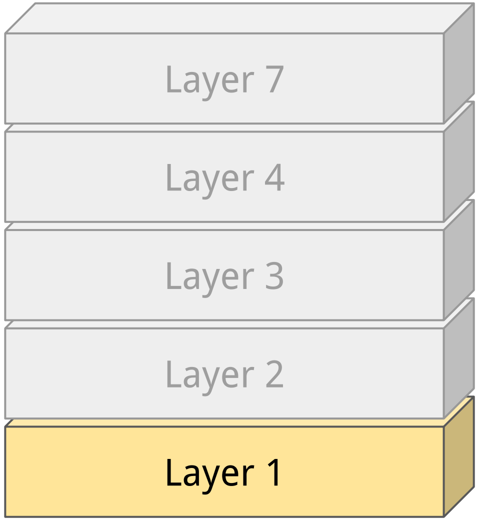
Forwarding & Ethernet

Fall 2024
[cs168.io](cs168.io)

Rob Shakir

Thanks to Murphy McCauley for some of the material!

Looking at Layers Again



Application → DNS, HTTP, …

Transport → TCP

Network → IP

Data Link → Ethernet

Physical → Optical fibre, copper

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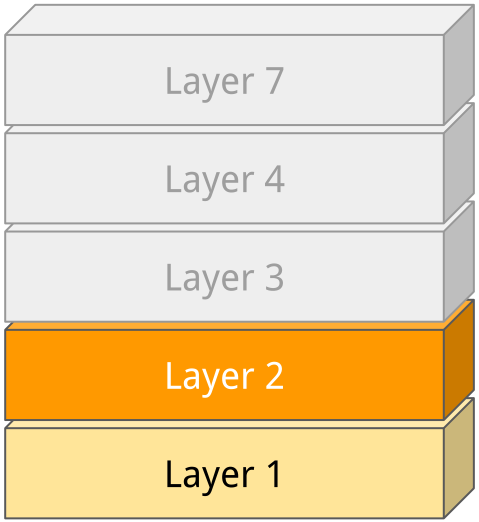
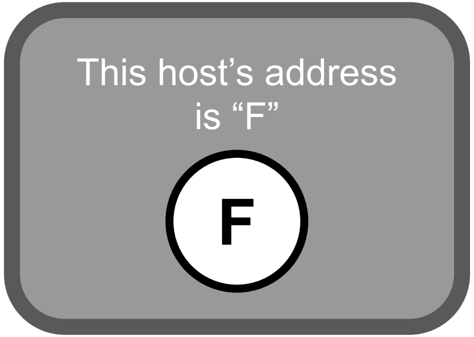


- Application → DNS, HTTP, …
- Transport → TCP
- Network → IP
- **Data Link → Ethernet**
- Physical → Optical fibre, copper

Lecture Plan

- We're going to start at the bottom of our set of layers.
    - And work-up, covering the layers in more detail.
- Today & next lecture:
    - Layer 2 & Ethernet.
    - How do packets get forwarded?
- Next week **- forwarding and routing**.
    - How do we know where packets need to go?

Drawing Hosts…



Connecting Nodes Together

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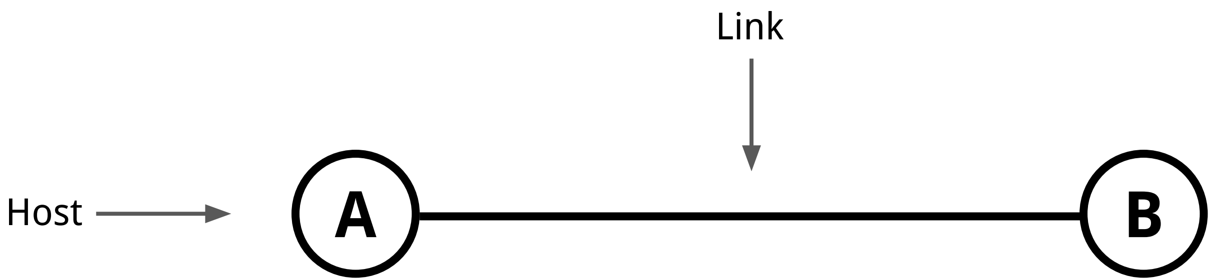

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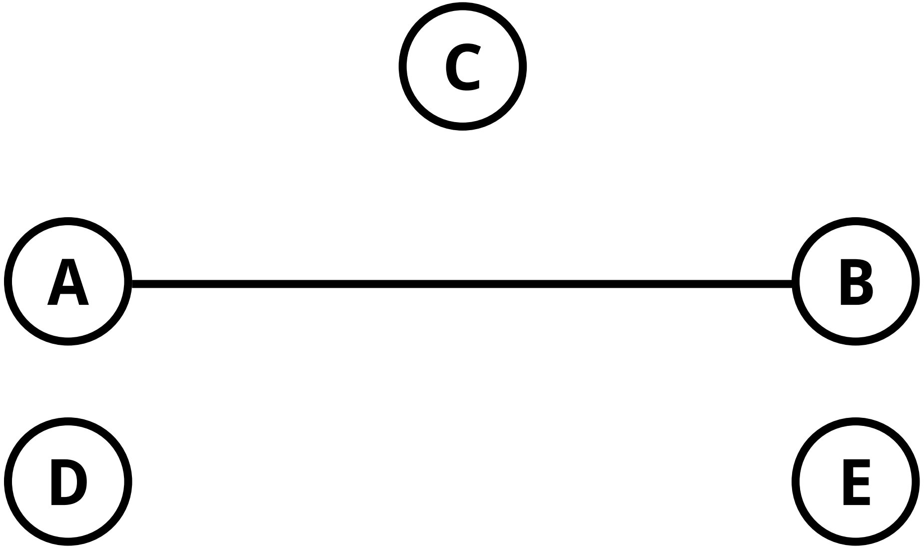
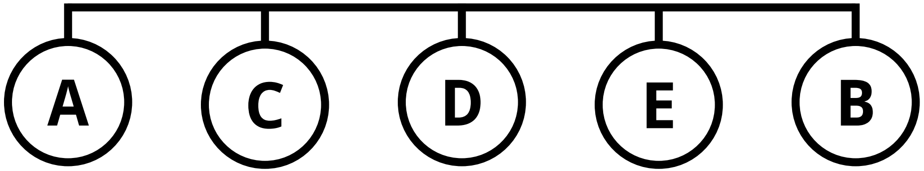


Now what?

How can we connect this new host?



Naïve solution - connect all our hosts together
via a shared medium.

Some history - ALOHANet

- Norman Abramson had a problem at the University of Hawaii in 1968.
    - How do we allow people on other islands access to the U of H computer?

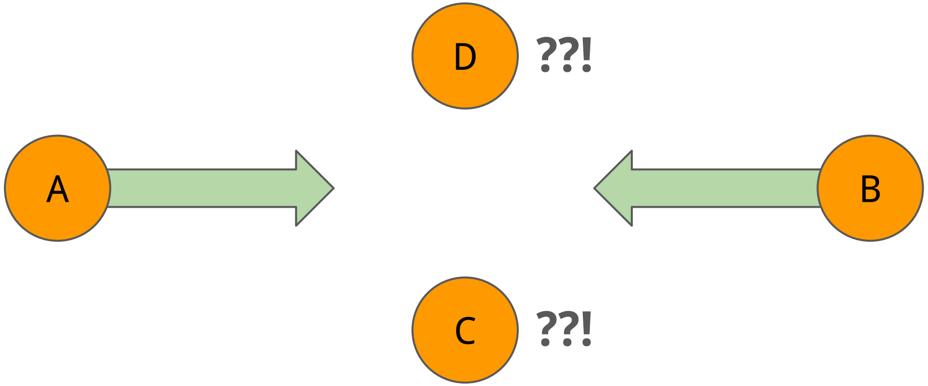
- ALOHANet
    - Additive Links On-line Hawaii Area
    - Wireless communications from terminals (computers) on other islands.
    - Hugely influential.

- ALOHANet was wireless - in radio networks there is a *shared medium* (the electromagnetic spectrum).

Shared Media

- In a network with a *shared medium*, then transmissions from different nodes may interfere or *collide* with each other.

- We need a way to allocate the medium to everyone wanting to use it…
  - A **multiple access protocol**.



Common Multiple Access Protocol approaches

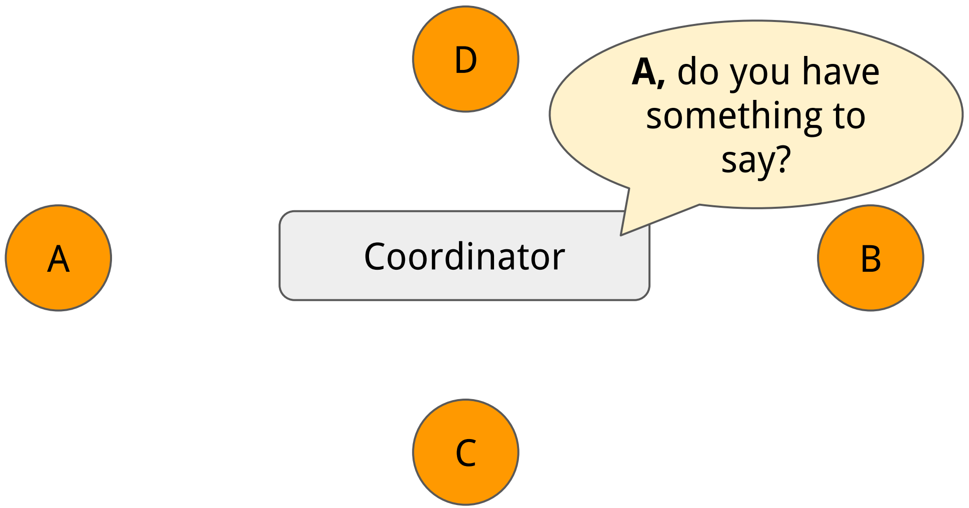
- Divide the medium by frequency – **frequency-division multiplexing**.
  - Give each connected node some slice of frequencies.
  - Can be wasteful – only a specific amount of frequency to allocate.
  - Not everyone has something to say all the time (many frequencies idle).

- Divide the medium by time - **time-division multiplexing.**
  - Divide time into fixed slots and allocate them to each connected node.
  - Same downside – only so much time, many slots are idle.

- Alternative: can connected nodes take turns?

Turn-taking Schemes

- Polling protocols.
  - A coordinator decides when each connected node can speak.
  - e.g., Bluetooth



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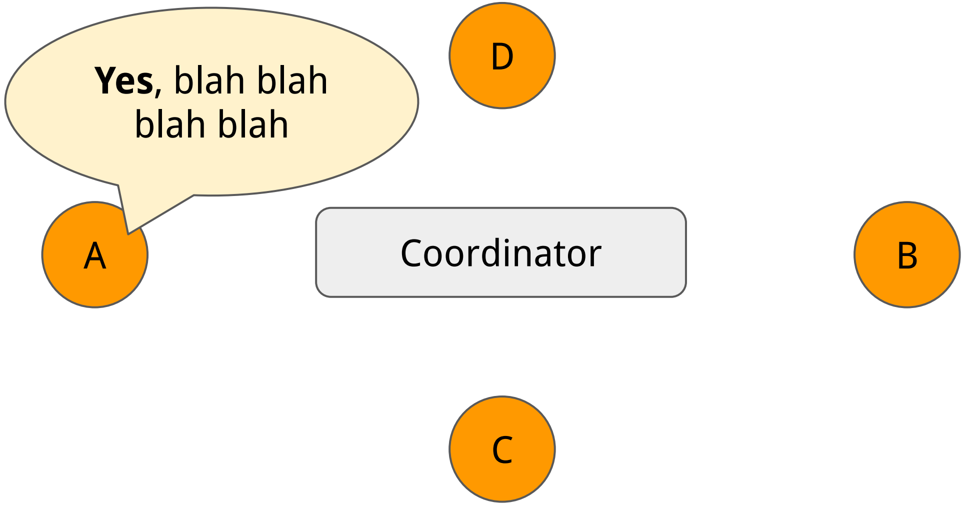

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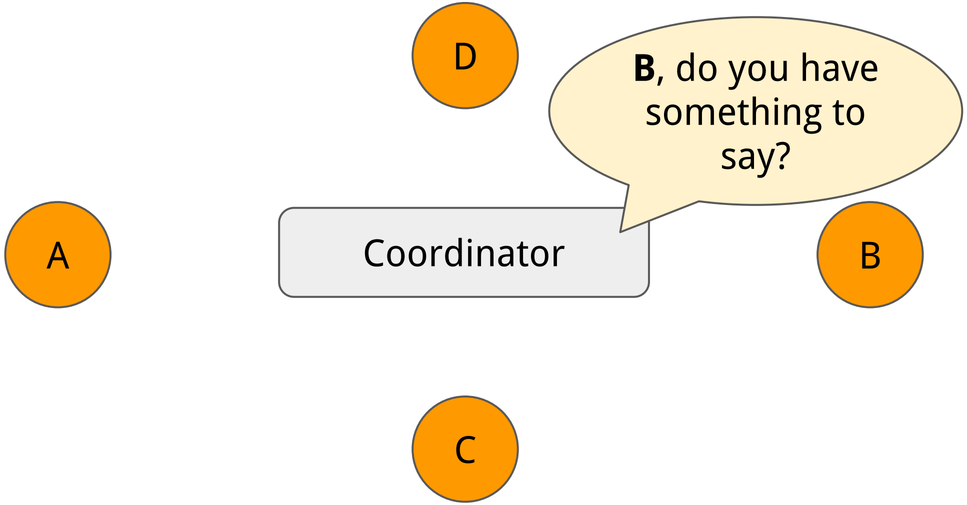

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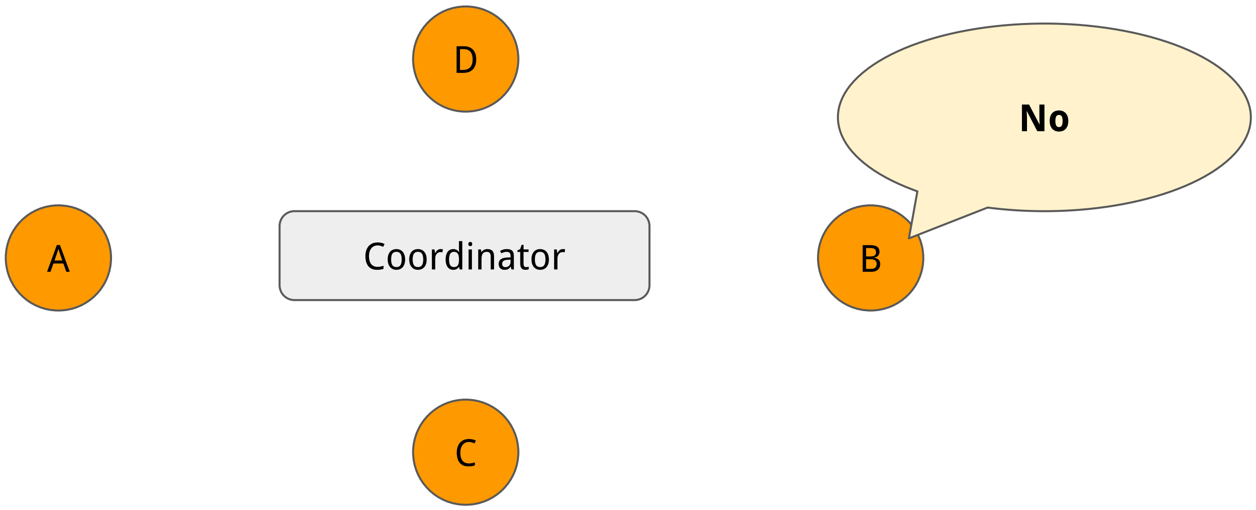
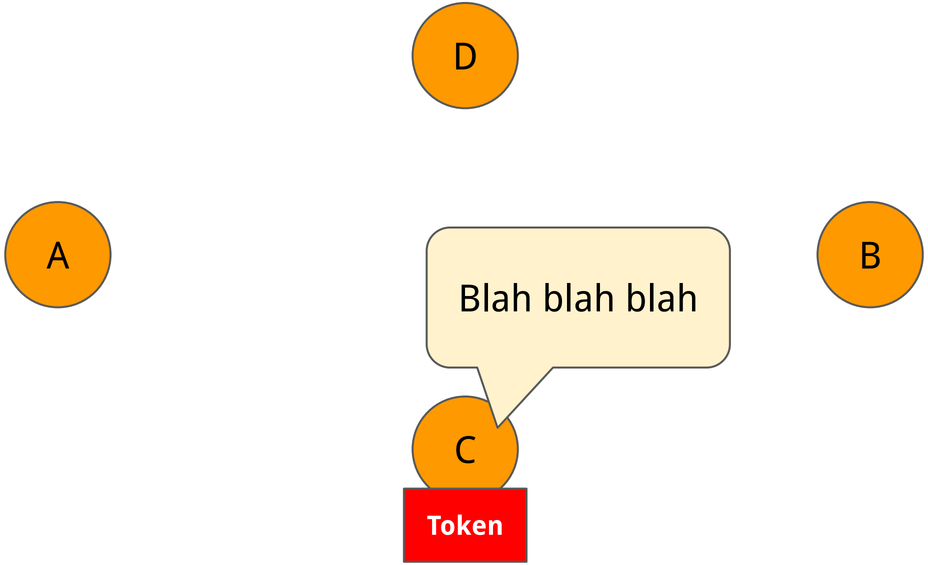


Turn-taking Schemes

- Token-passing
  - Virtual “token” passed around, only the holder can transmit.
  - IBM Token Ring and FDDI.



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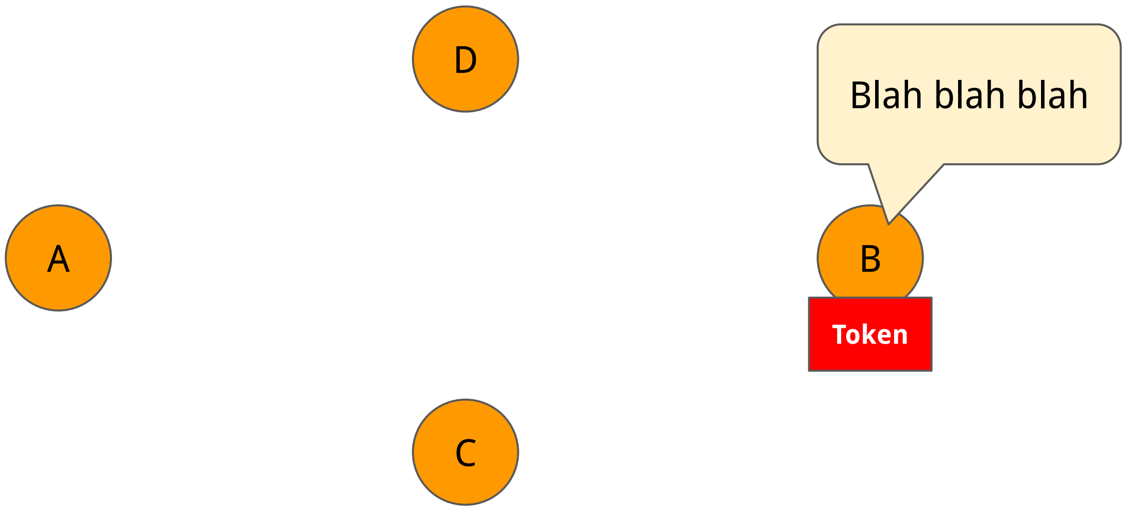


Alternative – *Random Access*

- Both of these mechanisms are **partitioning approaches**.
  - Essentially, we are dividing by time – but dynamically.
  - Require some form of inter-node communication.

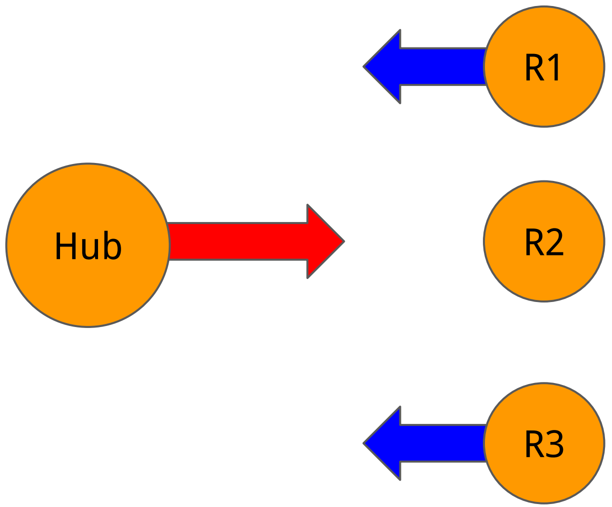
- An alternate idea – just allow for nodes to talk when they have something to say.
  - And deal with collisions when they occur.

- Used by ALOHANet and then later in Ethernet.

ALOHANet's Random Access

- Hub node on Oahu.
- Remote nodes across Hawaii.

- Used two frequencies:
    - **Hub transmits on its own frequency.**
        - Only one sender – no collisions.
        - All remote nodes listen to this frequency.
    - **All remote sites transmit on one frequency.**
        - May collide.
        - Only the hub listens to the remote frequency.



ALOHANet: Pure ALOHA random access scheme

- If remote has a packet – just send it.
  - No *a priori* coordination among remote sites.

- When the hub gets a packet – send ACK.

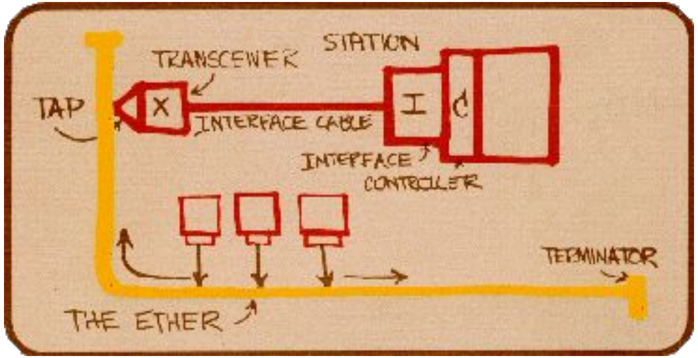
- If two remote sites transmitted at once, collisions results in a corrupted packet.
  - Hub doesn’t ACK!

- If a remote sender doesn’t get the expected ACK – then:
  - Wait a random amount of time.
  - Then resend, probably avoiding collisions this time.

Questions?

Ethernet

- Invented in 1973 at the Palo Alto Research Center (PARC).
- Originally aimed to allow computers to share printers and files.
- Has continued to be iterated on for the last 50 years.
    - Speeds in 1980 were 10**M**bps.
    - Speeds in 2024 are 800**G**bps.



https://www.ieee802.org/3/ethernet_diag.html

Ethernet and CSMA

- Ethernet – used as the most common wired *Data Link* protocol.

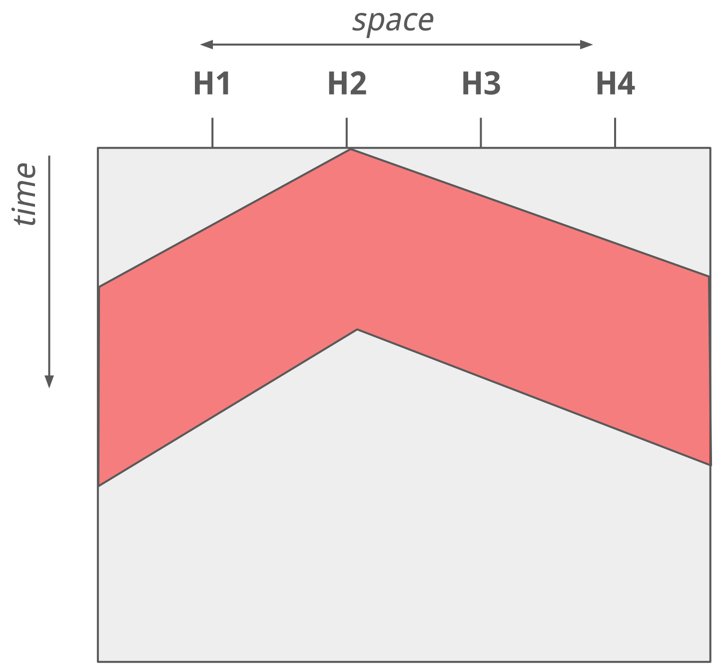
- Refined the ALOHA multiple access protocol to allow access to a shared Ethernet bus resulting in ***Carrier Sense Multiple Access*** **(CSMA).**

- Where ALOHA is rude, CSMA is polite.
    - Rather than just starting talking, and dealing with collisions…
    - CSMA listens first, and then starts to talk when it is quiet.
    - “Listen” means sensing the signal (carrier) on the shared medium.

Ethernet: CSMA and propagation delay

- CSMA does not necessarily avoid collisions – because of **propagation delay**.

- t=0:
    - H2 transmits.
    - Signal propagates through the shared media.



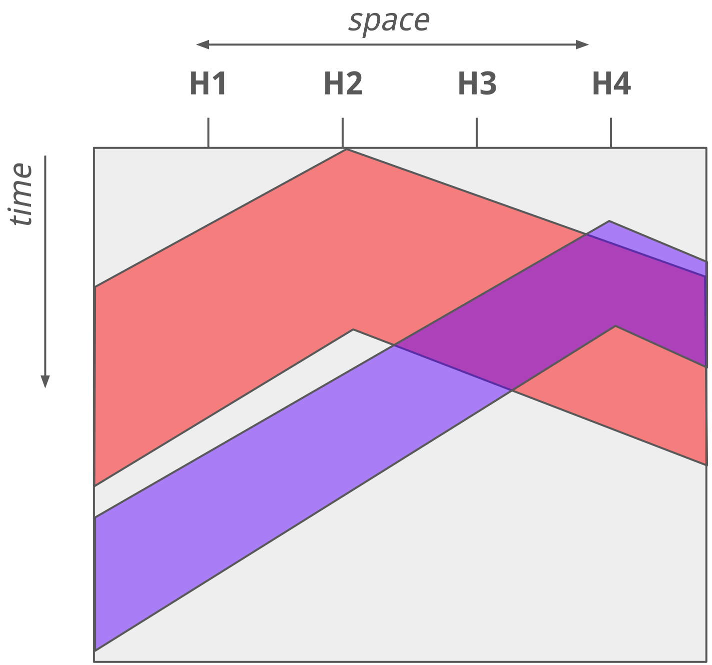
Ethernet: CSMA and propagation delay

- CSMA does not necessarily avoid collisions – because of **propagation delay**.

- t=0:
  - H2 transmits.
  - Signal propagates through the shared media.

- t=2:
  - H3 has heard, won't transmit.
  - H4 has not heard – it's safe to transmit!
    - Signal propagates as time goes by
    - …and collides with H2's signal.

- Solution: CSMA/CD.



Ethernet: CSMA/CD

- *Carrier Sense Multiple Access with Collision Detection* (CSMA/CD).
- Modification to the previous approach:
  - Listen <u>whilst</u> you talk.
  - If you start hearing something whilst you are still transmitting **– stop!**
    - Hence - detect the collision.
- Some additional complexities – but this is the core idea.
- What do we do after detecting a collision?

Ethernet: CSMA/CD

- After collision – wait a random amount of time and retransmit.

- If the link has many senders who want to talk (has high contention) we may keep colliding.

- Use randomised *binary exponential backoff…*
    - If retransmit after collision also collides, wait up to twice as long.
    - Continue doubling for every subsequent collision.
    - Retransmits fast when possible, slowing down where necessary.

Questions?

Forwarding & Ethernet Continued

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Recap

- Started to think about Layer 2 networking.

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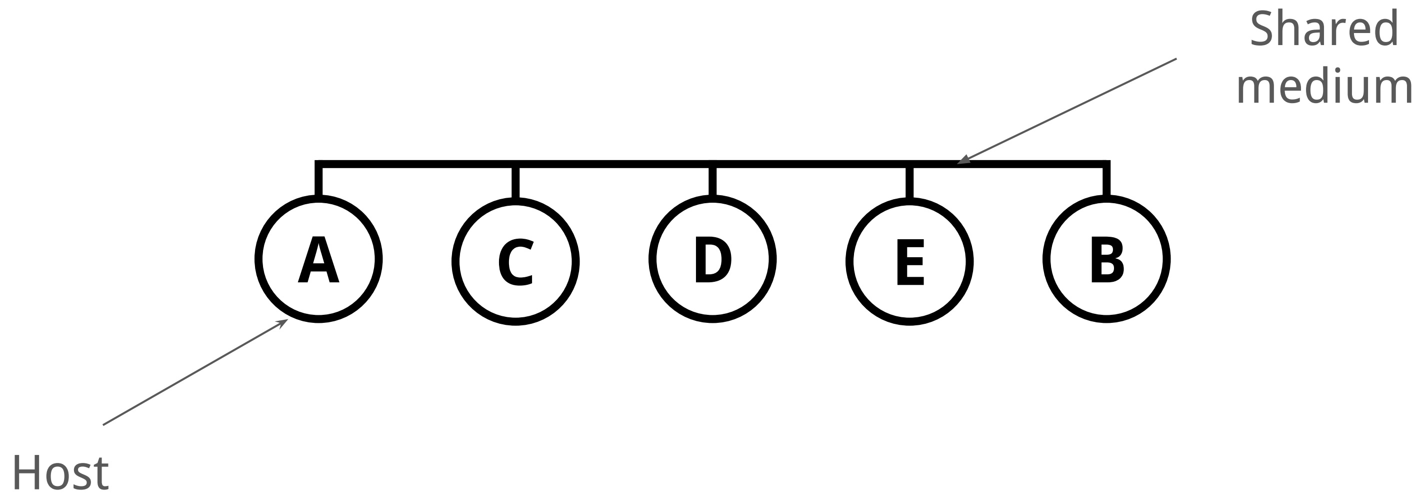

Transmission onto a Shared Medium

- We discussed that hosts need to have a means to determine <u>how</u> to share the medium.
  - We can use strict partitioning approaches – by time or frequency.
  - Or more dynamic ways to share time.

- Dynamic mechanisms can either:
  - Have inter-host messaging (e.g., a coordinator, or a token) to avoid collisions.
  - Or use a means to deal with collisions when they do occur.

- Ethernet uses *Carrier Sense Multiple Access with Collision Detection.*
  - Which allows a host to both detect when another host is transmitting
  - And detect when collisions occur – and back off.

Clarifying L1 and L2

- Questions after last lecture – how does this relate to packets?
- Let’s look at what Layer 1 and Layer 2 are.

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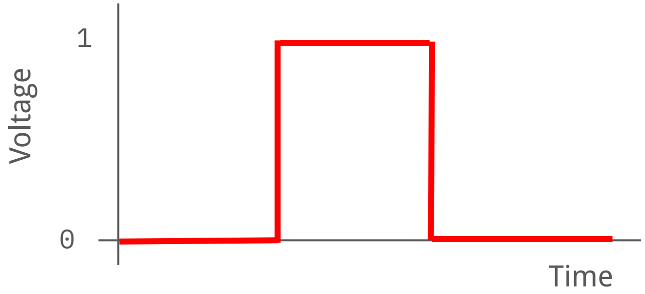

- L1: How to send data onto a particular medium (fibre, copper, radio).

- How to take some data and turn it into a signal that can be interpreted at the other end of the connection.

Clarifying L1 and L2

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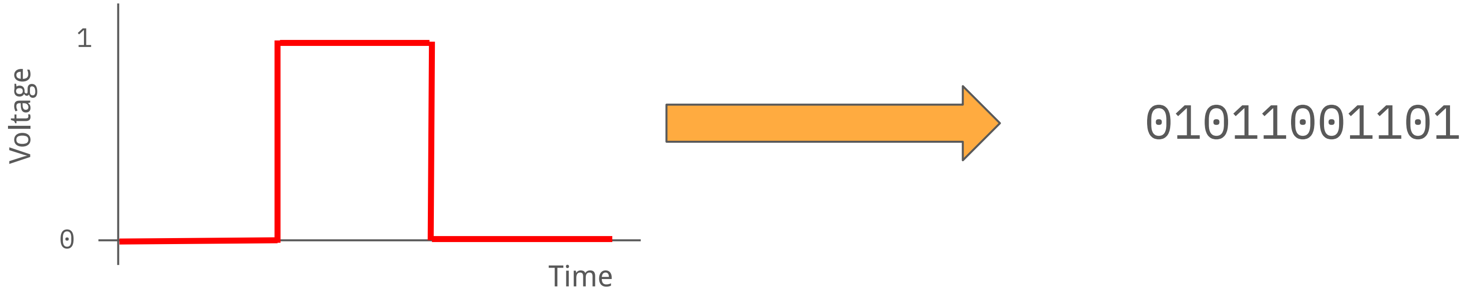
- Let's look at what Layer 1 and Layer 2 are.



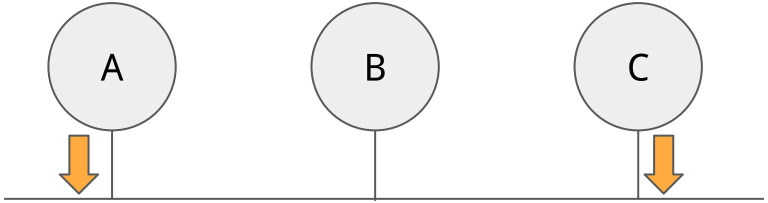
We can think of the "output" of Layer 1 as a string of bits.

Clarifying L1 and L2

- Layer 2 then takes this string of bits and makes it into a *packet*.

Simple host-to-host.

If A transmits to B ⇒ string of bits is a valid packet (using the same parsing rules).



Shared medium.

Collisions can occur – string of bits might not be a valid packet.

Layer 2 defines the rules for how to deal with this (e.g., CSMA/CD).

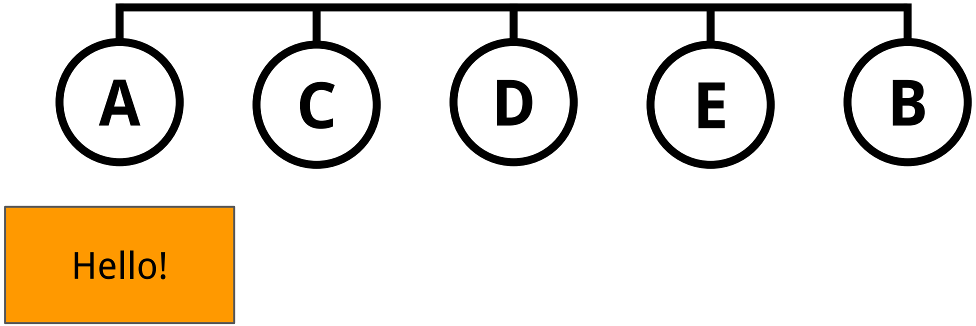
Clarifying L1 and L2

- Layer 2 protocols such as Ethernet define how we deal with sending and receiving a string of bits, <u>independently</u> of what the underlying Layer 1 protocol looks like.

- The input to Layer 2 is a set of bits, that we then parse into an Ethernet *frame.*

Questions?

Sending messages between computers on an Ethernet.



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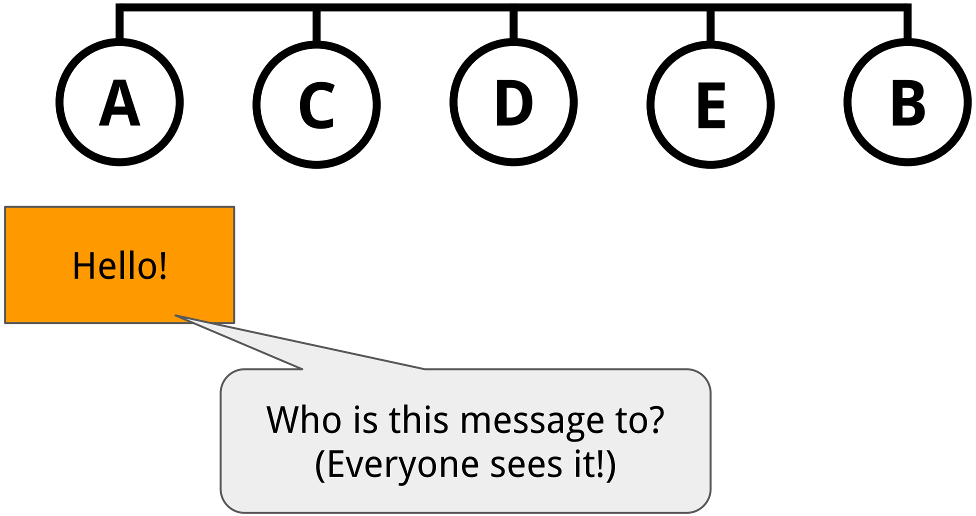

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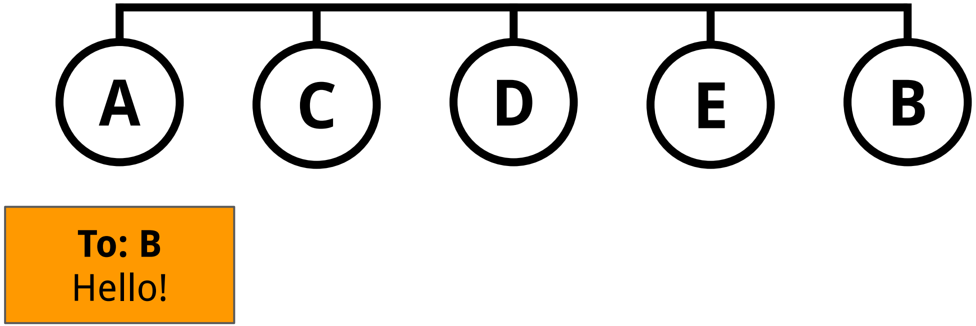

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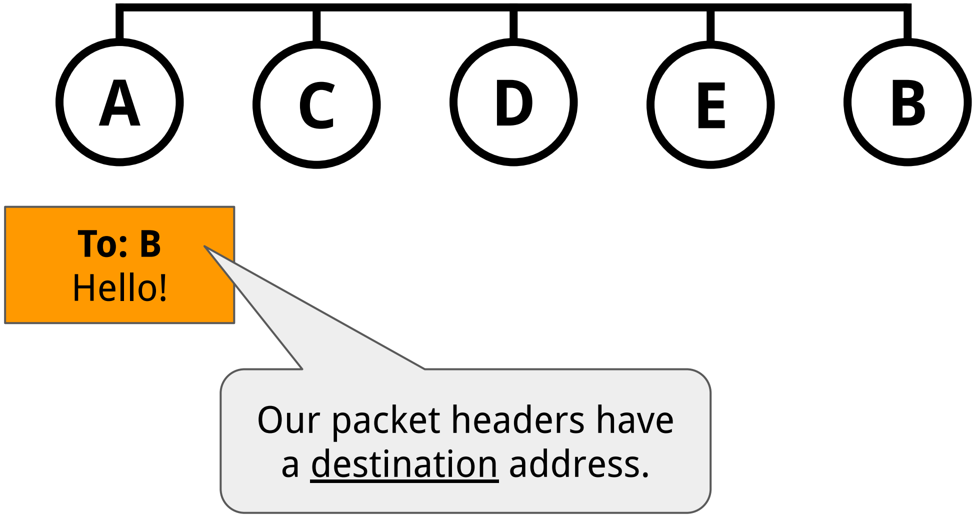

Recall from earlier, Packets

- Packet has…
  - Payload (the actual data)
  - Headers (metadata)
    - Must* contain...

Metadata (headers)					Data/Payload
Src Addr	**Dst Addr**	**Type**	**Version**	**...**	**<html><head><title>My Website</title><head> ...**

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        - Or more than one! (Why?)

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      - …which implies that **a host has an address**!
        - Or more than one! (Why?)
        - **For now, one address per host.**

Metadata (headers)					Data/Payload
Src Addr	Dst Addr	Type	Version	...	<html><head><title>My Website</title><head> ...

Ethernet Addressing

- If I send a signal (shout in this room) – everyone gets the message.

- But we do want some way to be able to identify the destination of a particular message.
  - e.g., just talk to one person in the room – not talk to everyone!

- We therefore need some form of addressing to be able to identify different hosts connected to the same medium.
  - Like we would use a *name* within this room to talk to one another.

Ethernet: Addresses

- Ethernet has Media Access Control (MAC) addresses.
  - These are Layer 2 addresses – we don't need to know anything about what is inside the Ethernet *Frame* (i.e., it doesn't matter whether it's IPv4, IPv6, or even IP at all!)
  - We'll talk about what can come inside this frame — at the moment it is a bunch of bytes.

- MAC addresses are 48-bits.
  - Usually shown as six two-digit hex numbers with colons.
  - Sometimes referred to as `ether` or `link` addresses.

```
▸ ifconfig en0
en0:
flags=8863<UP,BROADCAST,SMART,RUNNING,SIMPLEX,MULTICAST>
mtu 1500
        options=400<CHANNEL_IO>
        ether f8:ff:c2:2b:36:16
```

```
rjs@jumphost:~$ ip link show ens4
2: ens4: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1460
qdisc mq state UP mode DEFAULT group default qlen 1000
    link/ether 42:01:0a:8a:00:03 brd ff:ff:ff:ff:ff:ff
    altname enp0s4
```

Ethernet: MAC Addresses

- MAC addresses are allocated according to organisation.
  - Usually the manufacturer of the Ethernet network interface card (NIC).
- Typically stored permanently in the NIC (“burned in”) .
  - Often can be overridden by software.
- Structure:
  - Two bits of flags (we won’t discuss this)
  - 22-bits identifying company/organisation (e.g., device manufacturer)
  - 24-bits of identifying space.
- Usually supposed to be globally unique.
  - You might plug your computer in *anywhere*…

Ethernet: Types of communication

- We will typically talk about **unicast.**
    - Send to any one recipient.

- There are other models that we might care about:
    - Speak to everyone in the room – **broadcast**.
    - Speak to everyone who has joined a group in the room – **multicast**.
    - Send to any one member of a group - **anycast.**

- Ethernet supports both multicast and broadcast.
    - And generally they are not distinguished from each other at the Ethernet level.
    - We will briefly cover these if we get time.

Questions?

Ethernet: Unicast

- Unicast is the typical type of communication used on the Internet.
  - A source host wants to talk to a specific destination host.

- The Ethernet header has the fields that allow for unicast forwarding.
  - A data packet in Ethernet is referred to as a *frame*.

Preamble (7)	SFD (1)	Dest. MAC (6)	Src. MAC (6)	EtherType (2)	Payload	FCS (4)	IPG (12)

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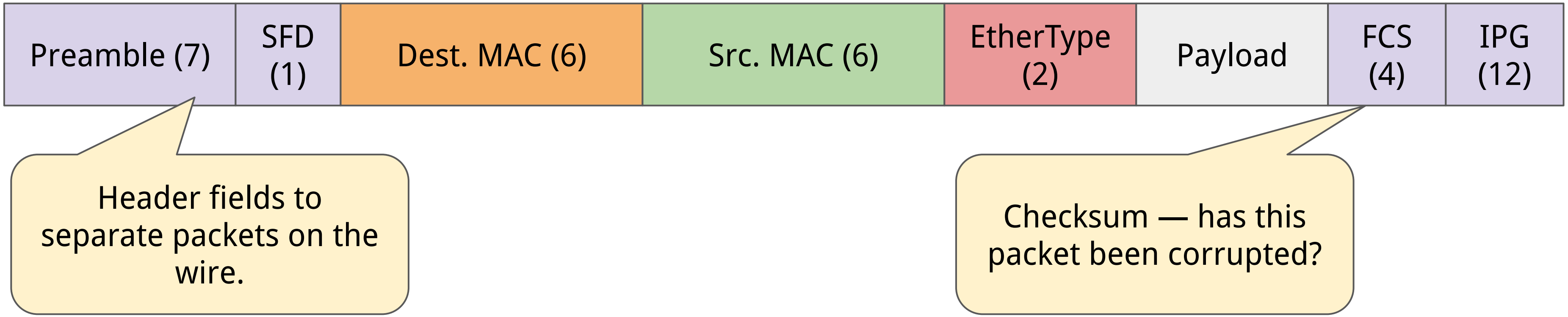

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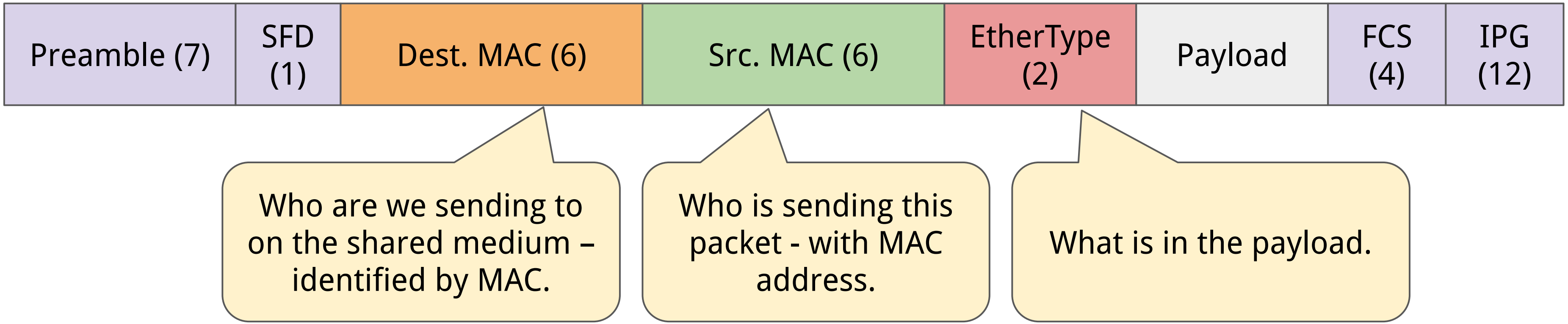


Ethernet: Unicast

- To send a packet to a specific destination host - we set the destination MAC to a specific remote machine’s MAC address.
- Packets go to everyone on the shared medium (wire).
- Receivers check the destination MAC to determine whether the packet is destined to them.
    - “Is dst MAC == `42:01:0a:8a:00:03`? It’s for me!”

Ethernet: Broadcast

- Broadcast – send to everyone!
  - Specifically, everyone on the specific Ethernet network…
  - …everyone on the same cable.

- The packet already reaches everyone – they are connected to the *shared media.*
  - We need receivers to listen.

- Broadcast is implemented using the all ones address.
  - `FF:FF:FF:FF:FF:FF`

Ethernet: Multicast

- Multicast – send to all members of a group.
  - Trivial on classic Ethernet – since everyone gets the packet.

- Implemented by having specific addresses – one of the flags in the address set to 1.
  - `01:00:00:00:00:00`
  - Normal addresses all have an even first byte.
  - This 1 is the first bit on the wire – bytes are sent low bit first.

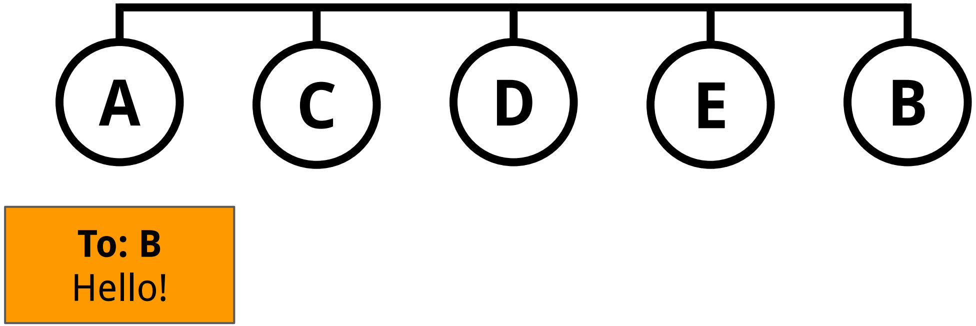
- Broadcast is just a special case of multicast – where everyone is in a group.

Why do we need multicast in a LAN?

- Apple invention: Bonjour/mDNS.
- iPhone wants to discover any Apple TV, or HomePod that it can play music on.
  - It can actively discover this “hey local Apple products, are there any speakers?”.
  - Sends to a multicast group that all Apple products join by default.
  - Equally, HomePod/Apple TV can advertise “I am an Apple TV!”.
- Actually uses DNS advertisements that are sent to multicast addresses.
  - Using specific types of records – e.g., SRV – to advertise capabilities.

Questions?

Inefficiencies of a single bus



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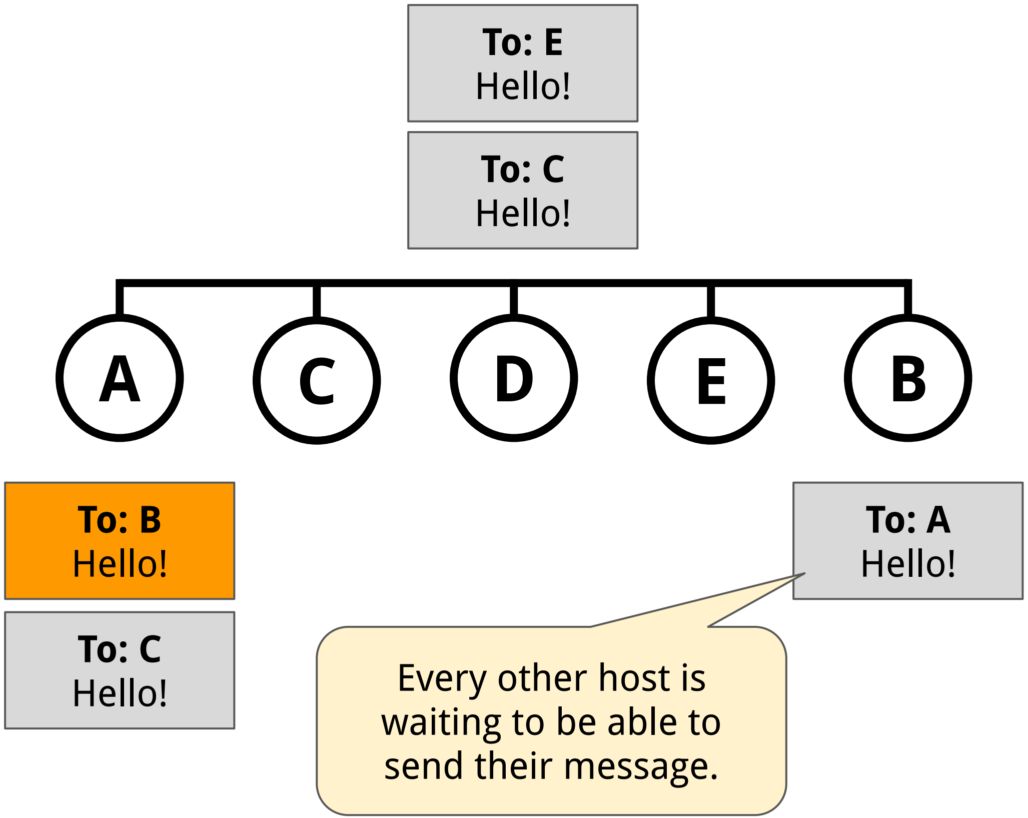

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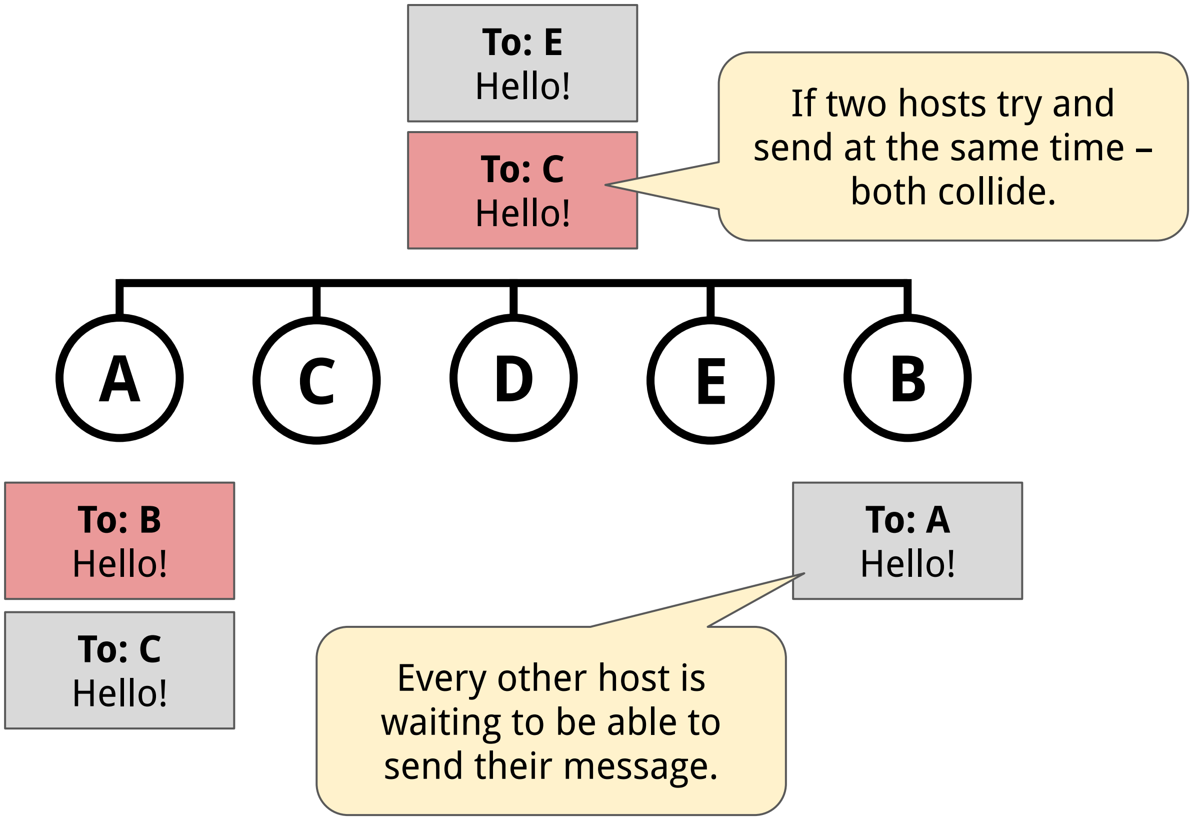


Inefficiencies of a Shared Medium

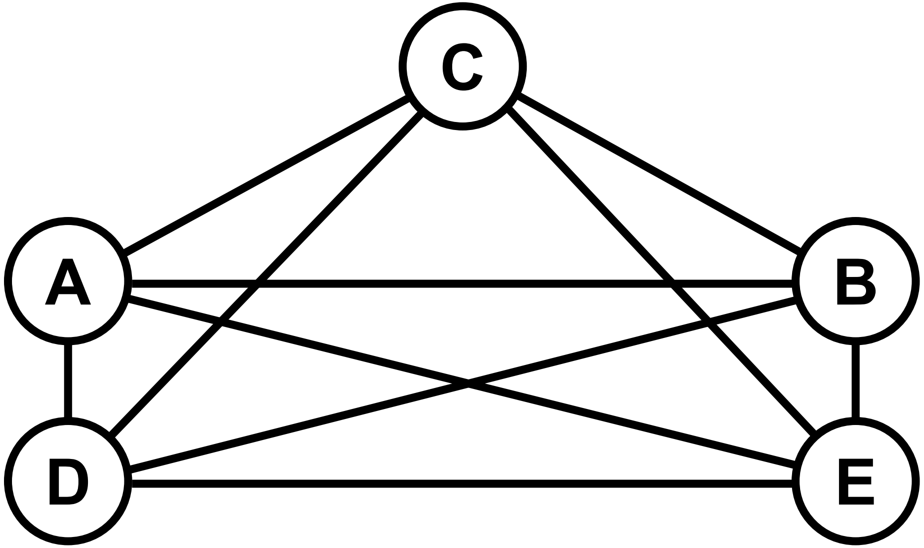
- The best case scenario is that someone is always sending.

- Assuming our shared medium has some bandwidth limit, **B**, this is the best we can do.
  - **B** is dictated based on how we signal packets on the wire.
  - May be do to do with modulation speed, or amount of spectrum available.

- Equally – we need everyone to be connected to the shared medium.
  - Inverse square law – eventually we are not going to be able to propagate the signal!

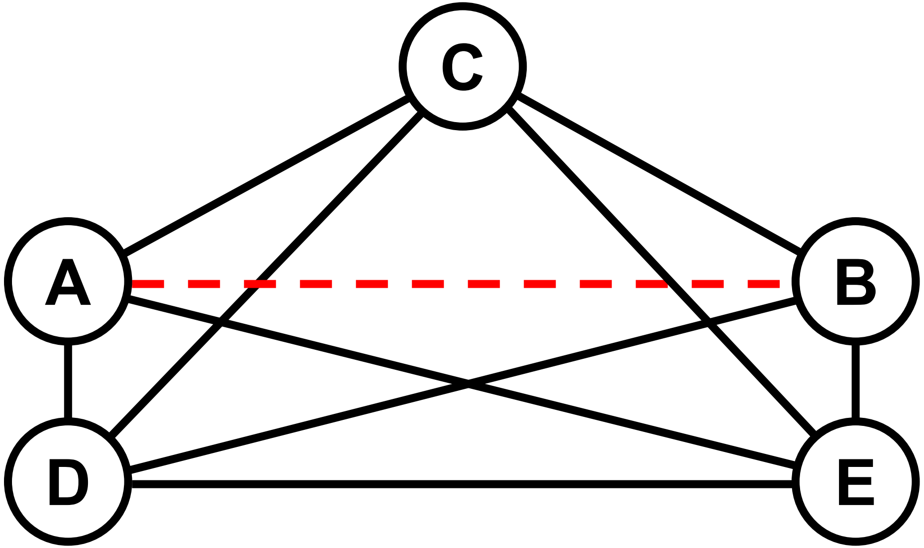
- **So**, can we do better?

Connecting Nodes Together



Is there a problem with this approach?

Connecting Nodes Together



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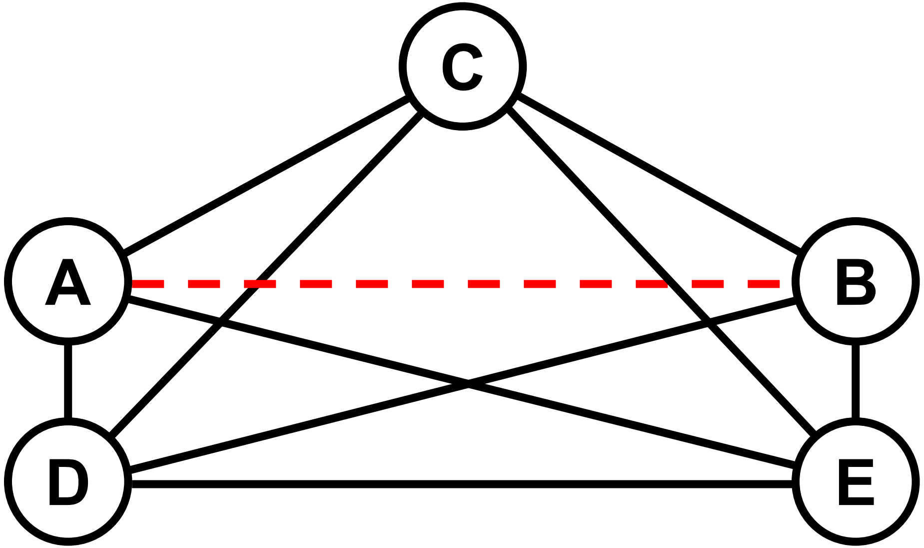
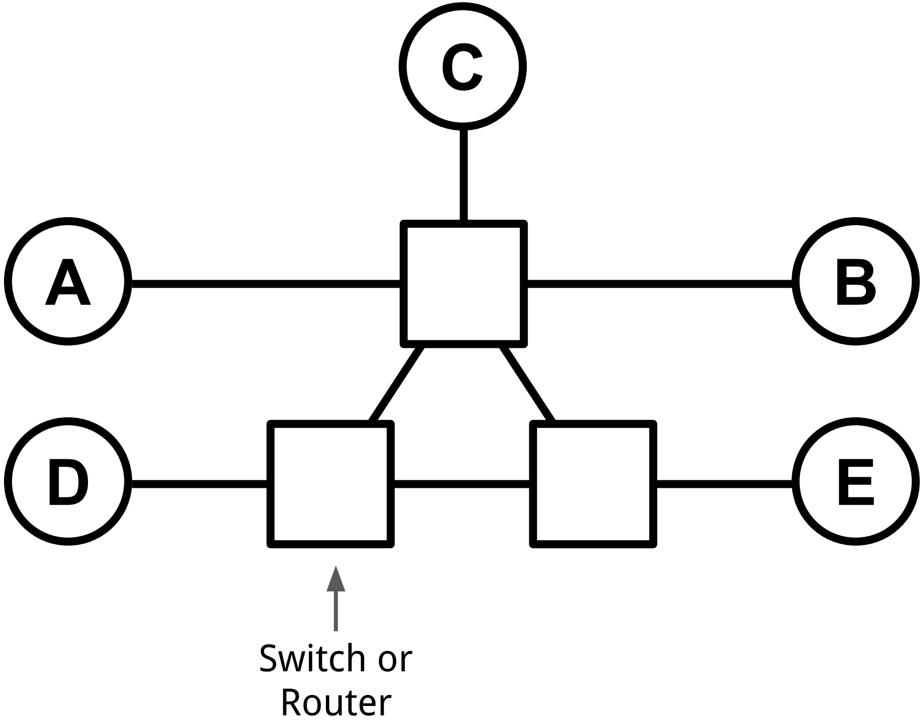


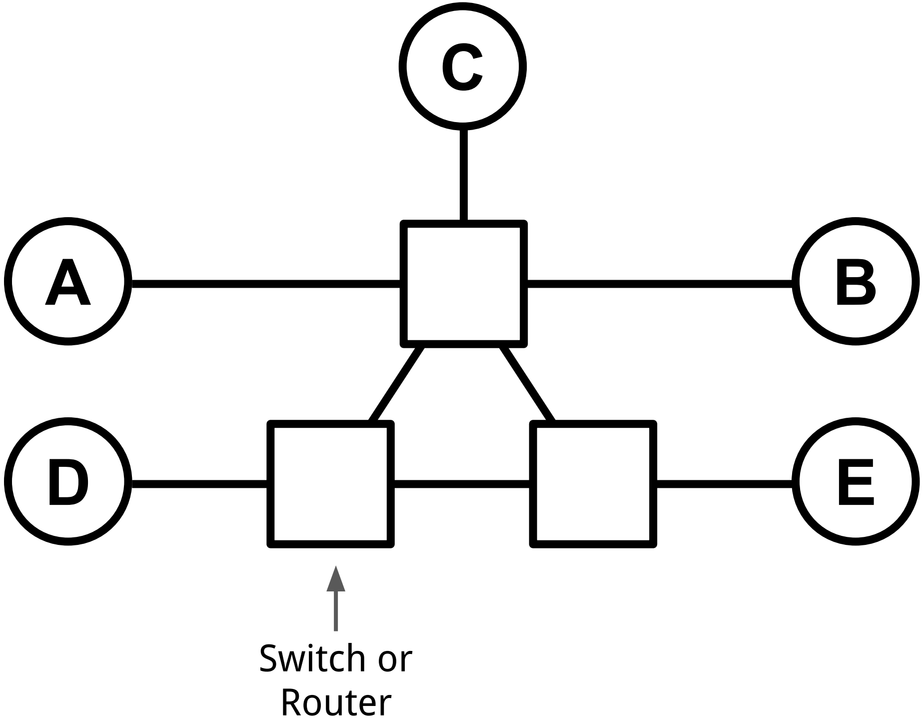
Is there anything *good* about this approach?

Connecting Nodes Together



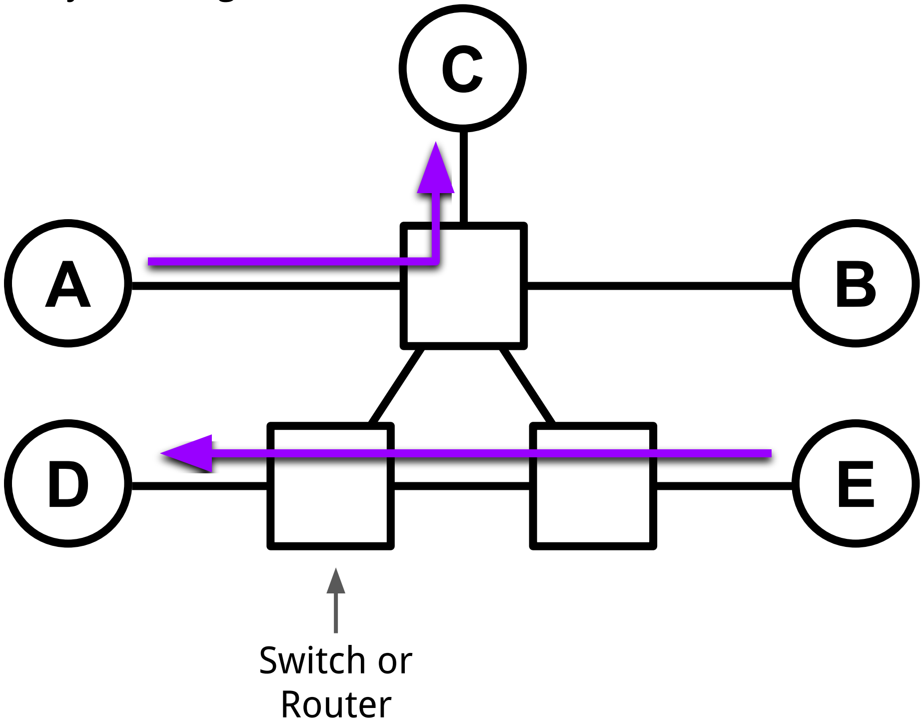
Connecting Nodes Together

- Way fewer links than a full mesh!



Connecting Nodes Together

- Way fewer links than a full mesh!
- But more capacity than just a single link!



Connecting Nodes Together

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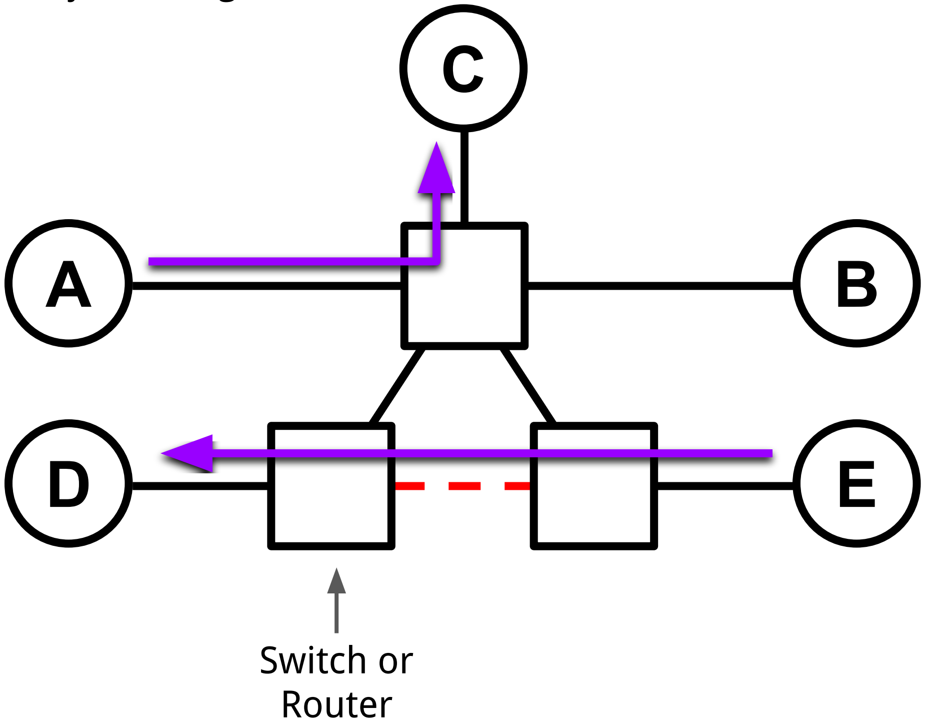
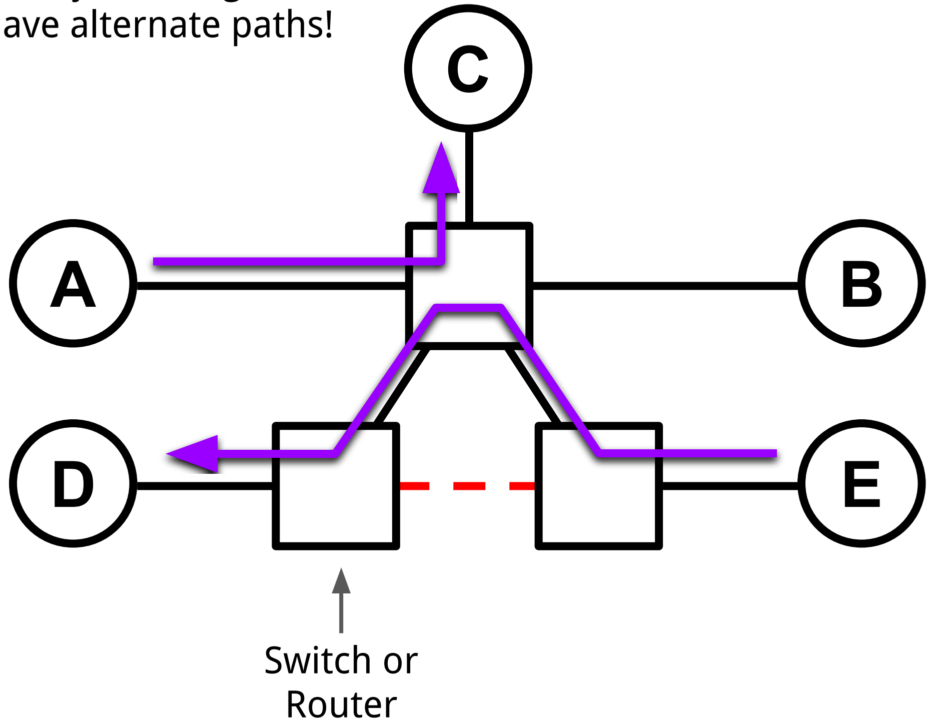


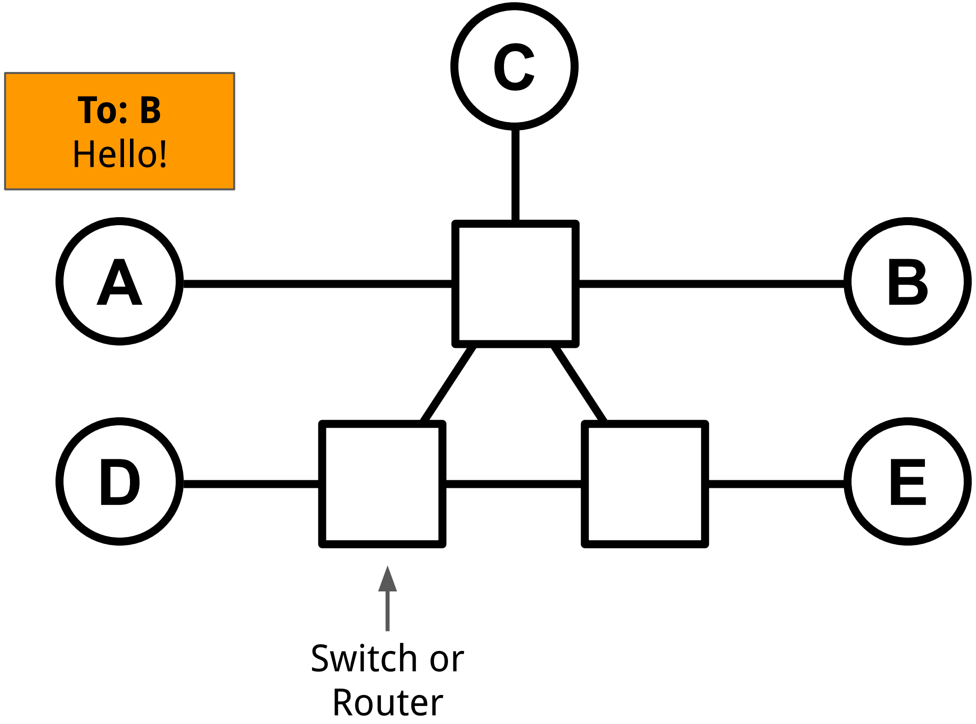
Connecting Nodes Together

- Way fewer links than a full mesh!
- But more capacity than just a single link!
- With the ability to have alternate paths!



Questions?

But, we just created a new problem!



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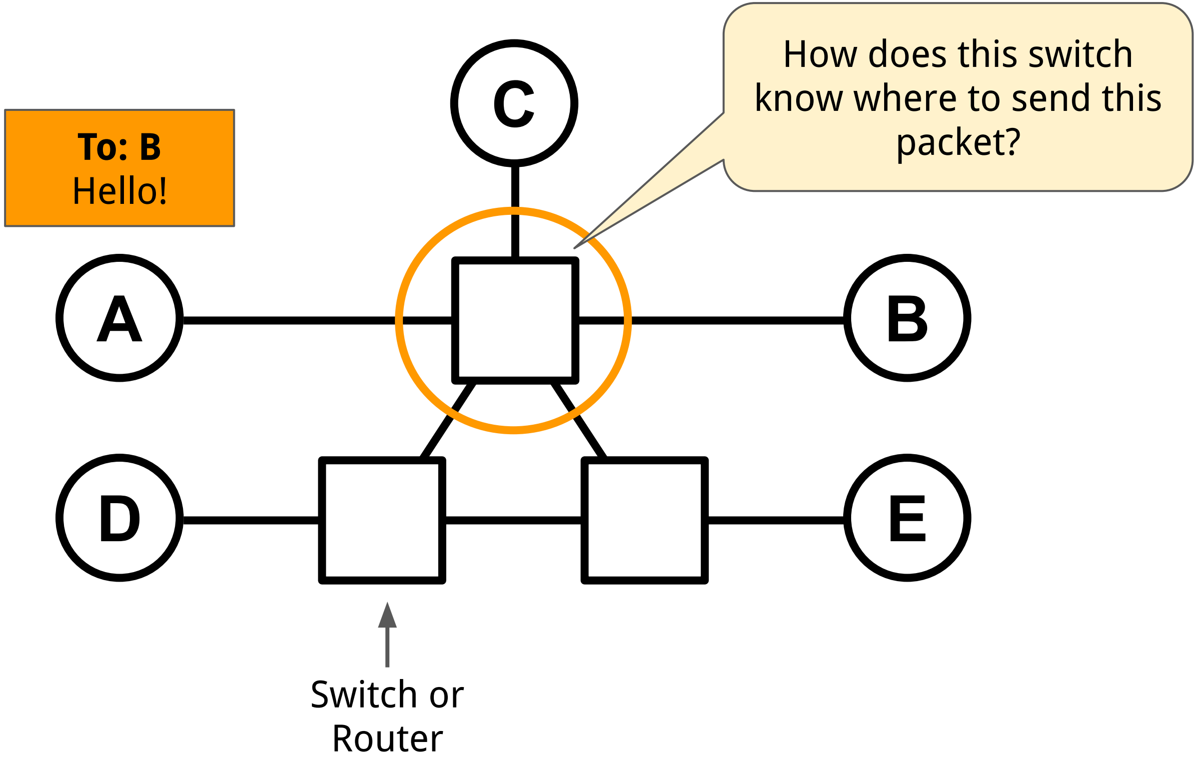
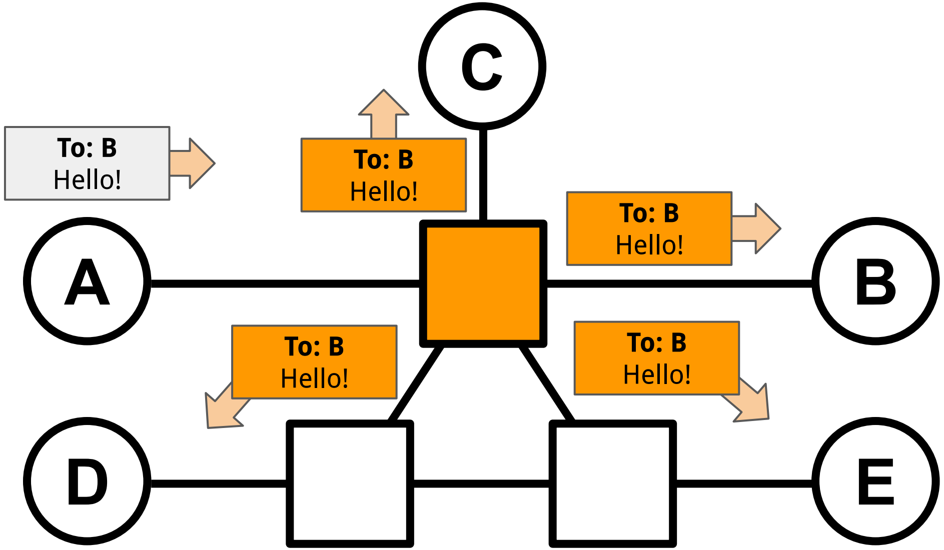
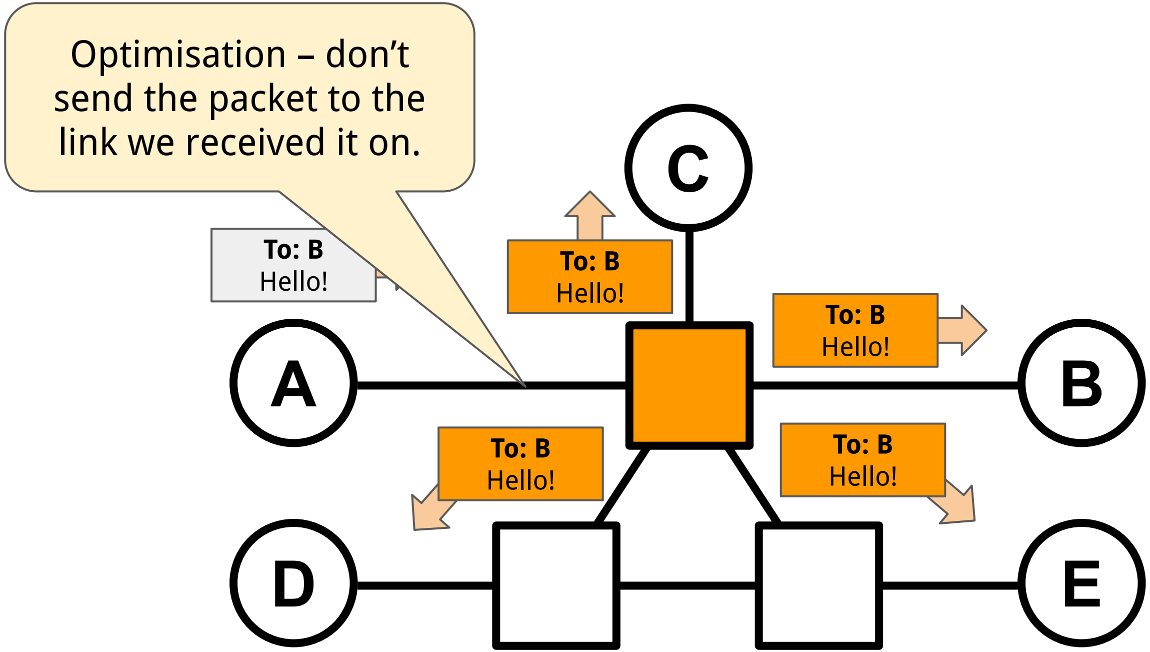


Naïve approach to forwarding



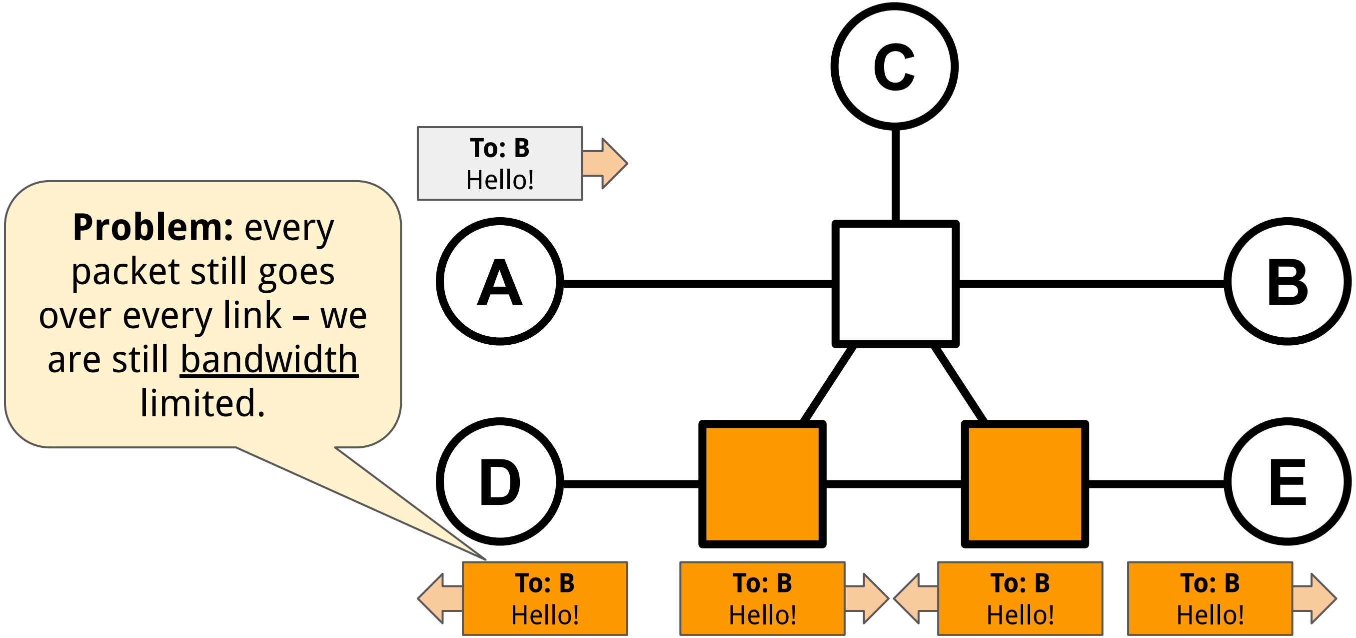
Flooding – send the packet to every port on the switch.

Naïve approach to forwarding

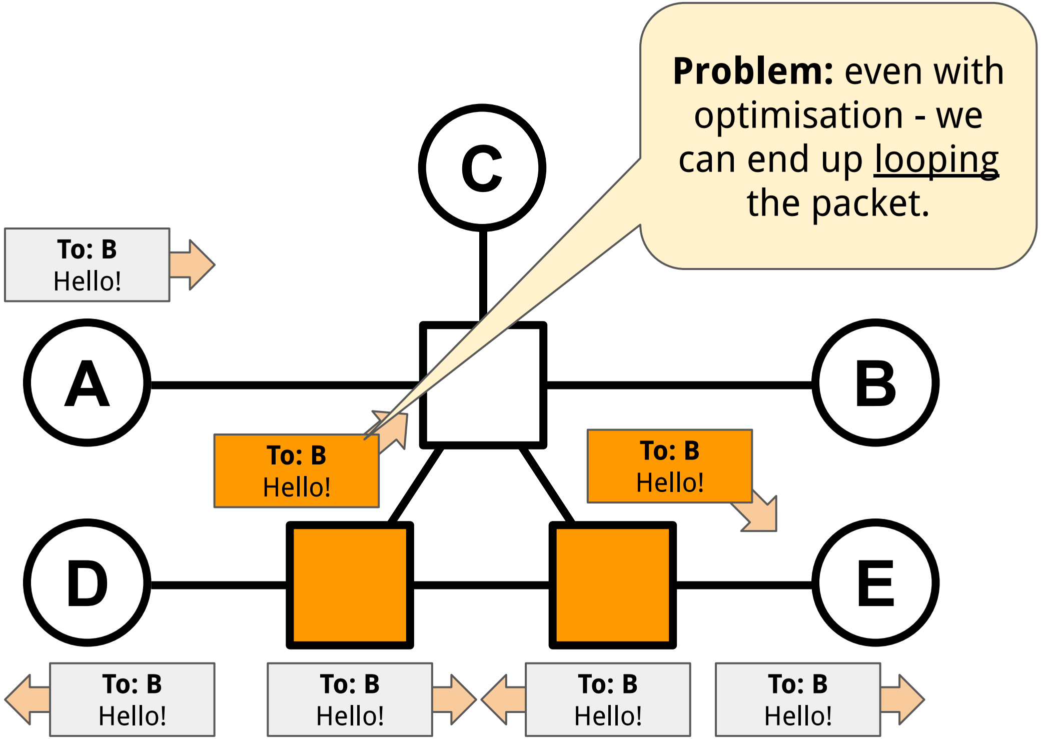


Flooding – send the packet to every* port on the switch.

Naïve approach to forwarding



Naïve approach to forwarding



Questions?

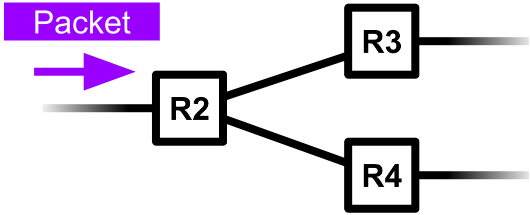
Forwarding challenges

- Our naïve approach is problematic.

- We need to solve two problems:
  - How to avoid wasting bandwidth by sending a packet to everyone even if they are not interested.
  - How to deal with the fact that the *topology* of the network might mean that flooding a packet causes it to be looped.

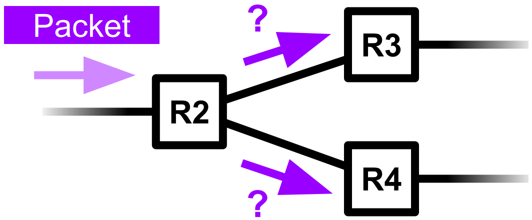
- Let’s start with the first one.

The Challenge of Forwarding



- When packet arrives...

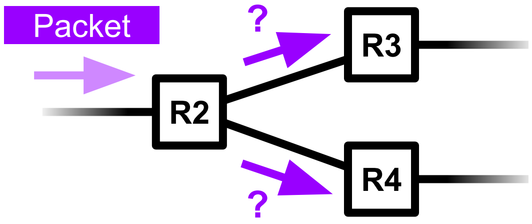
The Challenge of Forwarding



- When packet arrives, switch ***forwards*** it to one of its neighbors

- You need to make the decision about which neighbor *fast* (~nanoseconds)
- Implies the decision process is *simple*

The Challenge of Forwarding

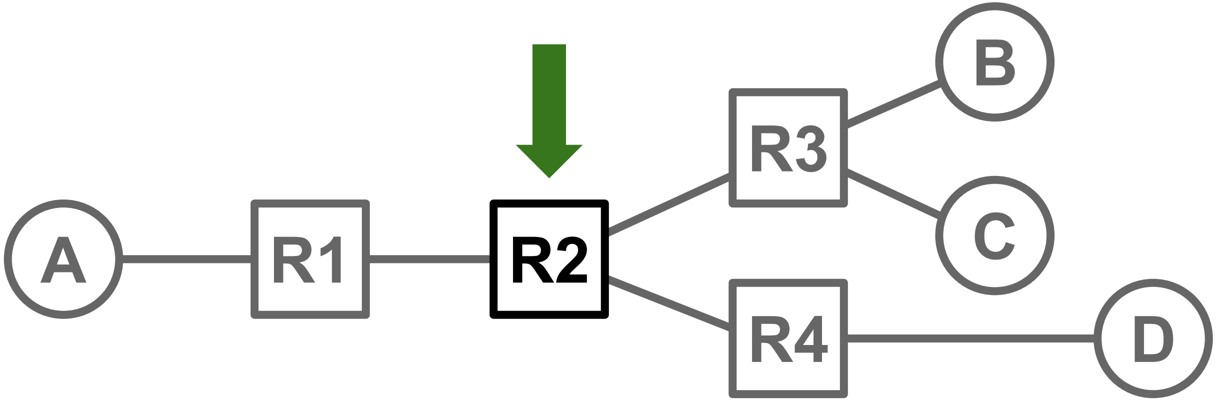


- When packet arrives, switch ***forwards*** it to one of its neighbors

- You need to make the decision about which neighbor *fast* (~nanoseconds)
- Implies the decision process is *simple*

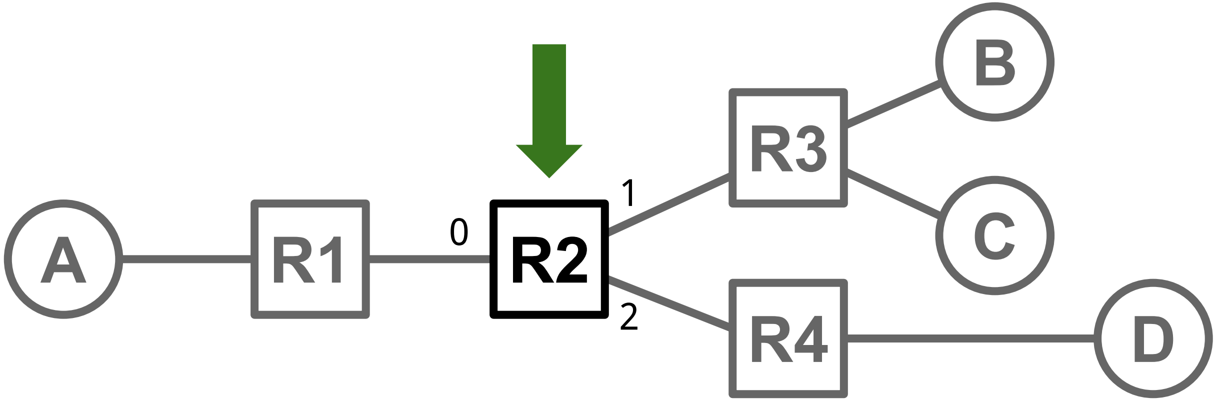
- Solution: Use a table

Forwarding with a Table



R2's Table	
Dst	***NextHop***
A	R1
B	R3
C	R3
D	R4

Forwarding with a Table



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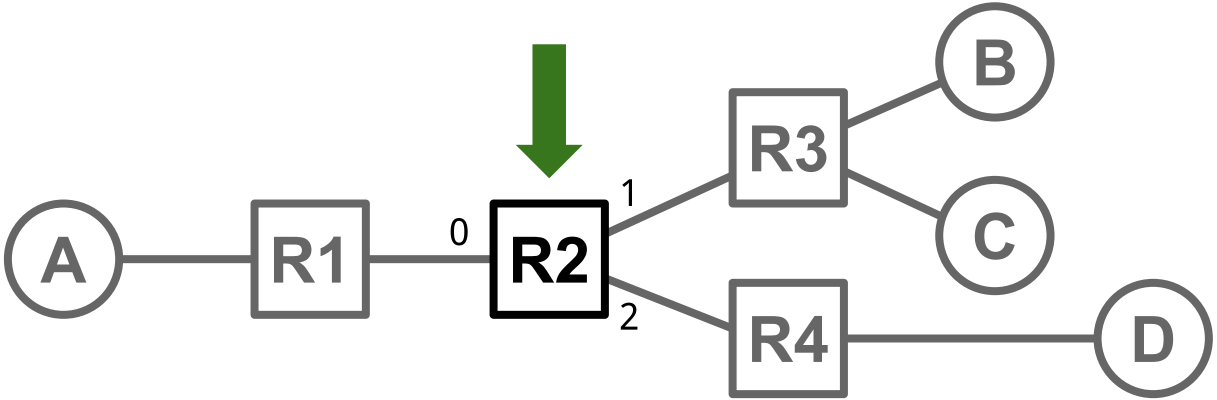

R2's Table	
Dst	*NextHop*
A	R1
B	R3
C	R3
D	R4

.. or ..

R2's Table	
Dst	*Port*
A	0
B	1
C	1
D	2

Forwarding with a Table

- Given the tables, decision *depends only on destination field of packet*
- .. we are doing what's called ***destination-based forwarding/routing***
  - Very common
  - An "archetypal" Internet assumption (and basically the default)

R2's Table	
Dst	***NextHop***
A	R1
B	R3
C	R3
D	R4

.. or ..

R2's Table	
Dst	***Port***
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B	1
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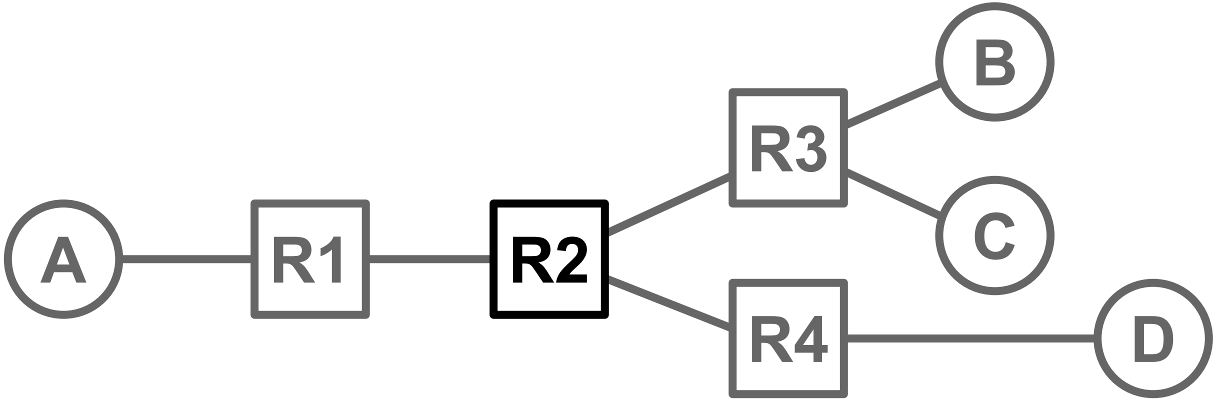
Questions?

How do tables get populated?



R2's Table	
Dst	***NextHop***

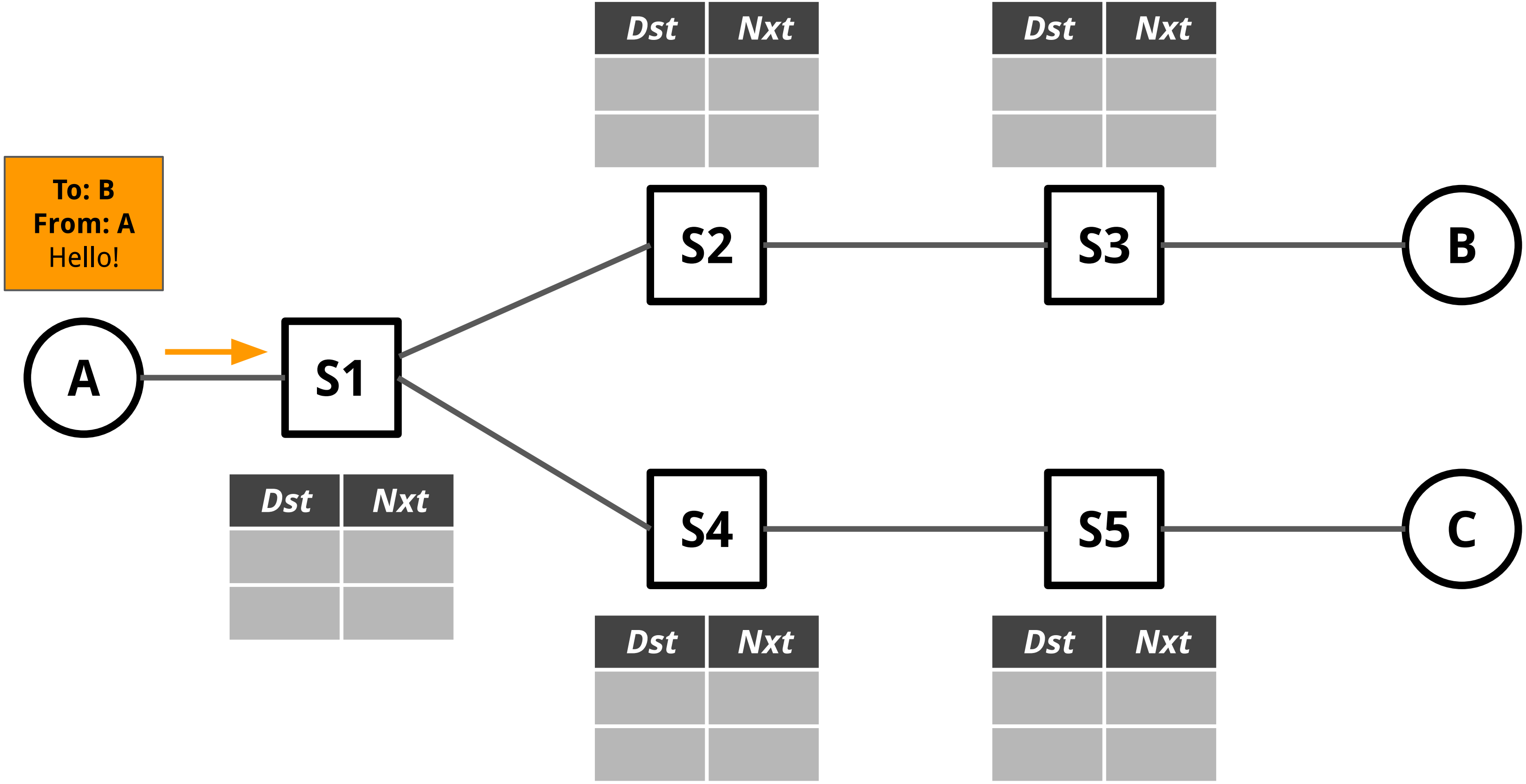
To be able to make our forwarding decision – we need to populate this table.

Approaches to populating forwarding tables

- When a packet comes along – look at where it came from – and use this to help us learn where hosts are connected.

- Very simple!
    - We need to look at the packet that we see on the data plane.
    - No need for any kind of *a priori* knowledge of how the network topology works.

Learning Switches



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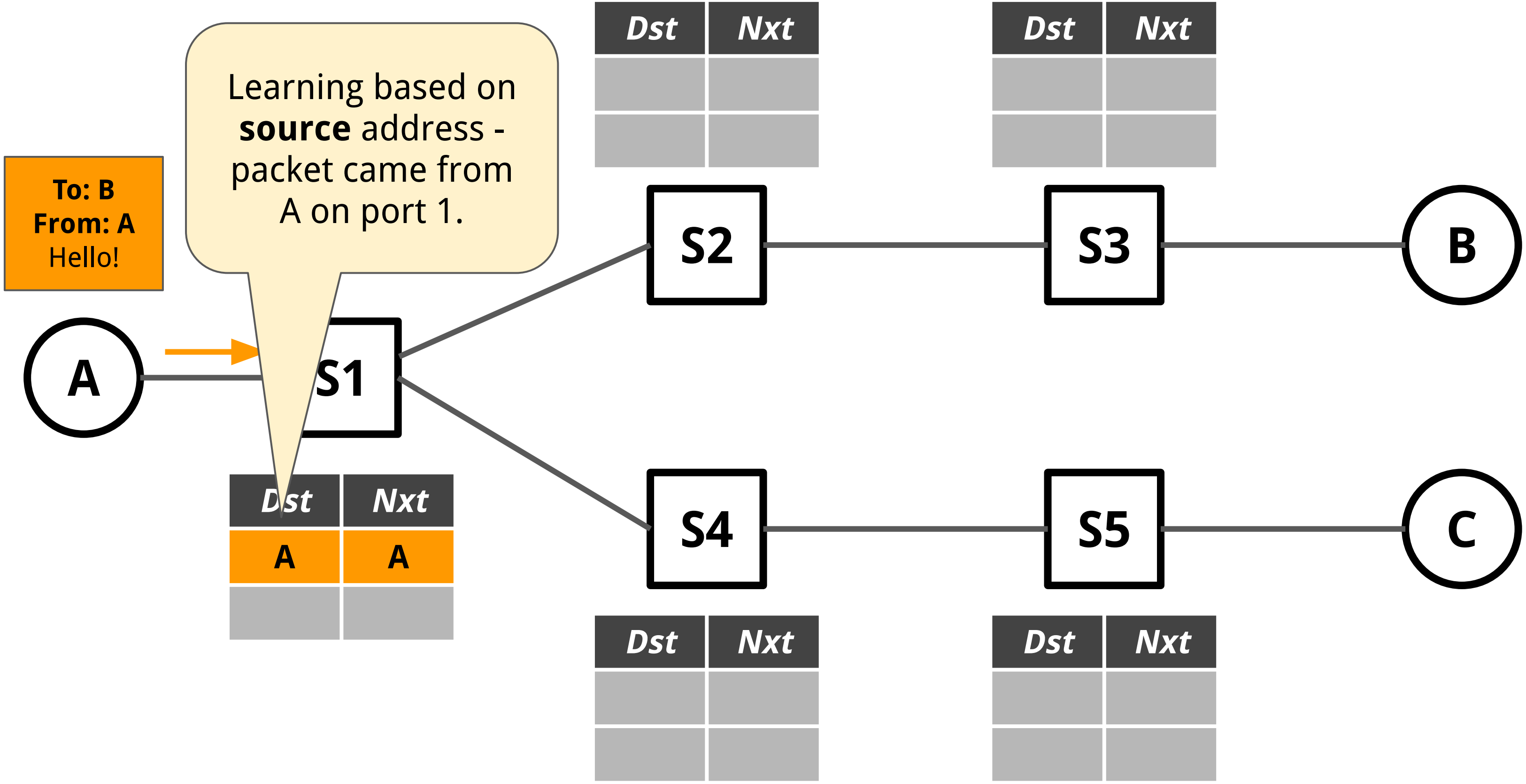

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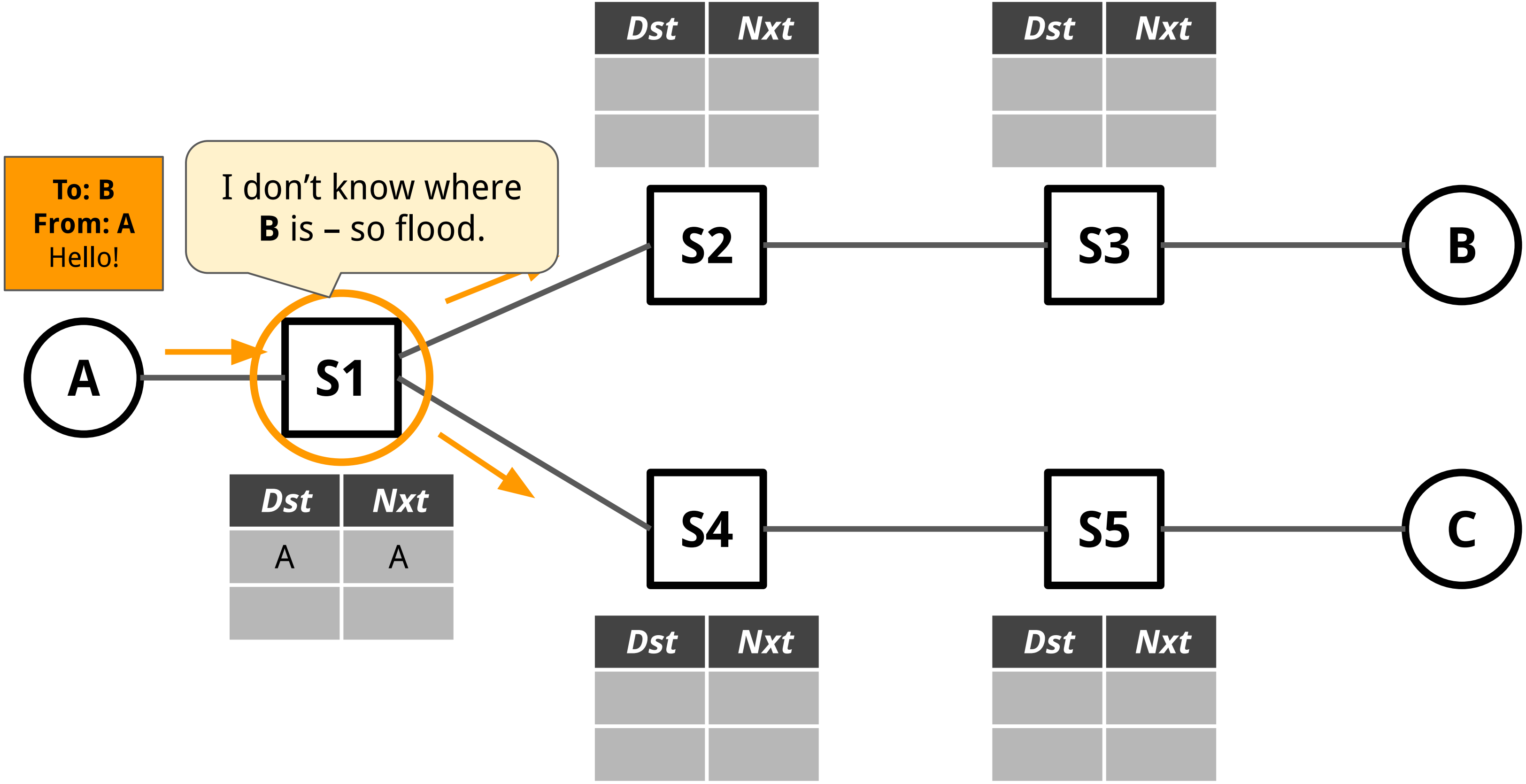

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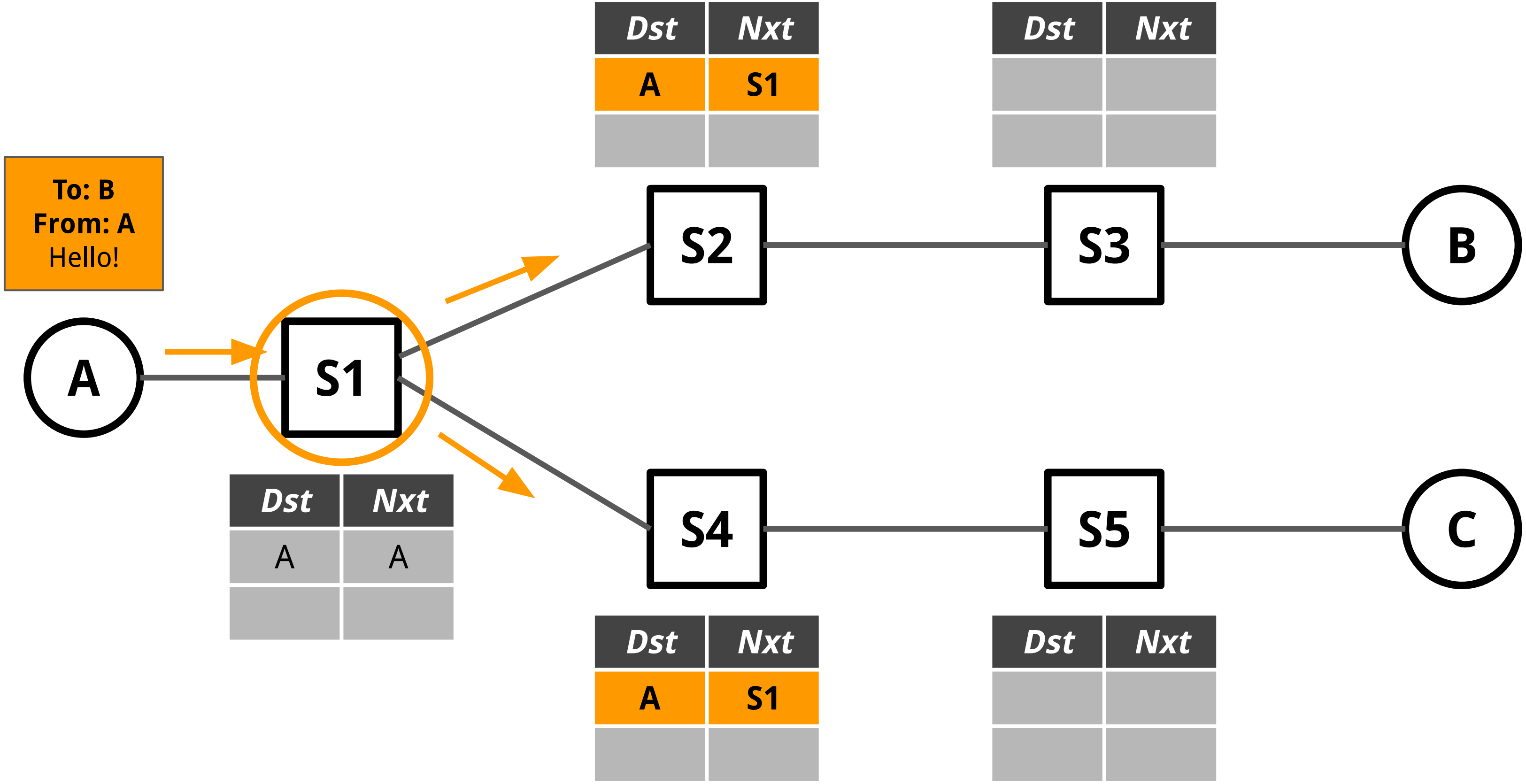

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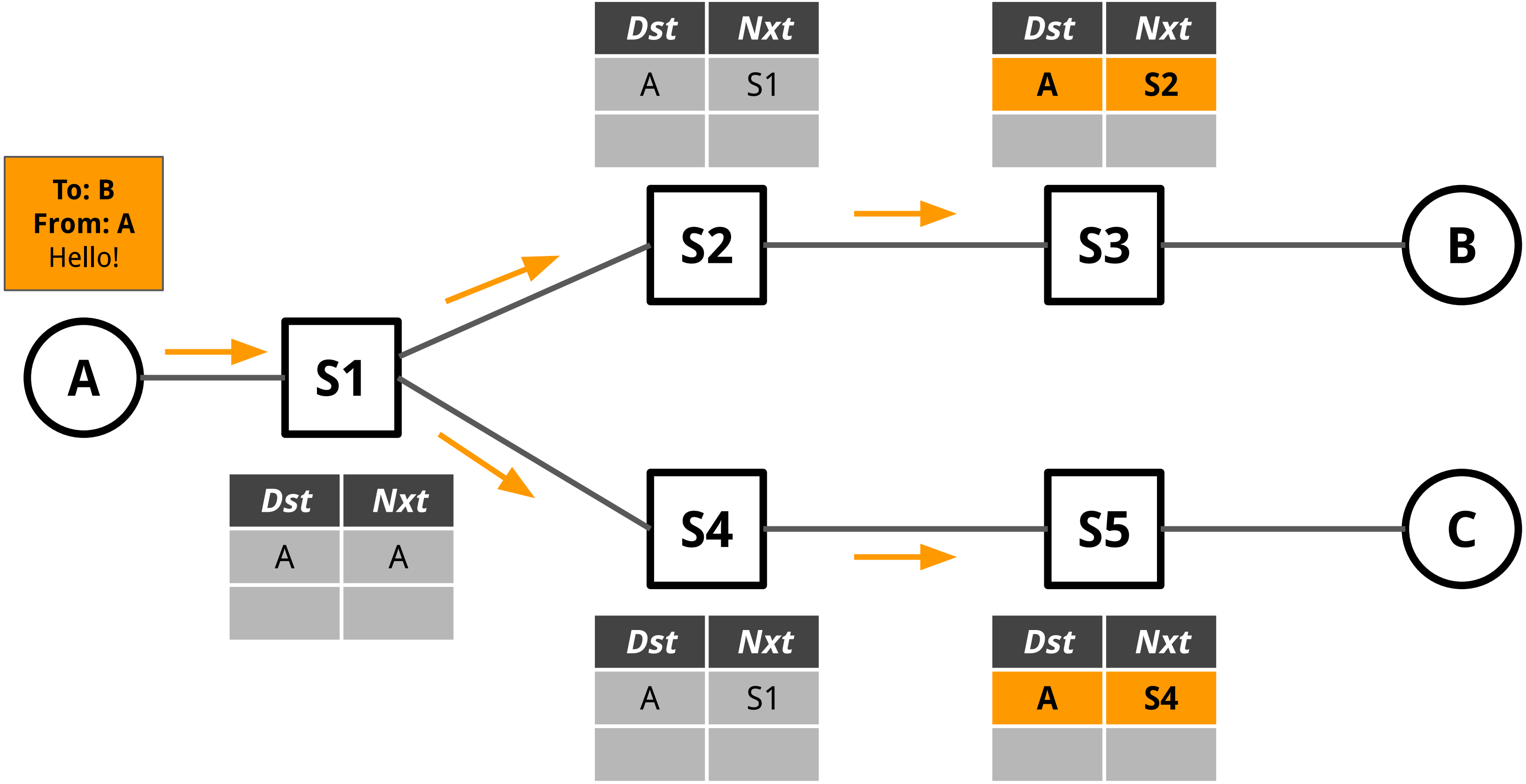

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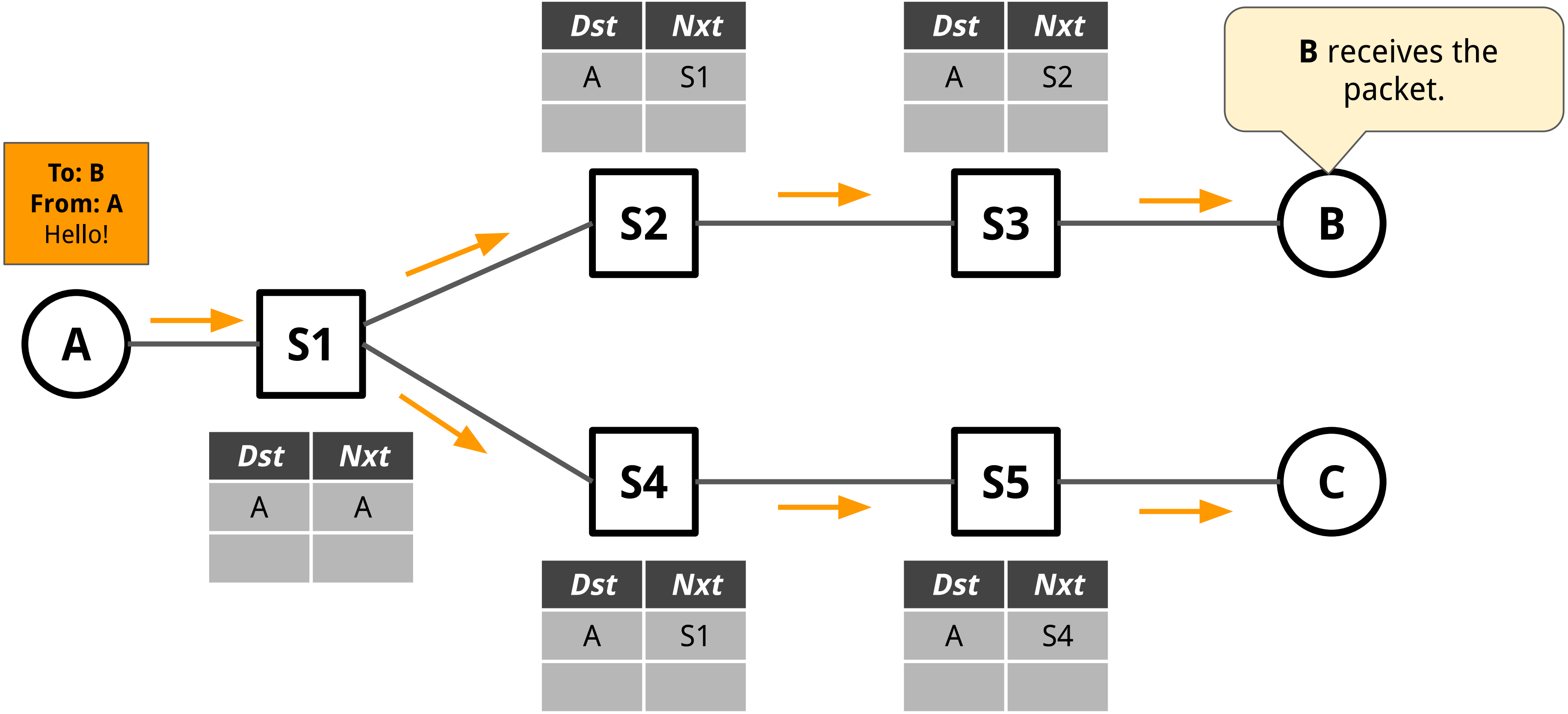

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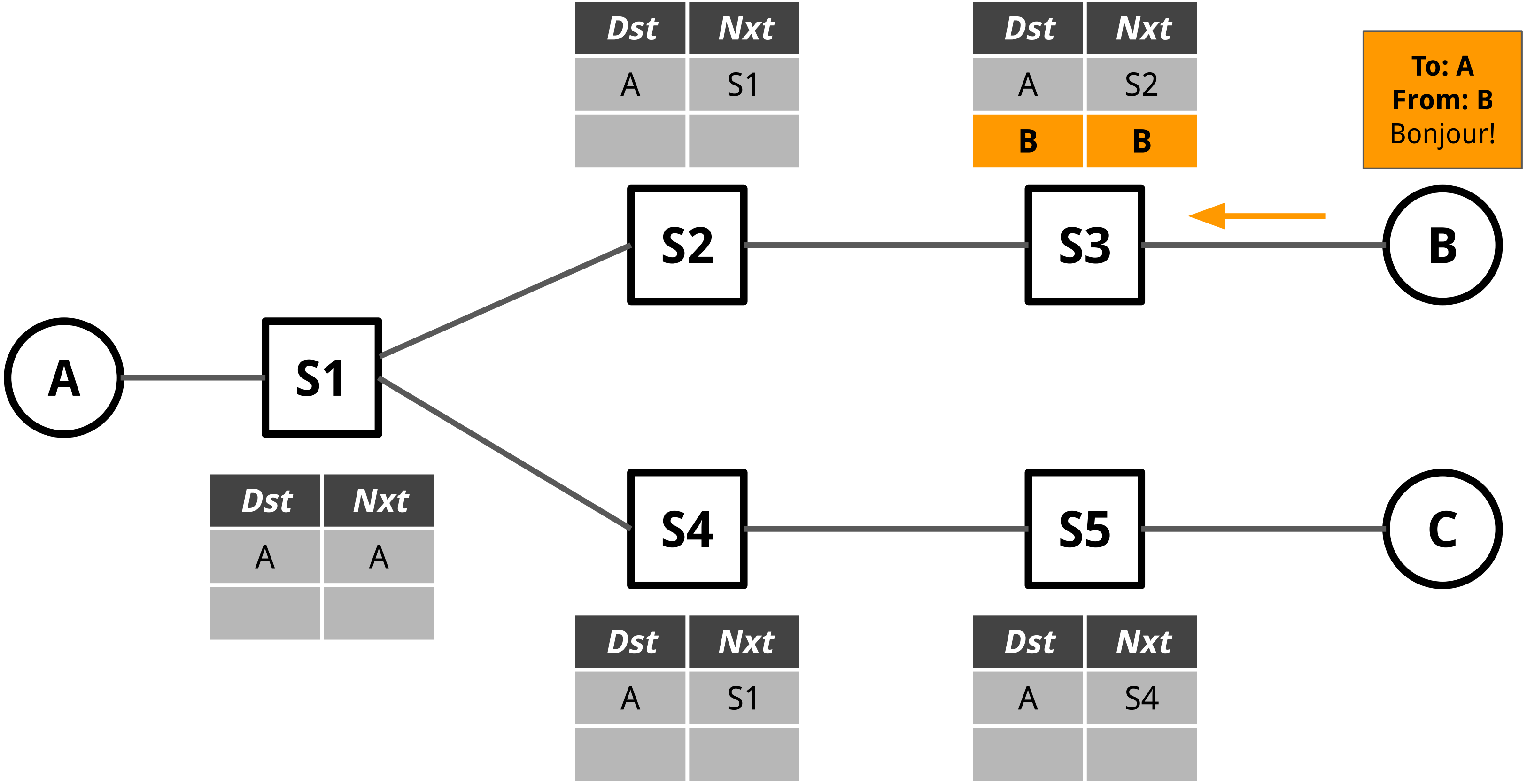

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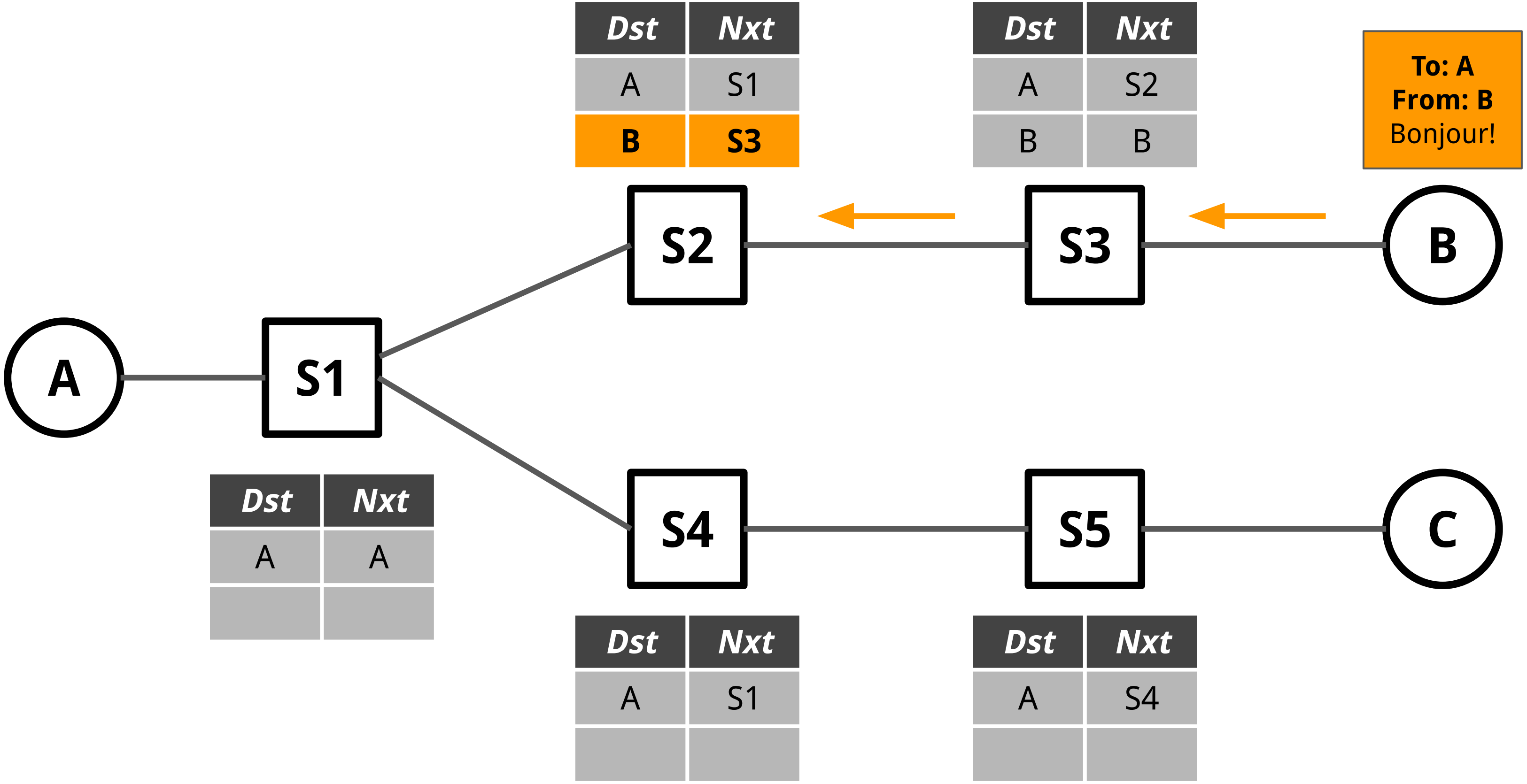

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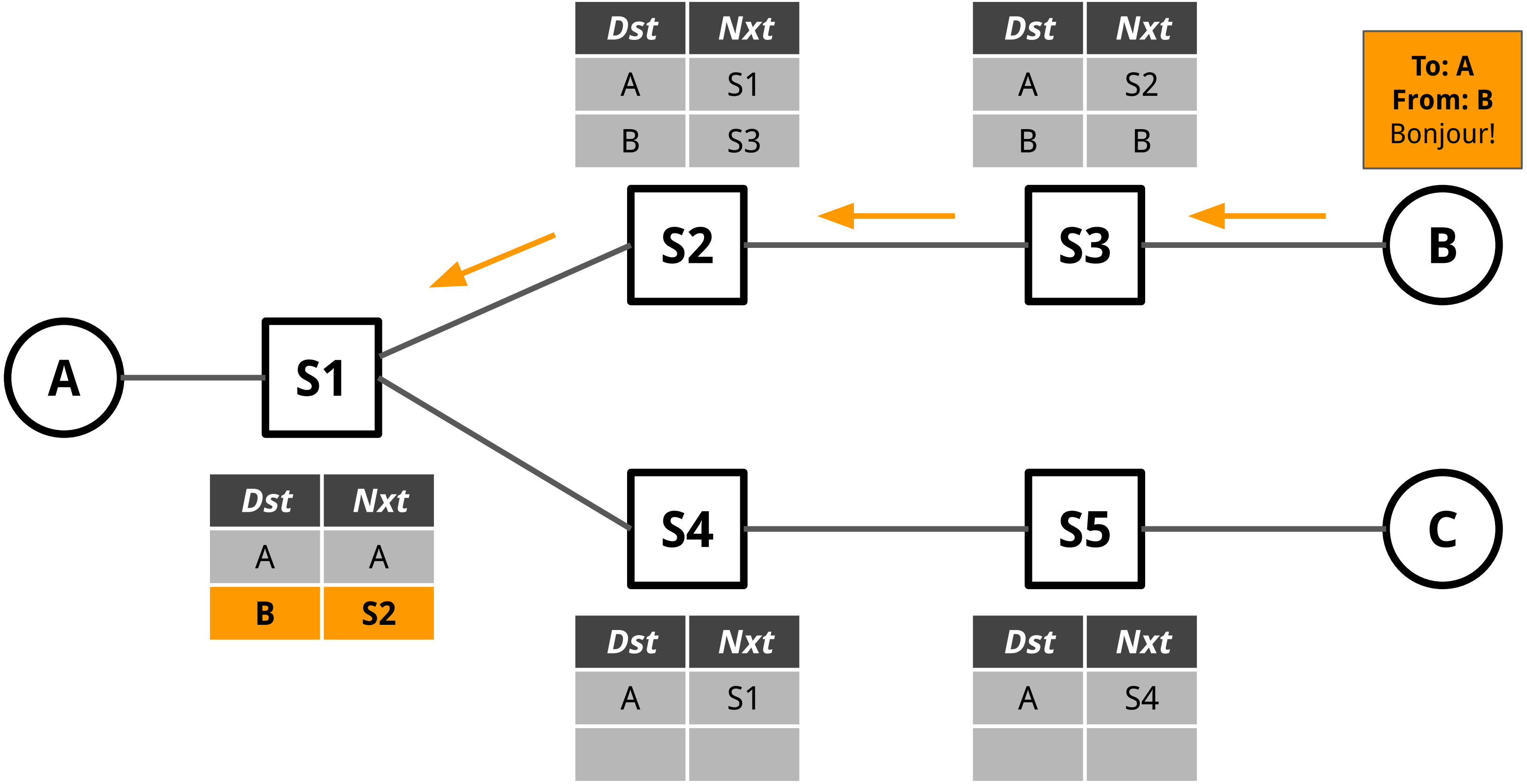

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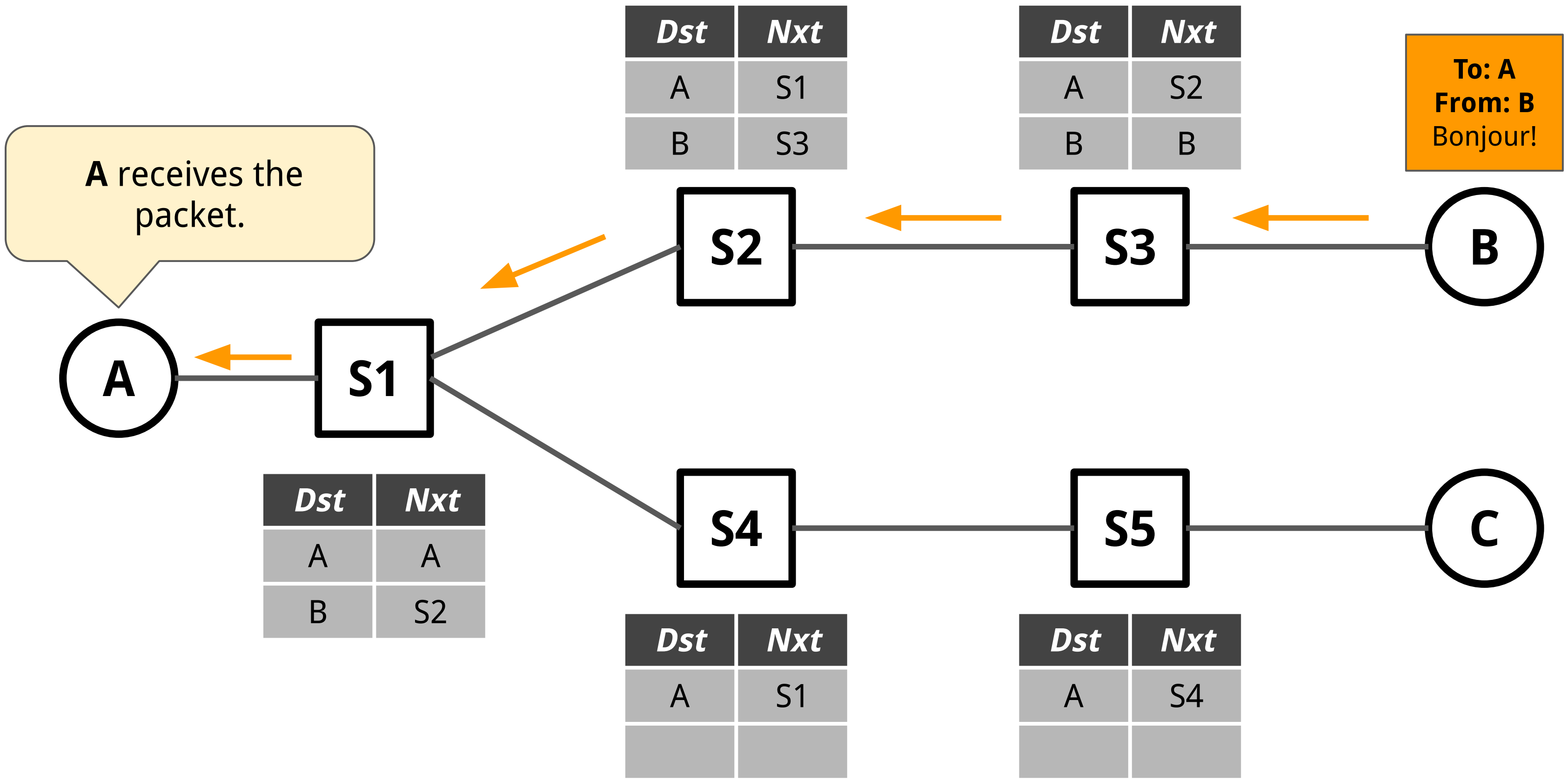

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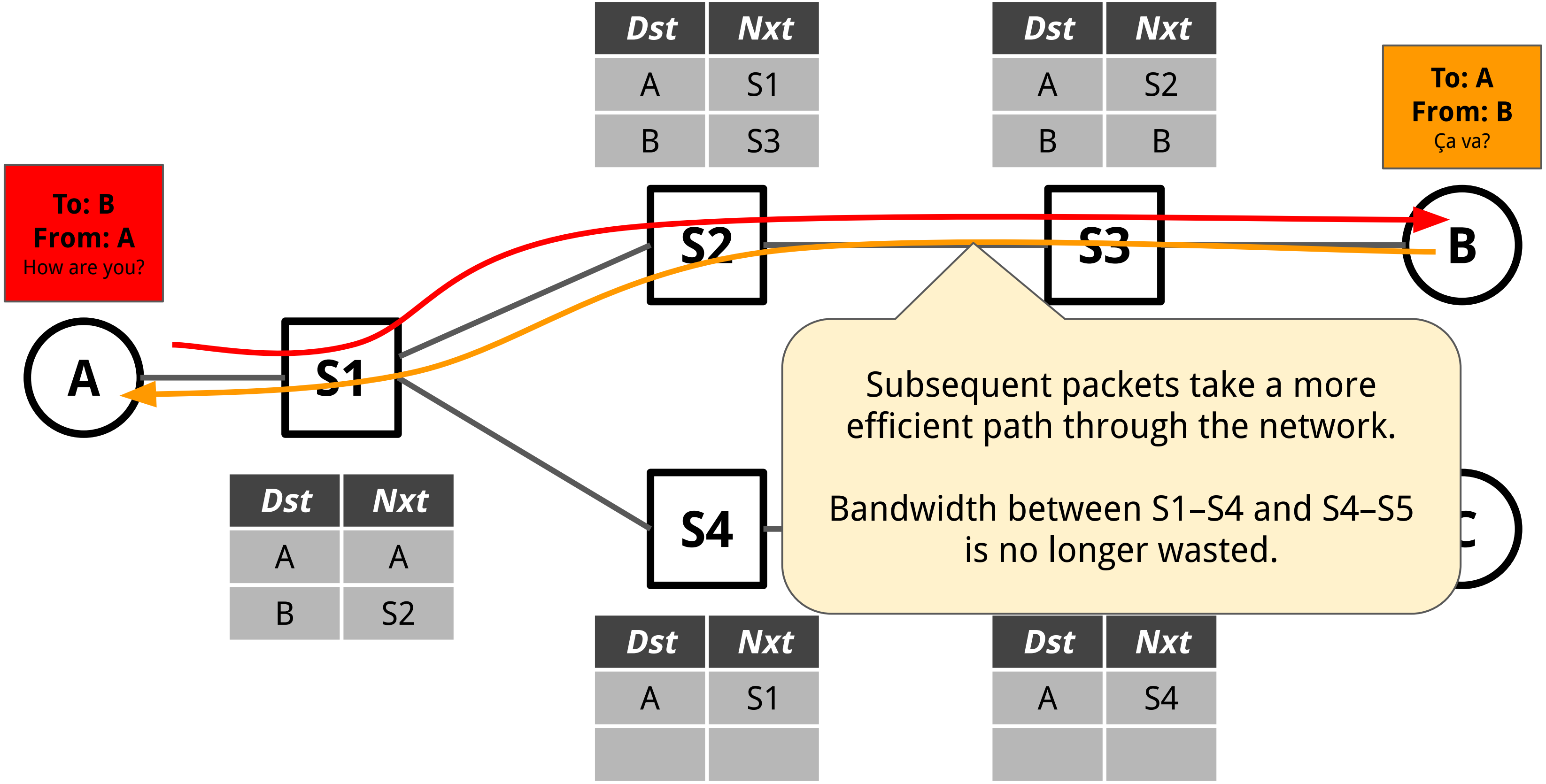

Dst	Nxt
A	S1
B	S3

Dst	Nxt
A	S2
B	B

Dst	Nxt
A	A
B	S2

Dst	Nxt
A	S1

Dst	Nxt
A	S4

Subsequent packets take a more efficient path through the network.

Bandwidth between S1–S4 and S4–S5 is no longer wasted.

Learning Switches

- Each switch decides whether it is going to flood.
  - One switch may flood a packet when it neighbour does not.
  - Based on whether there is a **forwarding table entry**.

- At each switch:
  - If a forwarding table entry exists → send on the port specified.
  - Else → flood out of all ports (except the incoming port) if not.

Learning Switches in Pseudocode

```
on arrival of packet from neighbour previous_hop:
    # Learn
    table[packet.source].next_hop = previous_hop
    table[packet.source].ttl = 600 * time.second

    # Forward
    if packet.destination in table:
        next_hop = table[packet.destination].next_hop
        if next_hop == previous_hop:
            packet.drop()
        else:
            packet.forward_to(next_hop)
    else:
        packet.flood_to_neighbours(except=previous_hop)
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Why do we need this **time to live?**

Learning Switches in Pseudocode

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```

Why do we need this **source port check?**

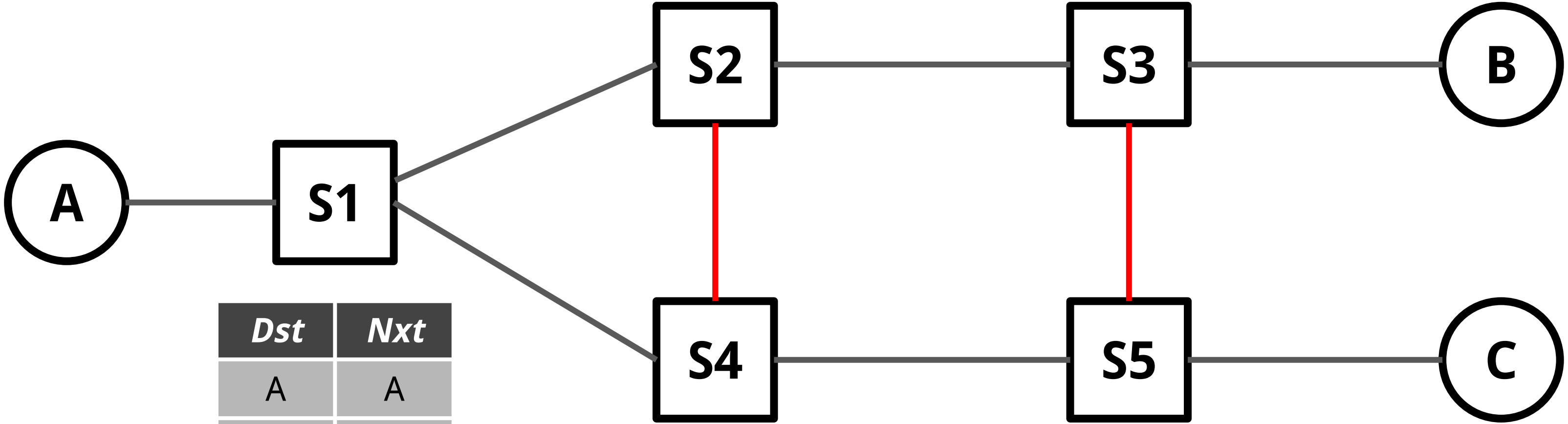
Learning Switches

S2:

Dst	Nxt
A	S1
B	S3

S3:

Dst	Nxt
A	S2
B	B



S1:

Dst	Nxt
A	A
B	S2

S4:

Dst	Nxt
A	S1

S5:

Dst	Nxt
A	S4

Learning Switches

- A major problem with learning switches:
  - Floods when the destination is unknown.
  - … floods have problems when the topology has loops.
- How do we prevent there being looped packets?
- Brute force solution…
  - Remove the loops.
  - Disable links until we have a topology that connects to all hosts but does not have any loops.
  - This is a spanning tree (we'll come back and discuss these more later).

Spanning Tree Protocol

- How do we make a spanning tree from an arbitrary network?
- Step 1: Find a path from every switch to the root.
- Step 2: Disable data delivery on every link not on a path to the root.
- Step 3: When the tree breaks (a link on it fails) start over.

Spanning Tree Protocol

- How do we make a spanning tree from an arbitrary network?
- Step 1: Find a path from every switch to the root.
    - If there are multiple links – how do we choose? We need an idea of a link or a node **preference** or **cost**.
- Step 2: Disable data delivery on every link not on a path to the root.
- Step 3: When the tree breaks (a link on it fails) start over.

Spanning Tree Protocol: Step 1 (Paths to root)

- Step 1: Find the least cost path from every switch to the root.

- Give every switch a unique, orderable ID (based on the Ethernet address)

- Work to find:
  - The root (the switch with the lowest ID)
  - The best path to the root (lowest cost).

Spanning Tree Protocol: Step 1 (Paths to root)

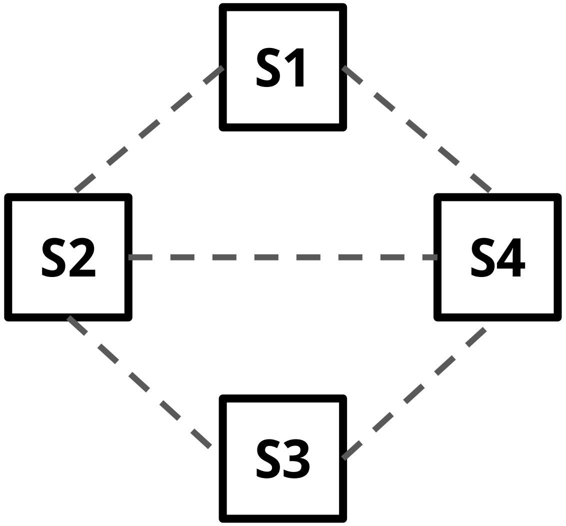
- Start out: all switches think that they are the root.
- Sends a message to its neighbour to say (“`The root is` **`<me>`** `and I can reach it in` **`<zero>`** `hops!`”).

- On receiving a message from a neighbour:
    - First, compare the root ID to what we think the root ID is…
    - If it’s smaller than the current ID – it is a better root, use it as a root.
    - If its larger than the current ID – it is a worse root, ignore it.
        - (We’ll come back to what happens if it’s the same!)
    - … and send a triggered update to your neighbours telling you about your new state.

Spanning Tree Protocol: Step 2 (Disable links)

- Step 2: Disable data delivery on every link not on a shortest path to root.

- Wait, why is this so complicated?
  - It's not as easy as you might think…

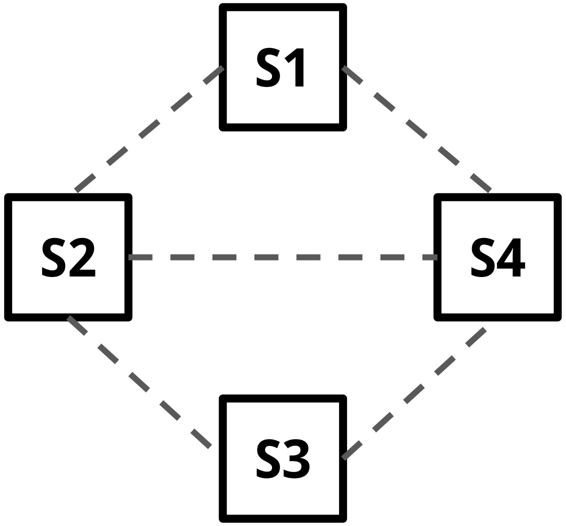


Spanning Tree Protocol: Step 2 (Disable links)

- Step 2: Disable data delivery on every link not on a shortest path to root.

- Wait, why is this so complicated?
    - It's not as easy as you might think…

- Strategy:
    - **Enable** the link along your best path to root
    - **Disable** the other links to switches closer than the root to you.
        - … they are not on your best path
        - … and you can't possibly be on theirs (you are farther than the root than them!)
    - Leave the other links for the other switches to decide
        - … they are all farther from the root than you
        - … so you're closer
        - … so the above enable/disable rules work for them.

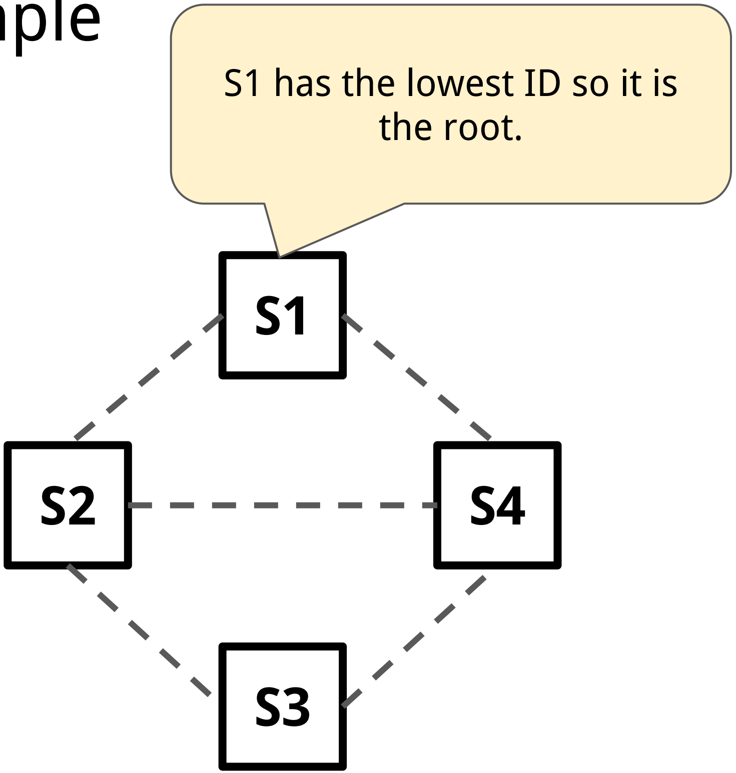


Spanning Tree Protocol: Step 2 Example

- Dashed links are unknown.
- Green links are enabled.
- Red links are disabled.

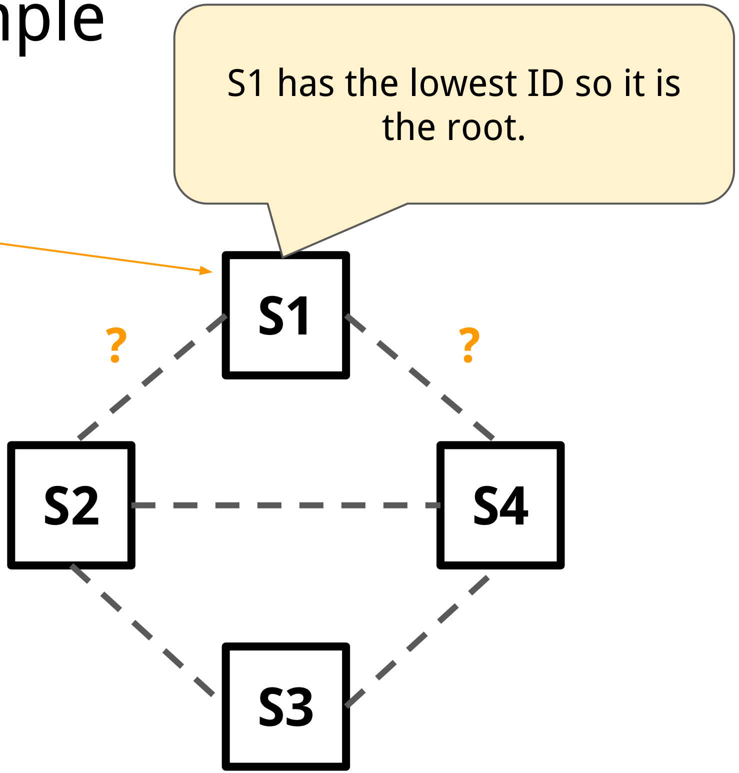
- S1 is the root (lowest ID)

- Step 1 is complete – we know about our neighbours.



Spanning Tree Protocol: Step 2 Example

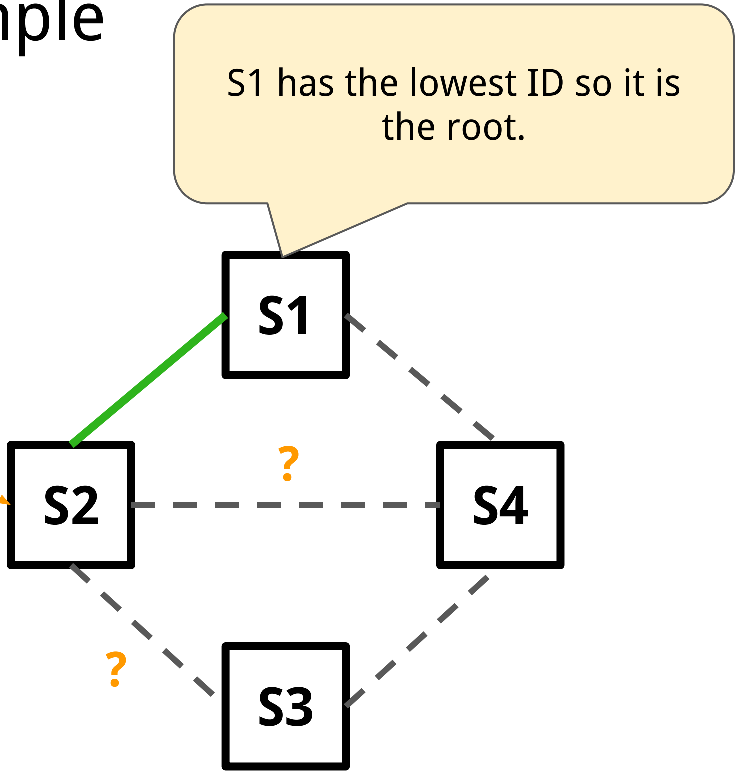
- S1's perspective
  - S1–S2: Unknown
  - S1–S4: Unknown



Spanning Tree Protocol: Step 2 Example

- S2’s perspective
  - S2–S1: Enabled
  - S2–S3: Unknown
  - S2–S4: Unknown

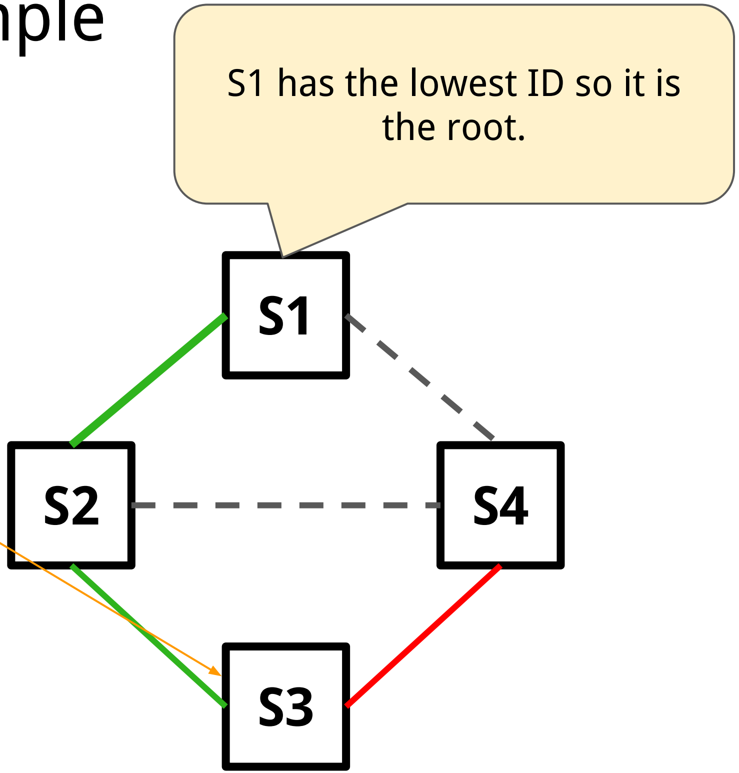
- S4 has the same distance to the root – but has a higher ID – so it’s farther from the root.



Spanning Tree Protocol: Step 2 Example

- S3's perspective
  - S3–S2: Enabled
  - S2–S4: Disabled

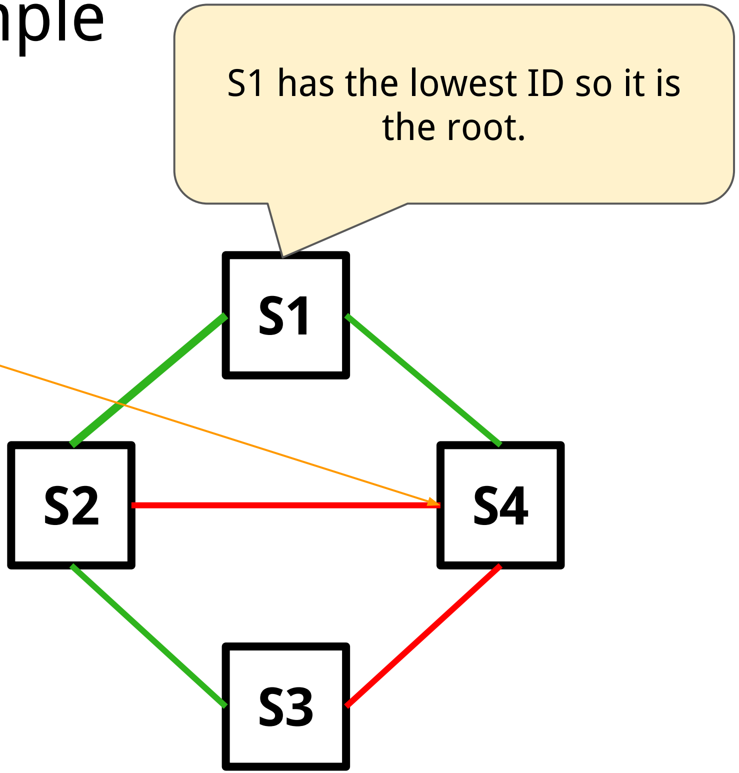
- S2:
  - Closer to the root than S4 (same distance, but lower ID)
- S4:
  - Closer than we are, but not on the shortest path – disable.



Spanning Tree Protocol: Step 2 Example

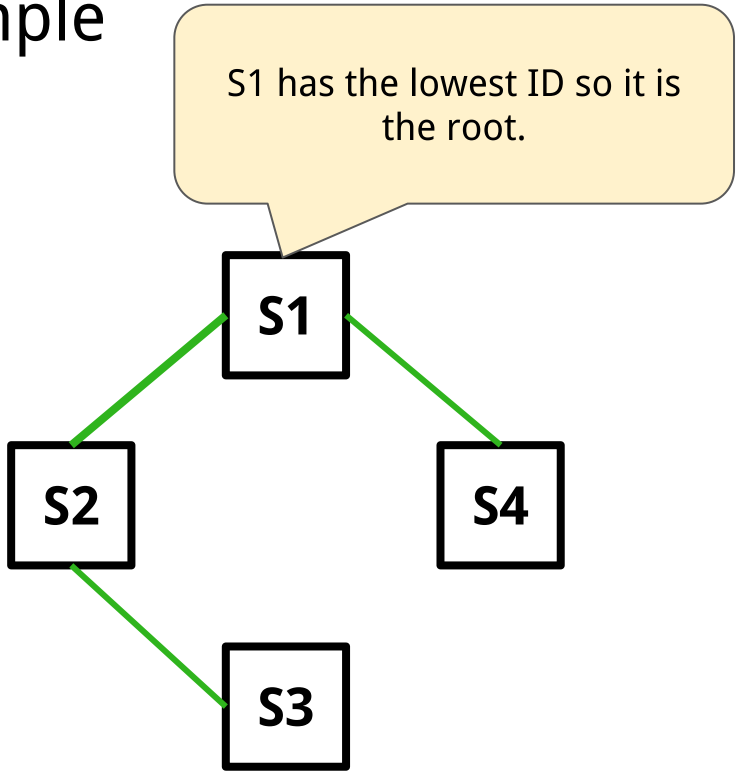
- S4's perspective
  - S4–S1: Enabled
  - S4–S3: Unknown
  - S4–S2: Disabled

- S2:
  - Closer to the root (same distance, but smaller ID).



Spanning Tree Protocol: Step 2 Example

- We've got a spanning tree!
- And it matches the next-hops each switch came up with from Step 1!



Spanning Tree Protocol: Step 2 (Disable links)

- Step 2 Recap…
- No ties when comparing distance – break ties using a switch's ID.
- Each switch:
  - **Enables** the link along the best path to the root (and all links to hosts!)
  - **Disables** every other link to a neighbour closer to the root.
  - Lets the furthest-away neighbour decide the rest!
- In this way - a switch closer doesn't disable a link needed by a switch that's farther.
  - Doesn't require explicit co-ordination (no need to ask "do you need this link?")
  - Exactly one switch is responsible for enabling or disabling each link.

Spanning Tree Protocol: Step 3

- Step 3: When the tree breaks (a link on it fails), start over.

- Starts the process at step 1 to re-discover a spanning tree.

Spanning Tree Protocol

- Notice, we had to exchange messages between switches to have some knowledge of the topology.
    - Done by the switch's **control plane**.

- We had to have some idea of **preference** or **cost** within the topology to decide what to enable/disable.

- **Spanning tree** is a (simple) "routing" protocol.
    - We'll talk more about different protocols and their approaches going forward.
    - Limited in functionality – simply to avoid us having a "loopy" topology that causes problems with learning switches.

Next Time

- Consider some of the problems of our Layer 2 network.

- Introduce more *routing protocols* and discuss different optimisation criteria that they might enable.