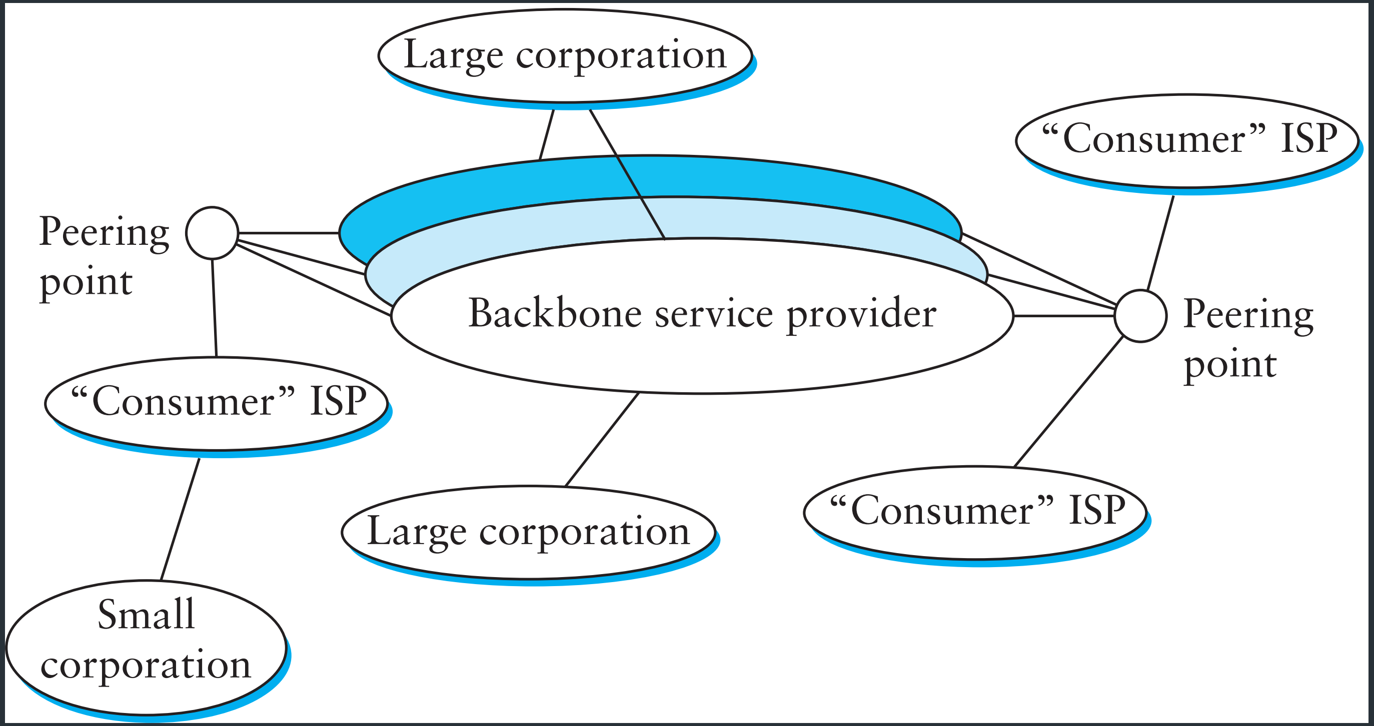
- Correspond to an administrative domain
  - AS's reflect organization of the Internet
  - E.g., Brown, large company, etc.
  - Identified by a 16-bit number (now 32)
- Goals
  - AS's choose their own local routing algorithm
  - AS's want to set policies about non-local routing
  - AS's need not reveal internal topology of their network

Internet structure, 1990



- Several independent organizations
- Hierarchical structure with single backbone

Internet structure, today



- Multiple backbones, more arbitrary structure