Computer Networks

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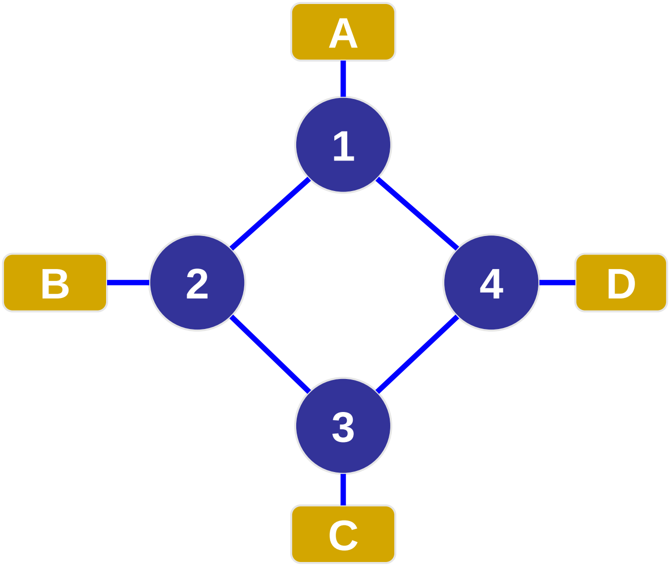
Material with thanks Mosharaf Chowdhury, and many other colleagues.

Ethernet topics

- Frames and framing
- Addressing
- Routing
- Forwarding
- Discovery

Flooding (still) leads to loops

- Example: A wants to broadcast a message
  - A sends packet to 1
  - 1 Floods to 2 and 4
  - 2 Floods to B and 3
  - 4 Floods to D and 3
  - 3 Floods packet from 2 to C and 4
  - 3 Floods packet from 4 to C and 2
  - 4 Floods packet from 3 to D and 1
  - 2 Floods packet from 3 to B and 1
  - 1 Floods packet from 2 to A and 4
  - 1 Floods packet from 4 to B and 2
  - ….



- Broadcast storm still happens in a switched network if it contains a cycle of switches

Spanning tree approach

- Take arbitrary topology
- Pick subset of links that form a spanning tree

Algorithm has two aspects

- Pick a root
  - Destination to which shortest paths go
  - Pick the one with the smallest identifier (MAC addr.)
- Compute shortest paths to the root
  - No shortest path can have a cycle
  - Only keep the links on shortest-paths
  - Break ties in some way (so we only keep one shortest path from each node)
- Ethernet’s spanning tree construction does both with a single algorithm

Breaking ties

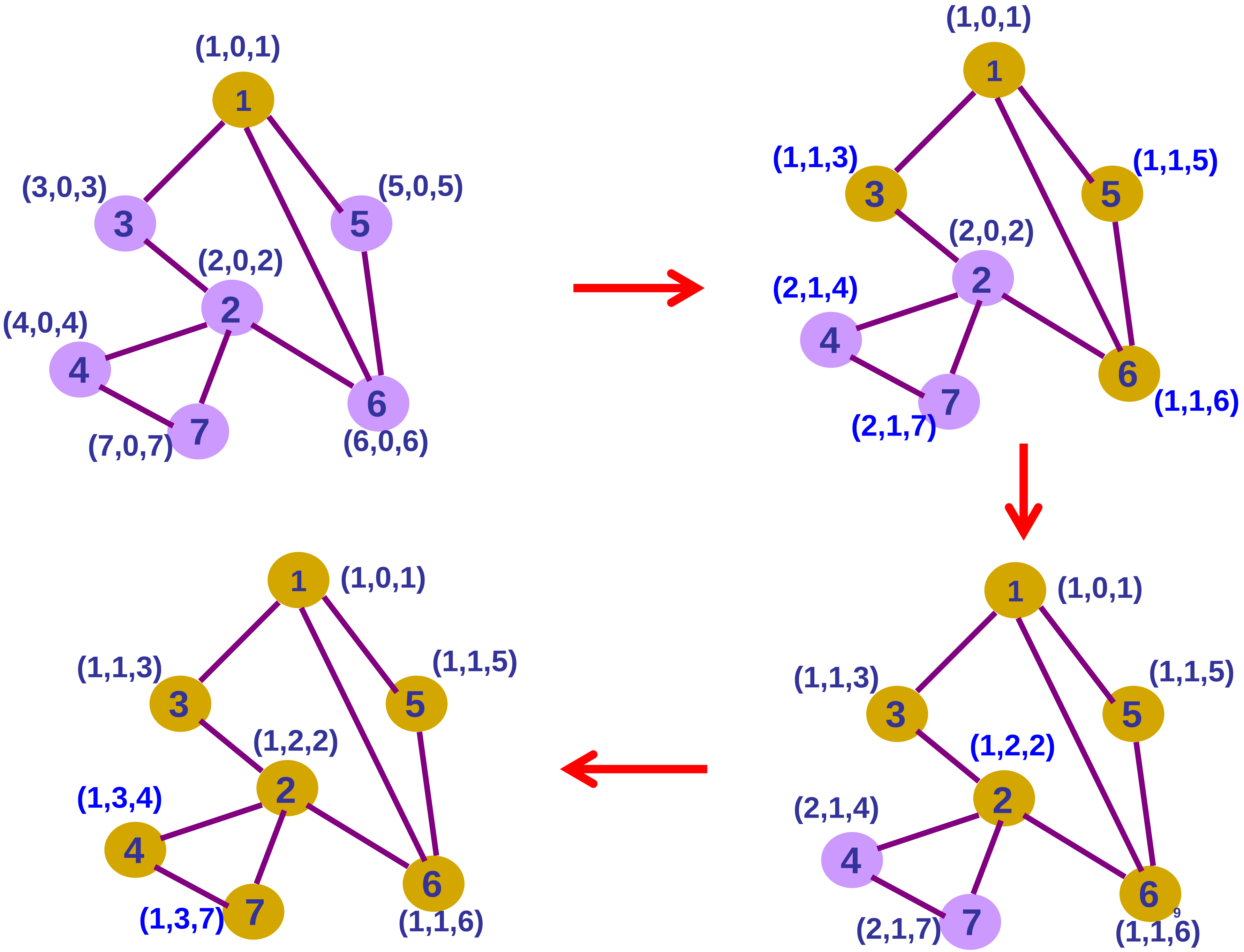
- When there are multiple shortest paths to the root, choose the path that uses the neighbor switch with the lower ID
  - One could use any tiebreaking system, but this is an easy one to remember and implement

Constructing a spanning tree

- Messages (Y, d, X)
  - From node X
  - Proposing Y as the root
  - And advertising a distance d to Y
- Switches elect the node with smallest identifier (MAC address) as root
- Each switch determines if a link is on its shortest path to the root; excludes it from the tree if not

Steps in the spanning tree algorithm

- Initially, each switch proposes itself as the root
  - Switch X announces (X, 0, X) to its neighbors
- Switches update their view of the root
  - Upon receiving (Y, d, Z) from Z, check Y's id
  - If Y's id < current root: set root = Y
- Switches compute their distance from the root
  - Add 1 to the shortest distance received from a neighbor
- If root or shortest distance to it changed, send neighbors updated message (Y, d+1, X)


(1,0,1)
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(3,0,3)
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(5,0,5)
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(2,1,7)
7
(1,1,6)

Robust spanning tree algorithm

- Algorithm must react to failures
  - Failure of the root node
  - Failure of other switches and links
- Root switch sends periodic root announcement messages
  - Other switches continue forwarding messages
- Detecting failures through timeout
  - If no word from root, time out and claim to be the root!

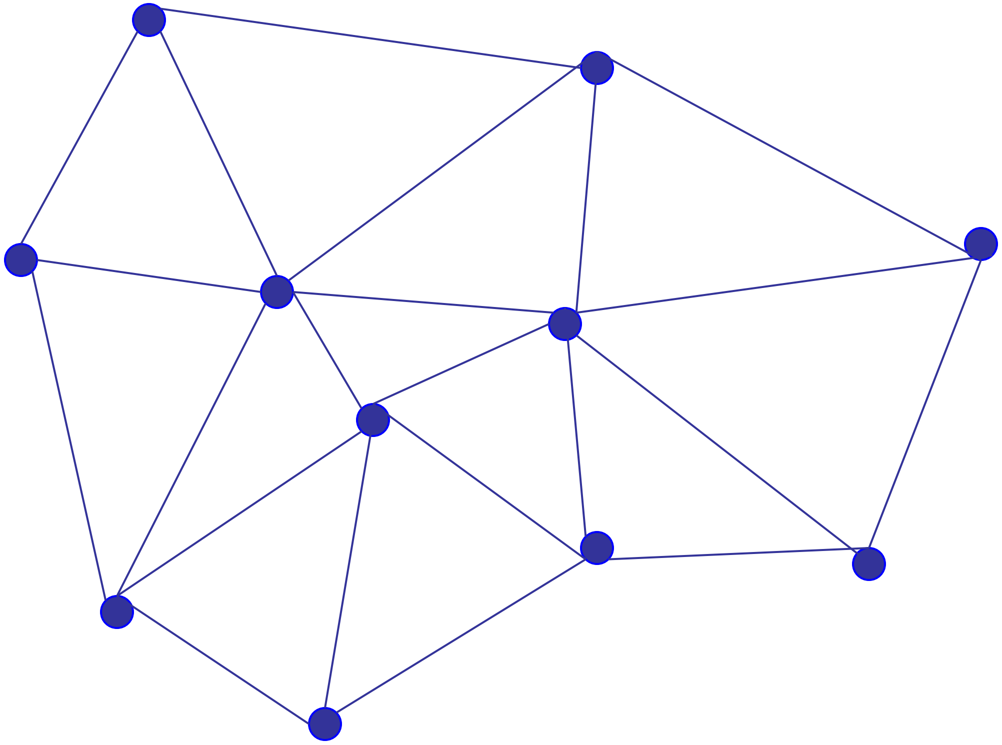
Ethernet topics

- Frames and framing
- Addressing
- Routing
- Forwarding
- Discovery

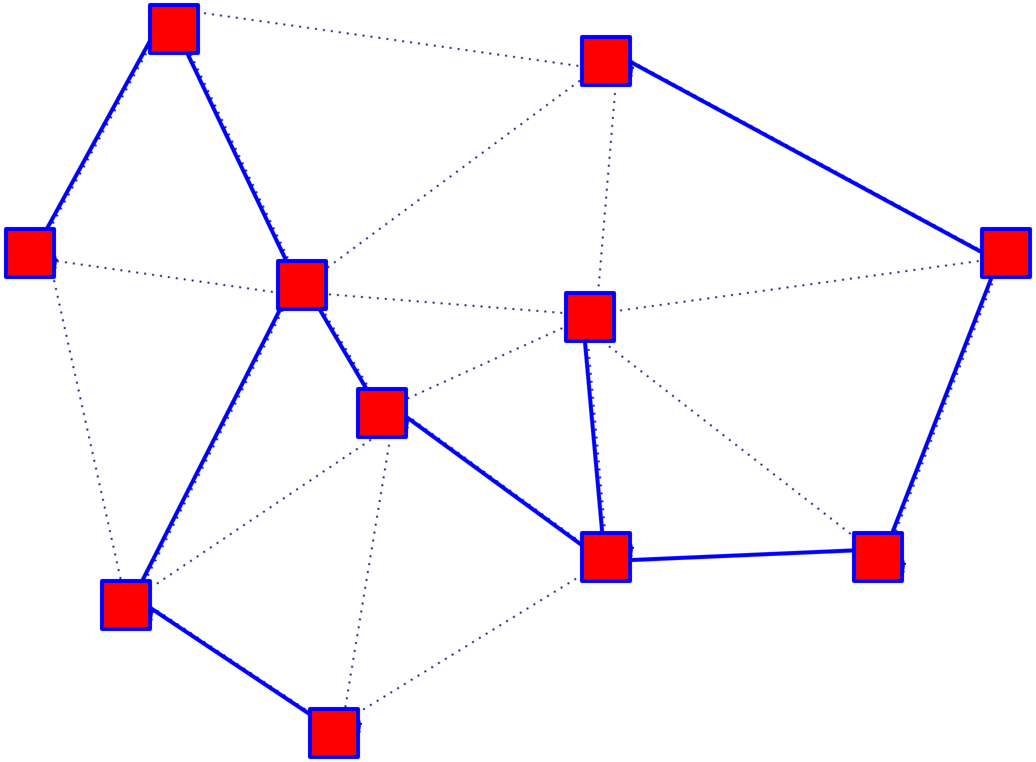
Flooding on a spanning tree

- Switches flood using the following rule:
    - (Ignore all ports not on spanning tree!)
    - Originating switch sends packet out all ports
    - When a packet arrives on one incoming port, send it out all ports other than the incoming port

Flooding on spanning tree



Flooding on spanning tree



But isn't flooding wasteful?

- Yes, but we can use it to bootstrap more efficient forwarding
- Idea: watch the packets going by, and learn from them
  - If node A sees a packet from node B come in on a particular port, it knows what port to use to reach B!
  - Works because there is only one path to B

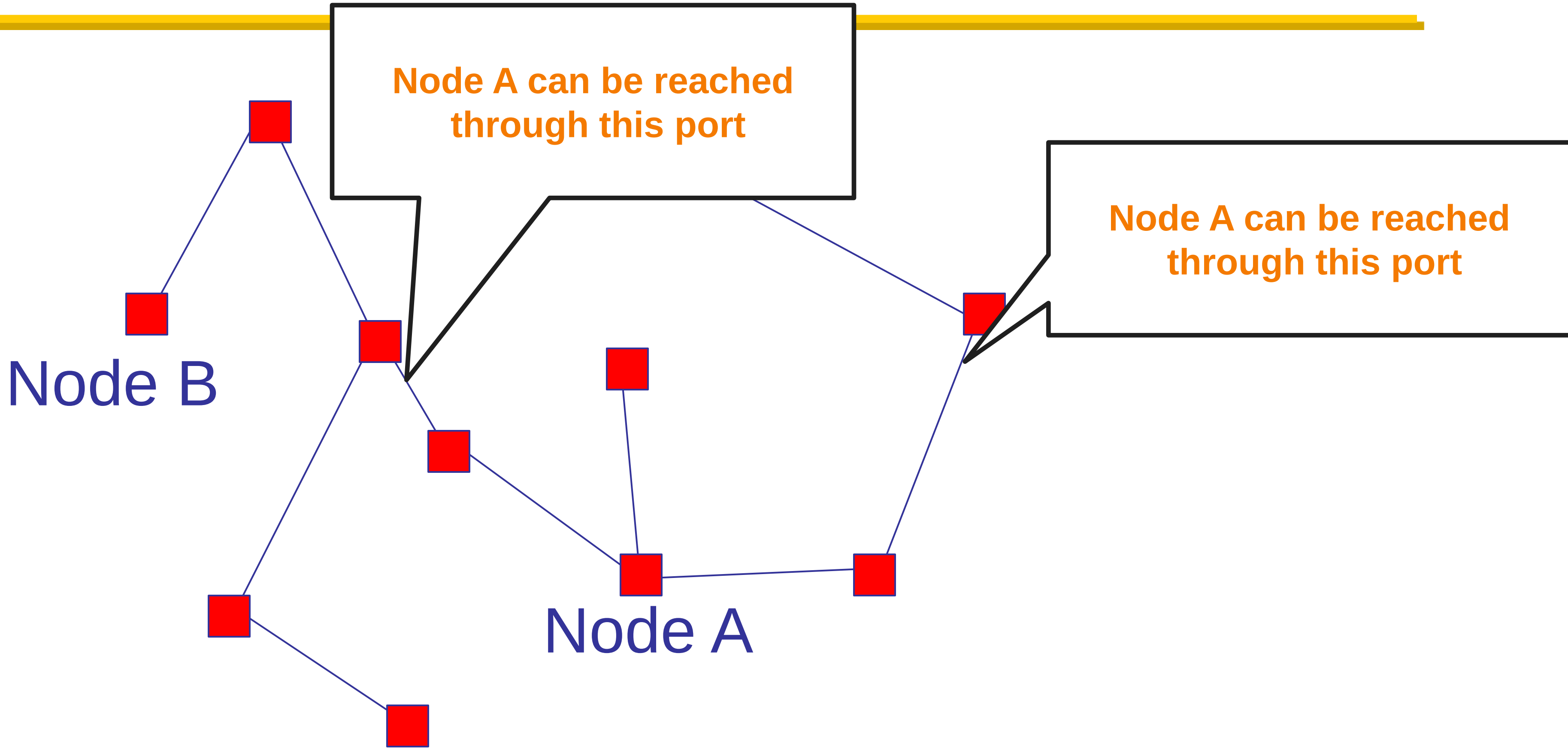
Nodes can “learn” routes

- Switch learns how to reach nodes by remembering where flooding packets came from
  - If flood packet from Node A entered switch on port 4, then switch uses port 4 to send to Node A

General approach

- Flood first packet to node you are trying to reach
- All switches learn where you are
- When destination responds, some switches learn where it is…
  - Only some switches, because packet to you follows direct path, and is not flooded

Learning from flood packets

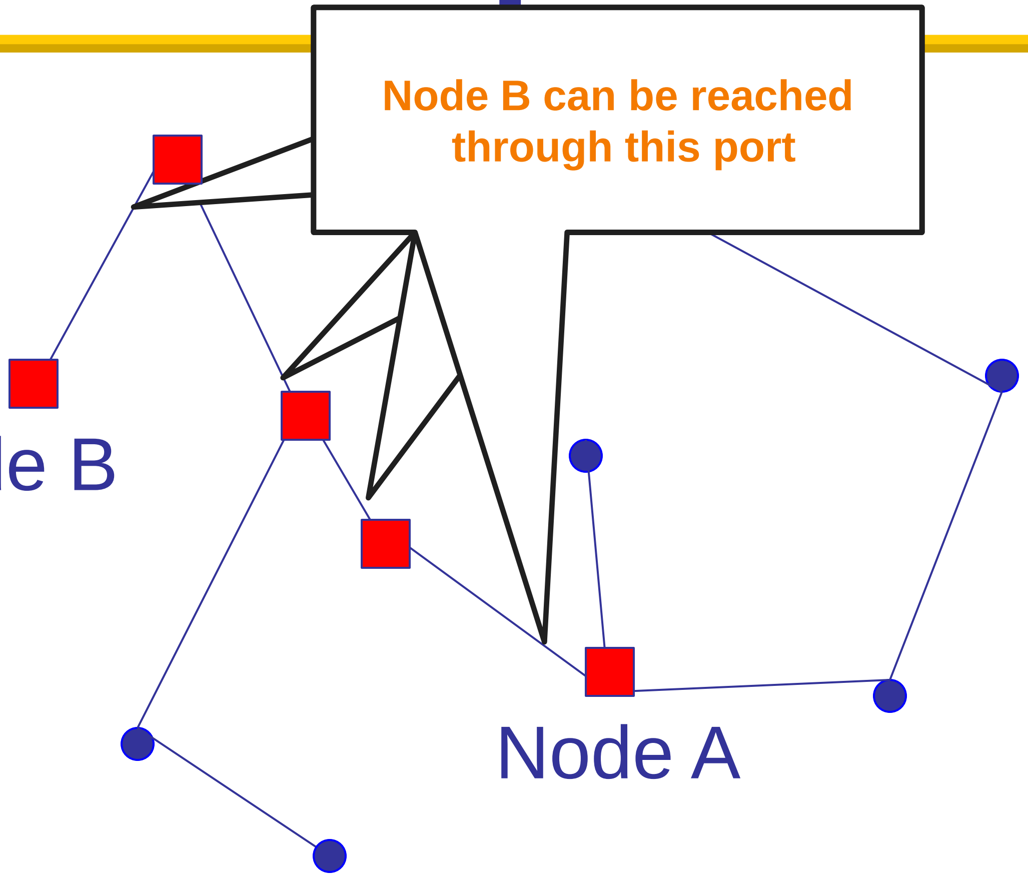


Node A can be reached through this port

Node A can be reached through this port

Once a node has sent a flood message, all other switches know how to reach it….

Node B responds

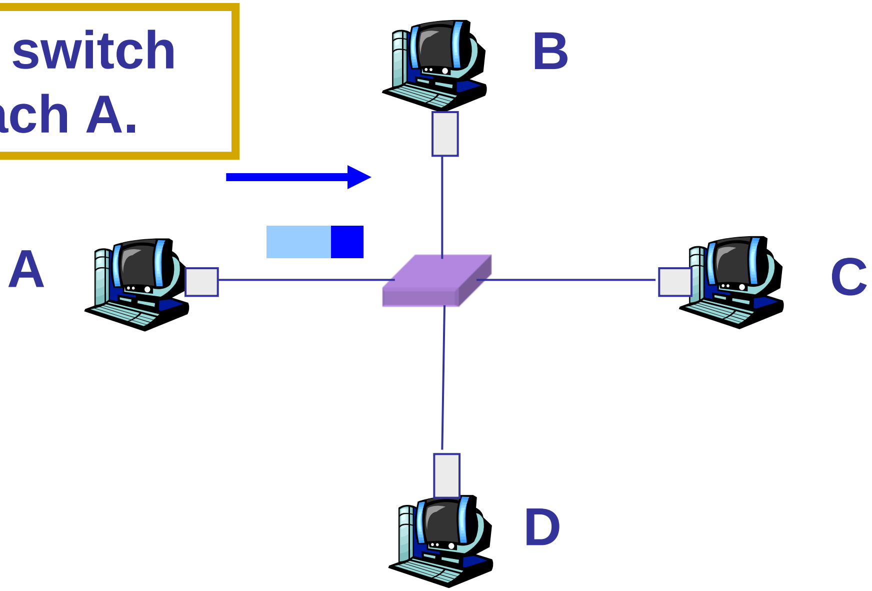


When a node responds, some of the switches learn where it is

Ethernet switches are “self learning”

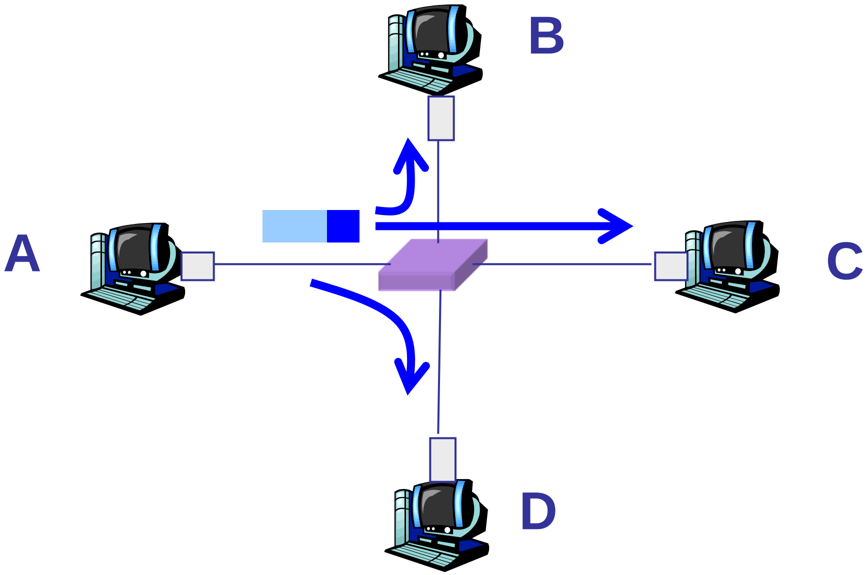
- When a packet arrives:
  - Inspect source MAC address, associate with incoming port
  - Store mapping in the switch table
  - Use time-to-live field to eventually forget mapping

Packet tells switch how to reach A.



Self learning: Handling misses

- When packet arrives with unfamiliar destination
- Forward packet out all other ports
- Response may teach switch about that destination



Summary of learning approach

- Avoids loop by restricting to spanning tree
  - This makes flooding possible
- Flooding allows packet to reach destination
- And in the process switches learn how to reach source of flood
- No route “computation”
- Forwarding entries a consequence of traffic pattern

Contrast

IP

- Packets forwarded on all available links
- Addresses can be aggregated
- Routing protocol computes loop-free paths
- Forwarding table computed by routing protocol

Ethernet

- Packets forwarded on subset of links (spanning tree)
- Flat addresses
- “Routing” protocol computes loop-free topology
- Forwarding table derived from data packets(+ spanning tree for floods)

Strengths of Ethernet's approach

- Plug-n-Play: zero-configuration / self-*
- Simple
- Cheap?

Weaknesses of Ethernet's approach

- Much of the network bandwidth goes unused
  - Forwarding is only over the spanning tree
- Delay in reestablishing spanning tree
  - Network is "down" until spanning tree rebuilt
  - Rebuilt spanning tree may be quite different
- Slow to react to host movement
  - Entries must time out
- Poor predictability
  - Location of root and traffic pattern determines forwarding efficiency

Link layer topics

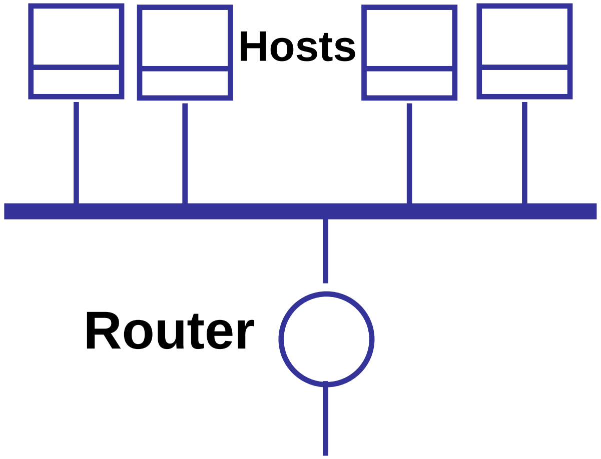
- Frames and framing
- Addressing
- Routing
- Forwarding
- Discovery and bootstrapping

Discovery

- A host is “born” knowing only its MAC address
- Must discover lots of information before it can communicate with a remote host B
  - What is my IP address?
  - What is B’s IP address? (remote)
  - What is B’s MAC address? (if B is local)
  - What is my first-hop router’s address? (if B is not local)
  - …

ARP and DHCP

- Link layer discovery protocols
  - ARP → Address Resolution Protocol
  - DHCP → Dynamic Host Configuration Protocol
  - Confined to a single local-area network (LAN)
  - Rely on broadcast capability



ARP and DHCP

- Link layer discovery protocols
- Serve two functions
  - Discovery of local end-hosts
    - »For communication between hosts on the same LAN
  - Bootstrap communication with remote hosts
    - »What's my IP address?
    - »Who/where is my local DNS server?
    - »Who/where is my first hop router?

DHCP

- Dynamic Host Configuration Protocol
  - Defined in RFC 2131
- A host uses DHCP to discover
  - Its own IP address
  - Its netmask
  - IP address(es) for its local DNS name server(s)
  - IP address(es) for its first-hop “default” router(s)

DHCP: Operation

- One or more local DHCP servers maintain required information
  - IP address pool, netmask, DNS servers, etc.
  - Application that listens on UDP port 67

DHCP: Operation

- One or more local DHCP servers maintain required information
- Client broadcasts a DHCP discovery message
  - L2 broadcast, to MAC address FF:FF:FF:FF:FF:FF

DHCP: Operation

- One or more local DHCP servers maintain required information
- Client broadcasts a DHCP discovery message
- One or more DHCP servers responds with a DHCP “offer” message
  - Proposed IP address for client, lease time
  - Other parameters

DHCP: Operation

- One or more local DHCP servers maintain required information
- Client broadcasts a DHCP discovery message
- One or more DHCP servers responds with a DHCP “offer” message
- Client broadcasts a DHCP request message
  - Specifies which offer it wants
  - Echoes accepted parameters
  - Other DHCP servers learn they were not chosen

DHCP: Operation

- One or more local DHCP servers maintain required information
- Client broadcasts a DHCP discovery message
- One or more DHCP servers responds with a DHCP “offer” message
- Client broadcasts a DHCP request message
- Selected DHCP server responds with an ACK

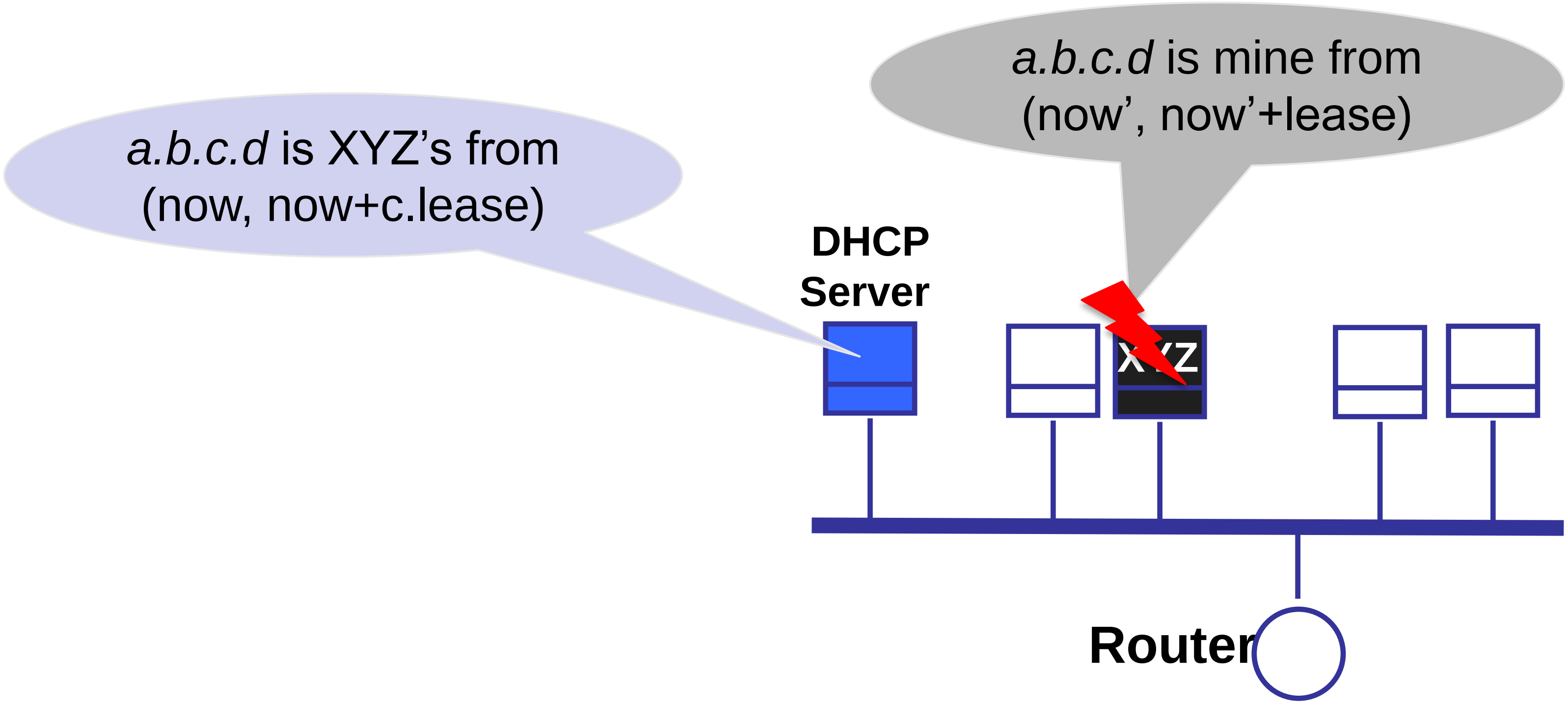
DHCP: Operation

- One or more local DHCP servers maintain required information
- Client broadcasts a DHCP discovery message
- One or more DHCP servers responds with a DHCP “offer” message
- Client broadcasts a DHCP request message
- Selected DHCP server responds with an ACK
- DHCP “relay agents” used when the DHCP server is not on the same broadcast domain

DHCP uses “soft state”

- Soft state: if not refreshed, state is forgotten
  - Hard state: allocation/revocation is deliberate
- Implementation:
  - Address allocations have a lease period
  - Server sets a timer for each allocation
  - Client must request a refresh before lease expires
  - Server resets timer when a refresh arrives and ACKs
    - »OR reclaims allocated address when timer expires
- Simple, yet robust under failure

Soft state under failure

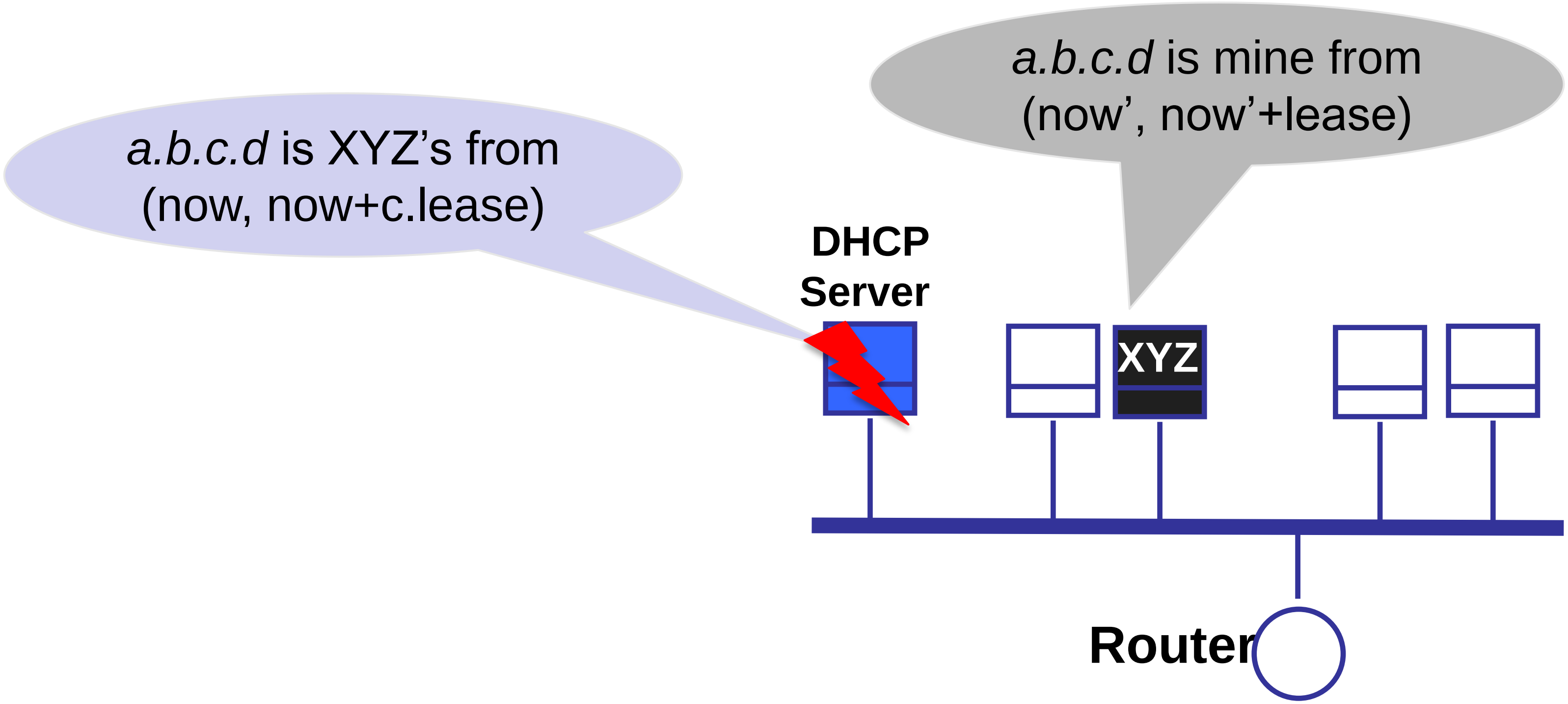


a.b.c.d is XYZ’s from (now, now+c.lease)

a.b.c.d is mine from (now’, now’+lease)

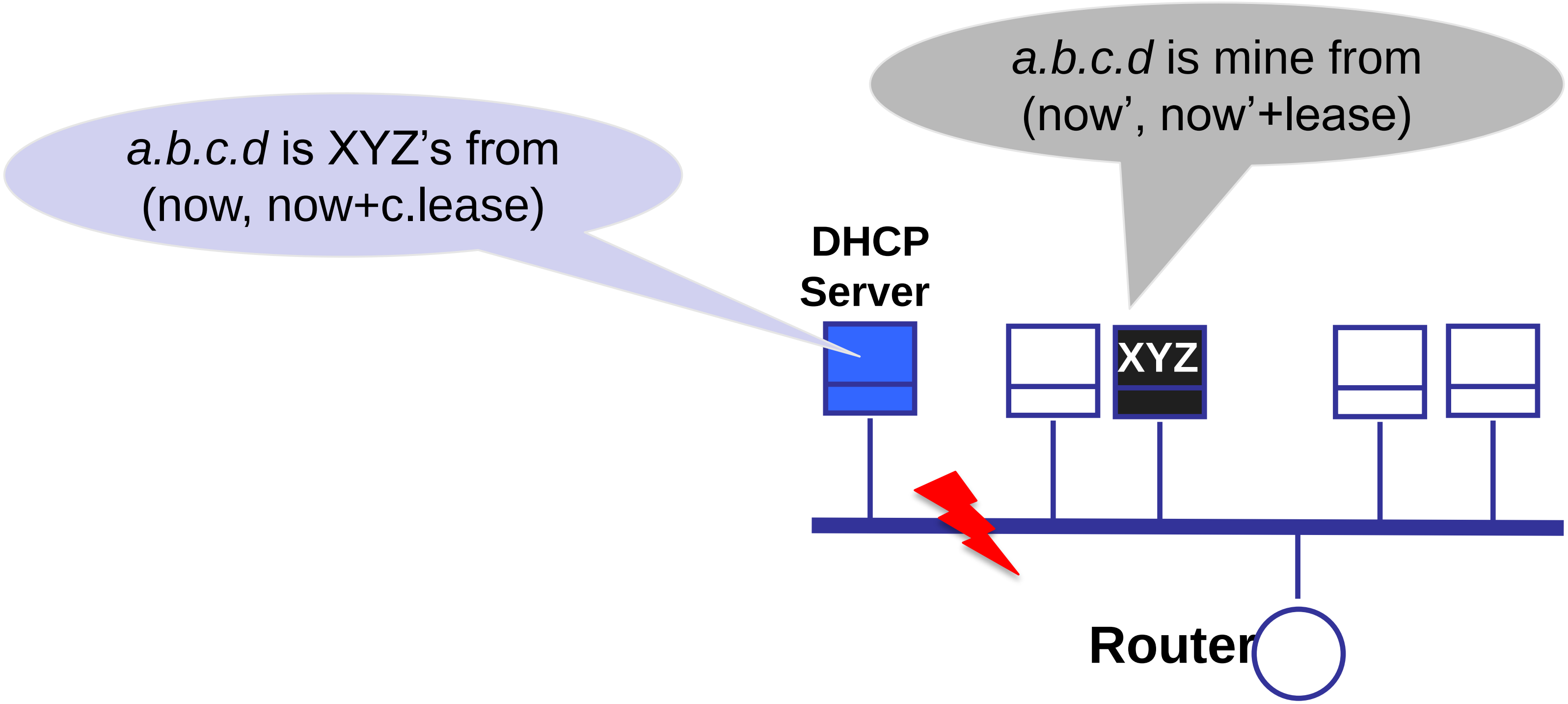
- What happens when host XYZ fails?
  - Refreshes from XYZ stop
  - Server reclaims a.b.c.d after O(lease period)

Soft state under failure


a.b.c.d is XYZ's from (now, now+c.lease)
a.b.c.d is mine from (now', now'+lease)
DHCP Server
XYZ
Router

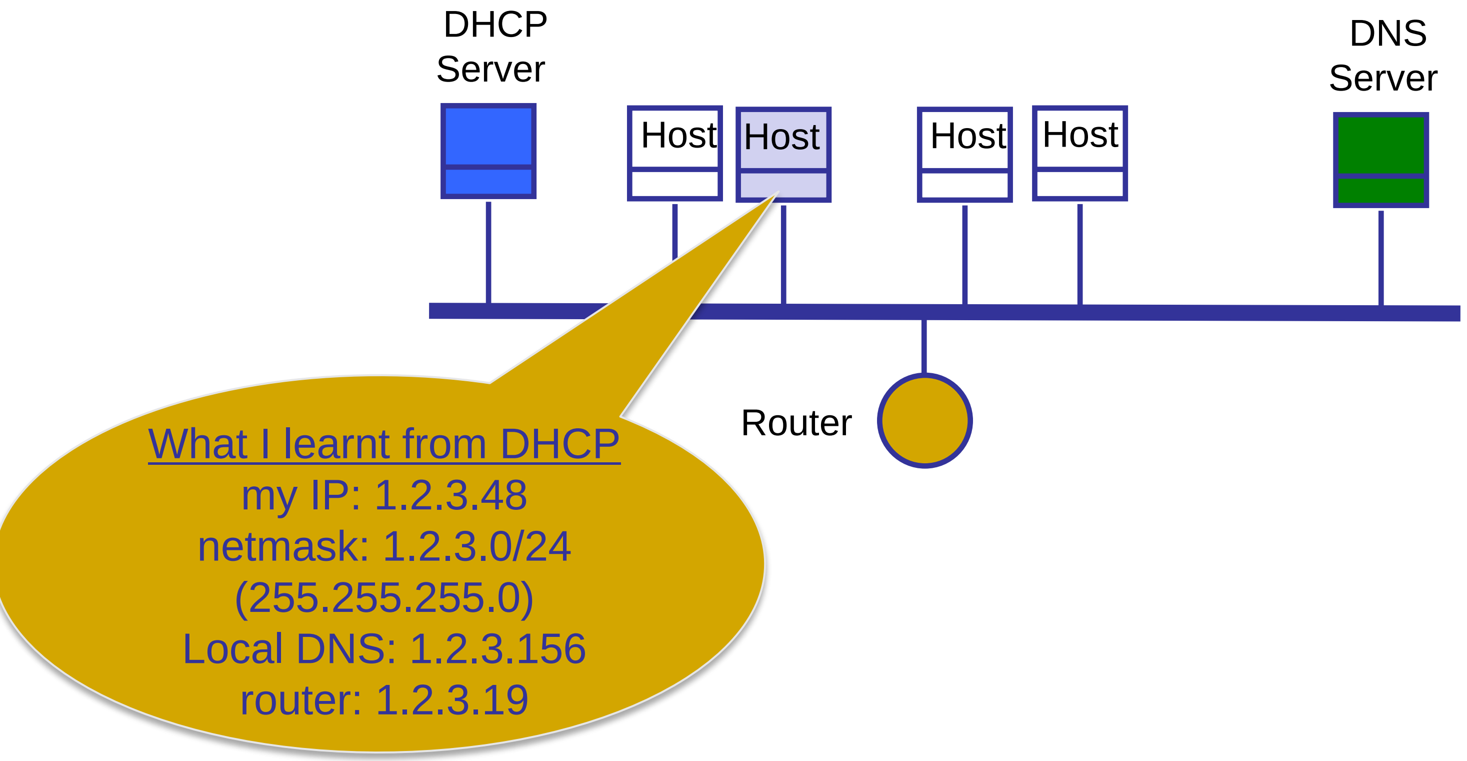
- What happens when server fails?
  - ACKs from server stop
  - XYZ releases address after O(lease period); send new request
  - A new DHCP server can come up from a `cold start' and we are back on track in ~lease time

Soft state under failure


a.b.c.d is XYZ's from (now, now+c.lease)
a.b.c.d is mine from (now', now'+lease)
DHCP Server
XYZ
Router

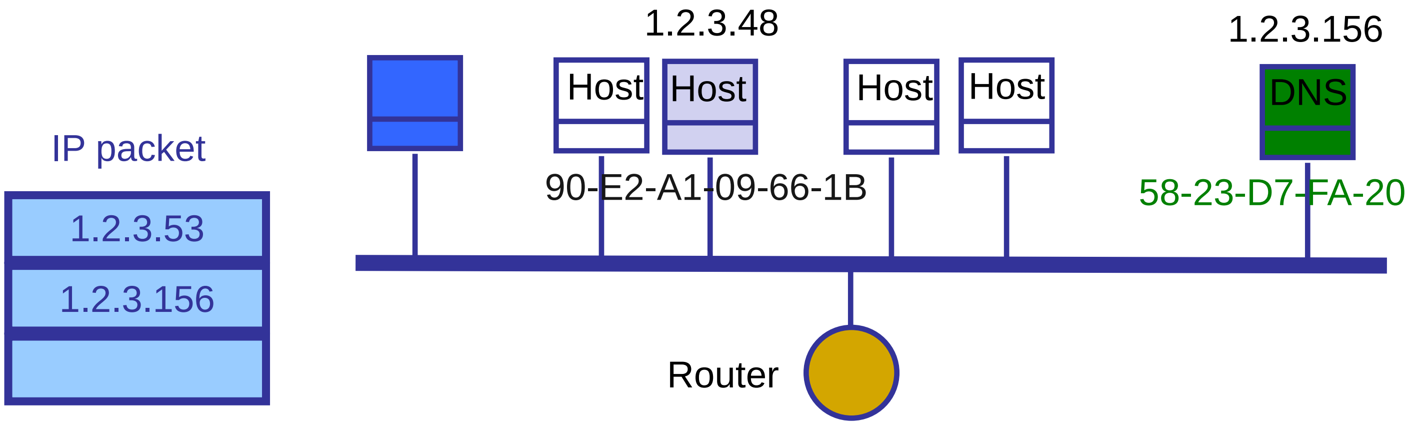
- What happens if the network fails?
  - Refreshes and ACKs don't get through
  - XYZ release address; DHCP server reclaims it

Are we there yet?



What I learnt from DHCP
my IP: 1.2.3.48
netmask: 1.2.3.0/24
(255.255.255.0)
Local DNS: 1.2.3.156
router: 1.2.3.19

Sending packets over link Layer



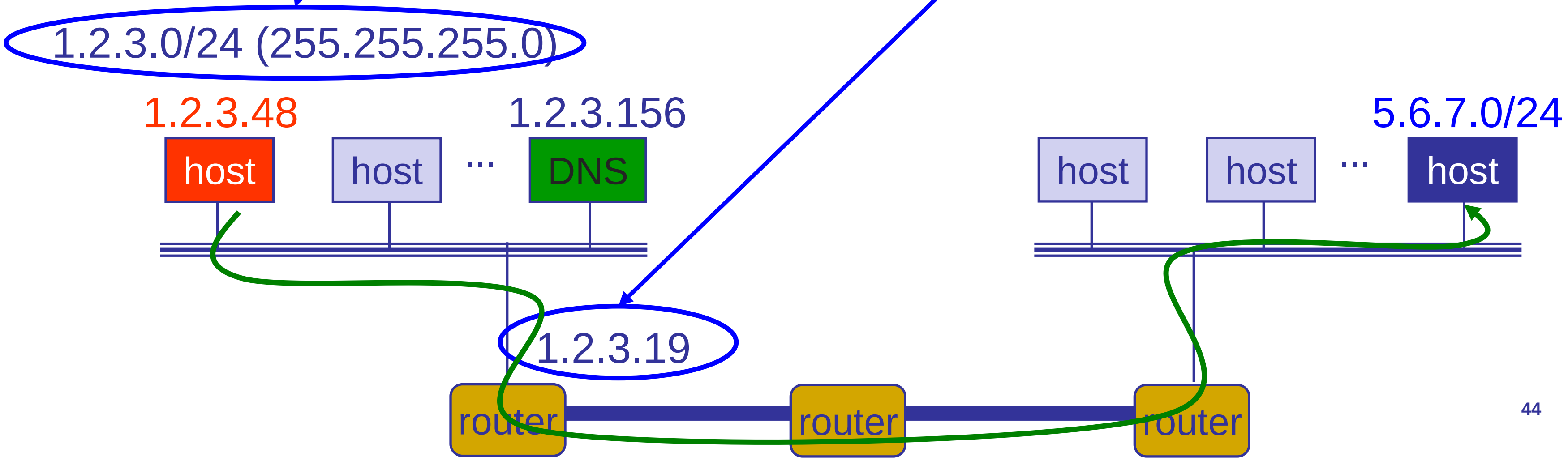
- Link layer only understands MAC addresses
  - Translate the destination IP address to MAC address
  - Encapsulate the IP packet in a link-level (Ethernet) frame

ARP: Address Resolution Protocol

- Every host maintains an ARP table
  - List of (IP address → MAC address) pairs
- Consult the table when sending a packet
  - Map dest. IP address to dest. MAC address
  - Encapsulate (IP) data packet with MAC header; xmit
- What if IP address not in the table?
  - Sender broadcasts: Who has IP address 1.2.3.156?
  - Receiver replies: MAC address 58-23-D7-FA-20-B0
  - Sender caches result in its ARP table

What if the destination is remote?

- Look up the MAC address of the first hop router
  - 1.2.3.48 uses ARP to find MAC address for first-hop router **1.2.3.19** rather than ultimate destination IP address
- How does the red host know the destination is not local?
  - Uses netmask (discovered via DHCP)
- How does the red host know about 1.2.3.19?
  - Also DHCP



Key ideas in both ARP and DHCP

- Broadcasting: Can use broadcast to make contact
  - Scalable because of limited size
- Caching: remember the past for a while
  - Store the information you learn to reduce overhead
- Soft state: eventually forget the past
  - Associate a time-to-live field with the information
  - … and either refresh or discard the information
  - Key for robustness in the face of unpredictable change

ID resolution in the networking stack

Layer	Examples	Structure	Configuration	Resolution Service
App. Layer	cse.umich.edu	Organizational hierarchy	~ manual	↕ DNS
Network Layer	123.45.6.78	topological hierarchy	DHCP	↕ ARP
Link layer	45-CC-4E-12-F0-97	vendor (flat)	hard-coded	

Discovery mechanisms

- We have seen two approaches
  - Broadcast (ARP, DHCP)
    - »Flooding does not scale
    - »No centralized point of failure
    - »Zero configuration
  - Directory service (DNS)
    - »No flooding / scalable
    - »Root of the directory is vulnerable (caching is key)
    - »Needs configuration to bootstrap (local, root servers, etc.)

Summary

- Spanning tree enables Ethernet to efficiently flood a network to learn routes while forwarding packets
- DHCP and ARP form the discovery backplane of networking and make everything work together