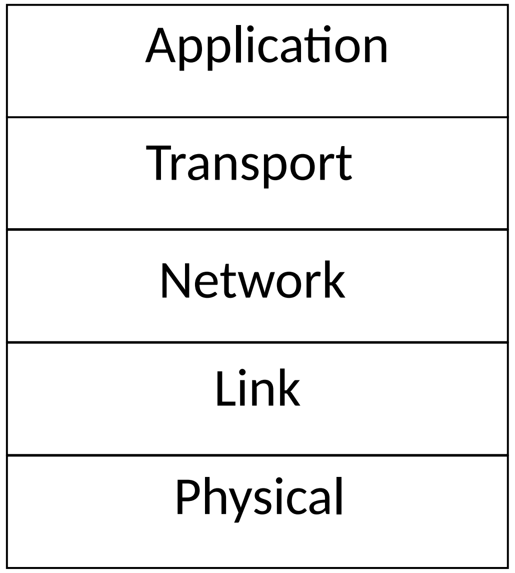
# Link Layer: Retransmissions

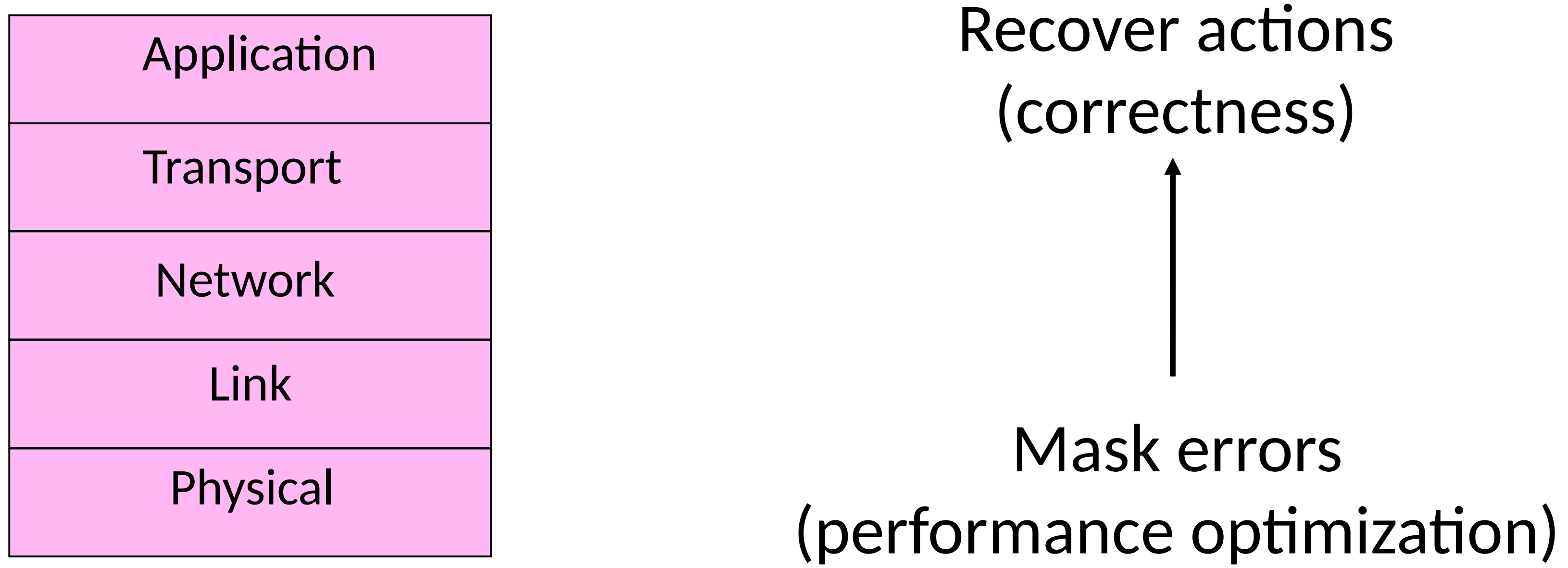
## Context on Reliability

- Where in the stack should we place reliability functions?



# Context on Reliability (2)

- Everywhere! It is a key issue
  - Different layers contribute differently


Application
Transport
Network
Link
Physical
Recover actions (correctness)
Mask errors (performance optimization)

## So what do we do if a frame is corrupted?

- From sender?
- From receiver?

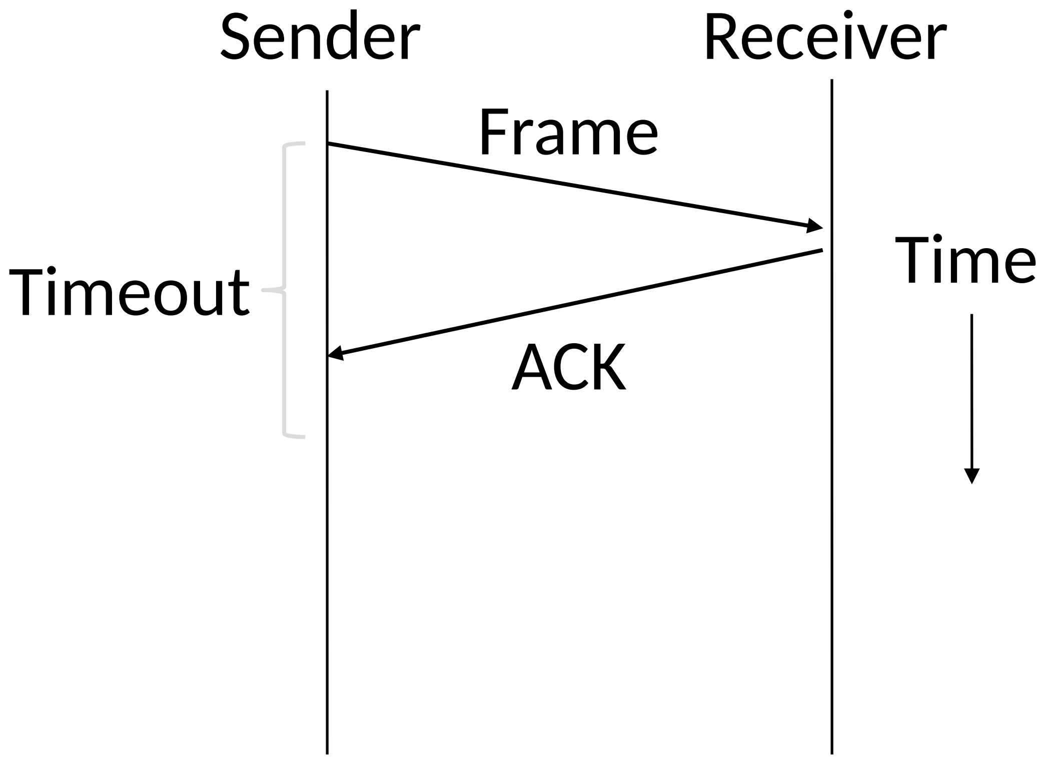
## ARQ (Automatic Repeat reQuest)

- ARQ often used when errors are common or must be corrected
  - E.g., WiFi, and TCP (later)

- Rules at sender and receiver:
  - Receiver automatically acknowledges correct frames with an ACK
  - Sender automatically resends after a timeout, until an ACK is received

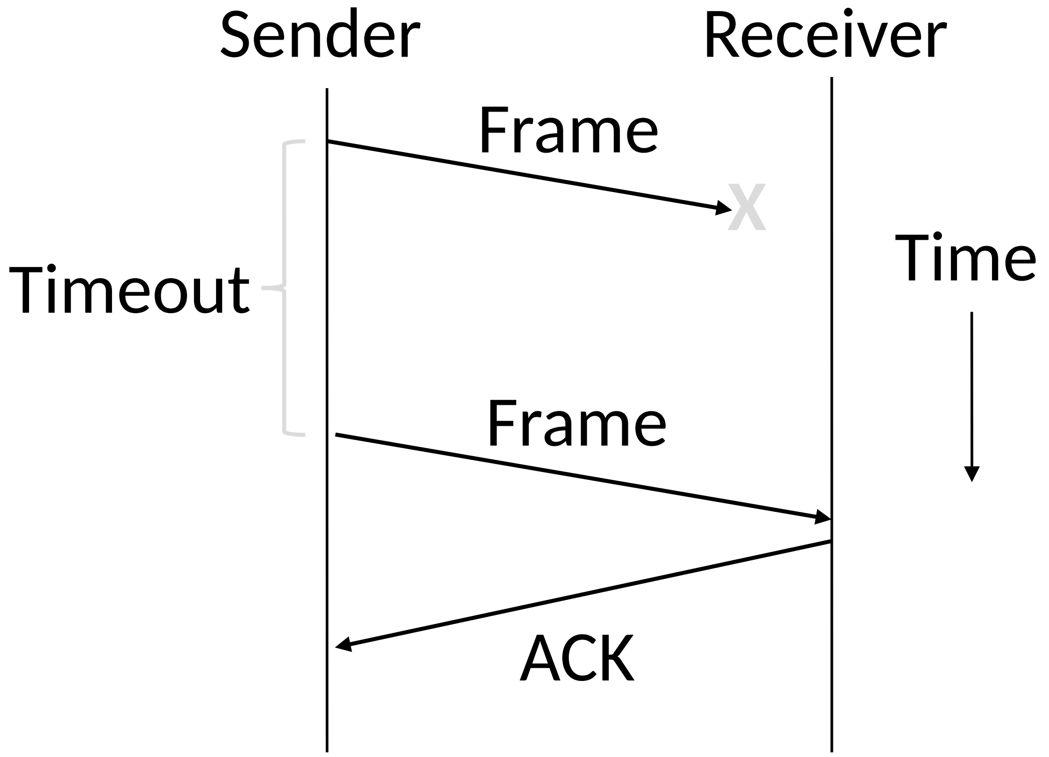
## ARQ (2)

- Normal operation (no loss)



# ARQ (3)

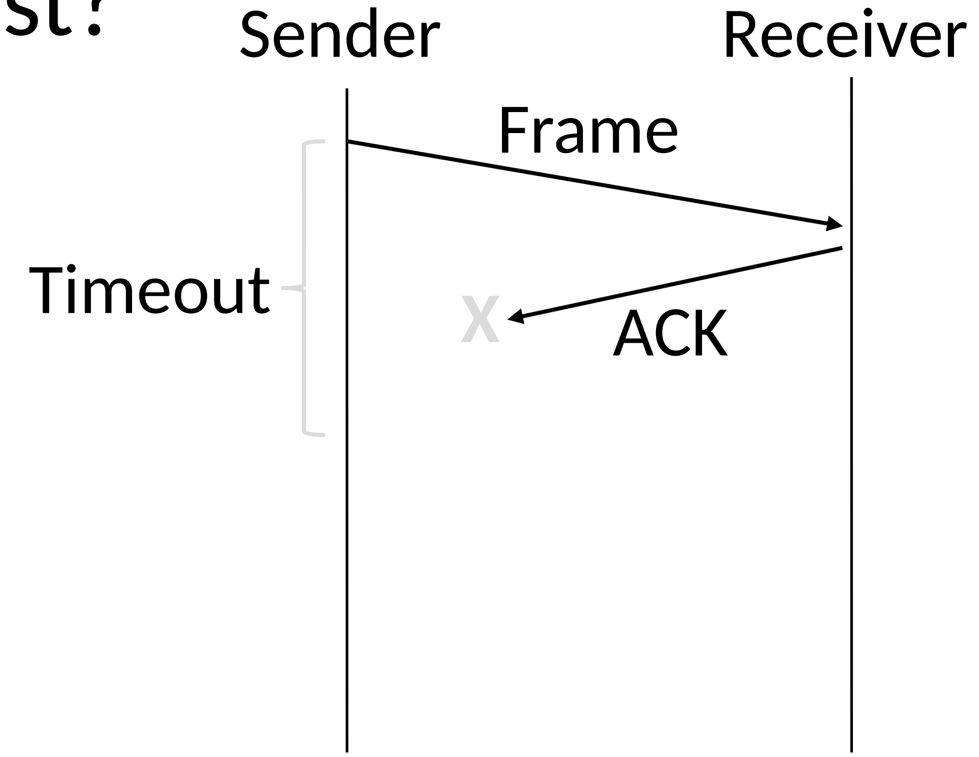
- Loss and retransmission



## So What’s Tricky About ARQ?

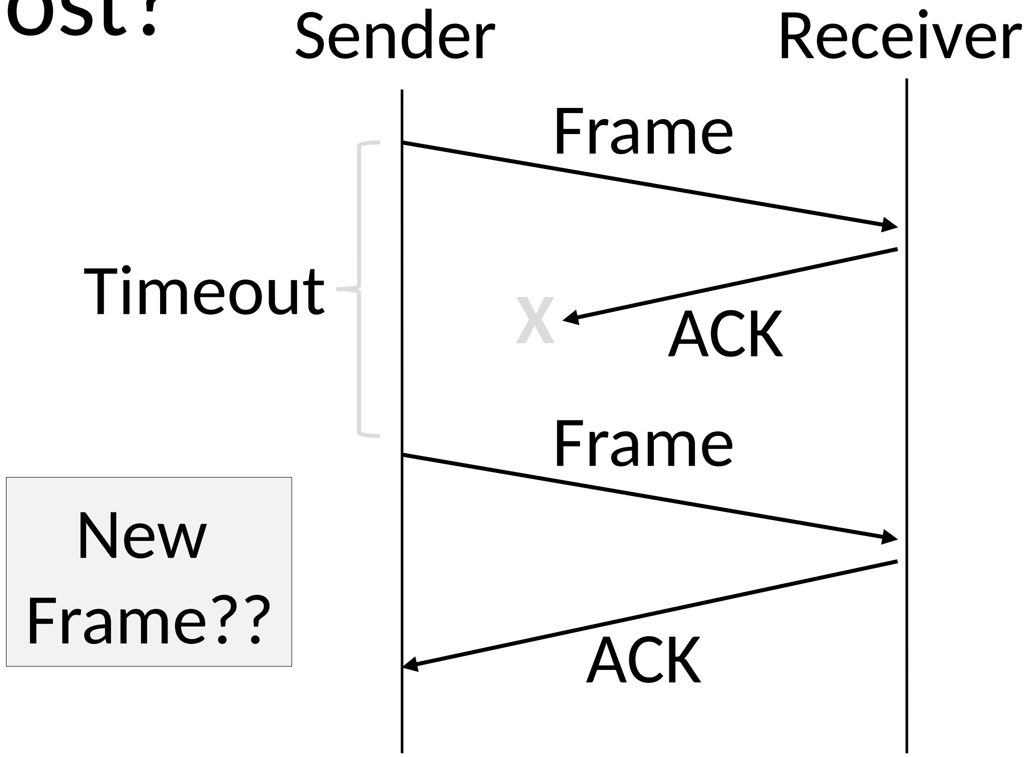
## Duplicates

- What happens if an ACK is lost?



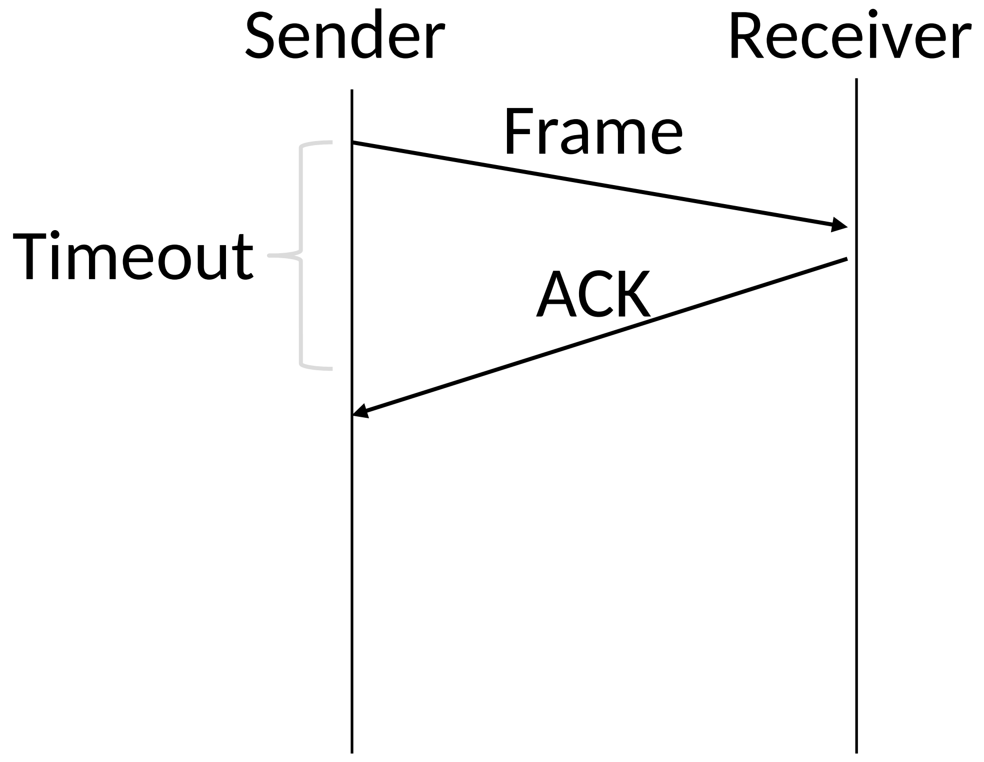
## Duplicates (2)

- What happens if an ACK is lost?



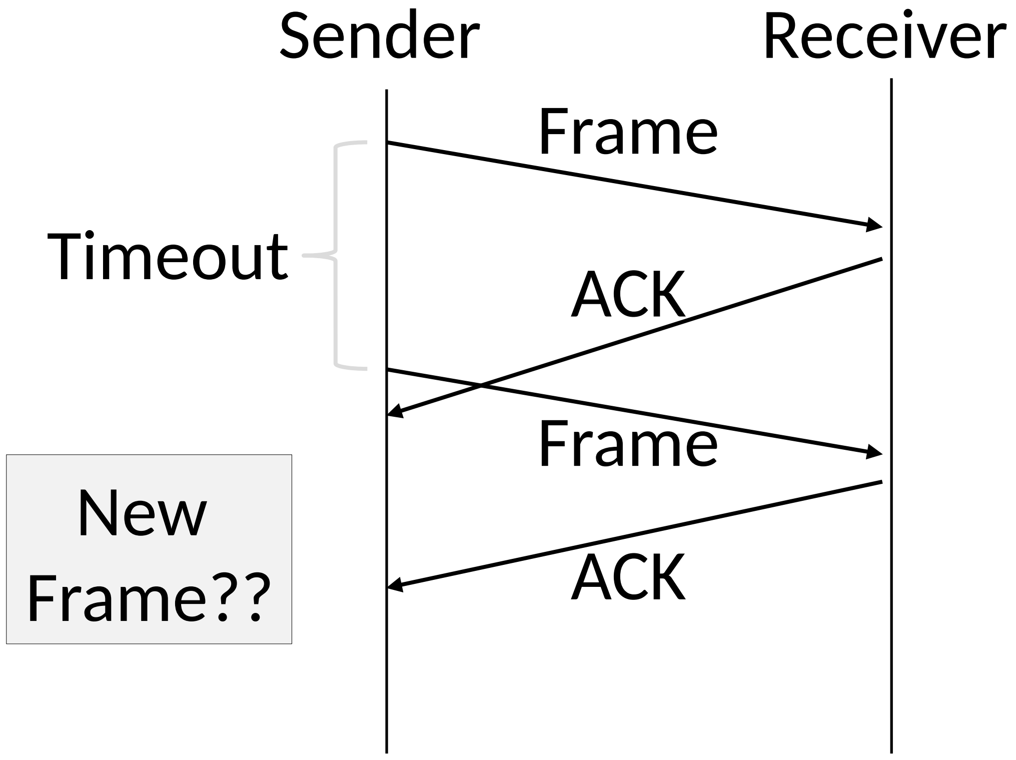
## Duplicates (3)

- Or the timeout is early?



## Duplicates (4)

- Or the timeout is early?



# So What’s Tricky About ARQ?

- Two non-trivial issues:
  - How long to set the timeout?
  - How to avoid accepting duplicate frames as new frames

- Want performance in the common case and correctness always

- Ideas?

## Timeouts

- Timeout should be:
  - Not too big (link goes idle)
  - Not too small (spurious resend)
- Fairly easy on a LAN
  - Clear worst case, little variation
- Fairly difficult over the Internet
  - Much variation, no obvious bound
  - We'll revisit this with TCP (later)

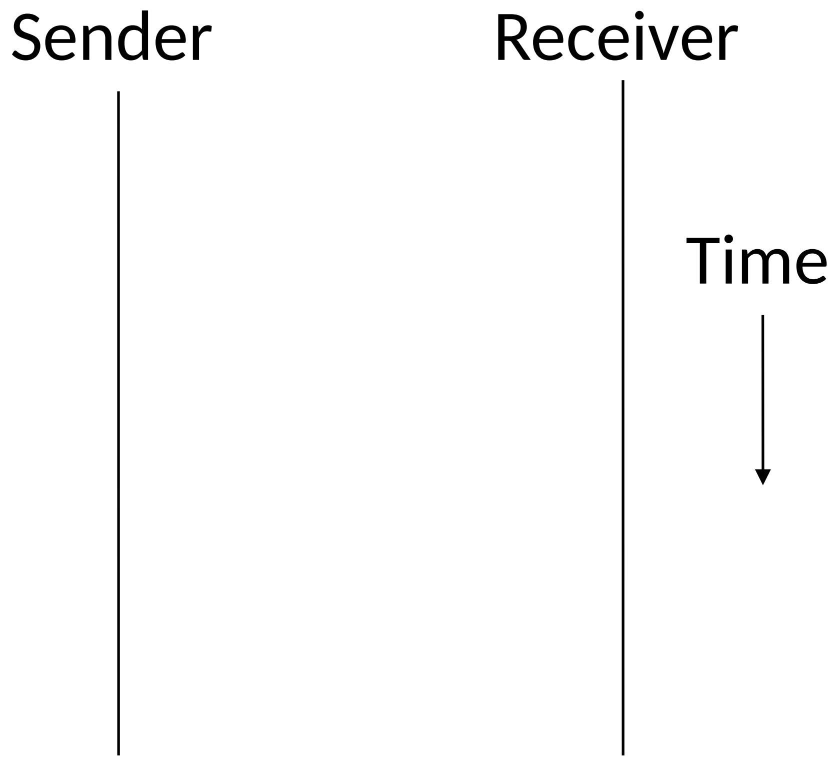
## Sequence Numbers

- Frames and ACKs must both carry sequence numbers for correctness

- To distinguish the current frame from the next one, a single bit (two numbers) is sufficient
    - Called <u>Stop-and-Wait</u>

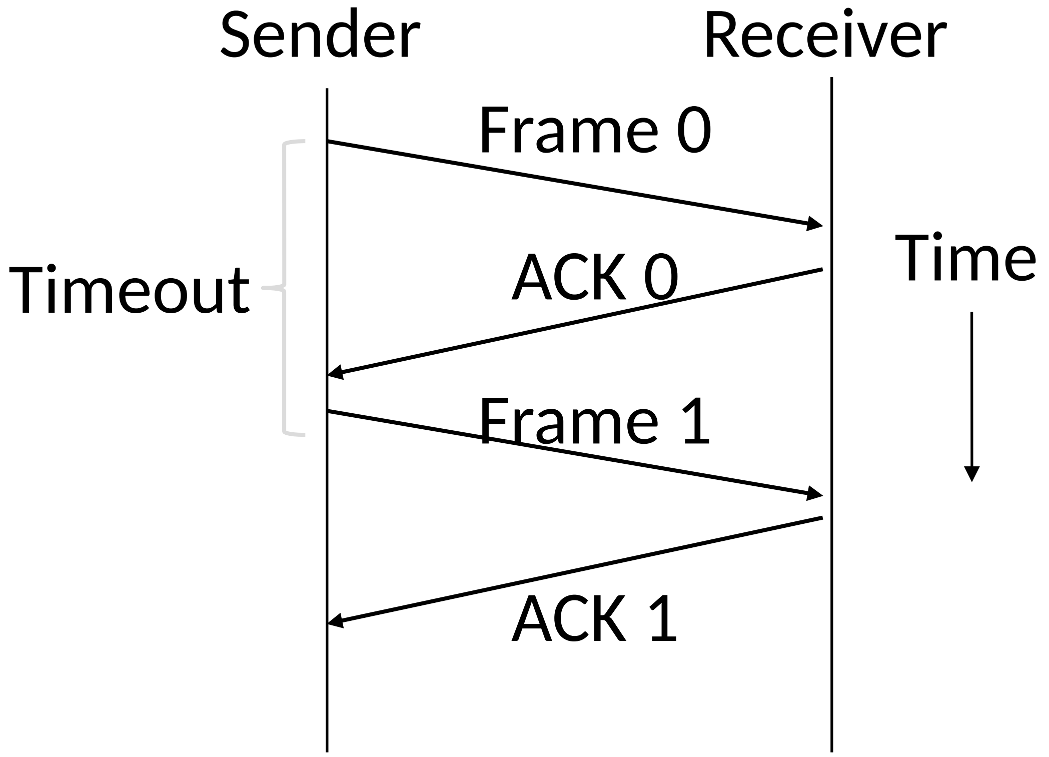
## Stop-and-Wait

- In the normal case:



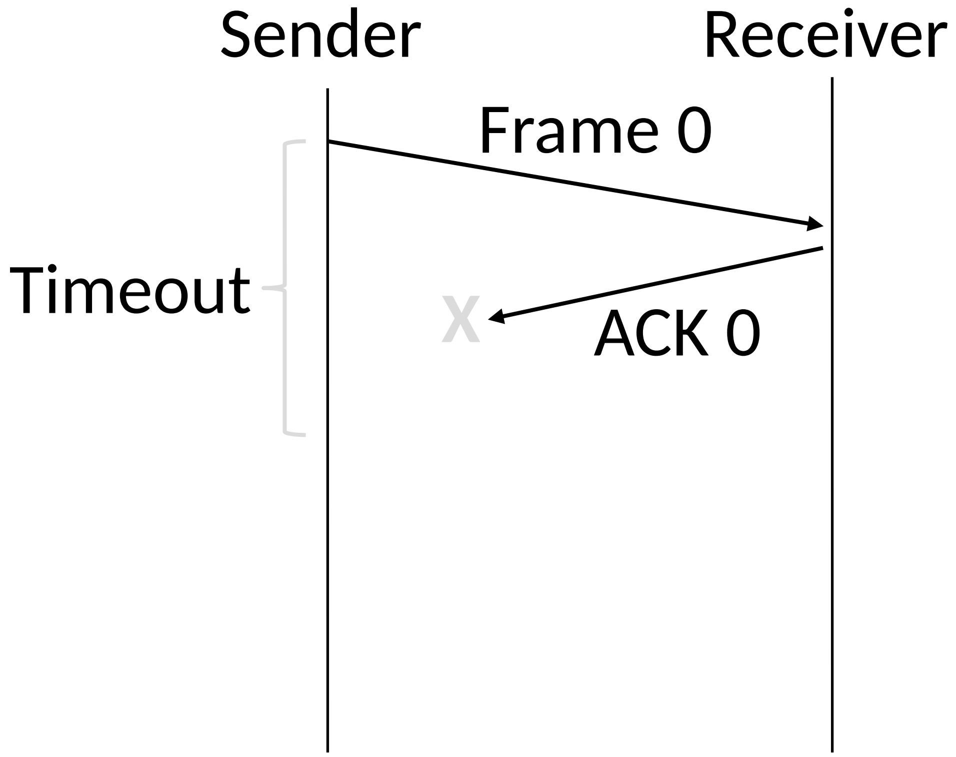
# Stop-and-Wait (2)

- In the normal case:



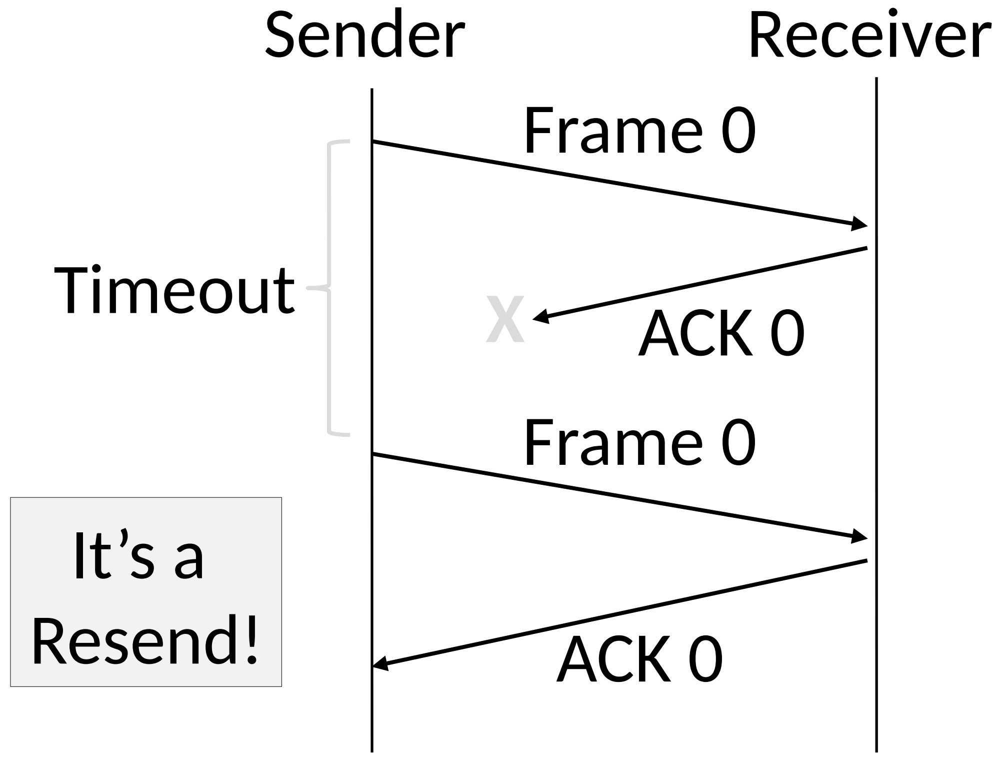
## Stop-and-Wait (3)

- With ACK loss:



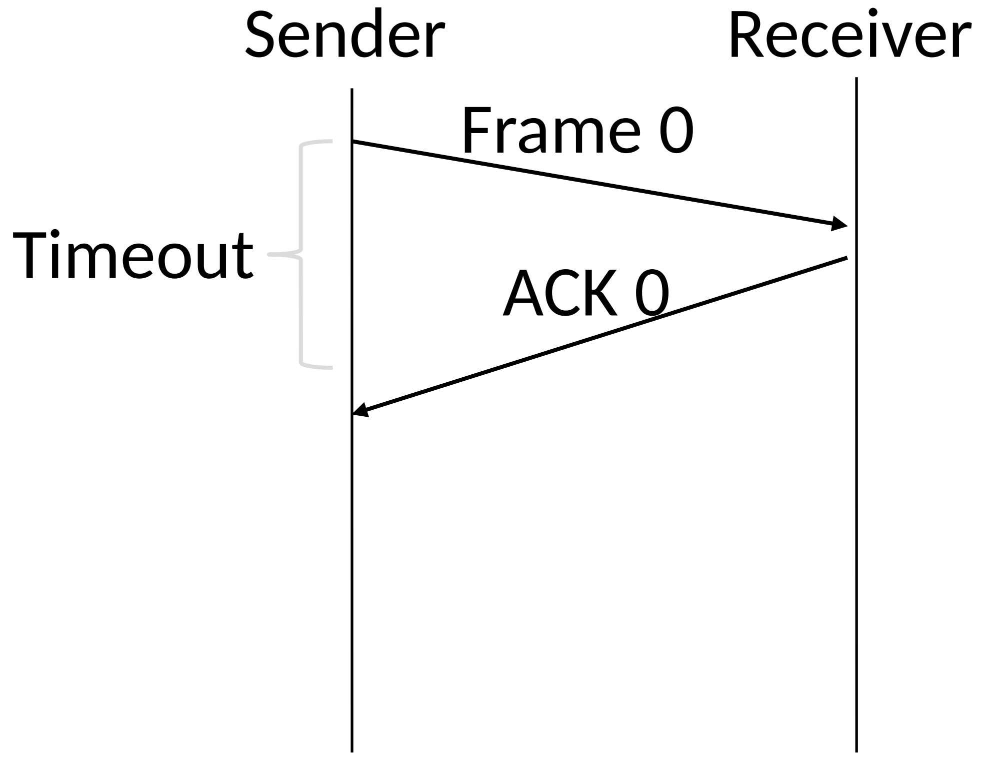
# Stop-and-Wait (4)

- With ACK loss:



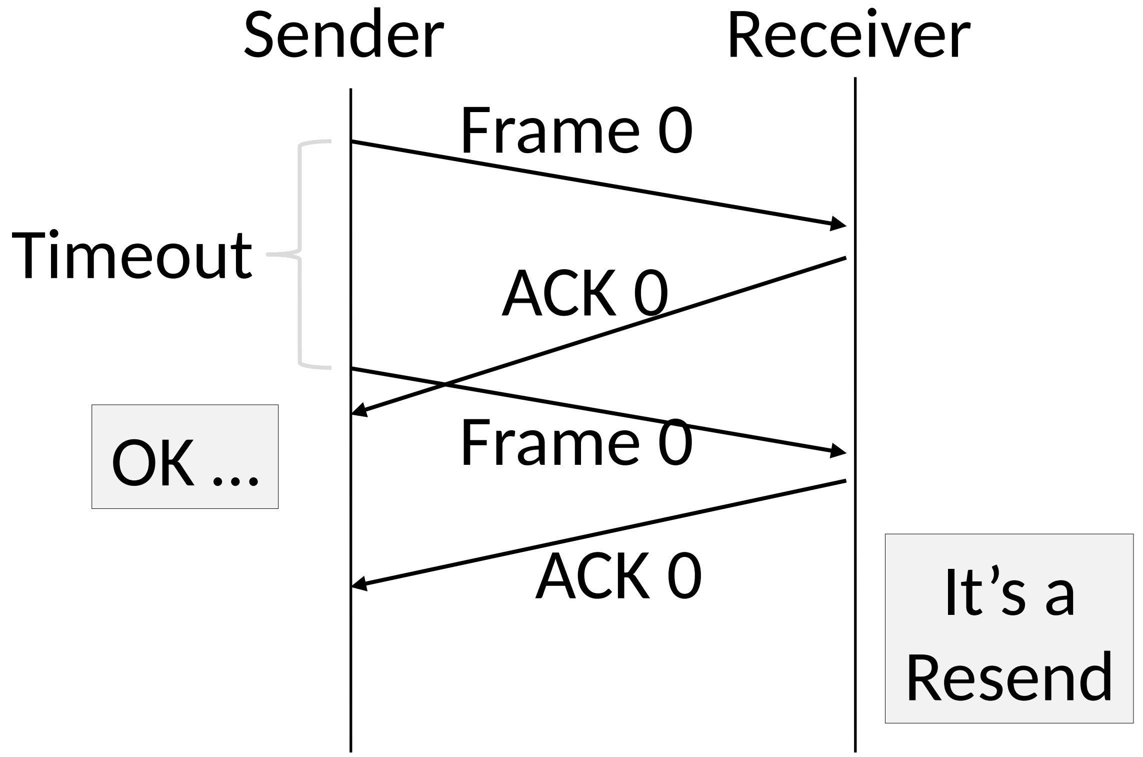
## Stop-and-Wait (5)

- With early timeout:



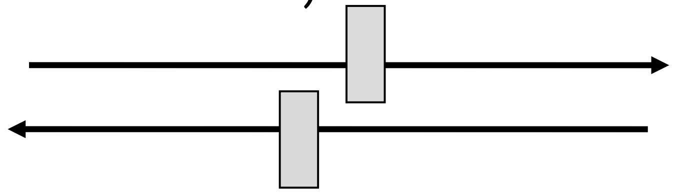
## Stop-and-Wait (6)

- With early timeout:



## Limitation of Stop-and-Wait

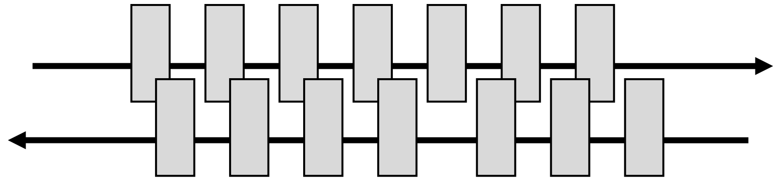
- It allows only a single frame to be outstanding from the sender:
  - Good for LAN, not efficient for high BD



- Ex: R=1 Mbps, D = 50 ms
  - How many frames/sec? If R=10 Mbps?

## Sliding Window

- Generalization of stop-and-wait
  - Allows W frames to be outstanding
  - Can send W frames per RTT (=2D)



  - Various options for numbering frames/ACKs and handling loss
    - Will look at along with TCP (later)

## Multiple Access

## Topic

- Multiplexing is the network word for the sharing of a resource
- What are some obvious ways to multiple a resource?

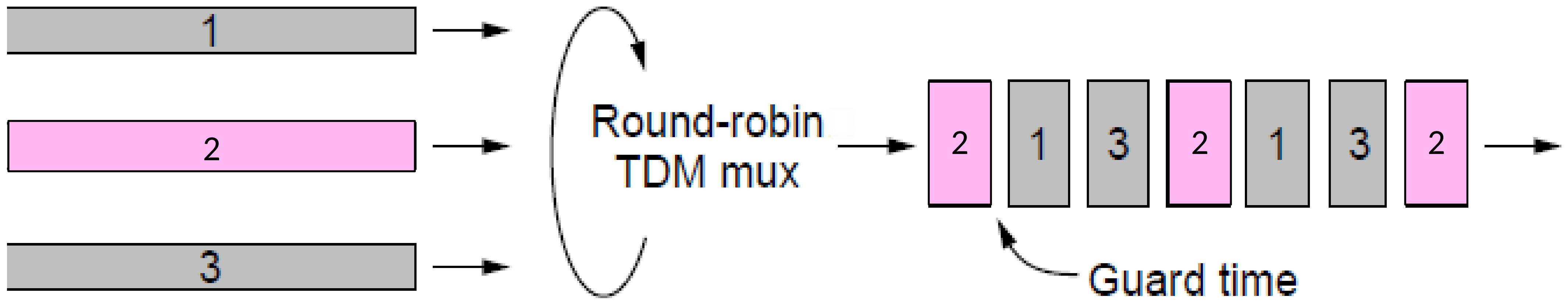
## Topic

- Multiplexing is the network word for the sharing of a resource

- Classic scenario is sharing a link among different users
  - Time Division Multiplexing (TDM)
  - Frequency Division Multiplexing (FDM)

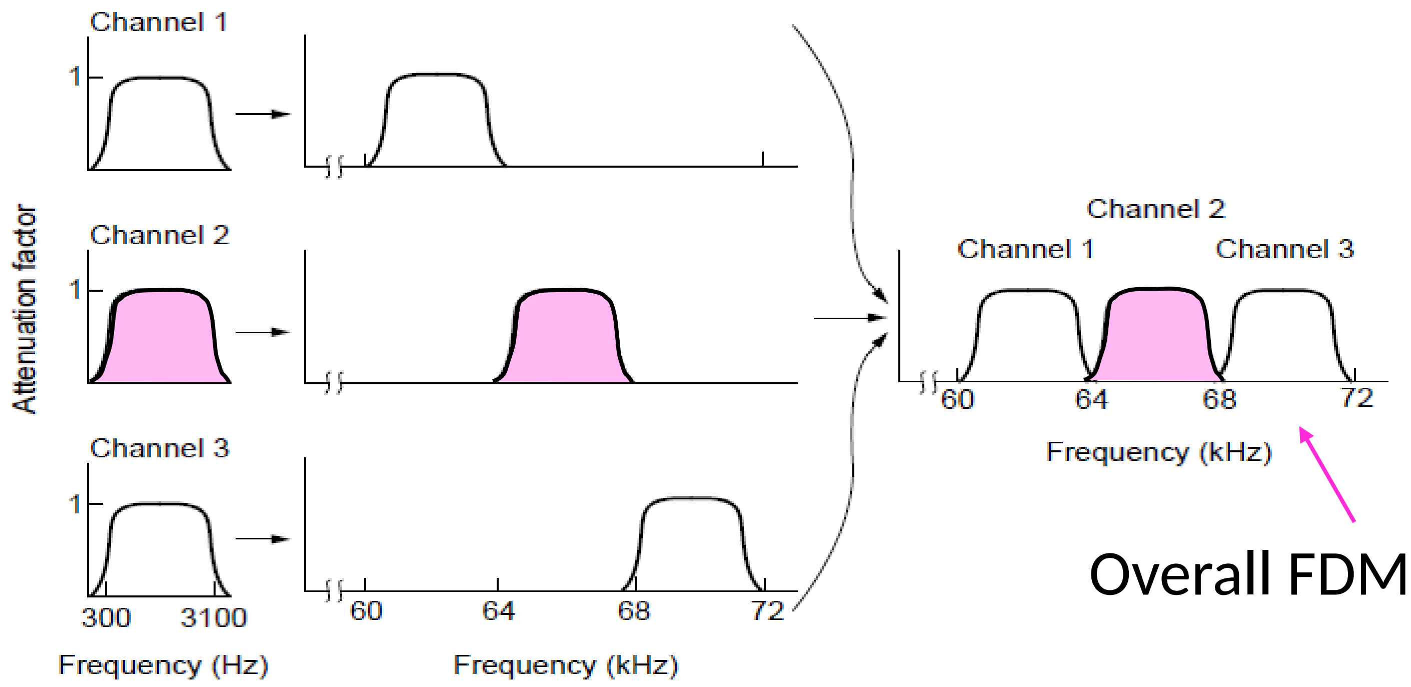
## Time Division Multiplexing (TDM)

- Users take turns on a fixed schedule



# Frequency Division Multiplexing (FDM)

- Put different users on different frequency bands



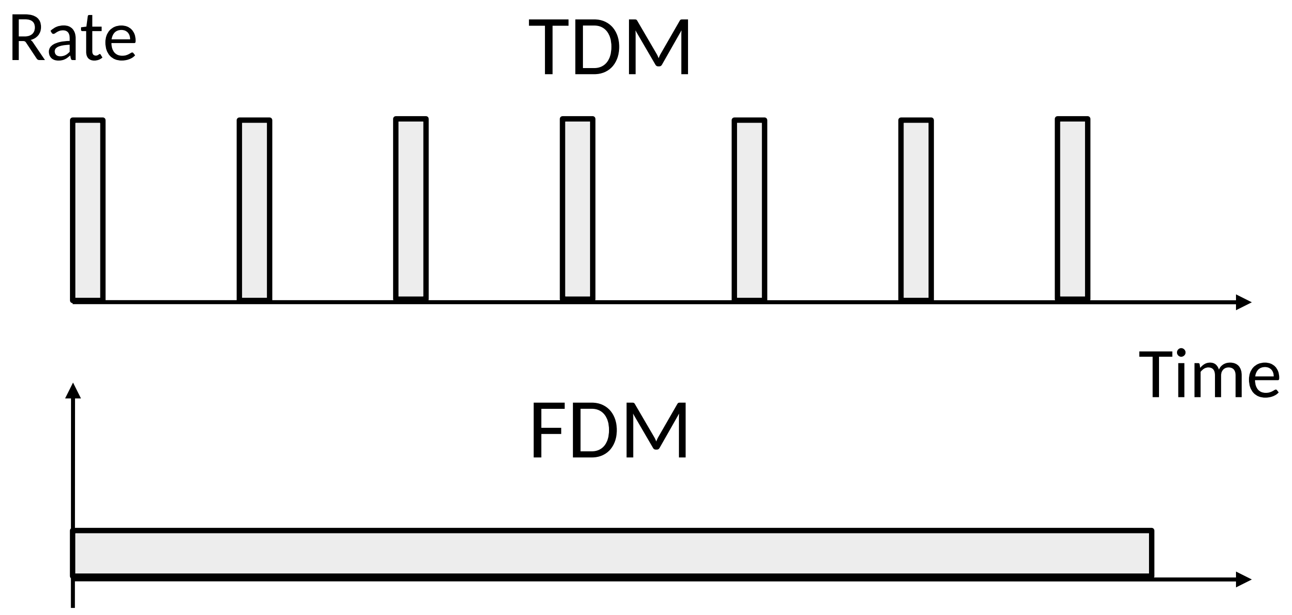
Overall FDM channel

## 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



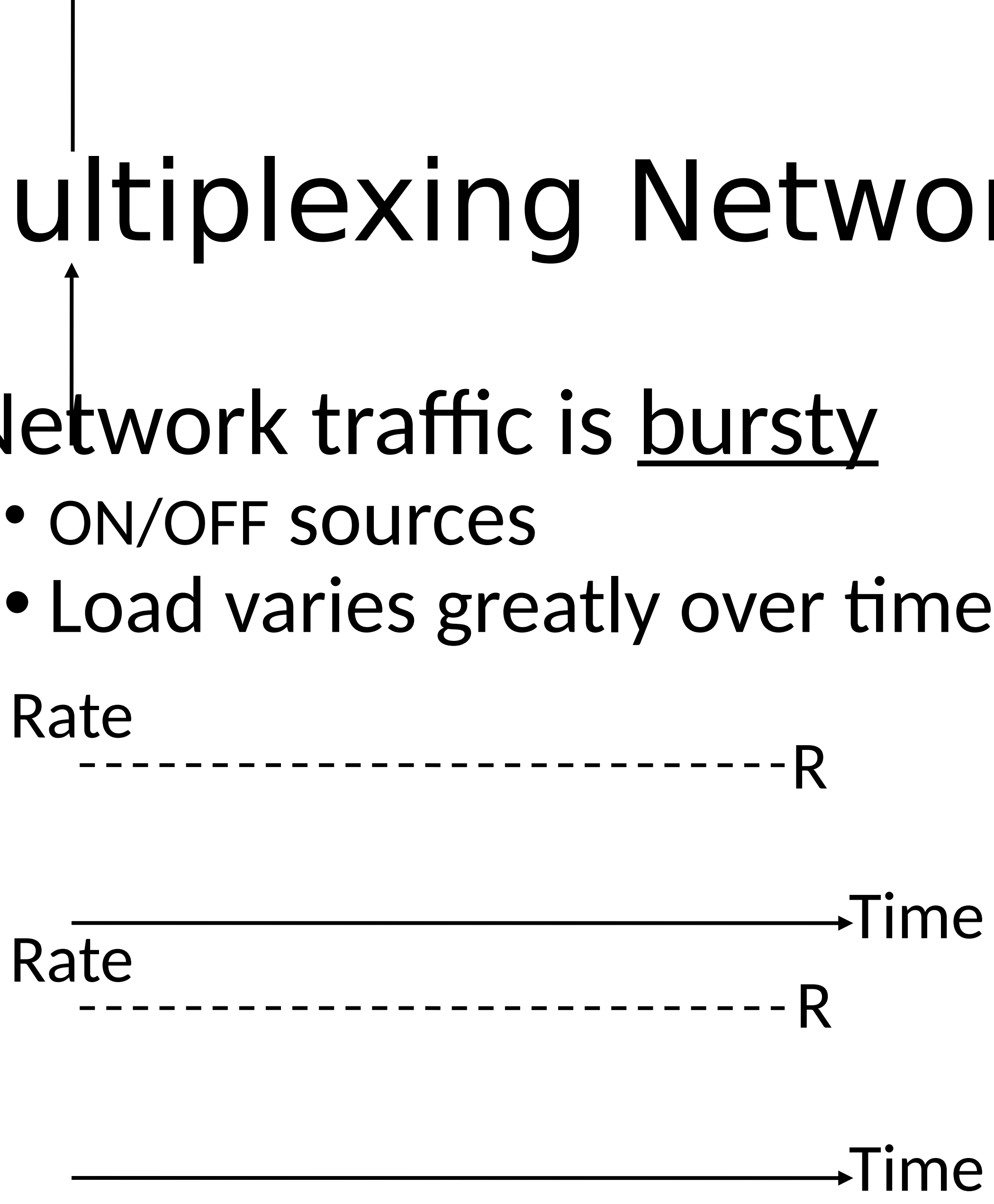
## TDM/FDM Usage

- 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

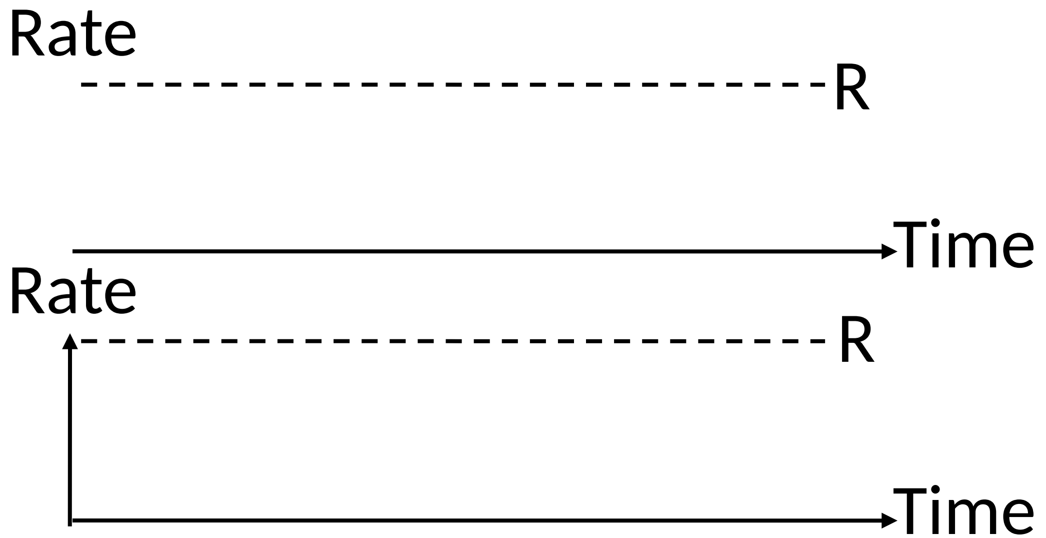
# Multiplexing Network Traffic

- Network traffic is <u>bursty</u>
  - ON/OFF sources
  - Load varies greatly over time



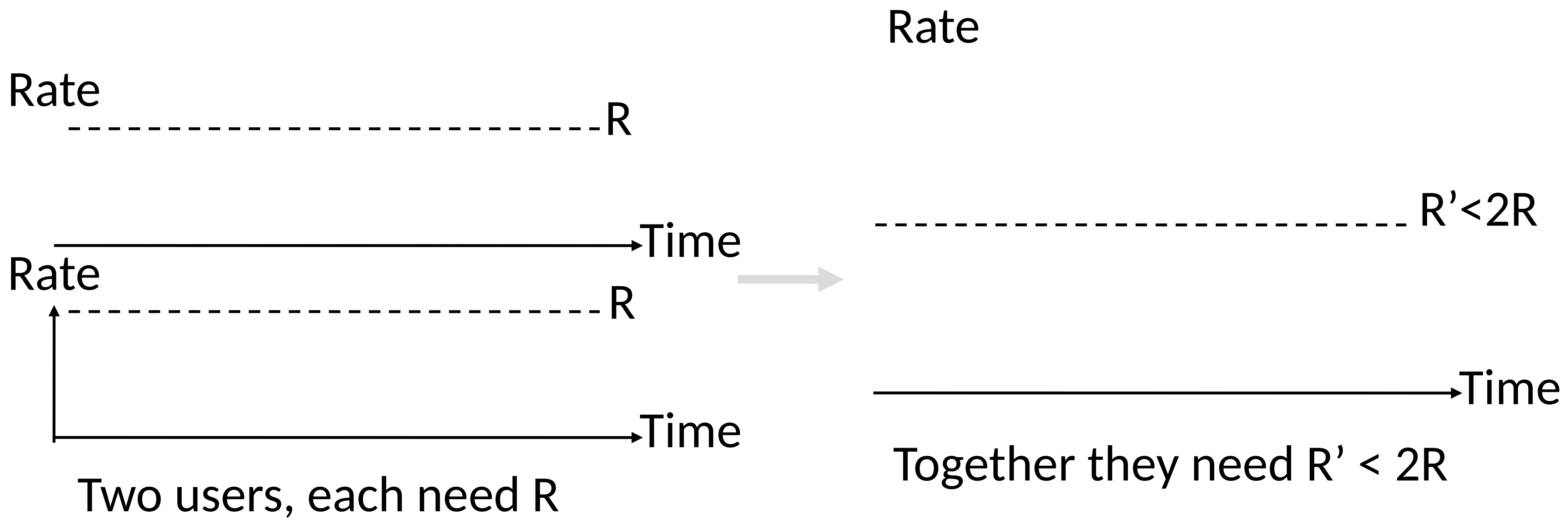
## Multiplexing Network Traffic (2)

- 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



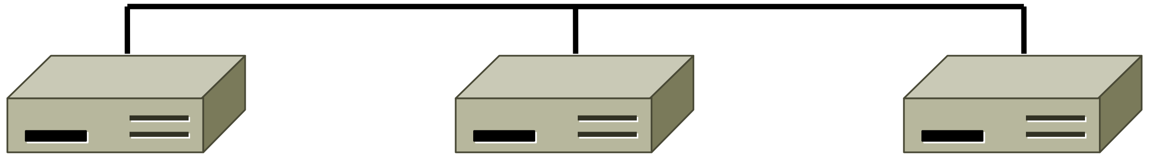
# How to control?

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

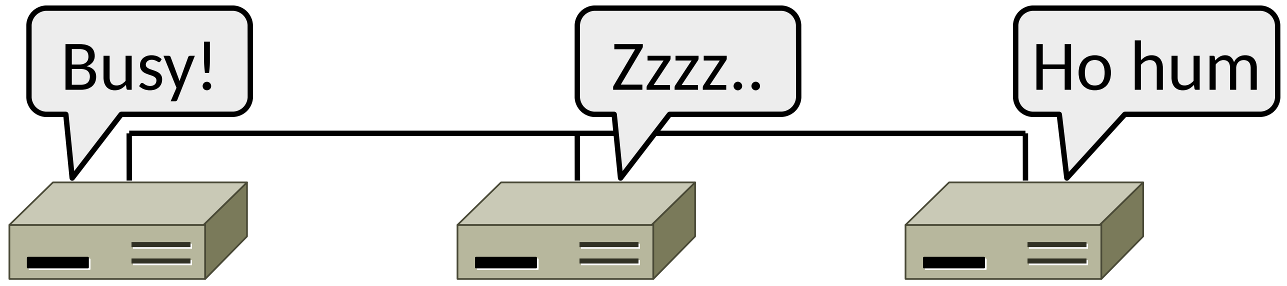
- How do nodes share a single link? Who sends when, e.g., in WiFI?
  - Explore with a simple model



- Assume no-one is in charge
  - Distributed system

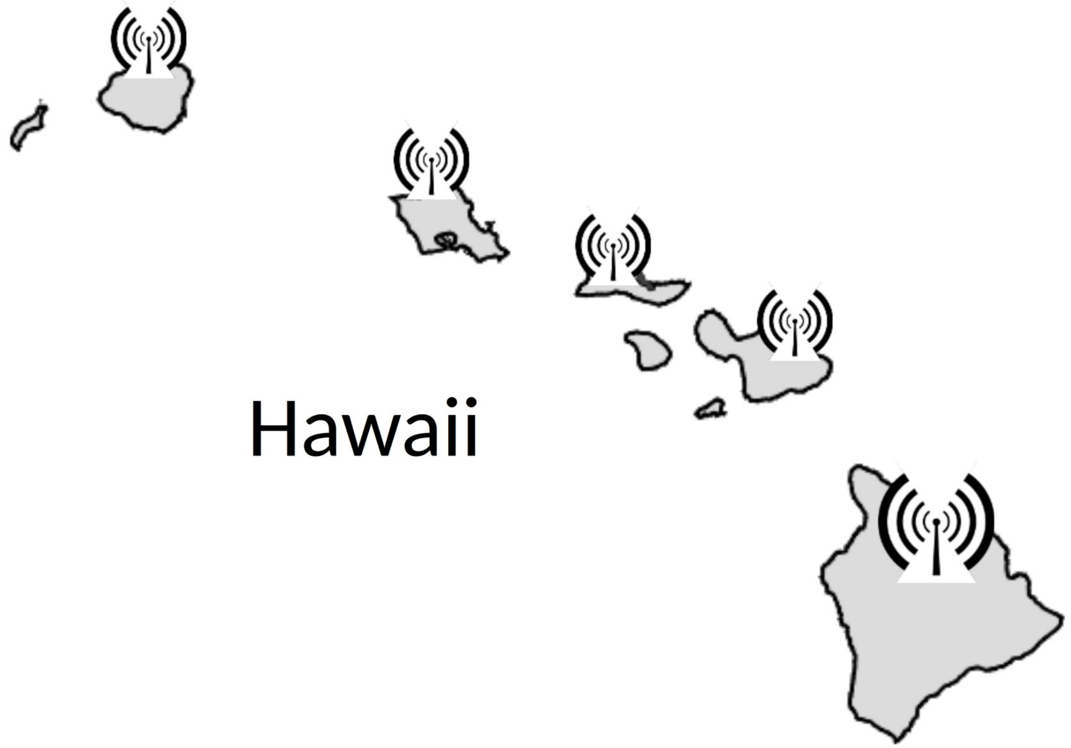
# Distributed (random) Access (2)

- We will explore random <u>multiple access control</u> (MAC) protocols
  - This is the basis for <u>classic Ethernet</u>
  - 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 …



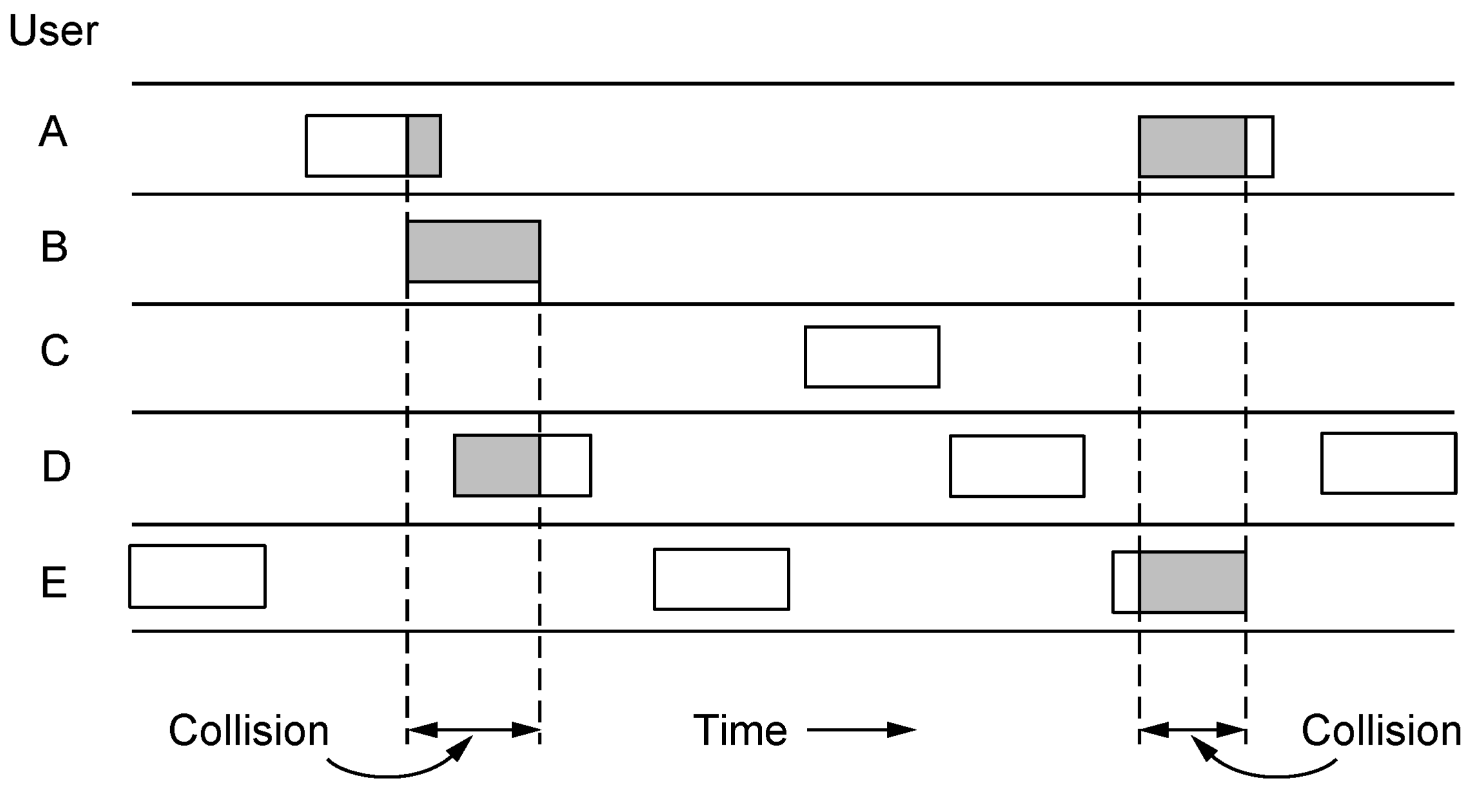
## ALOHA Protocol

- 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?

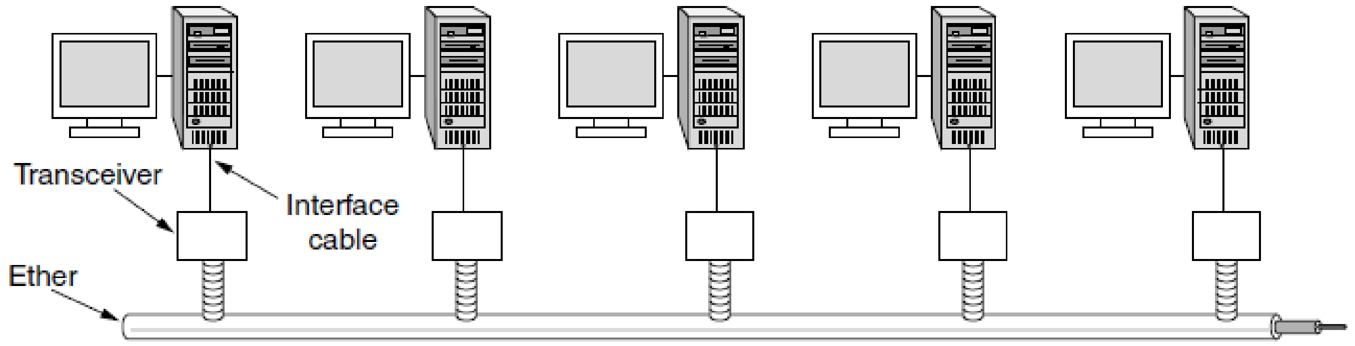


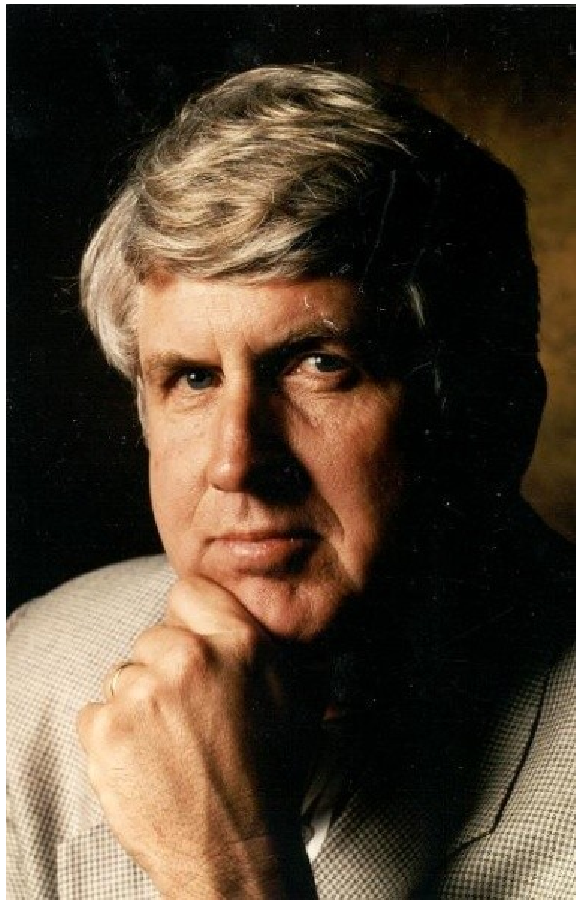
## ALOHA Protocol (3)

- 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



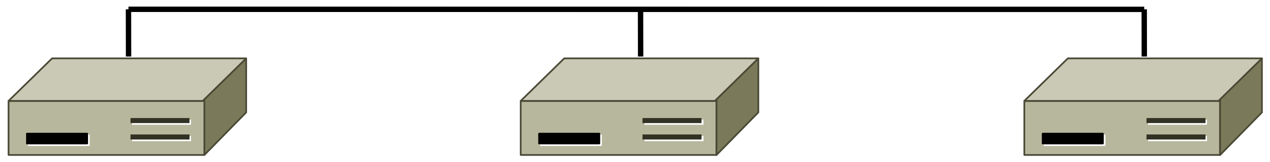

: © 2009 IEEE

## 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?

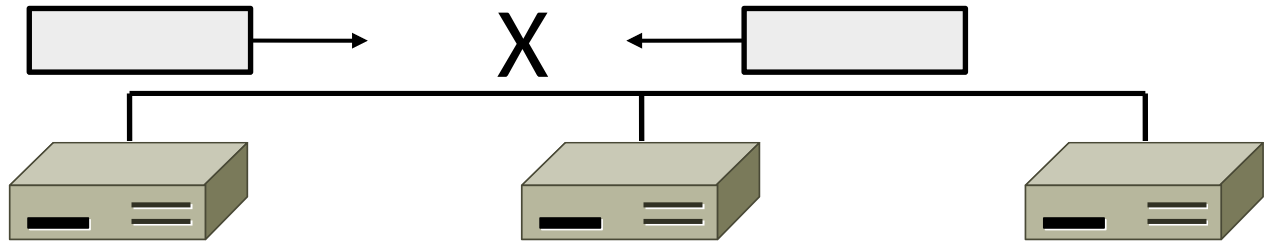
## CSMA (2)

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



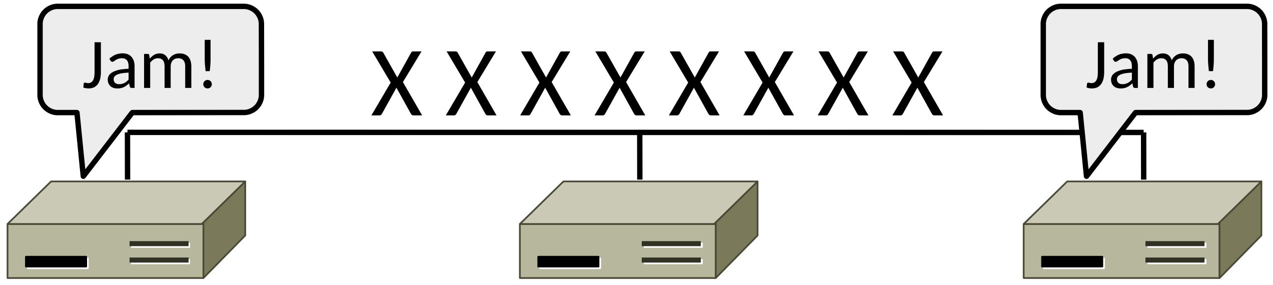
## CSMA (3)

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



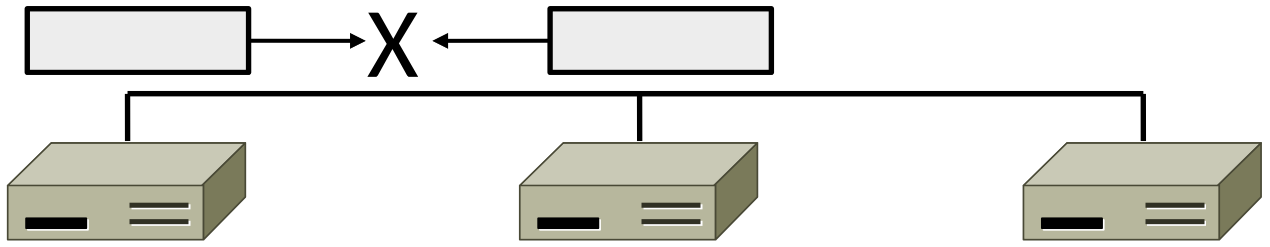
## CSMA/CD (with Collision Detection)

- 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



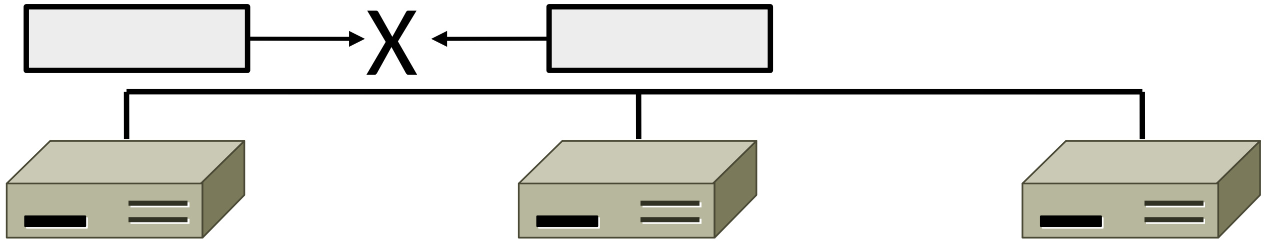
# CSMA/CD Complications

- Everyone who collides needs to know it happened
  - How long do we need to wait to know there wasn't a JAM?



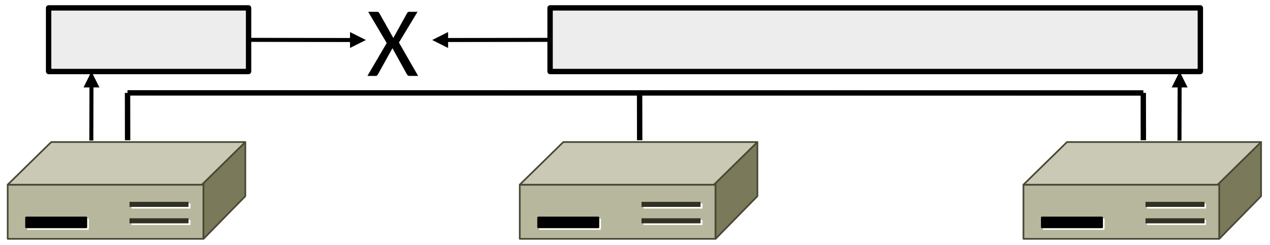
# CSMA/CD Complications

- 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



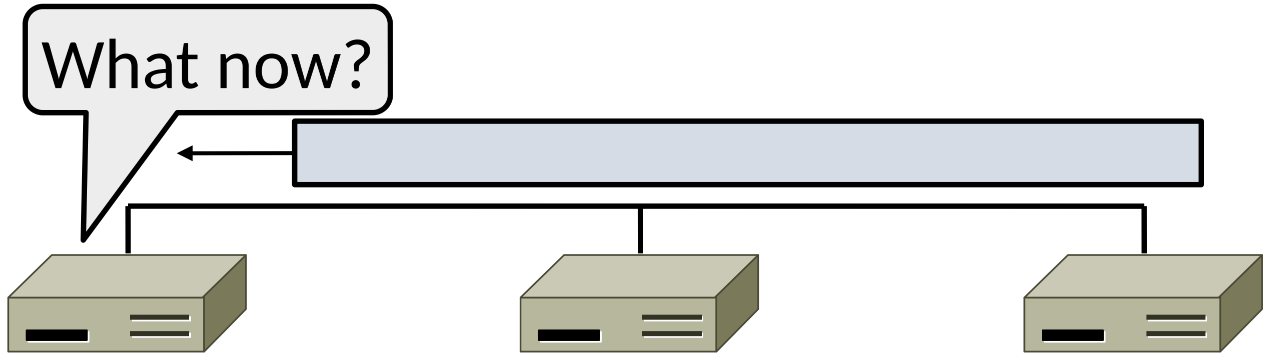
## CSMA/CD Complications (2)

- 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”

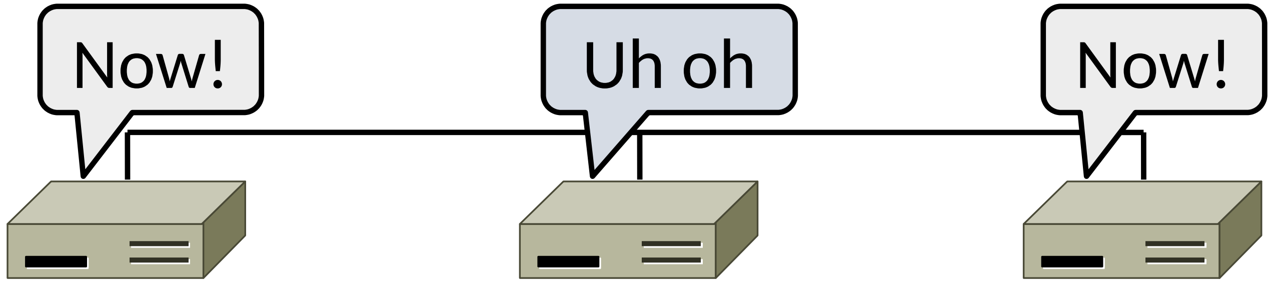
- What should a node do if another node is sending?



- Idea: Wait until it is done, and send

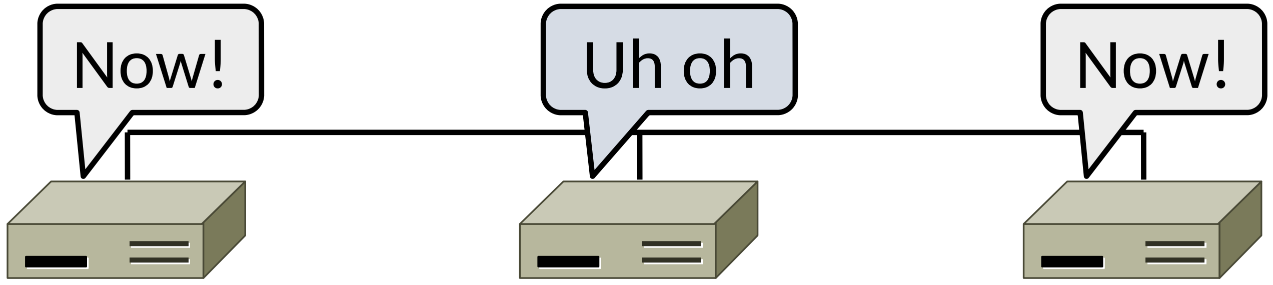
## CSMA “Persistence” (2)

- Problem is that multiple waiting nodes will queue up then collide
  - More load, more of a problem



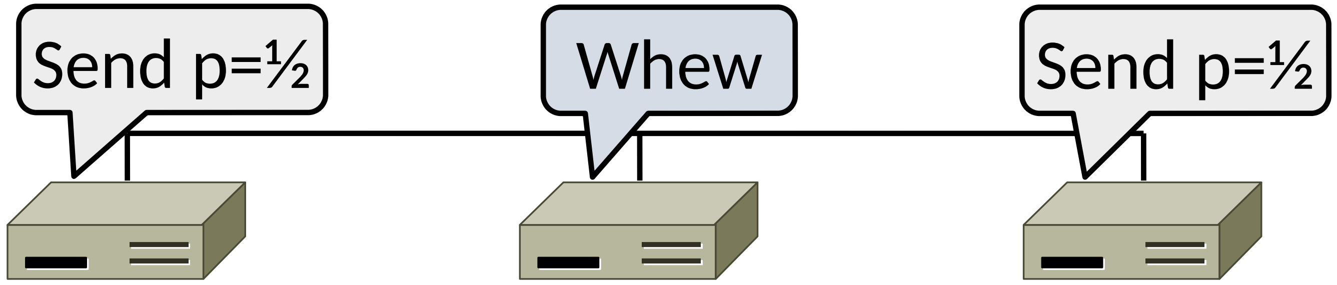
# CSMA “Persistence” (2)

- Problem is that multiple waiting nodes will queue up then collide
  - 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



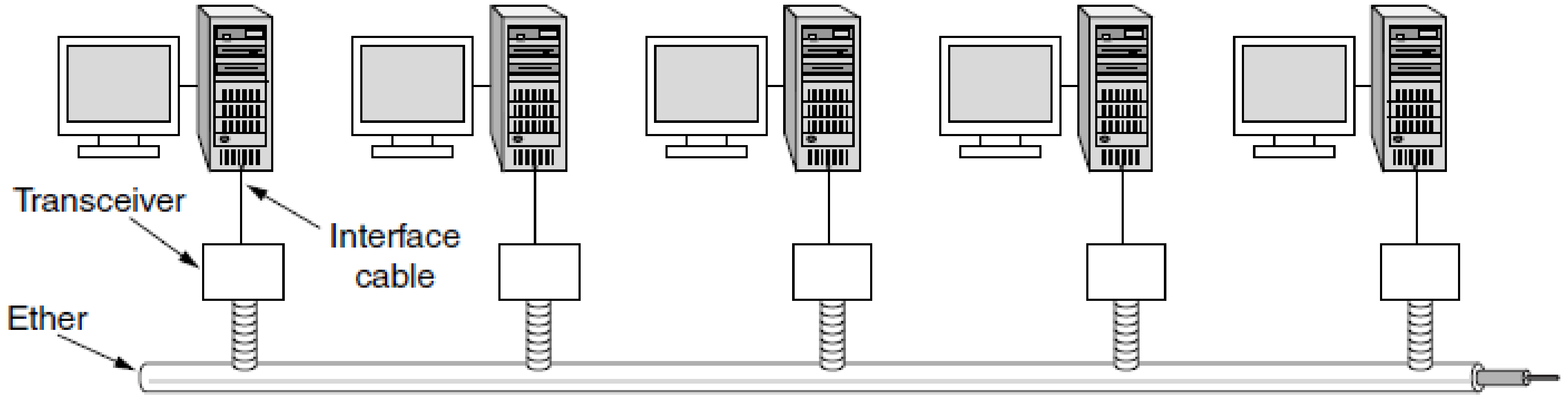
## Binary Exponential Backoff (BEB)

- 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

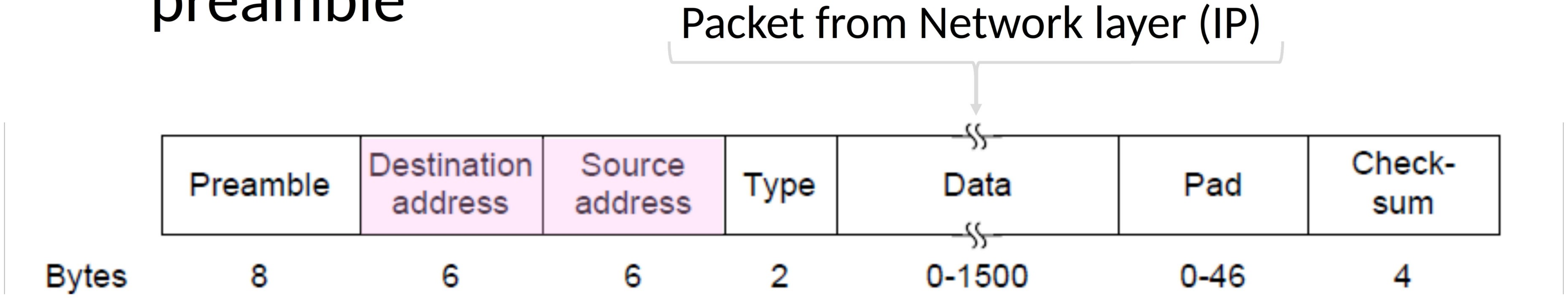
## Classic Ethernet, or IEEE 802.3

- 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”



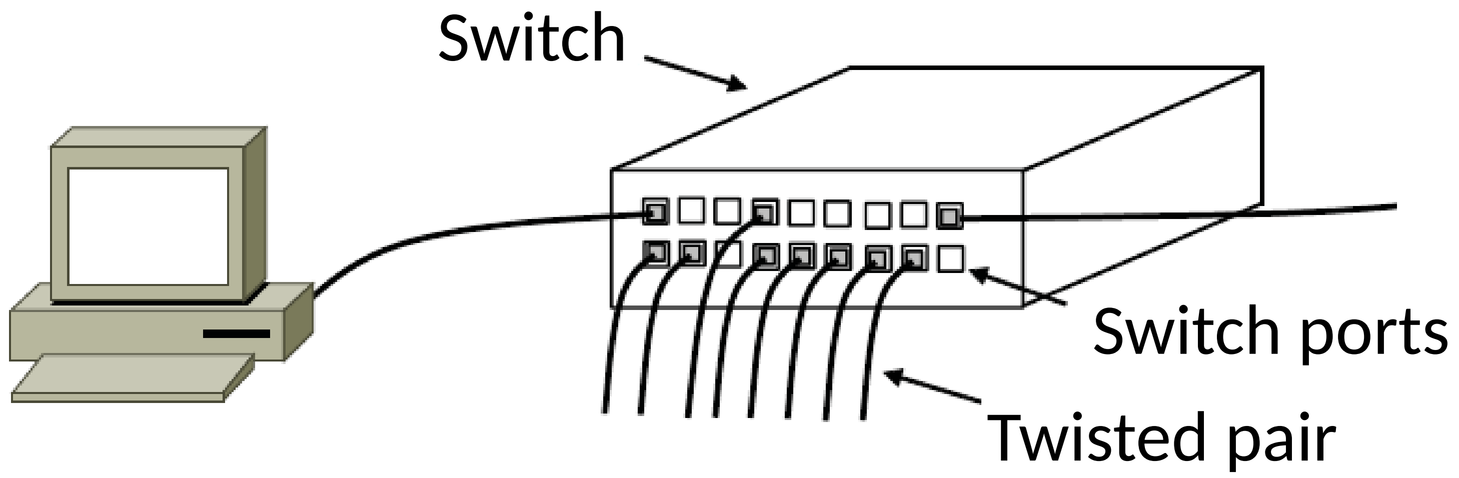
## Ethernet Frame Format

- 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



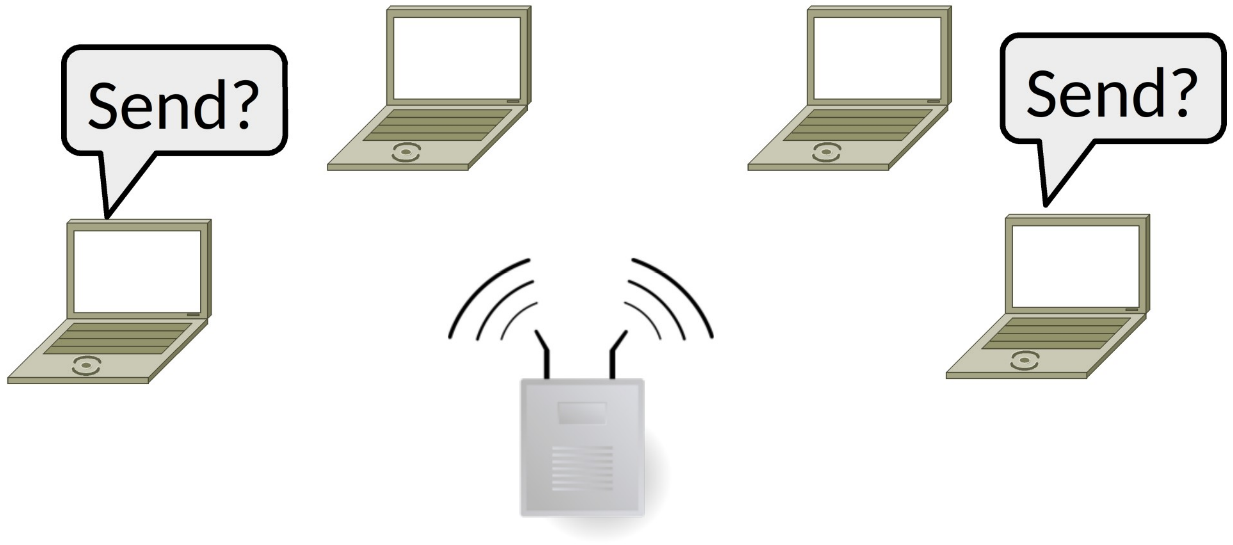
# Modern Ethernet

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



## Topic

- How do wireless nodes share a single link? (Yes, this is WiFi!)
  - Build on our simple, wired model



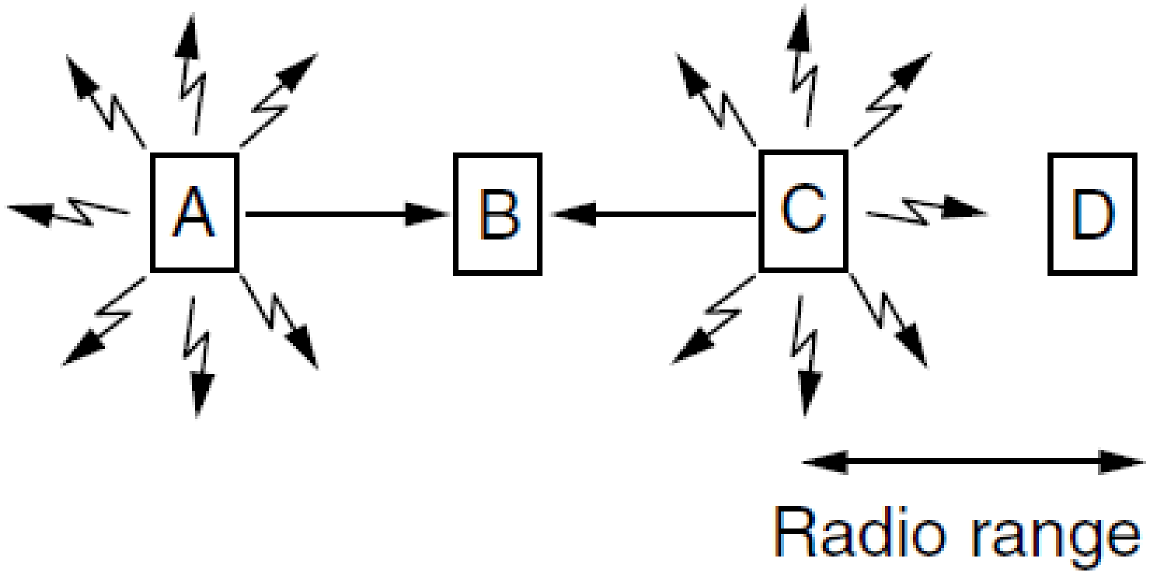
## Wireless Complications

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

≠ CSMA/CD

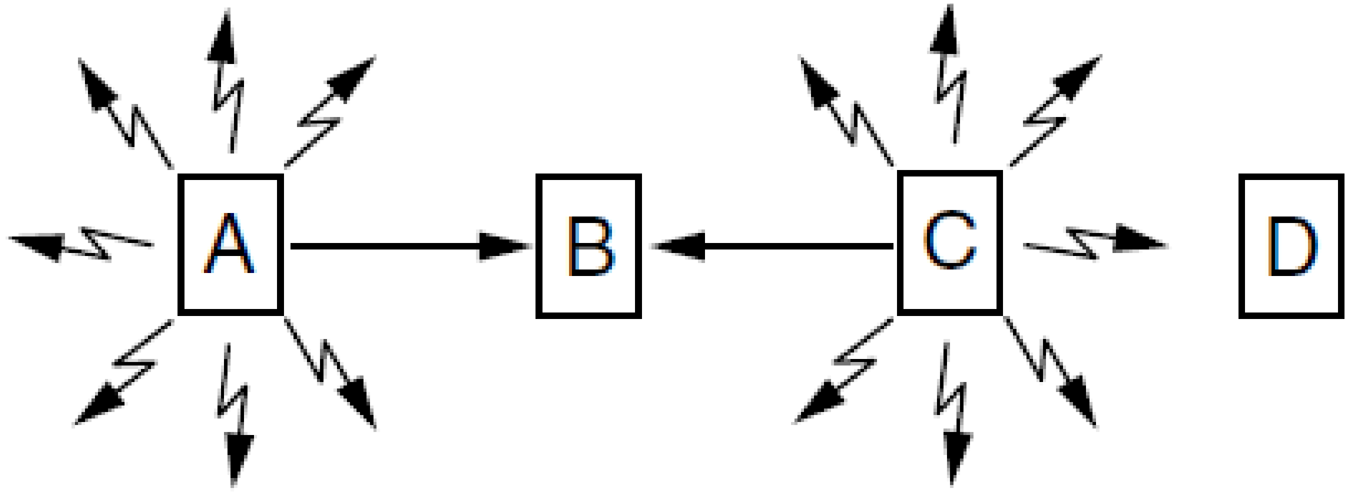
## No CS: Different Coverage Areas

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



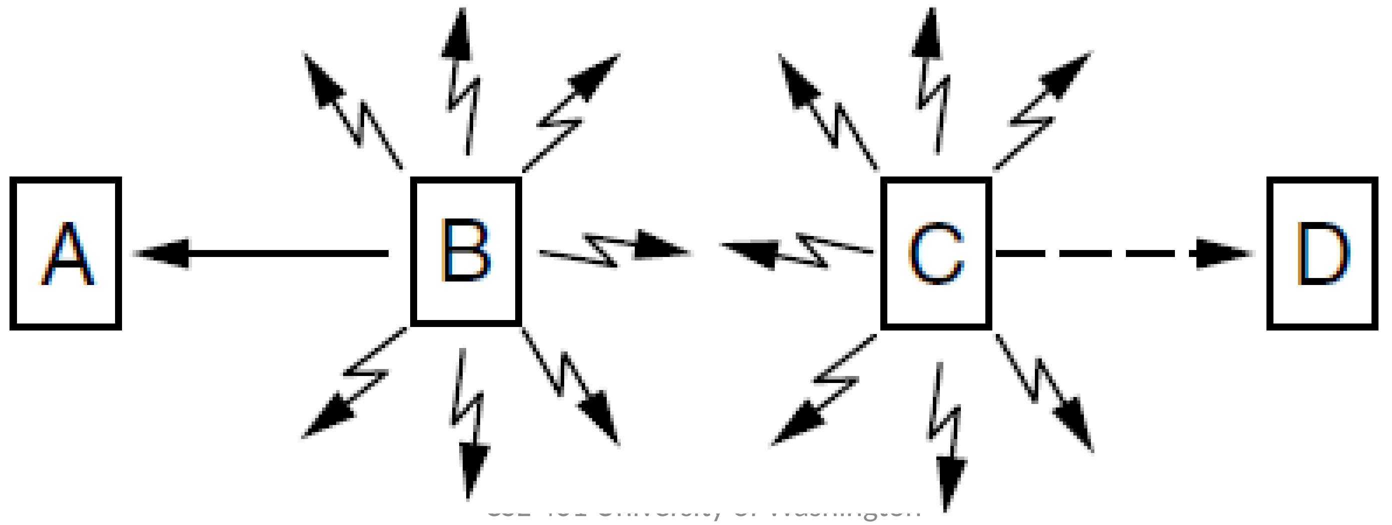
## No CS: Hidden Terminals

- 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



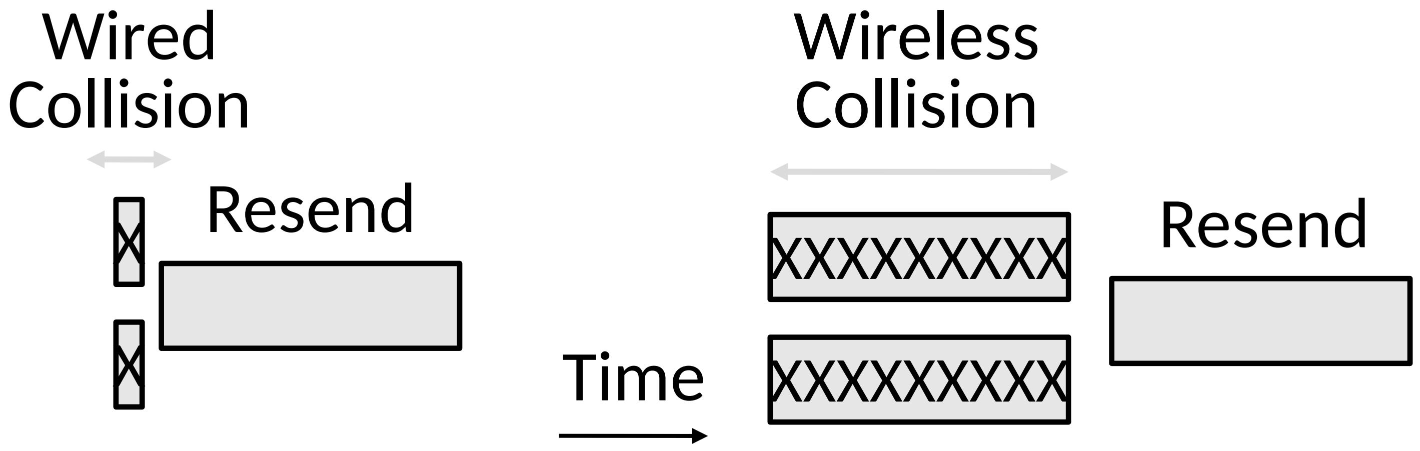
## No CS: Exposed Terminals

- B and C are <u>exposed terminals</u> 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

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



## Wireless Problems:

- Ideas?

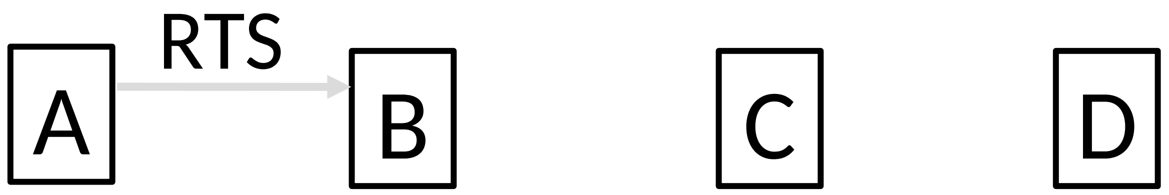
## MACA (Multiple Access with Collision Avoidance)

- MACA uses a short handshake instead of CSMA (Karn, 1990)
  - 802.11 uses a refinement of MACA (later)

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

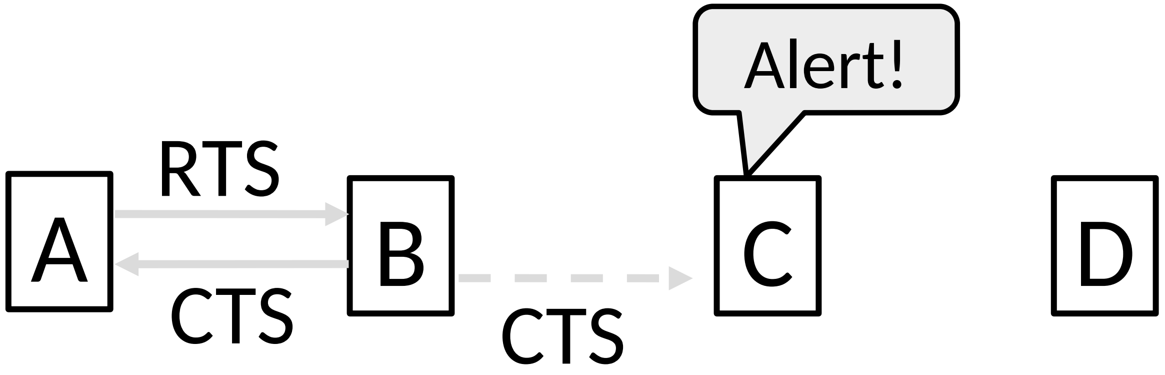
# MACA – Hidden Terminals

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



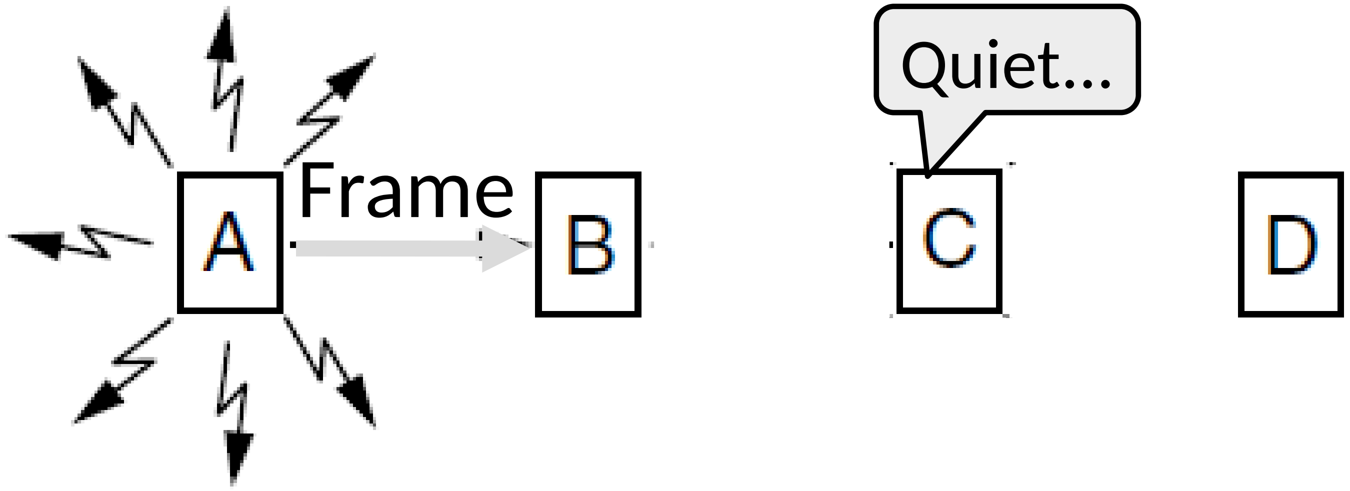
## MACA – Hidden Terminals (2)

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



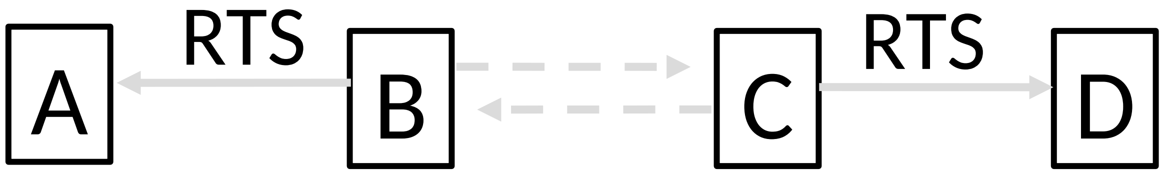
## MACA – Hidden Terminals (3)

- A $\rightarrow$ B with hidden terminal C
  3. A sends frame while C defers



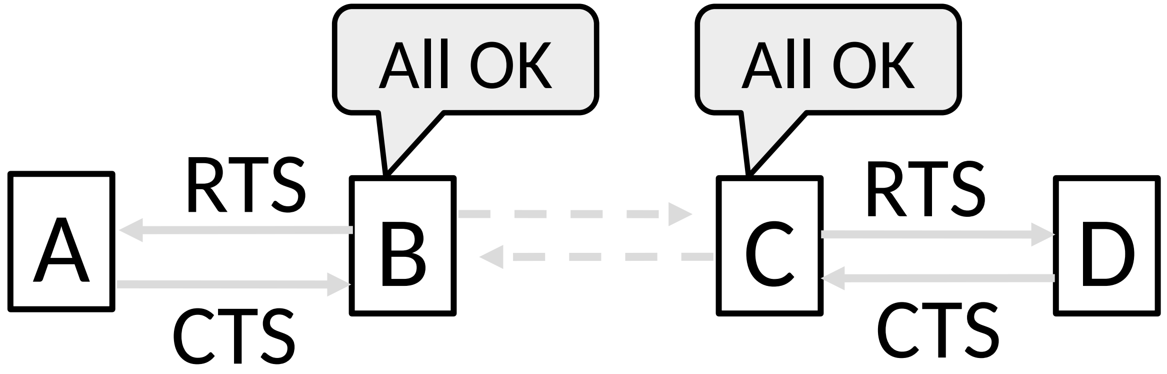
## MACA – Exposed Terminals

- B $\rightarrow$ A, C $\rightarrow$ D as exposed terminals
  - B and C send RTS to A and D



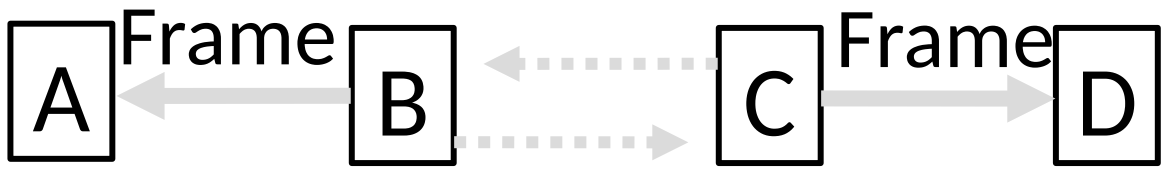
# MACA – Exposed Terminals (2)

- B $\rightarrow$ A, C $\rightarrow$ D as exposed terminals
  - A and D send CTS to B and C



## MACA – Exposed Terminals (3)

- B $\rightarrow$ A, C $\rightarrow$ D as exposed terminals
  - A and D send CTS to B and C

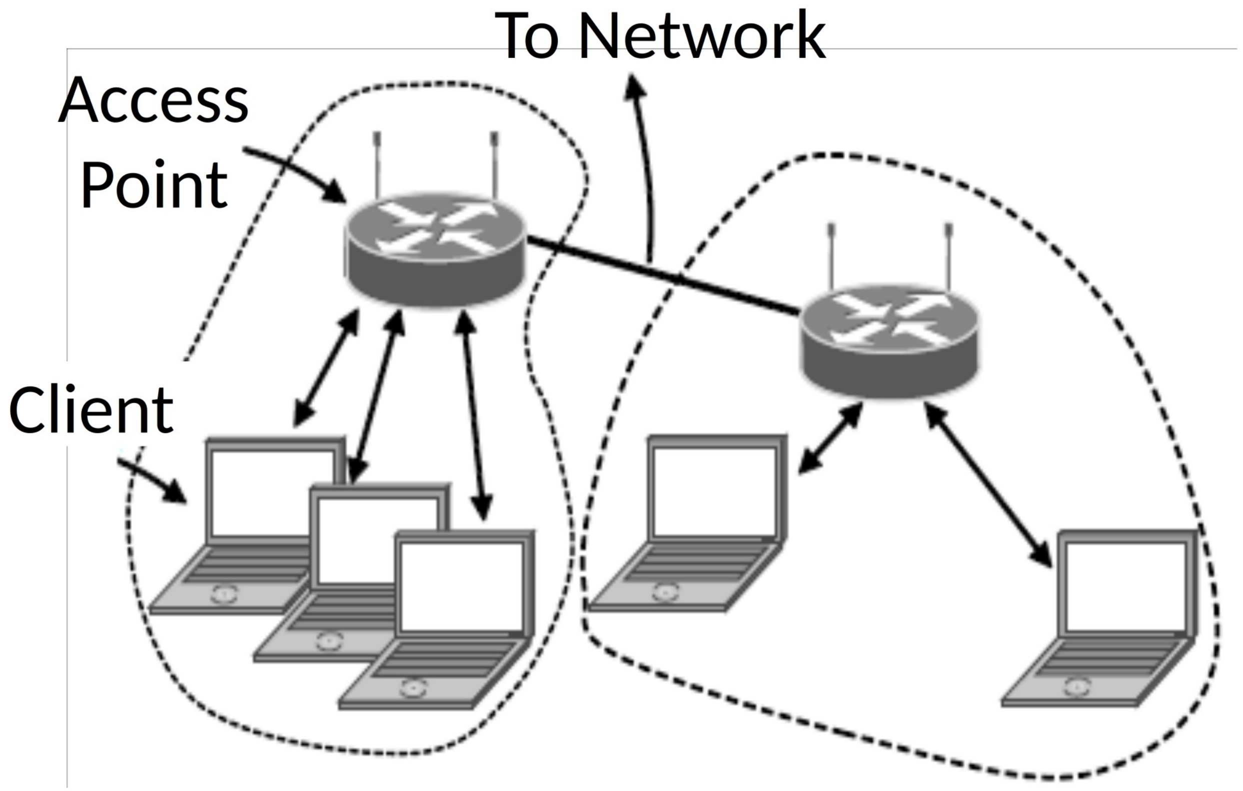


## MACA

- Assumptions? Where does this break?

# 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

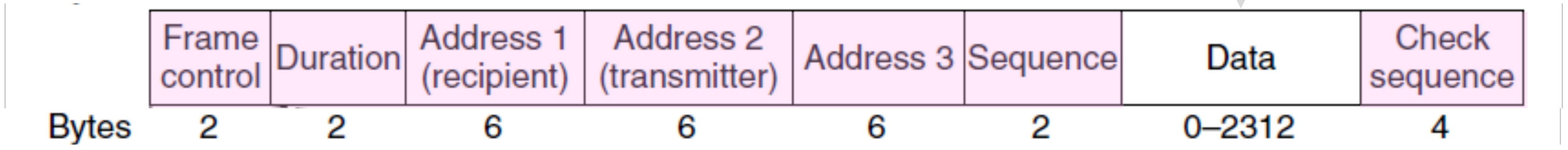
- Uses 20/40 MHz channels on ISM (unlicensed) bands
  - 802.11b/g/n on 2.4 GHz
  - 802.11 a/n on 5 GHz

- OFDM modulation (except legacy 802.11b)
  - Different amplitudes/phases for varying SNRs
  - Rates from 6 to 54 Mbps  plus error correction
  - 802.11n uses multiple antennas
    - Lots of fun tricks here

# 802.11 Link Layer

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

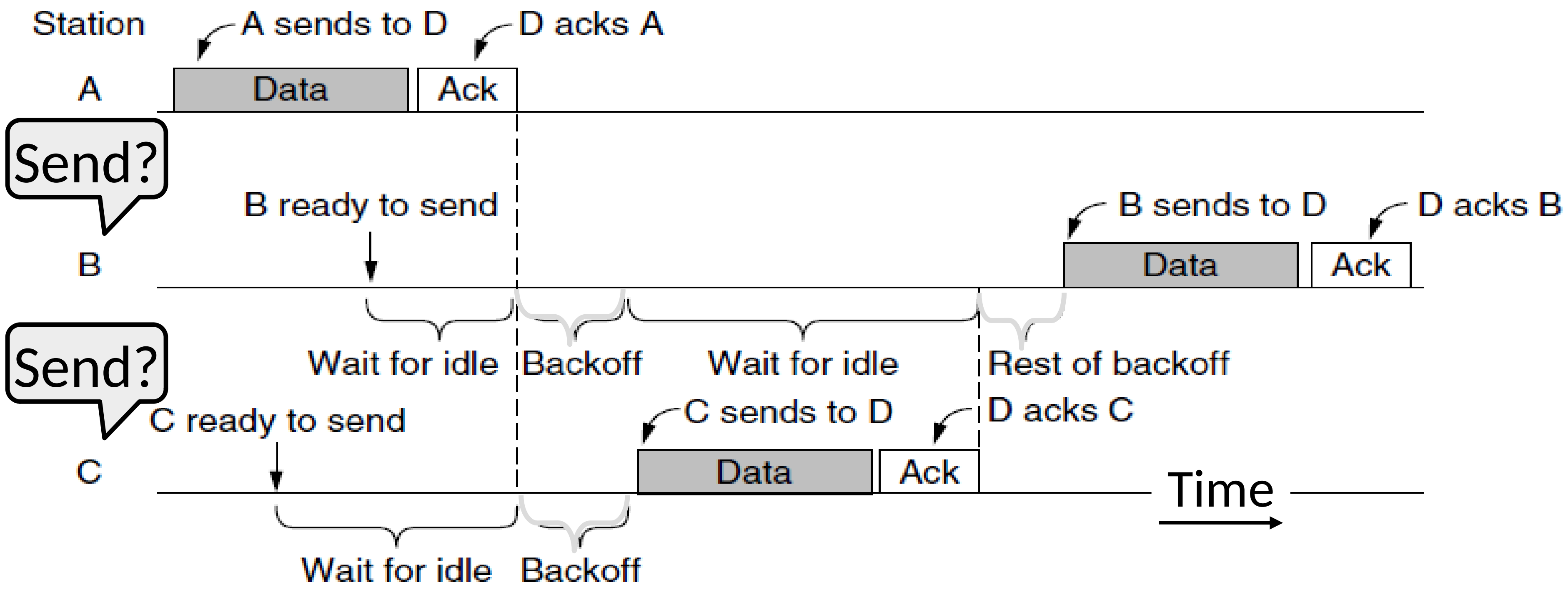
Packet from Network layer (IP)



| | 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!

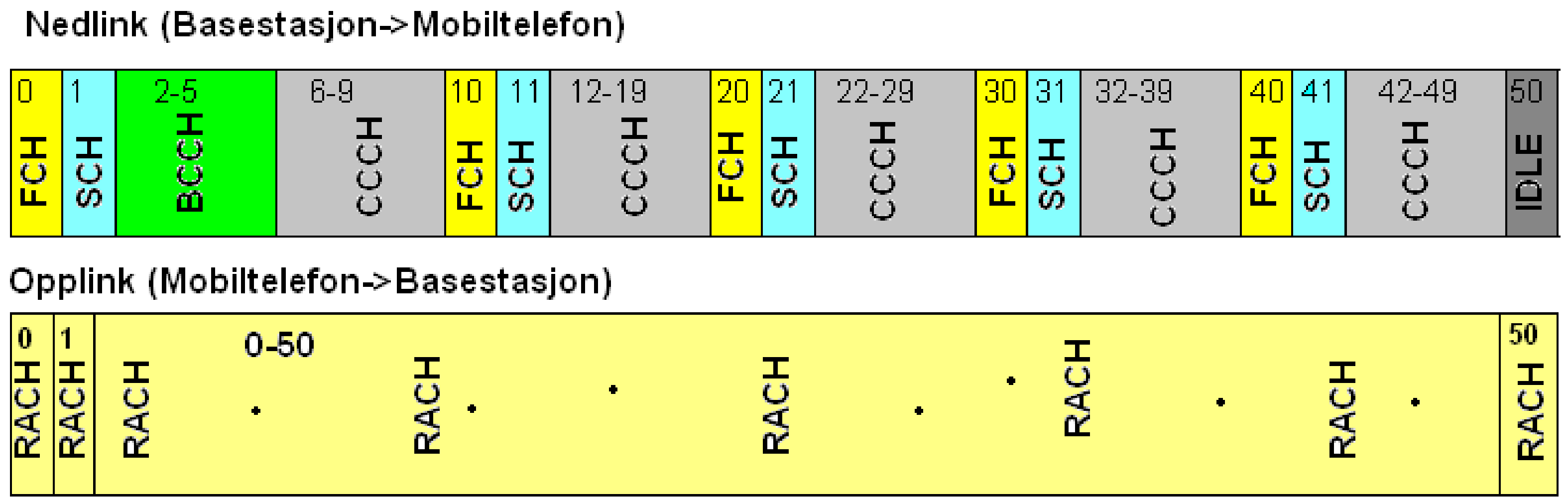


## Centralized MAC: Cellular

- 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

# GSM MAC

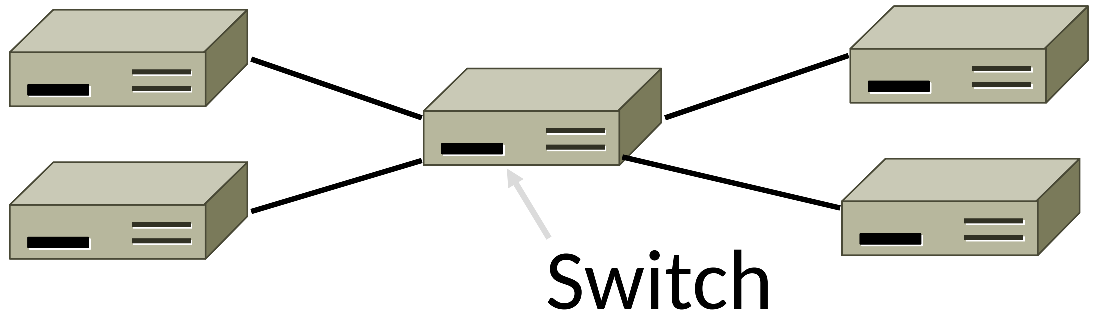
- FDMA/TDMA
- Use one channel for coordination – Random access w/BEB (no CSMA, can’t detect)
- Use other channels for traffic
  - Dedicated channel for QoS



## Link Layer: Switching

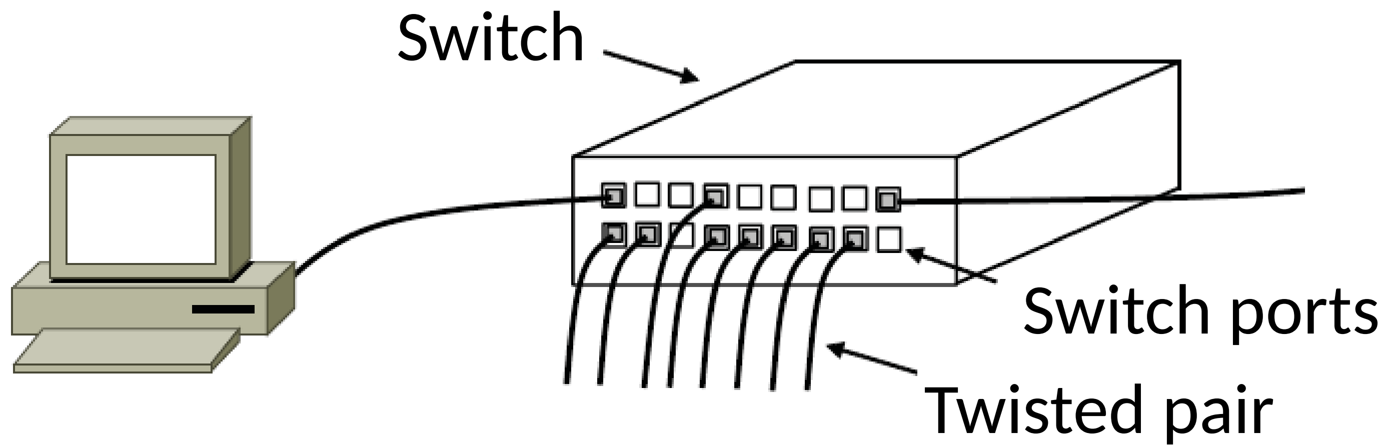
## Topic

- How do we connect nodes with a <u>switch</u> instead of multiple access
  - Uses multiple links/wires
  - Basis of modern (switched) Ethernet



## Switched Ethernet

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



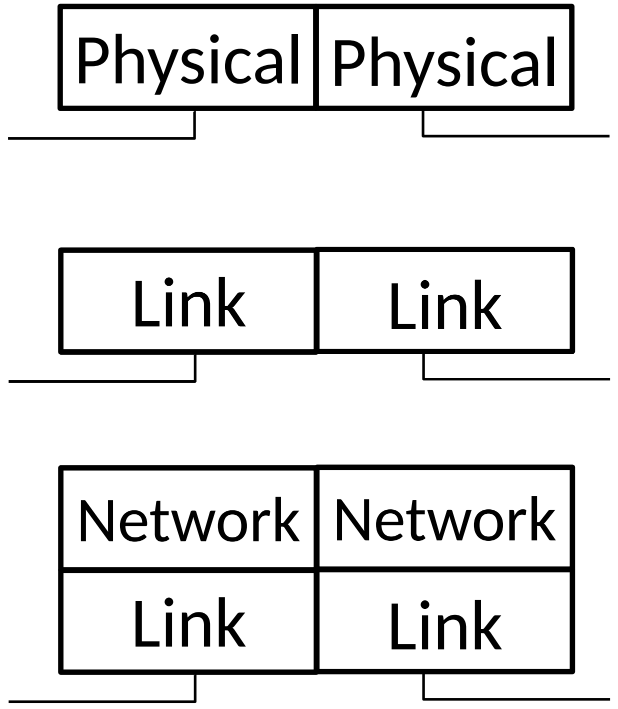
# What's in the box?

- Remember from protocol layers:

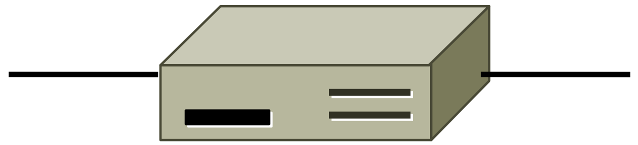
Hub, or repeater

Switch

Router

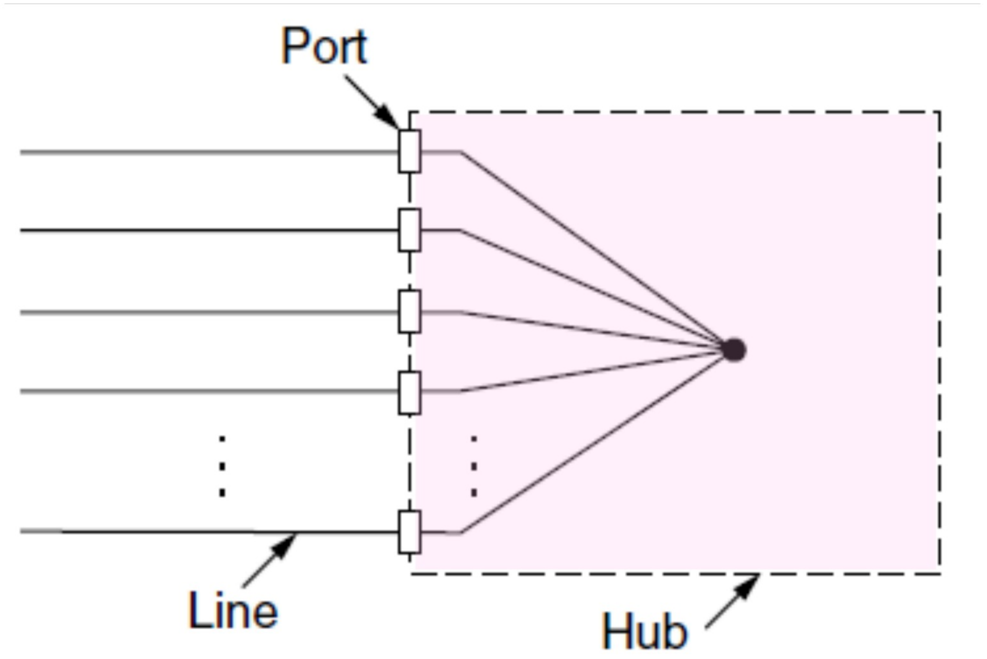


All look like this:



## Inside a Hub

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



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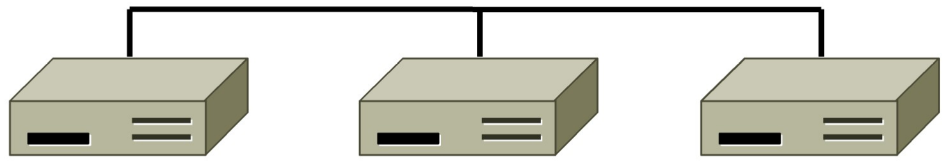
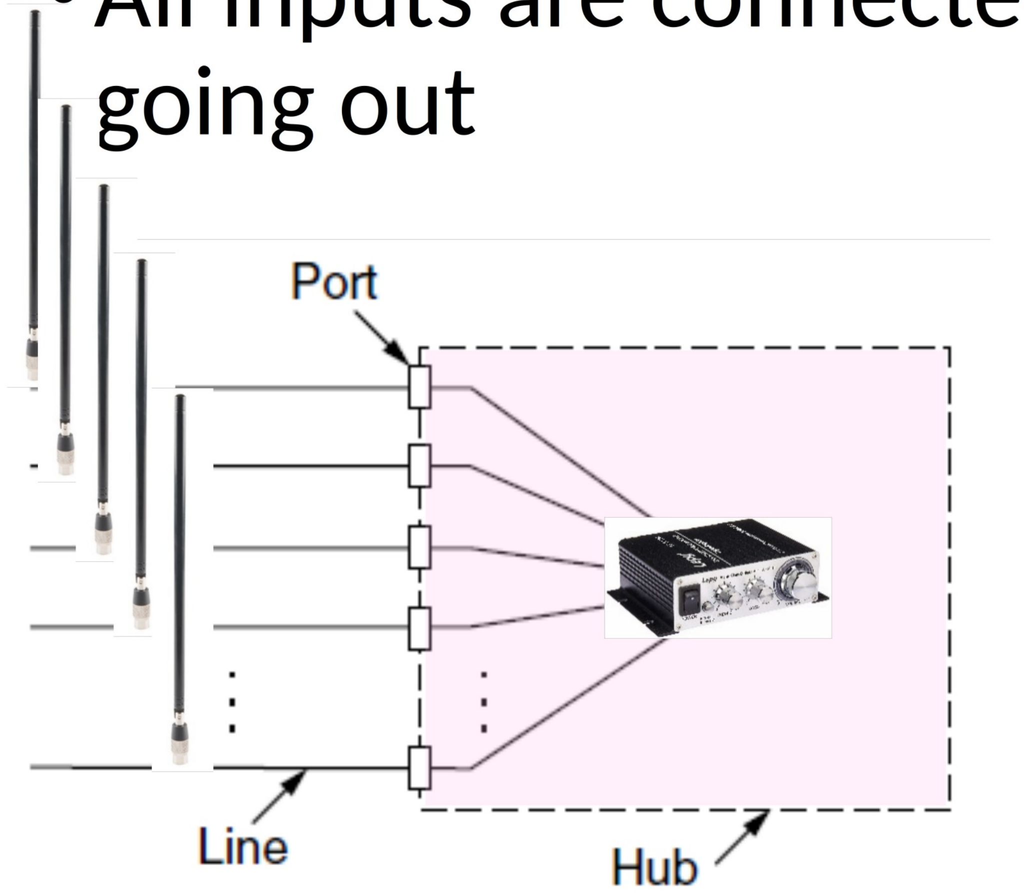


# Inside a Repeater

- All inputs are connected; then amplified before going out



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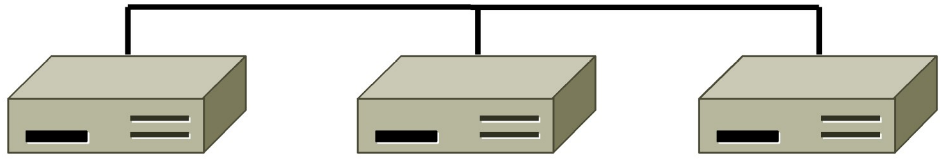
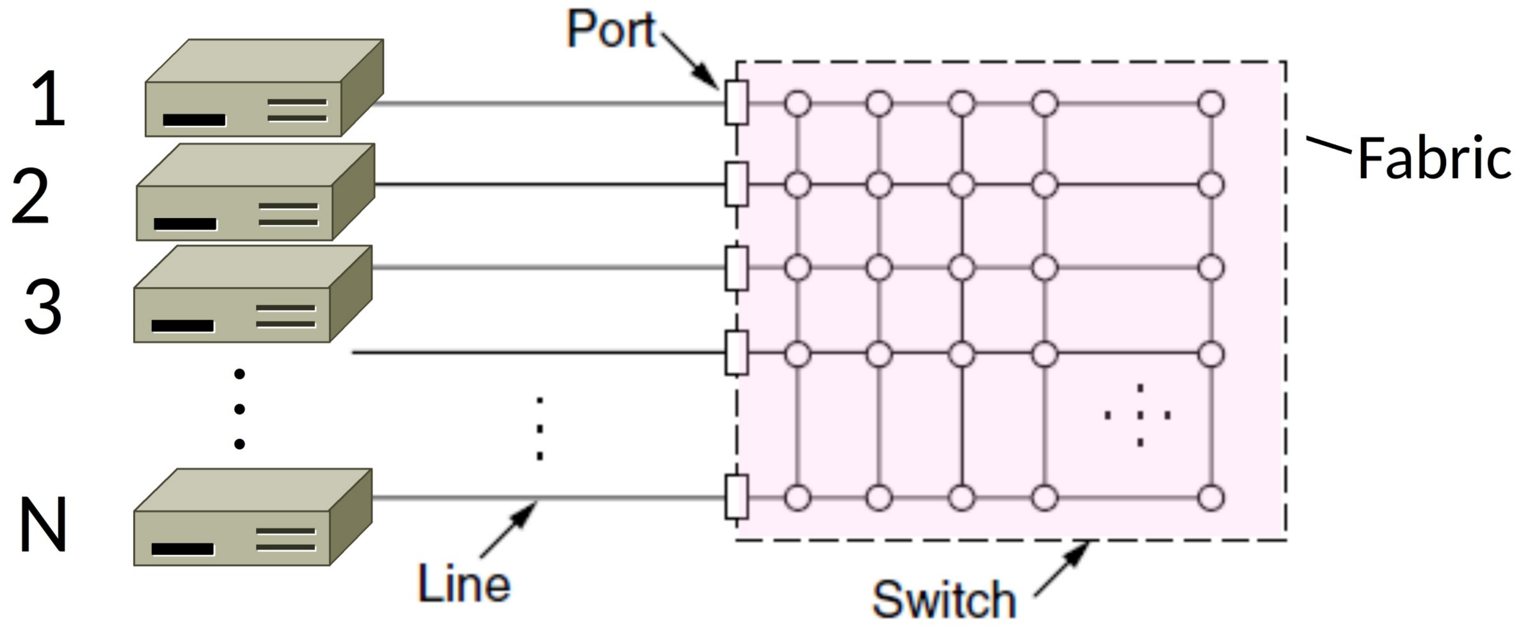


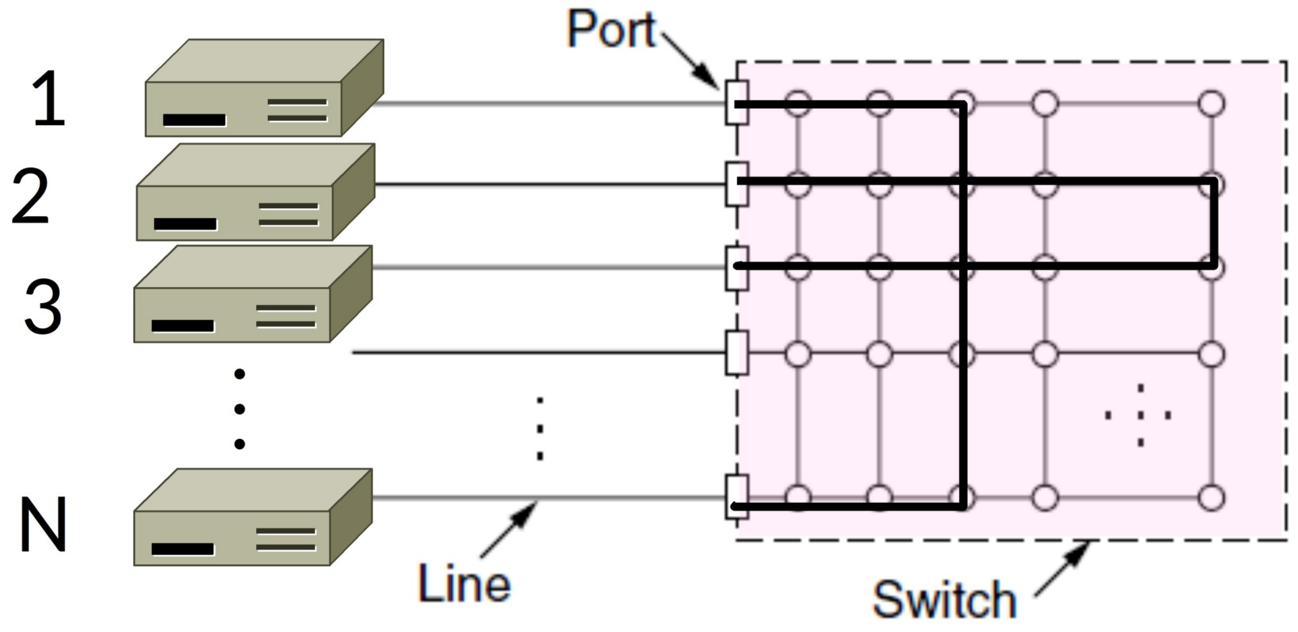
# Inside a Switch

- 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)

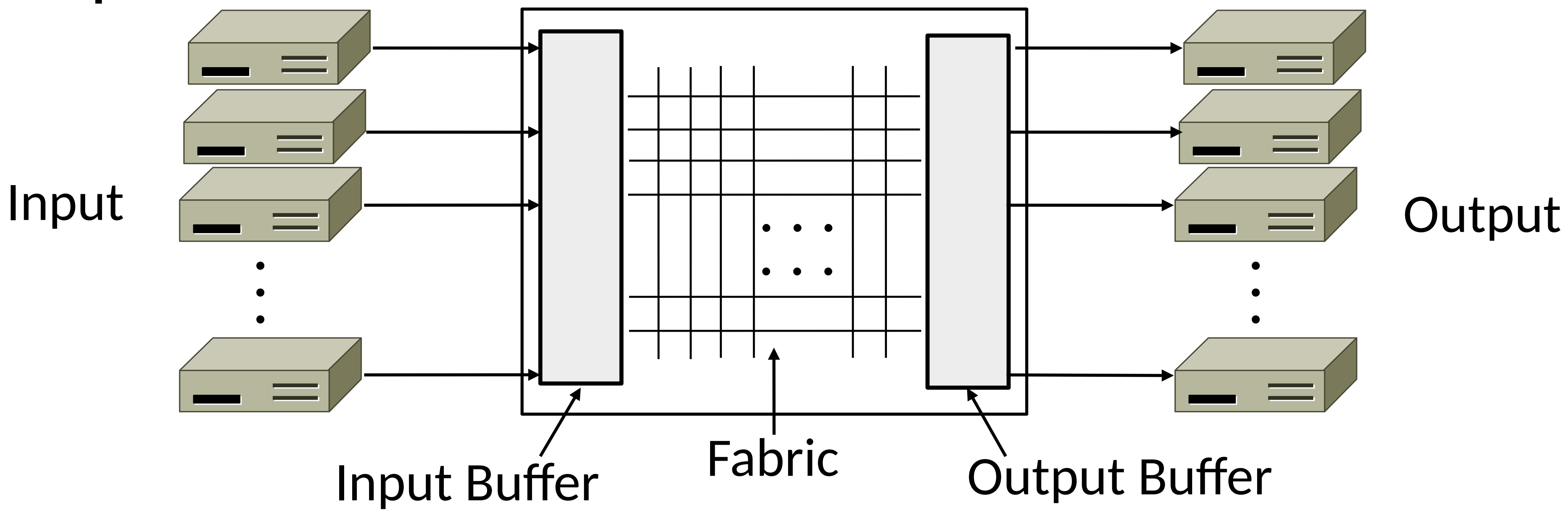
- Port may be used for both input and output (full-duplex)
  - Just send, no multiple access protocol



1 □ 4
and
2 □ 3

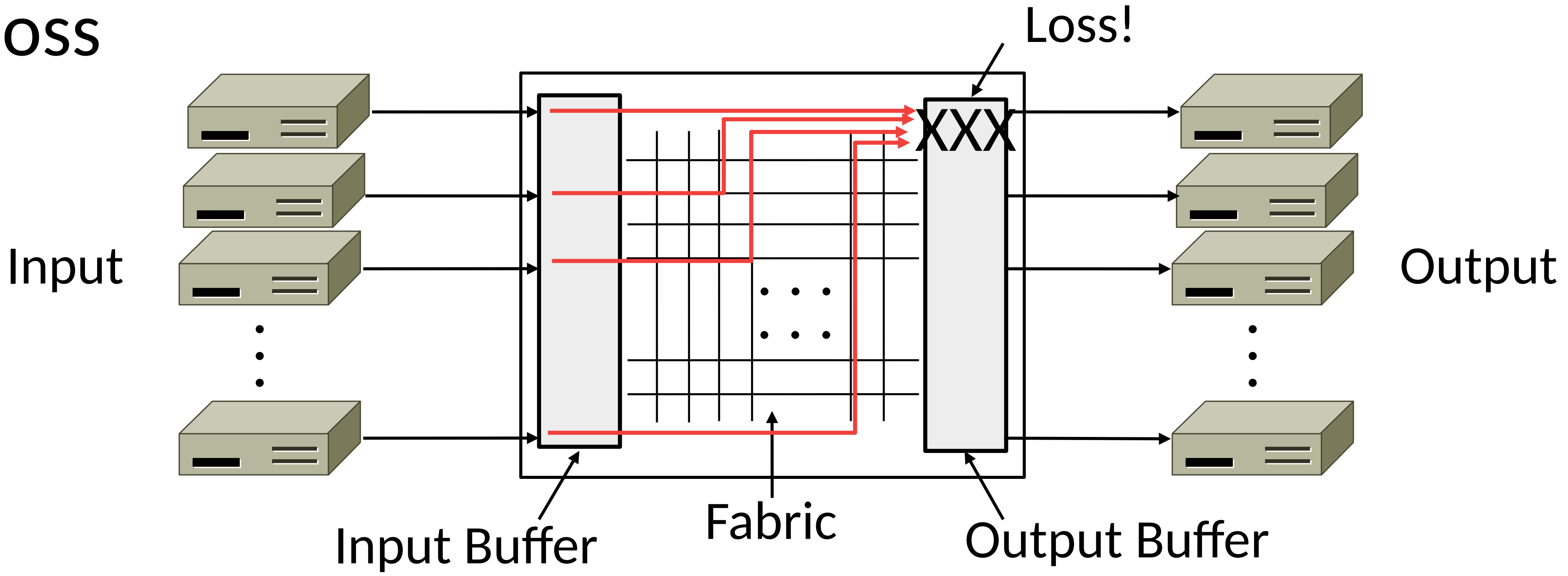
# Inside a Switch (3)

- Need buffers for multiple inputs to send to one output



# Inside a Switch (4)

- Sustained overload will fill buffer and lead to frame loss



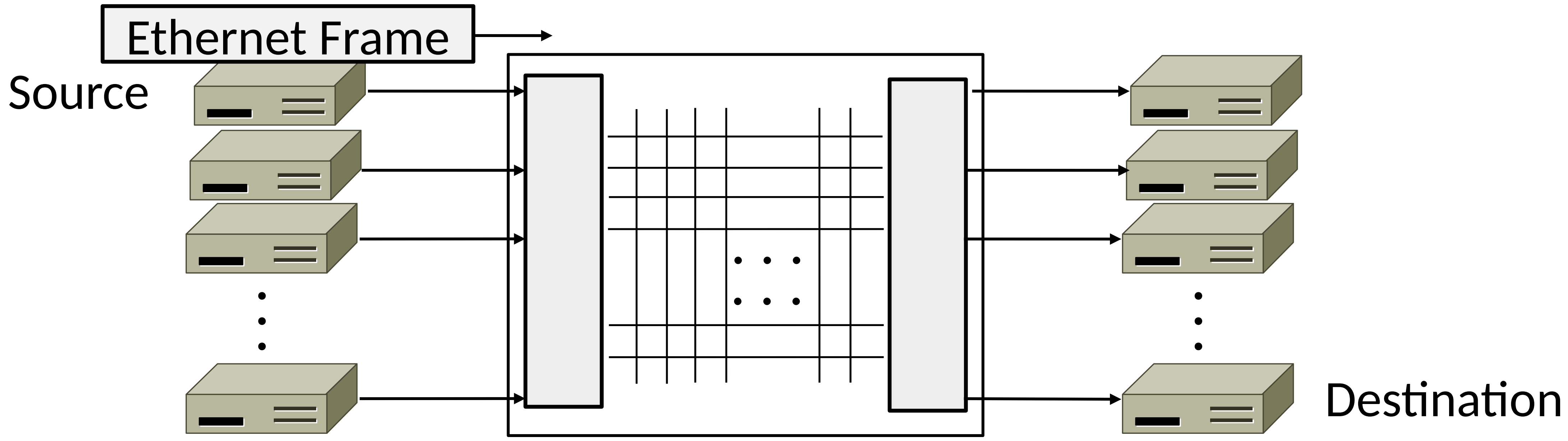
## Advantages of Switches

- 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

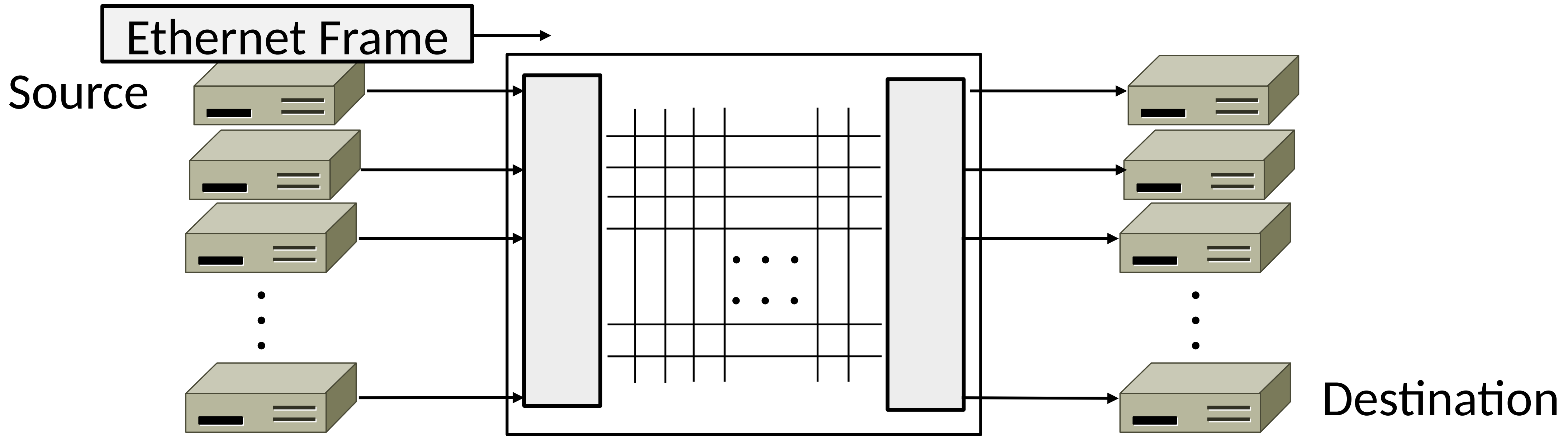
## Switch Forwarding

- 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?

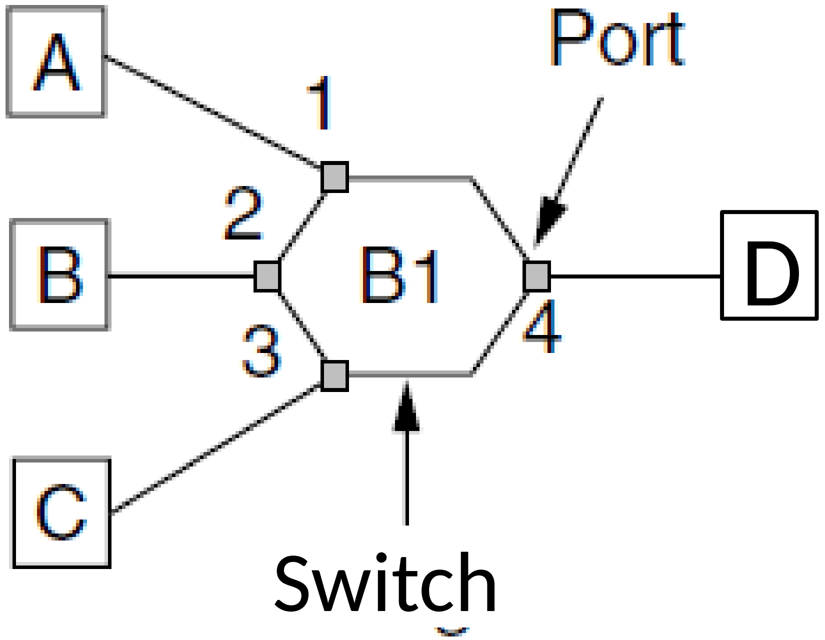


## Backward Learning

- 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)

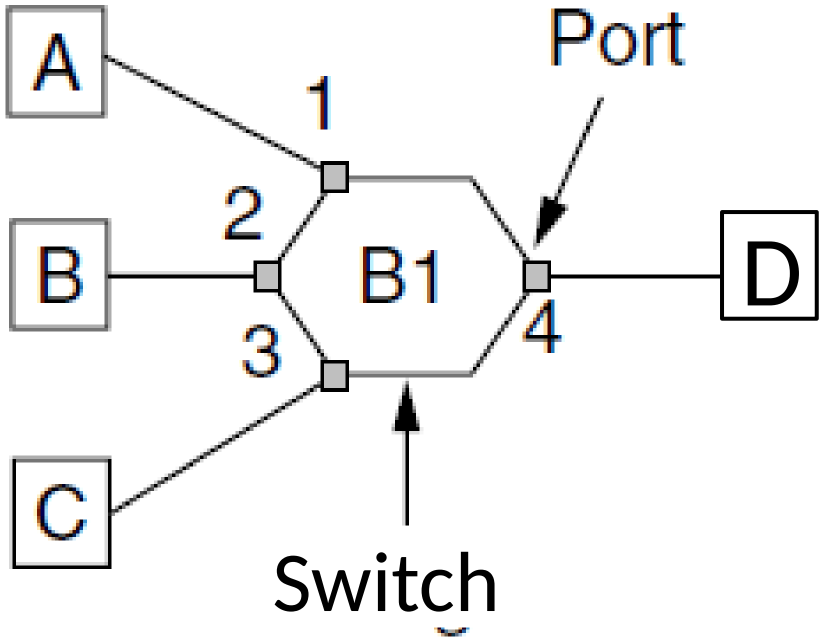
- 1: A sends to D



| Address | Port |
|---|---|
| A | |
| B | |
| C | |
| D | |

# Backward Learning (3)

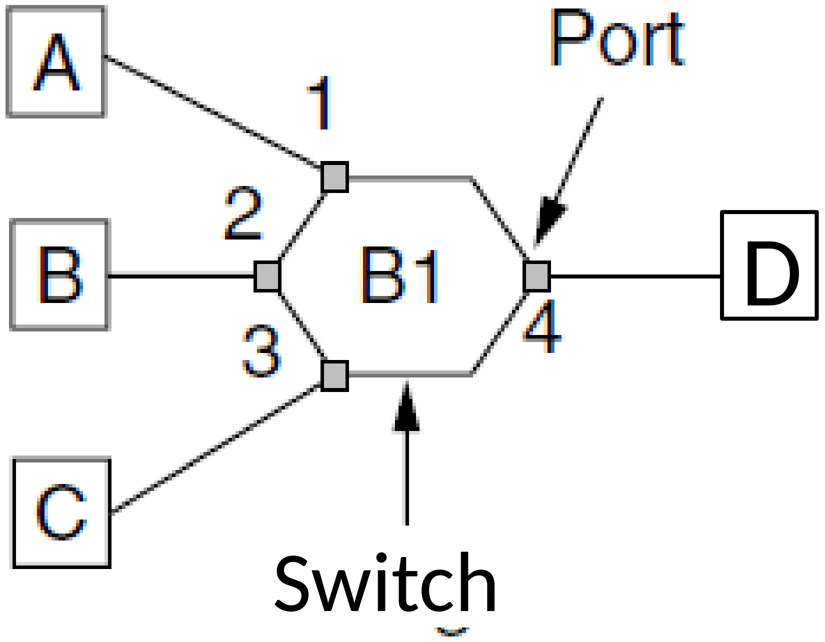
- 2: D sends to A



| Address | Port |
|---|---|
| A | 1 |
| B | |
| C | |
| D | |

# Backward Learning (4)

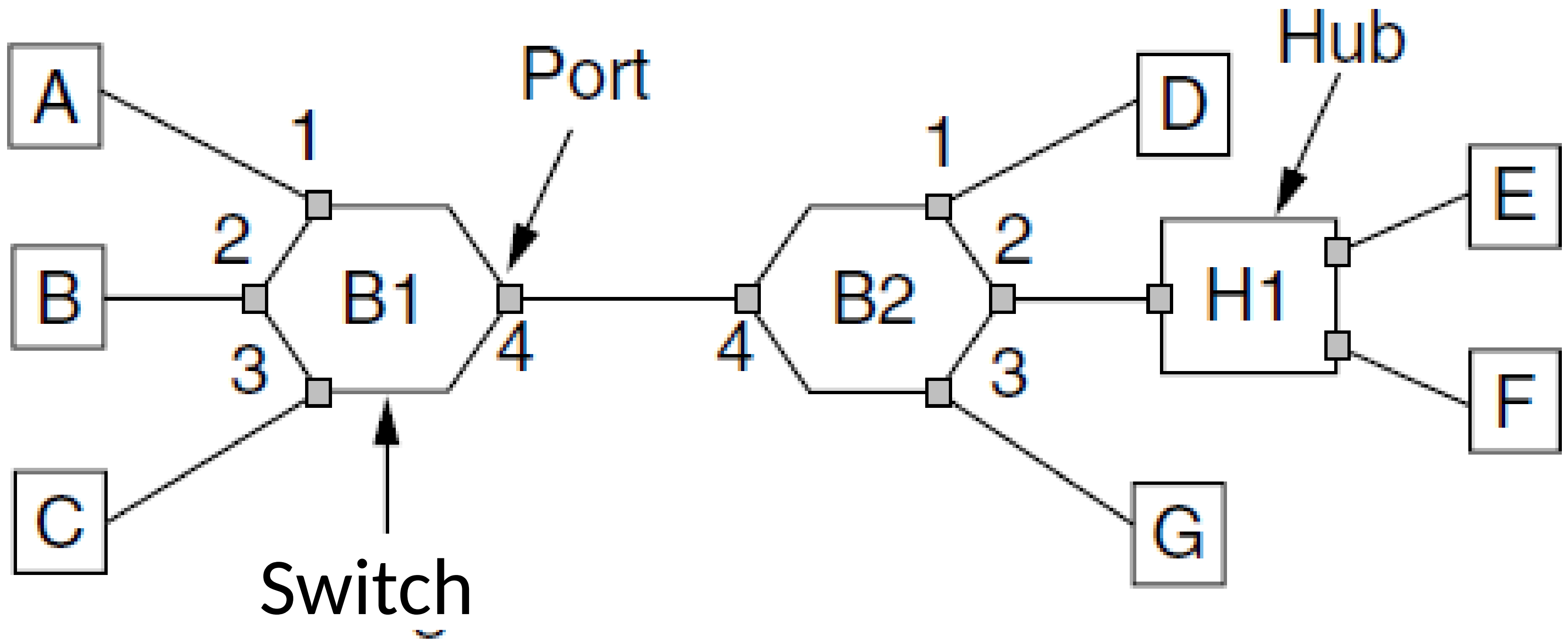
- 3: A sends to D



| Address | Port |
|---|---|
| A | 1 |
| B | |
| C | |
| D | 4 |

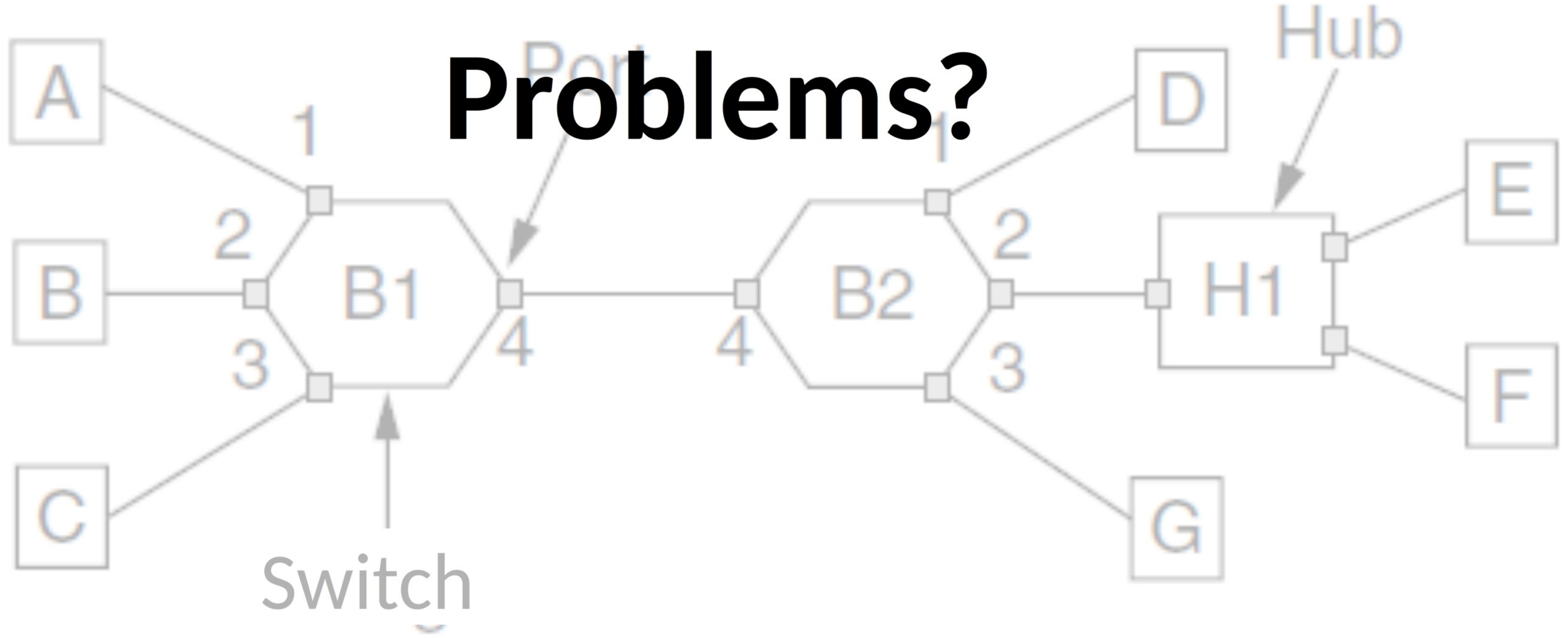
## Learning with Multiple Switches

- 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

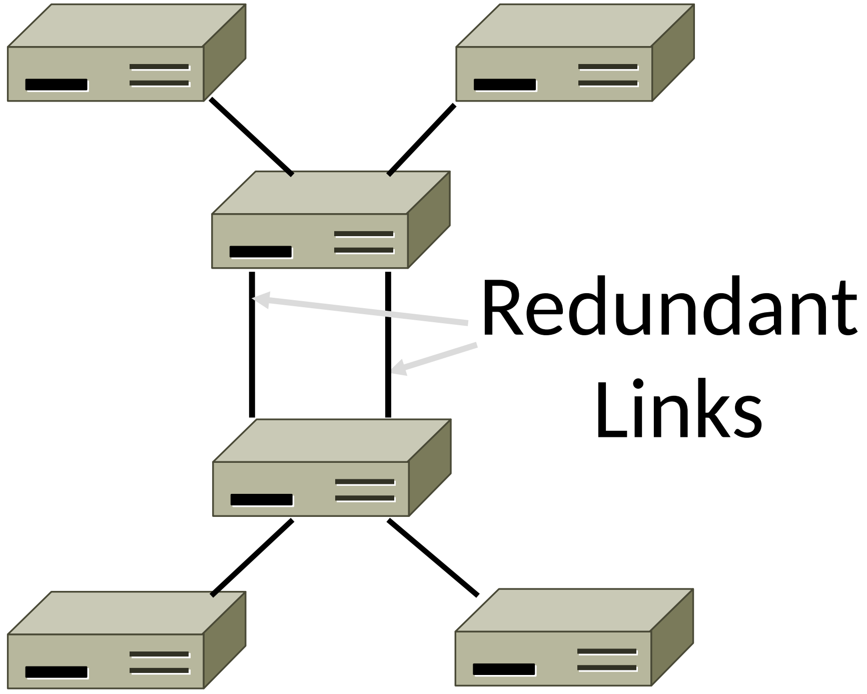


**Problems?**

# Problem – Forwarding Loops

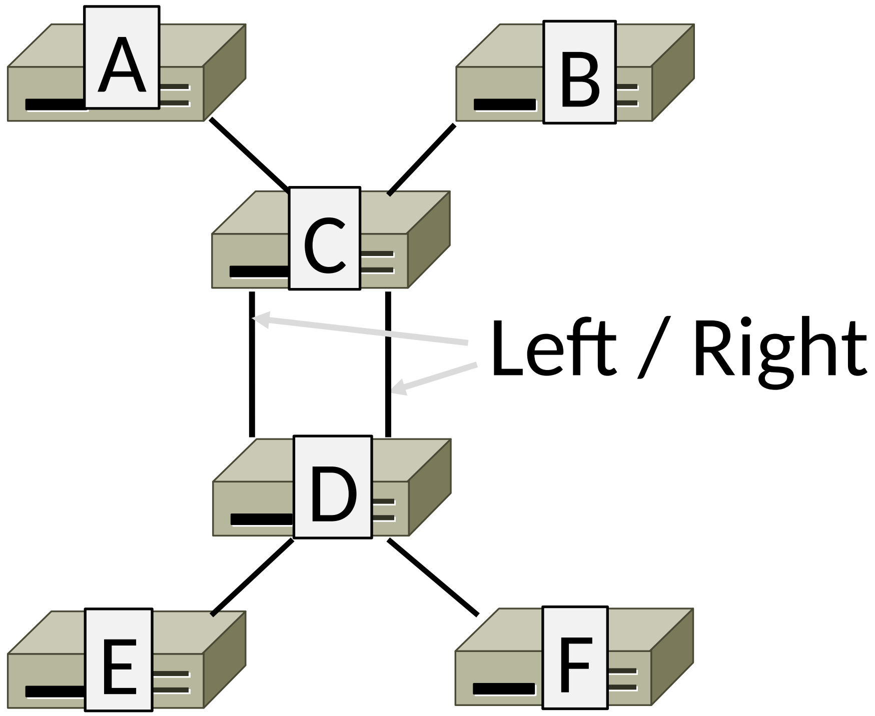
- May have a loop in the topology
  - Redundancy in case of failures
  - Or a simple mistake

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



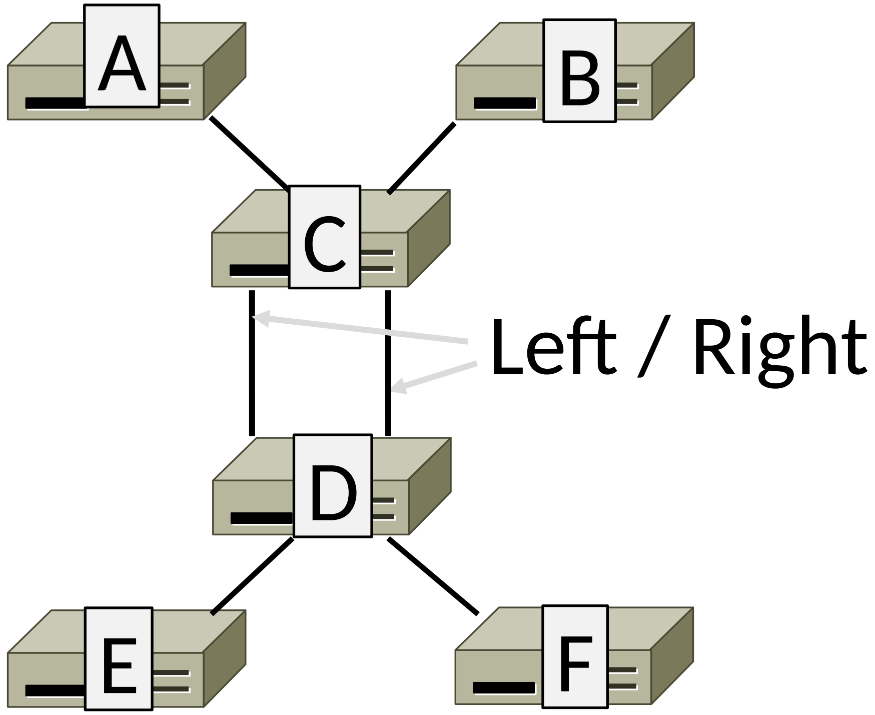
## Forwarding Loops (2)

- 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 → …

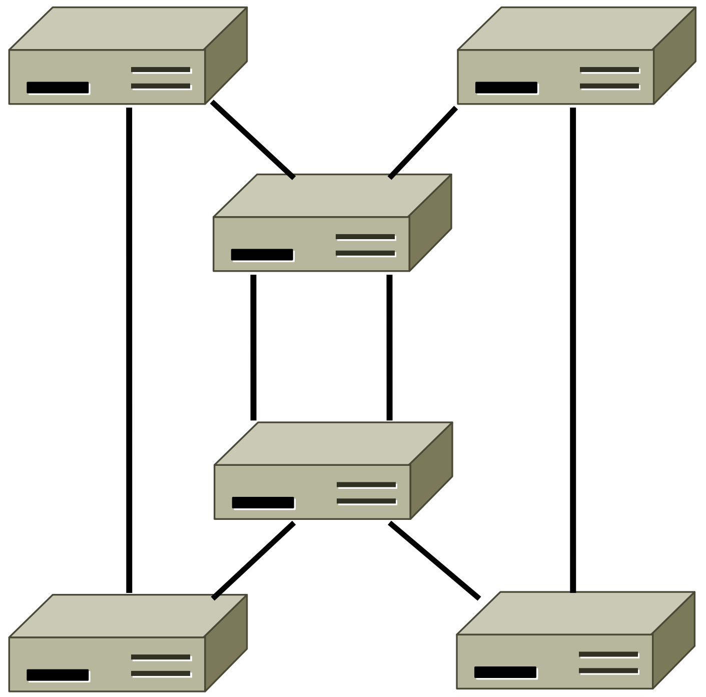


## Spanning Tree Solution

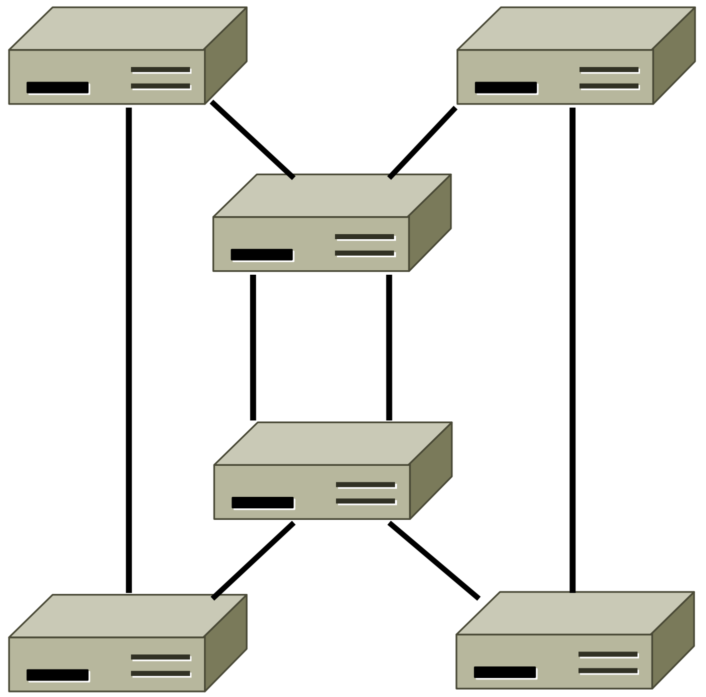
- Switches collectively find a spanning tree for the topology
  - A subset of links that is a tree (no loops) and reaches all switches
  - They switches forward as normal on the spanning tree
  - Broadcasts will go up to the root of the tree and down all the branches

# Spanning Tree (2)

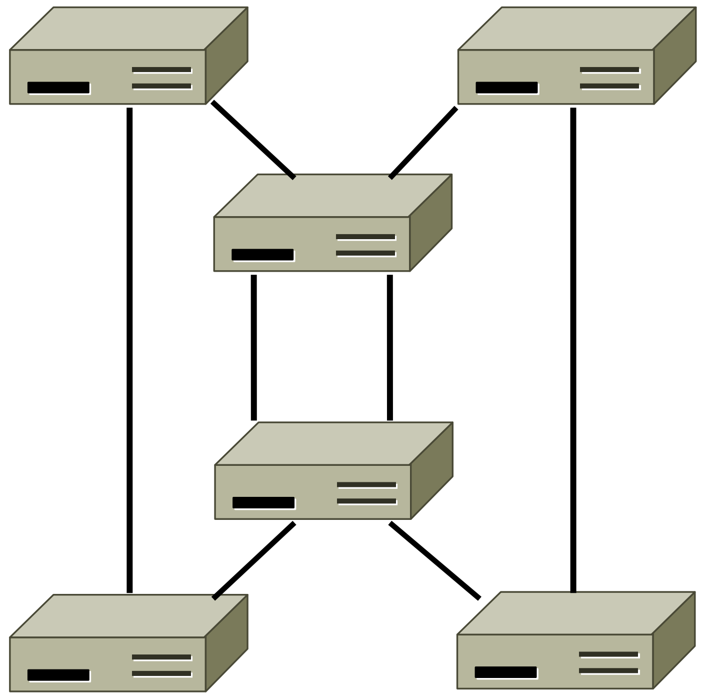
Topology



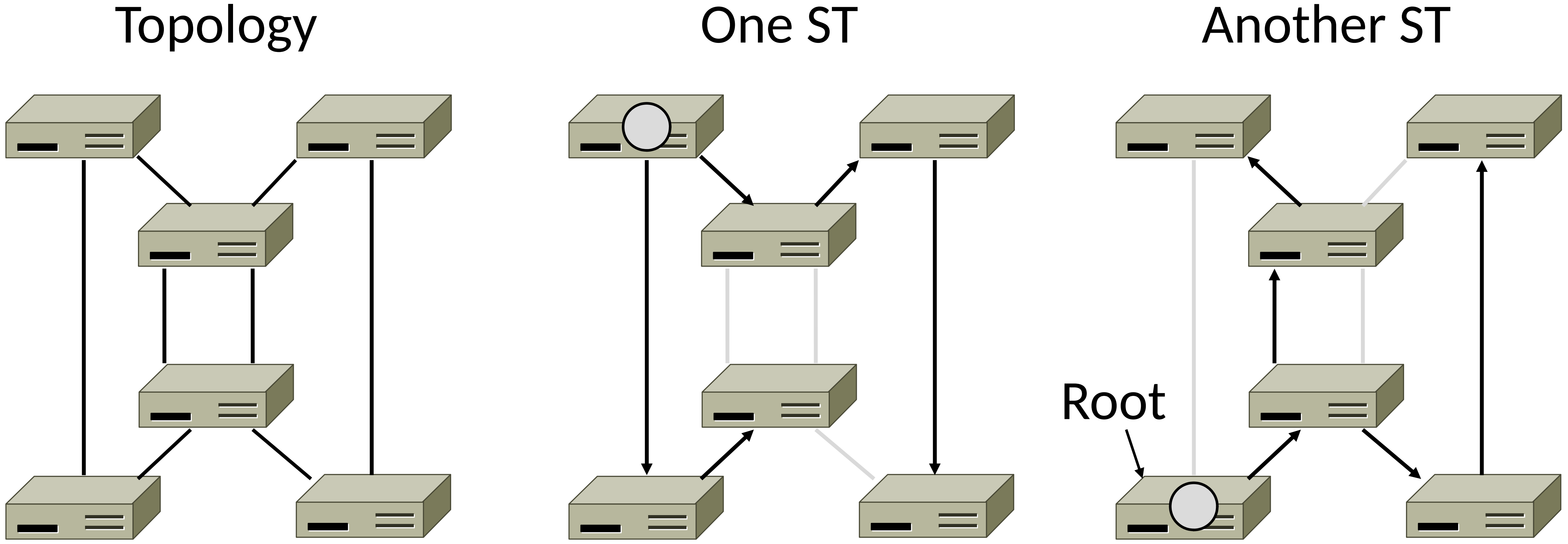
One ST



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)

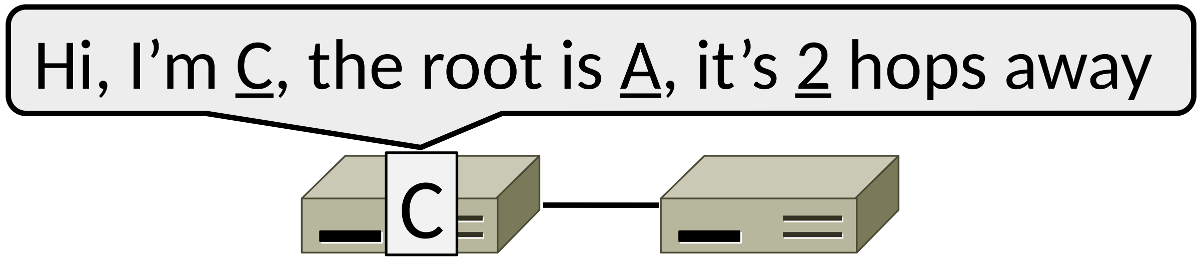
- Now focused on network security

## 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)

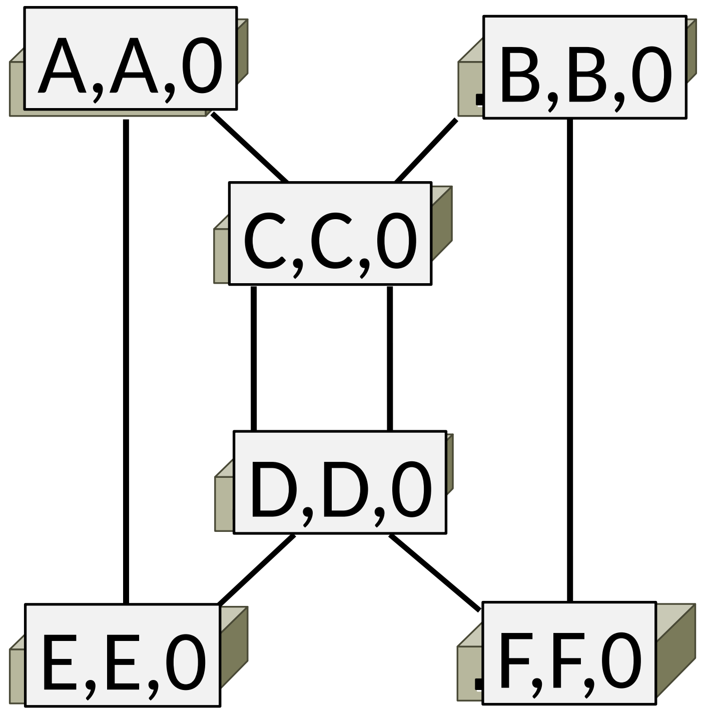
- Details:
  - Each switch initially believes it is the root of the tree
  - Each switch sends periodic updates to neighbors with:
    - Its address, address of the root, and distance (in hops) to root
    - Short-circuit when topology changes
  - Switches favors ports with shorter distances to lowest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



or (C, A, 2)

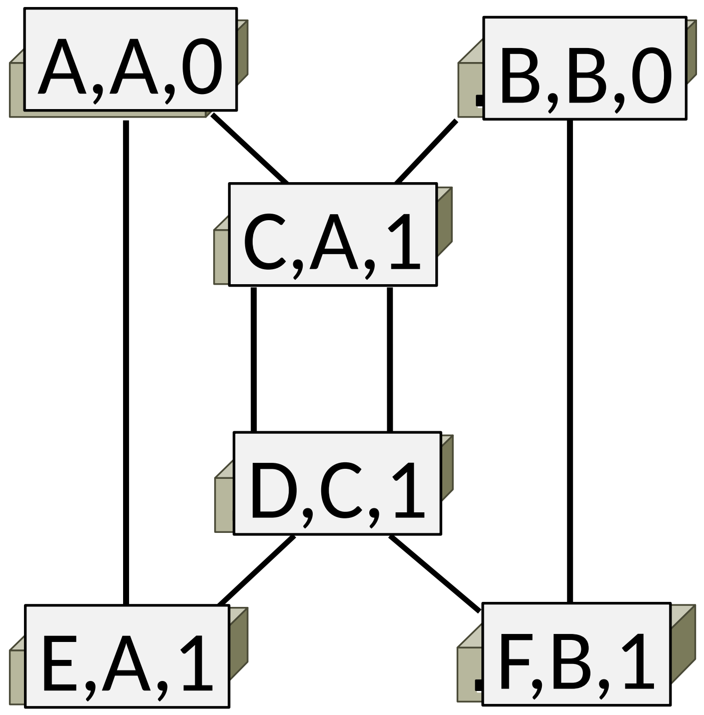
## Spanning Tree Example

- 1st round, sending:
  - A sends (A, A, 0) to say it is root
  - B, C, D, E, and F do likewise
- 1st 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)



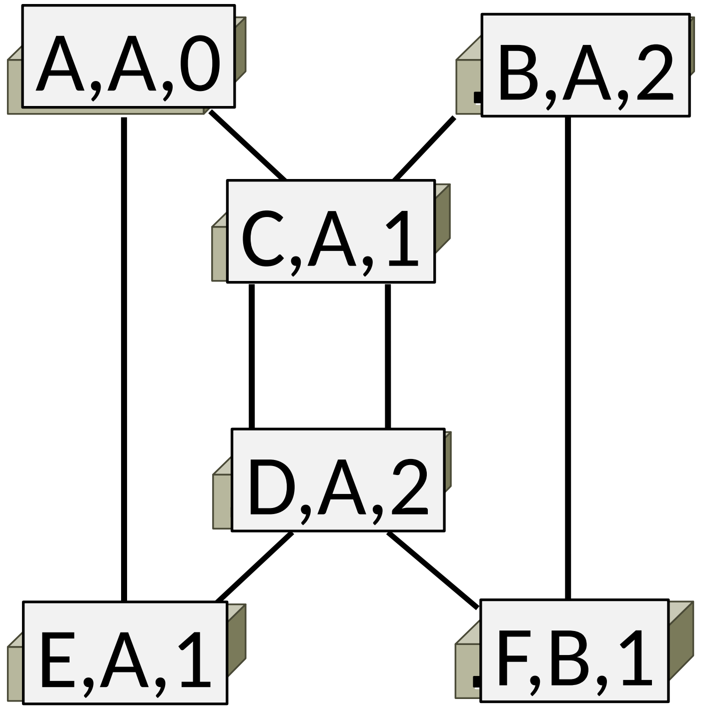
# Spanning Tree Example (2)

- 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)



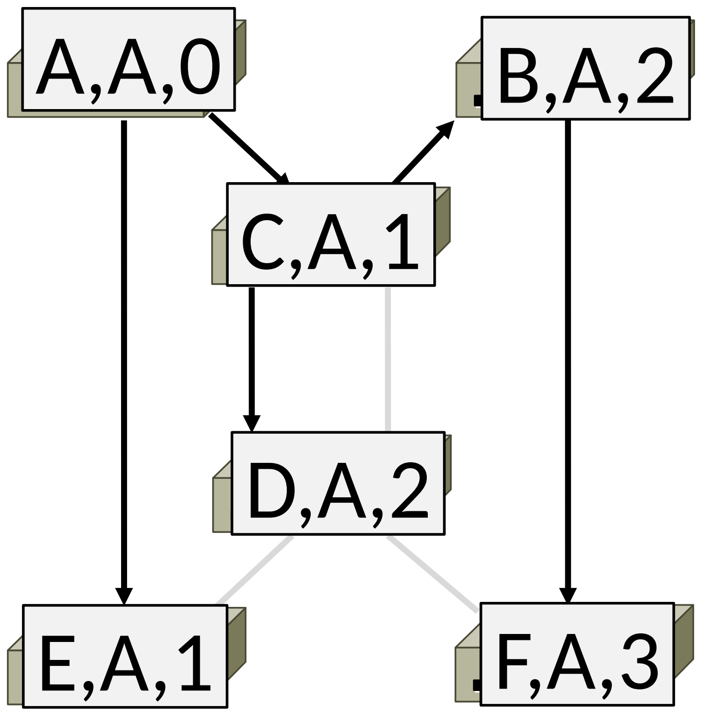
# Spanning Tree Example (3)

- 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



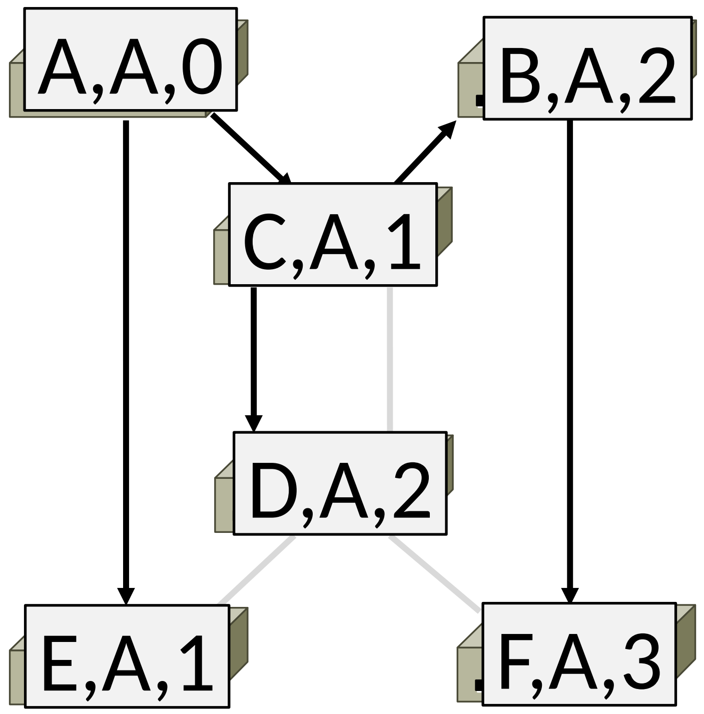
# Spanning Tree Example (4)

- 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)

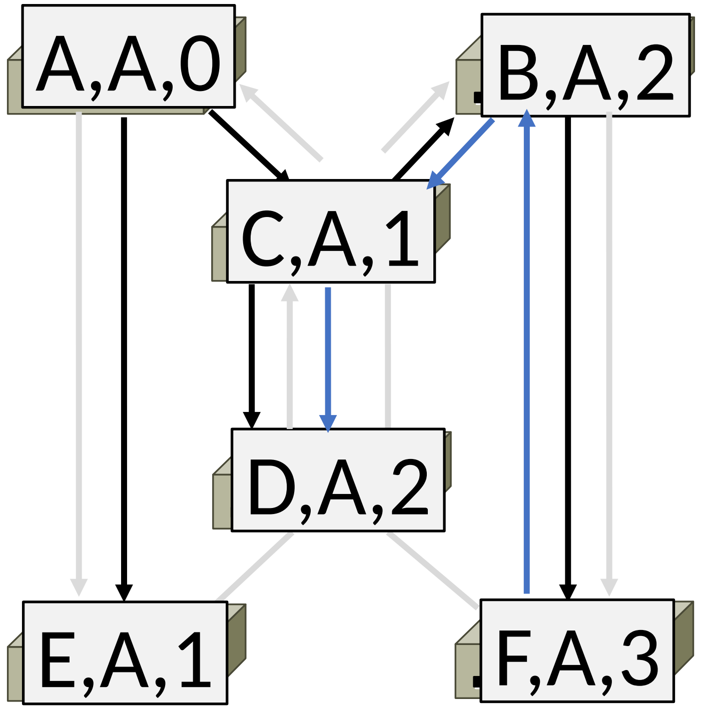
- Forwarding proceeds as usual on the ST
- Initially D sends to F:



- And F sends back to D:

# Spanning Tree Example (6)

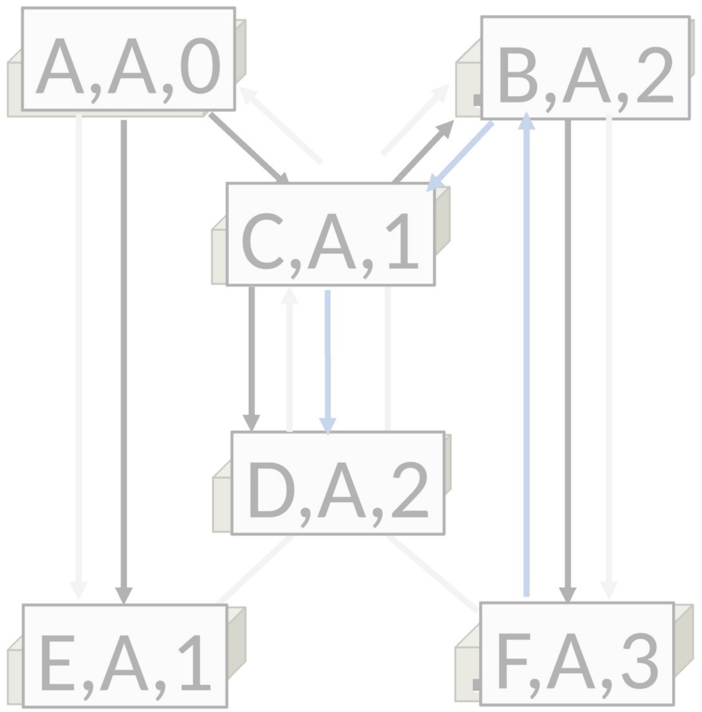
- Forwarding proceeds as usual on the ST
- Initially D sends to F:
  - D → C-left
  - C → A, B
  - A → E
  - B → F
- And F sends back to D:
  - F → B
  - B → C
  - C → D



## 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

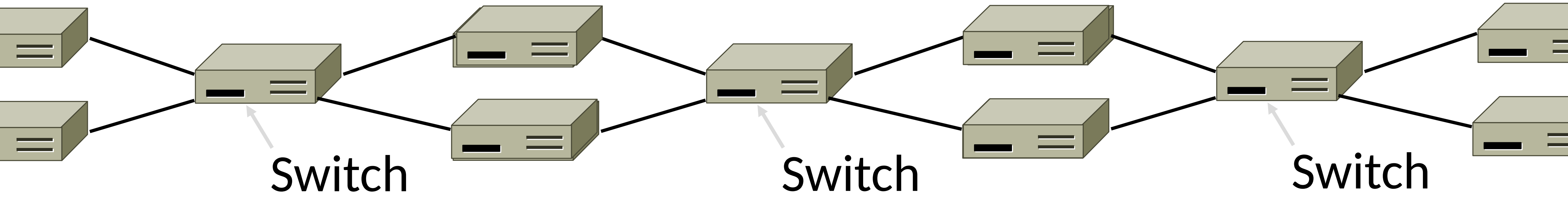
**Problems?**



## Link Layer: Software Defined Networking

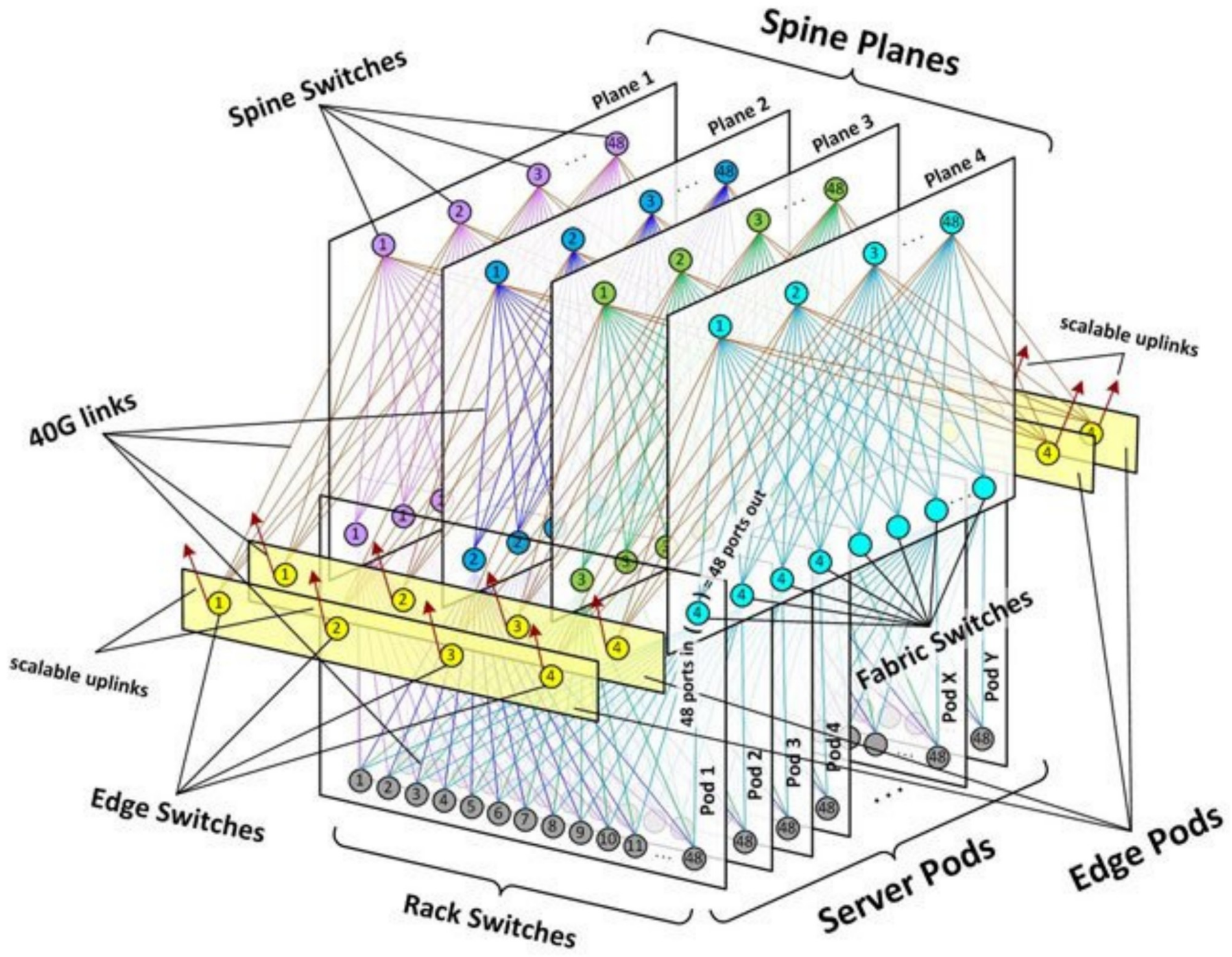
## Topic

- 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

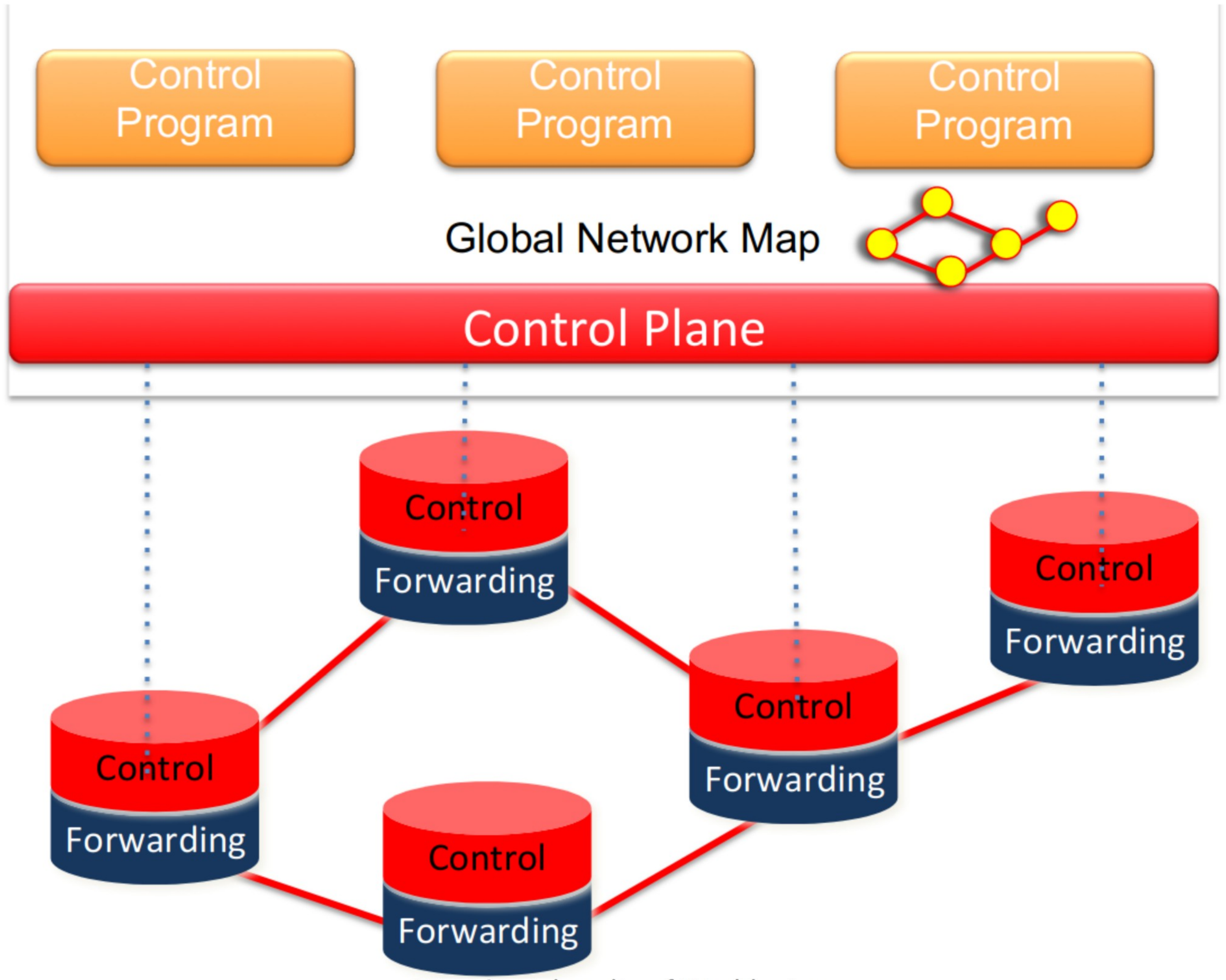
    - **Problems?**

## 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

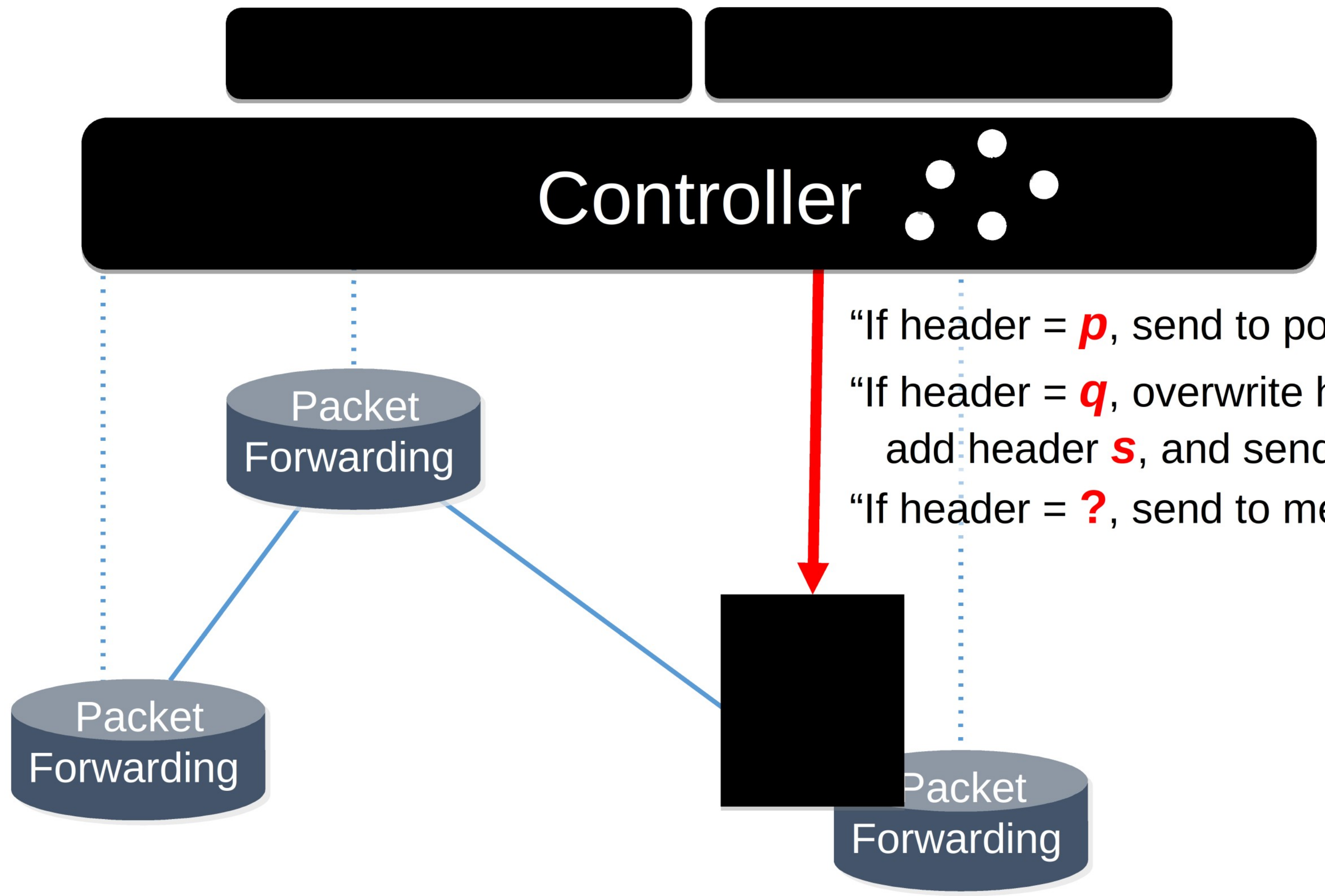


## SDN – Problem 2

- 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



“If header = ***p***, send to port 4”

“If header = ***q***, overwrite header with ***r***, add header ***s***, and send to ports 5,6”

“If header = **?**, send to me”

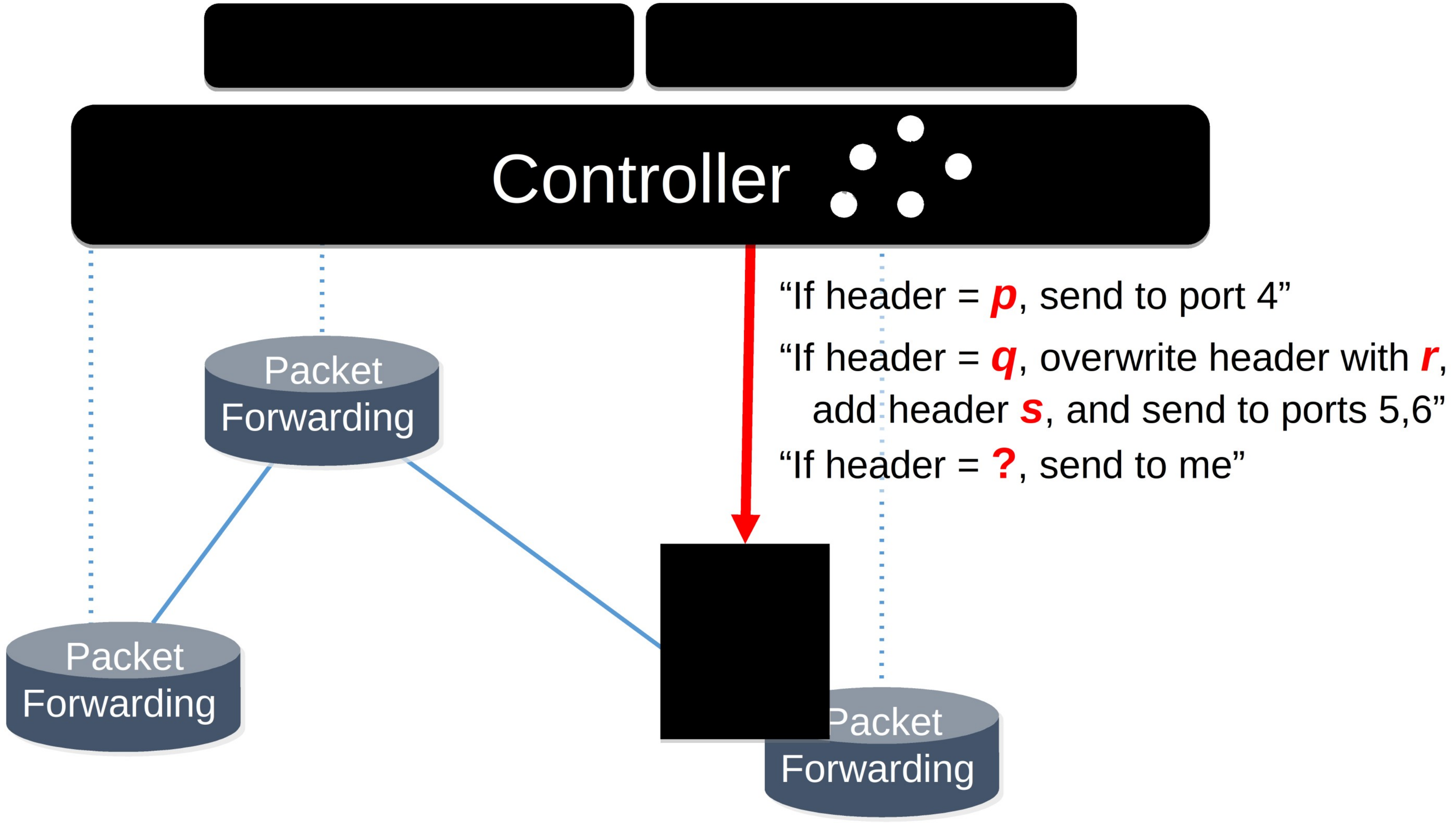
## SDN – OpenFlow

- 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 – OpenFlow



"If header = ***p***, send to port 4"

"If header = ***q***, overwrite header with ***r***, add header ***s***, and send to ports 5,6"

"If header = **?**, send to me"

## 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