The Link Layer: Ethernet

CPSC 433/533, Spring 2021

Anurag Khandelwal

Outline

- Frames and framing
- Addressing
- Routing
- Forwarding
- Discovery: Bootstrapping end-to-end communication

Medium Access Control Address

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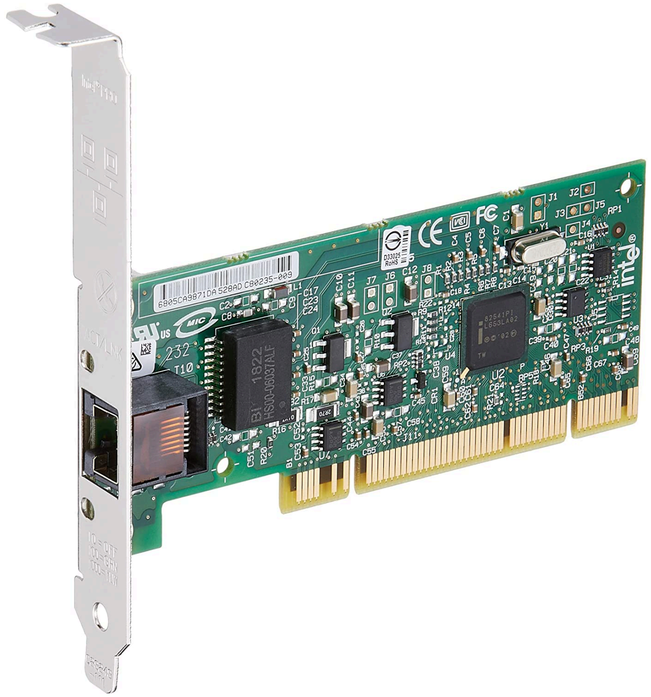
- **MAC address**
  - Numerical address associated with a network adapter
  - Flat namespace of 48 bits (e.g., 00-15-C5-49-04-A9 in HEX)



Medium Access Control Address

- **MAC address**
  - Numerical address associated with a network adapter
  - Flat namespace of 48 bits (e.g., 00-15-C5-49-04-A9 in HEX)
- **Hierarchical allocation**
  - Blocks: assigned to vendors (e.g., Dell) by the IEEE
    - First 24 bits (e.g., 00-15-C5-**-**-**)
  - Adapter: assigned by the vendor from its block
    - Last 24 bits (e.g., 00-15-C5-49-04-A9)

MAC address vs. IP address

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- **MAC addresses (used in link layer)**
  - *Hard-coded* when adapter is built
  - *Flat* namespace of 48 bits (e.g., 00-15-C5-49-04-A9)
  - Like a social security number
  - Portable and can stay the same as the host moves
  - Used to get packets between interfaces on the same network

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  - Like a social security number
  - Portable and can stay the same as the host moves
  - Used to get packets between interfaces on the same network
- **IP addresses**
  - *Configured*, or learned dynamically
  - *Hierarchical* namespace of 32 bits (e.g., 12.178.66.9)
  - Like a postal mailing address
  - Not portable, and depends on where the host is attached
  - Used to get a packet to destination IP subnet

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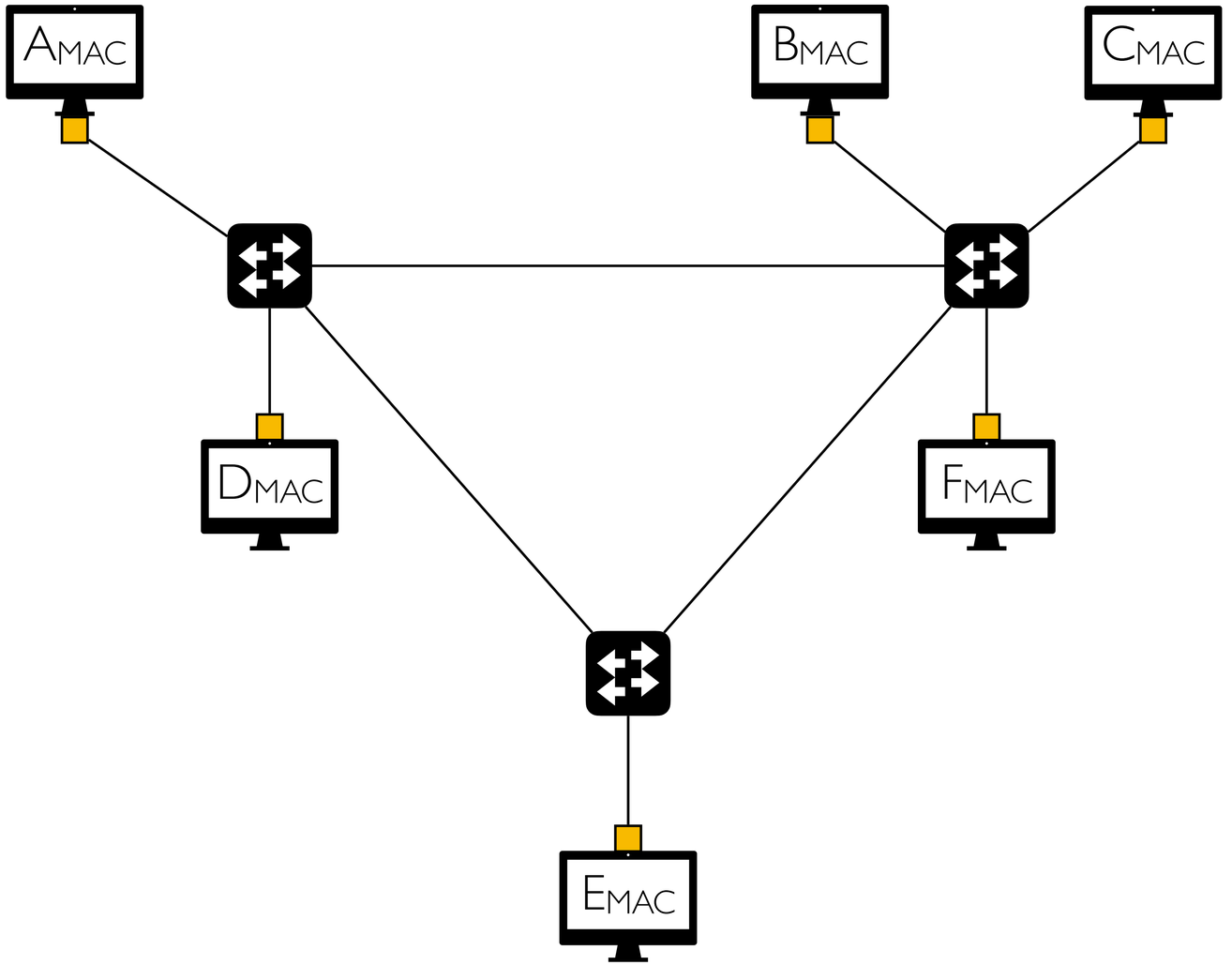
Routing with Switched Ethernet?



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- **Legacy**

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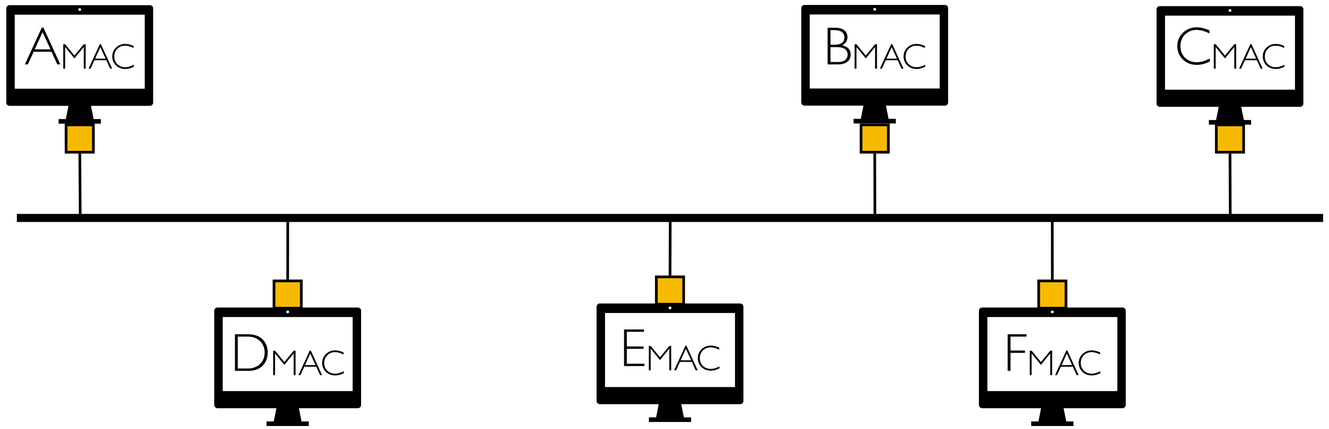
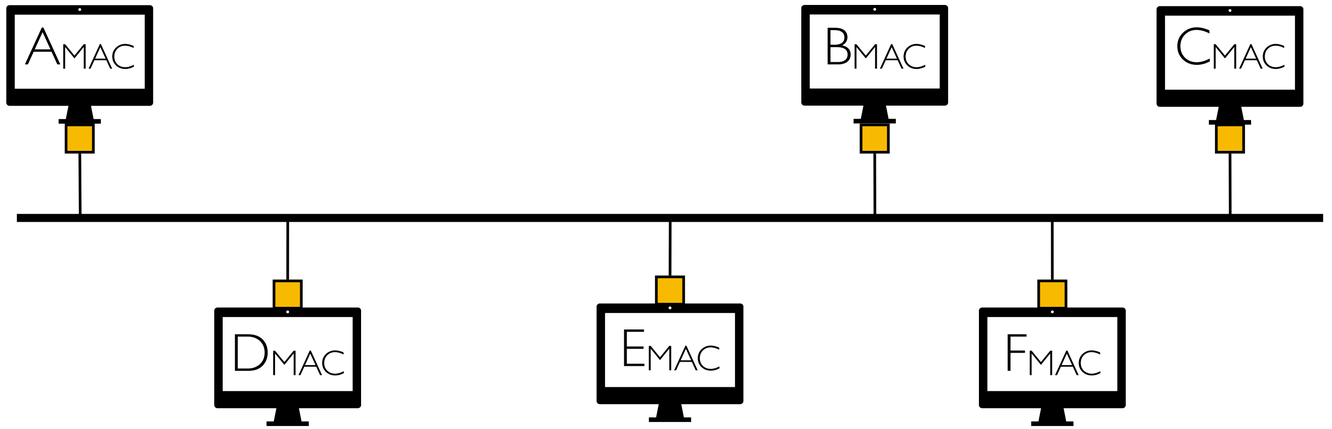


“Routing” with broadcast ethernet



- Sender transmits frame on to broadcast link

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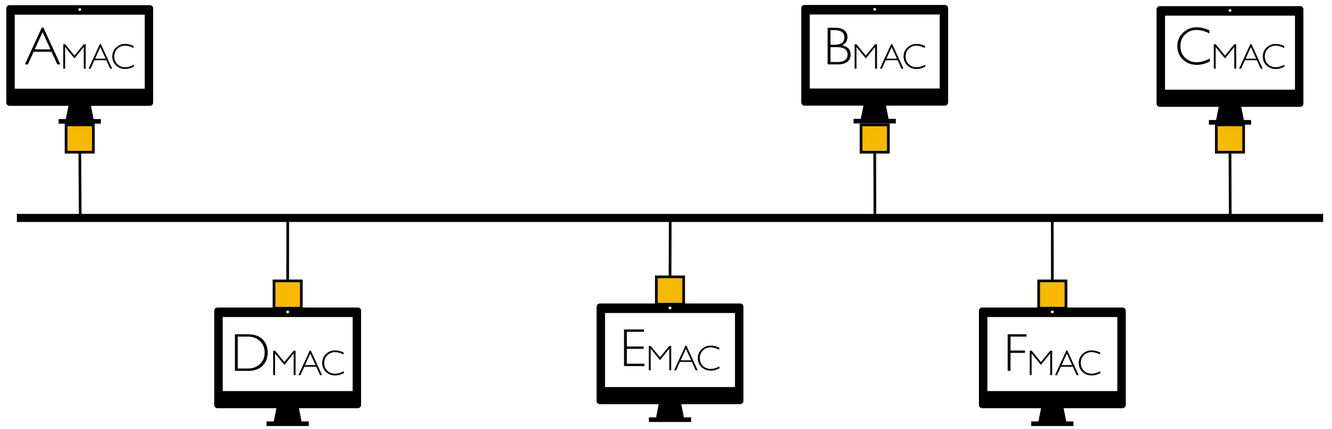

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- Frame contains destination MAC address

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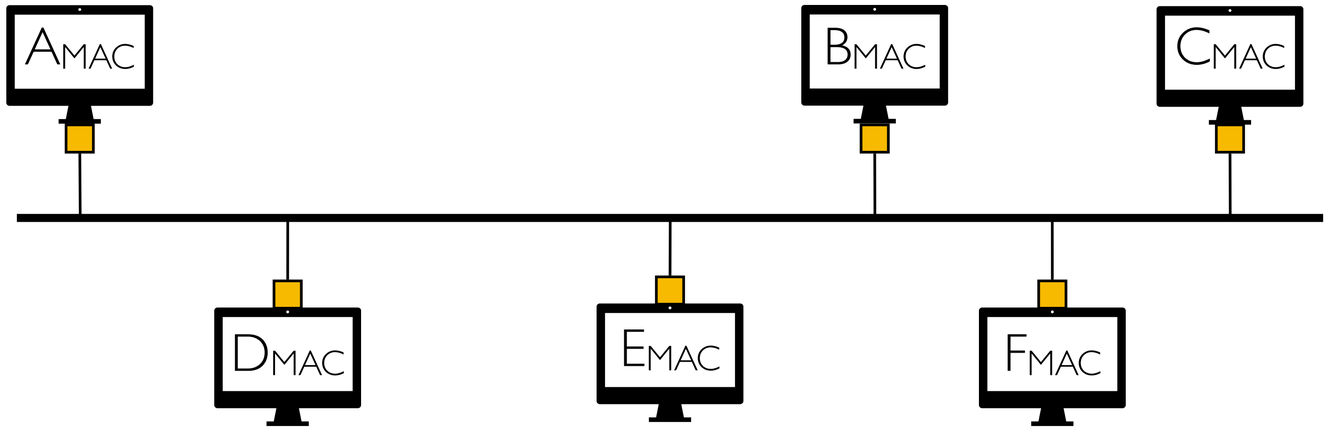
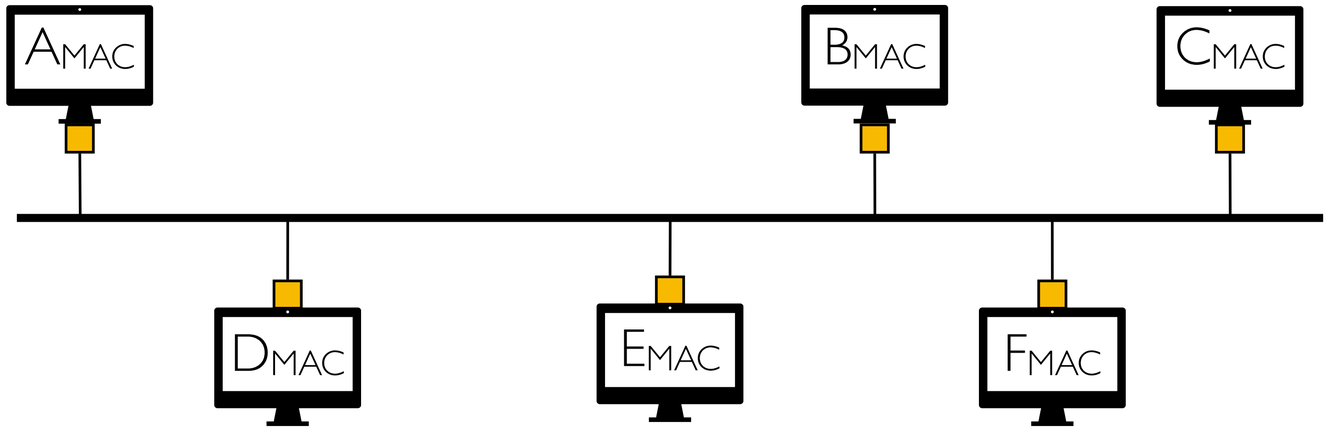


- Sender transmits frame on to broadcast link
- Frame contains destination MAC address
- Each receiver’s link layer passes the frame to the network layer
  - If destination address matches the receiver’s MAC address
  - Or if the destination address is the broadcast MAC address (ff:ff:ff:ff:ff:ff)

“Routing” with broadcast ethernet



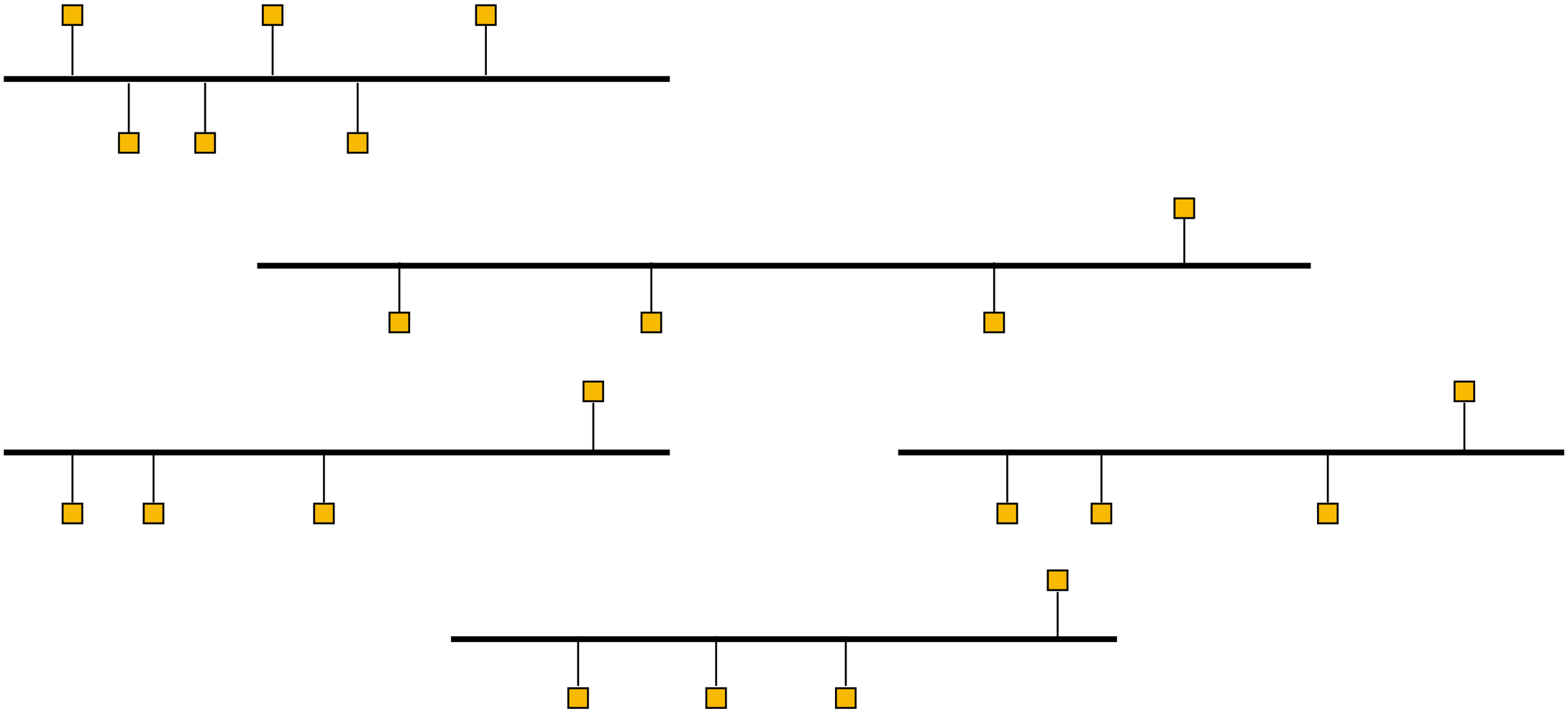
- **Ethernet is ‘plug-n-play’**
  - A new host plugs into the Ethernet and is good to go
  - No configuration by users or network operators
  - Broadcast as a means of bootstrapping communication

Why does Ethernet not use LS/DV?

- **Concerns over scalability**
  - Flat MAC addresses cannot be aggregated like IP addresses

- **Legacy**
  - Backward compatibility with broadcast Ethernet
  - Desire to maintain Ethernet's plug-n-play behavior
  - How broadcast Ethernet evolved

Some History: Routing in “Extended LANs”



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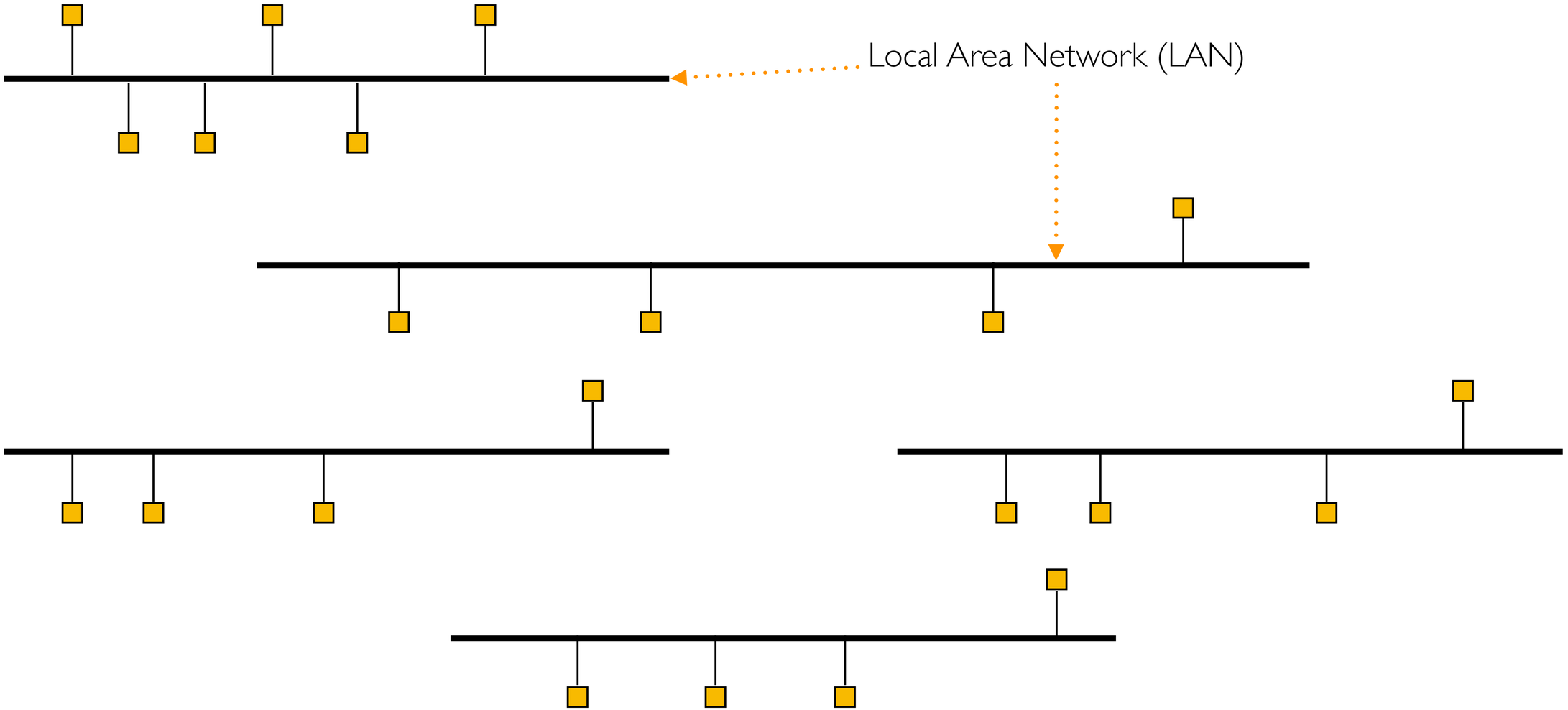

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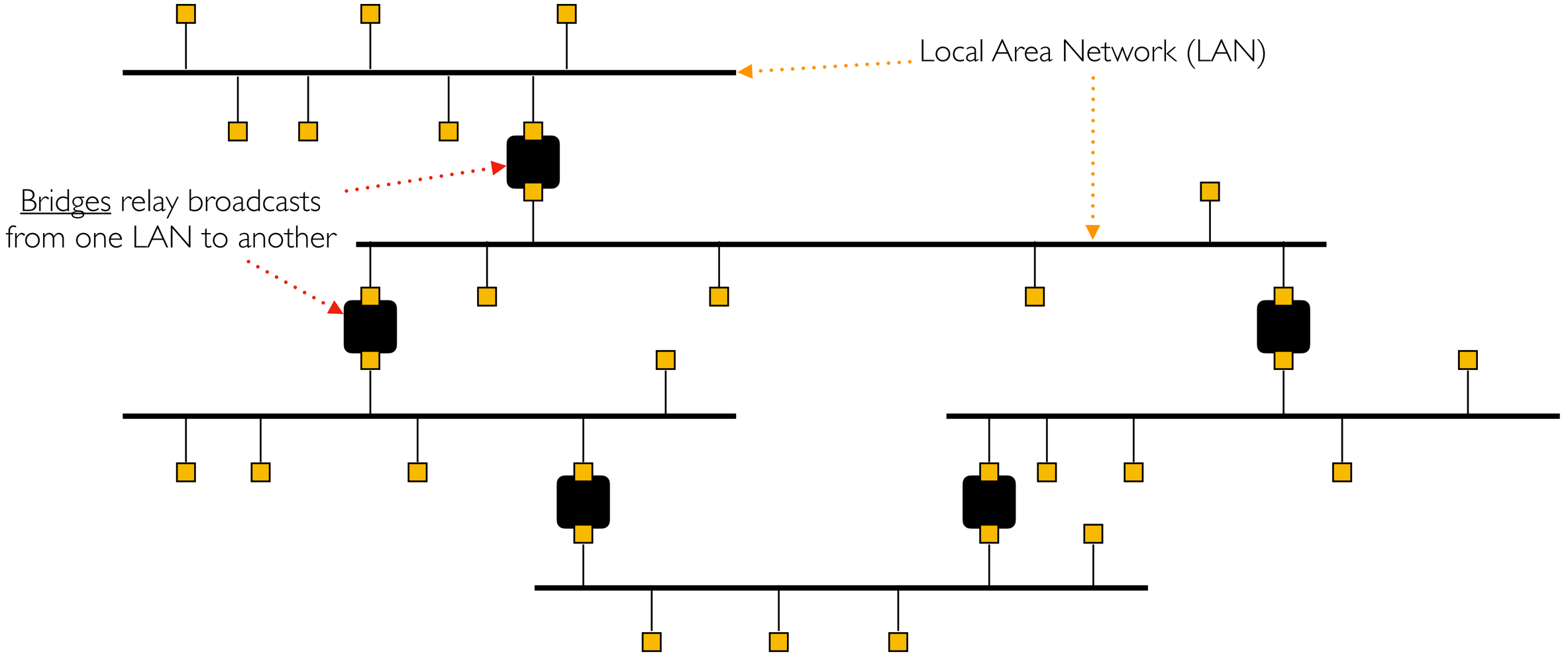

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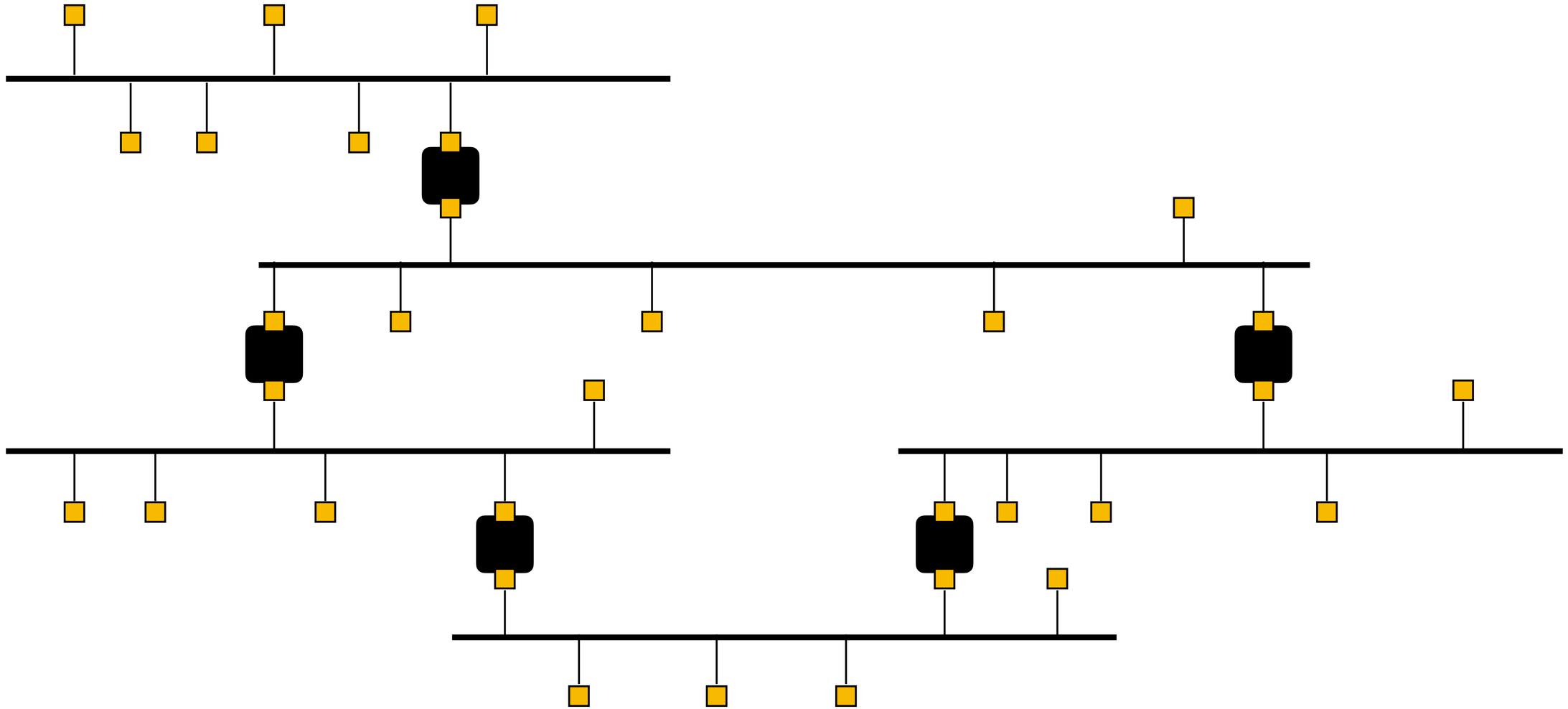

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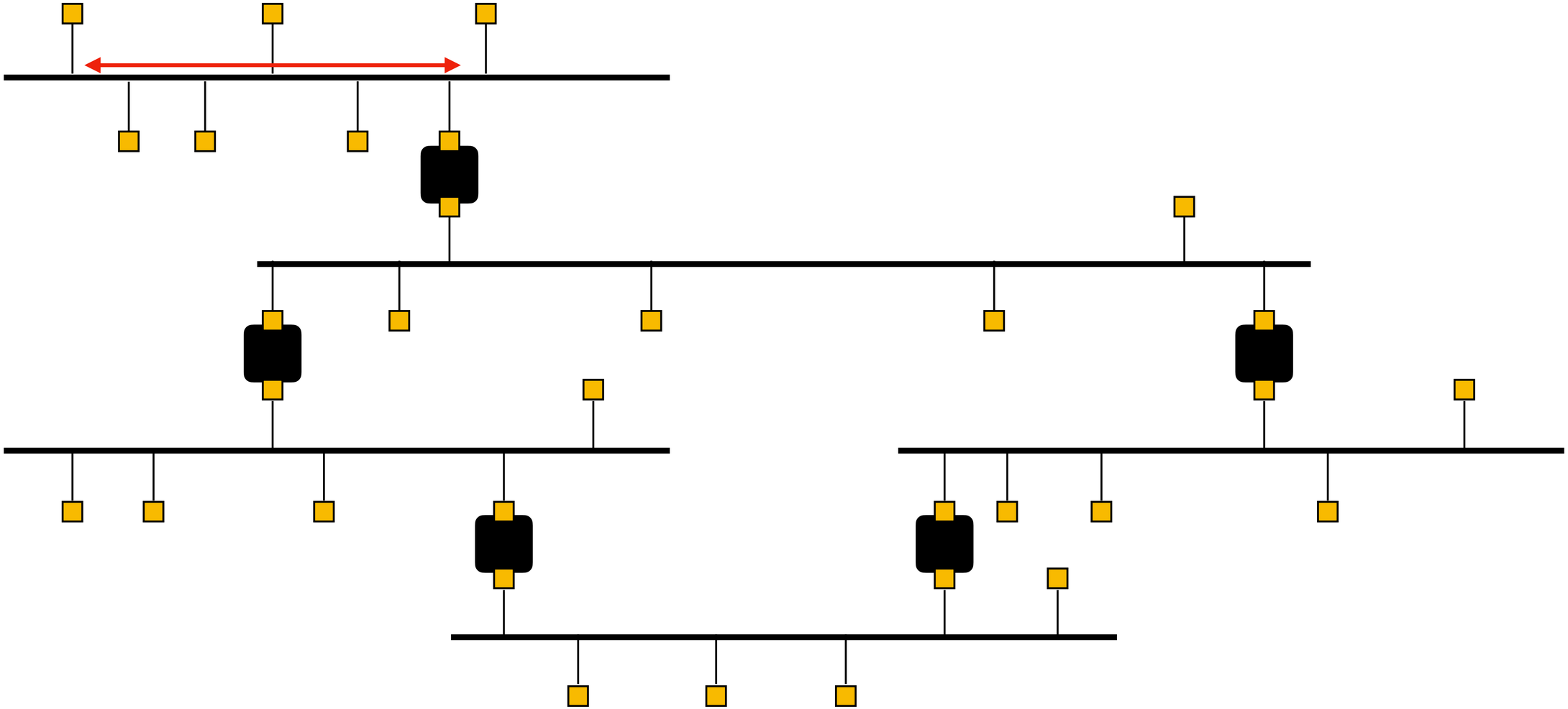

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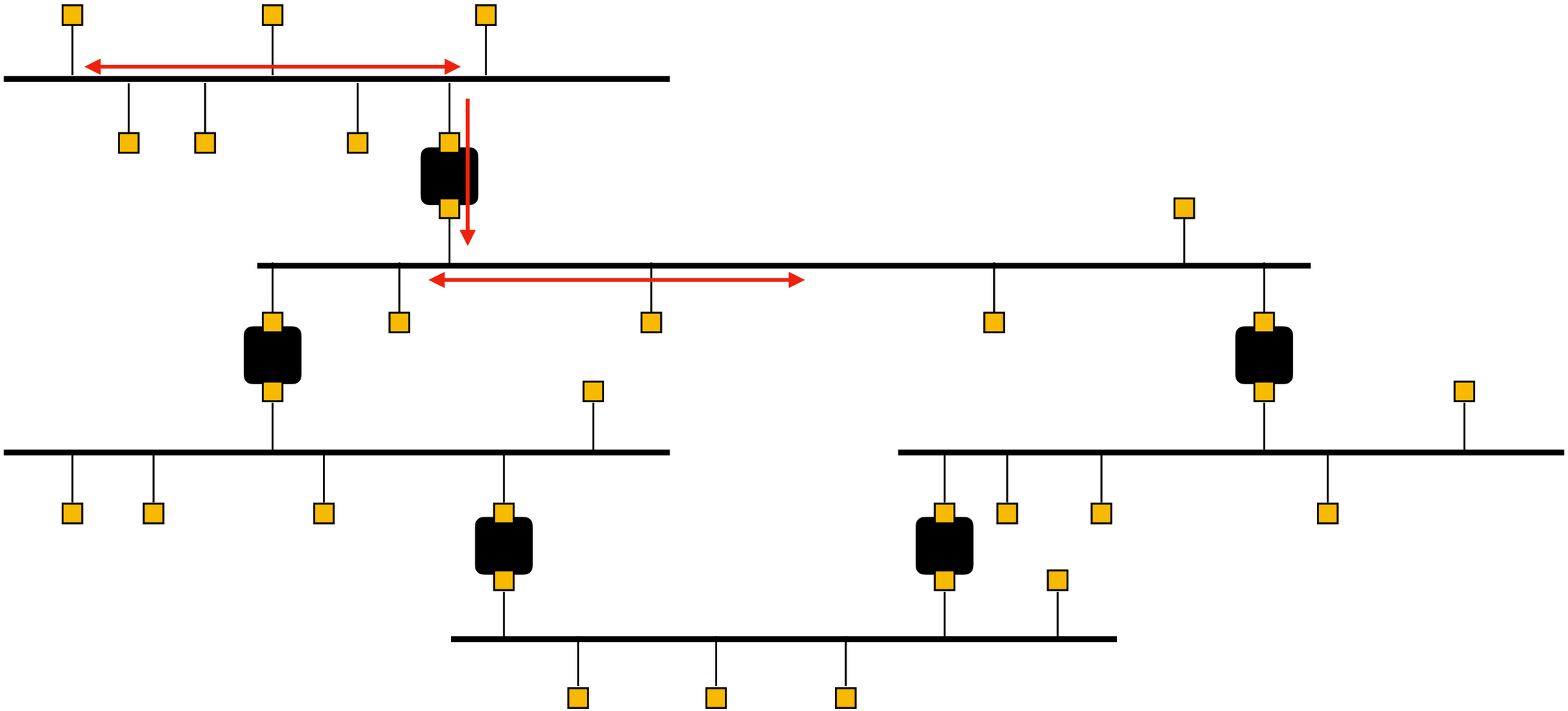

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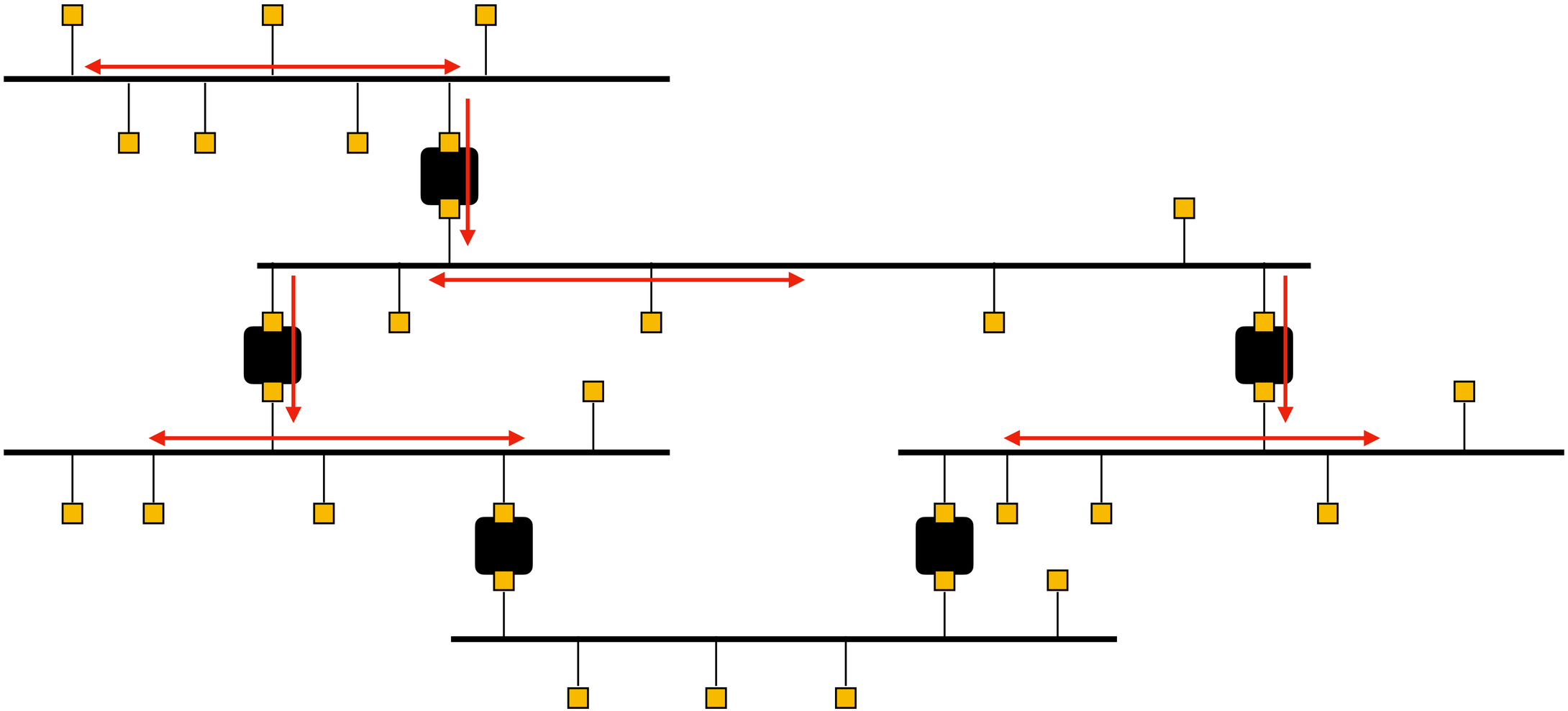

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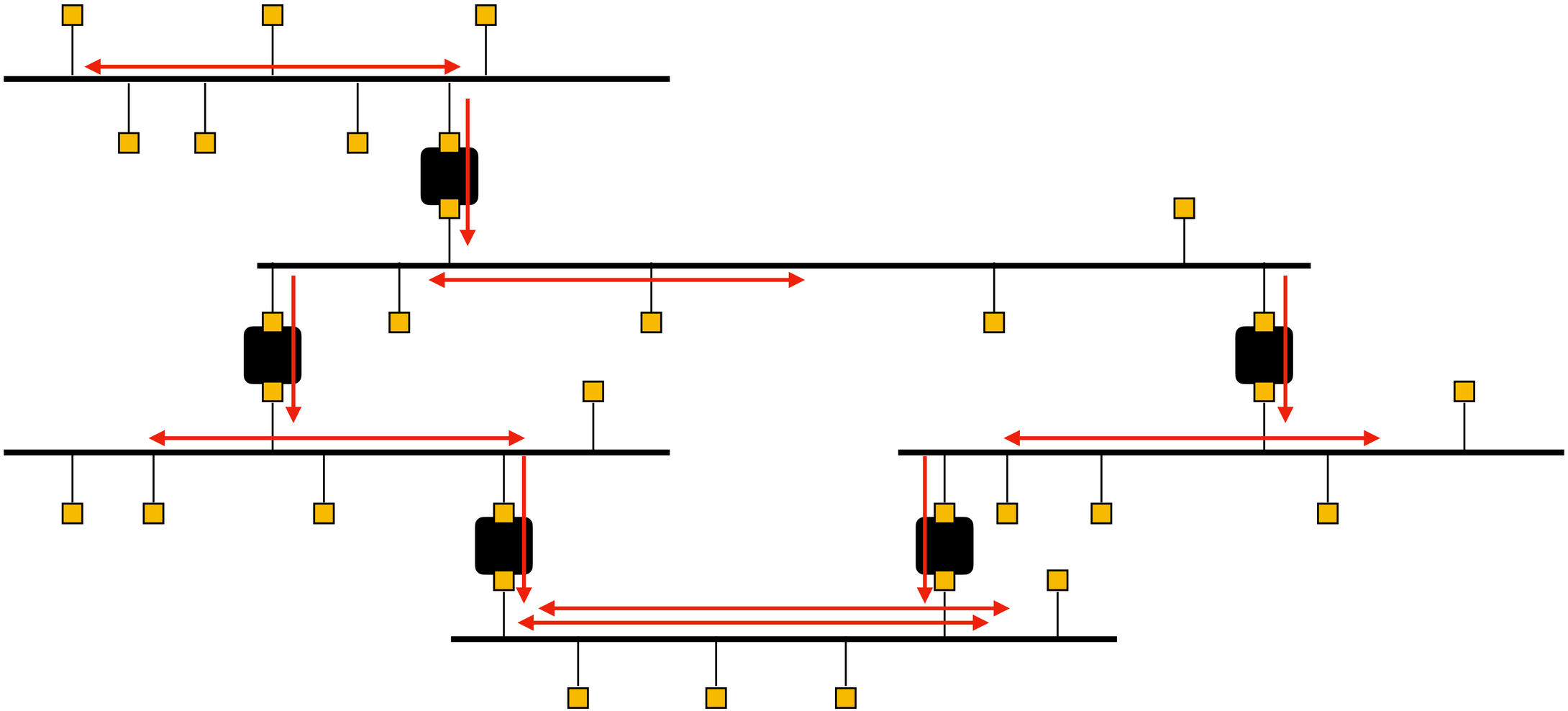

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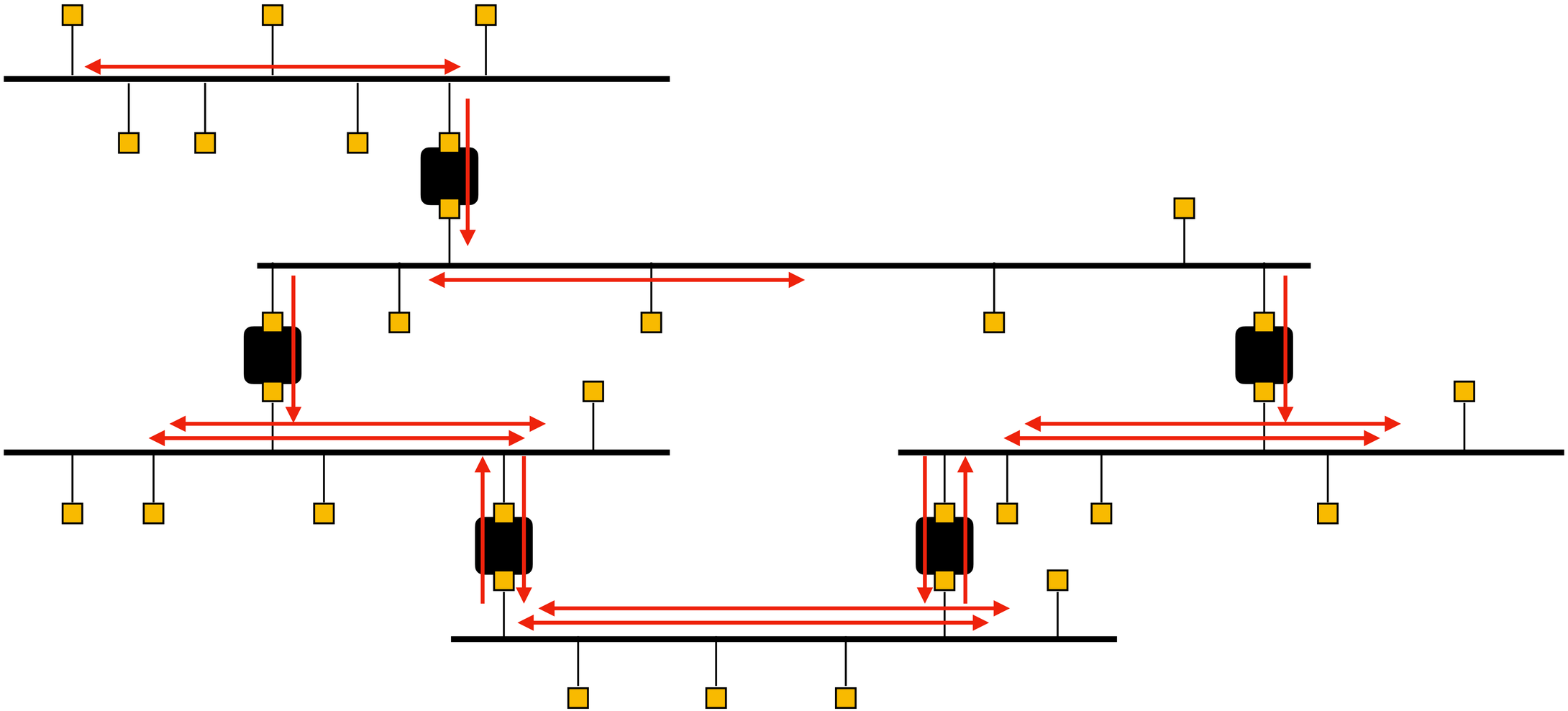

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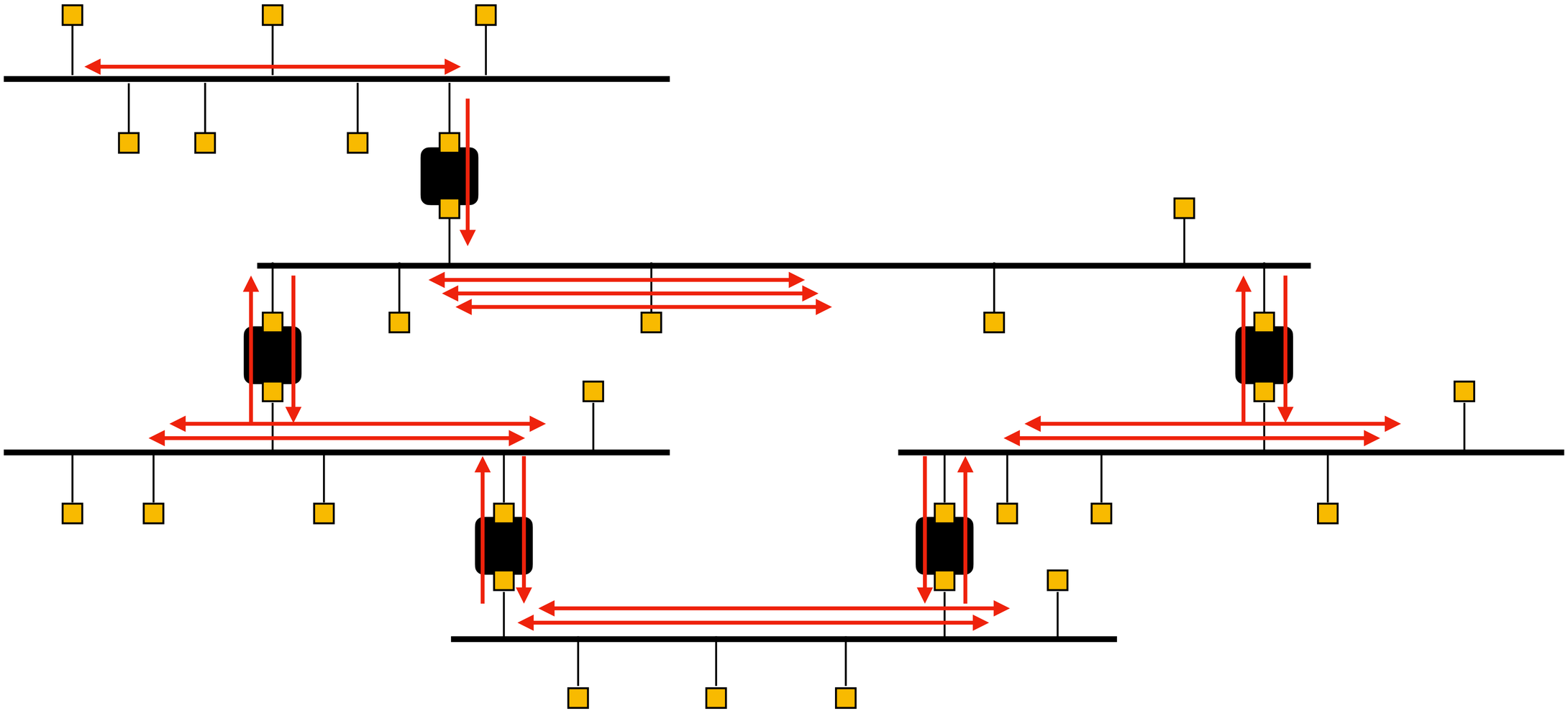

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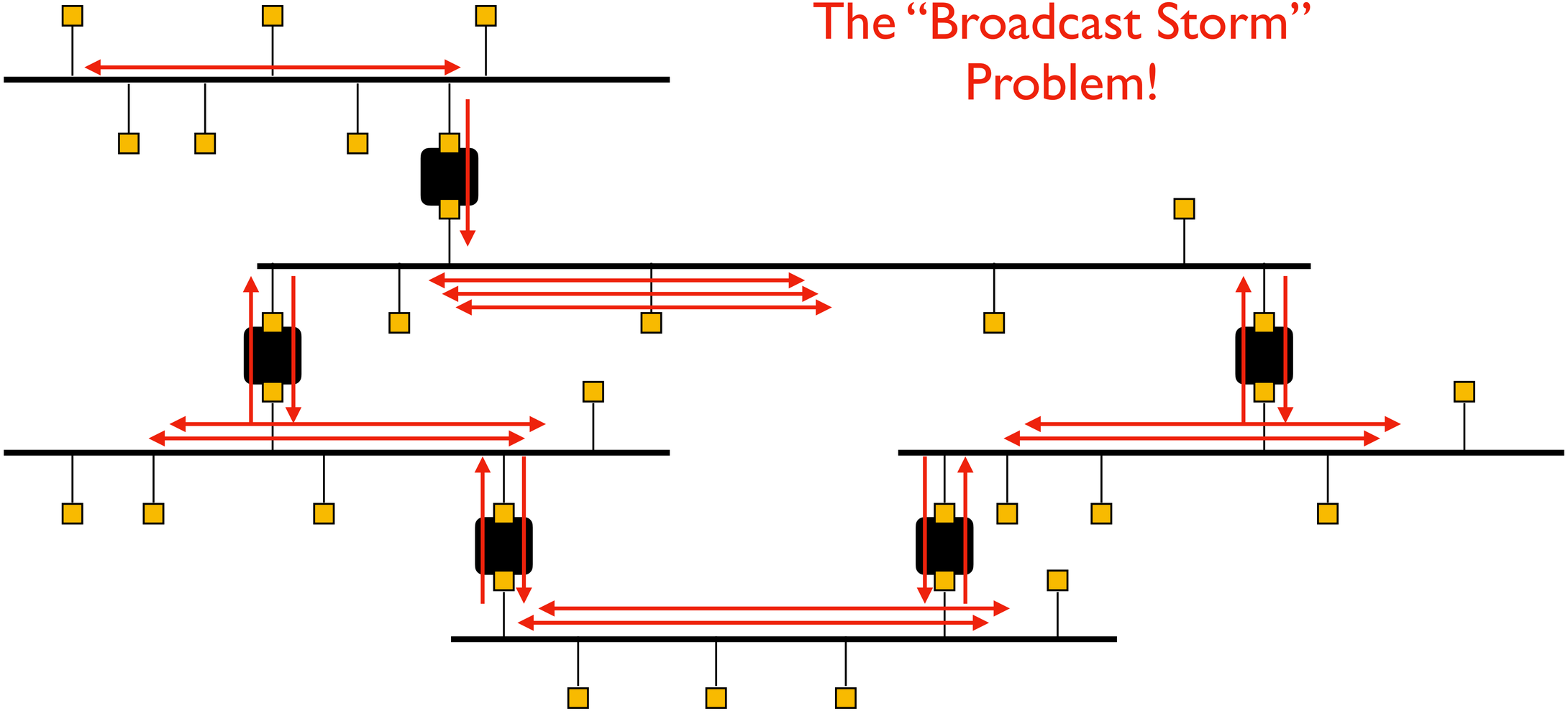

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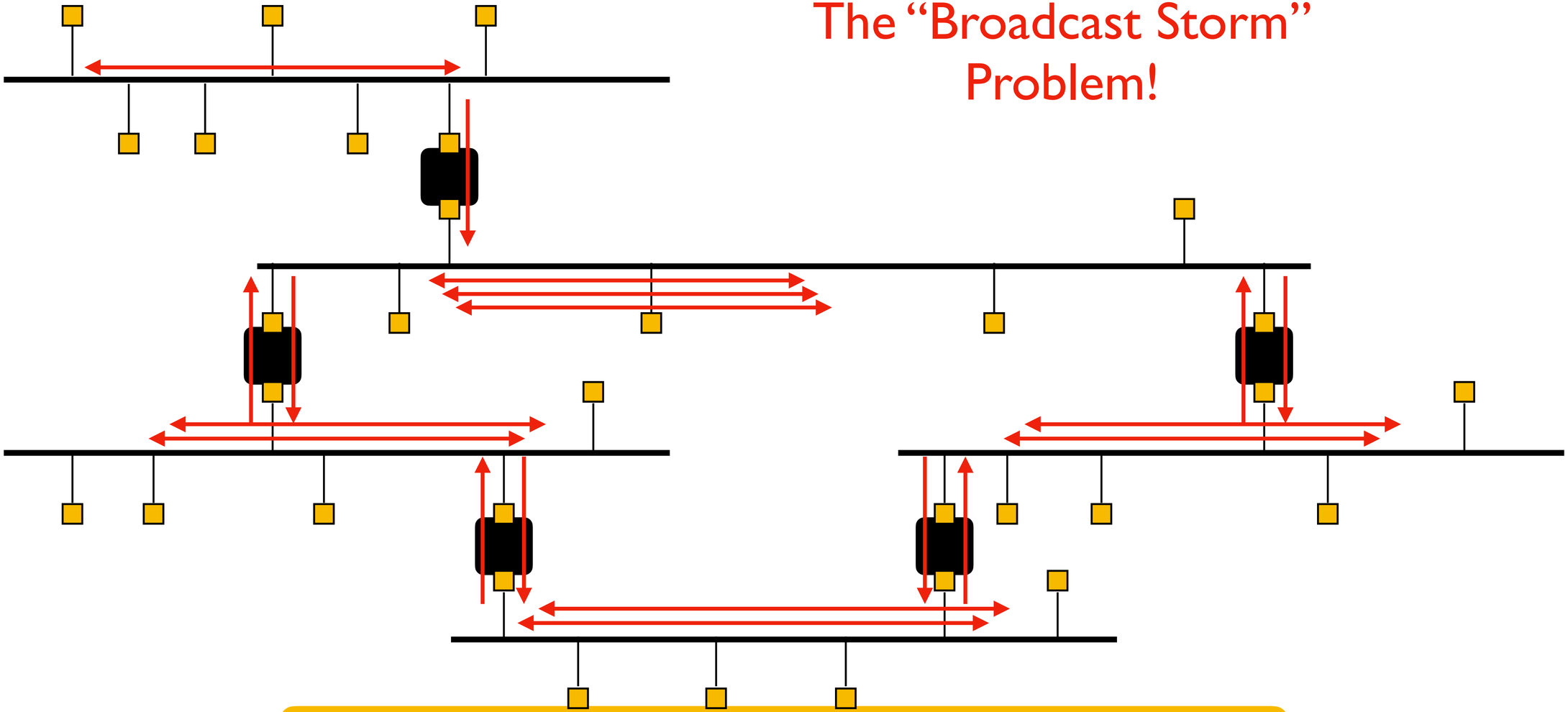

The "Broadcast Storm" Problem!

Insight: Why does this problem arise?

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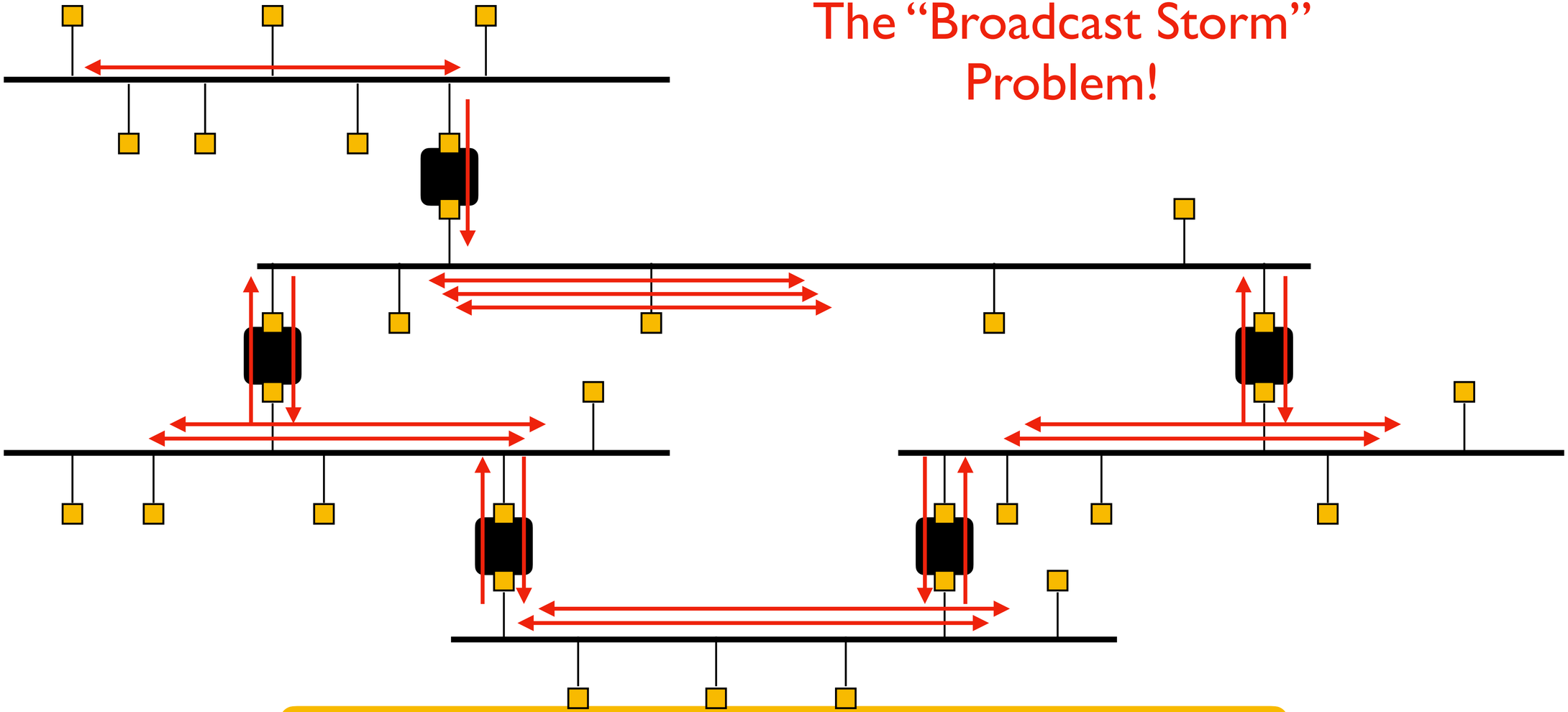

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Loops!

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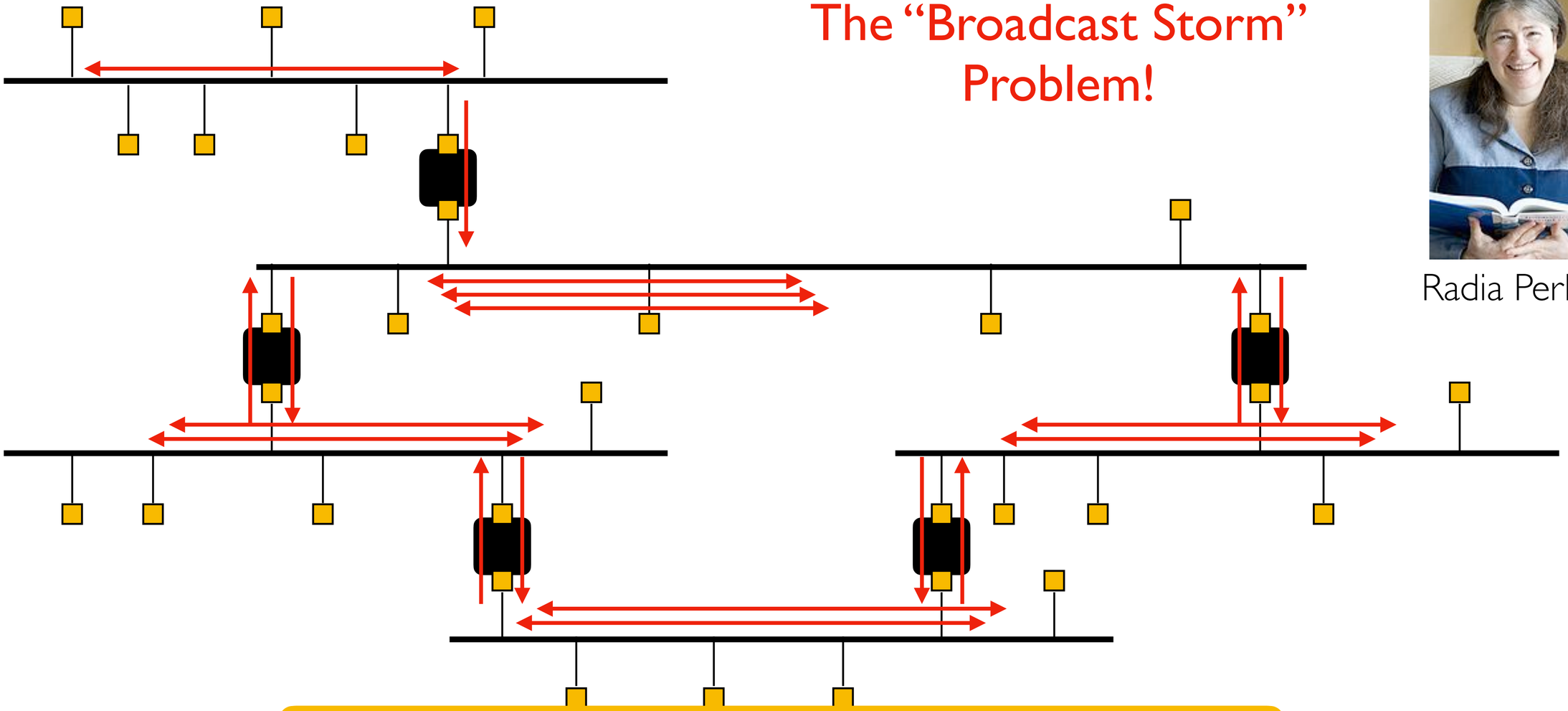


The "Broadcast Storm" Problem!

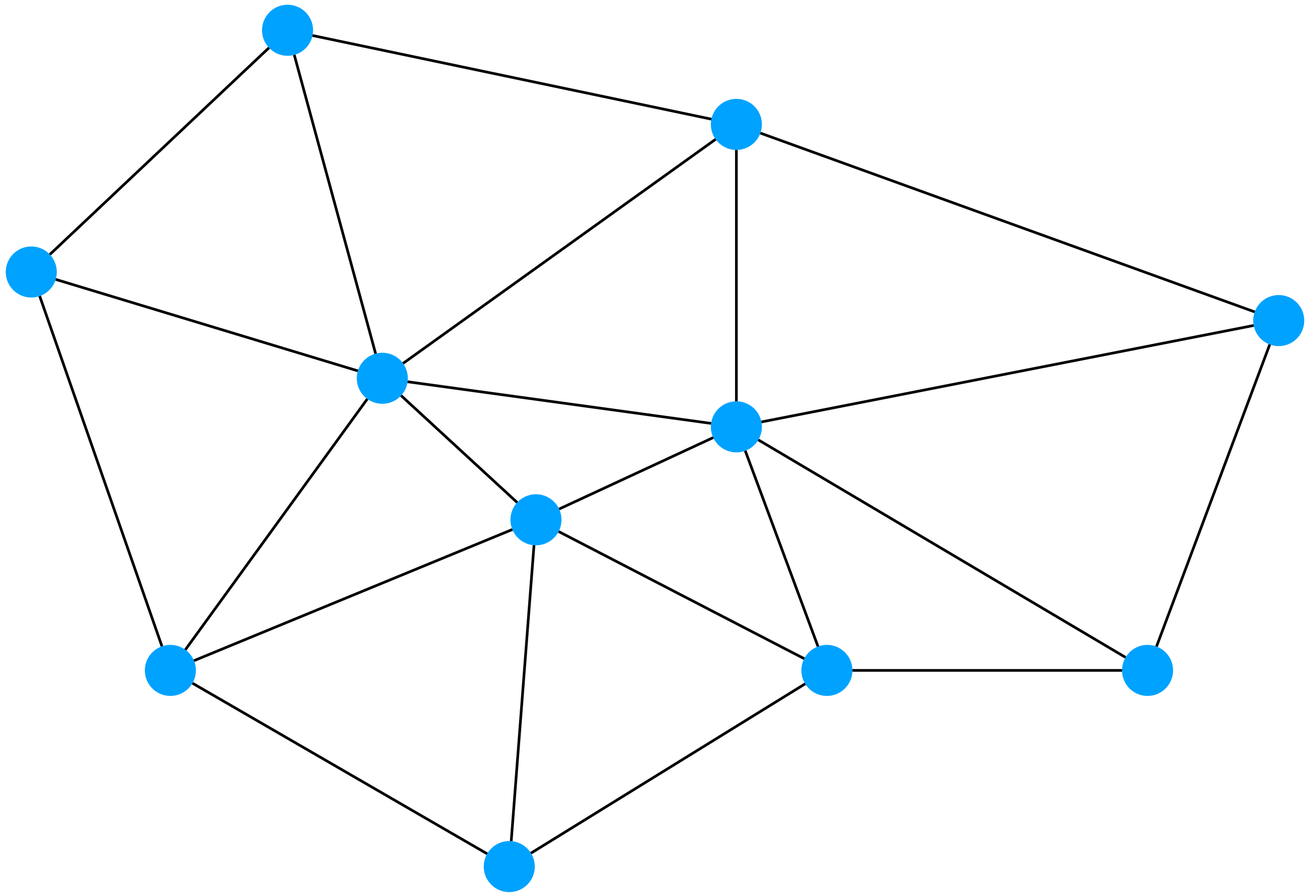
Radia Perlman

Perlman's Idea: eliminate loops in the topology

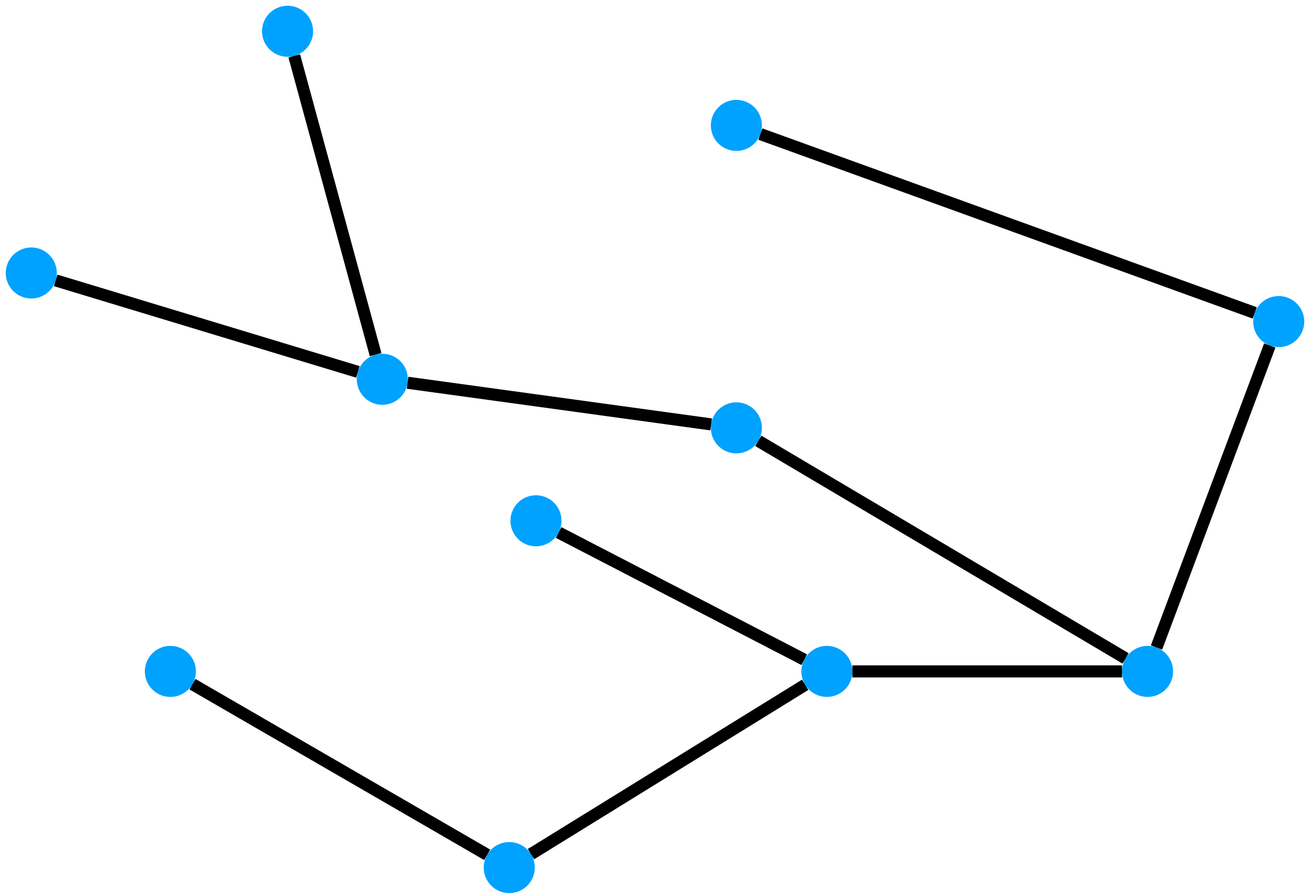
Easiest Way to Avoid Loops

- **Use a topology where loops are impossible!**
- **Take arbitrary topology**
- **Build spanning tree**
  - Sub-graph that includes all vertices but contains no cycles
  - Links not in the spanning tree are not used to forward frames
- **Only one path to destination on spanning trees**
  - So don't have to worry about loops!

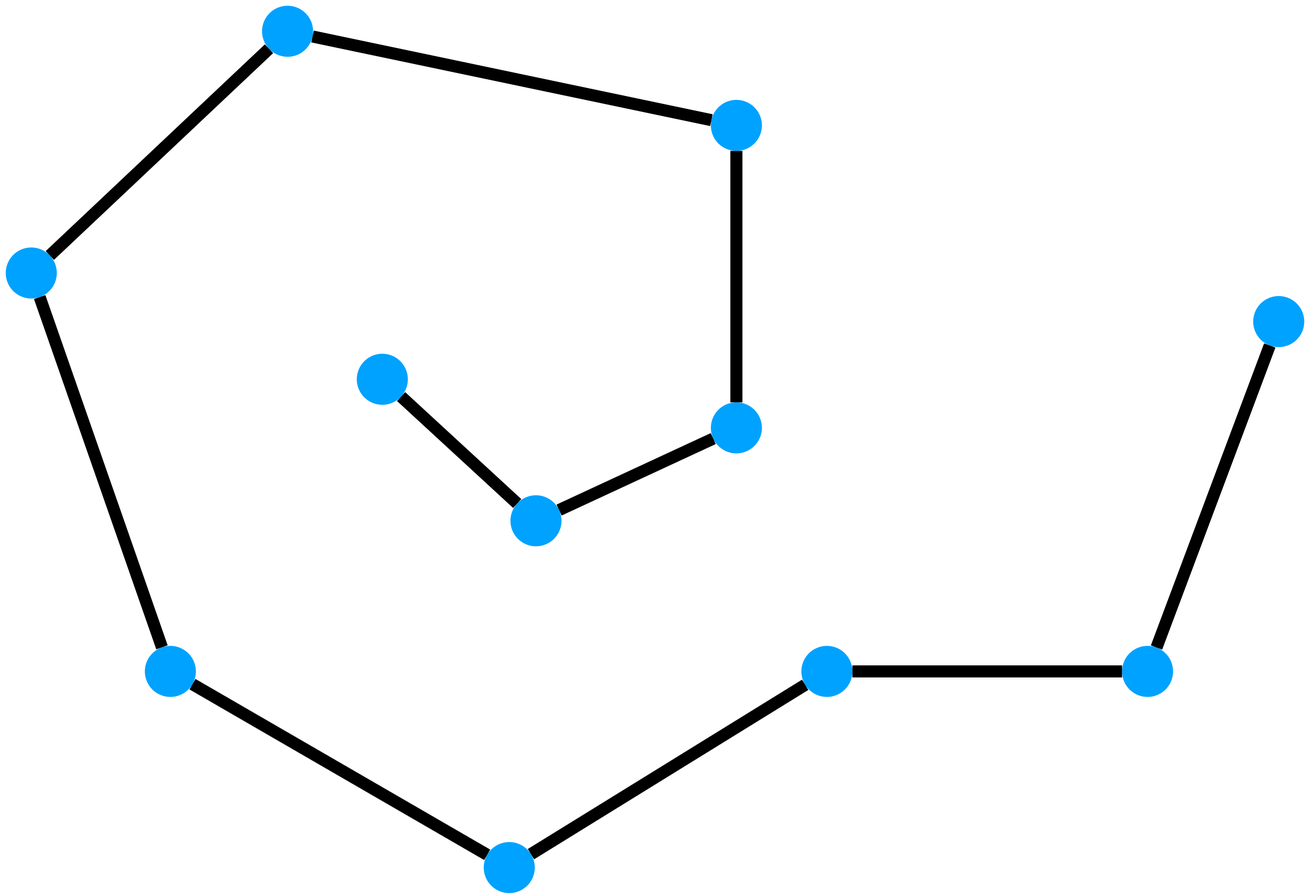
Consider Graph



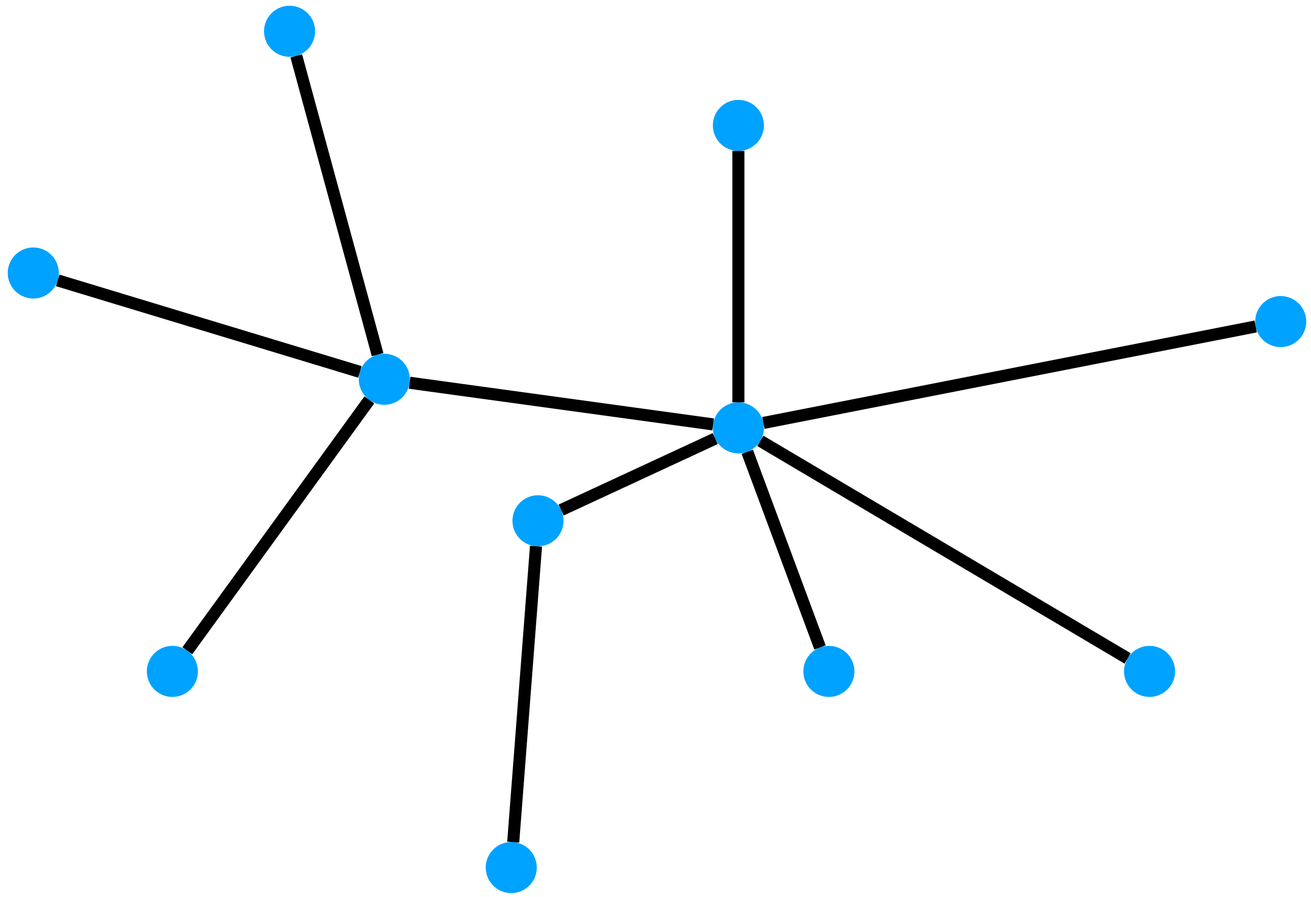
A Spanning Tree



Another Spanning Tree



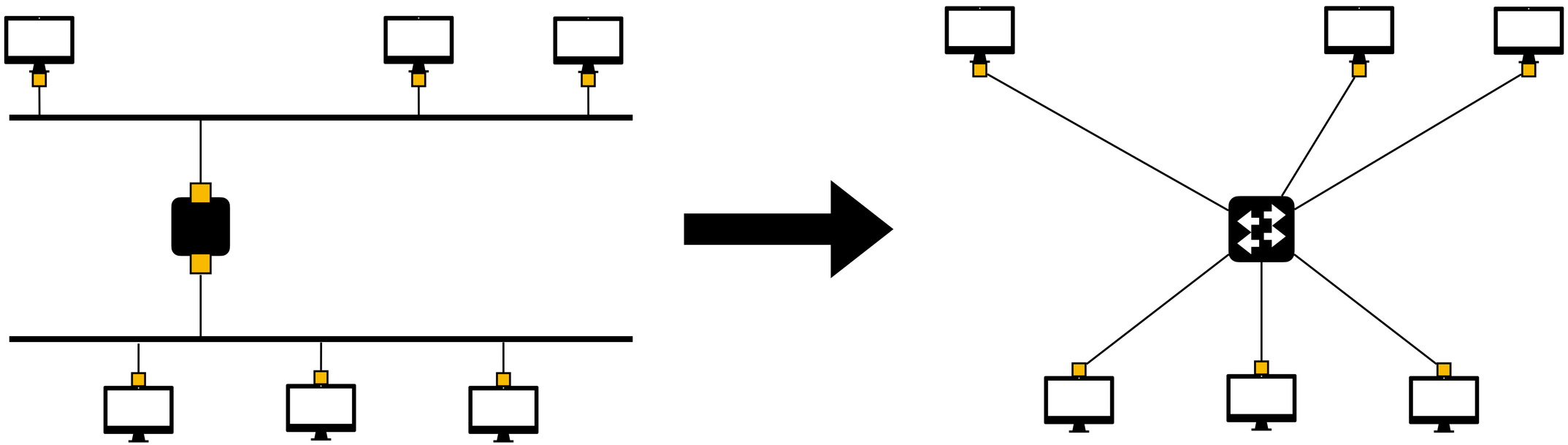
Yet Another Spanning Tree



Some History: Spanning Tree Protocol [Perlman'85]

- Protocol by which bridges construct a spanning tree
- Nice properties
  - Zero configuration (by operators or users)
  - Self healing
- Still used today

From Extended LANs to Switched Ethernet



Switched Ethernet

- Constraints (for backward compatibility)
  - No changes to end-hosts
  - Maintain plug-n-play aspect

- Earlier Ethernet achieved plug-n-play by leveraging a broadcast medium
  - *Can we do the same in a switched topology?*

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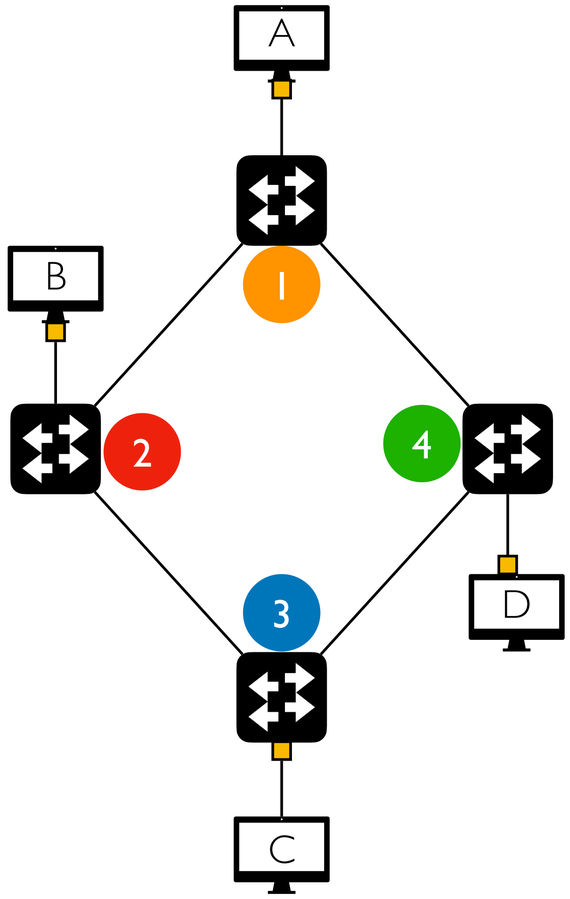
"Broadcast" packets on all interfaces except the interface you receive the packet from

Flooding with loops (still) leads to Broadcast Storm!



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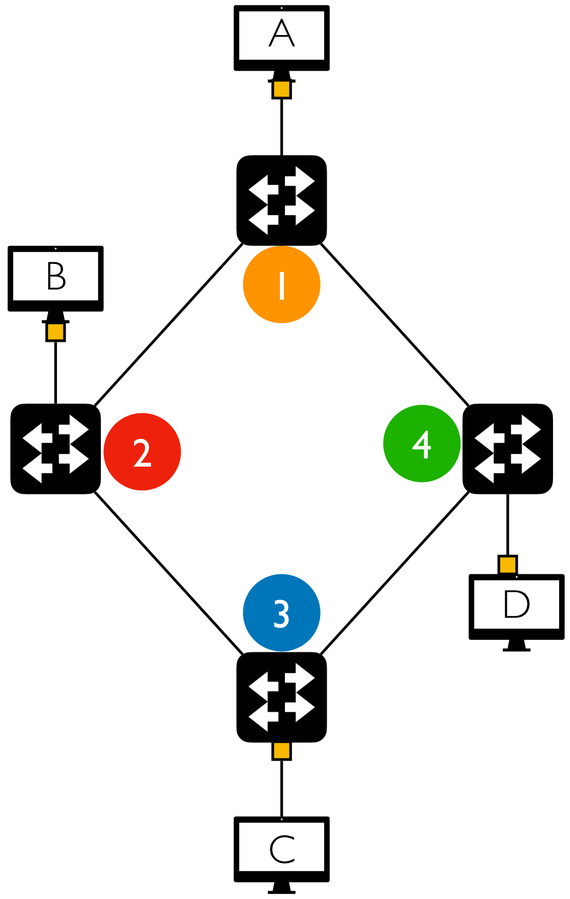

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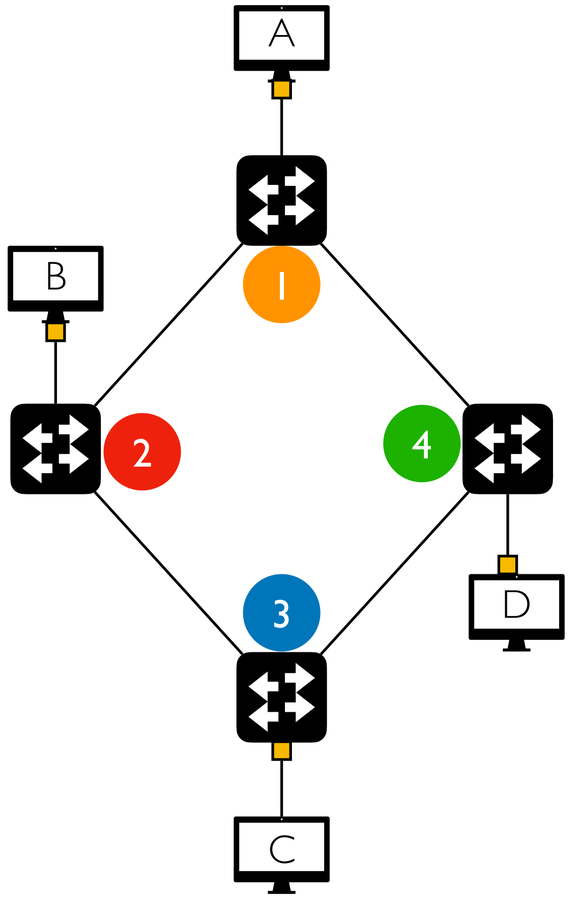

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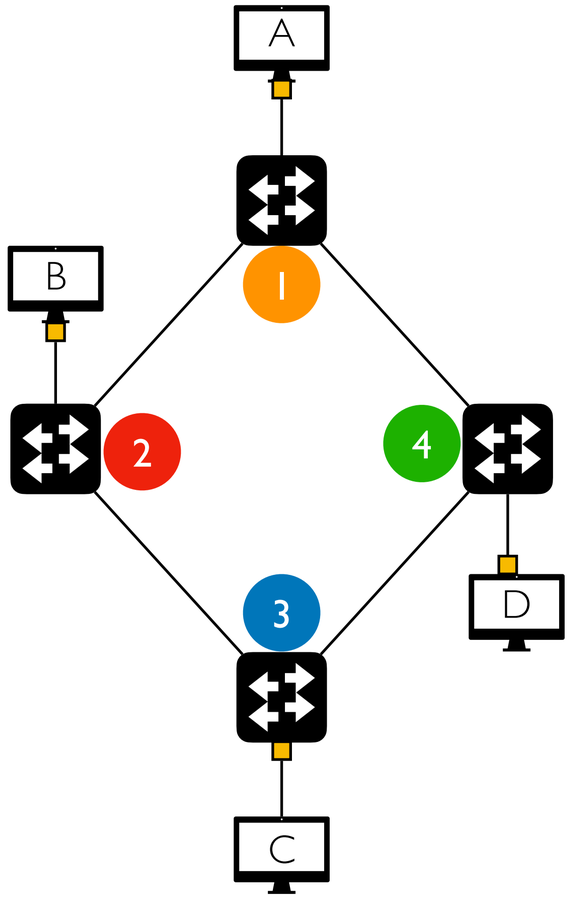
Example: A wants to broadcast a message

- A sends packet to 1
- 1 Floods to 2 and 4



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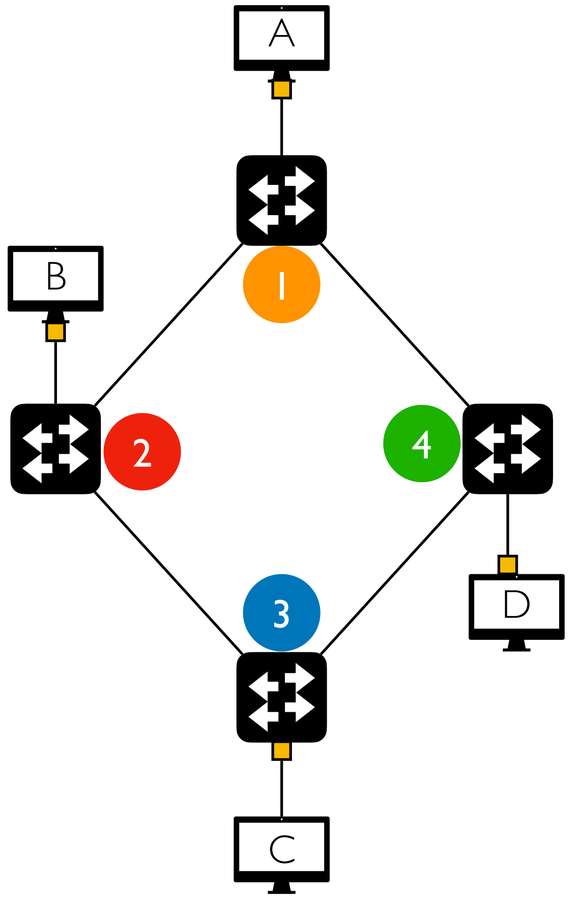
- 1 Floods to 2 and 4
- 2 Floods to B and 3, 4 Floods to D and 3



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Example: A wants to broadcast a message

- A sends packet to 1
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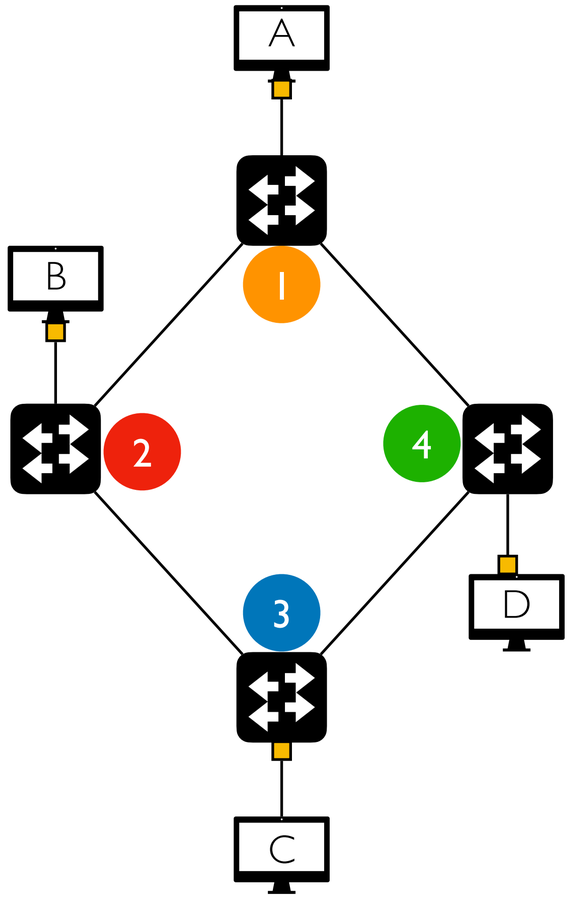
- 2 Floods to B and 3, 4 Floods to D and 3
- 3 Floods packet from 2 to C & 4, 3 Floods packet from 4 to C & 2



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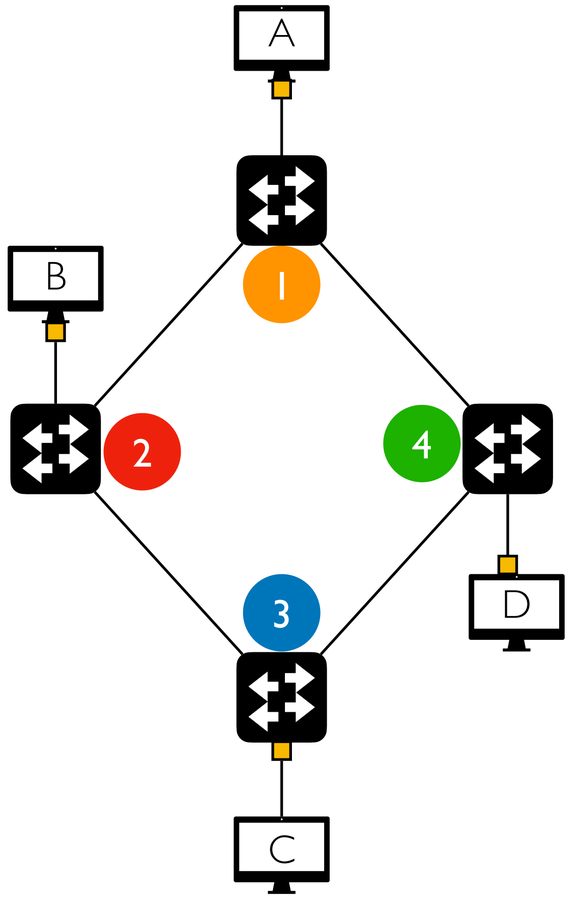
- 4 Floods packet from 3 to D & 1, 2 Floods packet from 3 to B & 1



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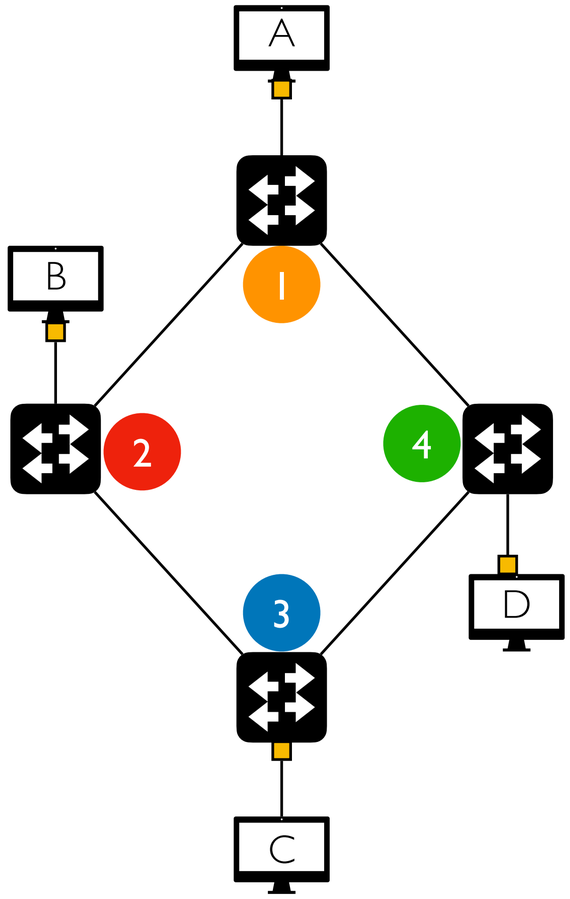
- 3 Floods packet from 2 to C & 4, 3 Floods packet from 4 to C & 2
- 4 Floods packet from 3 to D & 1, 2 Floods packet from 3 to B & 1
- 1 Floods packet from 2 to A & 4, 1 Floods packet from 4 to B & 2



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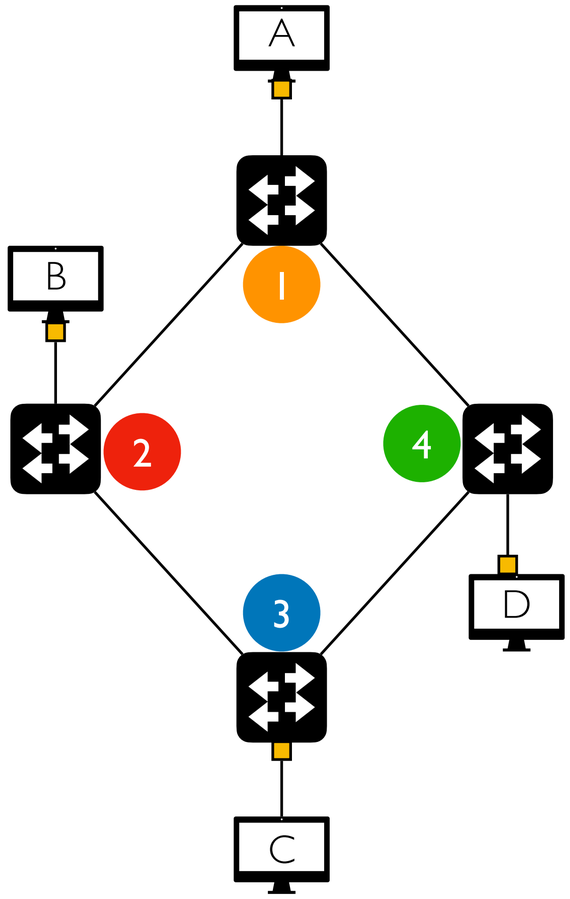
- …



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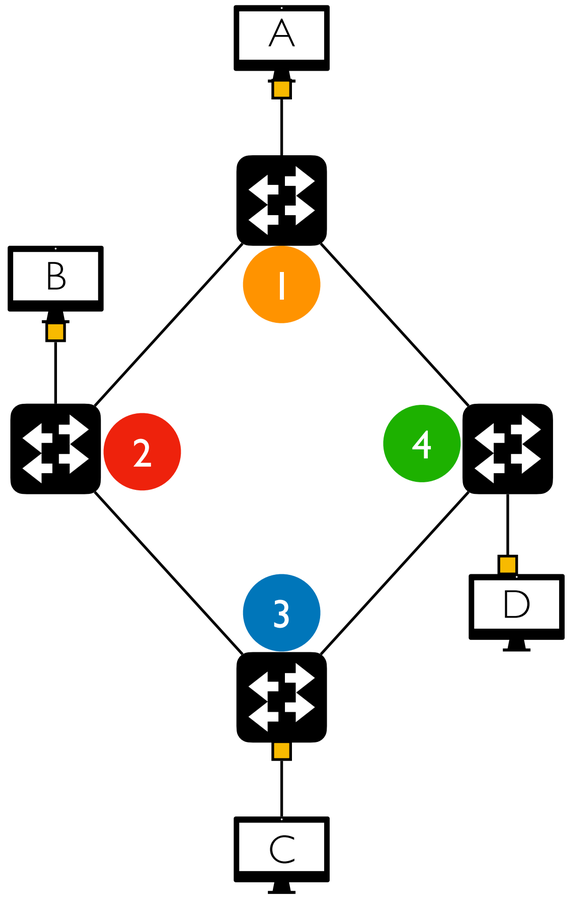
- 3 Floods packet from 2 to C & 4, 3 Floods packet from 4 to C & 2
- 4 Floods packet from 3 to D & 1, 2 Floods packet from 3 to B & 1
- 1 Floods packet from 2 to A & 4, 1 Floods packet from 4 to B & 2
- …

- *A "broadcast storm" if the network contains a cycle of switches*



Questions?

Spanning Tree Approach

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

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- **Ethernet's spanning tree construction does both (simultaneously) 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 tie-breaking system, but this is an easy one to remember and implement

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- **Each switch determines if a link is on its shortest path to the root; excludes it from the tree if not**
  - **d** to **Y** in the message

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- **If root or shortest distance to it has changed, send neighbors updated message (Y, d+1, X)**

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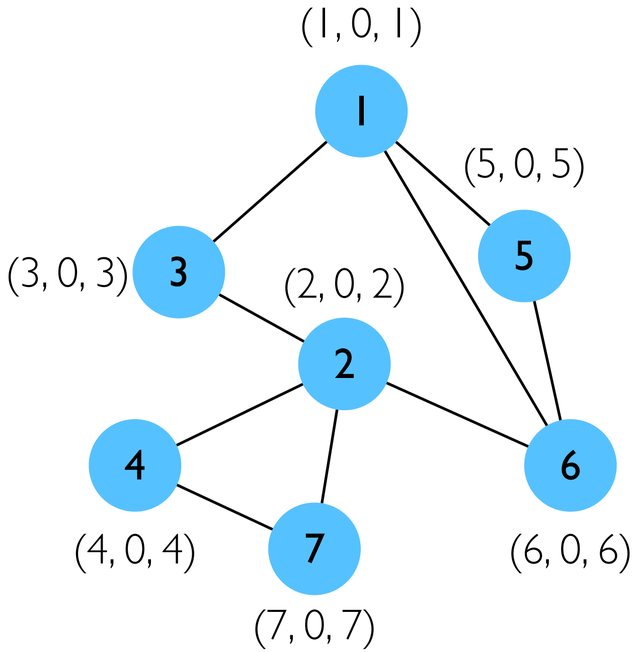

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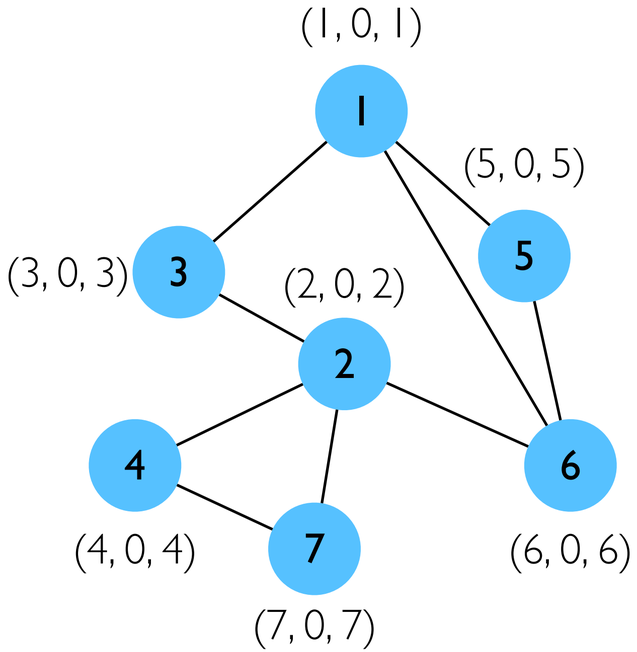

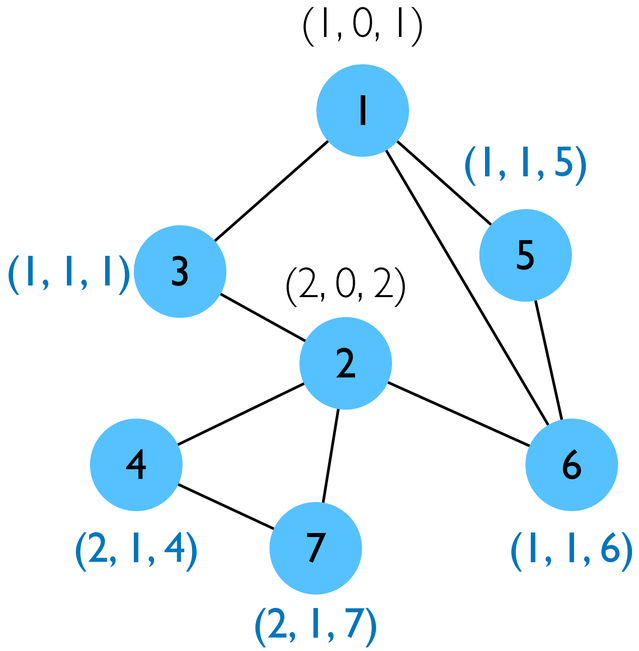

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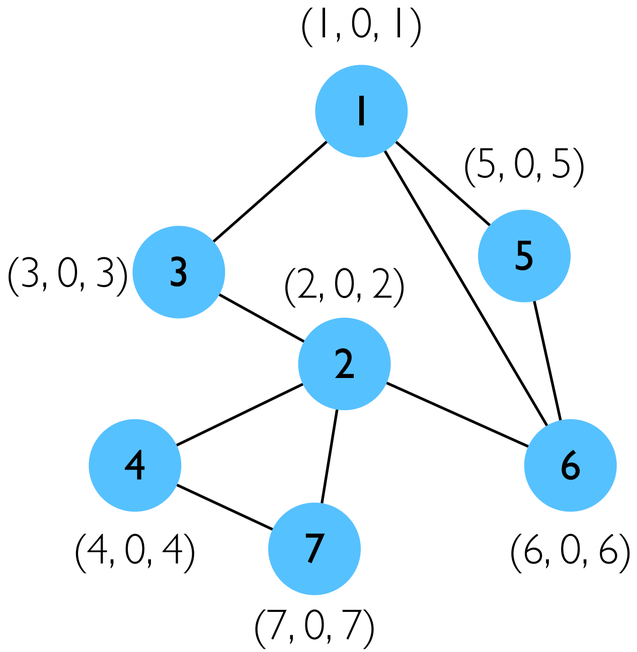

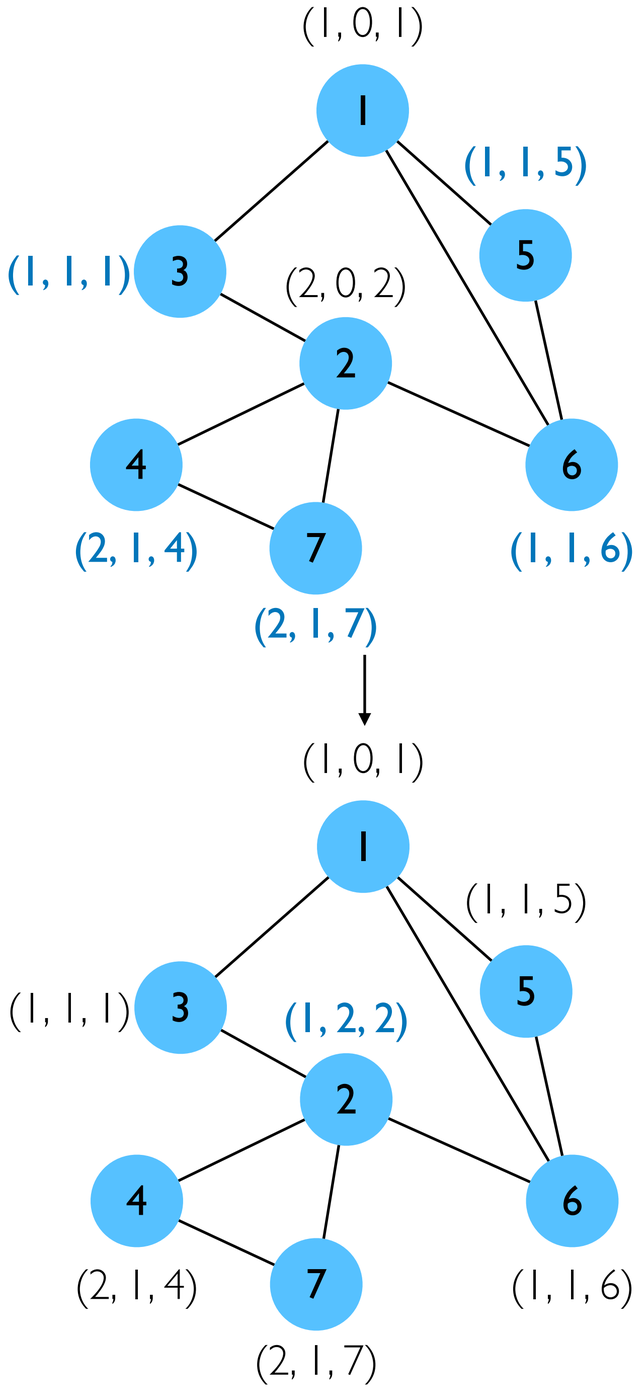

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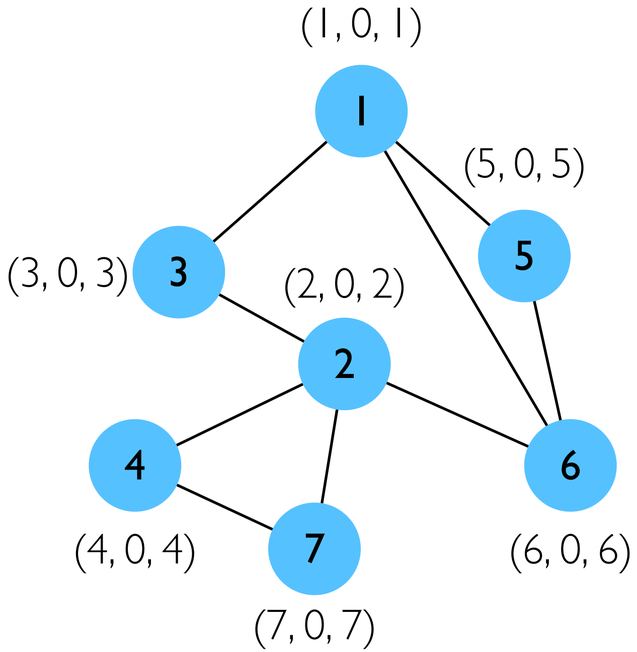

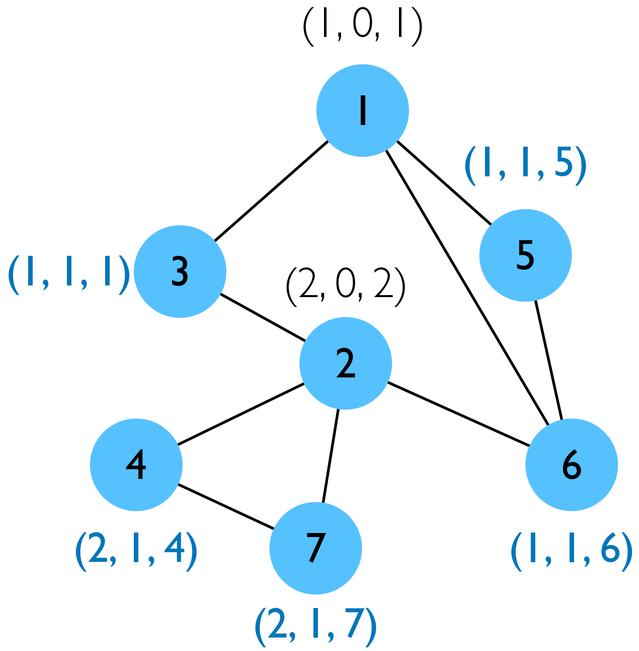

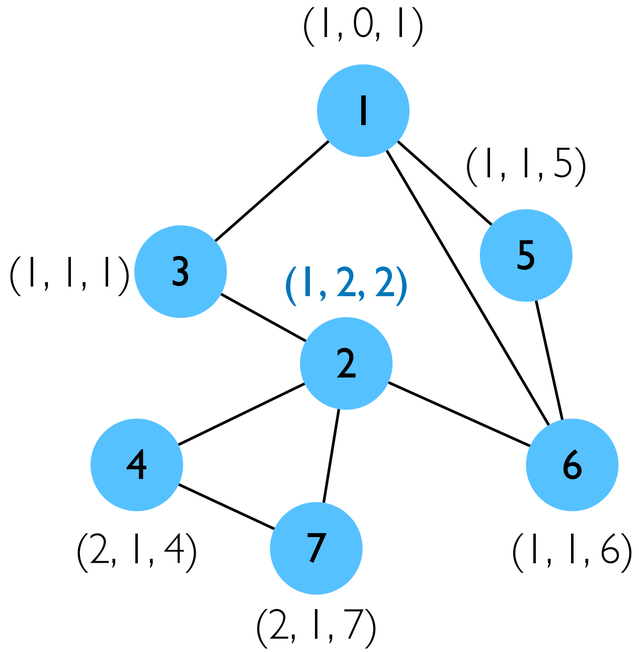

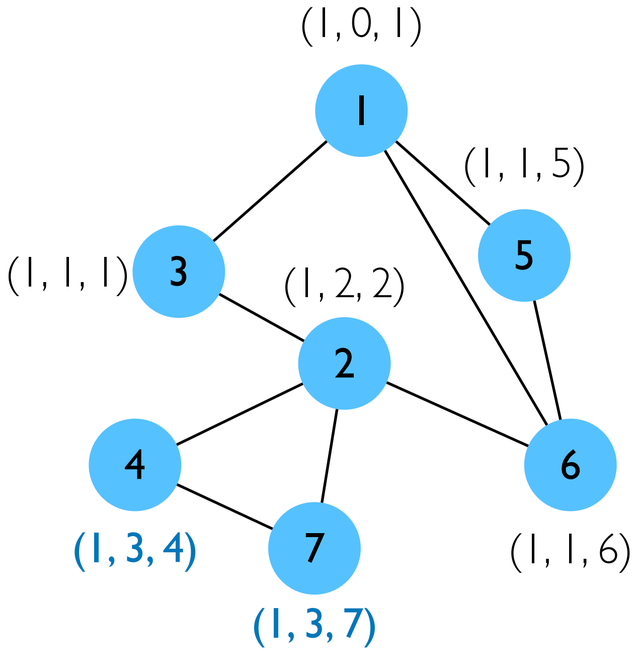

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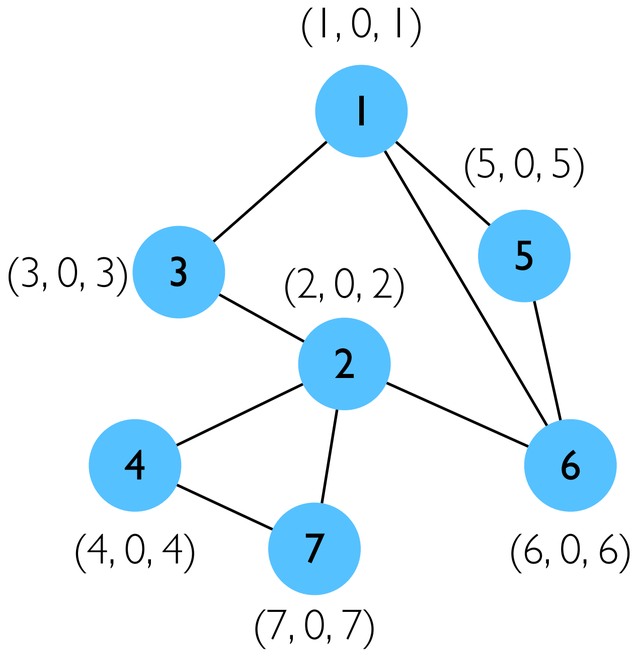

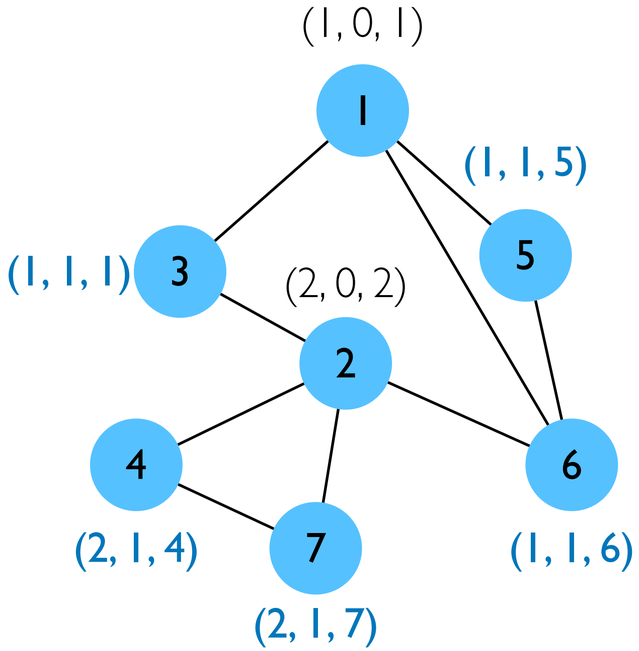

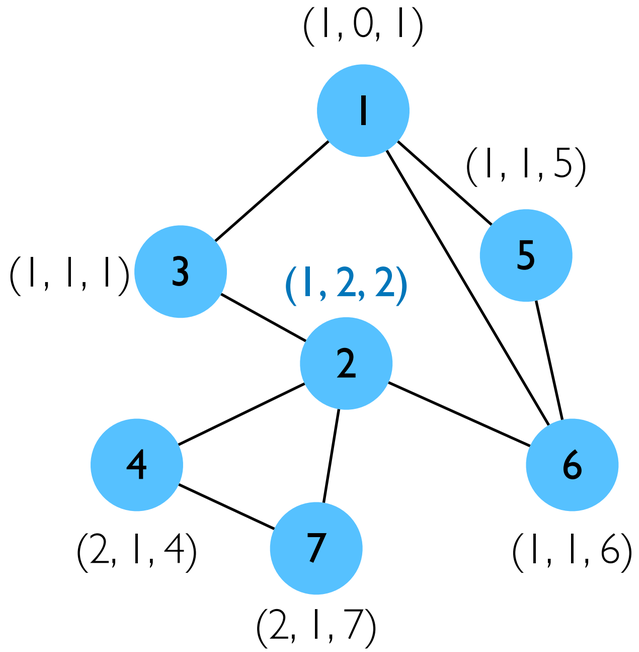

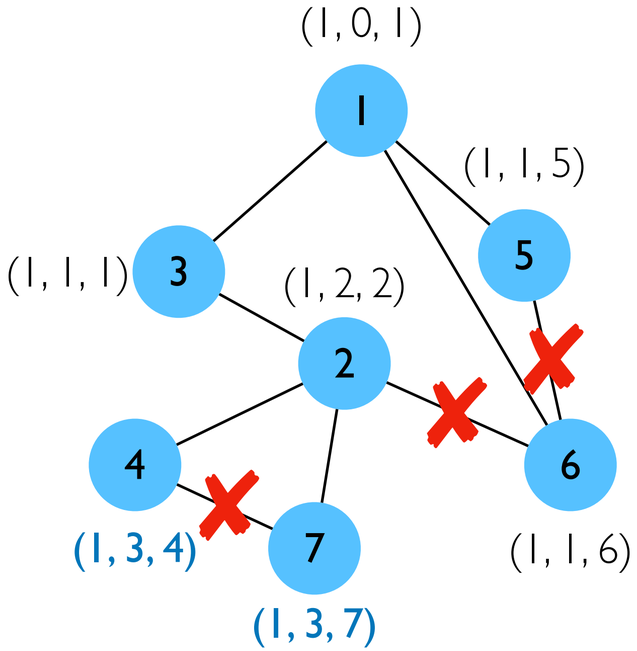

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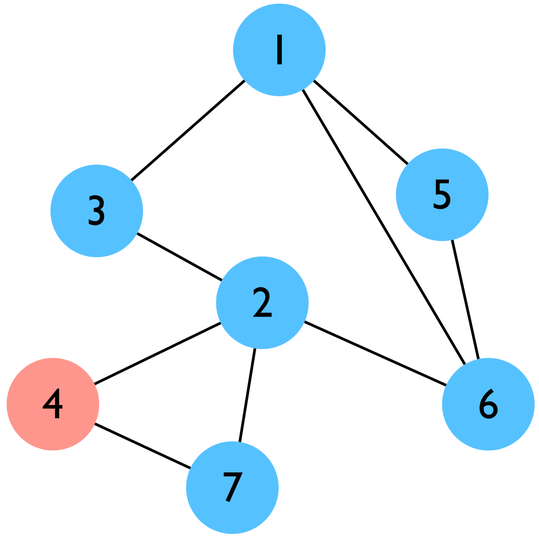

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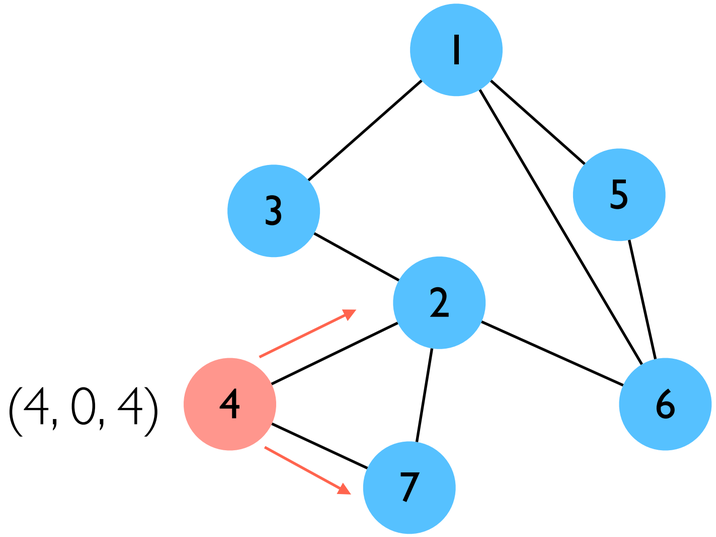

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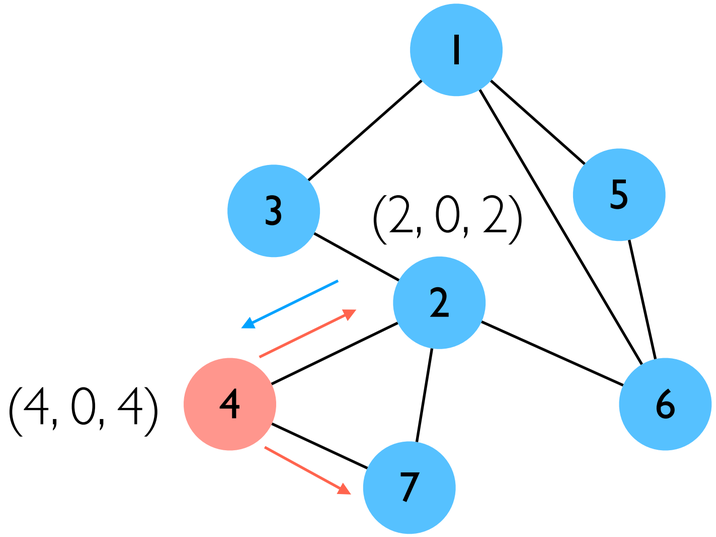

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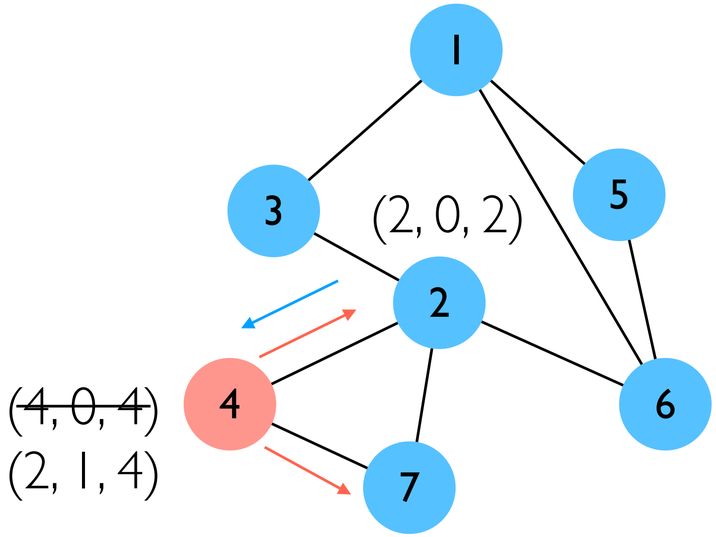

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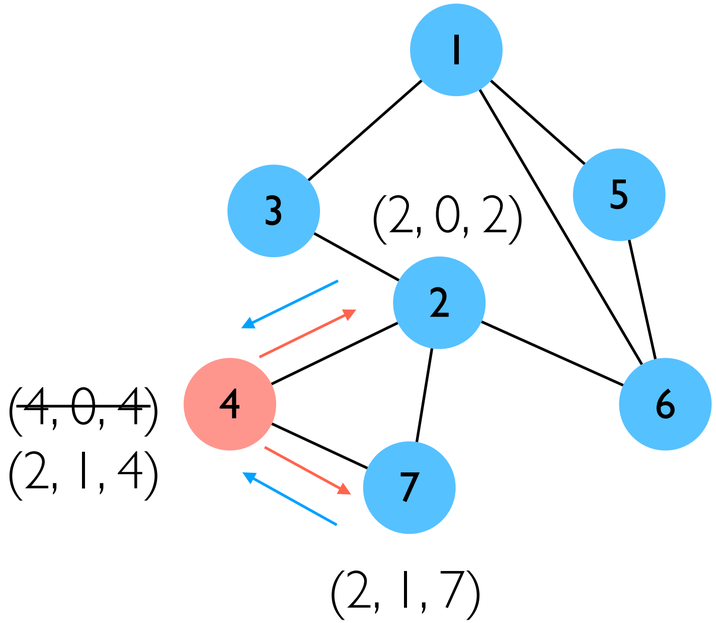

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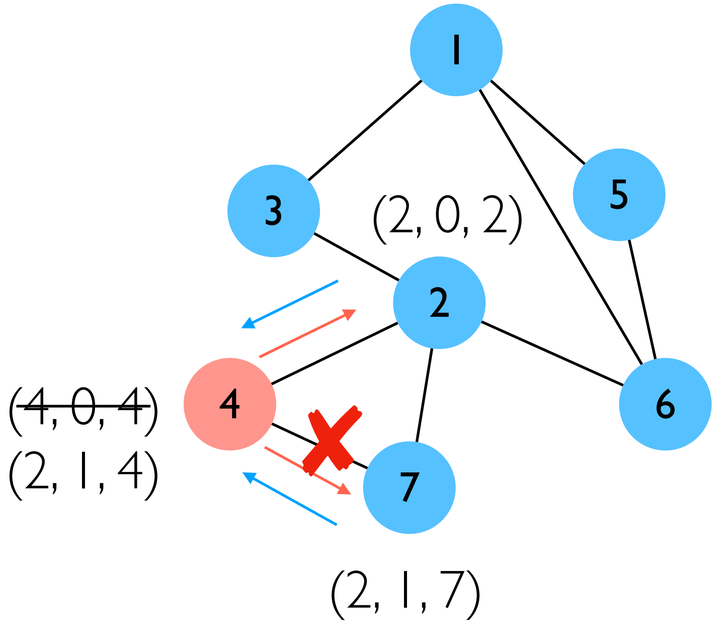

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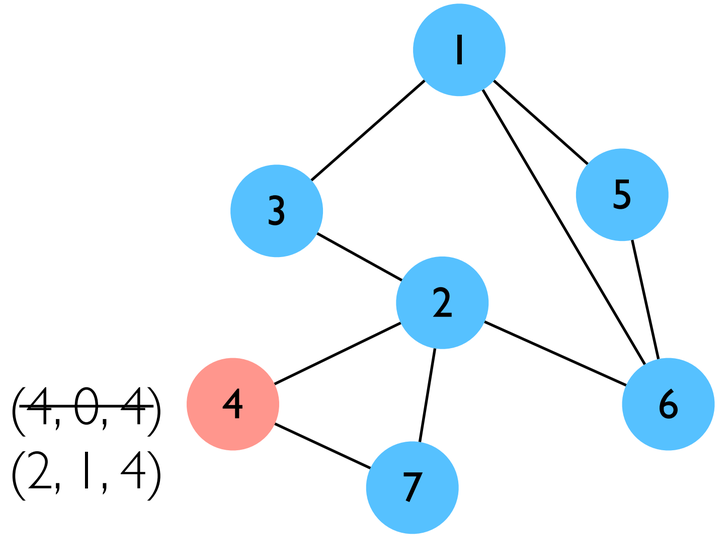

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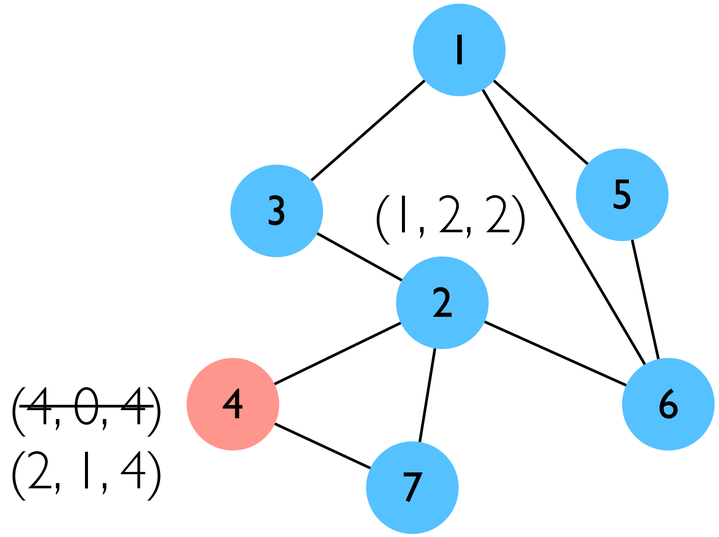

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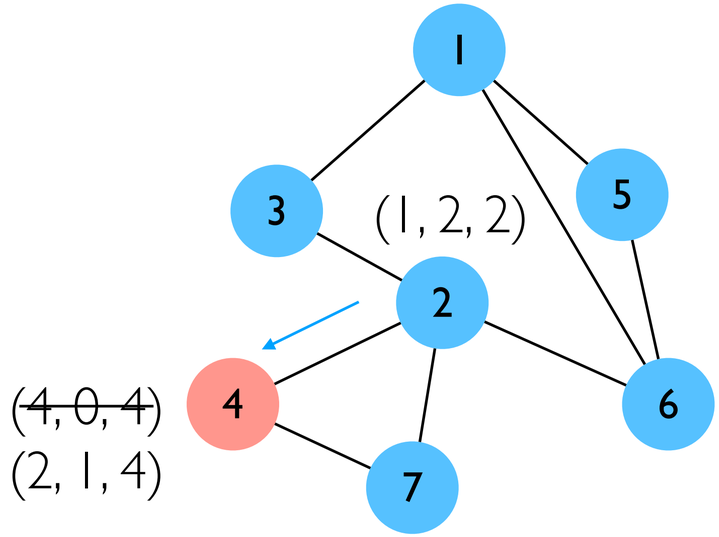

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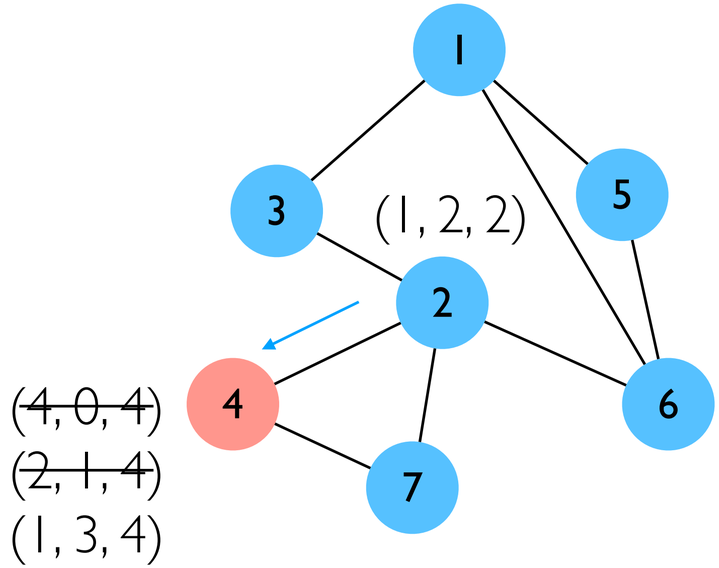

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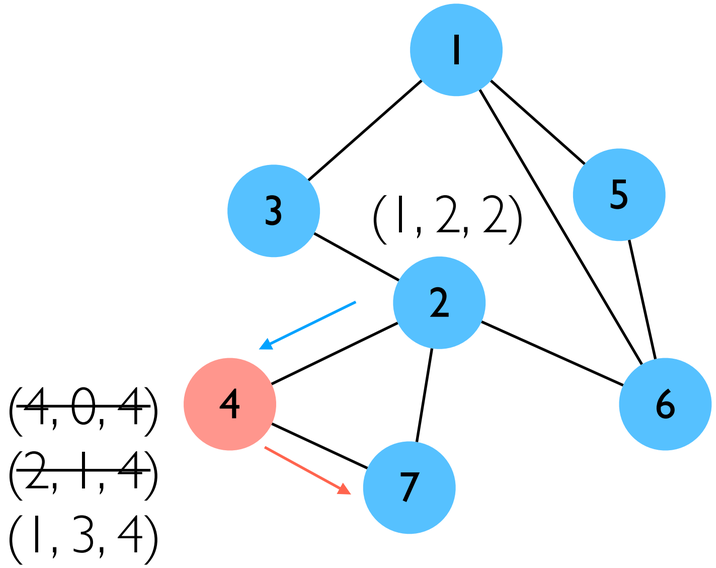

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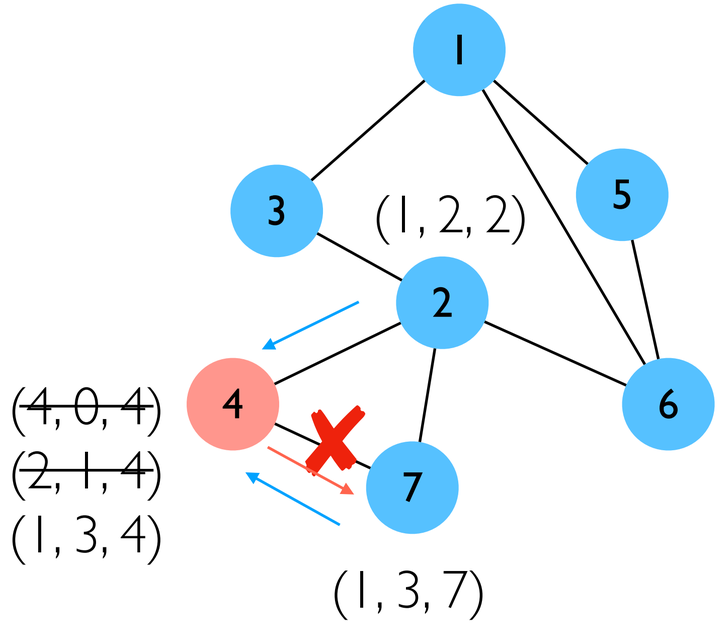


Robust Spanning Tree Algorithm

- **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 (*soft state*)**
  - If no word from root, *timeout and claim to be the root!*

Questions?

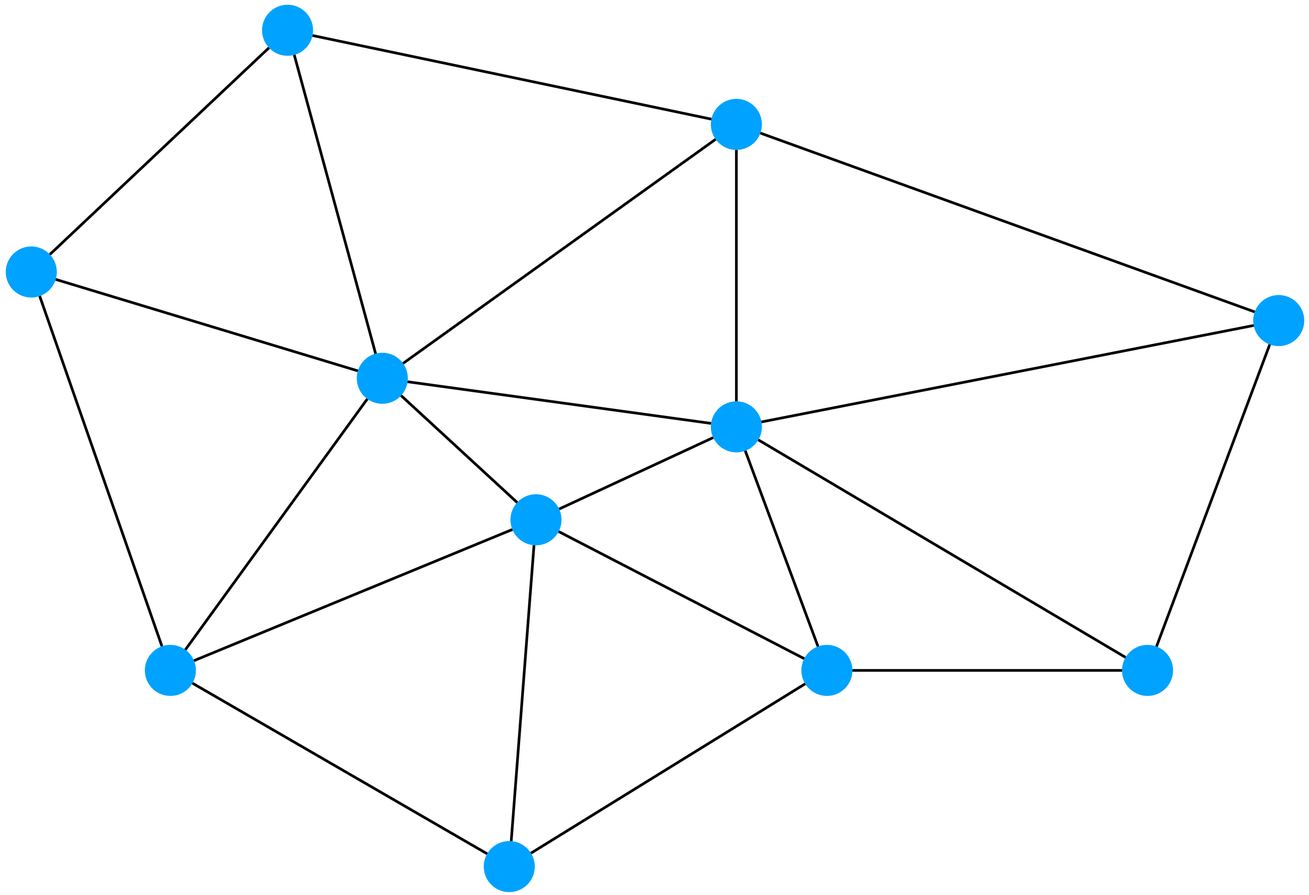
Outline

- Frames and framing
- Addressing
- Routing
- Forwarding
- Discovery: Bootstrapping end-to-end communication

Flooding on a Spanning Tree

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

Flooding on Spanning Tree



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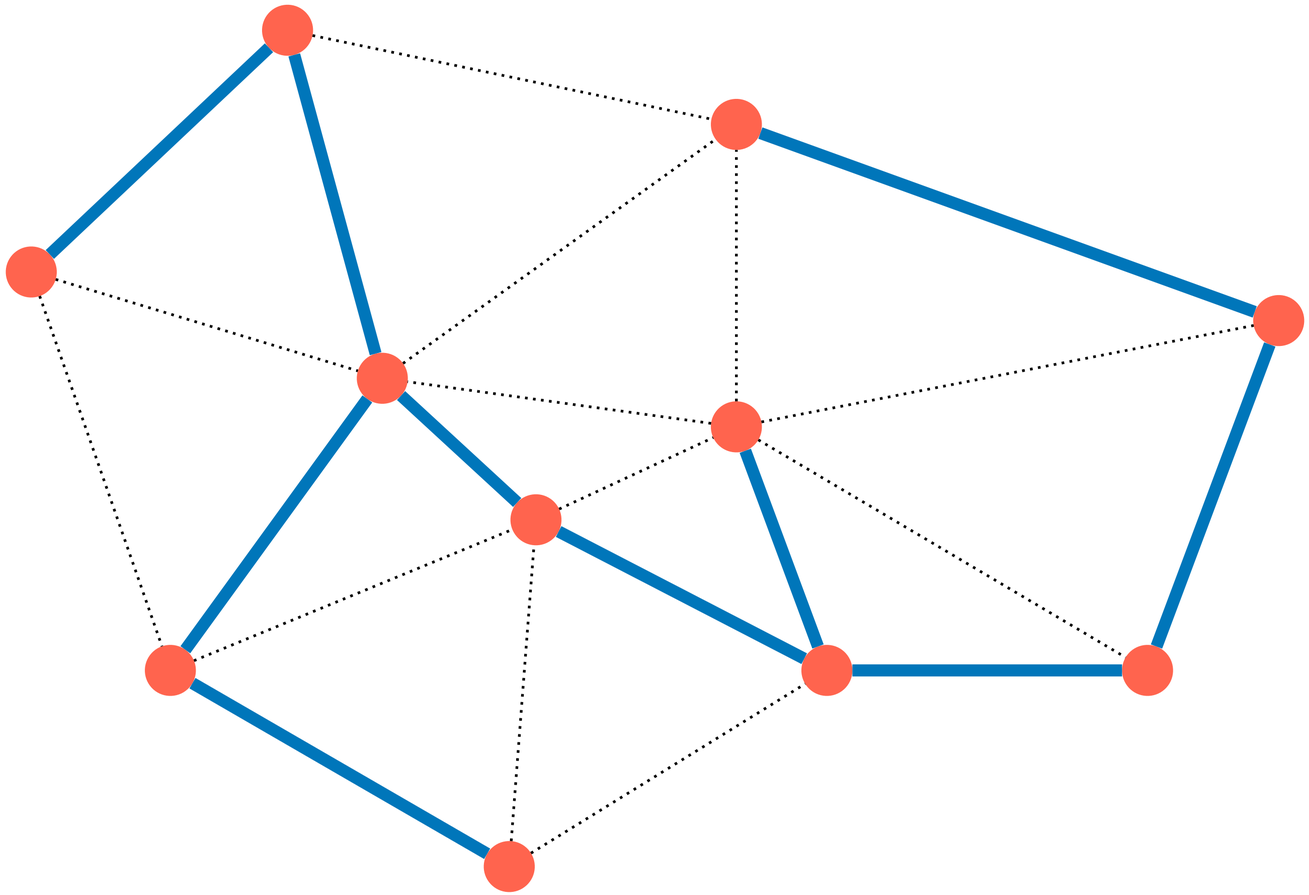

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- Yes, but we can use it to bootstrap more efficient forwarding
- Idea: watch the packets going by, and *learn* from them
  - If node A sees a packet from node B come in on a port, ***it knows what port to use to reach B!***
  - Works because there's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

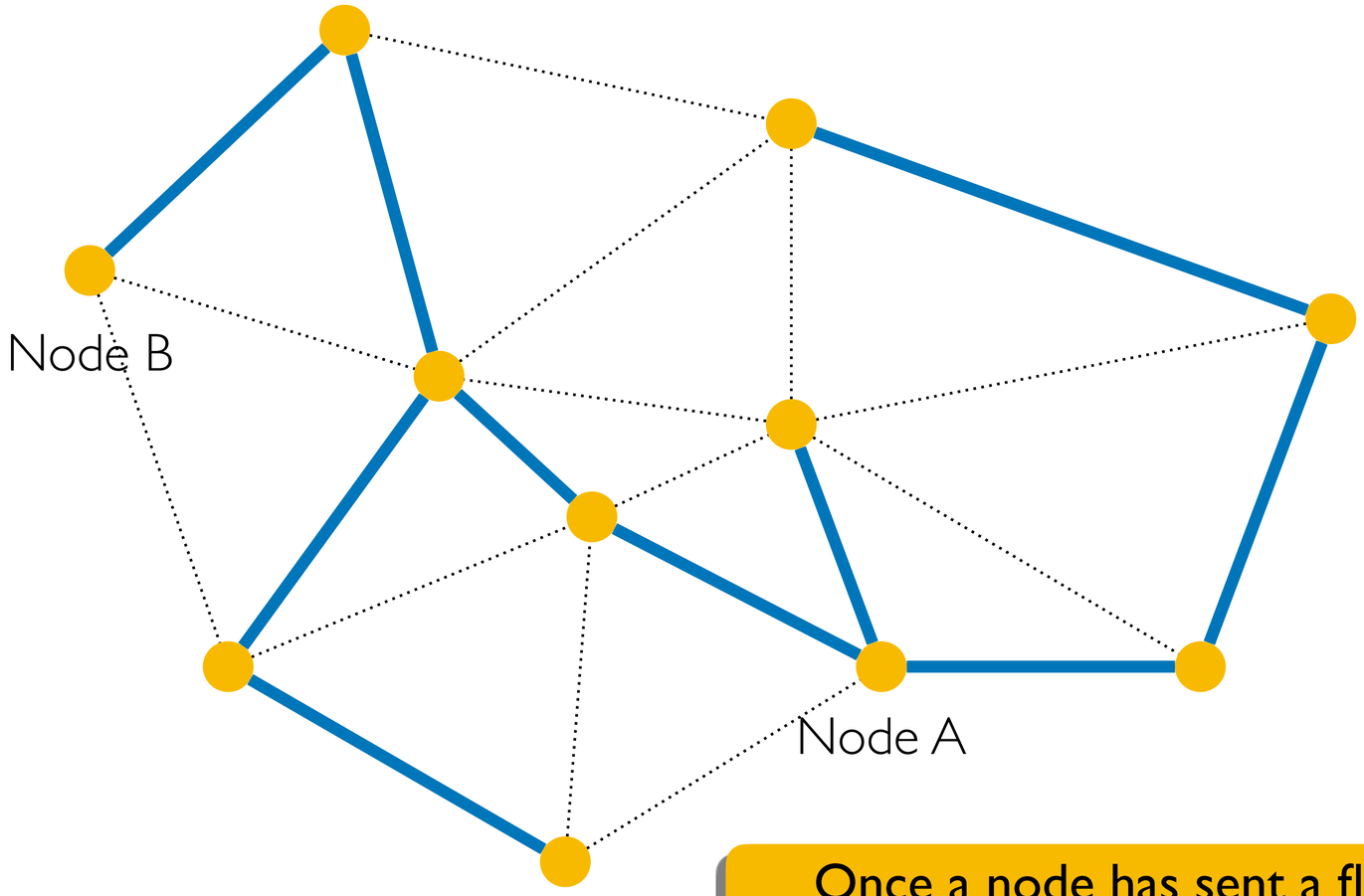
Nodes can “learn” routes

- **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



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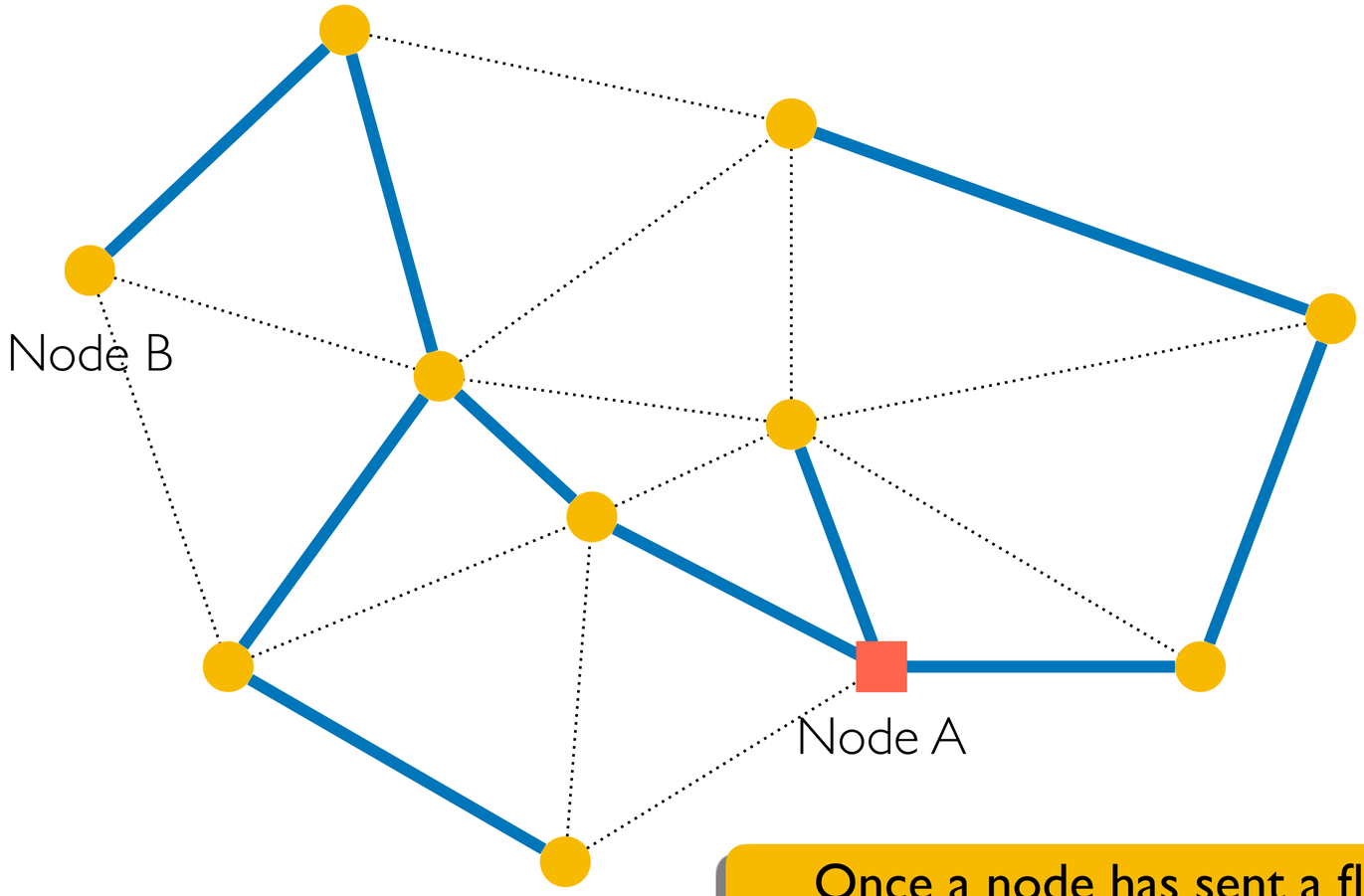

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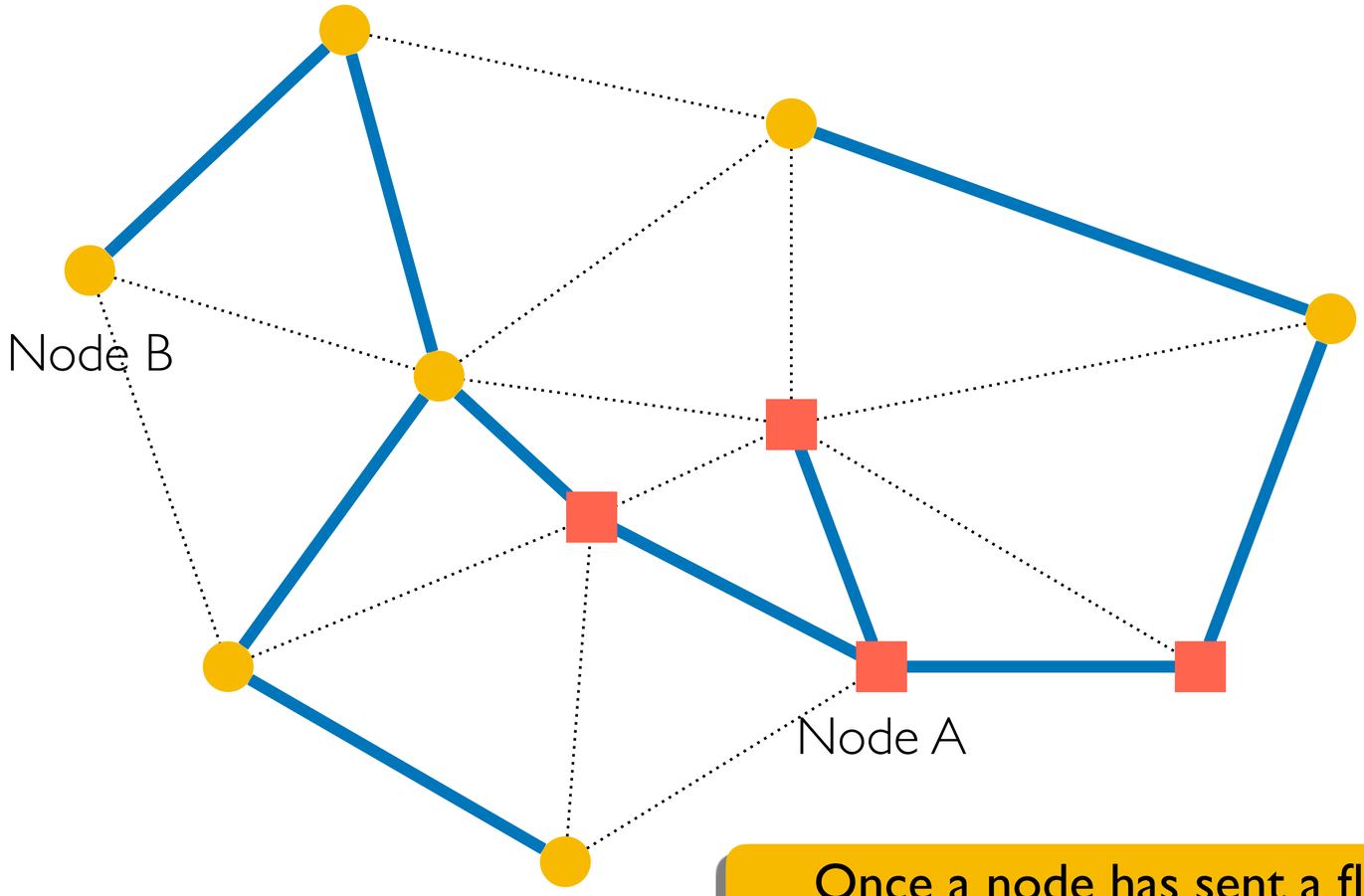

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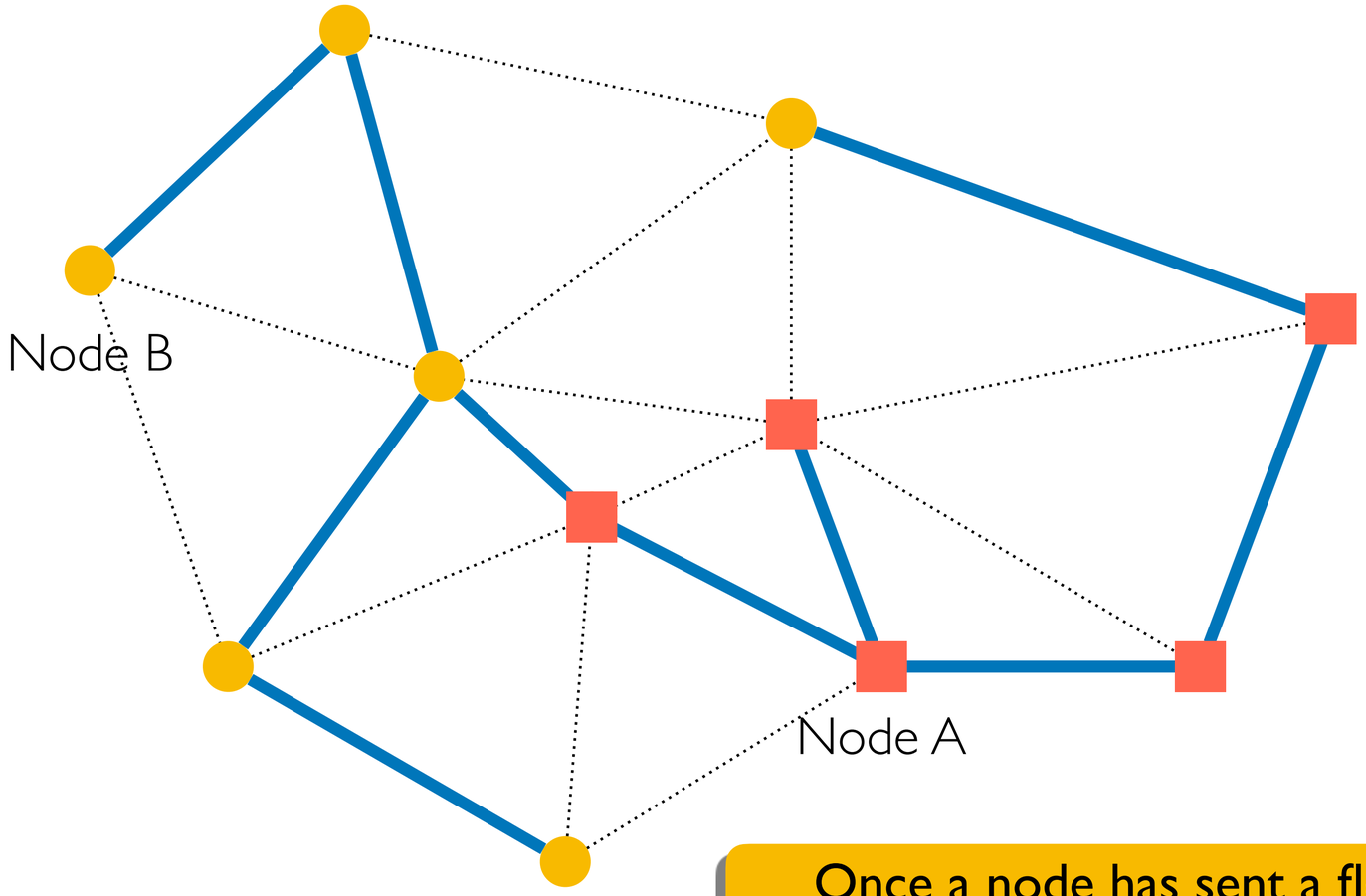

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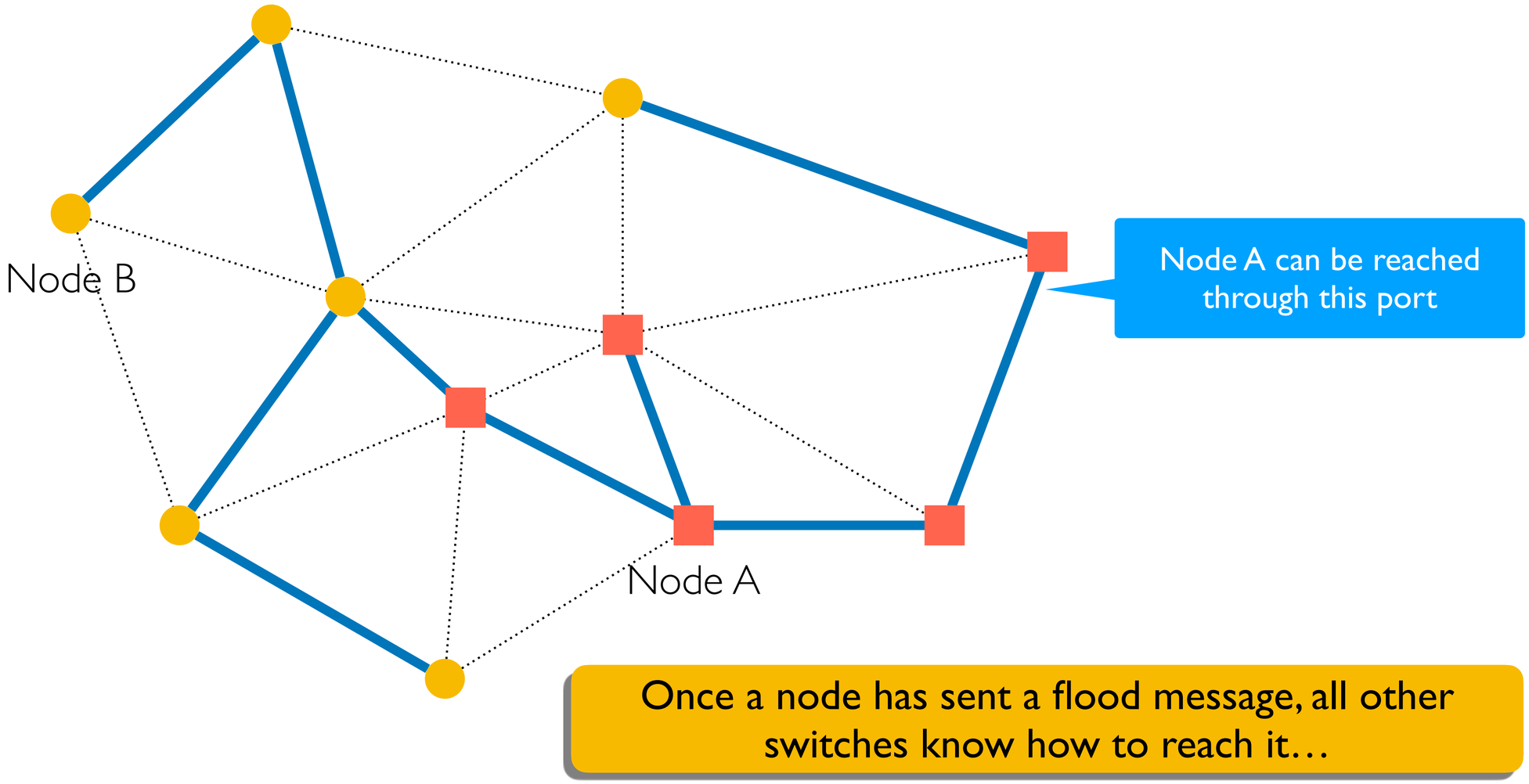

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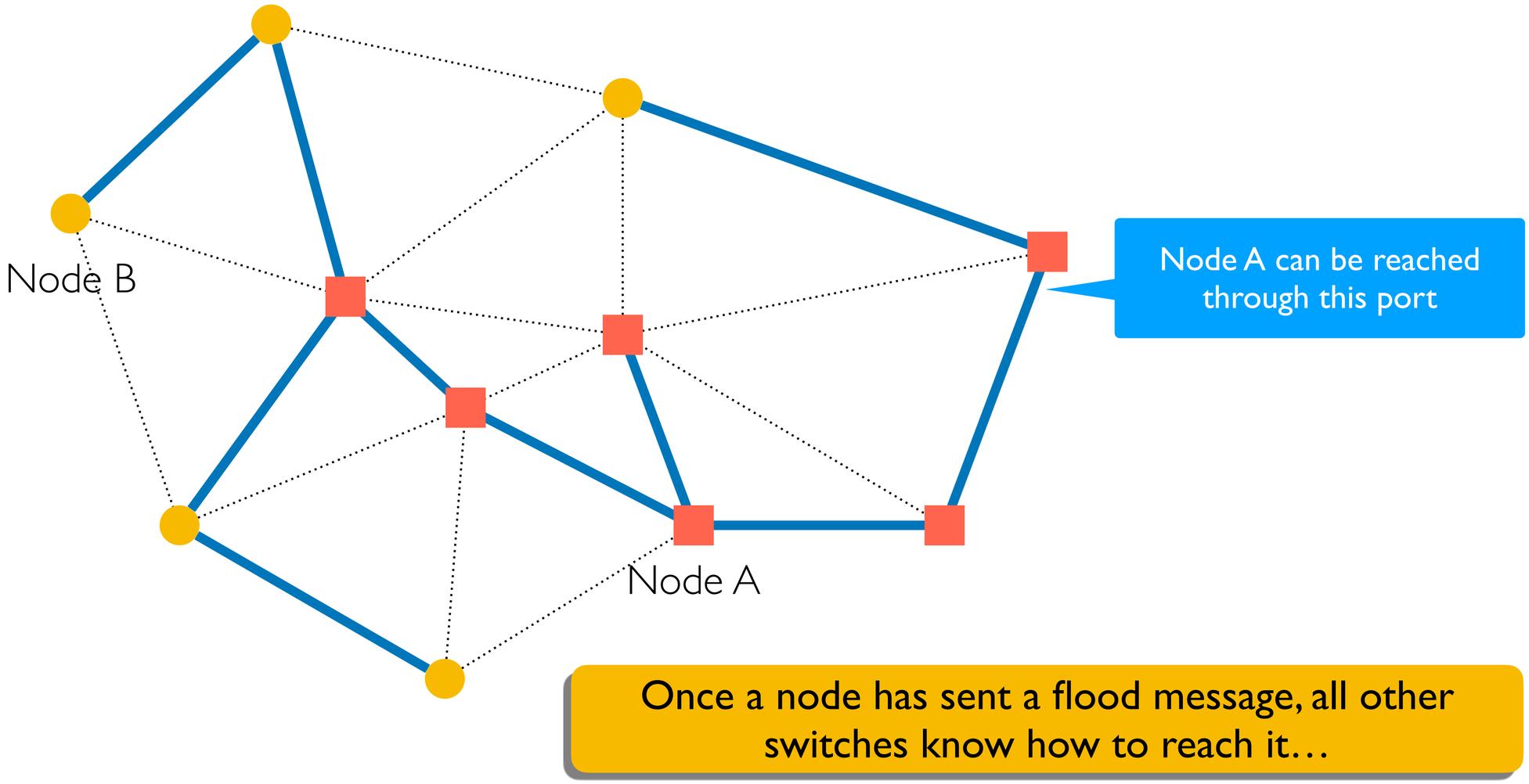

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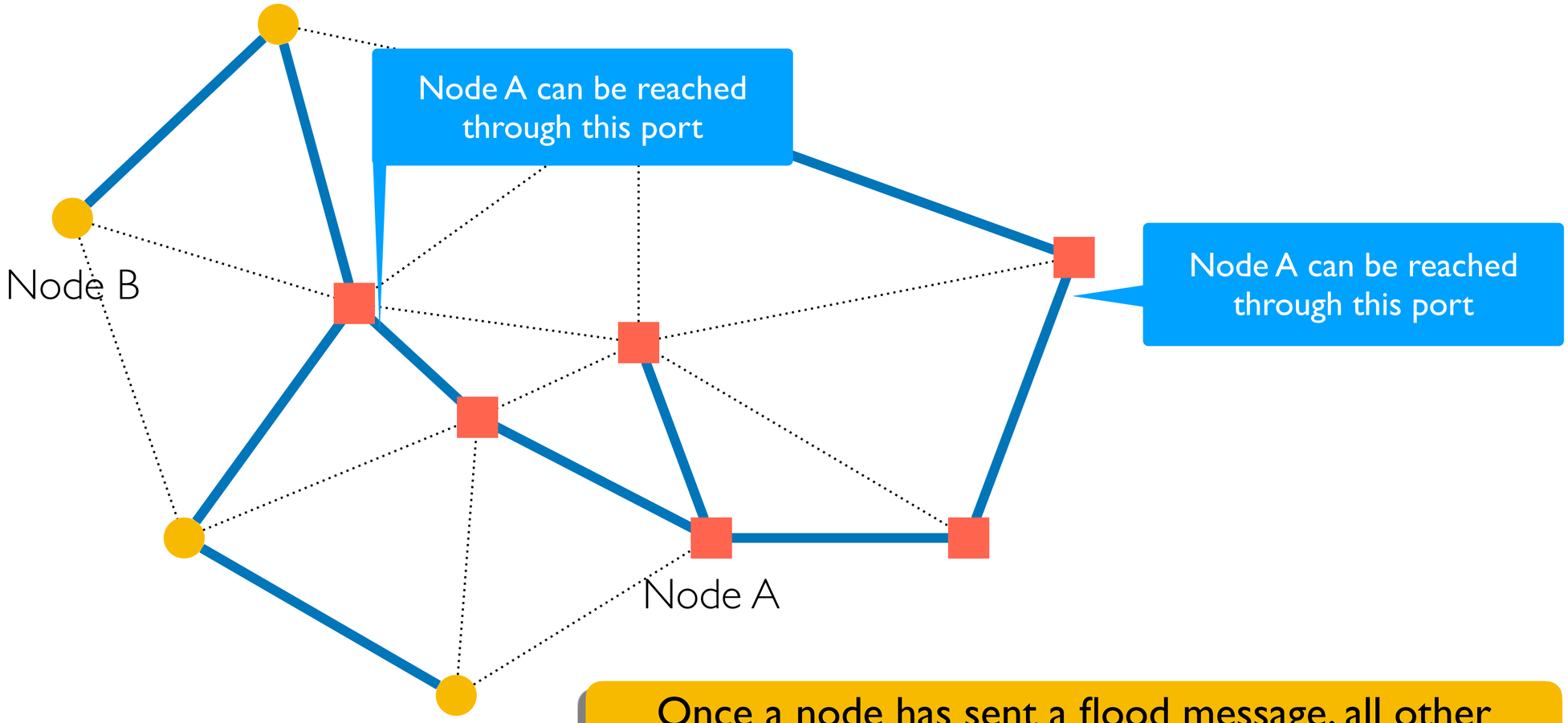

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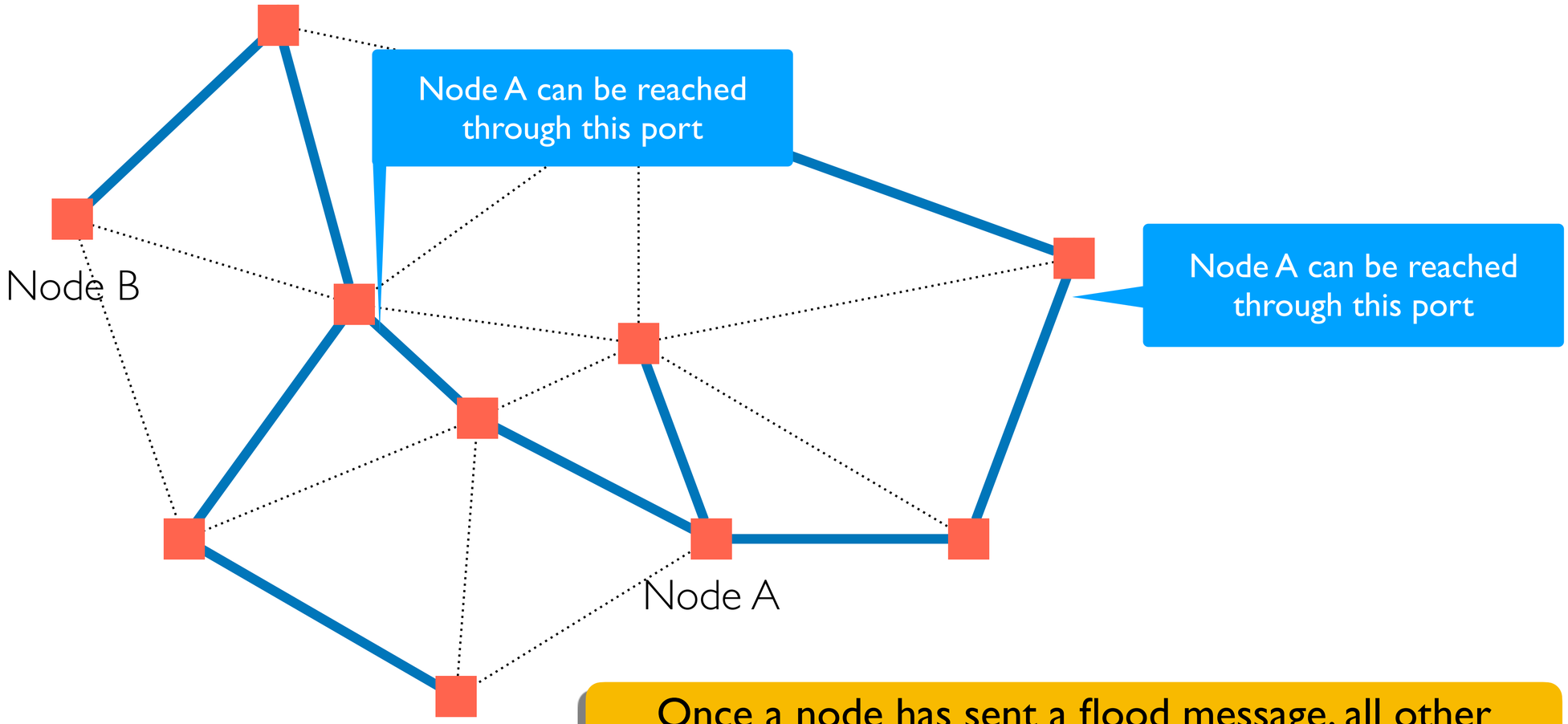

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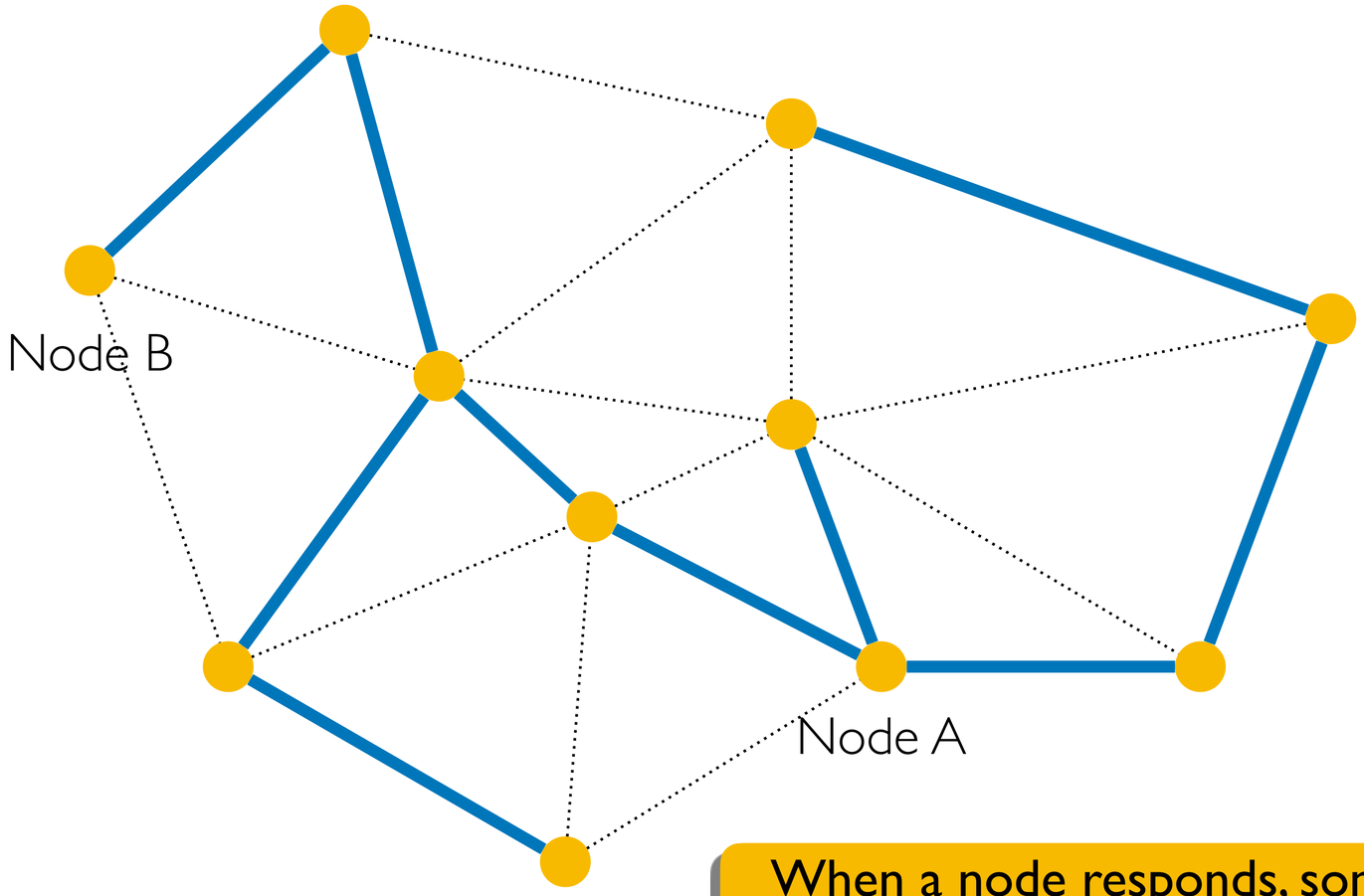

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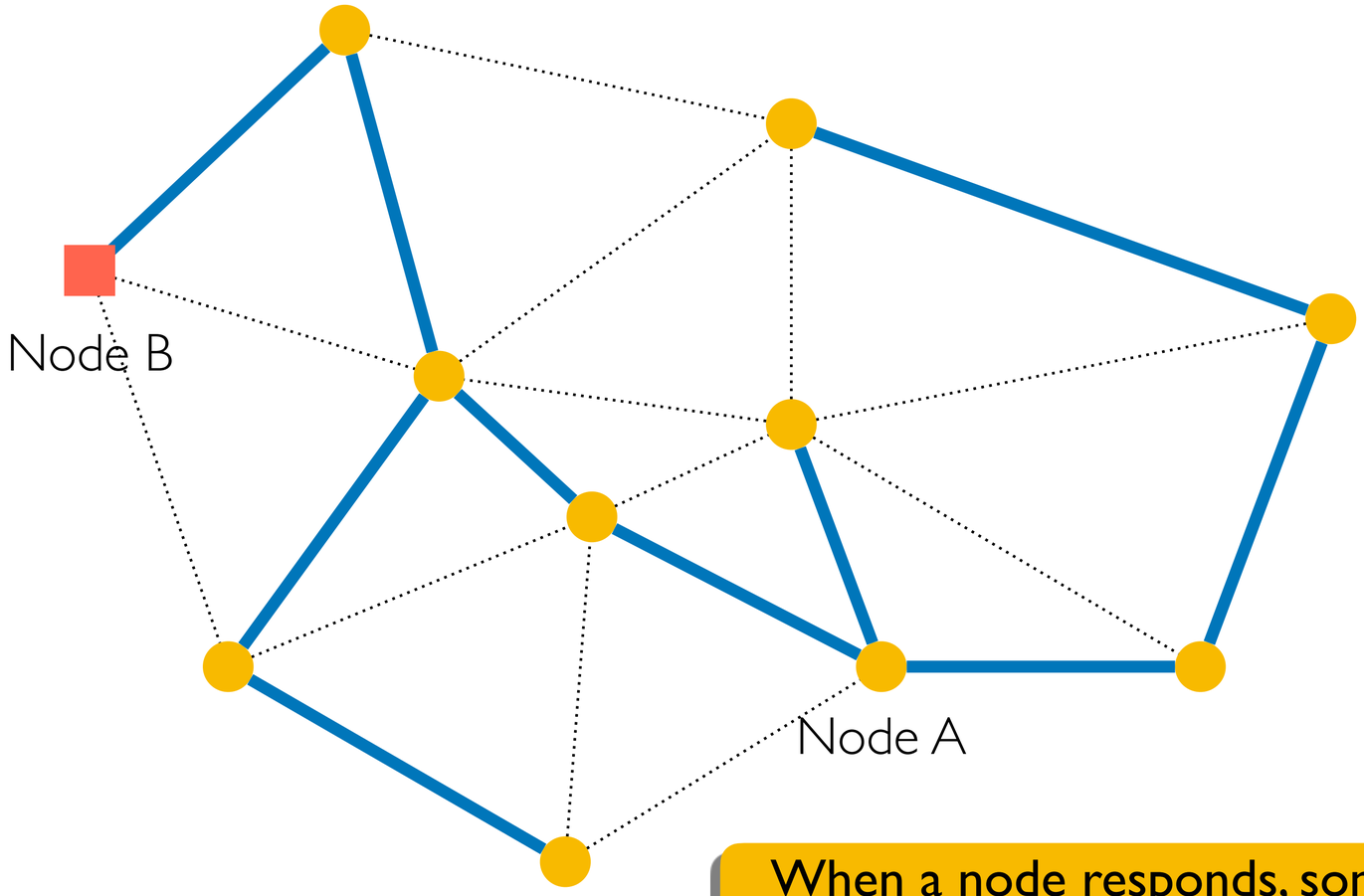

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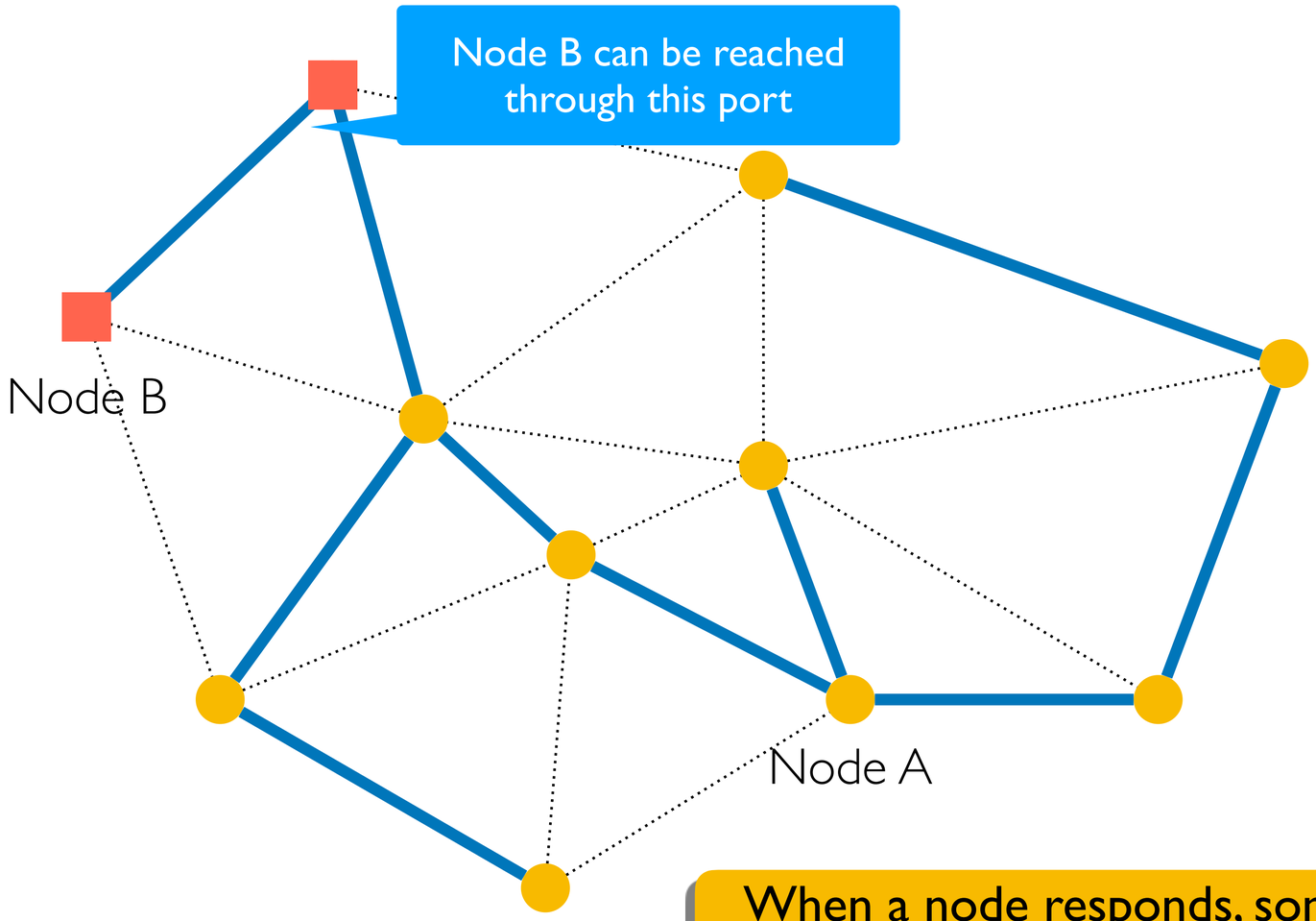

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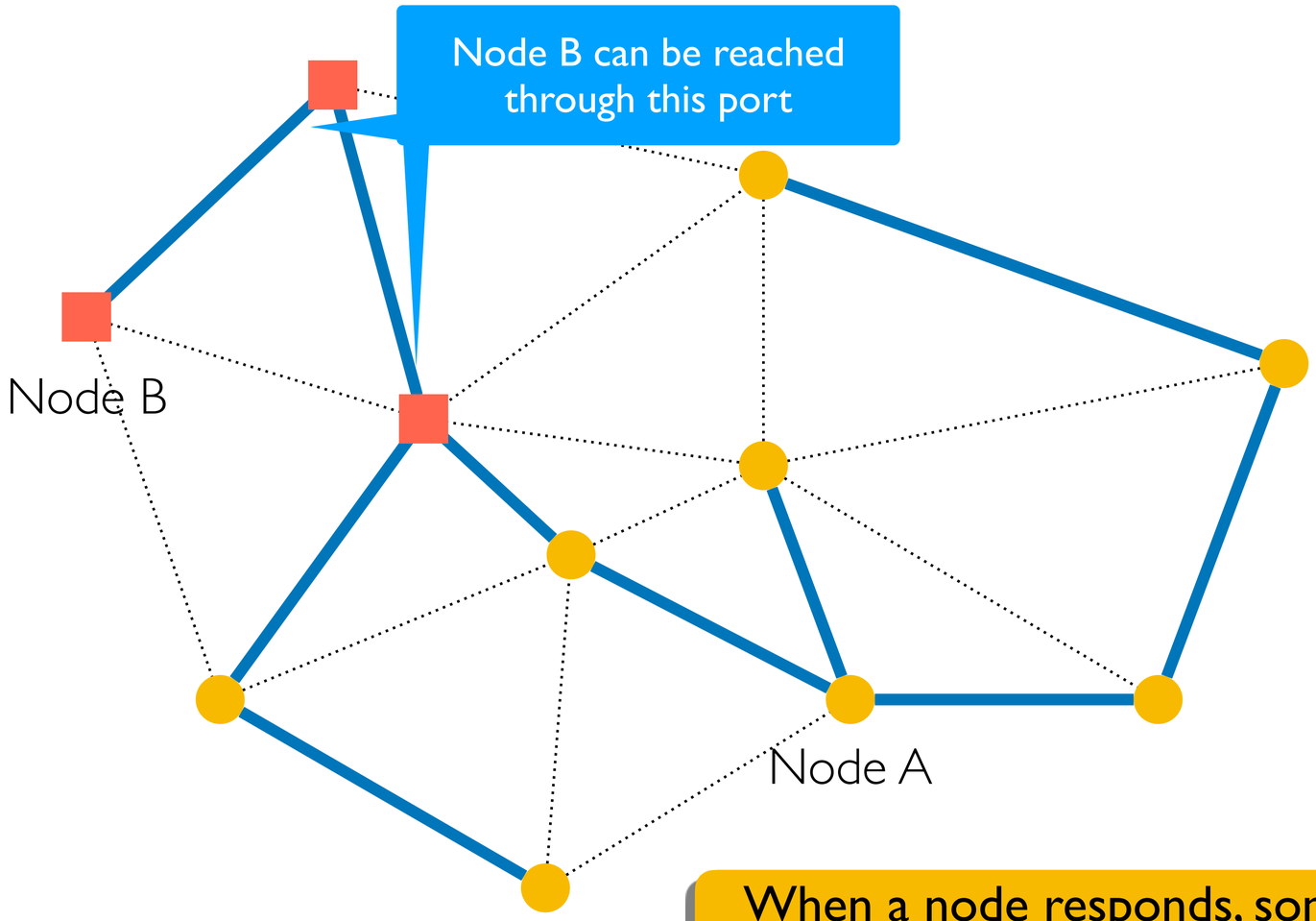

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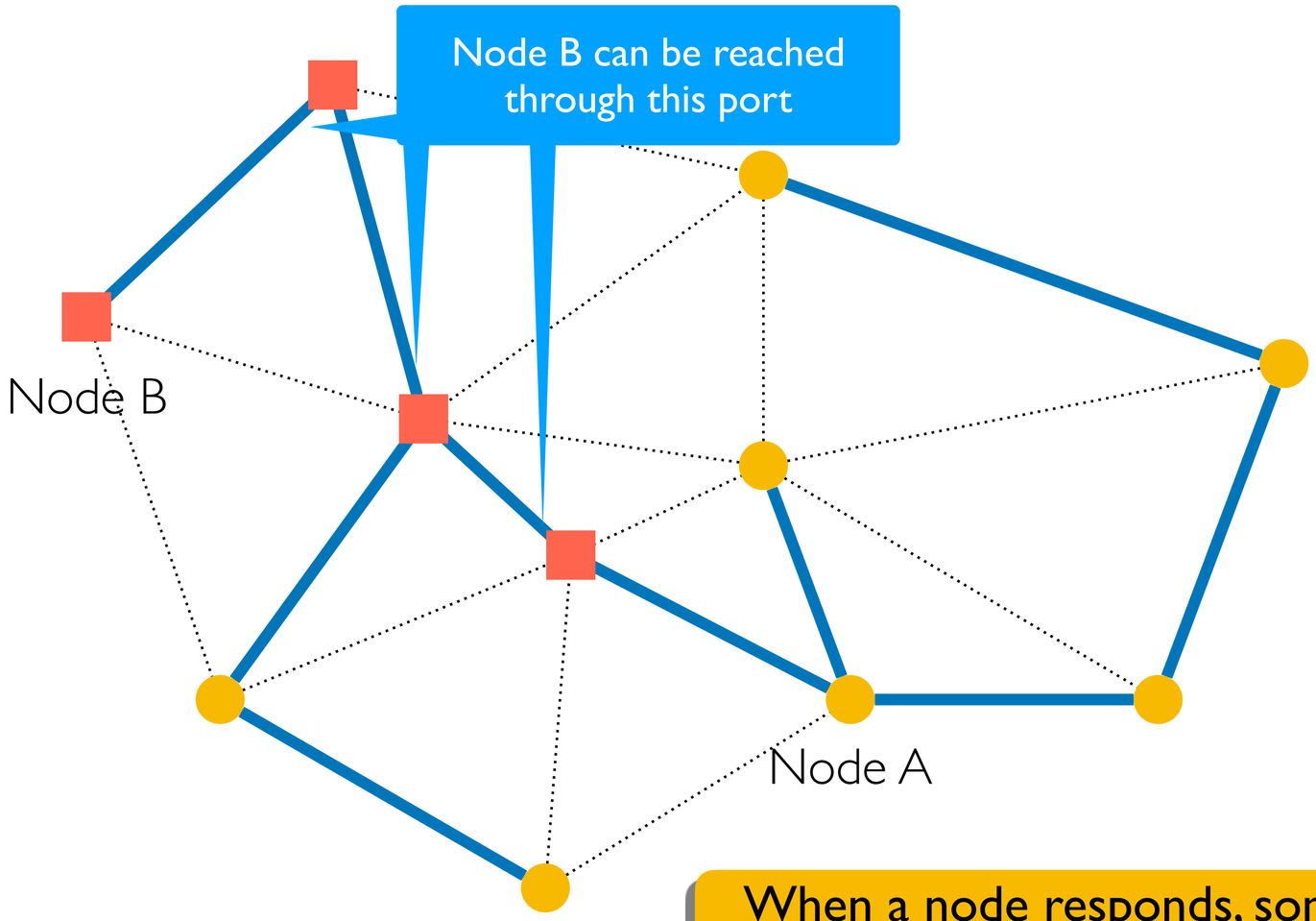

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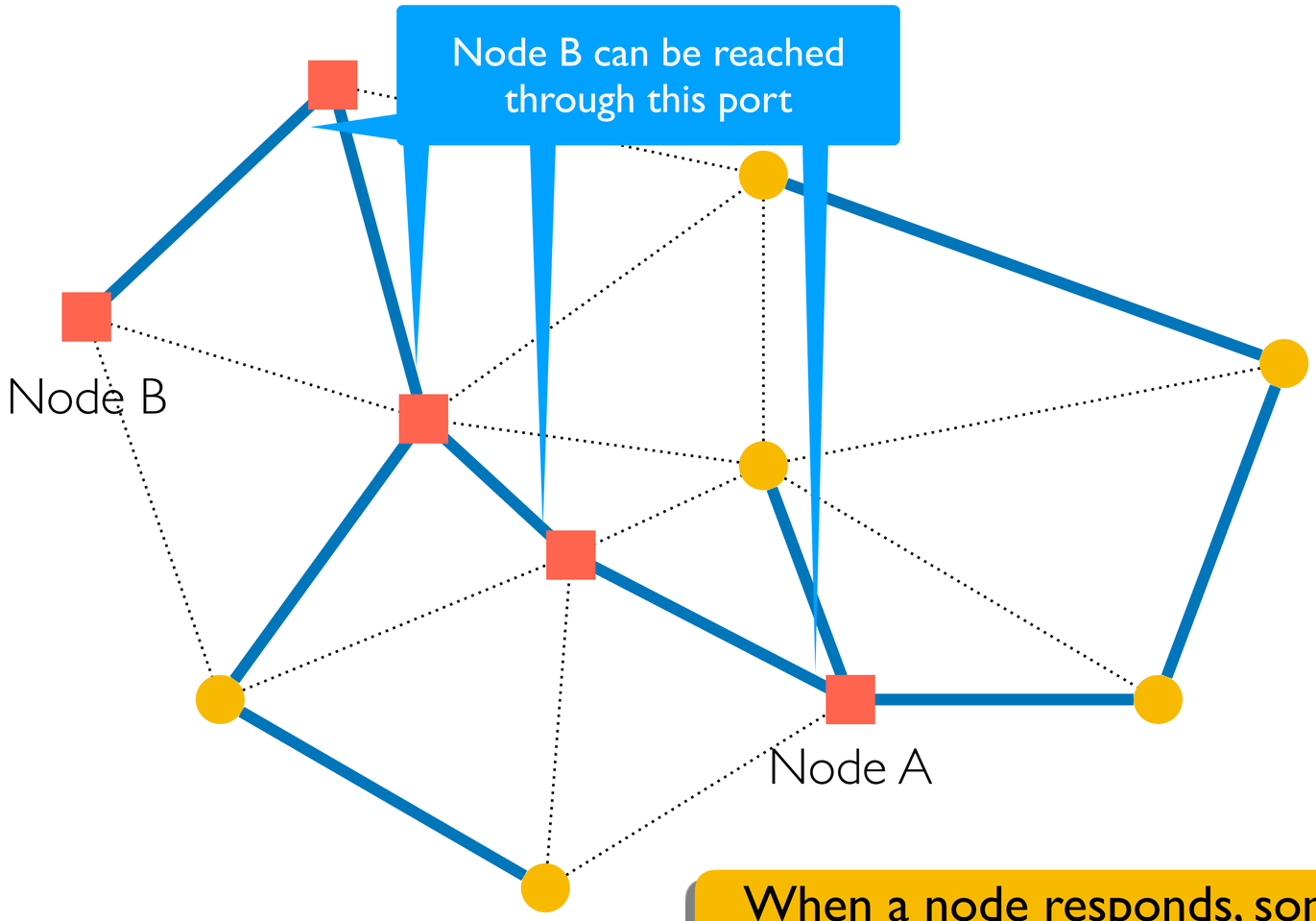

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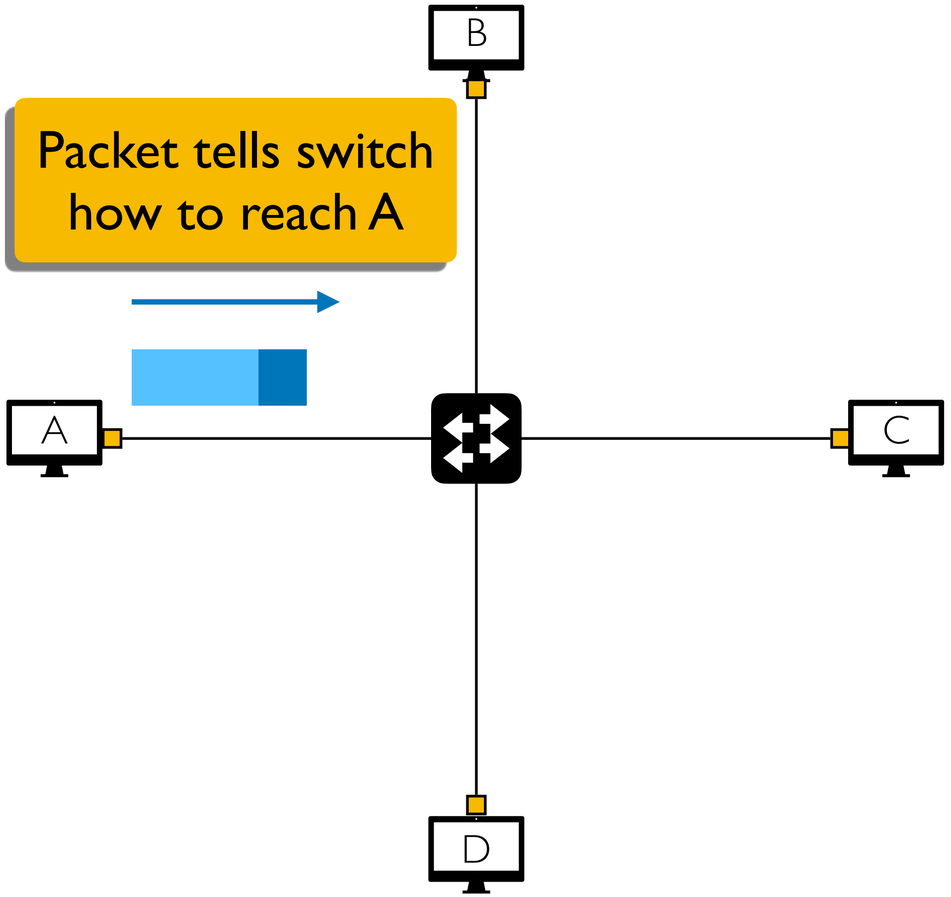

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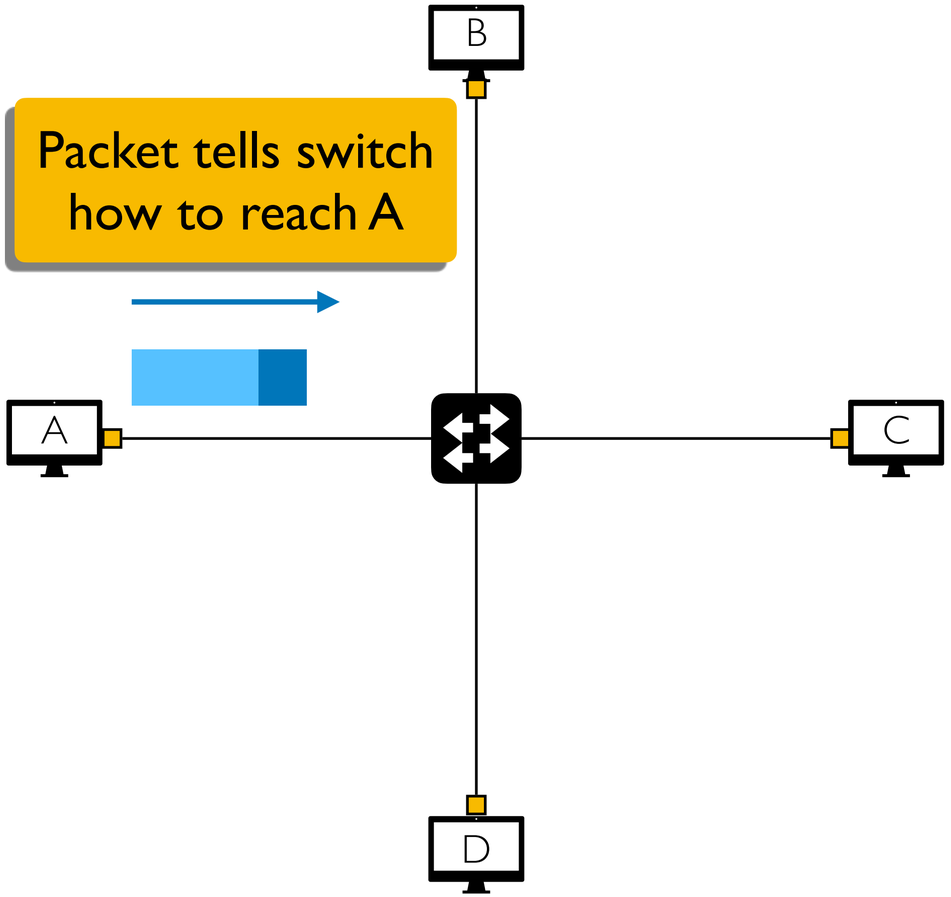

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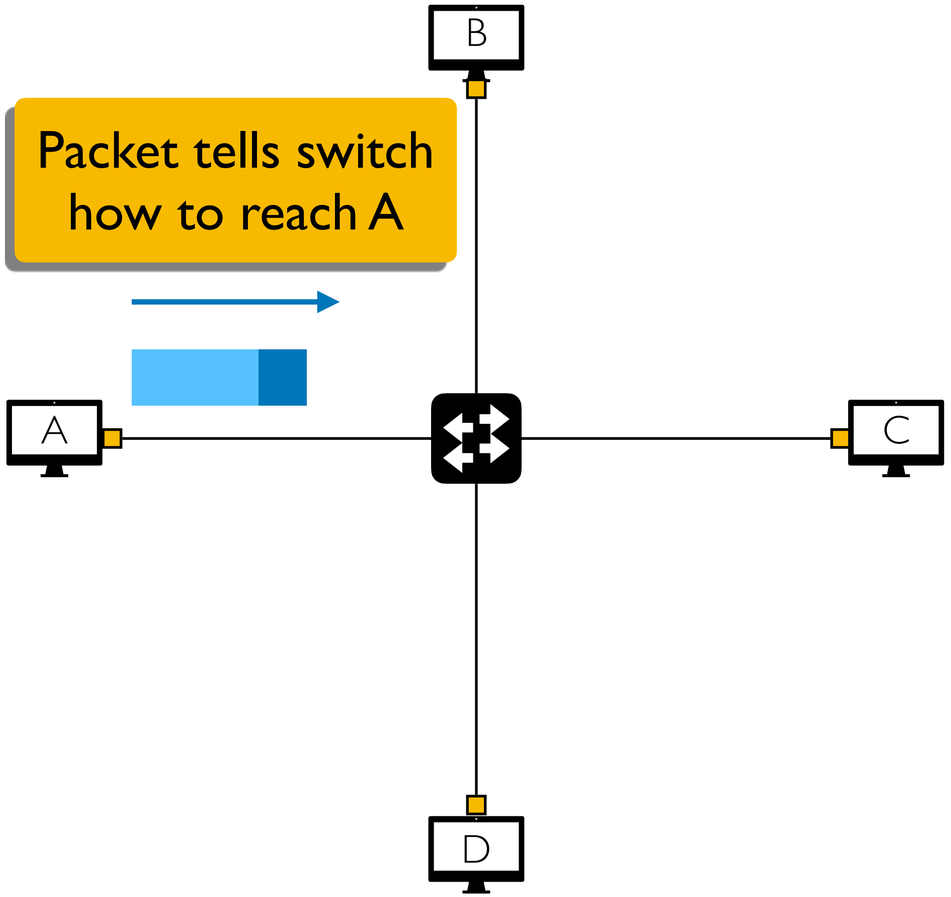

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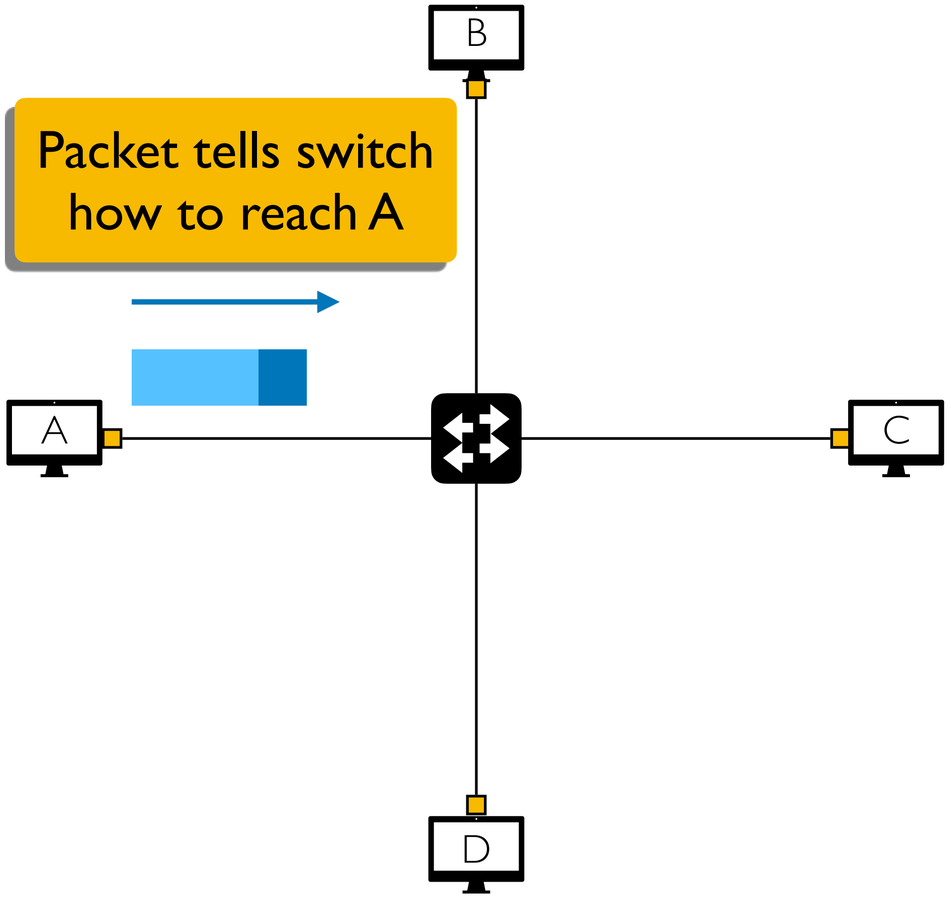

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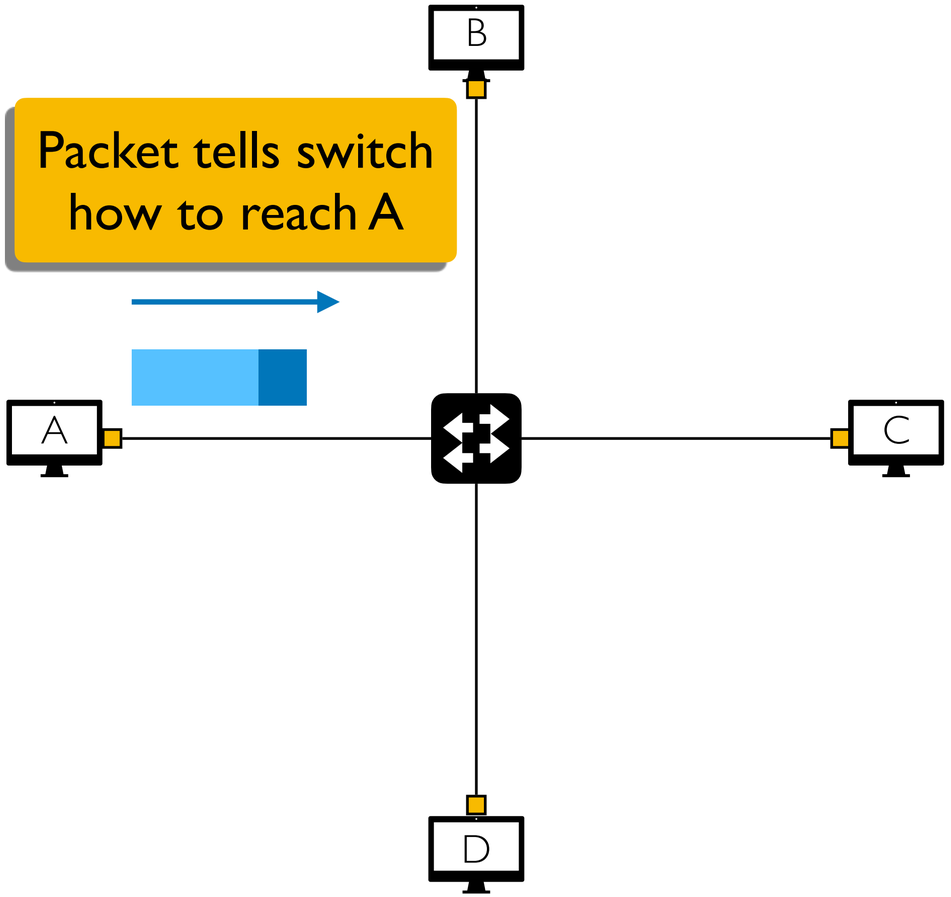

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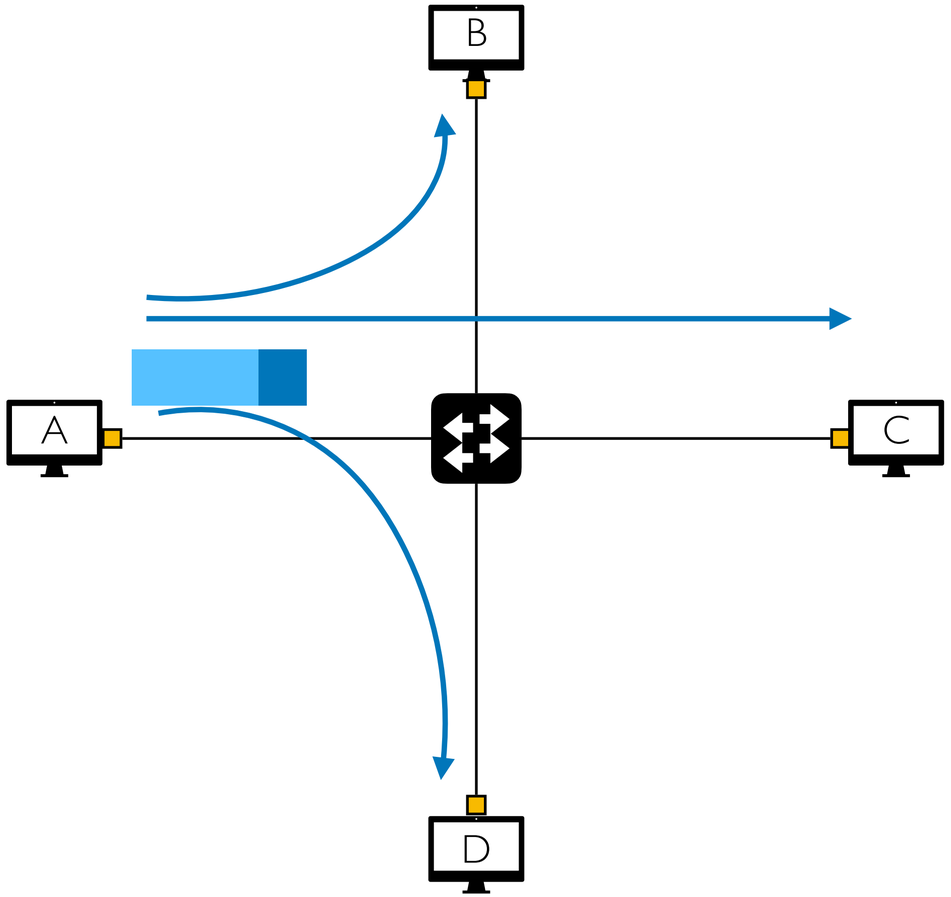

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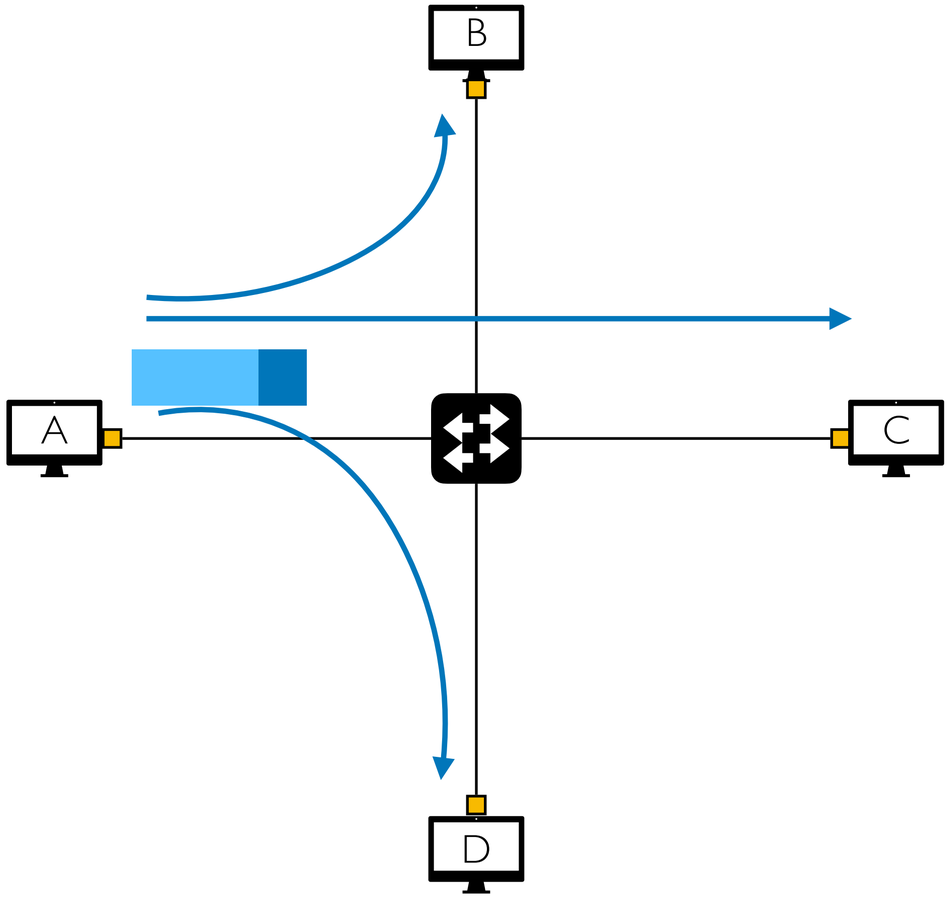

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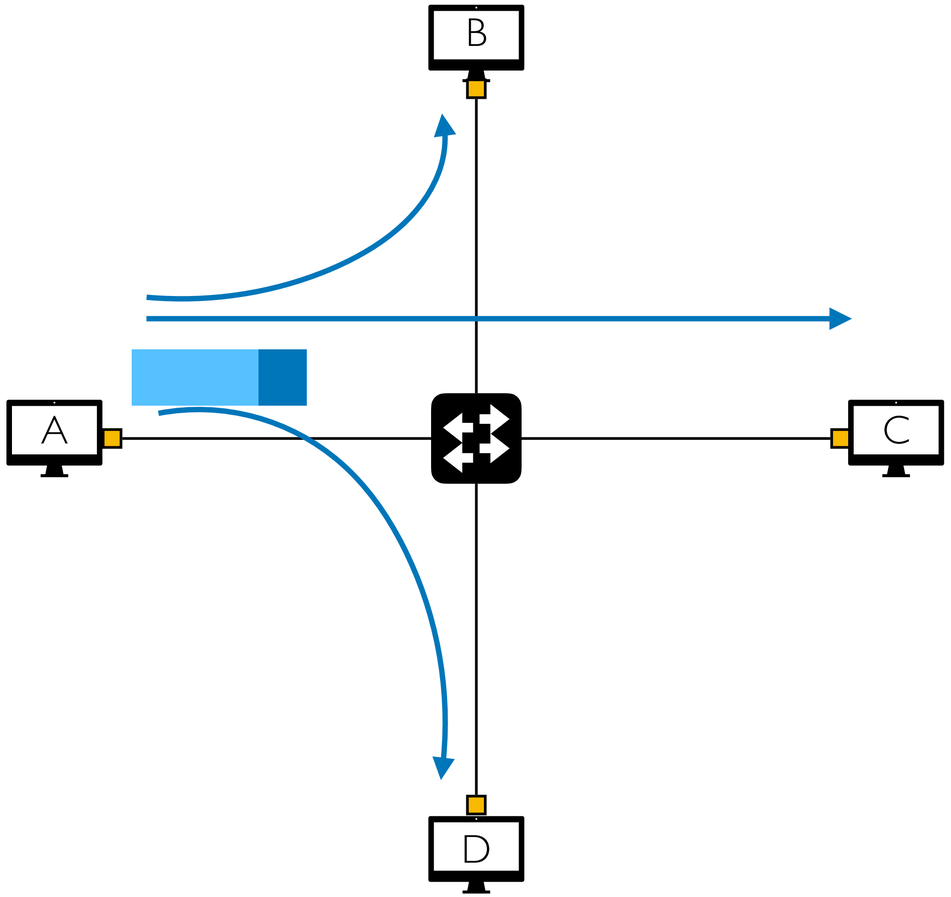

Self Learning: Handling Misses

When a packet arrives with unfamiliar destination:

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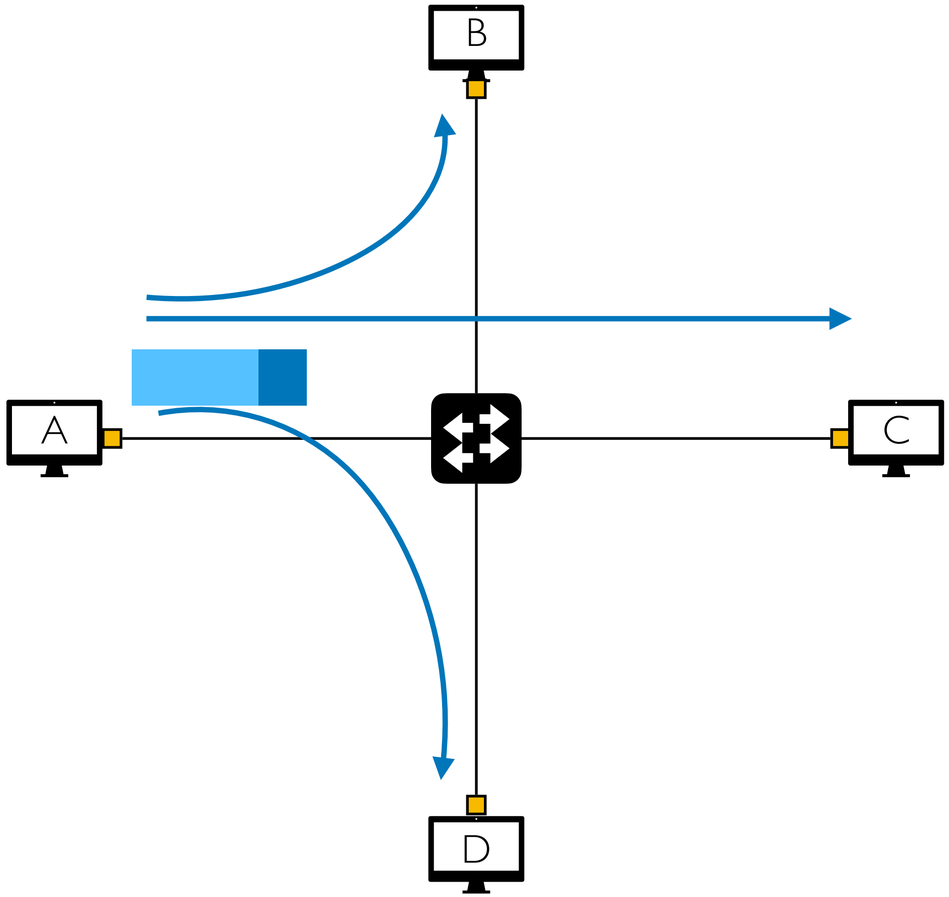
- Response may teach switch about that destination



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  - This makes flooding possible
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  - And in the process switches learn how to reach the source of flood
- **No route "computation"**
  - Forwarding entries a consequence of traffic pattern

Questions?

Contrast: IP vs. Ethernet

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- IP

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  - Packets forwarded on all links

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  - Forwarding table computed by routing protocol
- **Ethernet**
  - Packets forwarded on subset of links (spanning tree)
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  - "Routing" protocol computes loop-free *topology*
  - Forwarding table derived from data packets (+SPT floods)

Strengths of Ethernet's Approach

- Plug-n-Play
- Simple

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- **Much of the network bandwidth goes unused**
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- **Slow to react to host movement**
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- **Poor predictability**
  - Location of root and traffic patterns determines forwarding efficiency

Outline

- Frames and framing
- Addressing
- Routing
- Forwarding
- Discovery: Bootstrapping end-to-end communication

Discovery

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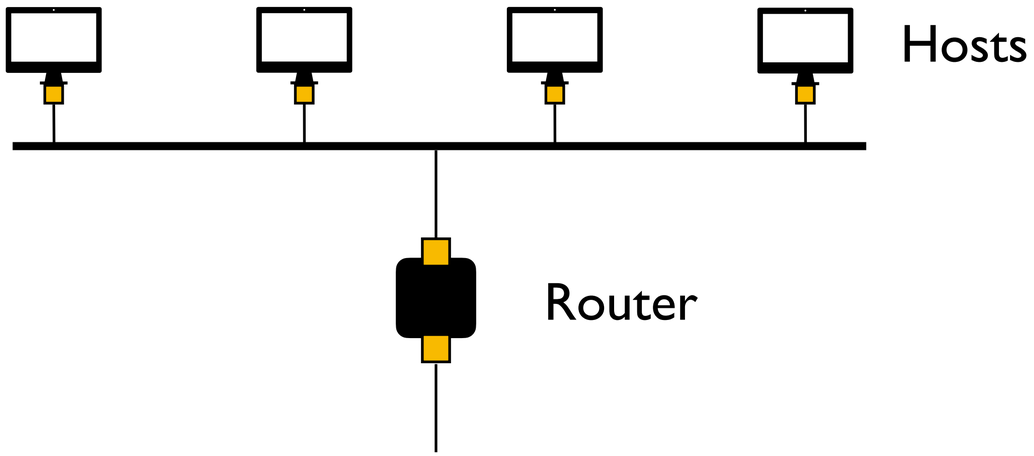
- Must discover lots of information before it can communicate with a remote host B
  - What is my IP address?
  - What is B's IP address?
  - What is B's MAC address? (if B is local)
  - What is my first-hop router's MAC address? (if B is not local)
  - …

ARP & 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



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  - Discovery of local end-hosts
    - For communication between hosts on the same LAN

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

Questions?

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

1. **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

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

DHCP: Operation

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3. One or more DHCP servers responds with a DHCP "offer" message
   - Proposed IP address for client, lease time
   - Other parameters

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4. Client *broadcasts* a DHCP request message
   - Specifies which offer it wants
   - Echoes accepted parameters
   - Other DHCP servers learn they were not chosen

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DHCP "relay agents" used when the DHCP server isn't on the same broadcast domain — see text!

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  - *Hard state:* allocation is **deliberately** returned/withdrawn
  - e.g., used to track address allocation in DHCP

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  - Server: sets a timer associated with the record of allocation
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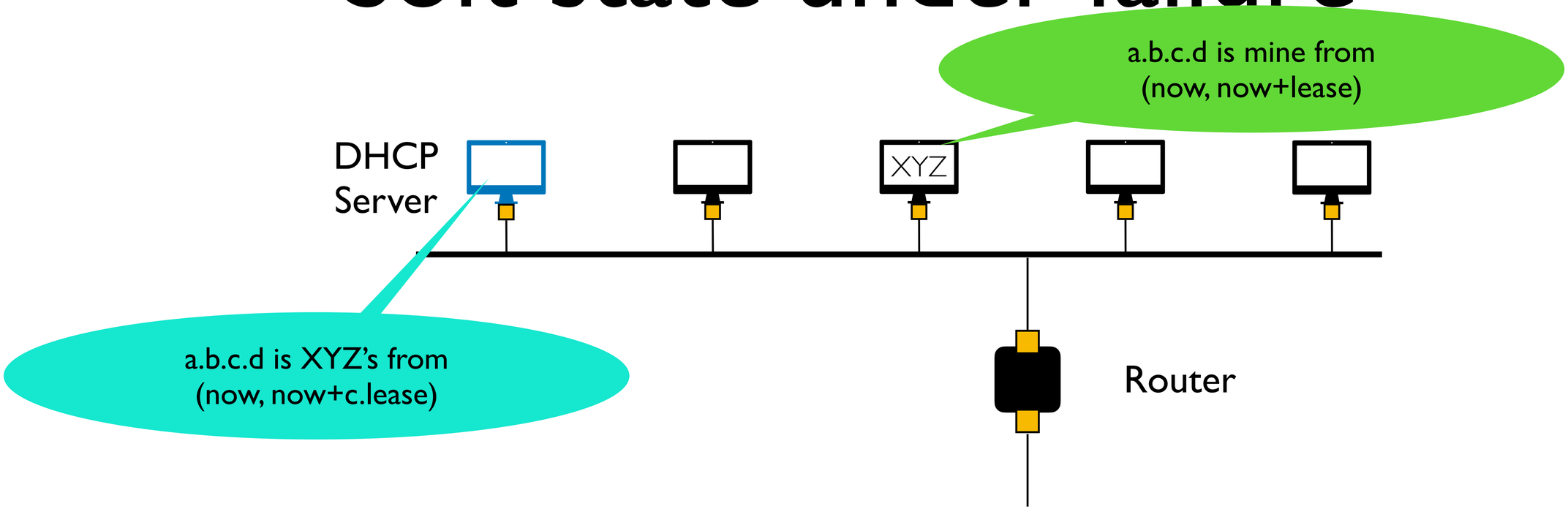
- **Simple, yet robust under failure**
  - State always fixes itself within (small constant of) lease time

Soft state under failure



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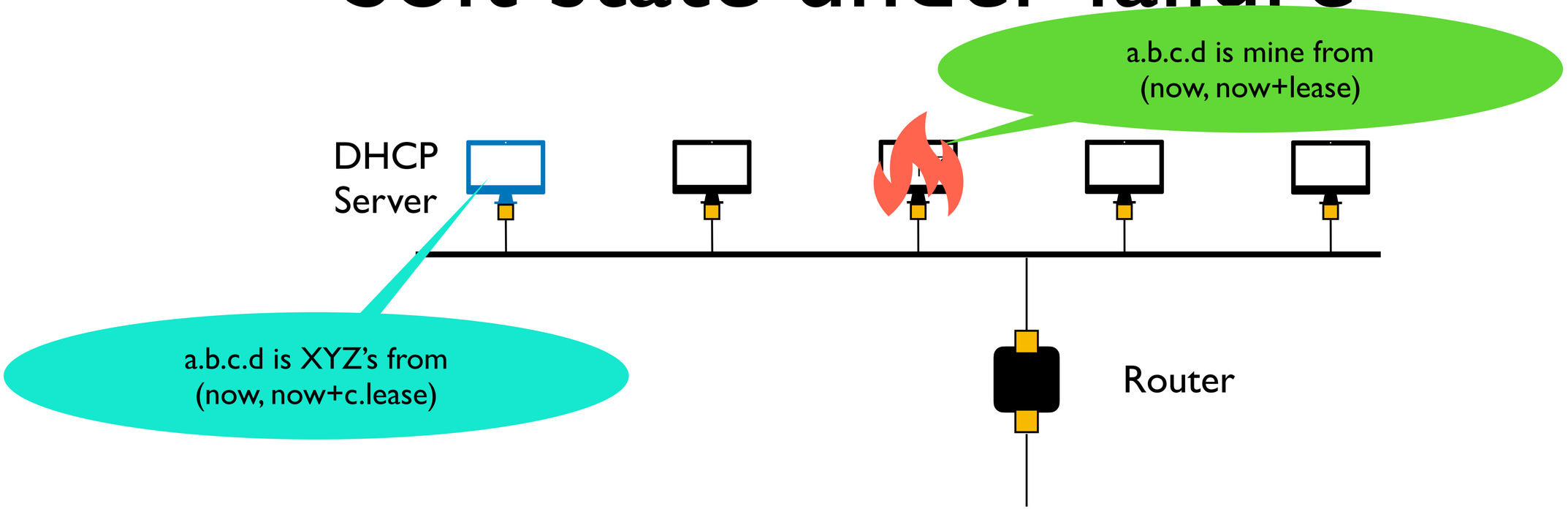

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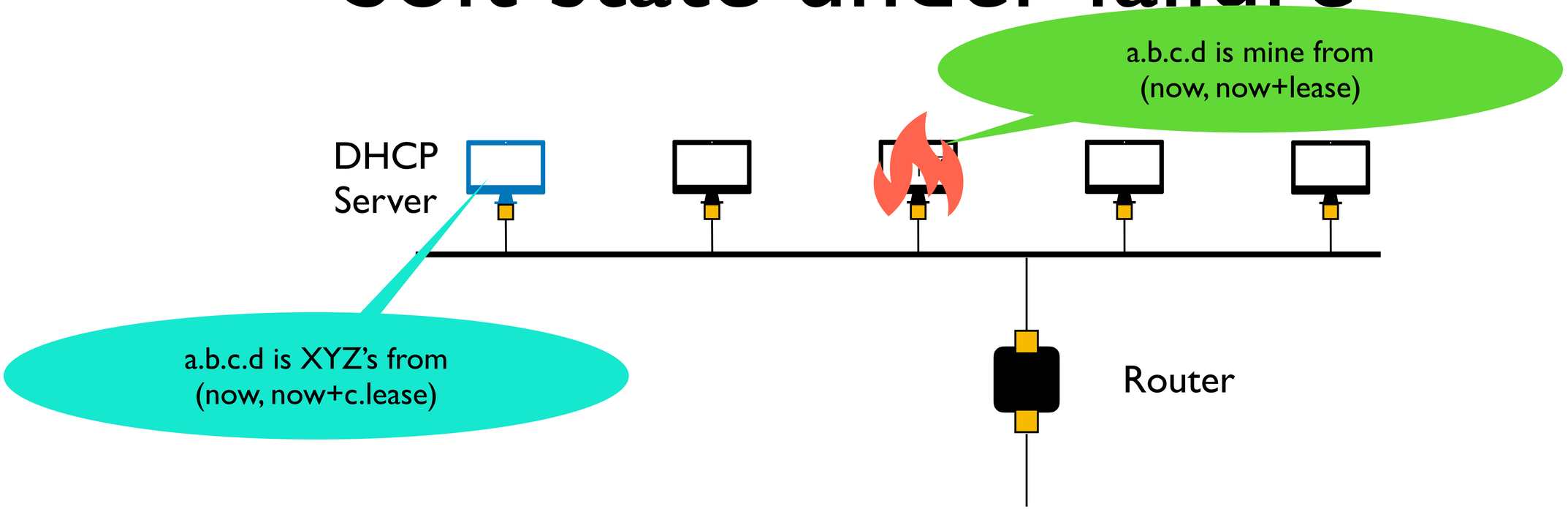

- **What happens when host XYZ fails?**
  - Renewals from XYZ stop
  - DHCP server reclaims a.b.c.d after O(lease period)

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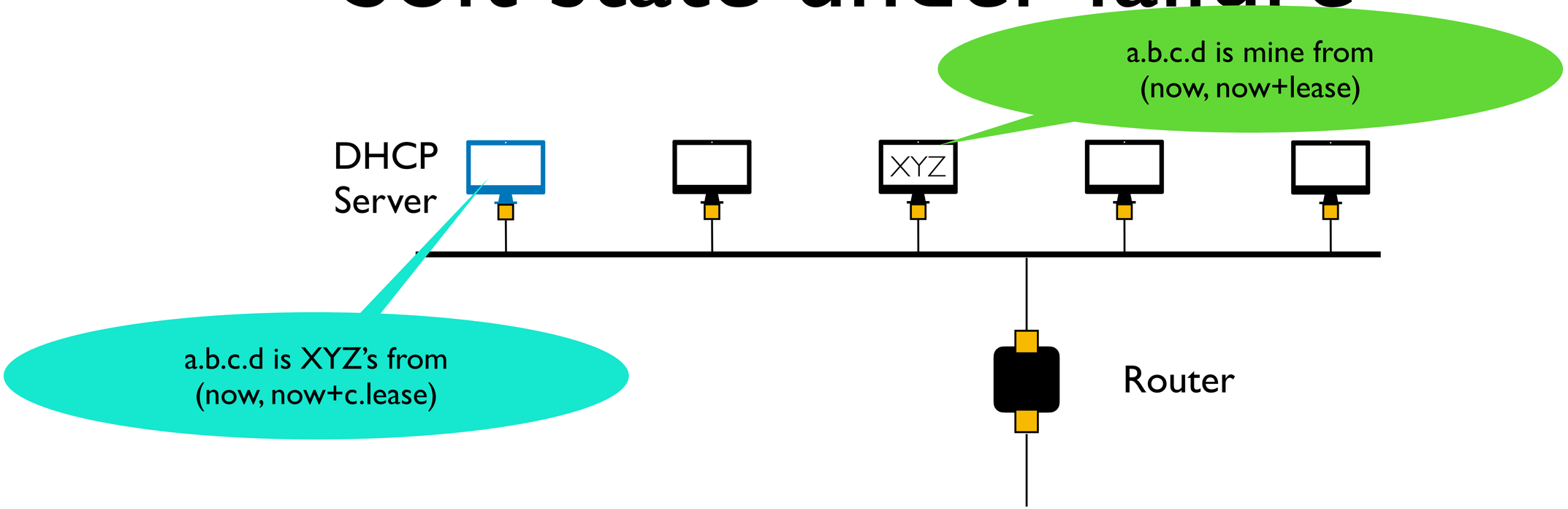

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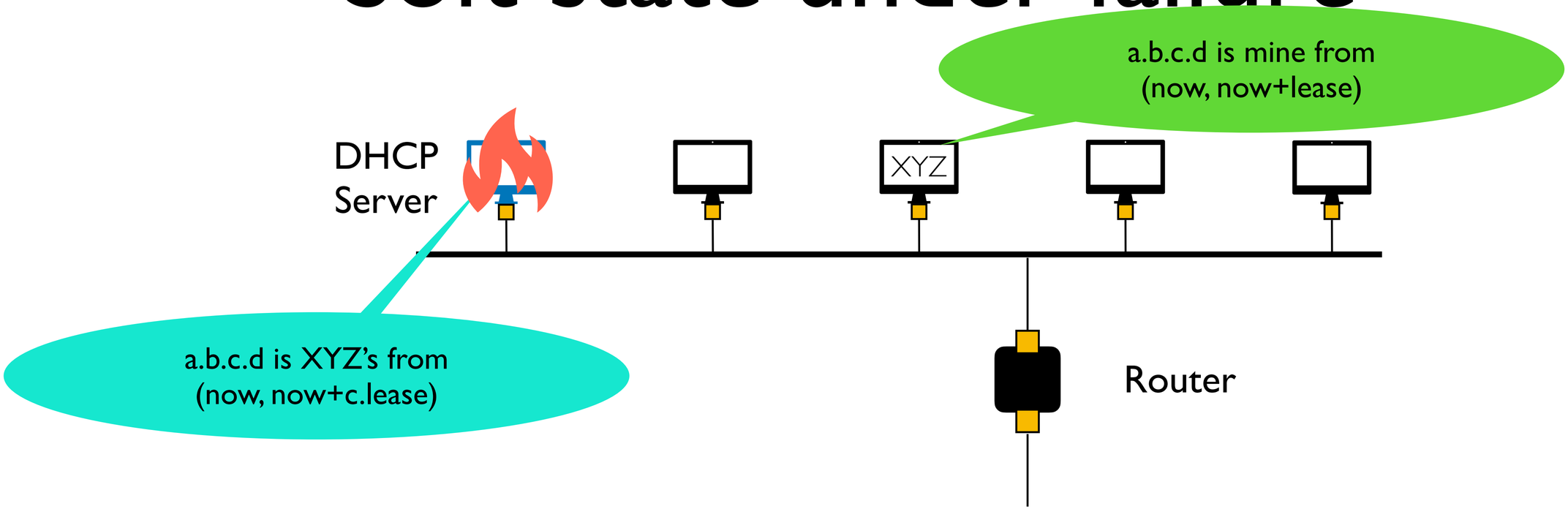

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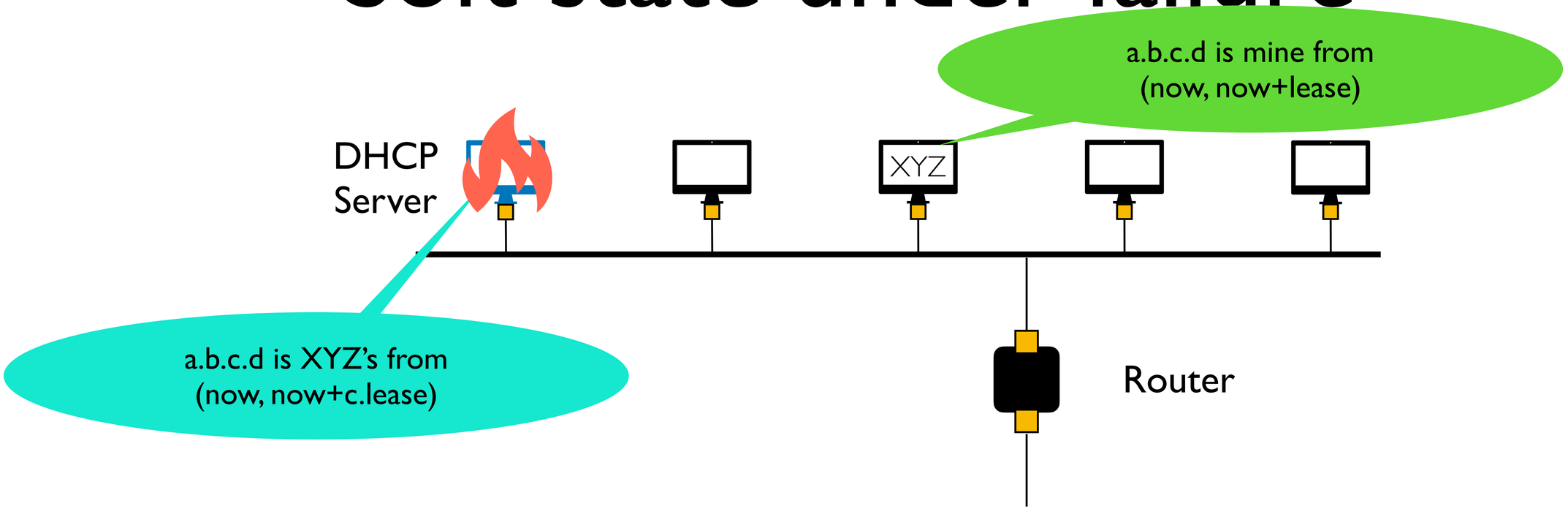
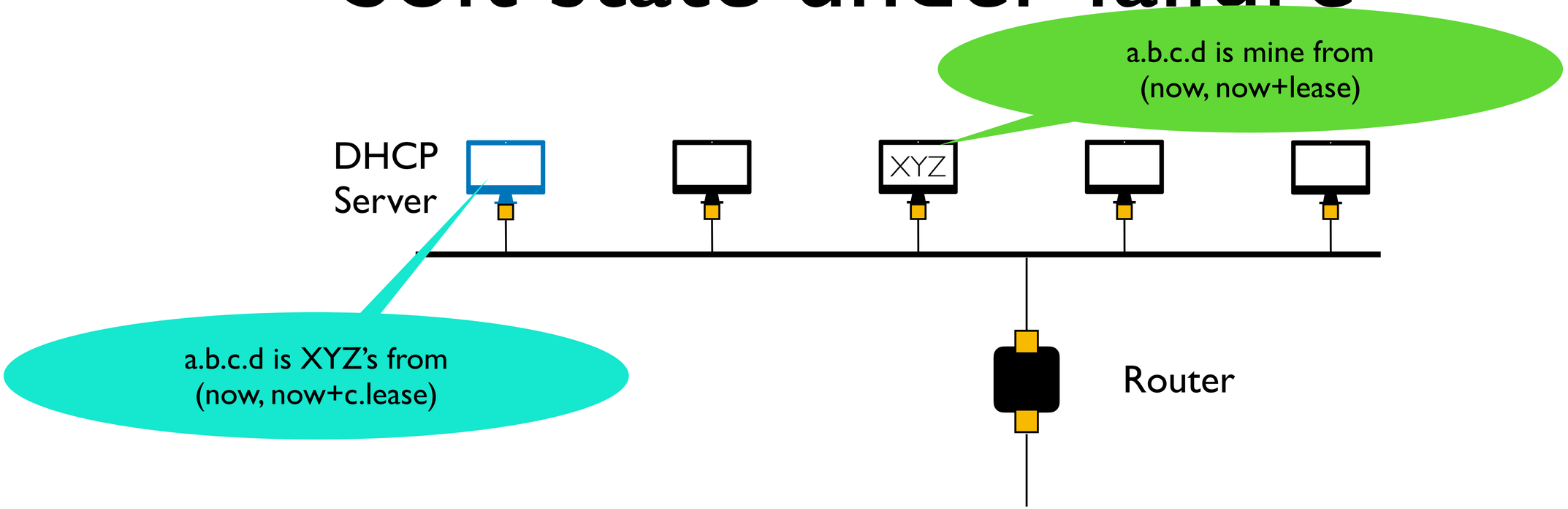


- **What happens when host DHCP Server fails?**
  - ACKs from DHCP Server stop
  - XYZ releases address after O(lease period); send new request
  - A new DHCP server can respond and we're back on track in ~lease time

Soft state under failure



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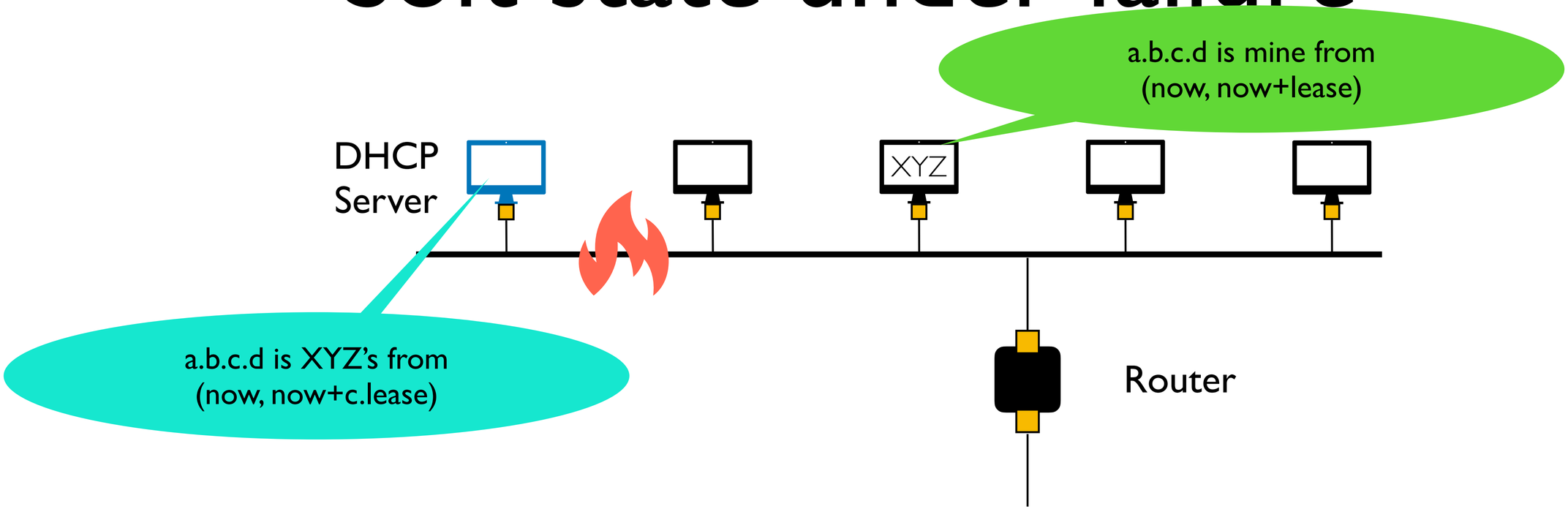

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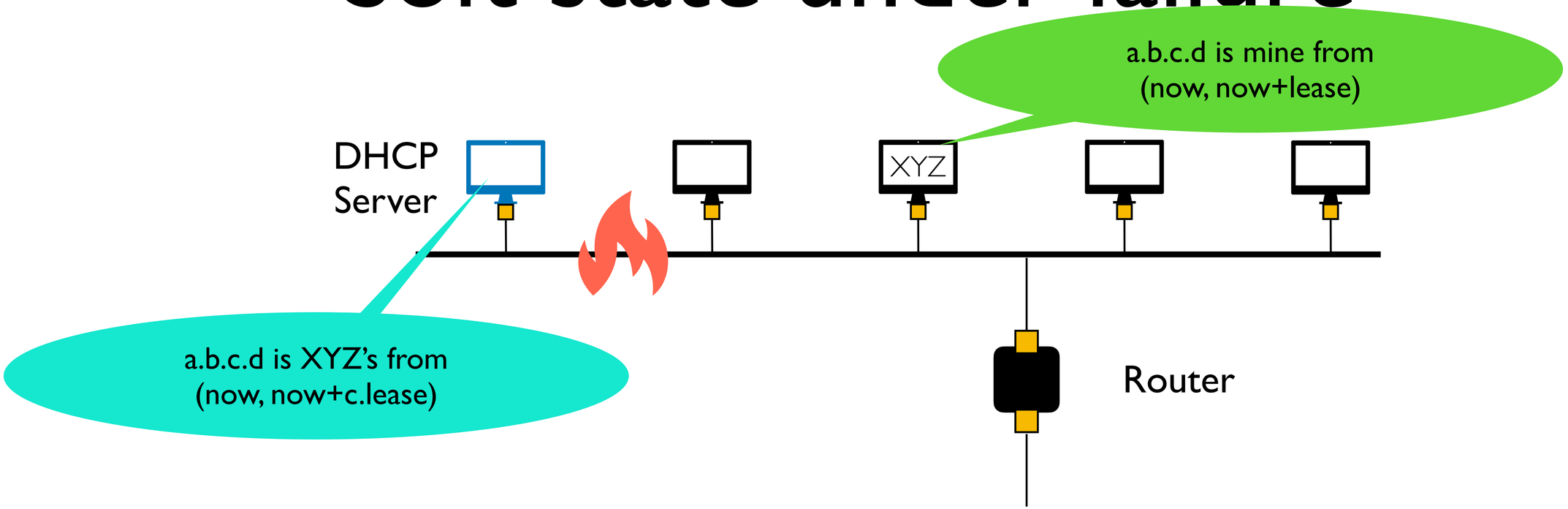

- **What happens if the network fails?**
  - Neither renewals nor ACKs get through
  - Independently: XYZ releases address; DHCP server reclaims it

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