CS4450

Computer Networks: Architecture and Protocols

Lecture 11
Intra-domain Routing: Deep Dive

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Goals for Today's Lecture

- **Continue learning about Routing Protocols**
  - Link State (Global view, Local computation)—done
  - **Distance Vector (Local view, Local computation)—more today**

- Maintain sanity: its one of the "harder" lectures
  - I'll try to make it -less- hard, but …
    - Pay attention
    - Review again tomorrow
    - Work out a few examples

Recap from last few lectures

Recap: Spanning Tree Protocol …

- Used in switched Ethernet to avoid broadcast storm
- Can be used for routing on the Internet (via “flooding” on spanning tree)
- **Three fundamental issues**:
    - Unnecessary processing at end hosts (that are not the destination)
    - Higher latency
    - Lower available bandwidth

Recap: Routing Tables

- **Routing table:**
  - Each switch: the next hop for each destination in the network

- **Routing state**: collection of routing tables across all nodes

- Two questions:
  - How can we **verify** given routing state is valid?
  - How can we **produce** valid routing state?

- Global routing state valid **if and only if**:
  - There are no **dead ends** (other than destination)
  - There are no **“persistent”** **loops**

Recap: The right way to think about Routing Tables

- Routing tables are nothing but ….
  - A collection of (directed) spanning tree
  - One for each destination
- **Routing Protocols**
  - Mechanisms to producing valid routing tables
  - What we will see:
    - "n" spanning tree protocols running in parallel

Recap: Three flavors of protocols for producing valid routing state

- **Create Tree, route on tree**
  - E.g., Spanning tree protocol (switched Ethernet)
  - **Good:** easy, no (persistent) loops, no dead ends
  - **Not-so-good:** unnecessary processing, high latency, low bandwidth
- **Obtain a global view:**
  - E.g., Link state (last lecture)
- **Distributed route computation:**
  - E.g., Distance vector
  - E.g., Border Gateway Protocol

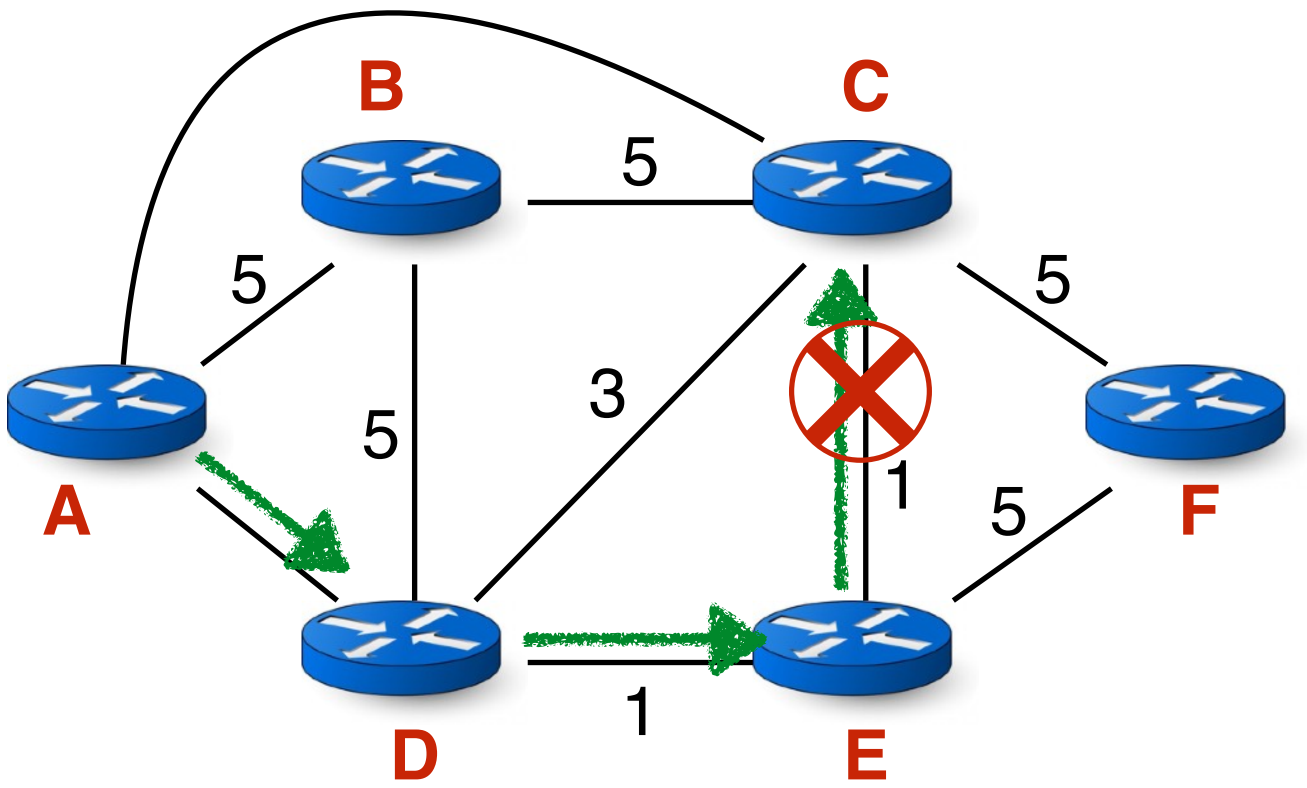
Recap: Where to create global view?

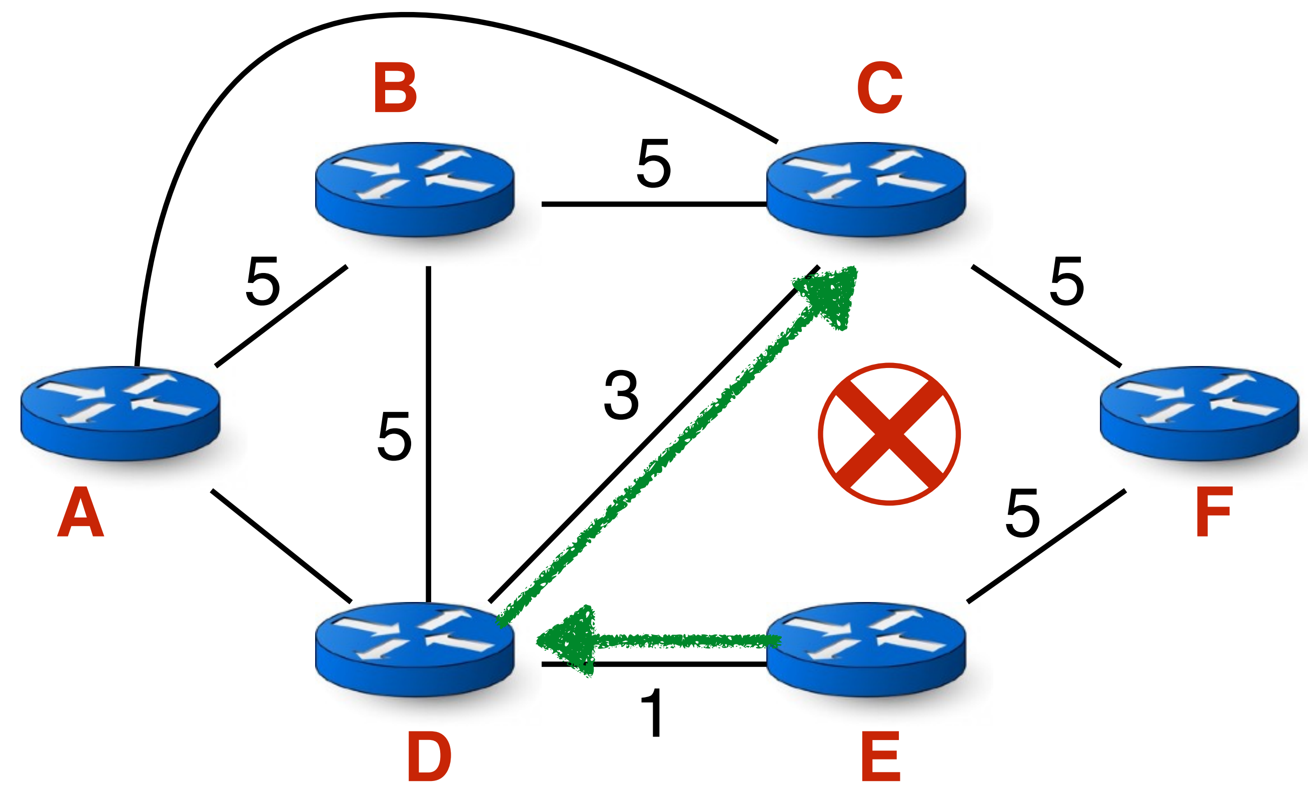
- One option: Central server
    - Collects a global view
    - Computes the routing table for each node
    - “Installs” routing tables at each node
    - **Software-defined Networks: later in course**

- Second option: At each router
    - Each router collects a global view
    - Computes its own routing table using Link-state protocol

- **Link-state routing protocol**
    - OSPF is a specific implementation of link-state protocol
        - IETF RFC 2328 (IPv4) or 5340 (IPv6)

Recap: Are Loops Still Possible?





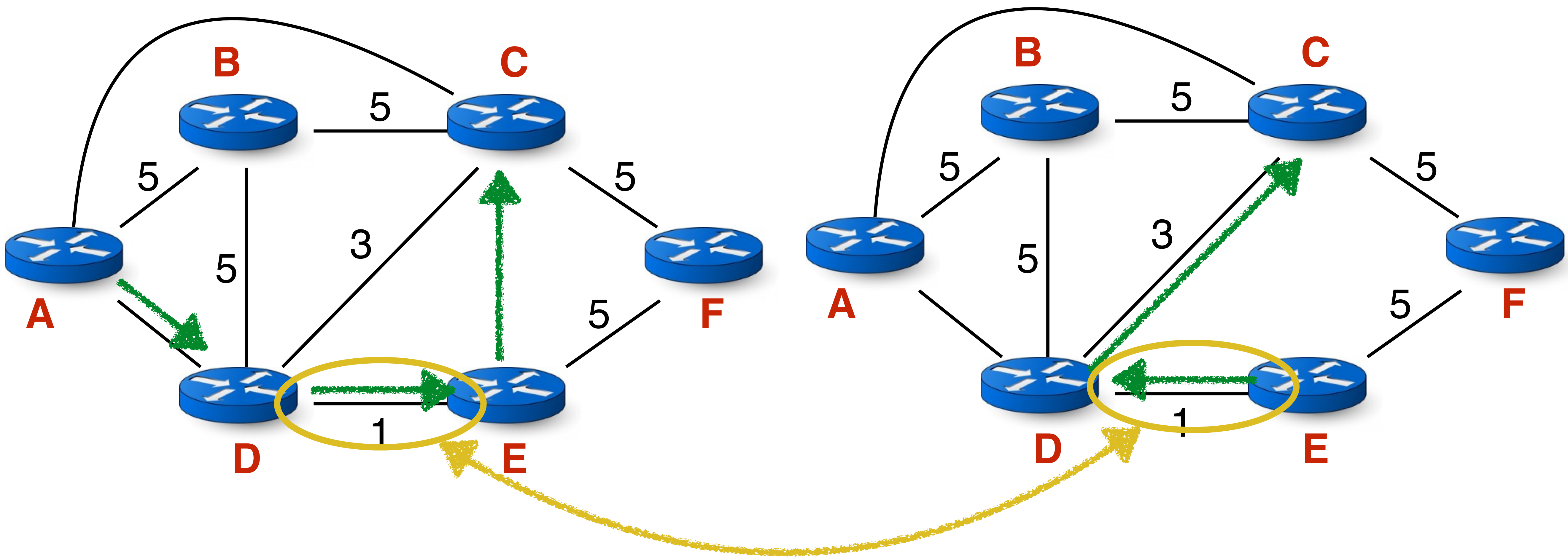
A and D think this is the path to C

E-C link fails, but D doesn't know yet

E thinks that this the path to C

E reaches C via D, D reaches C via E
Loop!

Recap: Transient Disruptions



- Inconsistent link-state views
    - Some routers know about failure before others
    - The shortest paths are no longer consistent
    - Can cause **transient forwarding loops**
        - **Transient loops are still a problem!**

Questions?

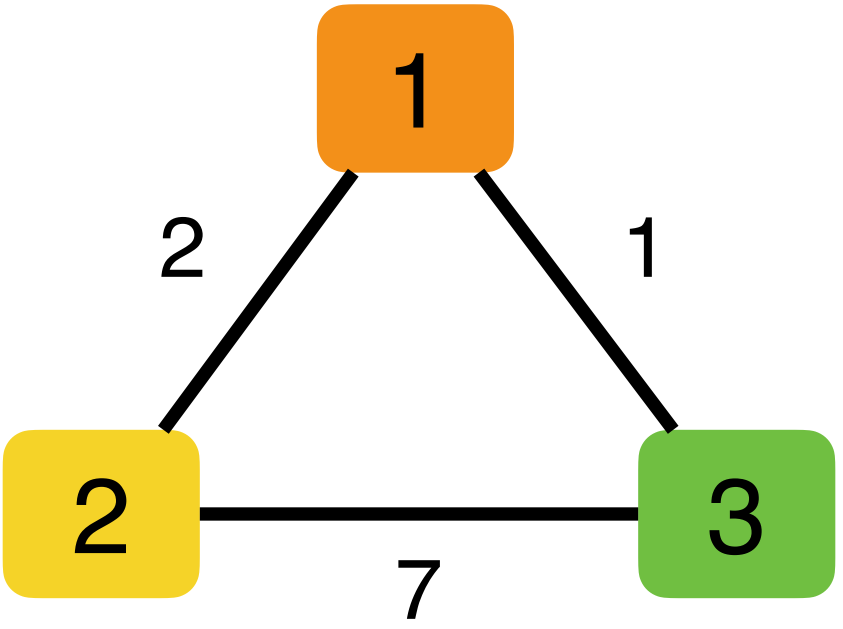
Distributed Route Computation

Recap: Distance-vector protocol with next-hops (no failures)

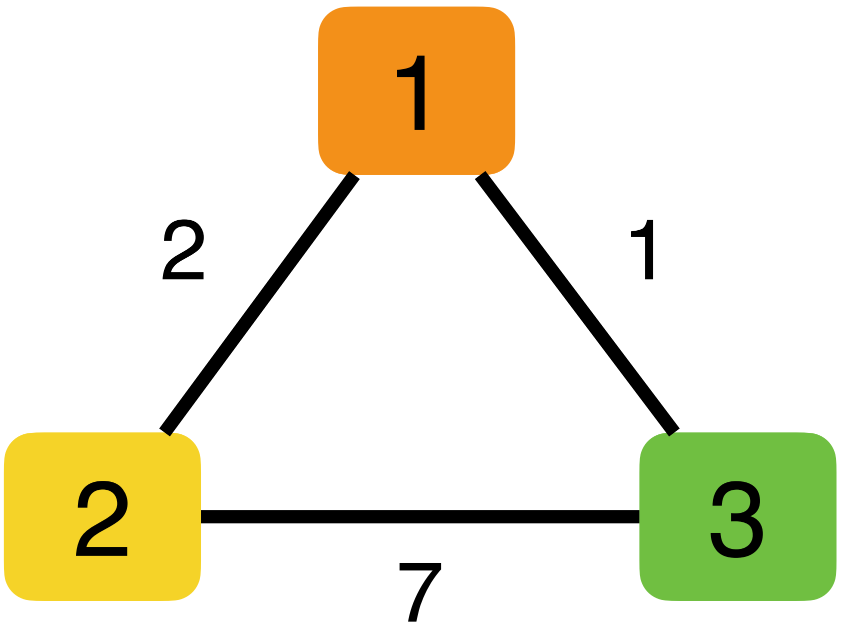
- **Messages (Y,d,X): For root Y; From node X; advertising a distance d to Y**
- Initially each switch X announces (X,0,X) to its neighbors
- Each switch X updates its view upon receiving each message
    - Upon receiving message (Y,d,Z) from Z~~, check Y's id~~
    - ~~If Y's id < current root: set root destination = Y~~
- Switch X computes its shortest distance from the ~~root~~ destination
    - If current_distance_to_Y > d + cost of link to Z:
        - update current_distance_to_Y = d + cost of link to Z
        - **update next_hop_to_destination = Z**
- If ~~root changed OR~~ shortest distance to the ~~root~~ destination changed, send all neighbors updated message (Y, current_distance_to_Y, X)

Lets run the Protocol on this example

(with next-hops)

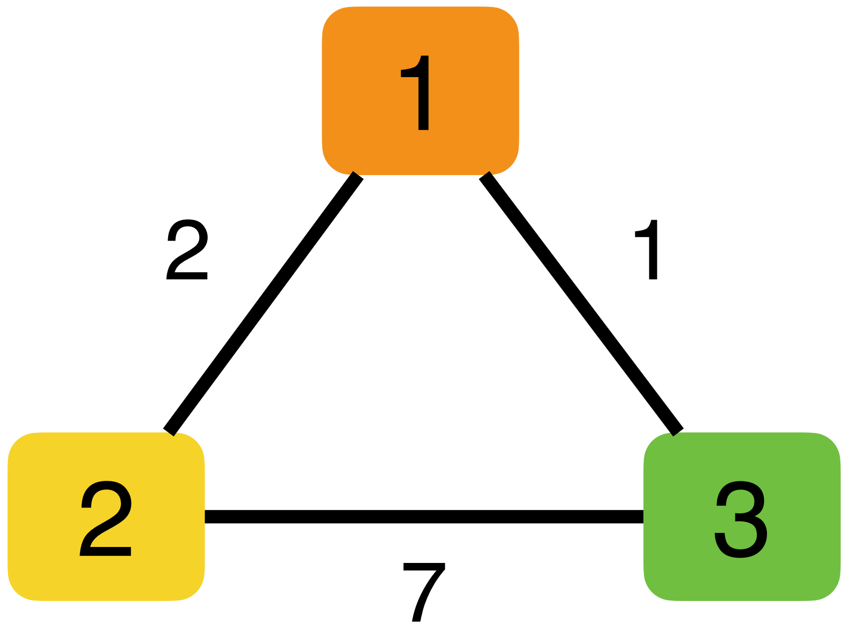


Round 1



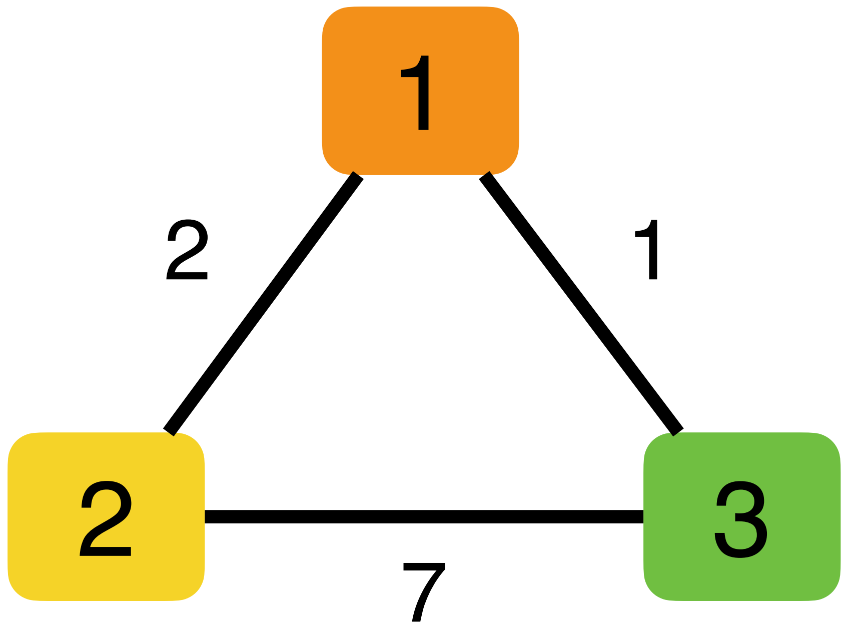
	Receive	Send	Next-hops
1		(1, 0, 1)	[-]
2		(2, 0, 2)	[-]
3		(3, 0, 3)	[-]

Round 2



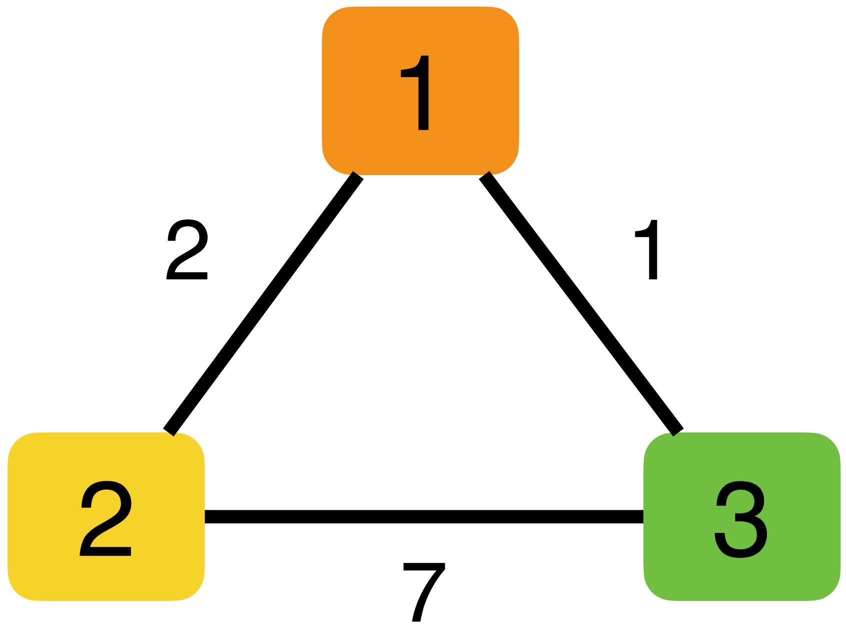
	Receive	Send	Next-hops
1 **(1, 0, 1)**	(2, 0, 2), (3, 0, 3)	(2, 2, 1), (3, 1, 1)	[-, 2, 3]
2 **(2, 0, 2)**	(1, 0, 1), (3, 0, 3)	(1, 2, 2), (3, 7, 2)	[1, -, 3]
3 **(3, 0, 3)**	(1, 0, 1), (2, 0, 2)	(1, 1, 3), (2, 7, 3)	[1, 2, -]

Round 3



	Receive	Send	Next-hops
1 **(1, 0, 1)** **(2, 2, 1),** **(3, 1, 1)**	(1, 2, 2), (3, 7, 2), (1, 1, 3), (2, 7, 3)		[-, 2, 3]
2 **(1, 2, 2),** **(2, 0, 2),** **(3, 7, 2)**	(2, 2, 1), (3, 1, 1), (1, 1, 3), (2, 7, 3)	(3, 3, 2)	[1, -, 1]
3 **(1, 1, 3),** **(2, 7, 3),** **(3, 0, 3)**	(2, 2, 1), (3, 1, 1), (1, 2, 2), (3, 7, 2)	(2, 3, 3)	[1, 1, -]

Round 4



	Receive	Send	Next-hops
1 **(1, 0, 1)** **(2, 2, 1),** **(3, 1, 1)**	(3, 3, 2), (2, 3, 3)		[-, 2, 3]
2 **(1, 2, 2),** **(2, 0, 2),** **(3, 3, 2)**	(2, 3, 3)		[1, -, 1]
3 **(1, 1, 3),** **(2, 3, 3),** **(3, 0, 3)**	(3, 3, 2)		[1, 1, -]

Why not Spanning Tree Protocol? Why Distance “Vector”?

- The same algorithm applies to all destinations
- Each node announces distance to **each** dest
    - I am distance d_A away from node A
    - I am distance d_B away from node B
    - I am distance d_C away from node C
    - …
- Nodes are exchanging a **vector** of distances

Distance Vector Protocol

- **Messages (Y,d,X): For root Y; From node X; advertising a distance d to Y**
- Initially each switch X initializes its routing table to (X,0,-) and distance infinity to all other destinations
- Switches announce their entire distance vectors (routing table w/0 next hops)
- Upon receiving a routing table from a node (say Z), each node X does:
  - For each destination Y in the announcement (distance(Y, Z) = d):
    - If current_distance_to_Y > d + cost of link to Z:
      - update current_distance_to_Y = d + cost of link to Z
      - update next_hop_to_destination = Z
- If shortest distance to any destination changed, send all neighbors your distance vectors

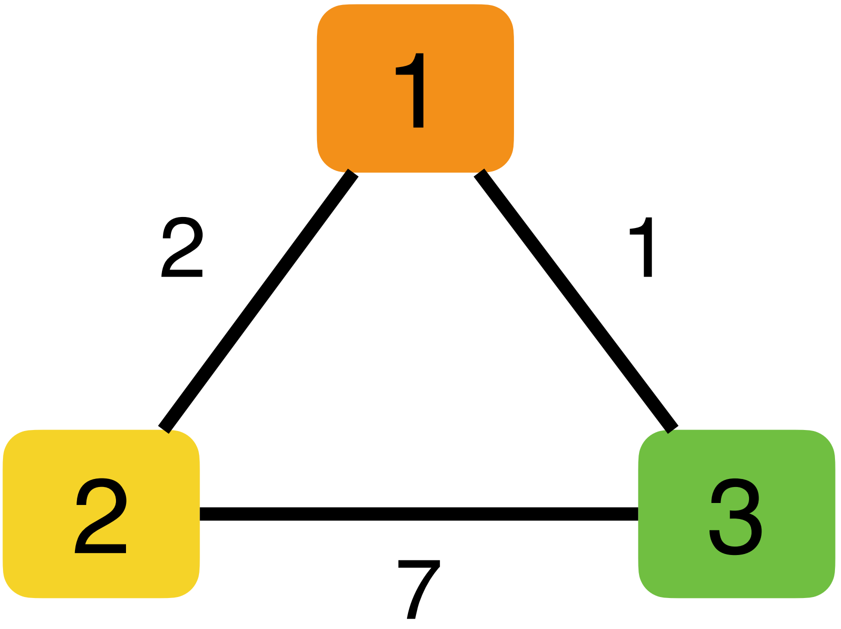
Two Aspects to This Approach

- **Protocol**:
  - Exchanging that routing information with neighbors
  - What and when for exchanges
  - RIP is a protocol that implements DV (IETF RFC 2080)
- **Algorithm**:
  - How to use the information from your neighbors to update your own routing tables?

Group Exercise:

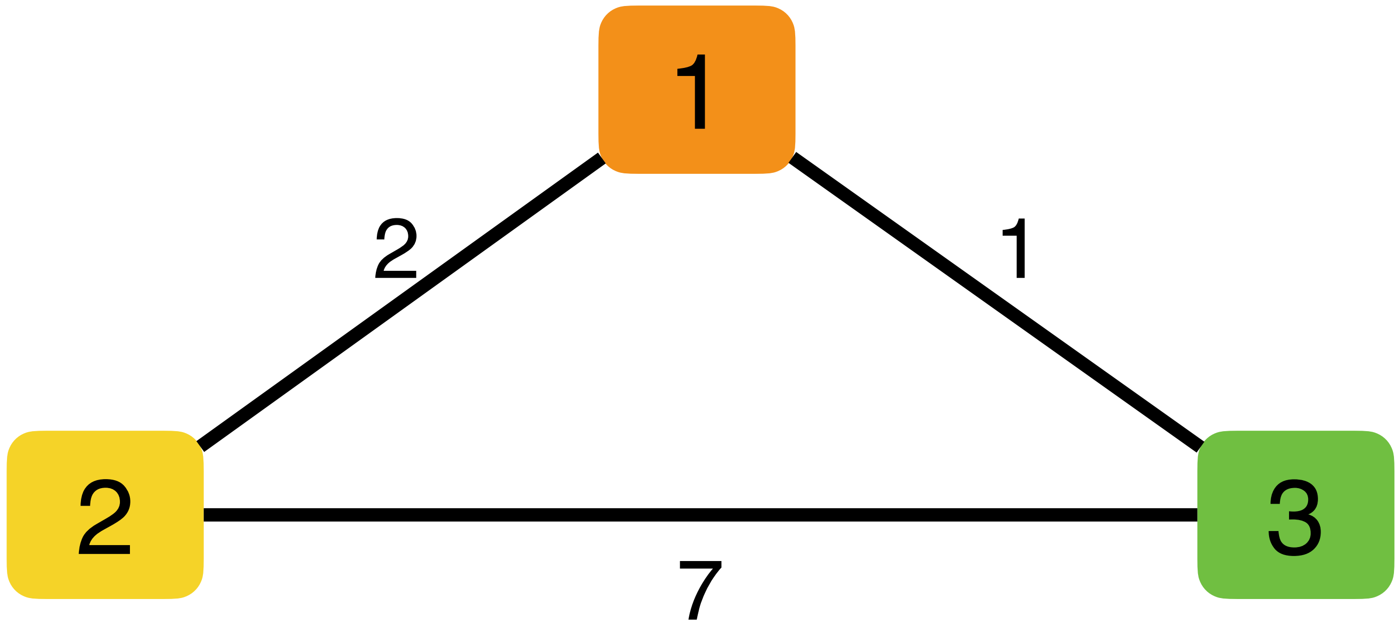
Lets run the Protocol again on this example

(this time with distance vectors)



Round 1

	distance	next-hop
1	0	-
2	infinity	
3	infinity	

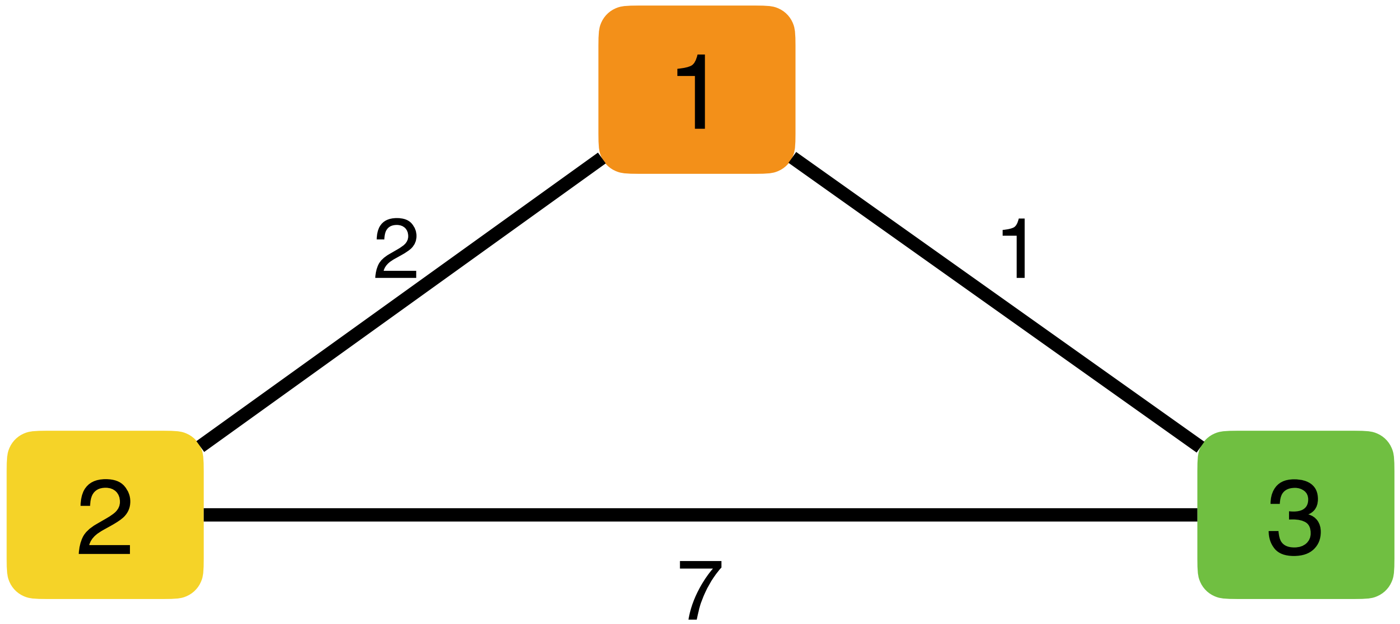


	distance	next-hop
1	infinity	
2	0	-
3	infinity	

	distance	next-hop
1	infinity	
2	infinity	
3	0	-

Round 2

	distance	next-hop
1	0	-
2	2	2
3	1	3

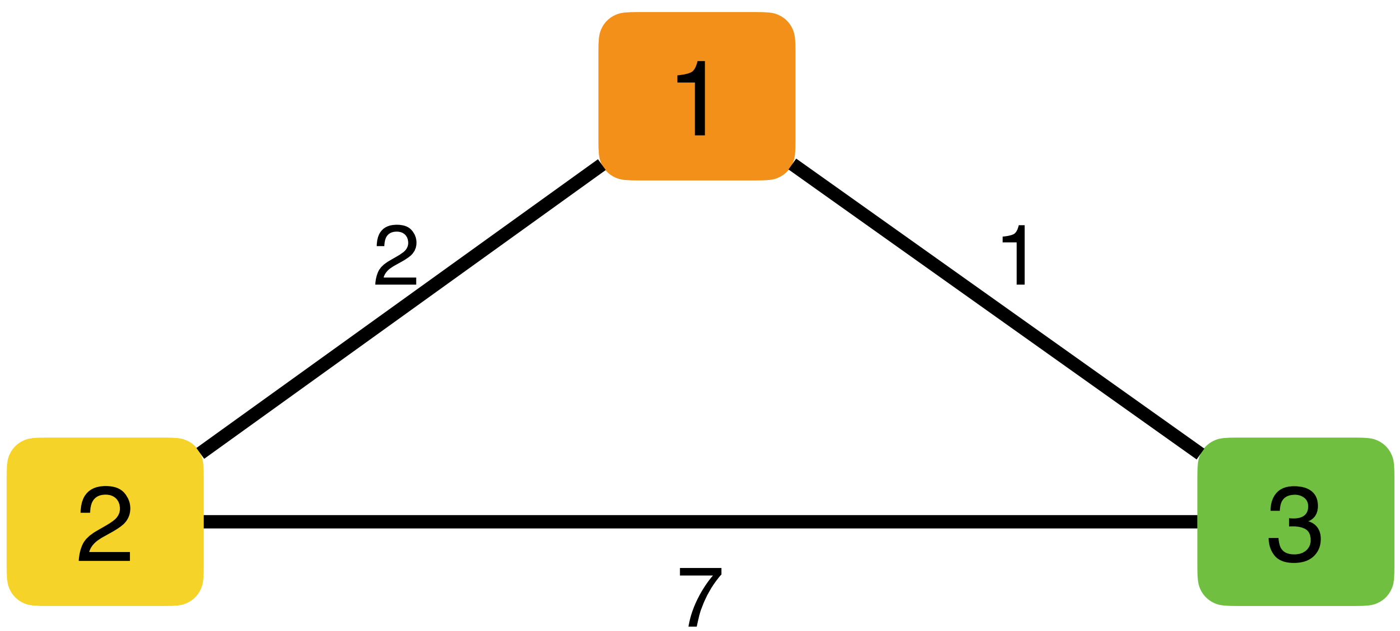


	distance	next-hop
1	2	1
2	0	-
3	7	3

	distance	next-hop
1	1	1
2	7	2
3	0	-

Round 3

	distance	next-hop
1	0	-
2	2	2
3	1	3

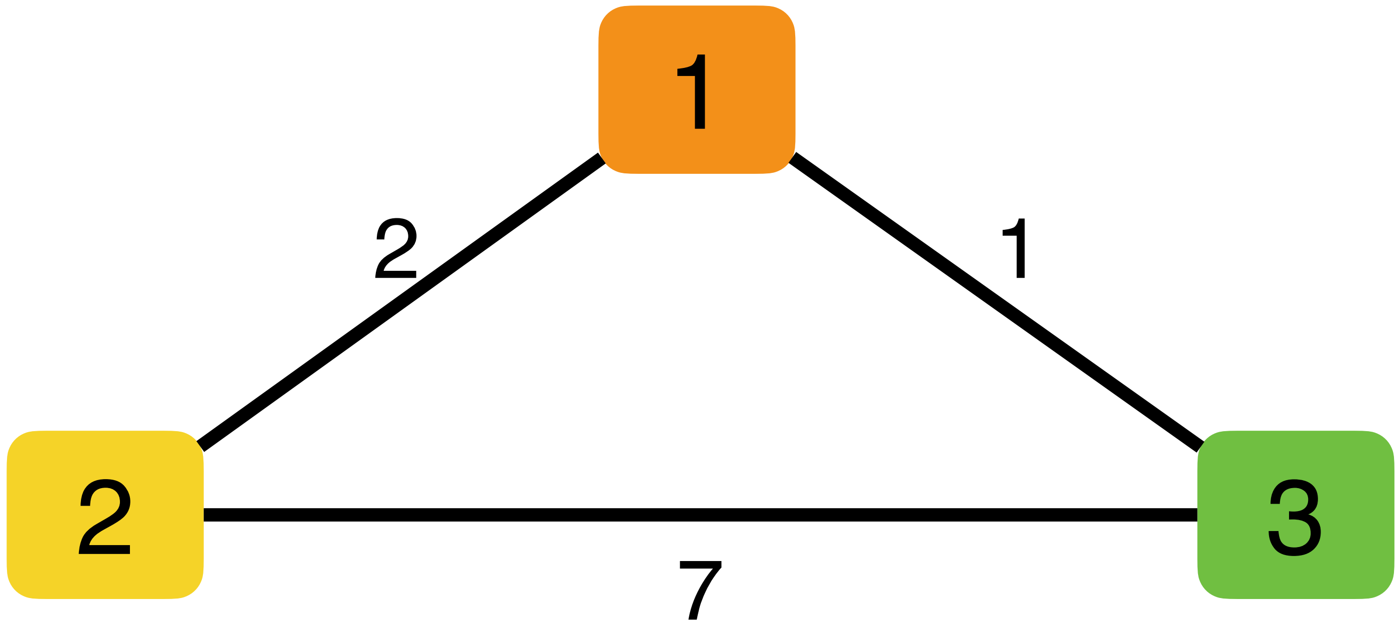


	distance	next-hop
1	2	1
2	0	-
3	3	1

	distance	next-hop
1	1	1
2	3	1
3	0	-

Round 4

	distance	next-hop
1	0	-
2	2	2
3	1	3



	distance	next-hop
1	2	1
2	0	-
3	3	1

	distance	next-hop
1	1	1
2	3	1
3	0	-

From Algorithm to Protocol

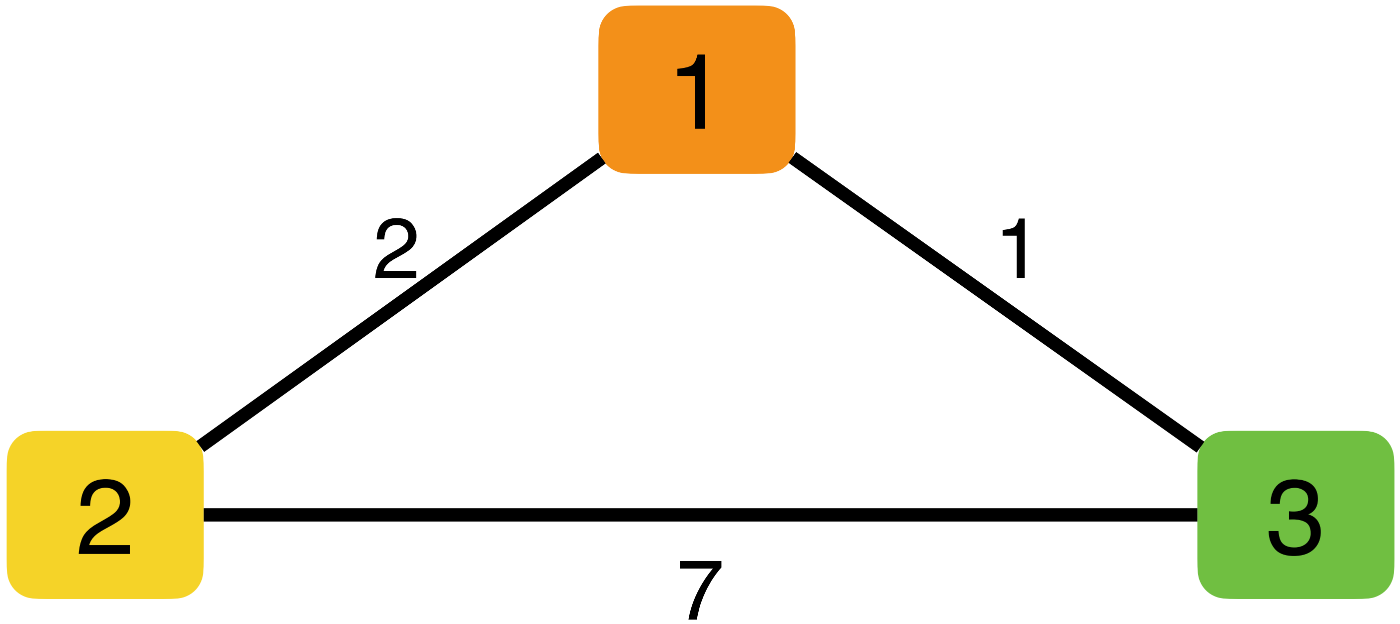
- Algorithm:
    - Nodes use Bellman-Ford to compute distances
- Protocol
    - Nodes exchange distance vectors
    - Update their own routing tables
    - And exchange again…
    - Details: when to exchange, what to exchange, etc….

Other Aspects of Protocol

- When do you send messages?
  - When any of the distance changes
    - What about when the cost of a link changes?
  - Periodically, to ensure consistency between neighbors
- What information do you send?
  - Could send entire vector
  - Or just updated entries
- Do you send everyone the same information
  - Consider the following slides

Three node network

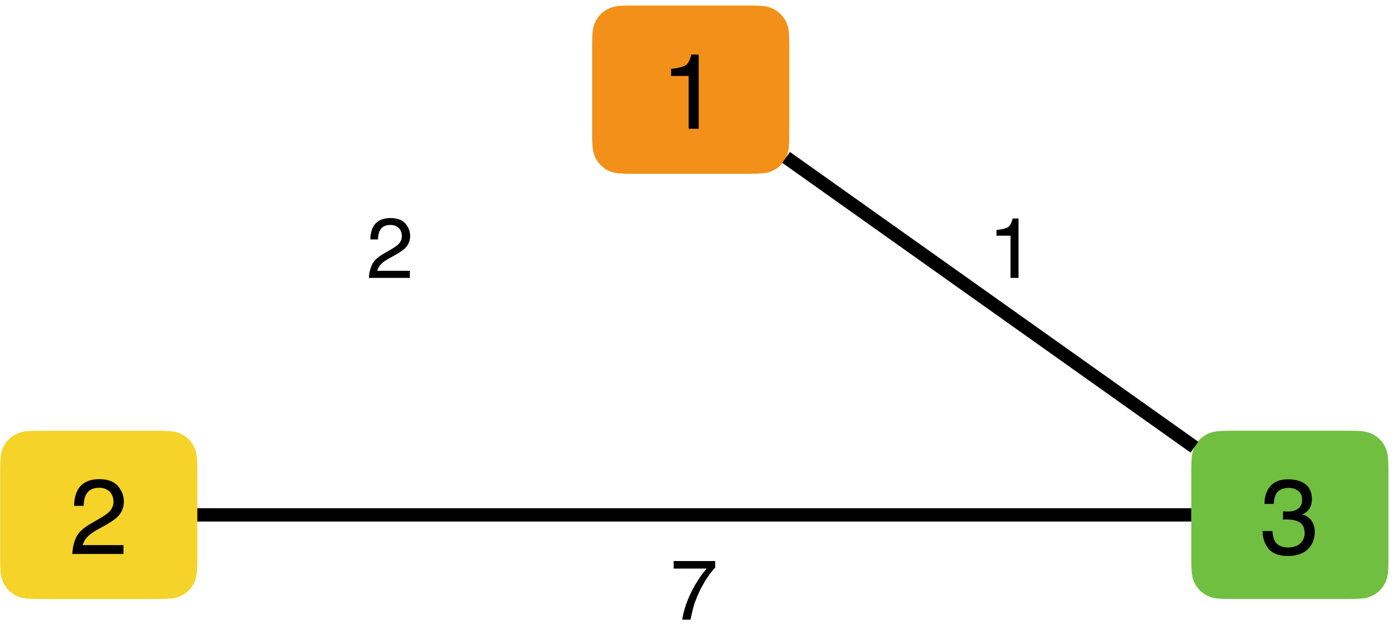
	distance	next-hop
1	0	-
2	2	2
3	1	3



	distance	next-hop
1	1	1
2	3	1
3	0	-

Three node network

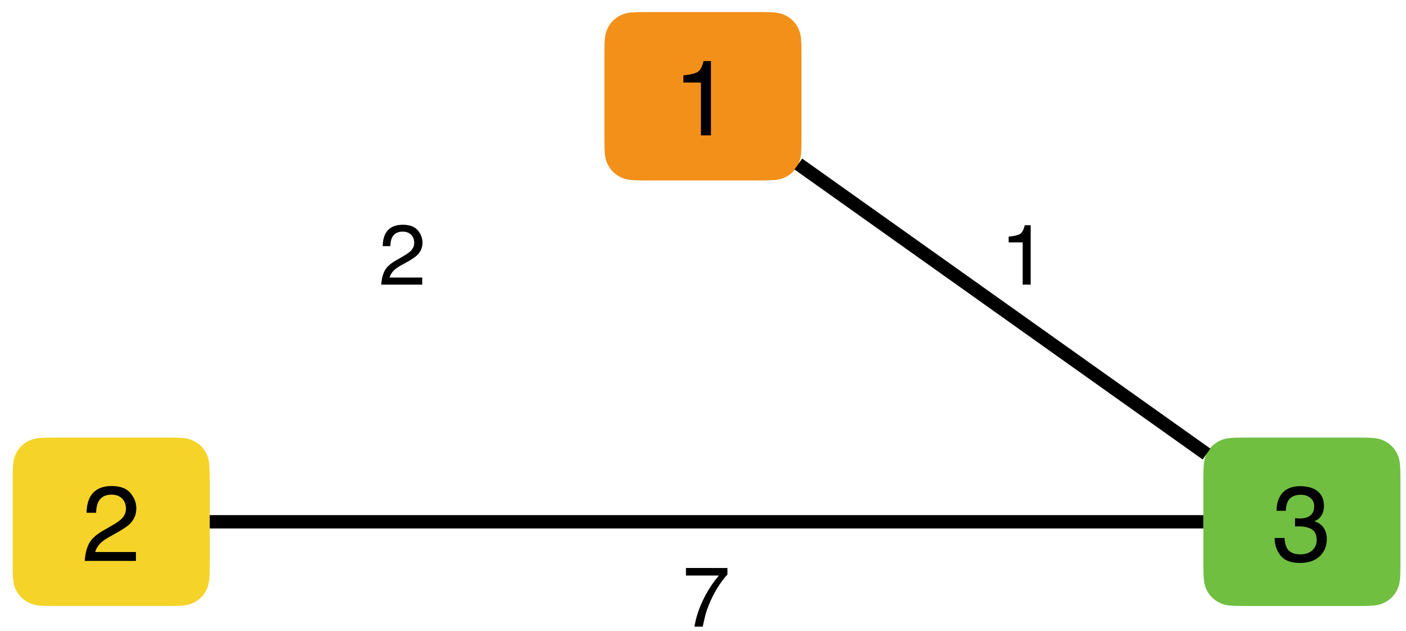
	distance	next-hop
1	0	-
2	infinity	
3	1	3



	distance	next-hop
1	1	1
2	3	1
3	0	-

Round 1

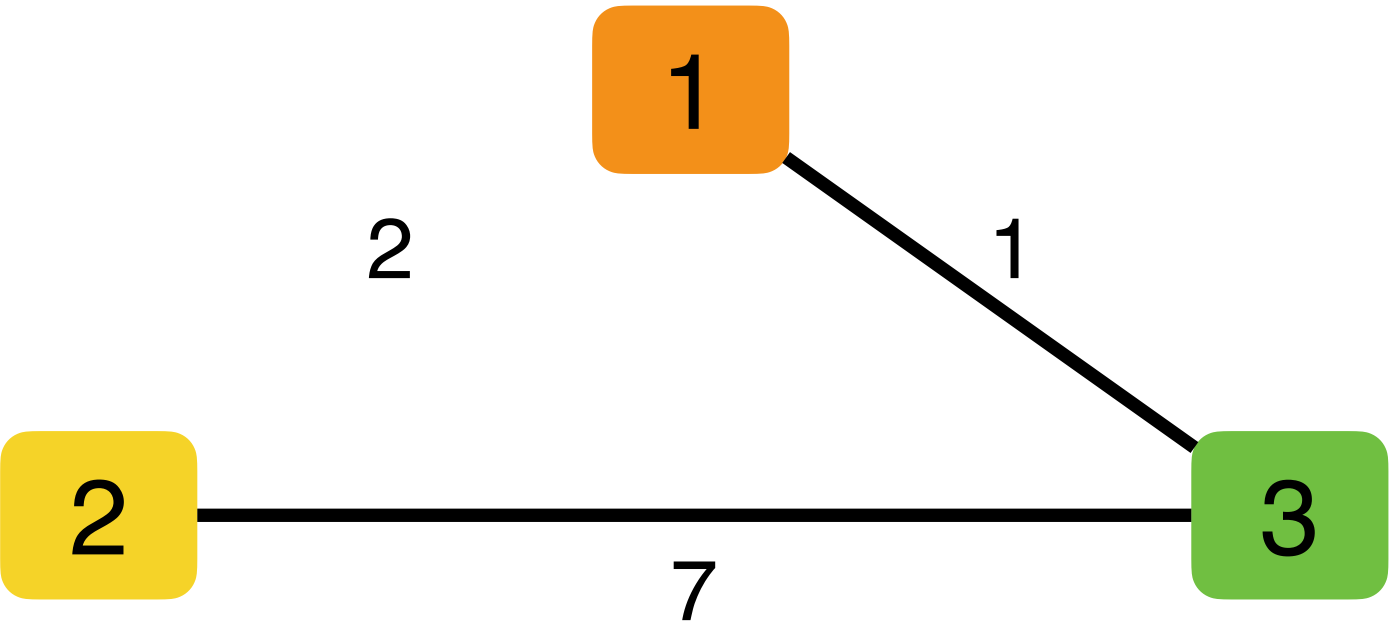
	distance	next-hop
1	0	-
2	**4**	**3**
3	1	3



	distance	next-hop
1	1	1
2	3	1
3	0	-

Round 2

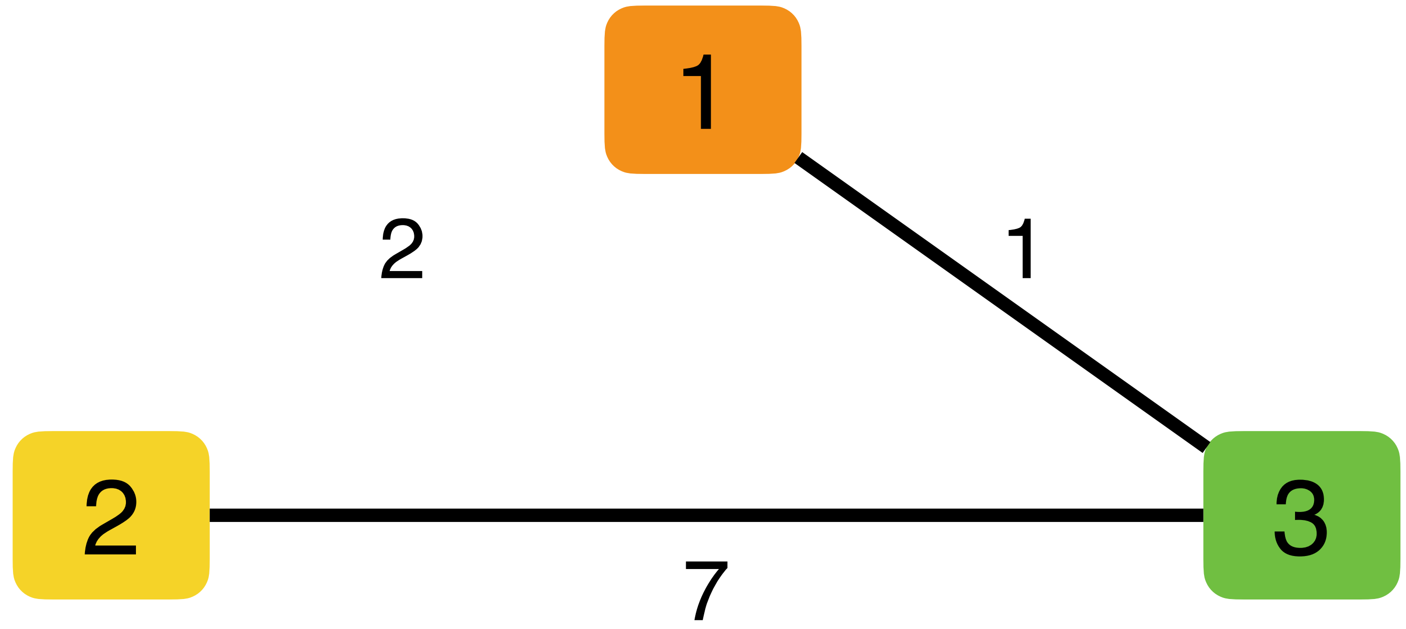
	distance	next-hop
1	0	-
2	4	3
3	1	3



	distance	next-hop
1	1	1
2	**5**	**1**
3	0	-

Round 3

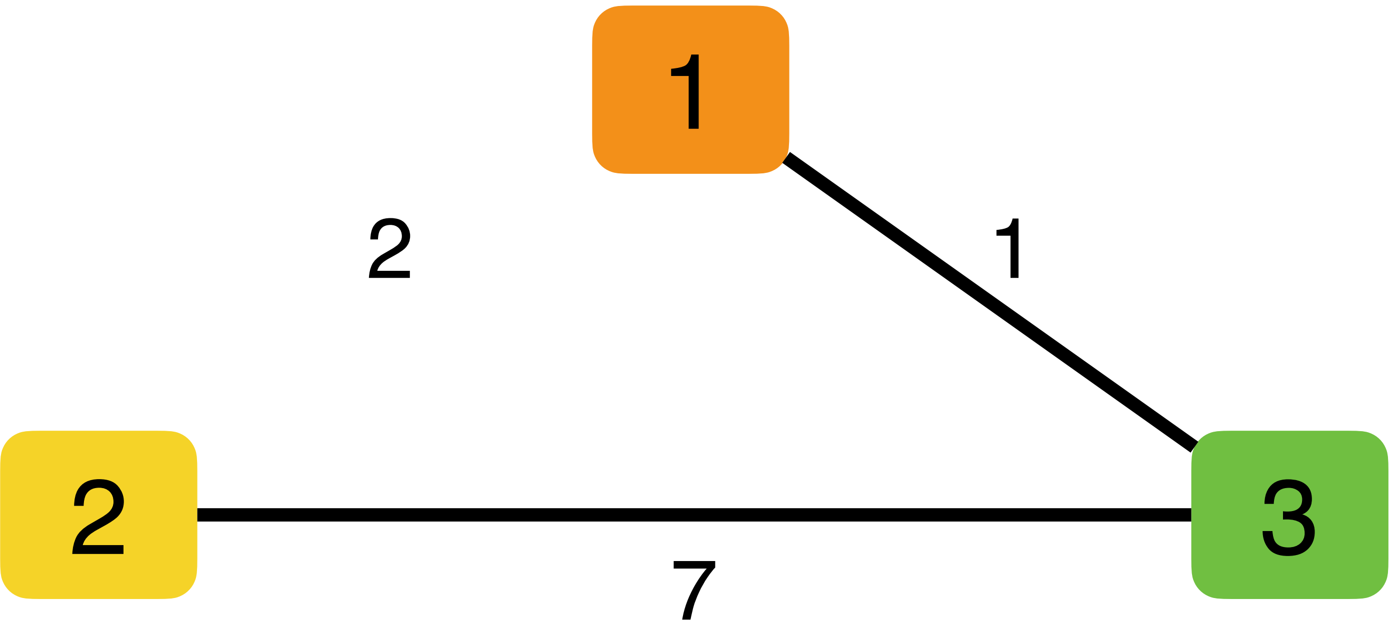
	distance	next-hop
1	0	-
2	6	3
3	1	3



	distance	next-hop
1	1	1
2	5	1
3	0	-

Round 4

	distance	next-hop
1	0	-
2	6	3
3	1	3

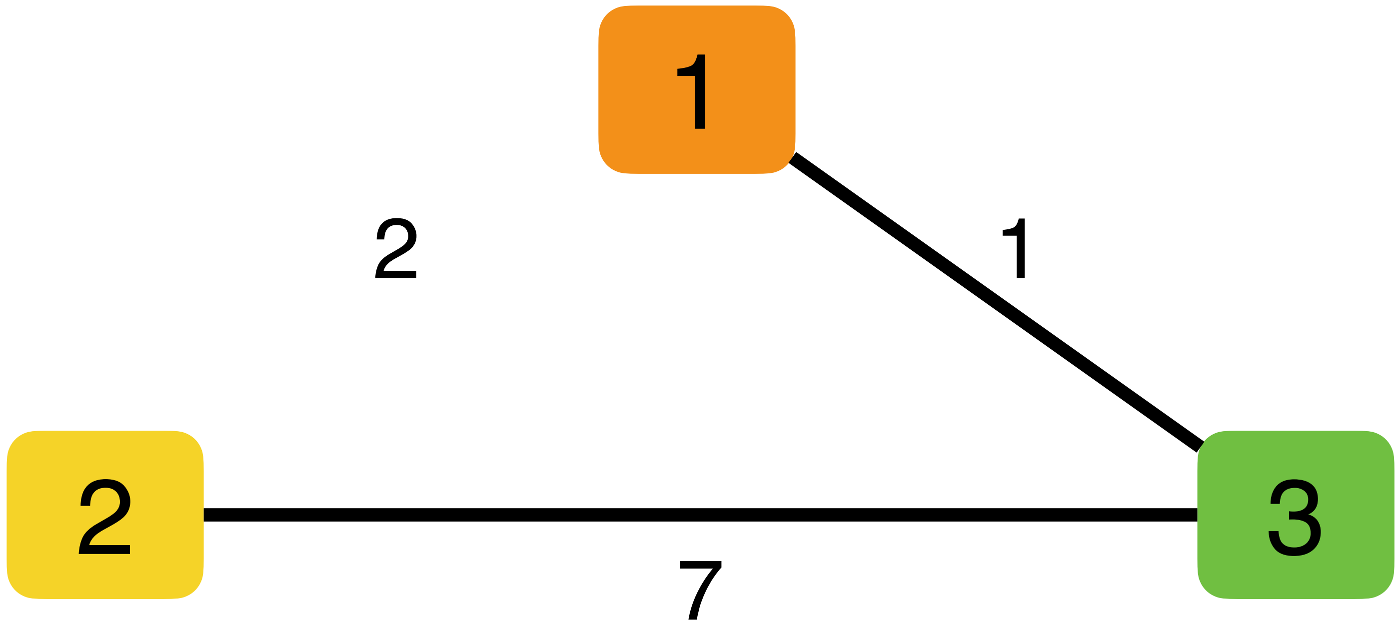


	distance	next-hop
1	1	1
2	7	1
3	0	-

COUNT-TO-INFINITY problem!!!!

Count-to-infinity problem

	distance	next-hop
1	0	-
2	6	3
3	1	3



	distance	next-hop
1	1	1
2	7	1
3	0	-

Not just due to failures:
Can happen with changes in cost!

How Can You Fix This?

- **Do not advertise a path back to the node that is the next hop on the path**
  - Called **“split horizon”**
  - Telling them about your entry going through them
    - Doesn’t tell them anything new
    - Perhaps misleads them that you have an independent path
- **Another solution: if you are using a next-hop’s path, then**:
  - Tell them not to use your path (by telling them cost of infinity)
  - Called “**poisoned reverse**”

Convergence

- Distance vector protocols can converge slowly
    - While these corner cases are rare
    - The resulting convergence delays can be significant

Comparison of Scalability

- **Link-State:**
  - Global flood: each router's link-state (#ports)
  - Send it once per link event, or periodically
- **Distance Vector:**
  - Send longer vector (#dest) just to neighbors
    - But might end up triggering their updates
  - Send it every time DV changes (which can be often)
- **Tradeoff:**
  - LS: Send it everywhere and be done in predictable time
  - DV: Send locally, and perhaps iterate until convergence

End of Distance-vector Routing

Internet Addressing

Addressing so far

- Each node has a “name”
  - We have so far worked only with names
  - Assumed that forwarding/routing etc. done on names
- Today:
  - Why do we need addresses?
  - Why do we assign addresses the way we assign addresses?

Three requirements for addressing

- **Scalable routing**
  - How must state must be stored to forward packets?
  - How much state needs to be updated upon host arrival/departure?
- **Efficient forwarding**
  - How quickly can one locate items in routing table?
- **Host must be able to recognize packet is for them**

Layer 2 (link layer): "Flat" Addressing

- Uses MAC address
  - "Names", remember? Used as identifier

- Unique identifiers hardcoded in the hardware
  - No location information

- Local area networks route on these "flat" addresses
  - **Spanning Tree Protocol runs on switches and hosts**
  - Each switch stores a separate routing entry **for each host**
  - End-hosts store nothing

- Upon receiving a packet, an end-host:
  - Puts destination's and its own MAC address in the header
  - Forwards it to the switch it is connected to

- **Destination is able to recognize the packet is for them using address**

How does this meet our requirements?

- **Scalable routing**
  - How much state to forward packets?
    - One entry per host per switch
  - How much state updated for each arrival/departure?
    - One entry per host per switch
- **Efficient forwarding**
  - Exact match lookup on MAC addresses (exact match is easy!)
- **Host must be able to recognize the packet is for them**
  - MAC address does this perfectly

Conclusion: L2 addressing does not enable scalable routing

How would you scale L2?

- Suppose we want to design a much larger L2 network
- Must use MAC address as part of the address
  - Only way host knows that the packet is for them
- **But how would you enable scalable routing?**
  - Small #routing entries (less than one entry per host per switch)
  - Small #updates (less than one update per switch per host change)

One possible Solution: Towards Internet-scale addressing

- Assign each end-host an addresses of the form — Switch:MAC
- Spanning Tree Protocol runs only on switches
  - So, each switch has one entry per switch (rather than per host)
- Upon receiving a packet, an end-host:
  - Puts destination's and its own Switch:MAC address in the header
  - Forwards it to the switch it is connected to
- **Switches forward the packet using first part of the address**
- **Destination is able to recognize the packet is for them using second part of the address**

Layer 3: Hierarchical addressing

- Routing tables cannot have entry for each switch in the Internet

- Use addresses of the form — Network:Host

- Routers know how to reach all networks in the world
    - Routing algorithms only announce “Network” part of the addresses
    - Routing tables now store a next-hop for each “network”

- Forwarding:
    - Routers ignore host part of the address
    - When the packet reaches the right network
        - Packet forwarded using Host part of the address
        - Using Layer 2

- **This was the original IP addressing scheme**

What do I mean by “network”

- In the original IP addressing scheme …
    - Network meant an L2 network
    - Often referred to as a “subnet”
    - There are too many of them now to scale

Aggregation

- **Aggregation:** single forwarding entry used for many individual hosts

- Example:
  - In our scalable L2 solution: aggregate was switch
  - In our scalable L3 solution: aggregate was network

- Advantages:
  - Fewer entries and more stable
  - Change of hosts do not change tables
    - Don’t need to keep state on individual hosts

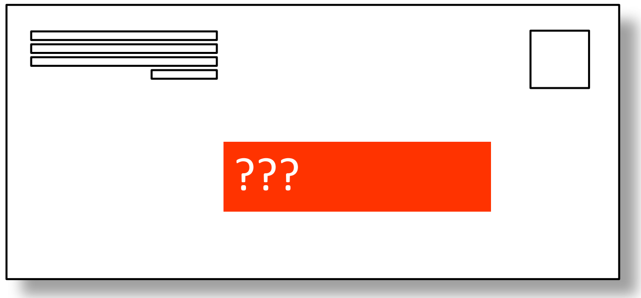
Hierarchical Structure

- The Internet is an “inter-network”
    - Used to connect networks together, not hosts

- Forms a natural two-way hierarchy
    - Wide Area Network (WAN) delivers to the right “network”
    - Local Area Network (LAN) delivers to the right host

Hierarchical Addressing

- Can you think of an example?
- Addressing in the US mail
    - Country
    - City, Zip code
    - Street
    - House Number
    - Occupant "Name"



IP addresses

- Unique 32 bit numbers associated with a host
- Use dotted-quad notation, e.g., 128.84.139.5

Country	City, State	Street, Number	Occupant
(8 bits)	(8 bits)	(8 bits)	(8 bits)
10000000	0-1010100	10001011	00000-101
128	84	139	5

Network

Host

Original Addressing mechanism

- First eight bits: network address (/8)
    - Slash notation indicates network address
- Last 24 bits: host address
- Assumed 256 networks were more than enough!!!
    - Now we have millions!

Suppose we want to accommodate more networks

- We can allocate more bits to network address

- Problem?
  - Fewer bits for host names
  - What if some networks need more hosts?

Today’s Addressing: CIDR

- Classless Inter-domain Routing
- Idea: Flexible division between network and host addresses
- Prefix is **network address**
- Suffix is **host address**
- **Example:**
    - **128.84.139.5/23 is a 23 bit prefix with:**
    - First 23 bits for network address
    - Next 9 bits for host addresses: maximum 2^9 hosts
- **Terminology: “Slash 23”**

Example for CIDR Addressing

- **128.84.139.5/23 is a 23 bit prefix with 2^9 host addresses**

10000000	0-1010100	10001011	00000-101
128	84	139	5

Network (23 bits)

Host (9 bits)

Allocating addresses

- Internet Corporation for Assigned Names and Numbers (ICANN) …
- Allocates large blocks of addresses to Regional Internet Registries
    - E.g., American Registry for Internet Names (ARIN) …
- That allocates blocks of addresses to Large Internet Service Providers (ISP)
- That allocate addresses to individuals and smaller institutions
- Fake example:
    - ICANN -> ARIN -> AT&T -> Cornell -> CS -> Me

Allocating addresses: Fake example

- ICANN gives ARIN several /8s
- ARIN given AT&T one /8, **128.0/8**
    - **Network prefix:** 10000000
- AT&T gives Cornell one /16, **128.84/16**
    - **Network prefix:** 10000000 01010100
- Cornell gives CS one /24, **128.84.139/24**
    - **Network prefix:** 10000000 01010100 10001011
- CS given me a specific address **128.84.139.5**
    - **Network prefix:** 10000000 01010100 10001011 00000101

How does this meet our requirements?

- To understand this, we need to understand the routing on the Internet
- And to understand that, we need to understand the Internet

More next lecture!