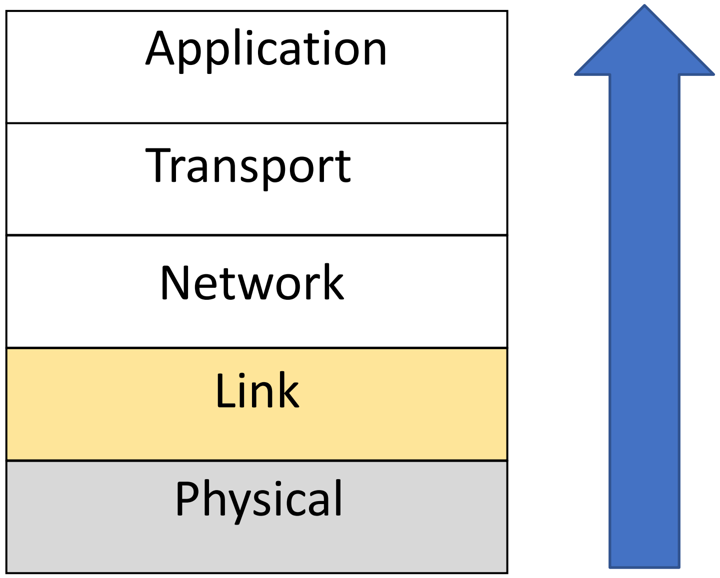
Where we are in the Course

- Today: Second to last day in the link layer!
  - We know now how to reliably send data between two users… how about more???



Multiple Access

Topic

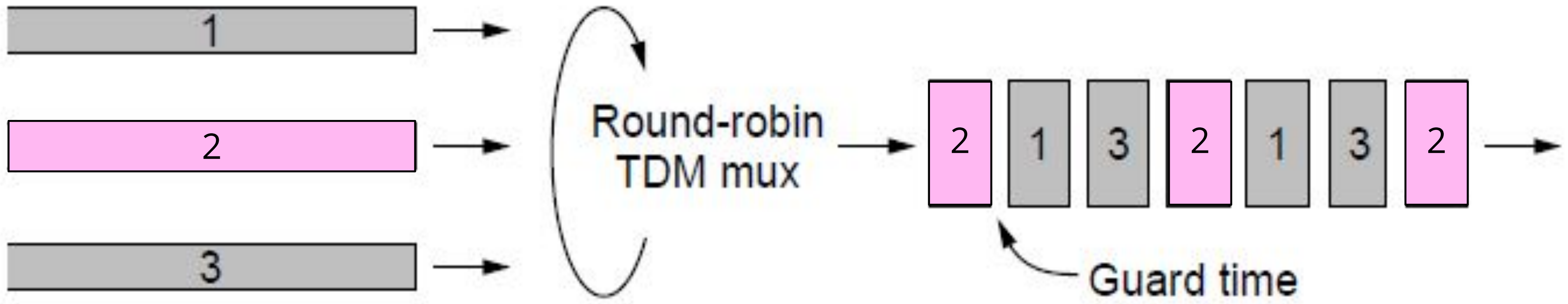
- Multiplexing is the network word for the sharing of a resource
- What are some straightforward ways to divide up a network resource (e.g., wire, air, etc)?

Topic

- Multiplexing is the network word for the sharing of a resource
- What are some straightforward ways to divide up a network resource (e.g., wire, air, etc)?
- Classic scenario is sharing a link among different users
  - Time Division Multiplexing (TDM)
  - Frequency Division Multiplexing (FDM)

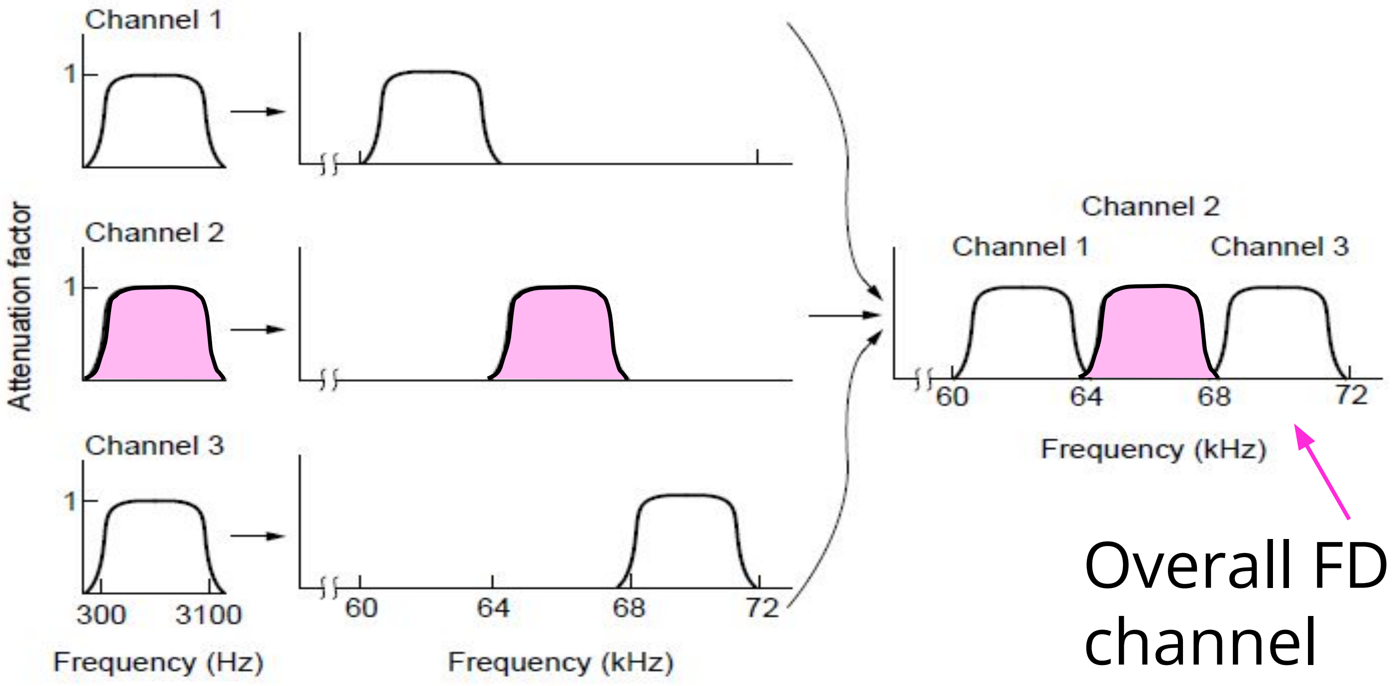
Time Division Multiplexing (TDM)

- Users take turns on a fixed schedule



Frequency Division Multiplexing (FDM)

- Put different users on different frequency bands



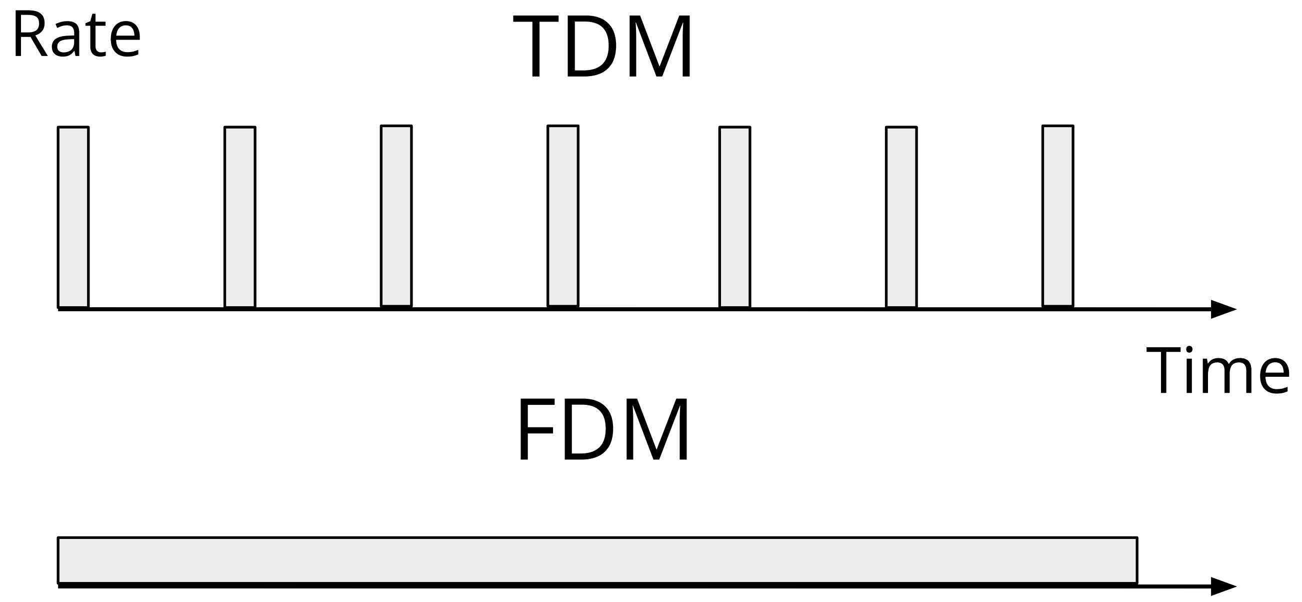
Overall FDM channel

TDM versus FDM

- Tradeoffs?

TDM versus FDM (2)

- In TDM a user sends at a high rate a fraction of the time; in FDM, a user sends at a low rate all the time

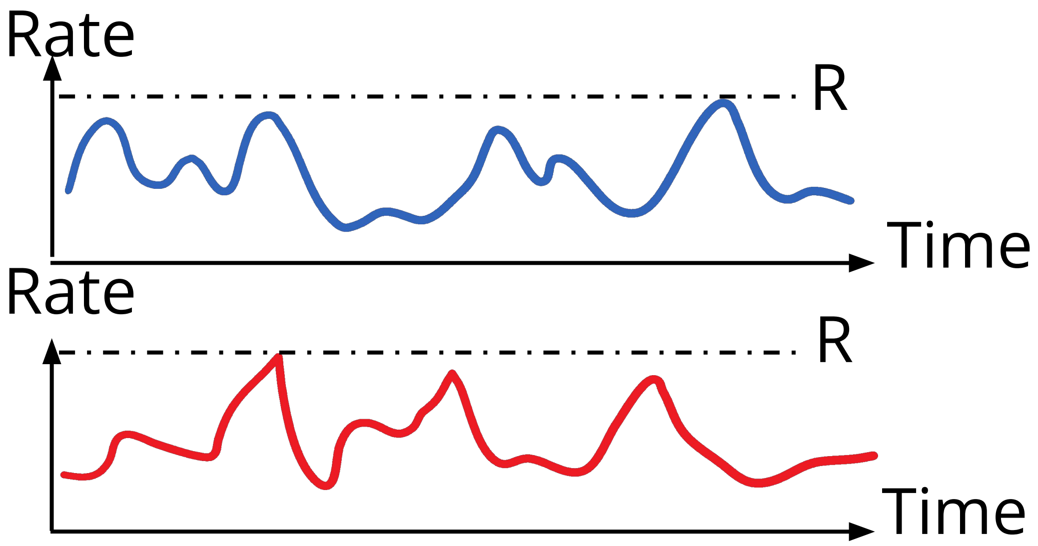


TDM/FDM Usage

- Statically divide a resource
  - Suited for continuous traffic, fixed number of users
- Widely used in telecommunications
  - TV and radio stations (FDM)
  - GSM (2G cellular) allocates calls using TDM within FDM

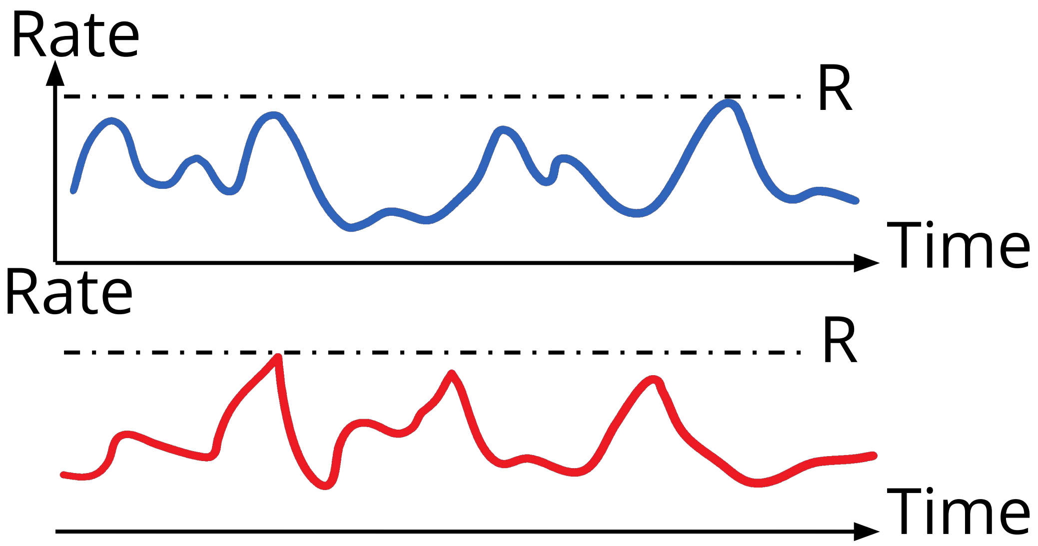
Multiplexing Network Traffic

- Network traffic is “bursty”
  - ON/OFF sources
  - Load varies greatly over time



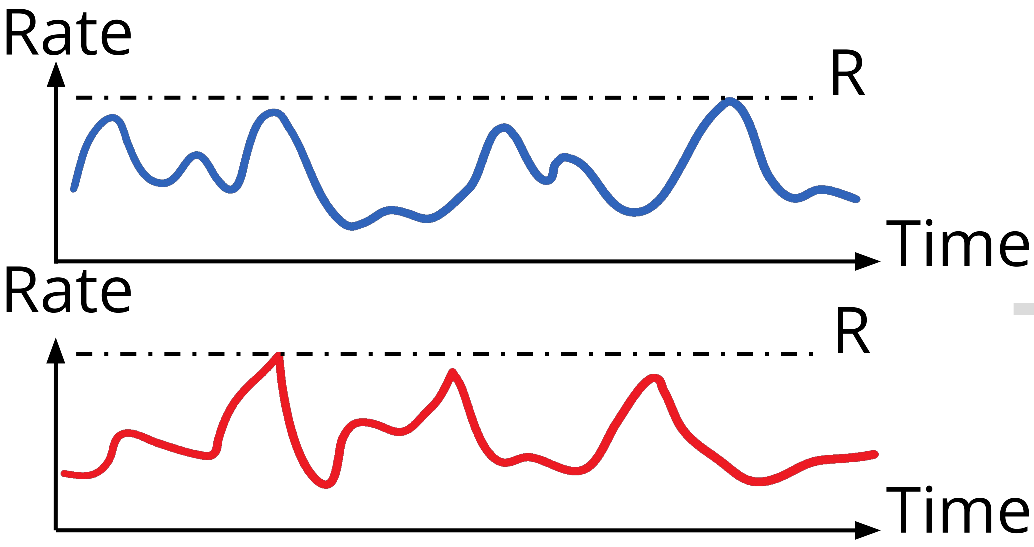
Multiplexing Network Traffic (2)

- Network traffic is <u>bursty!</u>
  - Inefficient to always allocate user their ON needs with TDM/FDM

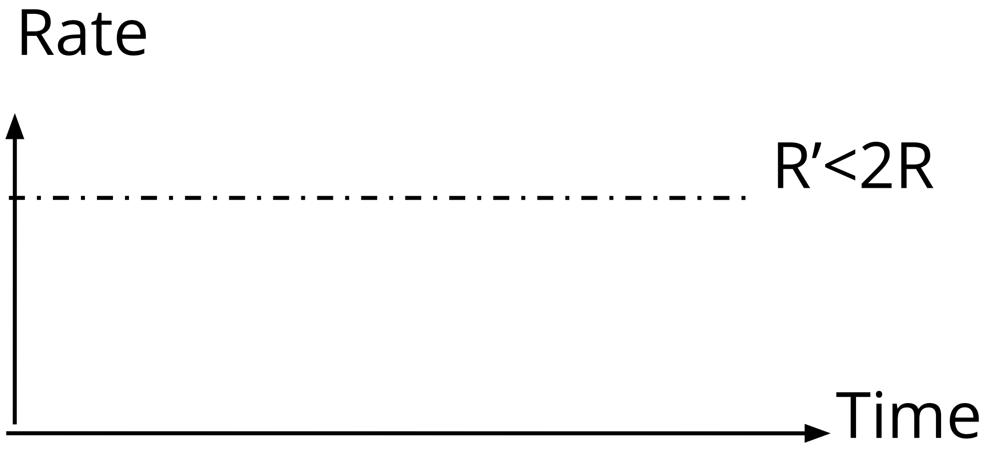


Multiplexing Network Traffic (3)

- Multiple access schemes multiplex users according to demands – for gains of statistical multiplexing



Two users, each need R



Together they need R’ < 2R

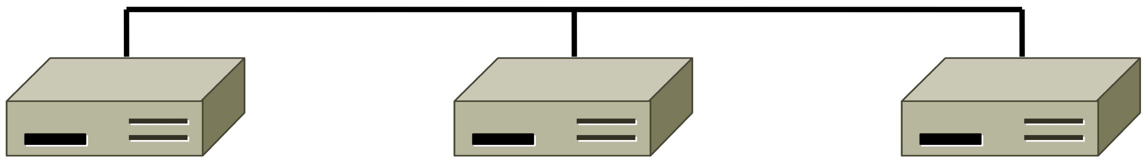
How to control?

Two classes of multiple access algorithms: Centralized and distributed

- Centralized: Use a privileged “Scheduler” to pick who gets to transmit and when.
  - Positives: Scales well, usually efficient.
  - Negatives: Requirements management, fairness
  - Examples: Cellular networks (tower coordinates)
- Distributed: Have all participants “figure it out” through some mechanism.
  - Positives: Operates well under low load, easy to set up, equality
  - Negatives: Scaling is really hard
  - Examples: Wifi networks

Distributed (random) Access

- How do nodes share a single link? Who sends when, e.g., in WiFI?
  - Explore with a simple model



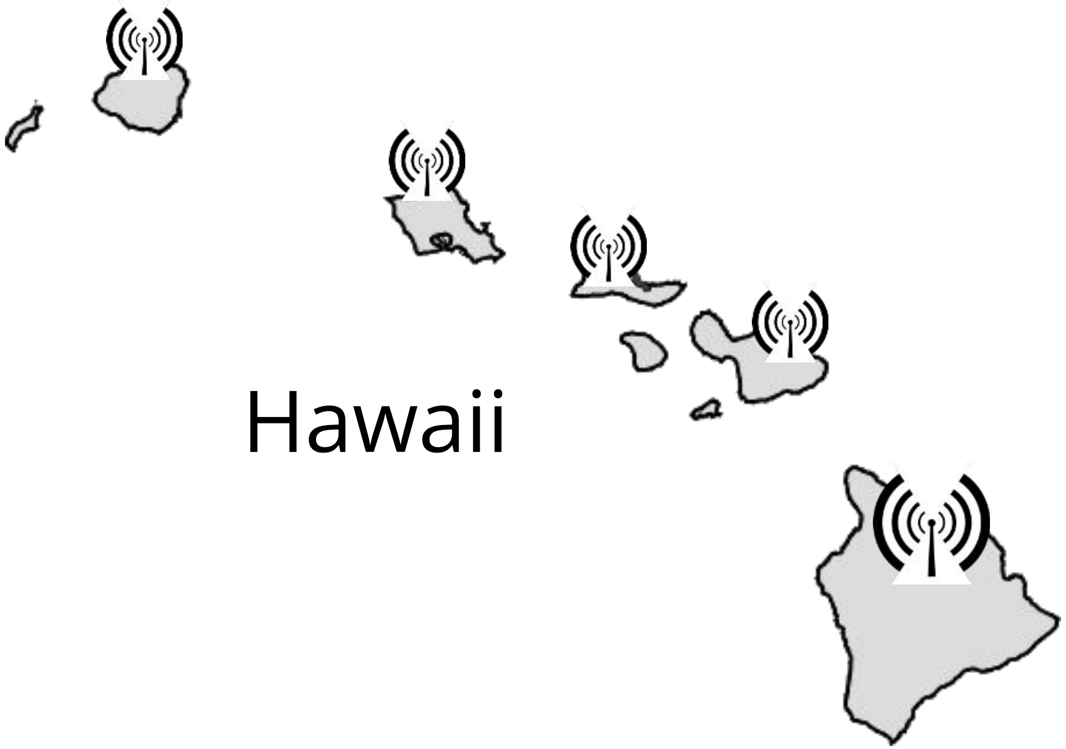
- Assume no-one is in charge
  - Distributed system

Distributed (random) Access (2)

- We will explore random multiple access control (MAC) protocols
  - This is the basis for classic Ethernet
- Remember: data traffic is bursty

ALOHA Network

- Seminal computer network connecting the Hawaiian islands in the late 1960s
  - When should nodes send?
  - A new protocol was devised by Norm Abramson …



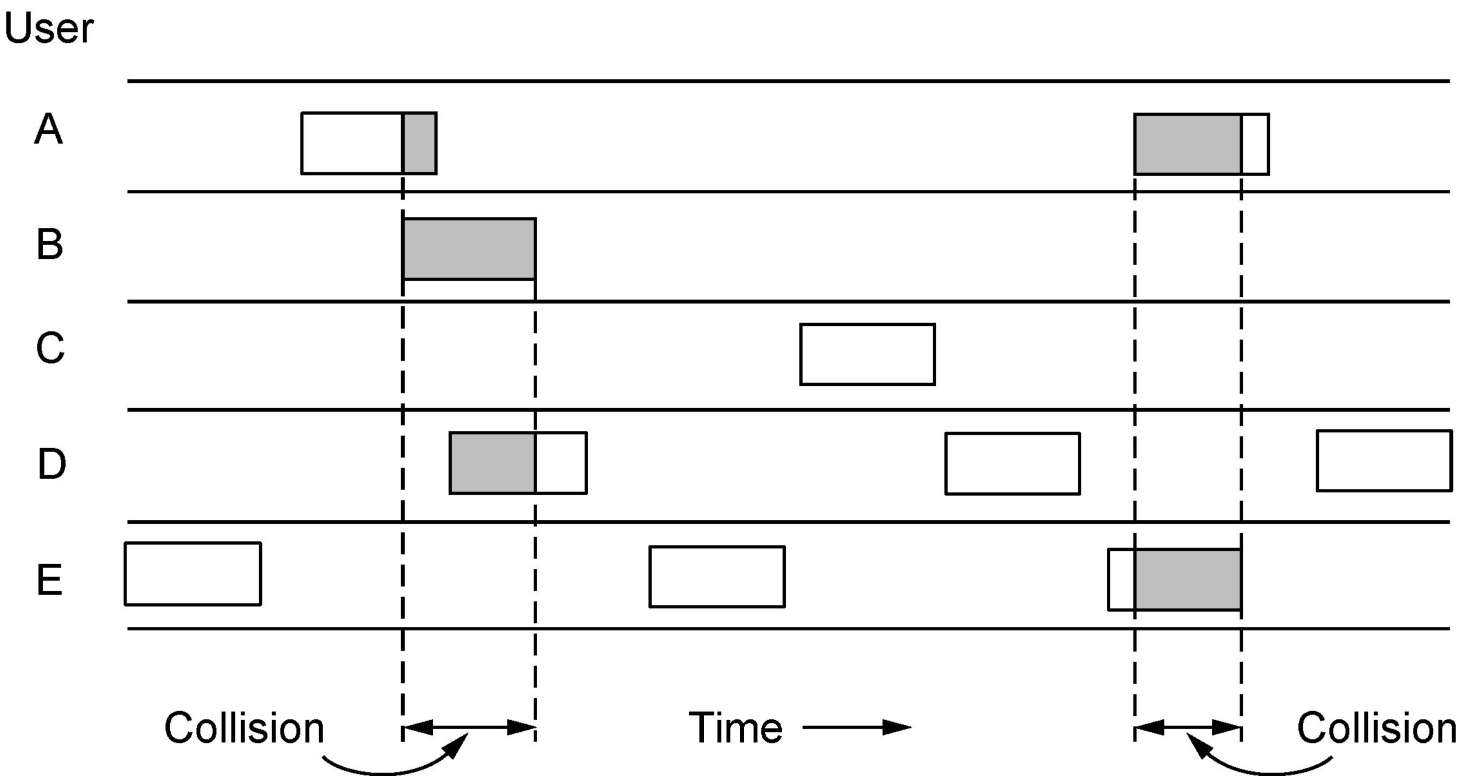
ALOHA Protocol

- Simple idea:
  - Node just sends when it has traffic.
  - If there was a collision (no ACK received) then wait a random time and resend
- That's it!

ALOHA Protocol (2)

- Some frames will be lost, but many may get through…

- Limitations?



ALOHA Protocol (3)

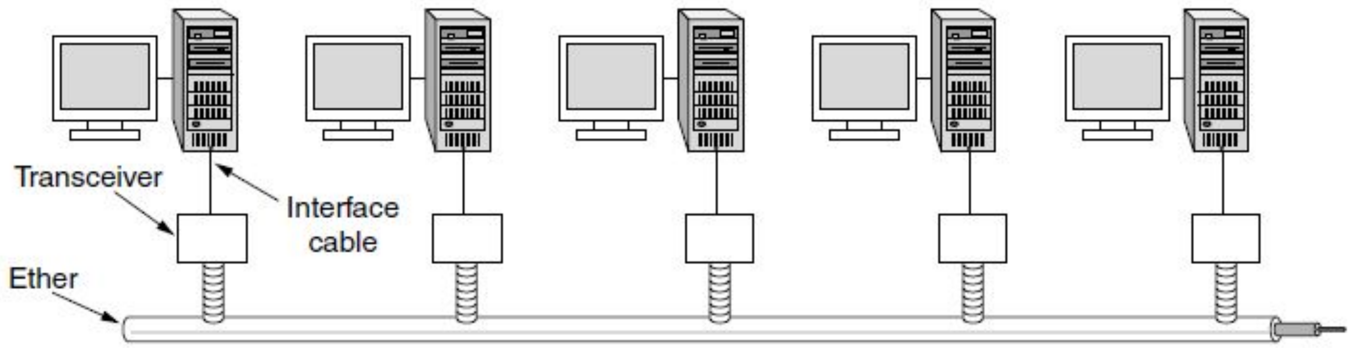
- Simple, decentralized protocol that works well under low load!

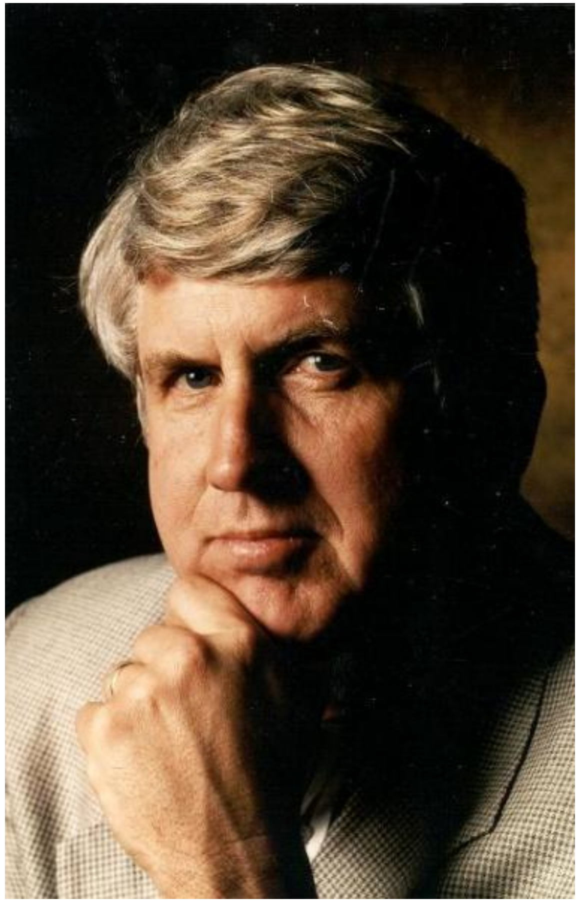
- Not efficient under high load
  - Analysis shows at most 18% efficiency
  - Improvement: divide time into slots and efficiency goes up to 36%

- We’ll look at other improvements

Classic Ethernet

- ALOHA inspired Bob Metcalfe to invent Ethernet for LANs in 1973
  - Nodes share 10 Mbps coaxial cable
  - Hugely popular in 1980s, 1990s





: © 2009 IEEE

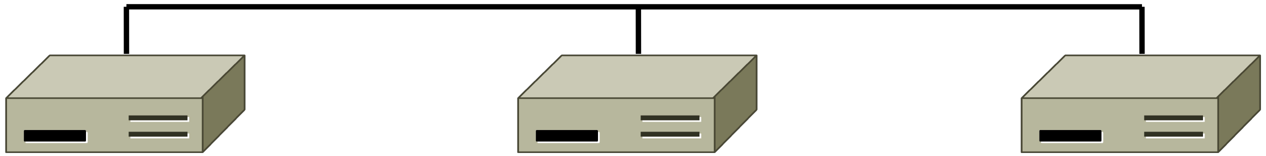
CSMA (Carrier Sense Multiple Access)

- Improve ALOHA by listening for activity before we send (Doh!)
  - Can do easily with wires, not wireless

- So does this eliminate collisions?
- Why or why not?

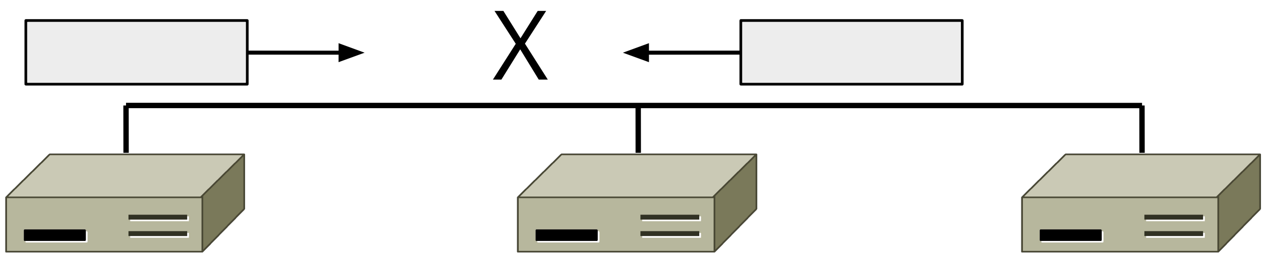
CSMA (2)

- Still possible to listen and hear nothing when another node is sending because of delay



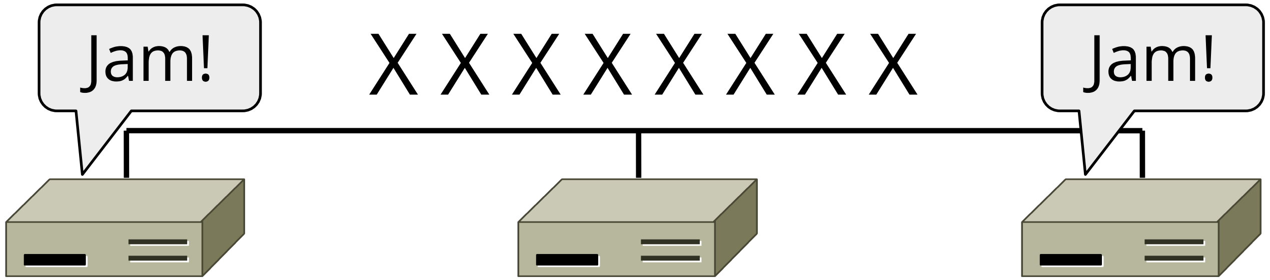
CSMA (3)

- CSMA is a good defense against collisions only when BD is small



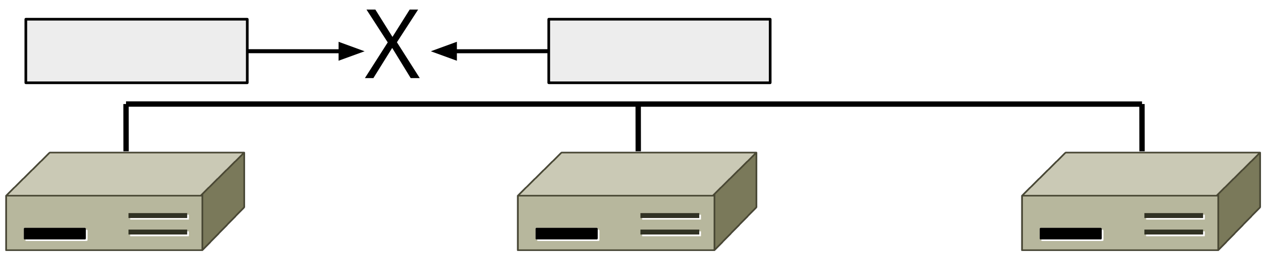
CSMA/CD (with Collision Detection)

- Can reduce the cost of collisions by detecting them and aborting (Jam) the rest of the frame time
  - Again, we can do this with wires



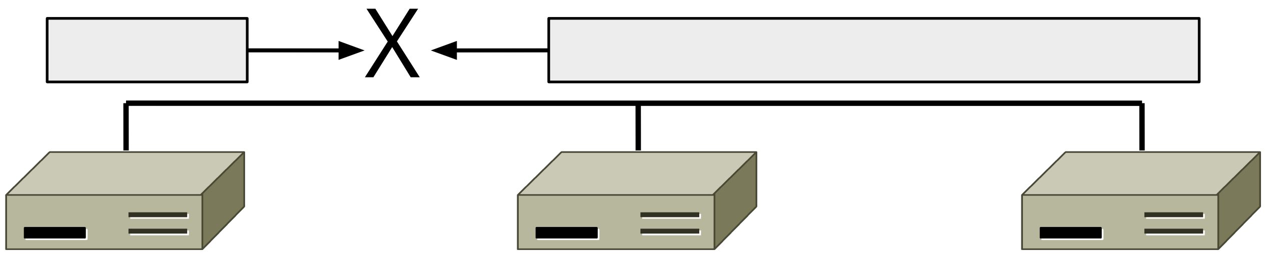
CSMA/CD Complications

- Everyone who collides needs to know it happened
  - How long do we need to wait to know there wasn't a JAM?
  - Time window in which a node may hear of a collision (transmission + jam) is 2D seconds



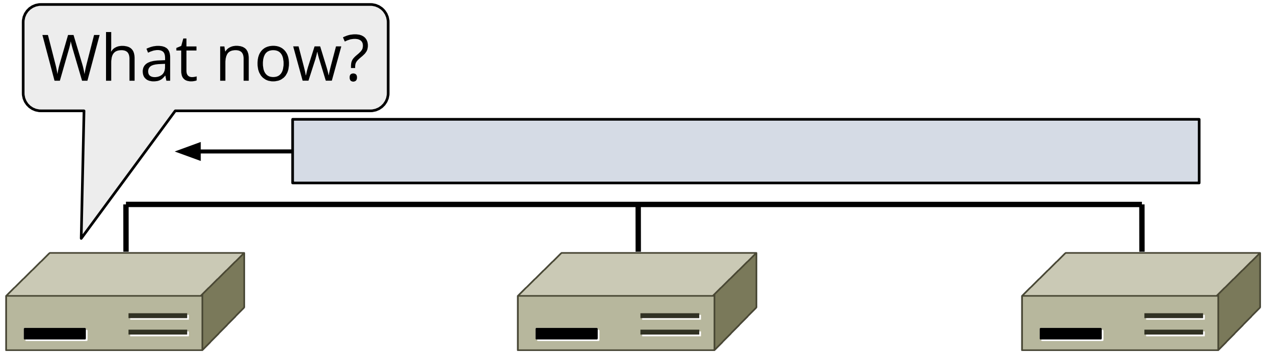
CSMA/CD Complications (2)

- Impose a minimum frame length of 2D seconds
  - So node can't finish before collision
  - Ethernet minimum frame is 64 bytes – Also sets maximum network length (500m w/ coax, 100m w/ Twisted Pair)



CSMA "Persistence"

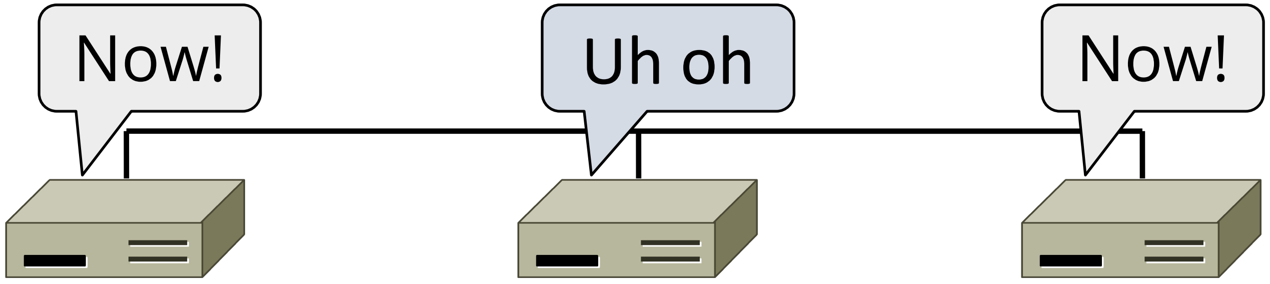
- What should a node do if another node is sending?



- Idea: Wait until it is done and send?

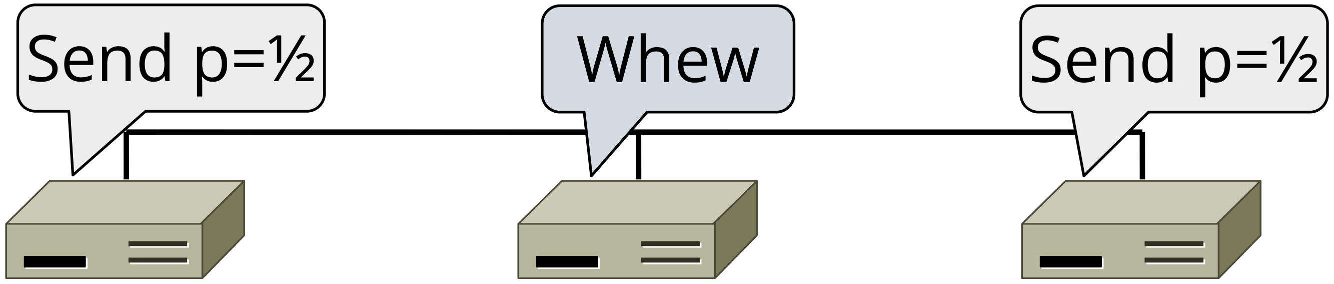
CSMA "Persistence" (2)

- Problem is that multiple waiting nodes will queue up then collide!
  - More load, more of a problem : (
- Ideas?



CSMA "Persistence" (3)

- Intuition for a better solution
  - If there are N queued senders, we want each to send next with probability 1/N



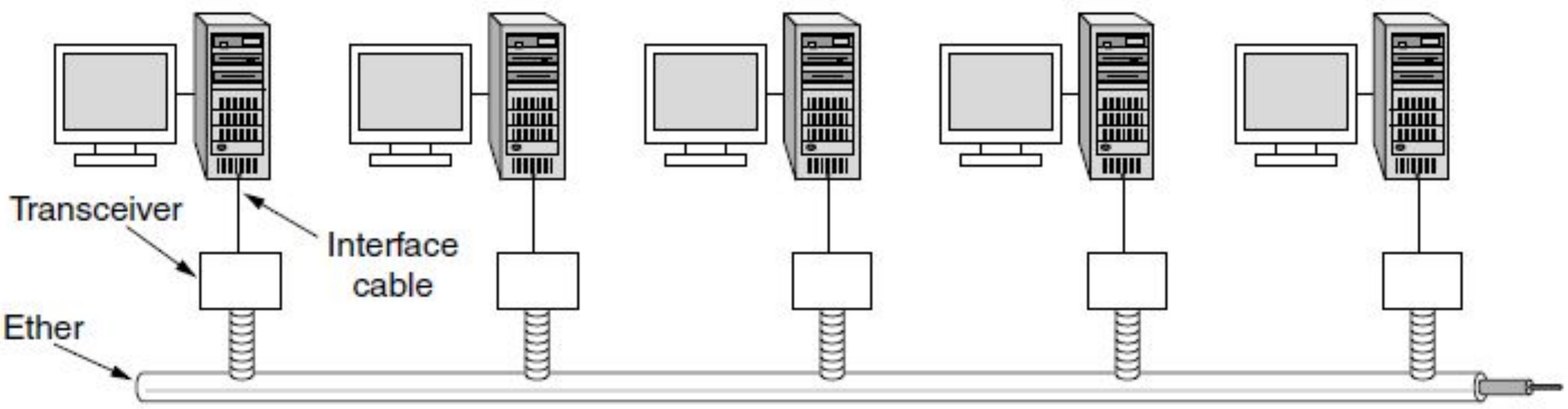
Binary Exponential Backoff (BEB)

- Cleverly estimates the probability
  - 1st collision, wait 0 or 1 frame times
  - 2nd collision, wait from 0 to 3 times
  - 3rd collision, wait from 0 to 7 times …

- BEB doubles interval for each successive collision
  - Quickly gets large enough to work
  - Very efficient in practice

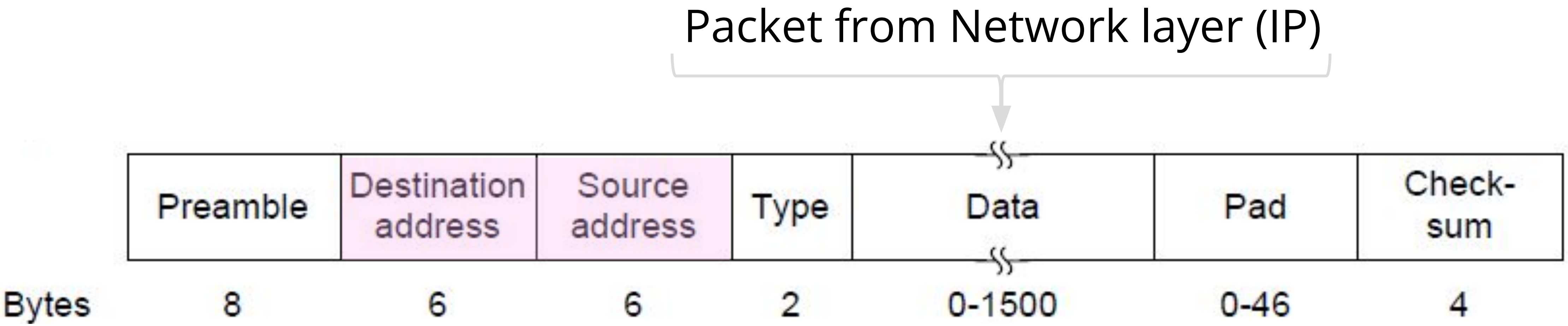
Classic Ethernet, or IEEE 802.3

- Most popular LAN of the 1980s, 1990s
  - 10 Mbps over shared coaxial cable, with baseband signals
  - Multiple access with "1-persistent CSMA/CD with BEB"



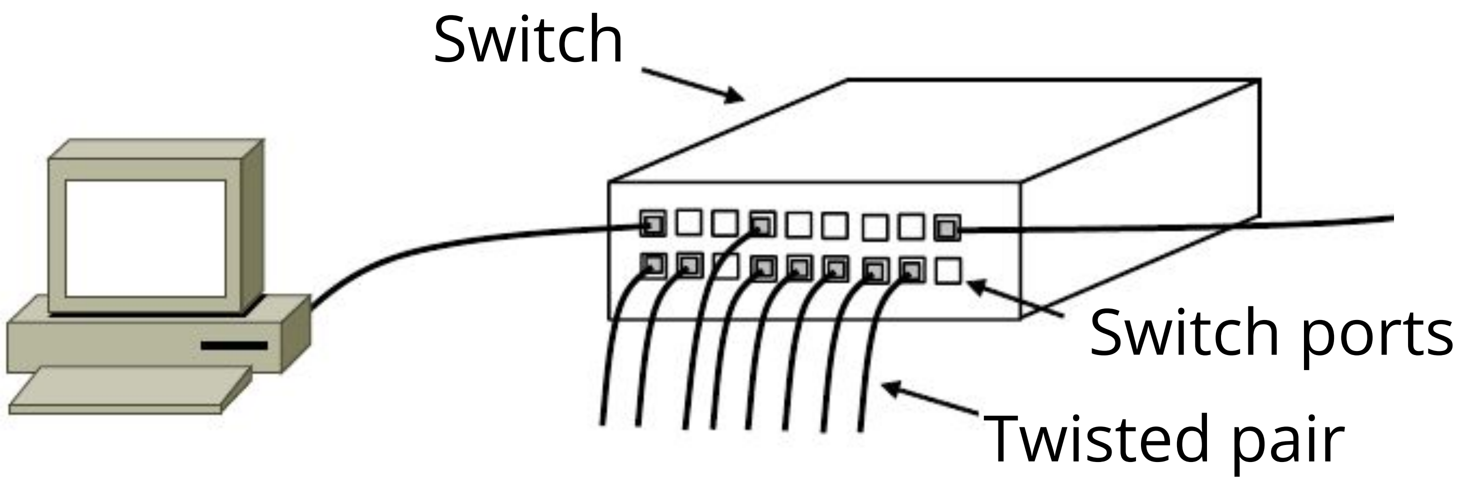
Ethernet Frame Format

- Has addresses to identify the sender and receiver
- CRC-32 for error detection; no ACKs or retransmission
- Start of frame identified with physical layer preamble

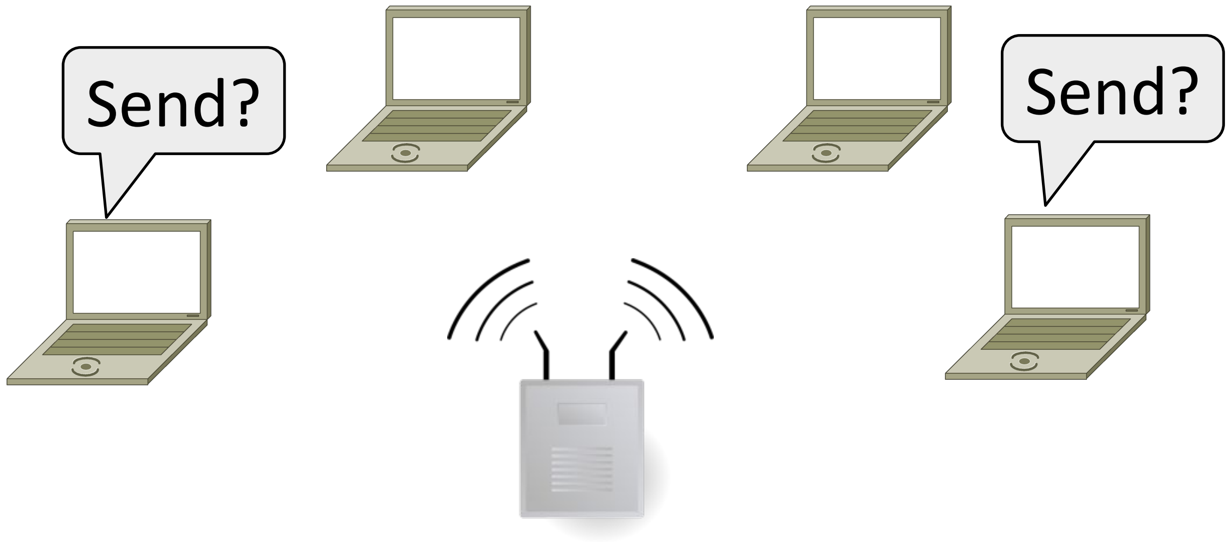


Modern Ethernet

- Based on switches, not multiple access, but still called Ethernet
  - We'll get to it in a later segment



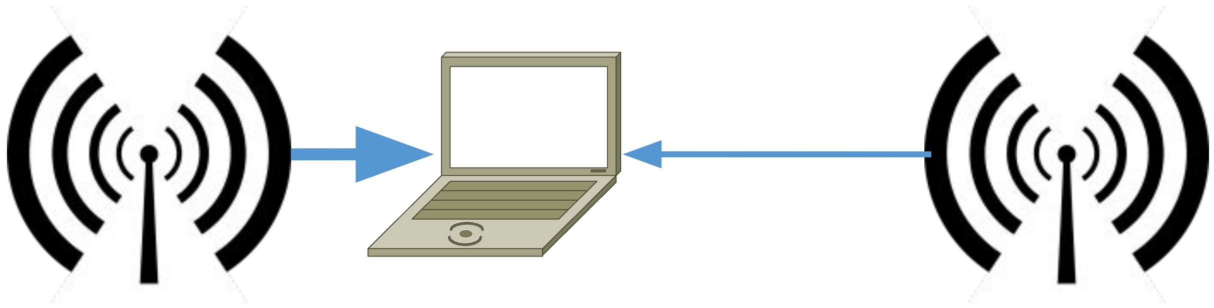
Wireless…



- How do wireless nodes share a link?
  - This is finally “WiFi”!
  - Build on our simple, wired model

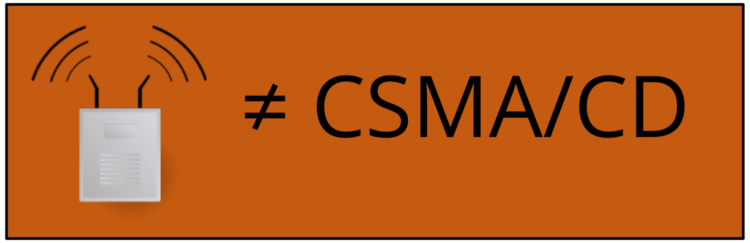
Wireless

- Sender radiates signal over a region
    - In many directions, unlike a wire, to potentially many receivers
    - Nearby signals (same freq.) interfere at a receiver; need to coordinate use



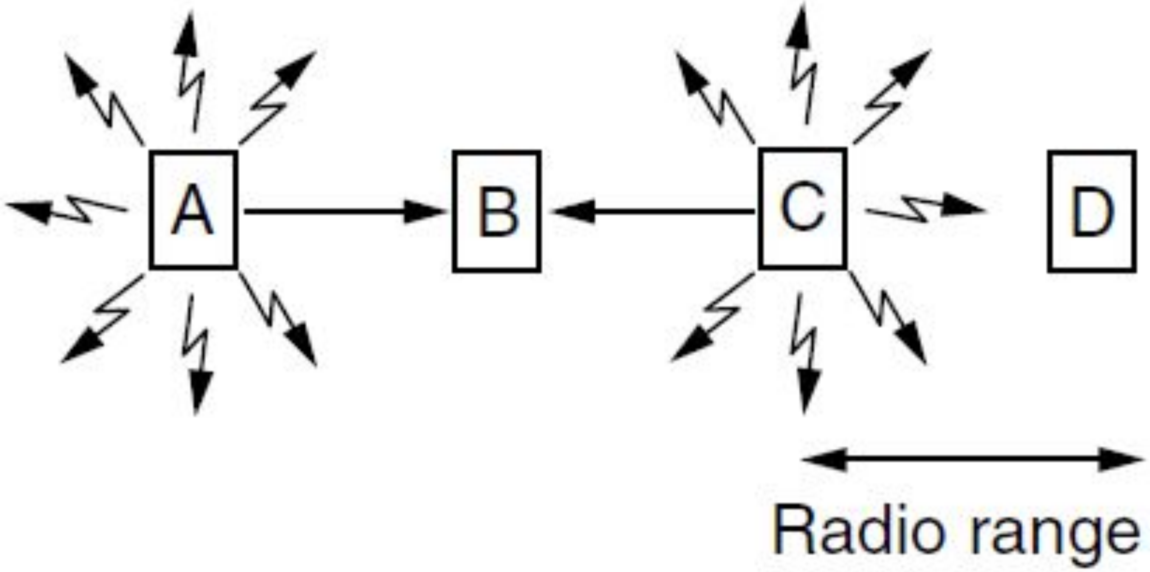
Wireless Complications

- Wireless is more complicated than the wired case (Surprise!)
  - Media is infinite – can't always Carrier Sense
  - Nodes can't hear while sending – can't Collision Detect



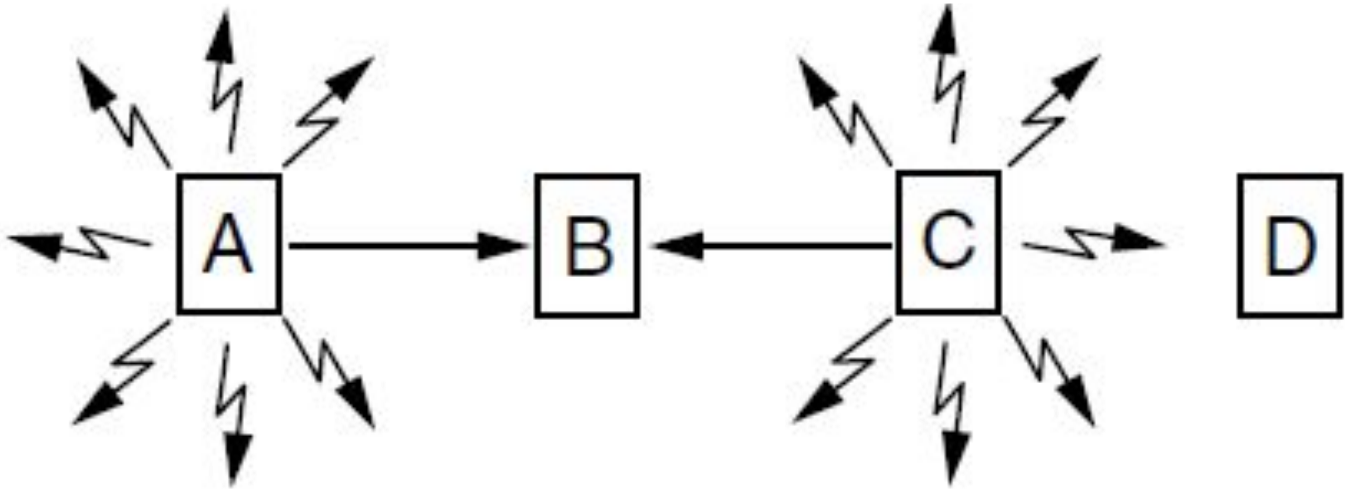
Limited CS: Different Coverage Areas

- Wireless signal is broadcast and received nearby, anywhere there is sufficient SNR



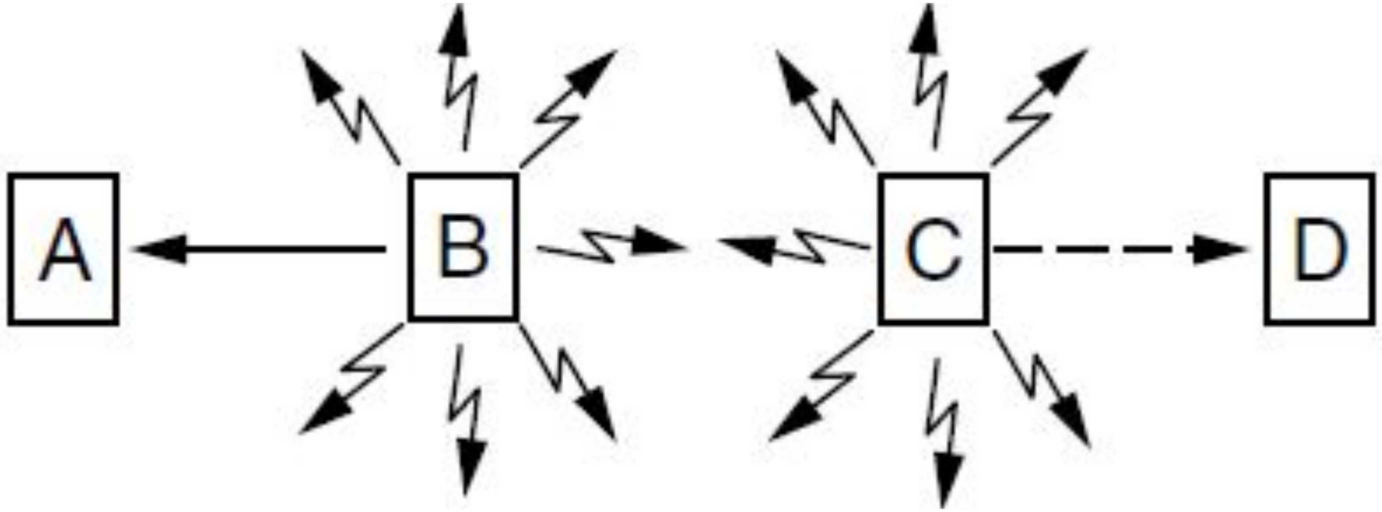
Limited CS: Hidden Terminals

- Nodes A and C are <u>hidden terminals</u> when sending to B
  - Can't hear each other (to coordinate) yet collide at B
  - We want to avoid the inefficiency of collisions



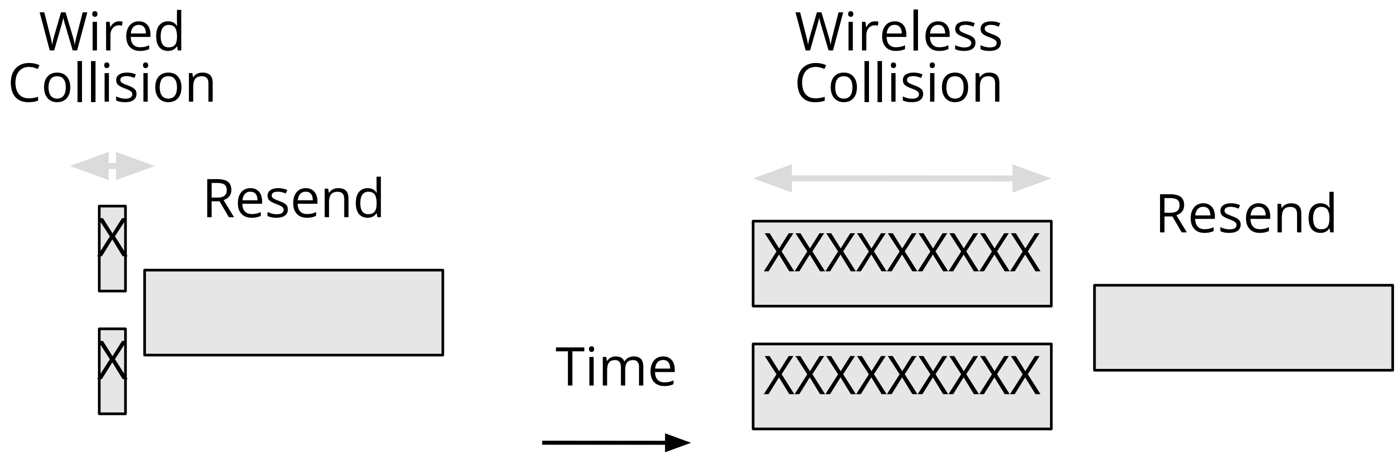
Limited CS: Exposed Terminals

- B and C are exposed terminals when sending to A and D
  - Can hear each other yet don't collide at receivers A and D
  - We want to send concurrently to increase performance



Nodes Can't Hear While Sending on the Same Frequency : (

- With wires, detecting collisions (and aborting) lowers their cost
- More wasted time with wireless



So Wireless Has Some Problems…

- Ideas?

Multiple Access with Collision Avoidance (MACA)

- MACA uses a short handshake instead of CSMA (Karn, 1990)
  - 802.11 WiFi uses a refinement of MACA (later)
  - Most modern wifi installations just tightly coordinate spectrum to avoid overlap

Protocol rules:

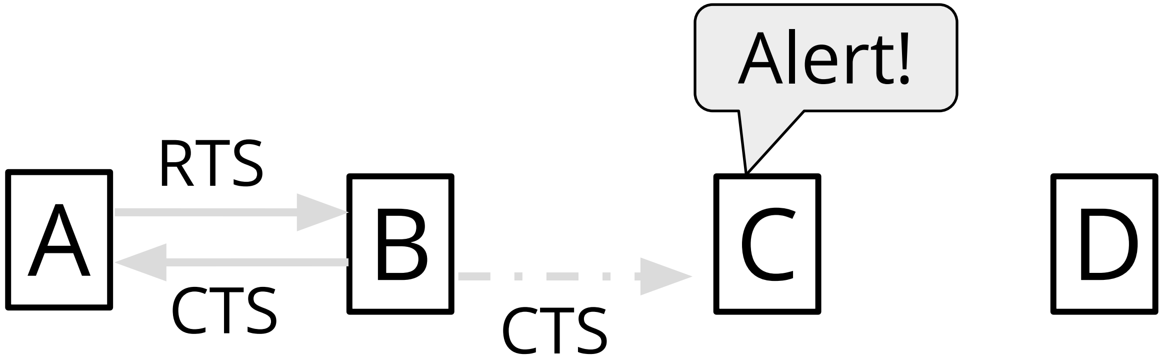
1. A sender node transmits a tiny RTS
   - (Request-To-Send, with frame length)
2. The receiver replies with a tiny CTS
   - (Clear-To-Send, with frame length)
3. Sender transmits the frame while *nodes hearing the CTS stay silent*
4. Collisions on the RTS/CTS are still possible, but less likely

MACA – Hidden Terminals

- A B with hidden terminal C
  1. A sends RTS, to B

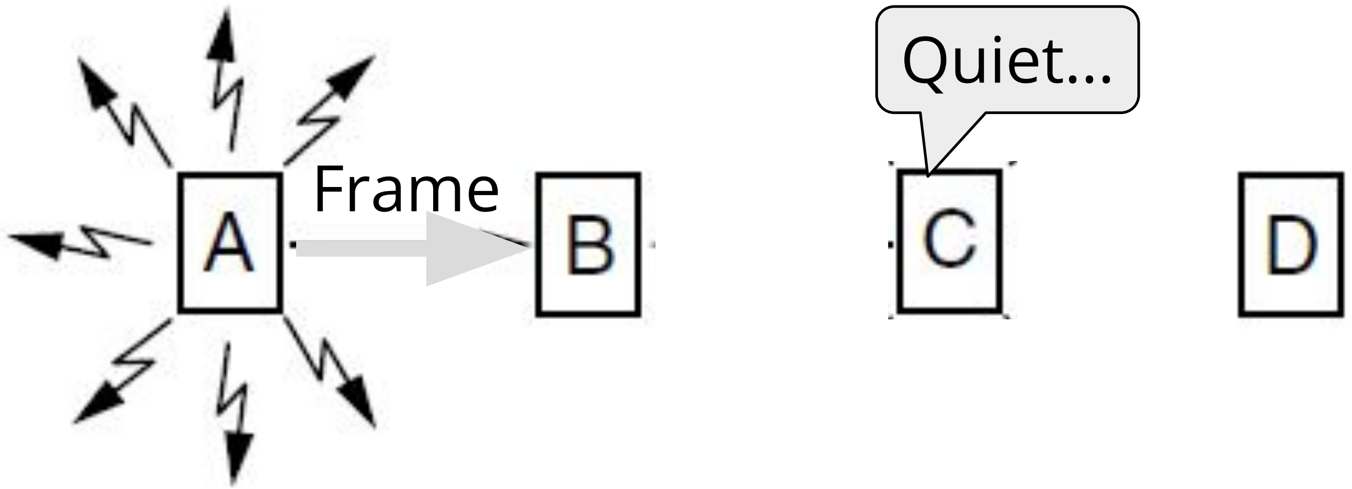
MACA – Hidden Terminals (2)

- A B with hidden terminal C
  1. A sends RTS, to B
  2. B sends CTS, to A, and C too



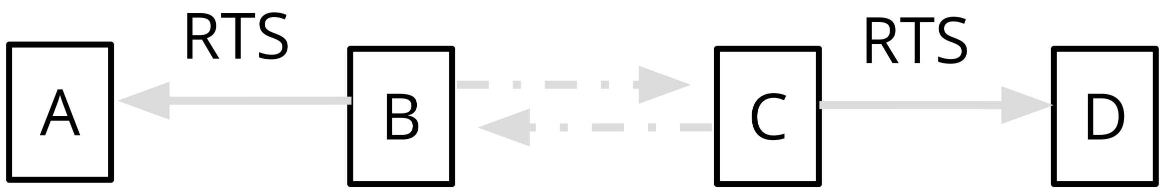
MACA – Hidden Terminals (3)

- A B with hidden terminal C
  1. A sends RTS, to B
  2. B sends CTS, to A, and C too
  3. A sends frame while C defers



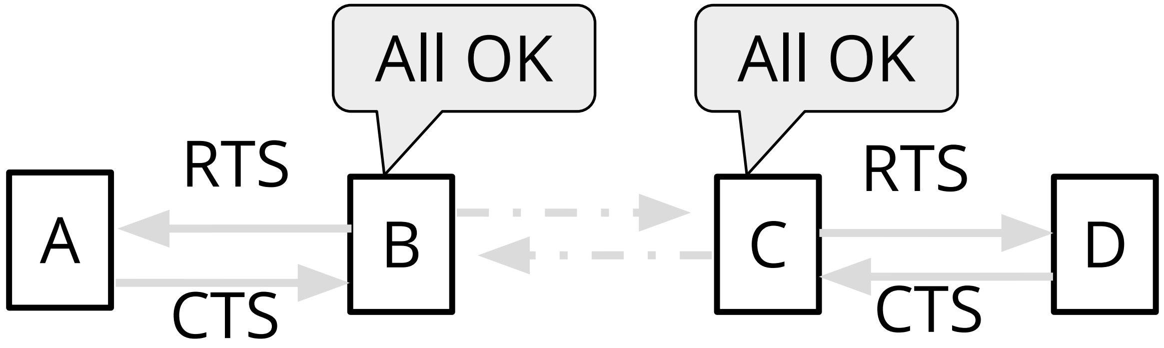
MACA – Exposed Terminals

- B A, C D as exposed terminals
  1. B and C send RTS to A and D
  2. A and D send CTS to B and C



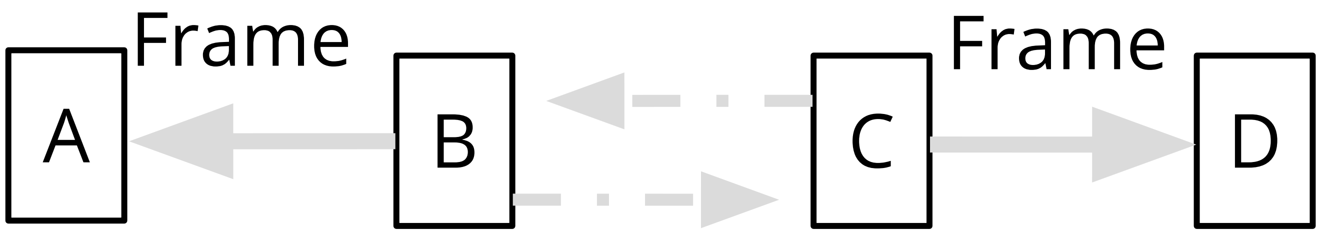
MACA – Exposed Terminals (2)

- B A, C D as exposed terminals
  1. B and C send RTS to A and D
  2. A and D send CTS to B and C



MACA – Exposed Terminals (3)

- B A, C D as exposed terminals
  1. B and C send RTS to A and D
  2. A and D send CTS to B and C
  3. B and C send Frame to A and D

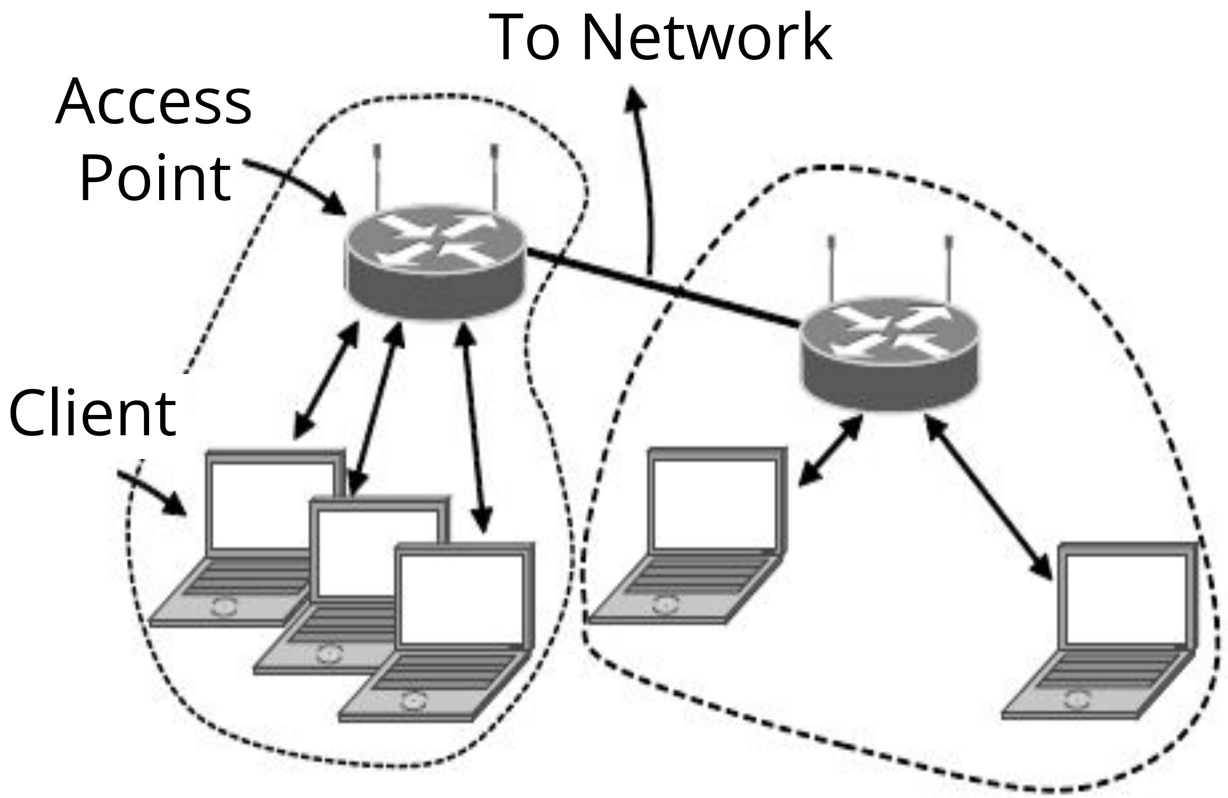


MACA

- Assumptions? Where does this break???
  - [3 minute breakouts]

802.11, or WiFi

- Very popular wireless LAN started in the 1990s
- Clients get connectivity from a (wired) AP (Access Point)
- It’s a multi-access problem
- Various flavors have been developed over time
  - Faster, more features



802.11 Physical Layer

- Uses 20/40/80/160 MHz channels on ISM (unlicensed) bands
  - 802.11b/g/n on 2.4 GHz
  - 802.11 a/n on 5 GHz
  - Wifi 6e on new 6GHz band (5.925-7.125)

- OFDM modulation (except legacy 802.11b)
  - Different “number of levels” and code rates for varying SNRs
  - 802.11n+ use multiple antennas (MIMO)
    - Lots of fun tricks here

802.11 Link Layer

"Listen before talk" (LBT) extension to CSMA. Conceptually similar to collision detection but best we can do in wireless.

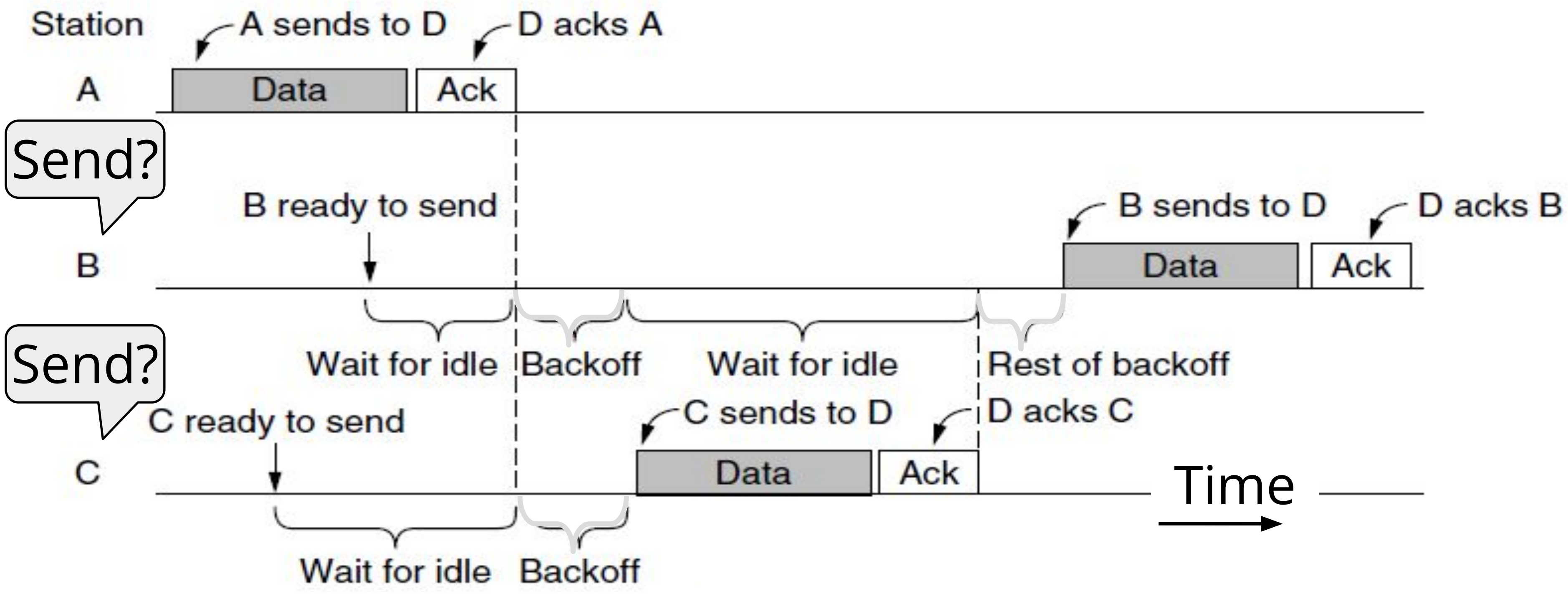
- Multiple access uses CSMA/CA; RTS/CTS optional
  - Frames are ACKed and retransmitted with ARQ (why?)
- Funky addressing (three addresses!) due to Access Point functionality
- Errors are detected with a 32-bit CRC
- Many, many features (e.g., encryption, power save)

Packet from Network layer (IP)

	Frame control	Duration	Address 1 (recipient)	Address 2 (transmitter)	Address 3	Sequence	Data	Check sequence
Bytes	2	2	6	6	6	2	0–2312	4

802.11 CSMA/CA for Multiple Access

- Still using BEB!



CSMA/CA and BEB can cause significant jitter

- Especially in crowded environments, *contention* can cause more of a problem with real-world performance than signal strength!
  - If your WiFi is unreliable in your apartment even though you have "5 bars"… contention is probably why

In general, petty tough to solve in a distributed setting : / … lots of heuristics, central coordination

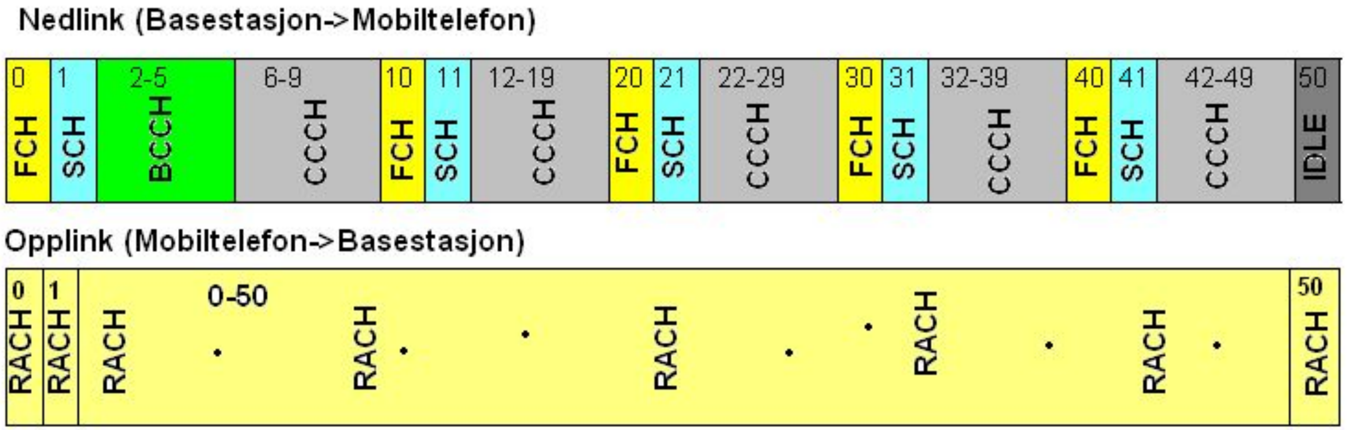
But mostly works "well enough" in practice!

A Centralized MAC: Traditional Cellular

- Spectrum suddenly very very scarce
  - We can’t waste all of it sending JAMs
- We have QoS requirements
  - Can’t be as loose with expectations
  - Can’t have traffic fail
- We also have client/server
  - Centralized control
  - Not peer-to-peer/decentralized
  - Basestation controls channel usage
  - Interference solved with legal system

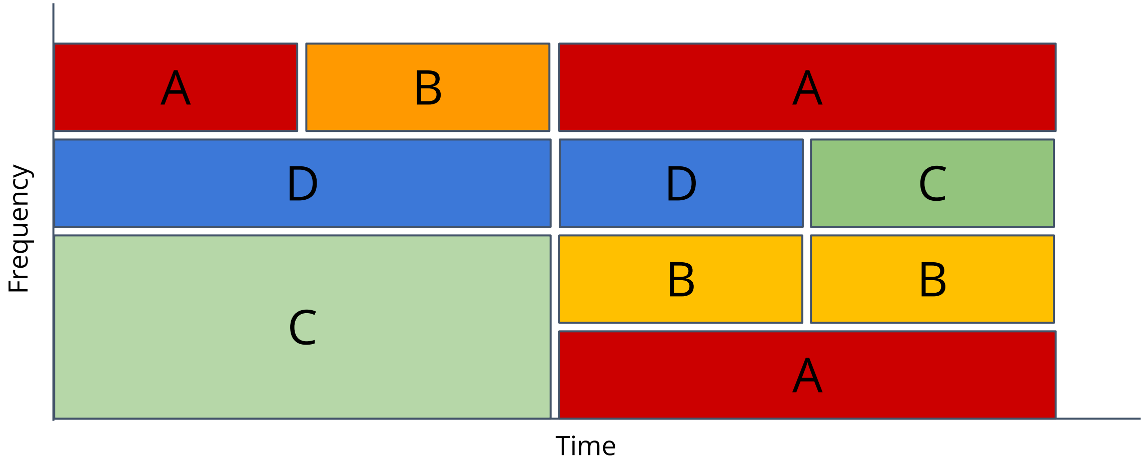
The GSM MAC

- Frequency division duplexing between Uplink/Downlink
  - TDMA within each channel for multiple users
- Use one channel for coordination
  - Random access w/BEB (no CSMA, can't detect)
- Use other channels for traffic
  - Dedicated channels for QoS



LTE/5G MAC

- Generalization of GSM system
- Centrally scheduled across time and frequency for multiple users by the basestation
  - QoS guarantees
- Can use Time Division or Frequency Division for UL/DL duplexing



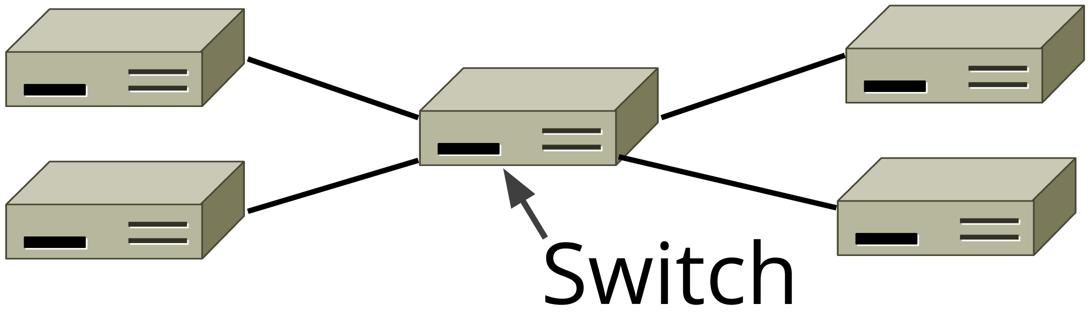
Alright, so we know how to mediate access to a shared link…

- but it was complicated
- and inefficient sometimes
- and led to jitter
- and meant only one person could use the medium at a time
- 😭

One last link layer trick: Switching

Switching as an alternative solution to multiple-access

- Connect nodes with a switch instead of multiple access
  - Uses multiple links/wires
  - Each node has a "dedicated line" to the switch
  - Basis of modern (switched) Ethernet



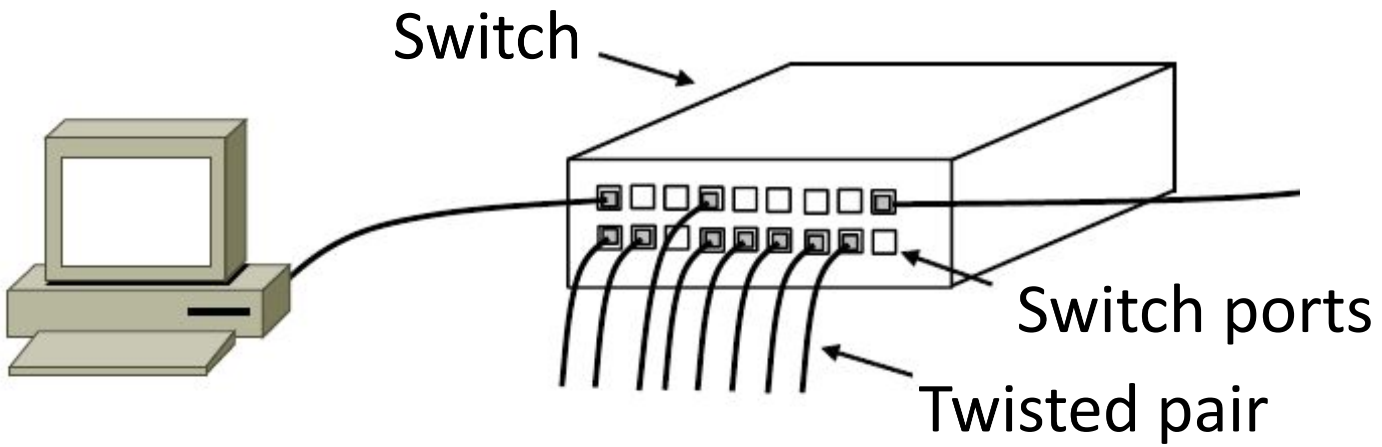
Advantages of Switches

- Switches and hubs (mostly switches) have replaced the shared cable of classic Ethernet
  - Convenient to run wires to one location
  - More reliable; wire cut is not a single point of failure that is hard to find

- Switches offer scalable performance
  - E.g., 100 Mbps **per port** instead of 100 Mbps for all nodes of shared cable / hub

Switched Ethernet

- Hosts are wired to Ethernet switches
  - Switch serves to connect the hosts
  - Wires usually run to a closet



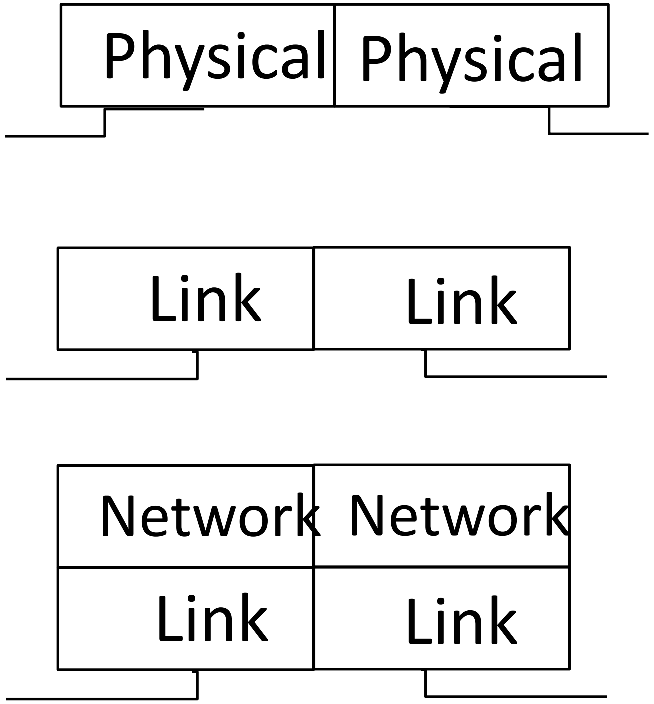
Aside: What's in the box?

- Many devices with multiple ethernet ports… not all are switches

Hub, or repeater

Switch

Router

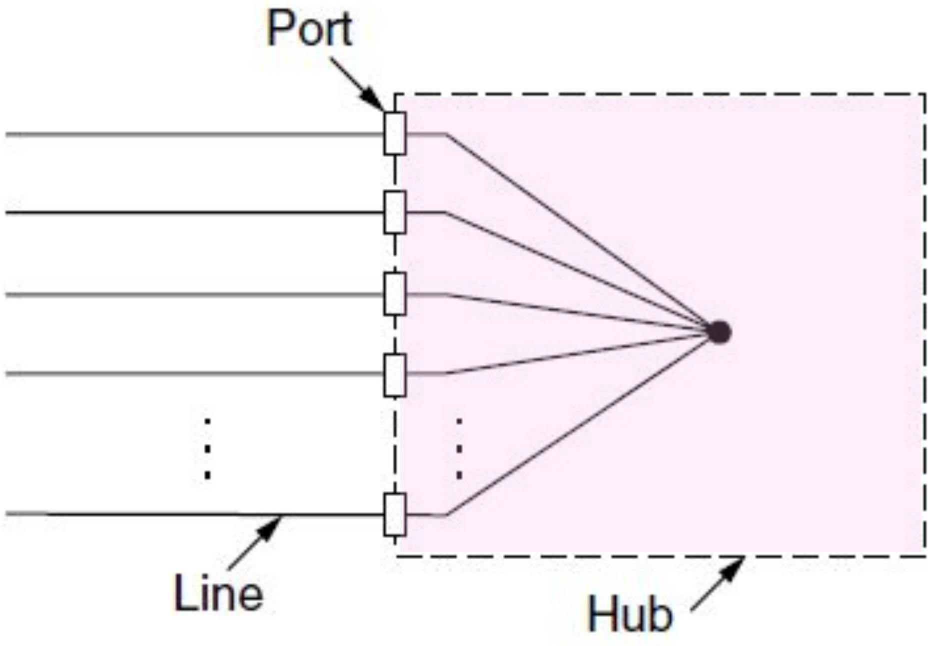


All look like this:

Programmable Switches can match and make decisions on arbitrary header fields, and can function as switches, routers, or other types of network hardware

Inside a Hub

- All ports are wired together; more convenient and reliable than a single shared wire



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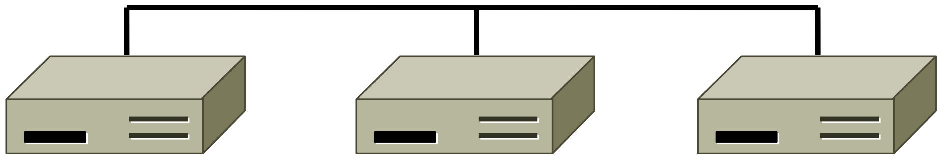
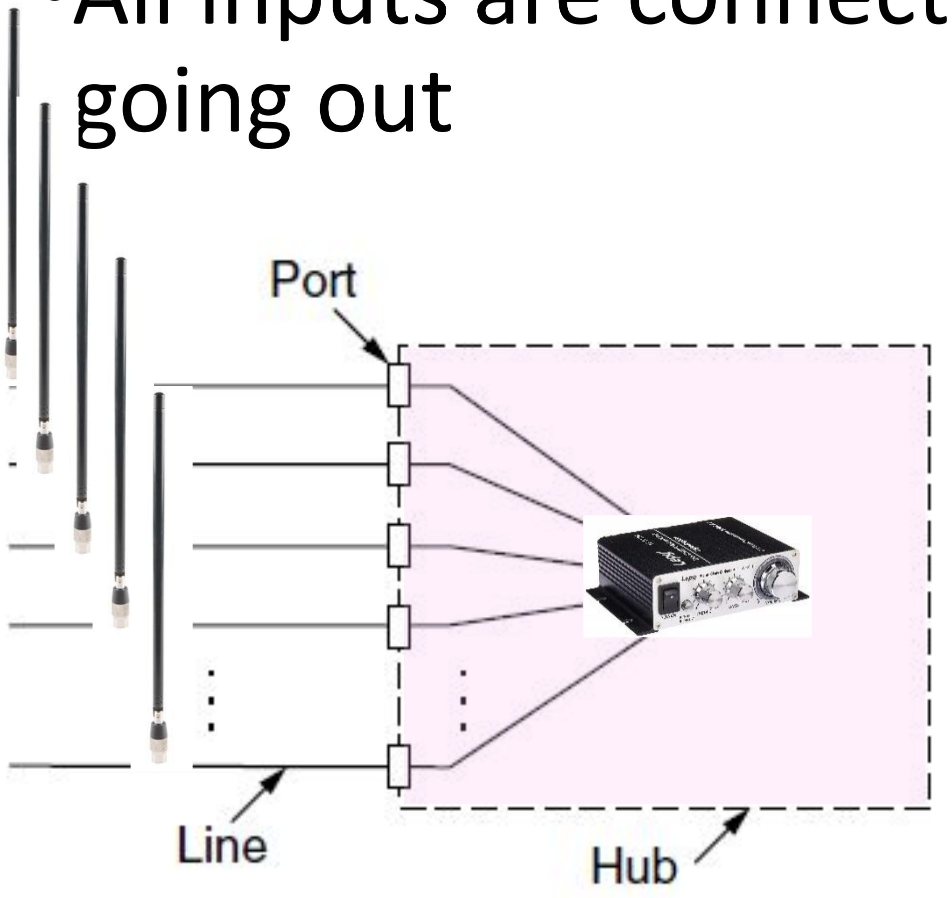
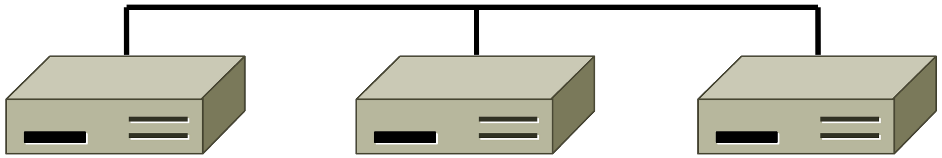


Inside a Repeater

- All inputs are connected; then amplified before going out

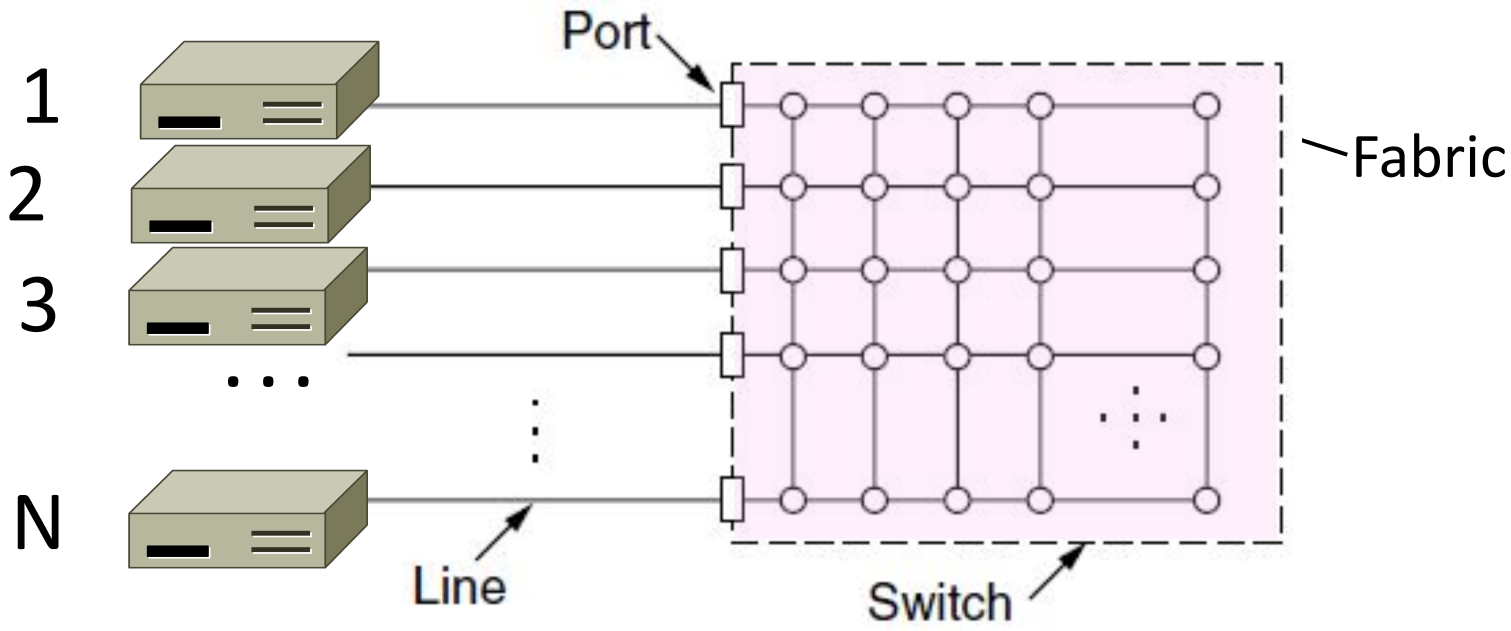


↔



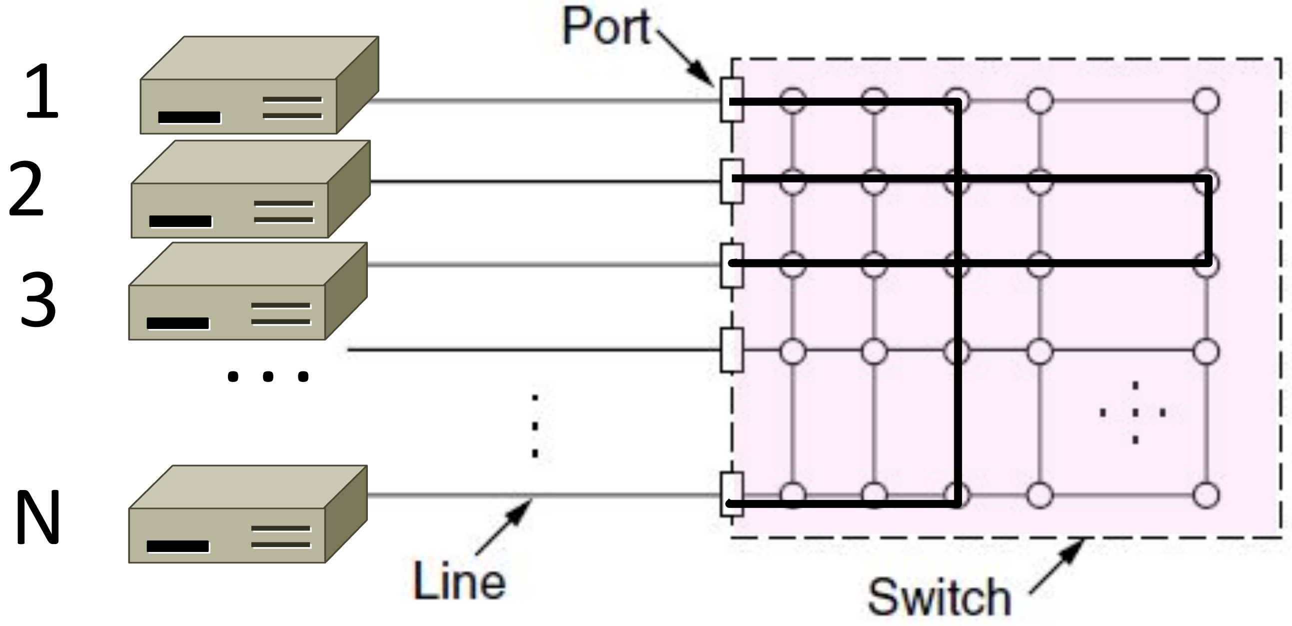
Inside a Switch

- Uses frame addresses (MAC addresses in Ethernet) to connect input port to the right output port; multiple frames may be switched in parallel



Inside a Switch (2)

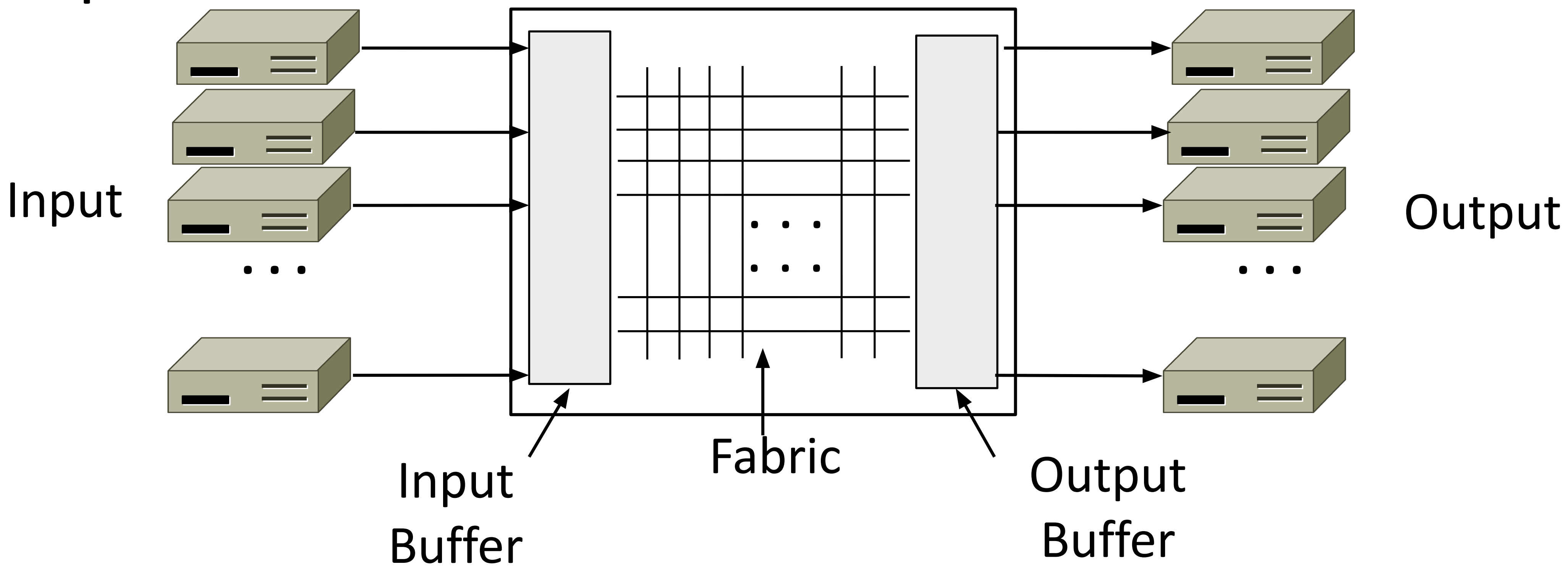
- Port may be used for both input and output (full-duplex)
  - Just send, no multiple access protocol (**Queues instead**)



1 → 4
and
2 → 3

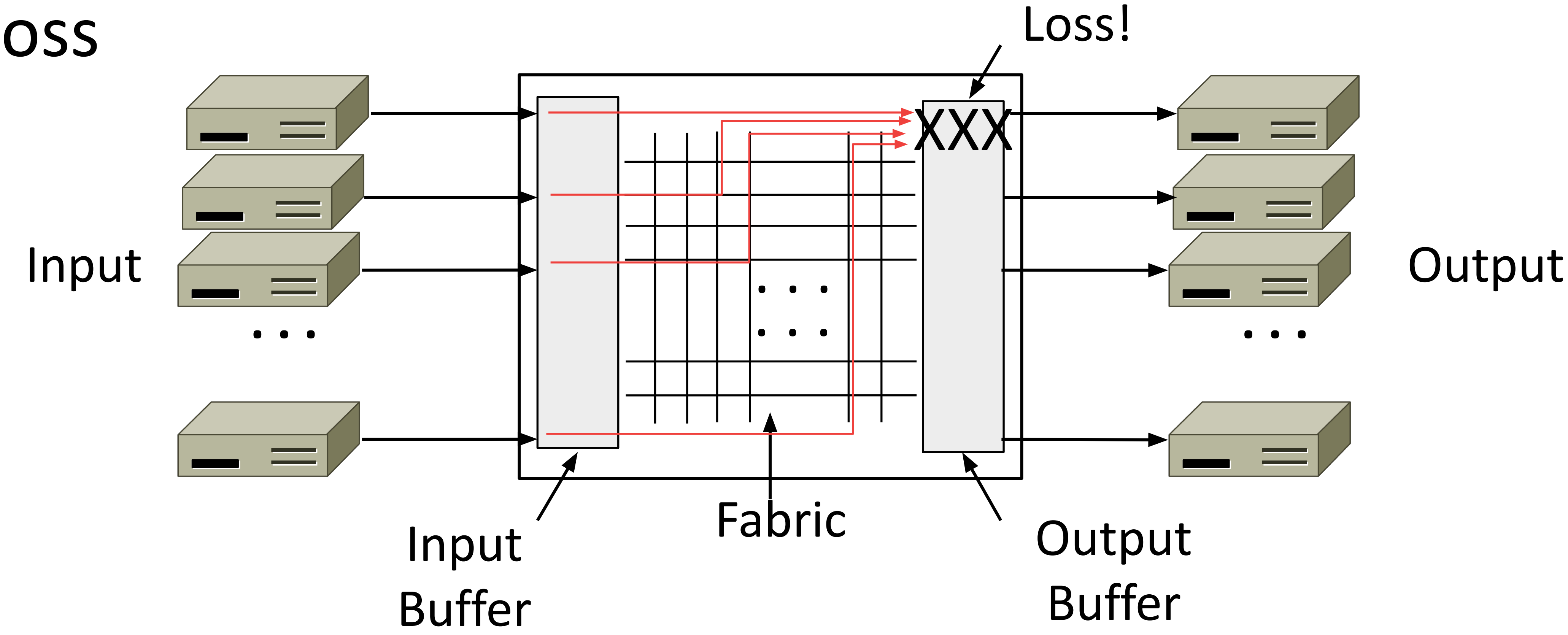
Inside a Switch (3)

- Need buffers for multiple inputs to send to one output



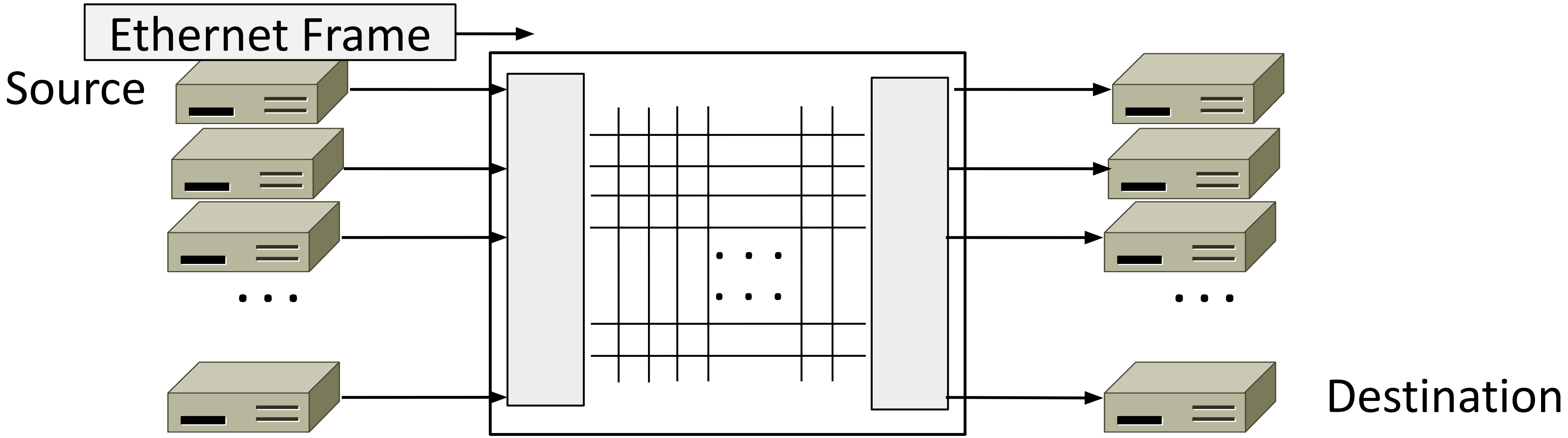
Inside a Switch (4)

- Sustained overload will fill buffer and lead to frame loss



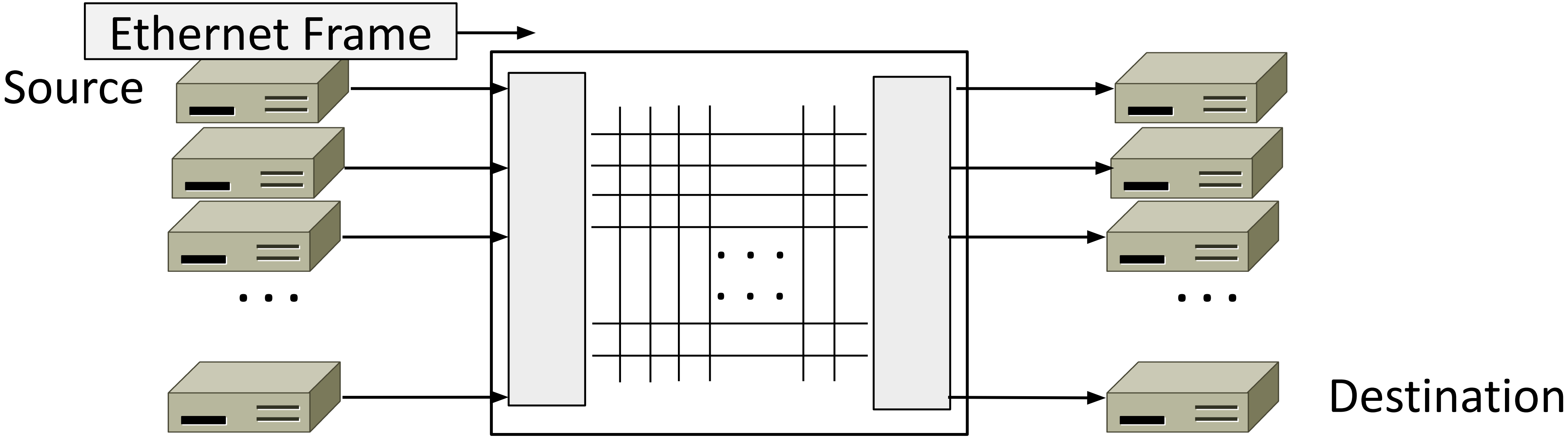
Switch Forwarding

- Switch needs to find the right output port for the destination address in the Ethernet frame. How?
  - Link-level, don’t look at IP



Switch Forwarding

- Ideas?

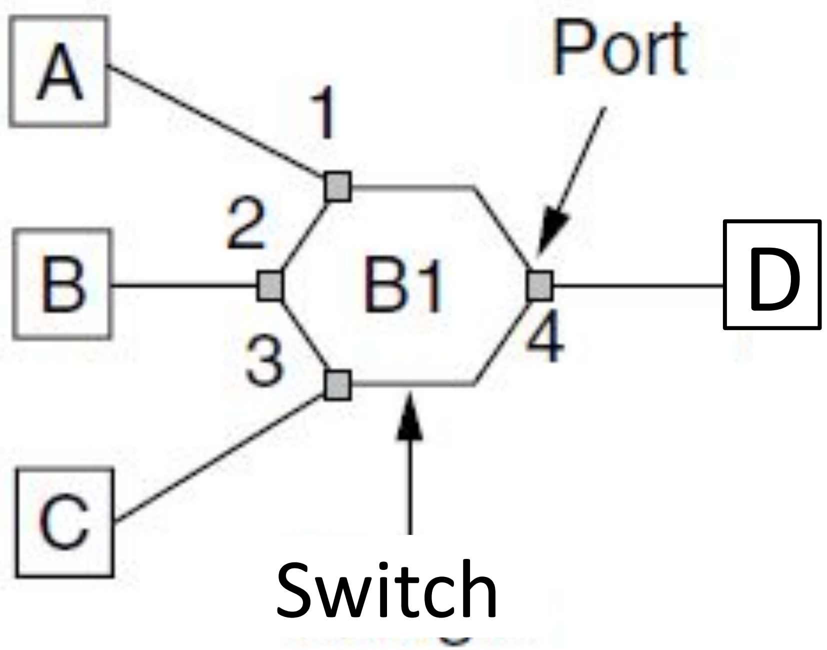


Backward Learning

- Switch forwards frames with a port/address table as follows:
  1. To fill the table, it looks at the source address of input frames
  2. To forward, it sends to the port, or else broadcasts to all ports

Backward Learning (2)

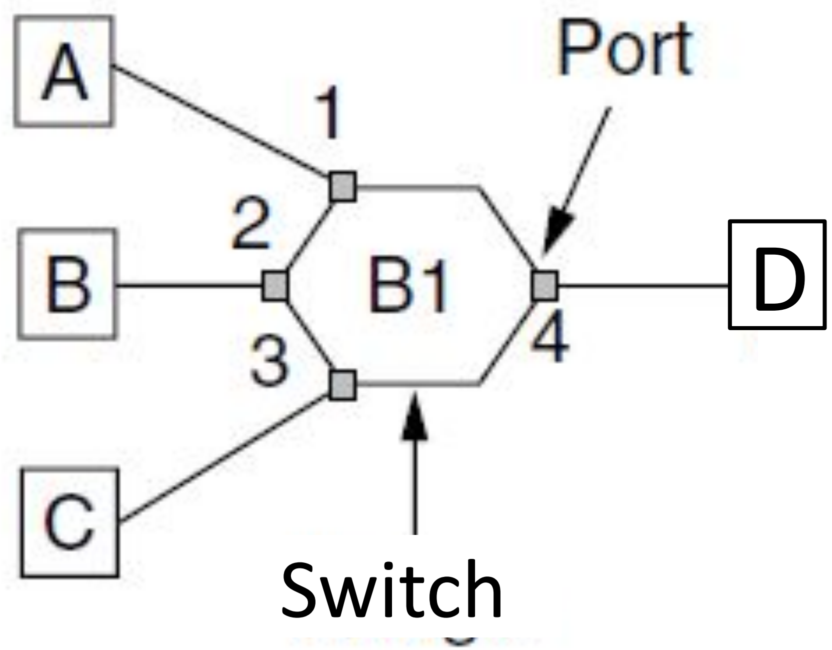
- 1: A sends to D



Address	Port
A	
B	
C	
D	

Backward Learning (3)

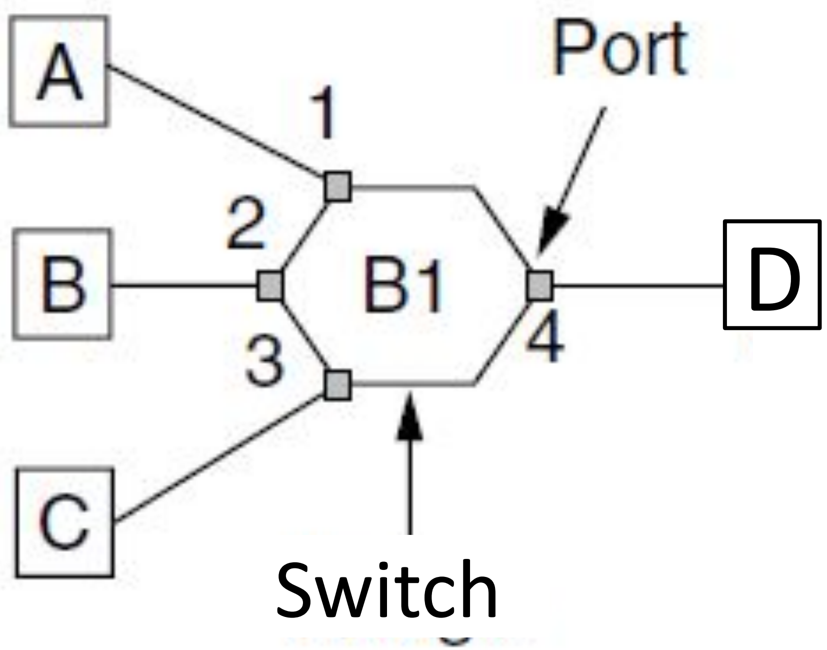
- 2: D sends to A



Address	Port
A	1
B	
C	
D	

Backward Learning (4)

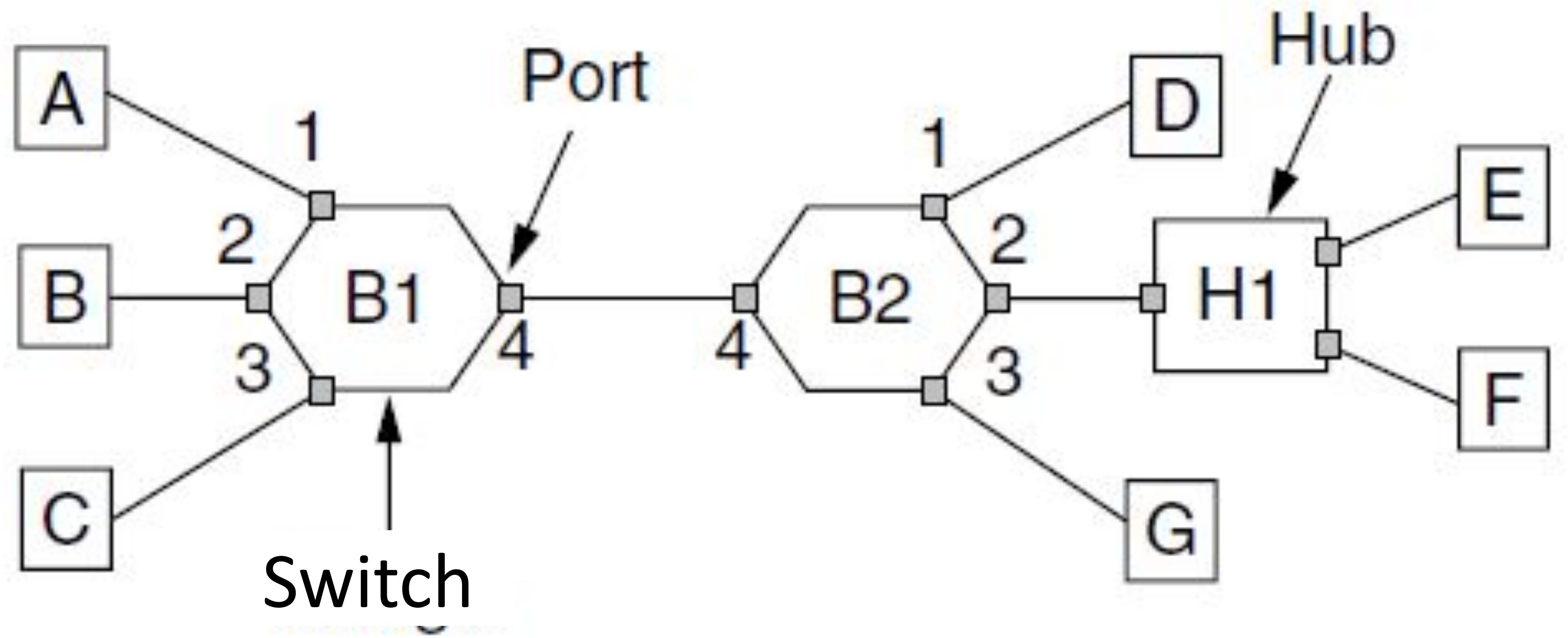
- 3: A sends to D



Address	Port
A	1
B	
C	
D	4

Learning with Multiple Switches

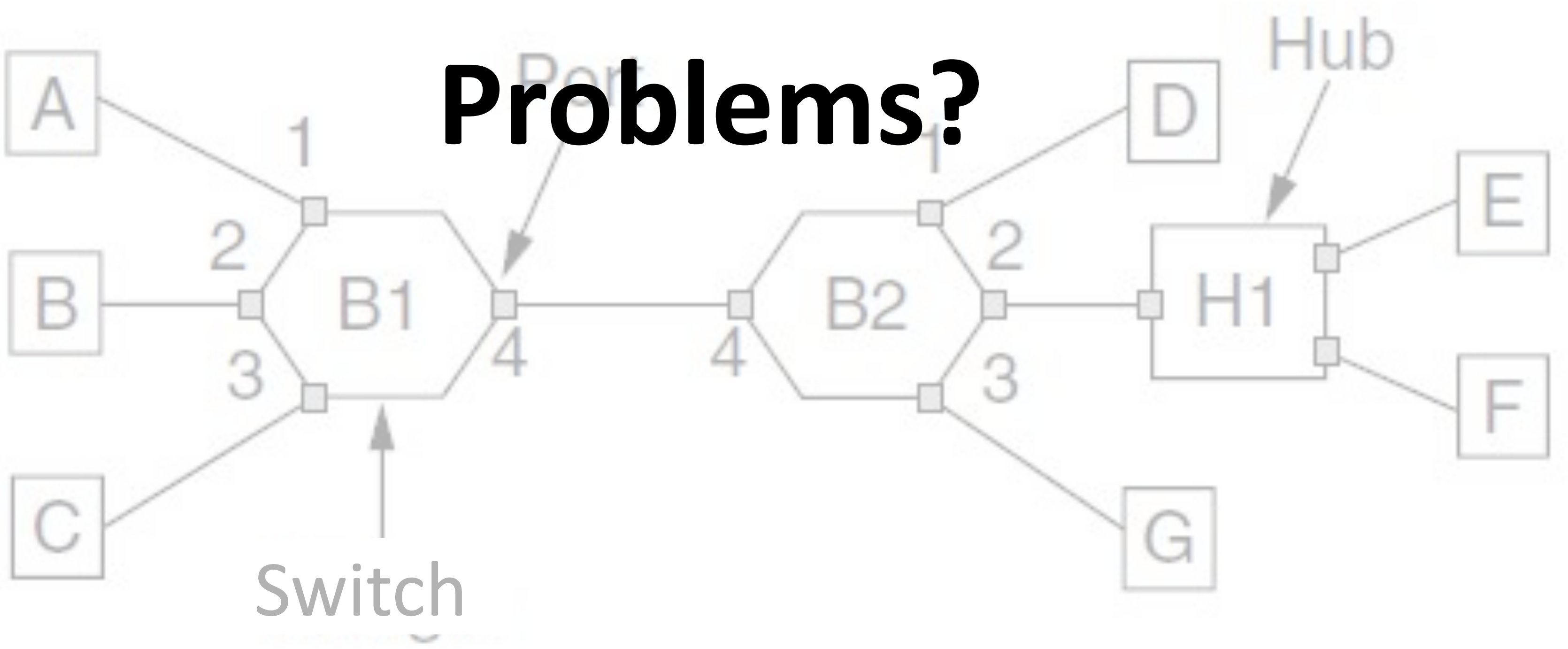
- Just works with multiple switches and a mix of hubs, e.g., A -> D then D -> A



Learning with Multiple Switches

- Just works with multiple switches and a mix of hubs, e.g., A -> D then D -> A

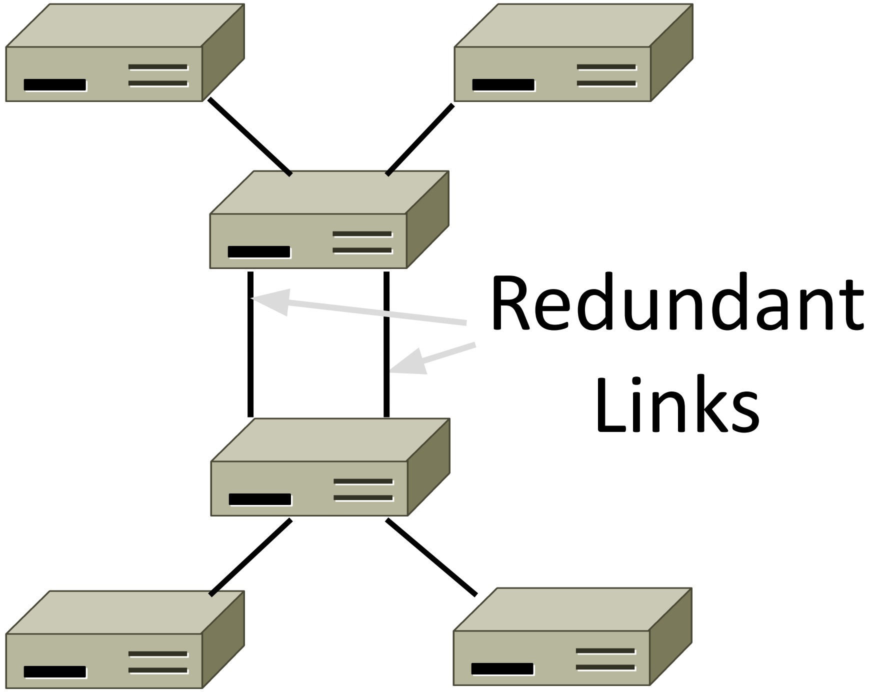
Problems?



Problem – Forwarding Loops

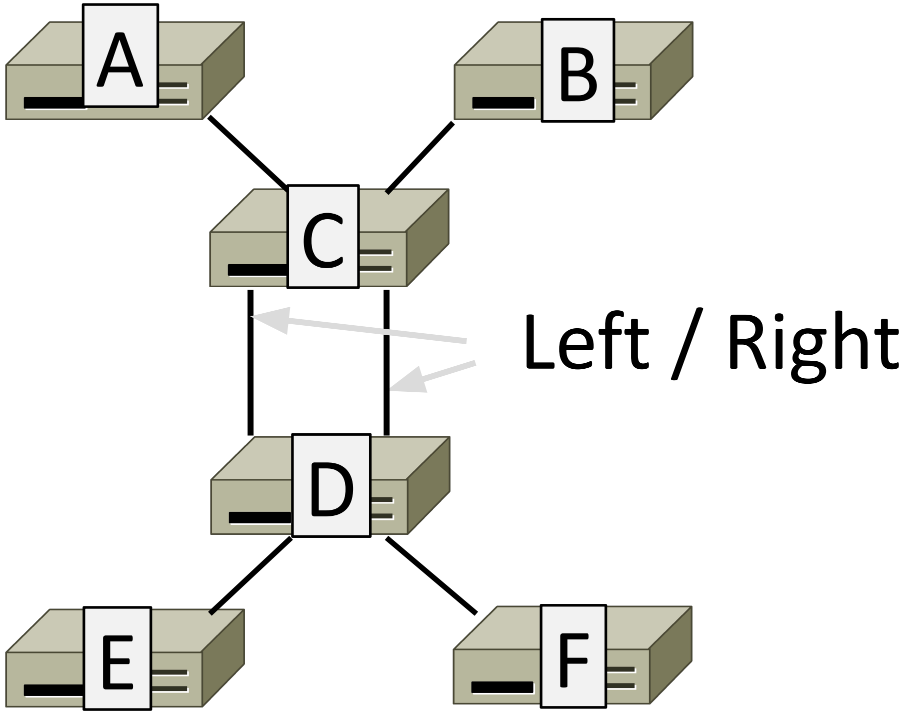
- May have a loop in the topology
  - Redundancy in case of failures
  - Or a simple mistake

- Want LAN switches to "just work"
  - Plug-and-play, no changes to hosts
  - But loops cause a problem …



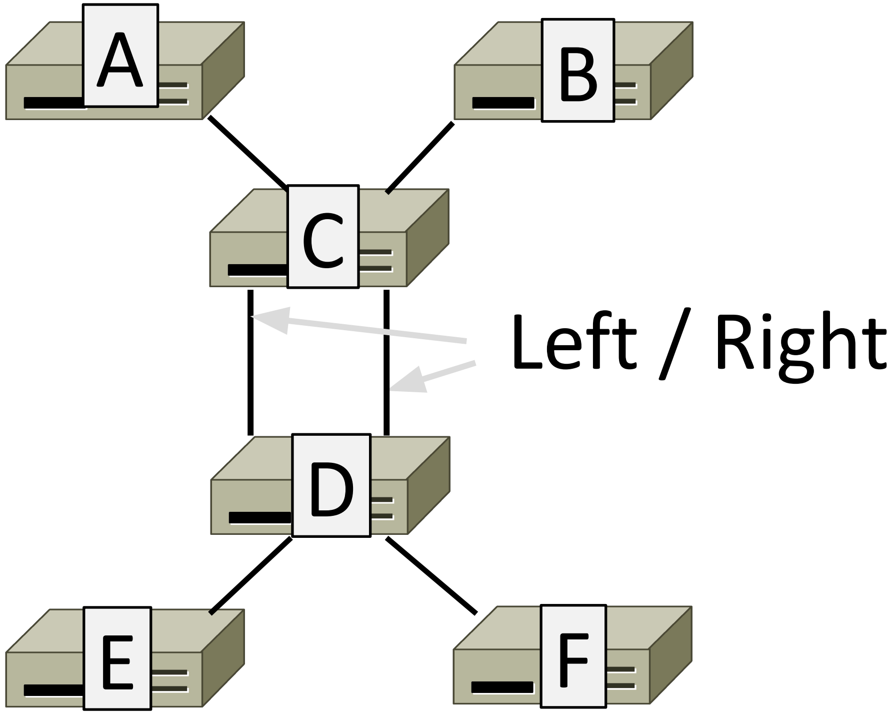
Forwarding Loops (2)

- Suppose the network is started and A sends to F. What happens?



Forwarding Loops (3)

- Suppose the network is started and A sends to F. What happens?
  - A → C → B, D-left, D-right
  - D-left → C-right, E, F
  - D-right → C-left, E, F
  - C-right → D-left, A, B
  - C-left → D-right, A, B
  - D-left → …
  - D-right → …

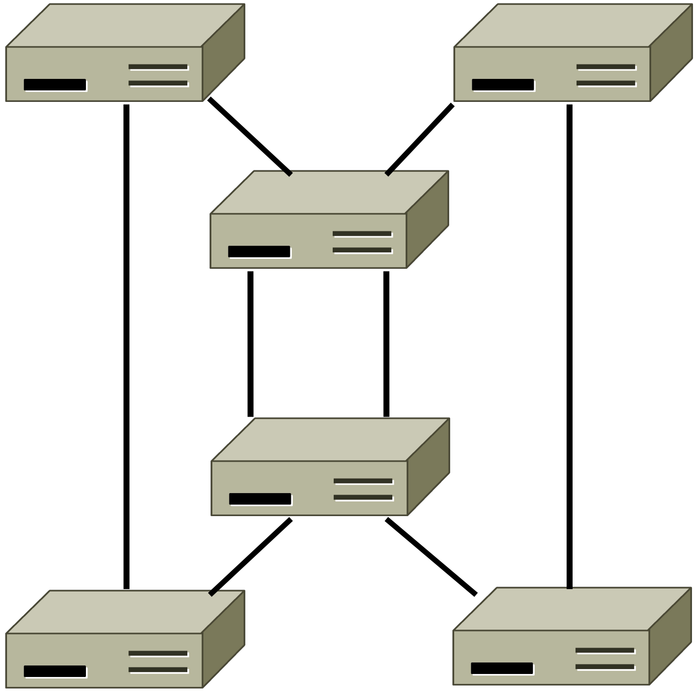


Spanning Tree Solution

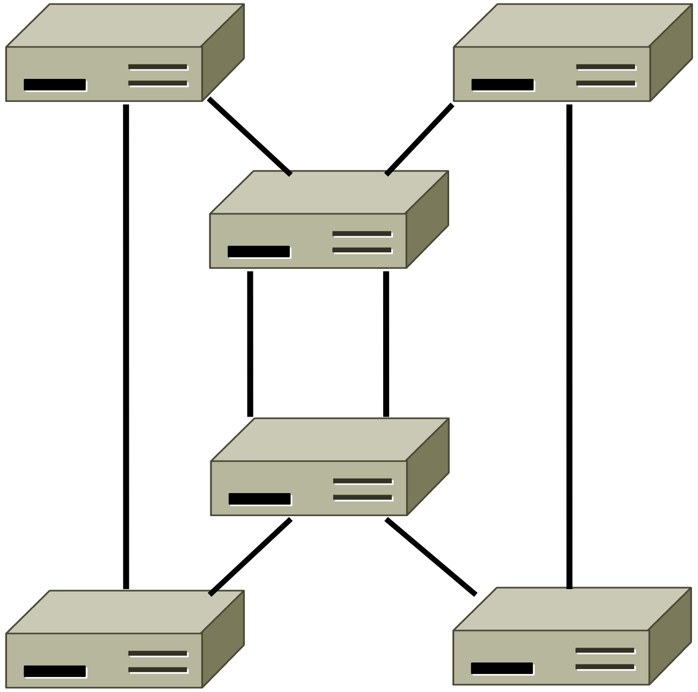
- Switches collectively find a spanning tree for the topology
  - A subset of links that is a tree (no loops) and reaches all switches
  - They switches forward as normal on the spanning tree
  - Broadcasts will go up to the root of the tree and down all the branches

Spanning Tree (2)

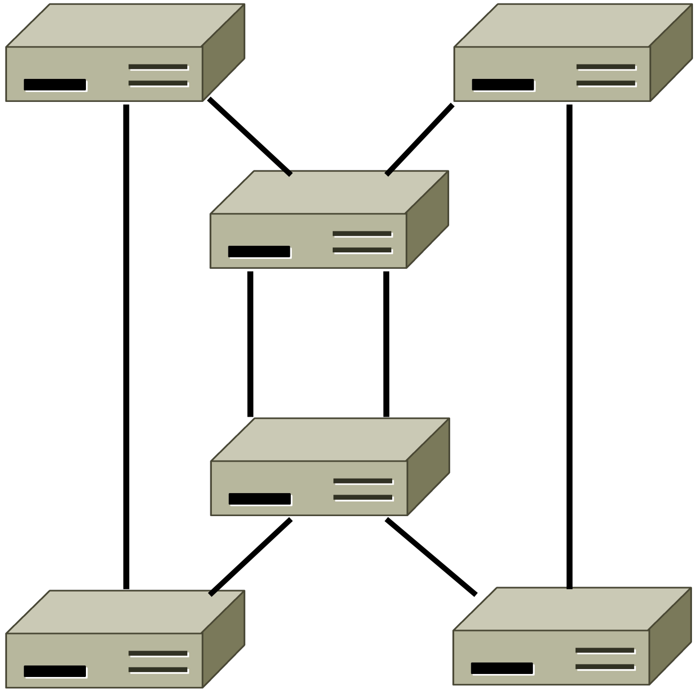
Topology



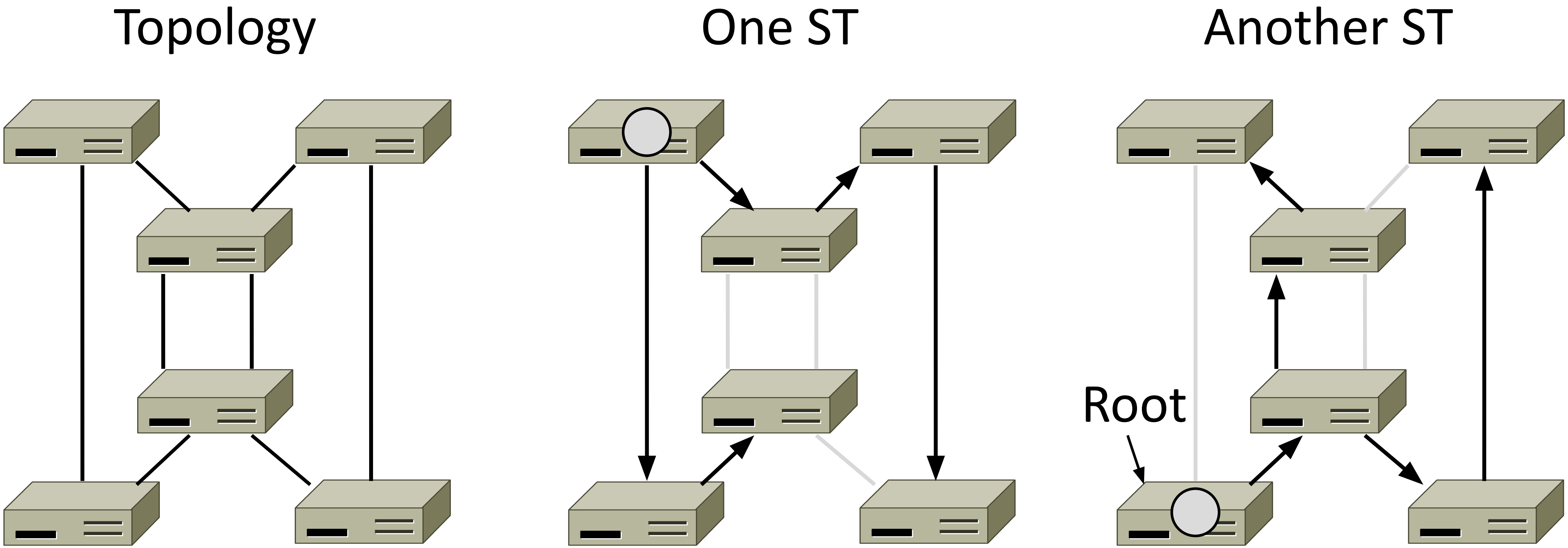
One ST



Another ST



Spanning Tree (3)



Spanning Tree Algorithm

- Rules of the distributed game:
  - All switches run the same algorithm
  - They start with no information
  - Operate in parallel and send messages
  - Always search for the best solution
- Ensures a highly robust solution
  - Any topology, with no configuration
  - Adapts to link/switch failures, …

Radia Perlman (1952–)

- Key early work on routing protocols
  - Routing in the ARPANET
  - Spanning Tree for switches (next)
  - Link-state routing (later)
  - Worked at Digital Equipment Corp (DEC)

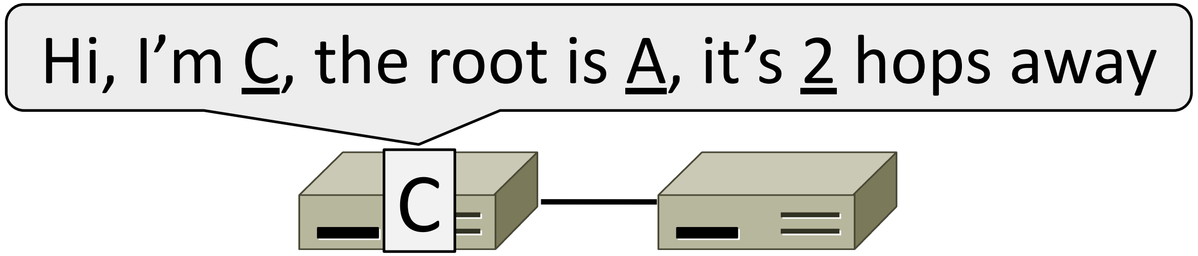
- Now focused on network security
  - Member of the Internet Hall of Fame
  - Previously has taught class at UW!

Spanning Tree Algorithm (2)

- Outline:
  1. Elect a root node of the tree (switch with the lowest address)
  2. Grow tree as shortest distances from the root (using lowest address to break distance ties)
  3. Turn off ports for forwarding if they aren't on the spanning tree

Spanning Tree Algorithm (3)

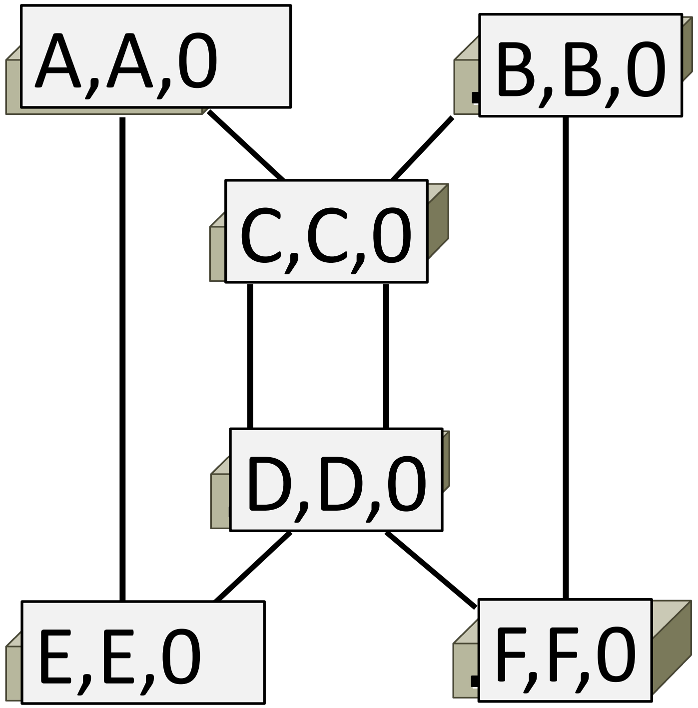
- Details:
  - Each switch initially believes it is the root of the tree
  - Each switch sends periodic updates to neighbors with:
    - Its address, address of the root, and distance (in hops) to root
    - Short-circuit when topology changes
  - Switches favors ports with shorter distances to lowest root
    - Uses lowest address as a tie for distances



or (C, A, 2)

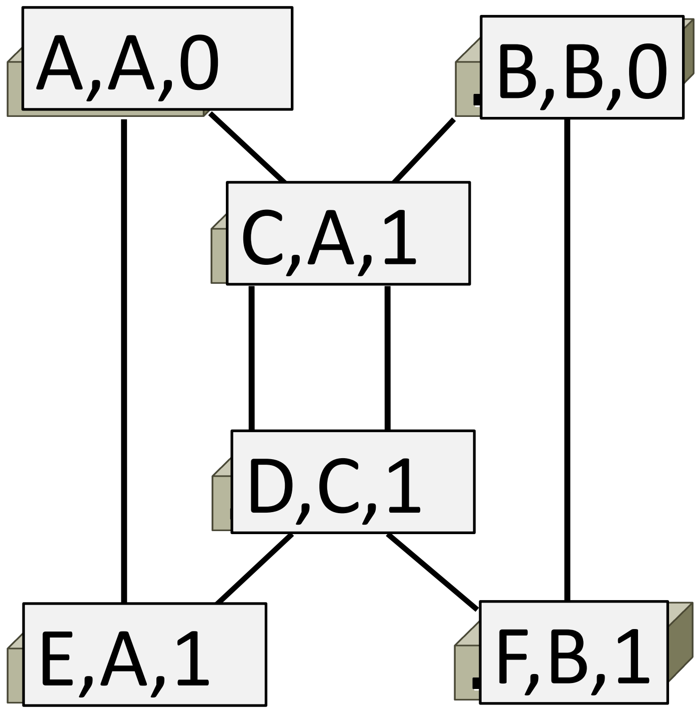
Spanning Tree Example

- 1^{st} round, sending:
  - A sends (A, A, 0) to say it is root
  - B, C, D, E, and F do likewise
- 1^{st} round, receiving:
  - A still thinks is it (A, A, 0)
  - B still thinks (B, B, 0)
  - C updates to (C, A, 1)
  - D updates to (D, C, 1)
  - E updates to (E, A, 1)
  - F updates to (F, B, 1)



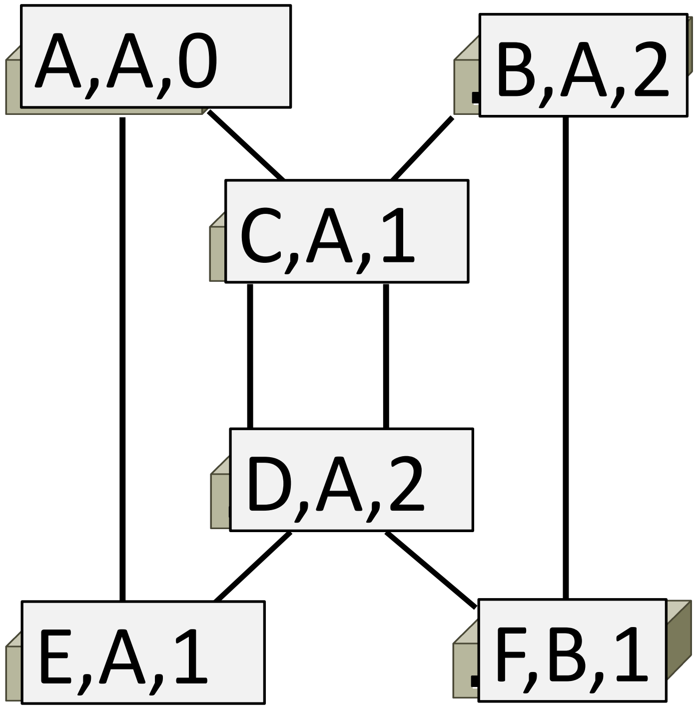
Spanning Tree Example (2)

- 2nd round, sending
  - Nodes send their updated state
- 2nd round receiving:
  - A remains (A, A, 0)
  - B updates to (B, A, 2) via C
  - C remains (C, A, 1)
  - D updates to (D, A, 2) via C
  - E remains (E, A, 1)
  - F remains (F, B, 1)



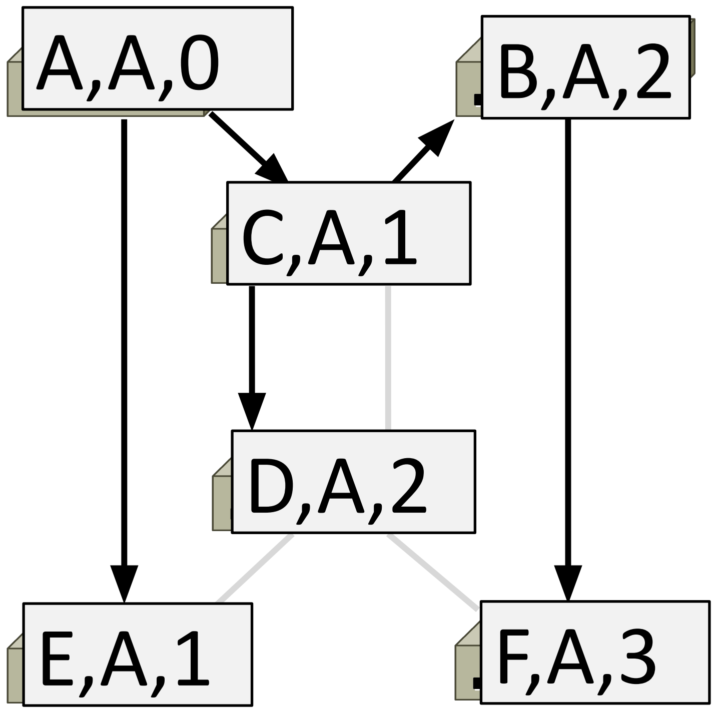
Spanning Tree Example (3)

- 3rd round, sending
  - Nodes send their updated state
- 3rd round receiving:
  - A remains (A, A, 0)
  - B remains (B, A, 2) via C
  - C remains (C, A, 1)
  - D remains (D, A, 2) via C-left
  - E remains (E, A, 1)
  - F updates to (F, A, 3) via B



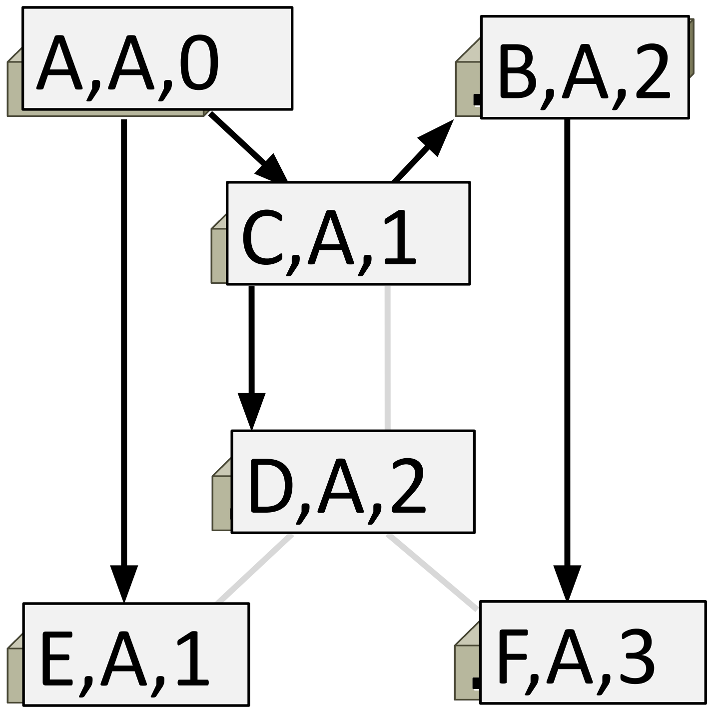
Spanning Tree Example (4)

- 4th round
  - Steady-state has been reached
  - Nodes turn off forwarding that is not on the spanning tree
- Algorithm continues to run
  - Adapts by timing out information
  - E.g., if A fails, other nodes forget it, and B will become the new root



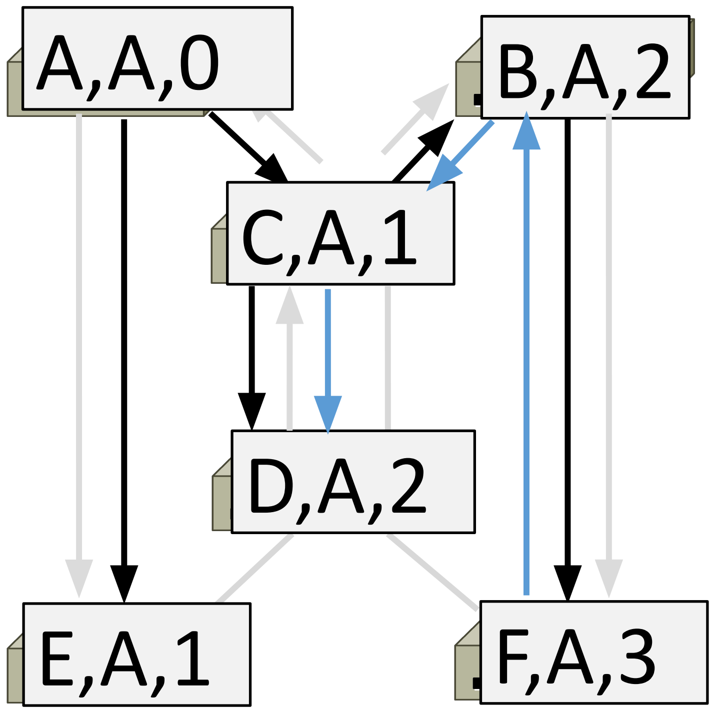
Spanning Tree Example (5)

- Forwarding proceeds as usual on the ST
- Initially D sends to F:
- And F sends back to D:



Spanning Tree Example (6)

- Forwarding proceeds as usual on the ST
- Initially D sends to F:
  - D → C-left
  - C → A, B
  - A → E
  - B → F
- And F sends back to D:
  - F → B
  - B → C
  - C → D



Algorhyme

I think that I shall never see
A graph more lovely than a tree.

A tree whose crucial property
Is loop-free connectivity.

A tree which must be sure to span
So packets can reach every LAN.

First the root must be selected.
By ID it is elected.

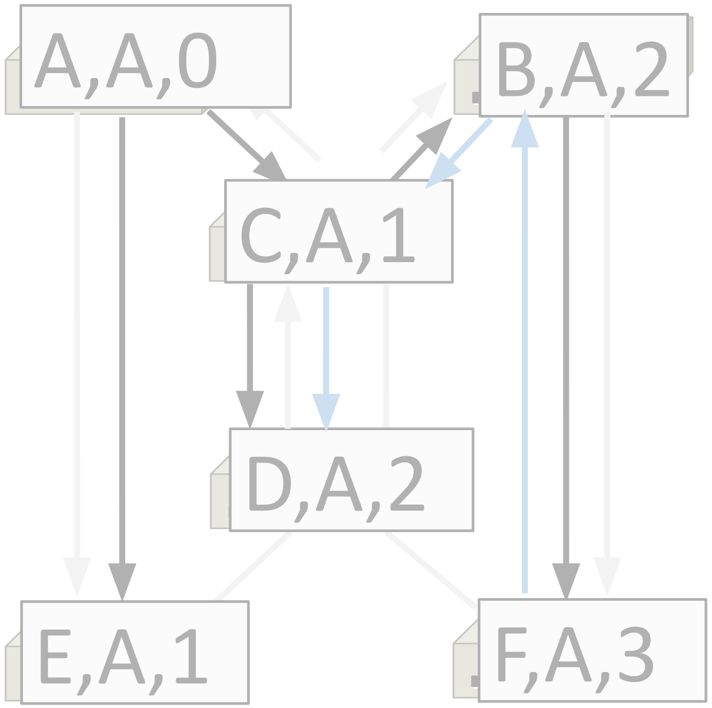
Least cost paths from root are traced.
In the tree these paths are placed.

A mesh is made by folks like me
Then bridges find a spanning tree.

Spanning Tree Example (6)

- Forwarding proceeds as usual on the ST
- Initially D sends to F:
  - D ⟶ C-left
  - C ⟶ A, B
  - A ⟶ E
  - B ⟶ F
- And F sends back to D:
  - F ⟶ B
  - B ⟶ C
  - C ⟶ D

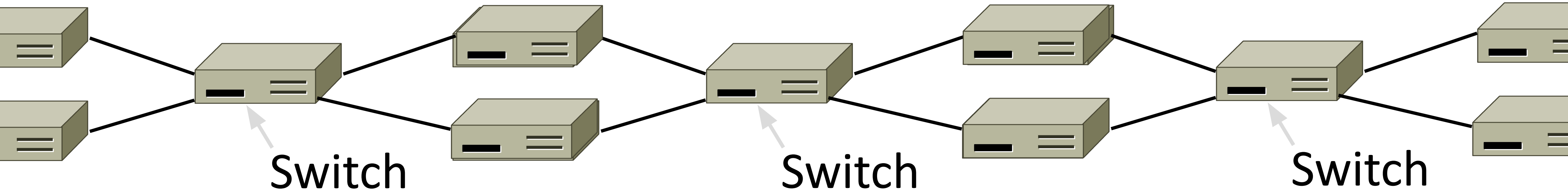
Problems?



Link++ Layer: Software Defined Networking

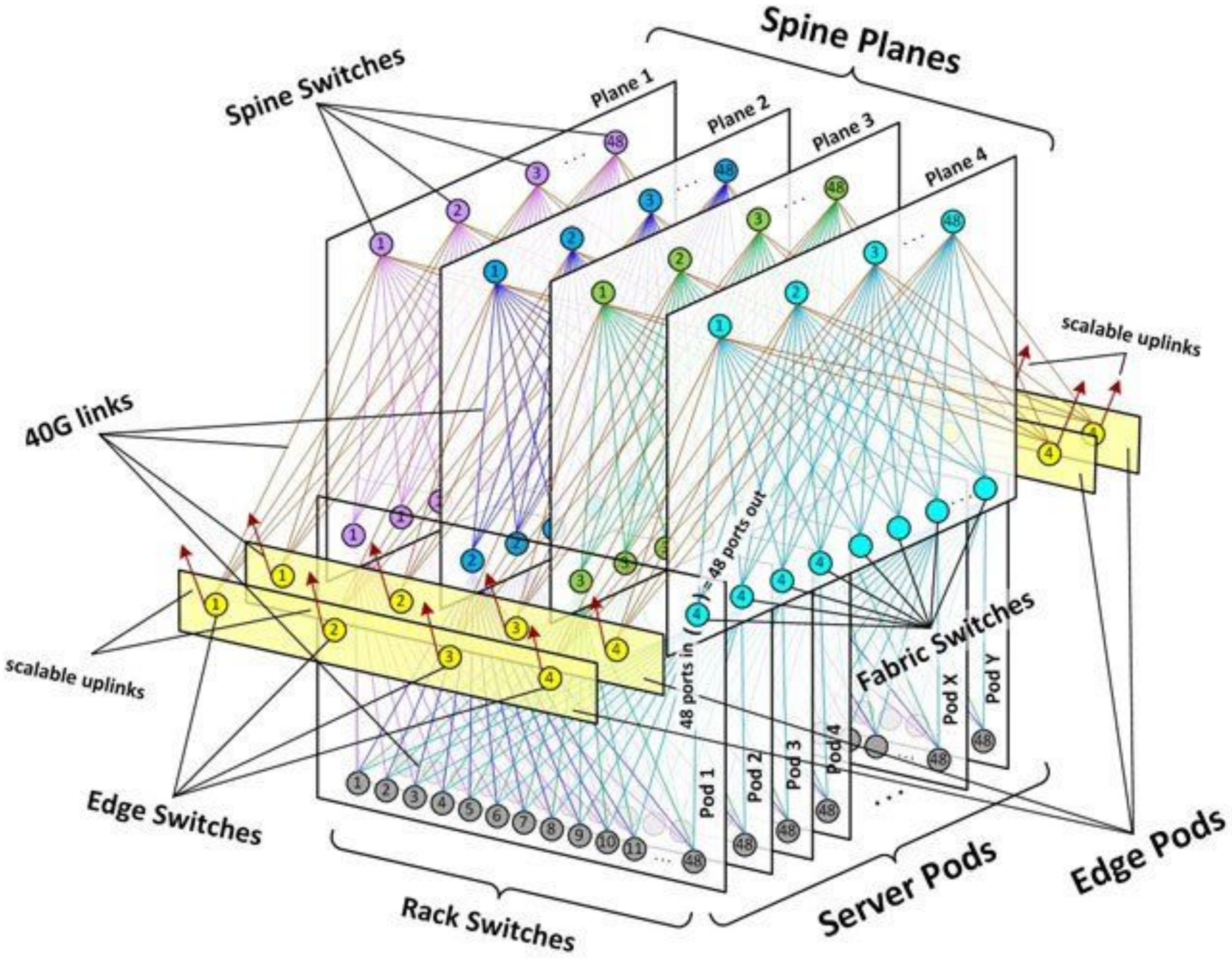
Topic

- How do we scale these networks up?
  - Answer 1: Network of networks, a.k.a. The Internet
  - Answer 2: Ah, just kinda hope spanning tree works?



Rise of the Datacenter

Datacenter Networking



Scaling the Link Layer

- Fundamentally, it's hard to scale distributed algorithms
  - Exacerbated when failures become common
  - Nodes go down, gotta run spanning tree again…
    - If nodes go down faster than spanning tree resolves, we get race conditions
    - If they don't, we may still be losing paths and wasting resources

- Ideas?

Software Defined Networking (SDN)

- Core idea: **stop being a distributed system**
  - Centralize the operation of the network
    - Create a “controller” that manages the network
  - Push new code, state, and configuration from “controller” to switches
    - Run link state with a global view of the network rather than in a distributed fashion.
    - Allows for “global” policies to be enforced.
    - Can resolve failures in more robust, faster manners

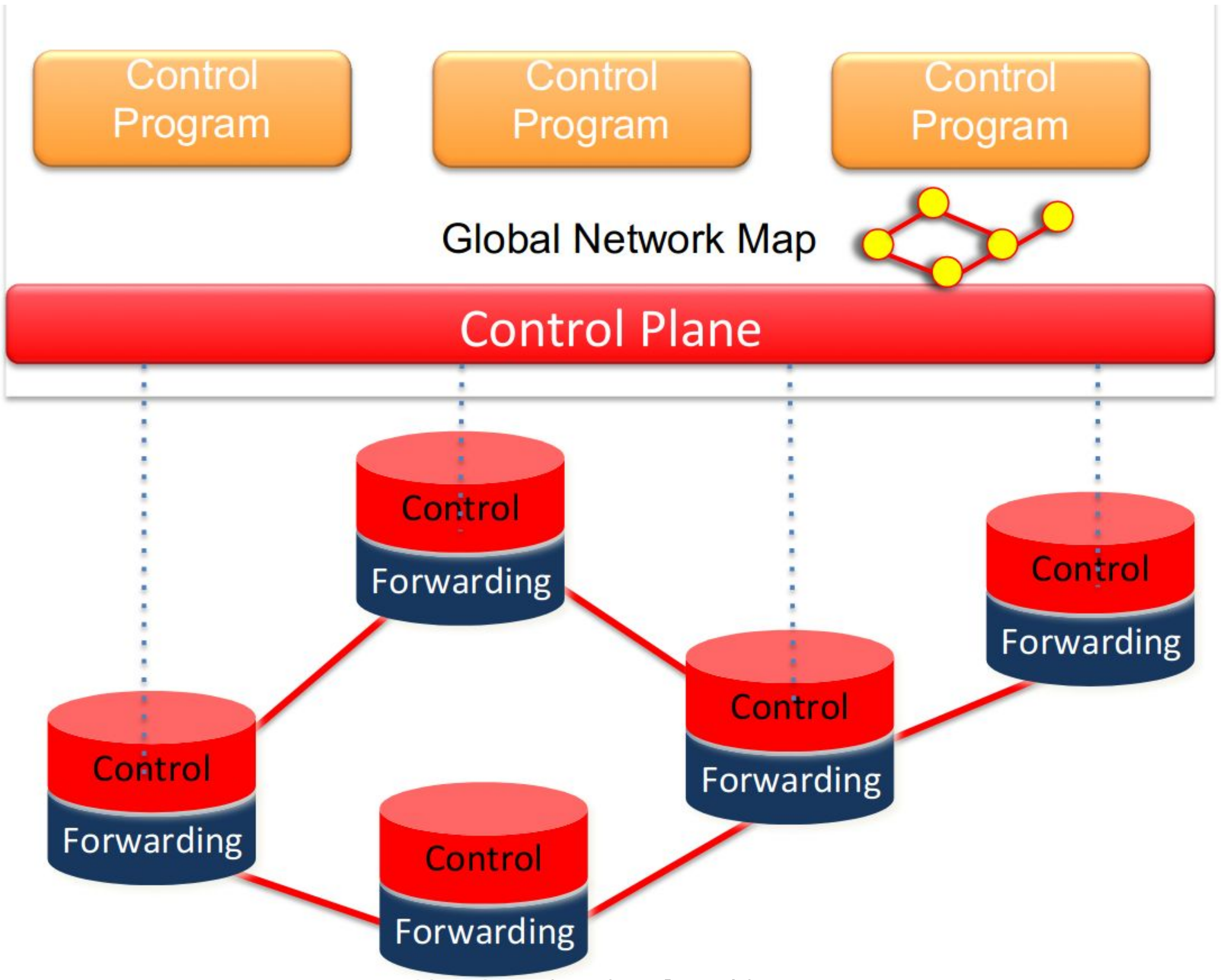
    - **Problems?**

SDN – Problem 1

- Problem: How do we talk to the switches if there's no network?
  - Seems a little chicken-and-egg
  - Nodes go down, gotta run spanning tree again…
    - If nodes go down faster than spanning tree resolves, we get race conditions
    - If they don't, we may still be losing paths and wasting resources

- Ideas?

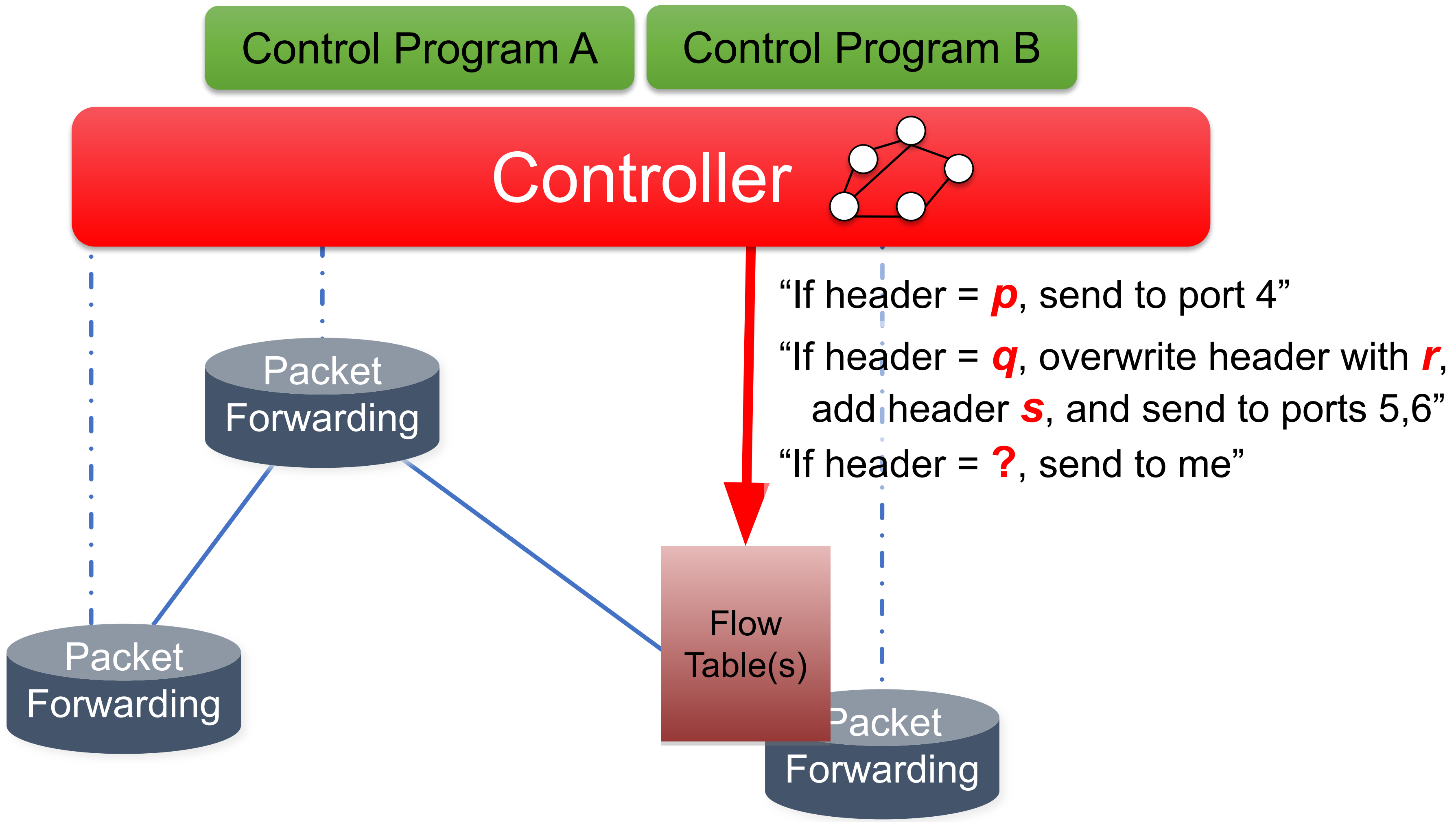
SDN – Control and Data Planes



SDN – Problem 2

- Problem: How do we efficiently run algorithms on switches?
  - These are extremely time-sensitive boxes
    - Gotta move the packets!
    - Need to be able to support
      - Fast packet handling
      - Quick route changes
      - Long-term policy updates
- Ideas?

SDN – OpenFlow



SDN – OpenFlow

- Two different classes of programmability
- At Controller
  - Can be heavy processing algorithms
  - Results in messages that update switch flow table
- At switch
  - Local flow table
  - Built from basic set of networking primitives
  - Allows for fast operation

SDN – Timescales

	Data	Control	Management
Time-scale	Packet (nsec)	Event (10 msec to sec)	Human (min to hours)
Location	Linecard hardware	Router software	Humans or scripts

SDN – Key outputs

- Simplify network design and implementation?
  - Sorta. Kinda pushed the complexity around if anything
- However...
  - Does enable code reuse and libraries
  - Does standardize and simplify deployment of rules to switches
  - Allows for fast operation

Access Networks

How networks cover wide areas?

- Access networks have different properties than in-office or in-datacenter networks
- Need to optimize the tradeoff between many dimensions:
  - Cost
  - Performance
  - Range
  - # of serviceable users
  - Maintainability
  - Regulation

The specific media impacts design

[2] media

noun, often attributive

Definition of MEDIA

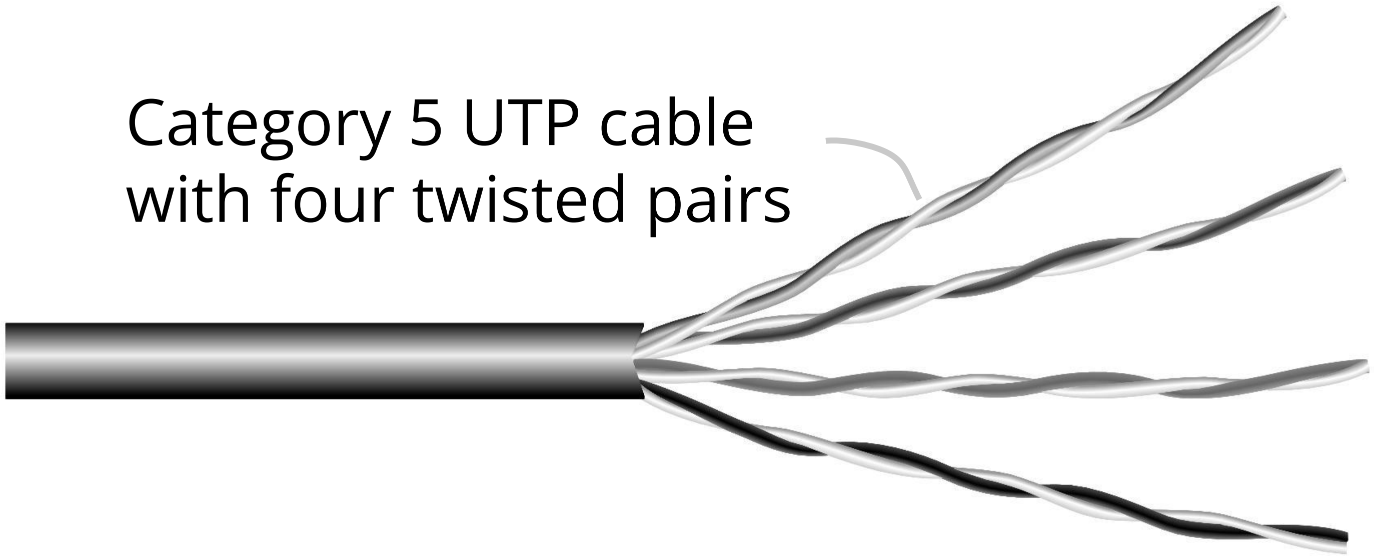
plural **medias**

1 : a medium of cultivation, conveyance, or expression • Air is a *media* that conveys sound.; *especially* : MEDIUM 2b

https://www.merriam-webster.com/dictionary/media

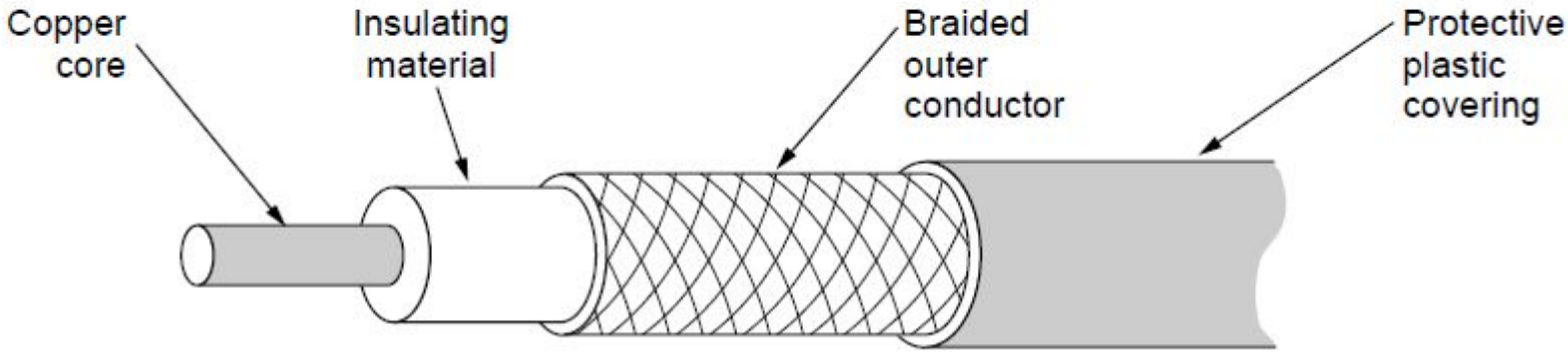
Wires – Twisted Pair

- Very common; used in LANs and telephone lines
  - Twists reduce radiated signal
  - Phone + DSL networks, Legacy ATT, CenturyLink



Wires – Coaxial Cable

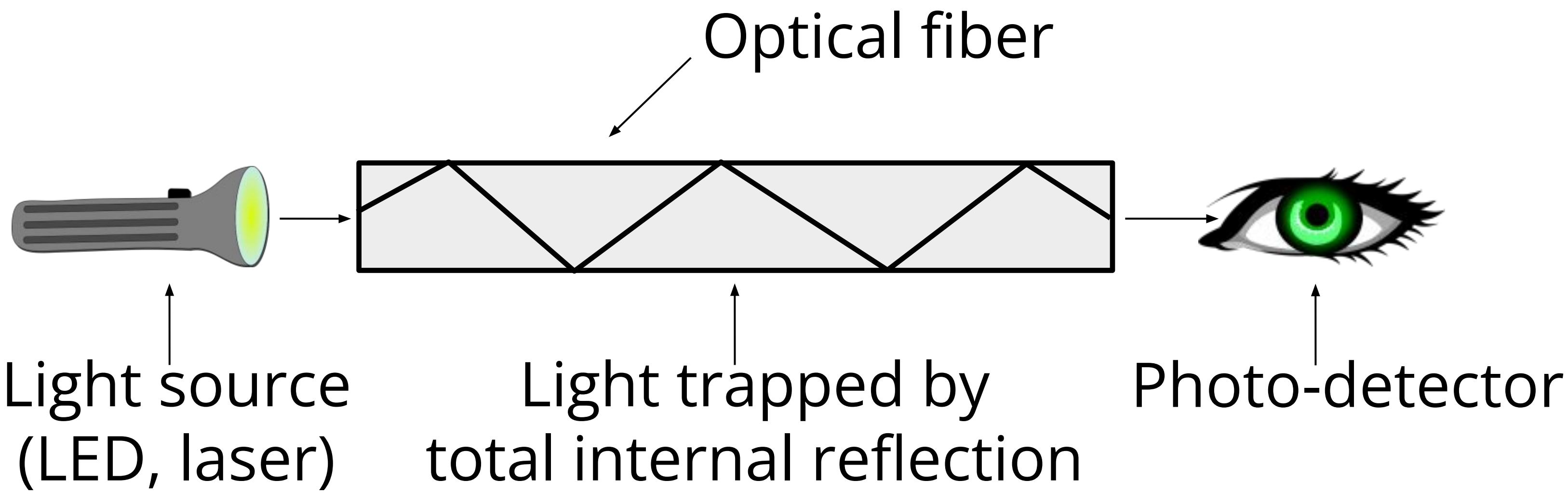
- Also common. Better shielding for better performance
  - Cable networks: comcast/xfinity, etc.



- Other kinds of wires too: e.g., electrical power (§2.2.4)

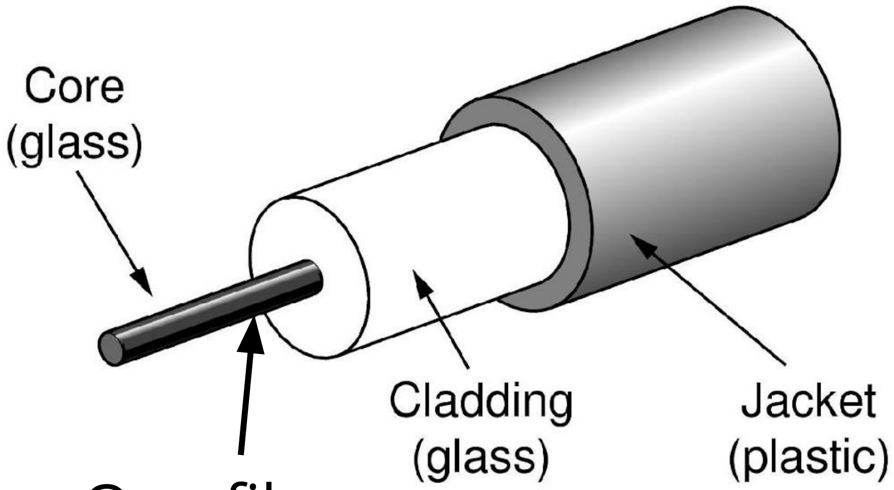
Fiber

- Long, thin, pure strands of glass
  - Enormous data rate (high speed) over long distances

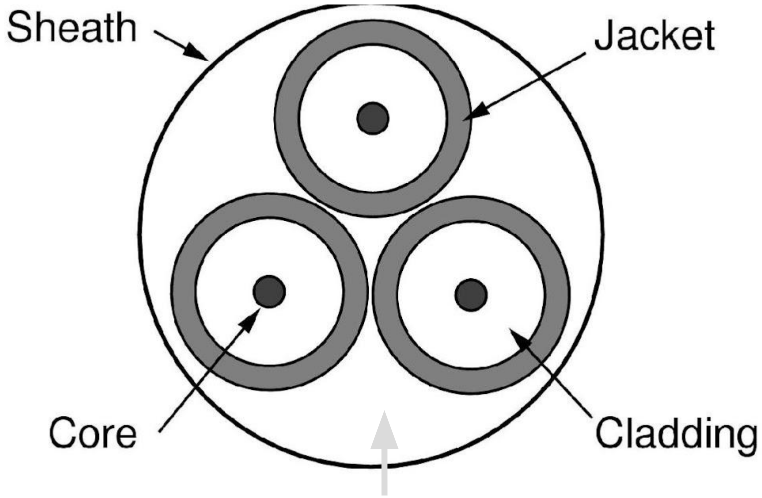


Fiber (2)

- Two varieties: multi-mode (shorter links, cheaper) and single-mode (up to ~100 km)



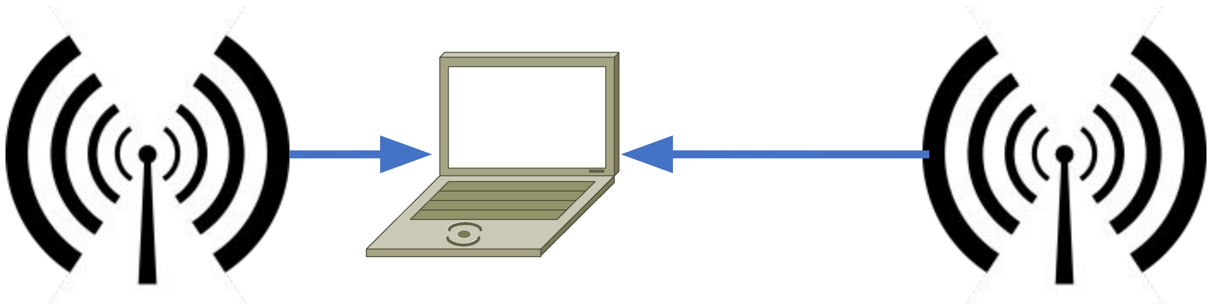
One fiber



Fiber bundle in a cable

Wireless

- Sender radiates signal over a region
  - Easier to deploy, don't need to run physical wires
  - Allows easy mobility (don't need to drag wire around :D)
  - But now need to manage interference, handle variability in the channel : (



More connections mean more complexity

- Access networks need to scale both from the perspective of the technical network… but also in their operation and management (O&M)
- New approaches to coordinating scarce spectrum (CBRS)
- Requires intelligent automation to keep manageable

Access networks are cool!

- But we’re done talking about them now :)
  - Any last questions?