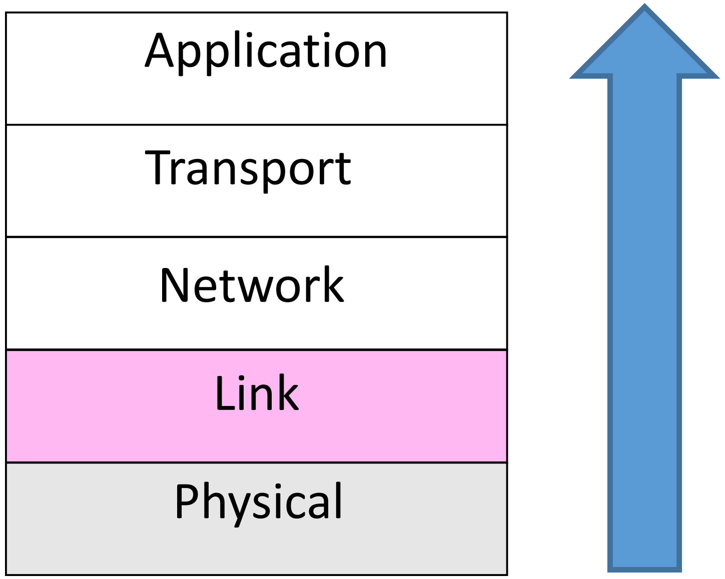
Link Layer

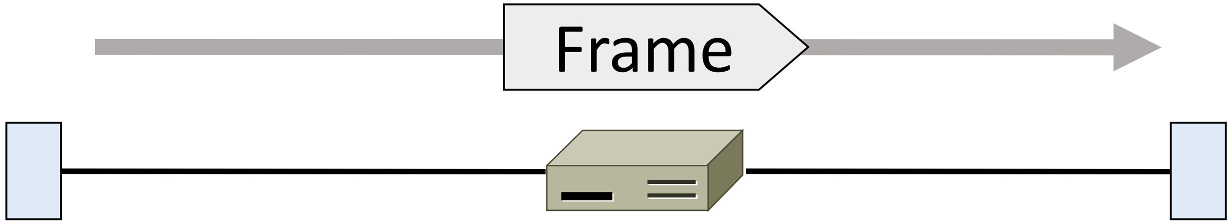
Where we are in the Course

- Moving on up to the Link Layer!

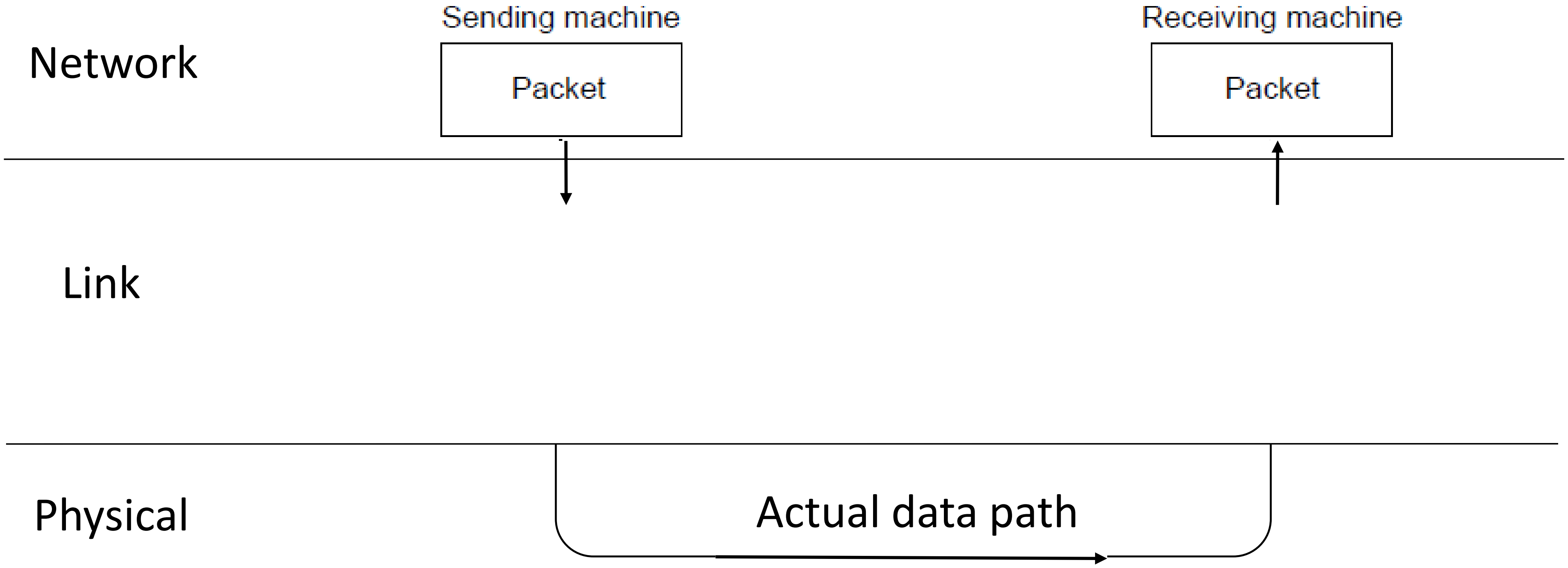


Scope of the Link Layer

- Concerns how to transfer messages over one or more connected links
  - Messages are frames, of limited size
  - Builds on the physical layer



In terms of layers …



Network

Sending machine

Packet

Receiving machine

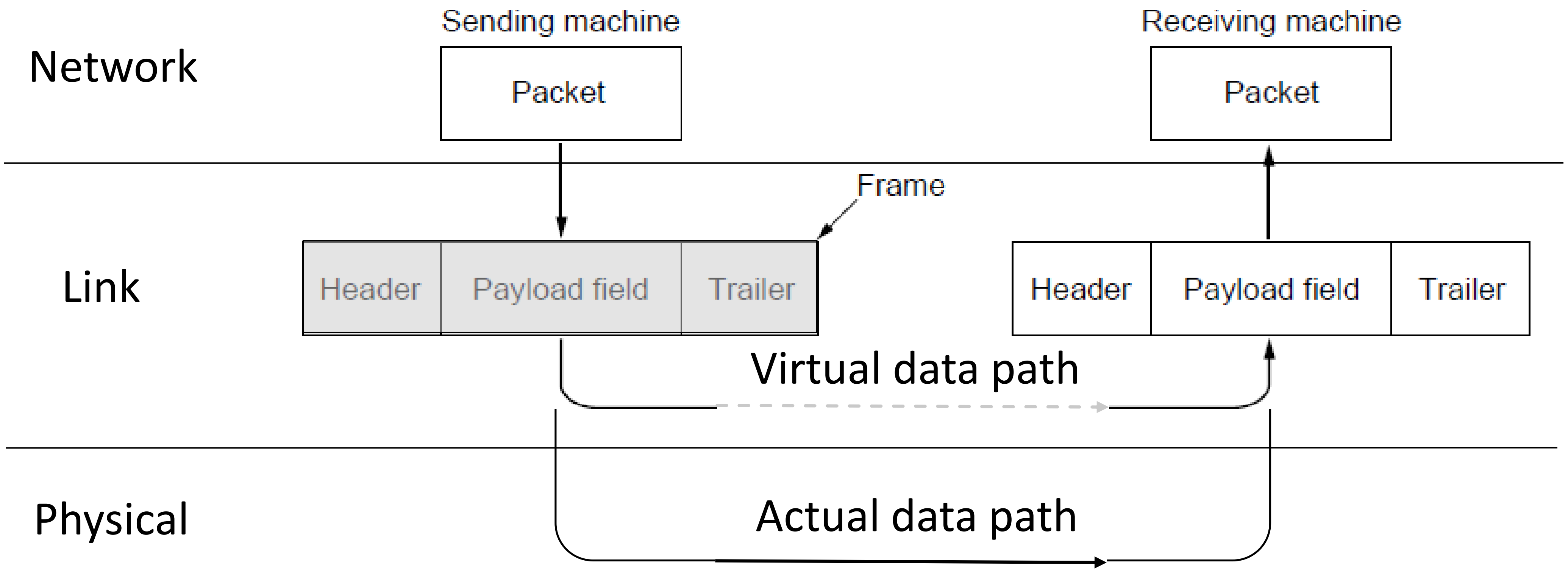
Packet

Link

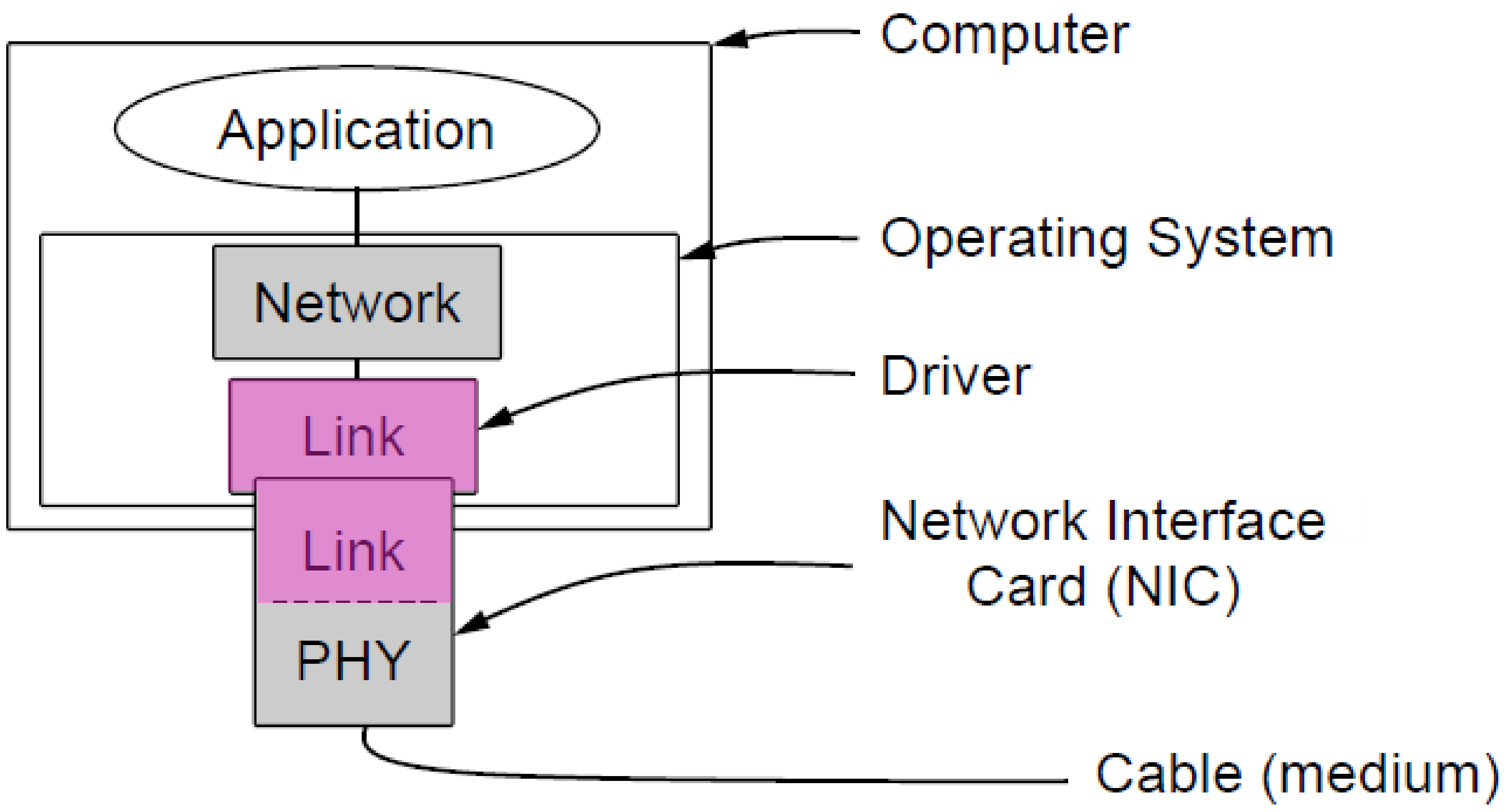
Physical

Actual data path

In terms of layers (2)



Typical Implementation of Layers (2)



Topics

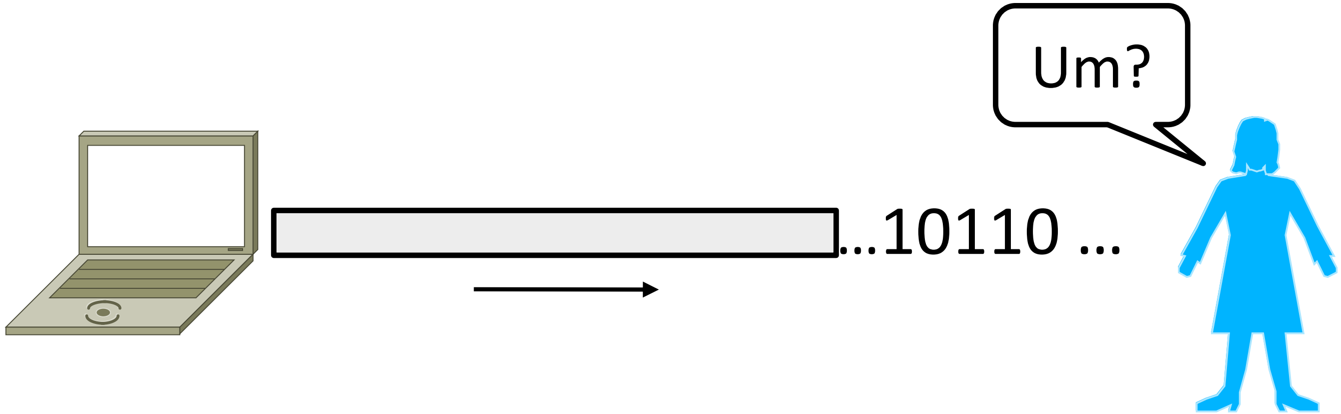
1. Framing
   - Delimiting start/end of frames
2. Error detection and correction
   - Handling errors
3. Retransmissions
   - Handling loss
4. Multiple Access
   - 802.11, classic Ethernet
5. Switching
   - Modern Ethernet

Framing

Delimiting start/end of frames

Topic

- The Physical layer gives us a stream of bits. How do we interpret it as a sequence of frames?



Framing Methods

- We’ll look at:
  - Byte count (motivation)
  - Byte stuffing
  - Bit stuffing

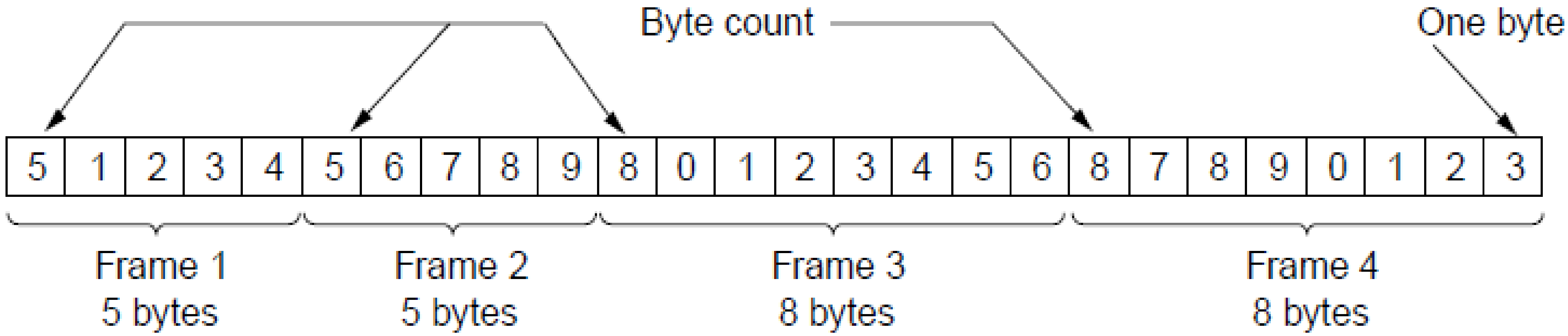
- In practice, the physical layer often helps to identify frame boundaries
  - E.g., Ethernet, 802.11

Simple ideas?

Byte Count

- First try:
  - Let’s start each frame with a length field!
  - It’s simple, and hopefully good enough …

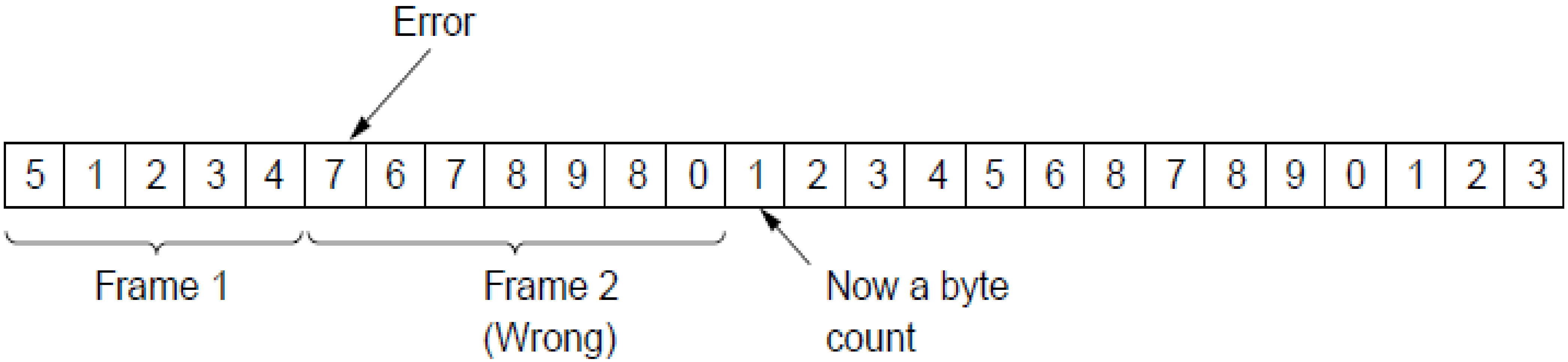
Byte Count (2)



5	1	2	3	4	5	6	7	8	9	8	0	1	2	3	4	5	6	8	7	8	9	0	1	2	3

Byte Count (3)

- Difficult to re-synchronize after framing error
  - Want a way to scan for a start of frame



5	1	2	3	4	7	6	7	8	9	8	0	1	2	3	4	5	6	8	7	8	9	0	1	2	3

Error

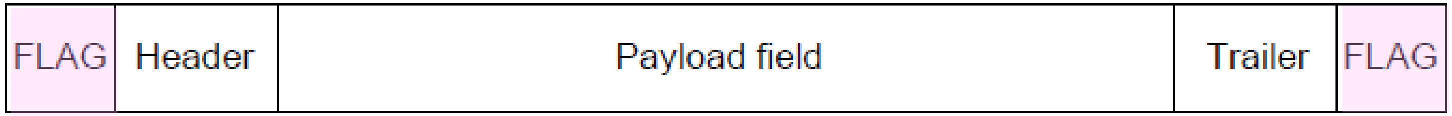
Frame 1

Frame 2 (Wrong)

Now a byte count

Byte Stuffing

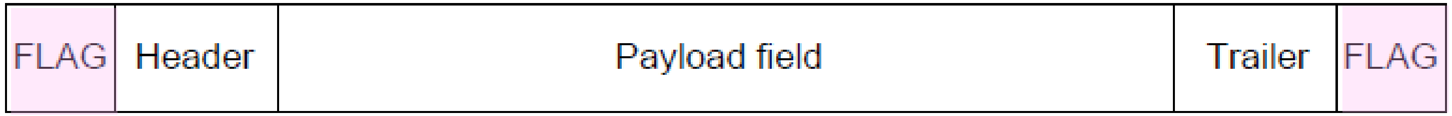
- Better idea:
    - Have a special flag byte value for start/end of frame
    - Replace (“stuff”) the flag with an escape code
    - Problem?



FLAG	Header	Payload field	Trailer	FLAG

Byte Stuffing

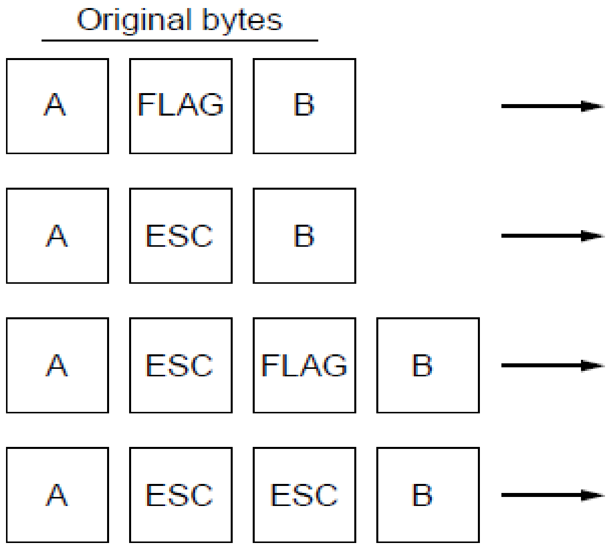
- Better idea:
  - Have a special flag byte value for start/end of frame
  - Replace ("stuff") the flag with an escape code
  - Complication: have to escape the escape code too!



FLAG	Header	Payload field	Trailer	FLAG

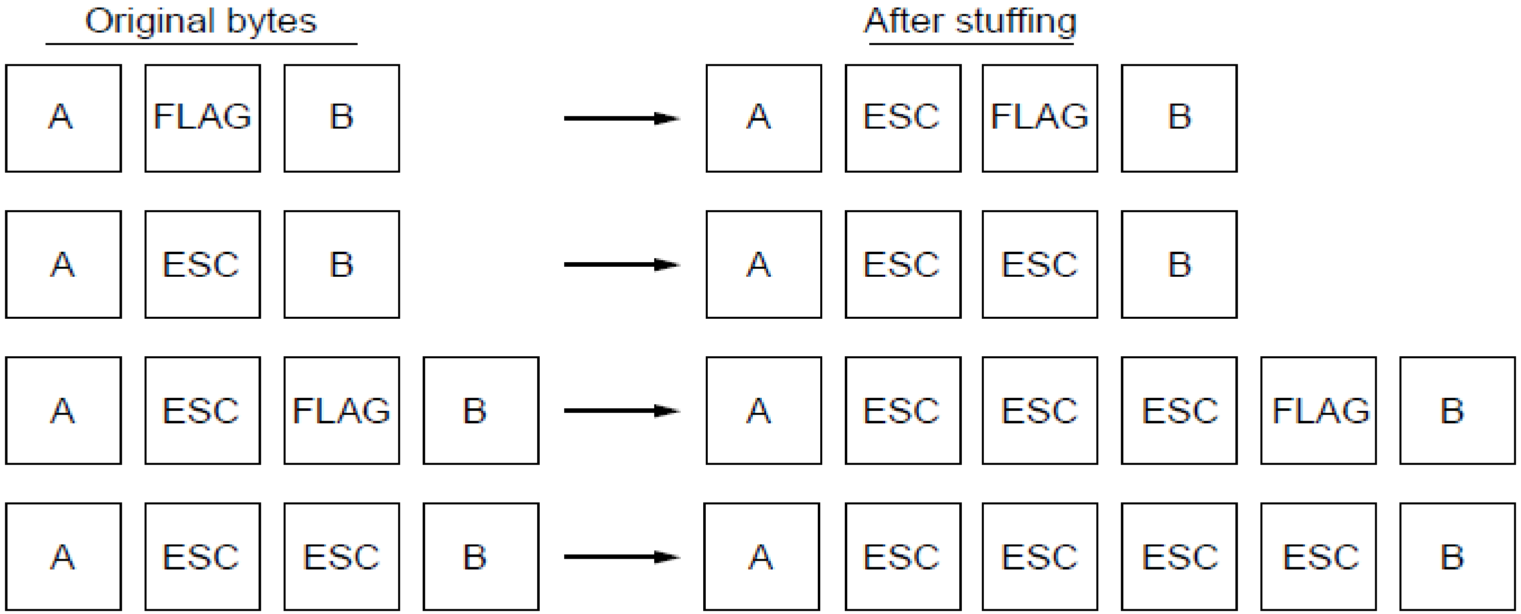
Byte Stuffing (2)

- Rules:
  - Replace each FLAG in data with ESC FLAG
  - Replace each ESC in data with ESC ESC



Byte Stuffing (3)

- Now any unescaped FLAG is the start/end of a frame



Original bytes		After stuffing
A FLAG B	→	A ESC FLAG B
A ESC B	→	A ESC ESC B
A ESC FLAG B	→	A ESC ESC ESC FLAG B
A ESC ESC B	→	A ESC ESC ESC ESC B

Unstuffing

You see:

1. Solitary FLAG?
2. Solitary ESC?
3. ESC FLAG?
4. ESC ESC FLAG?
5. ESC ESC ESC FLAG?
6. ESC FLAG FLAG?

Unstuffing

You see:

1. Solitary FLAG? -> Start or end of packet
2. Solitary ESC? -> Bad packet!
3. ESC FLAG? -> remove ESC and pass FLAG through
4. ESC ESC FLAG? -> removed ESC and then start or end of packet
5. ESC ESC ESC FLAG? -> pass ESC FLAG through
6. ESC FLAG FLAG? -> pass FLAG through then start or end of packet

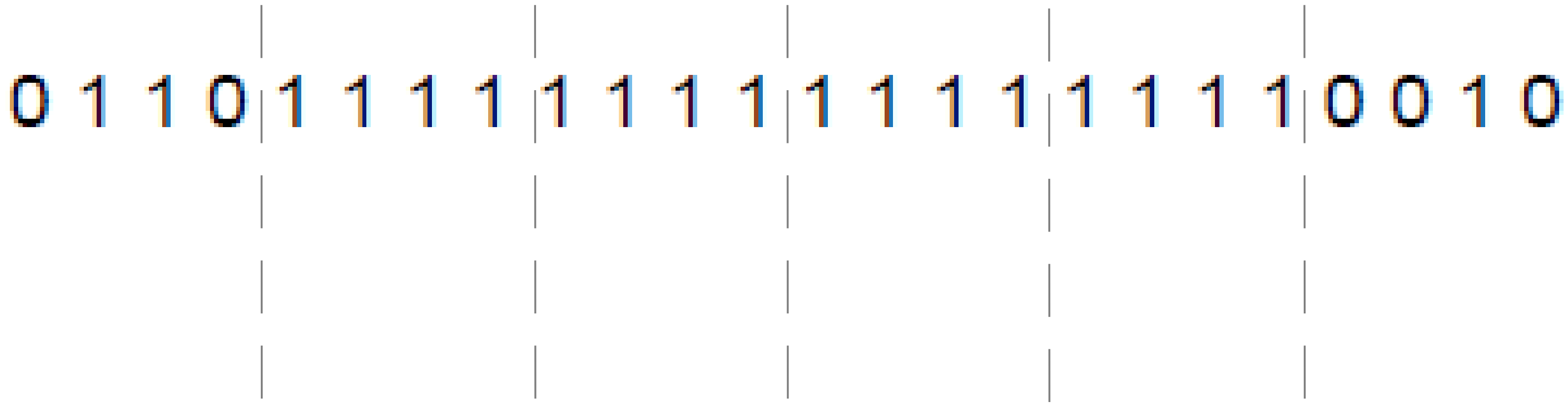
Bit Stuffing

- Can stuff at the bit level too
  - Call a flag six consecutive 1s
  - On transmit, after five 1s in the data, insert a 0
  - On receive, a 0 after five 1s is deleted

Bit Stuffing (2)

- Example:

Data bits



0 1 1 0 | 1 1 1 1 | 1 1 1 1 | 1 1 1 1 | 1 1 1 1 | 0 0 1 0

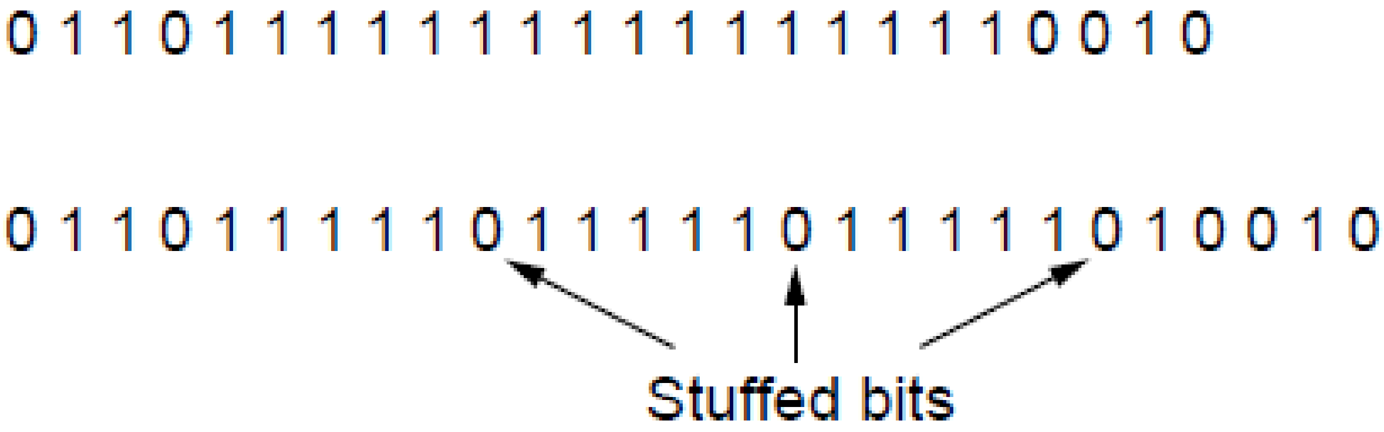
Transmitted bits
with stuffing

Bit Stuffing (3)

- So how does it compare with byte stuffing?

Data bits

Transmitted bits with stuffing

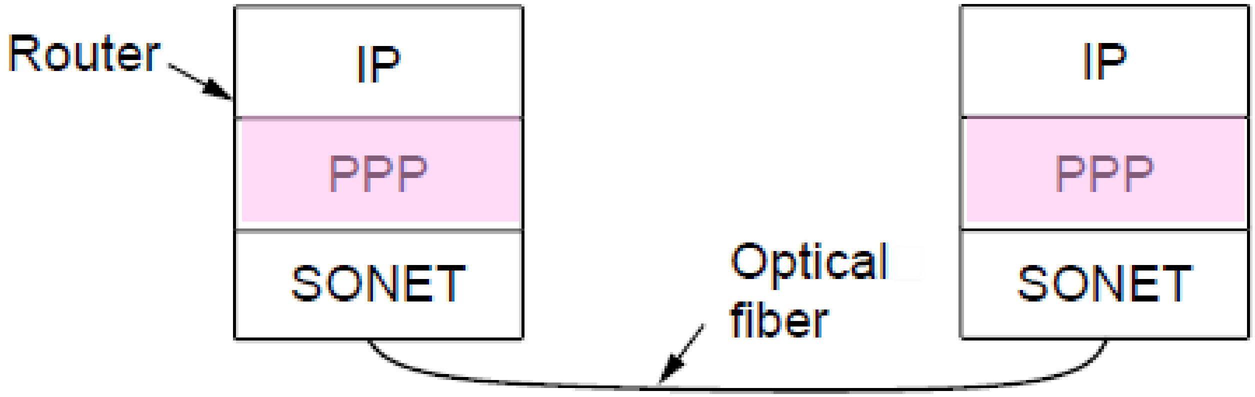


Link Example: PPP over SONET

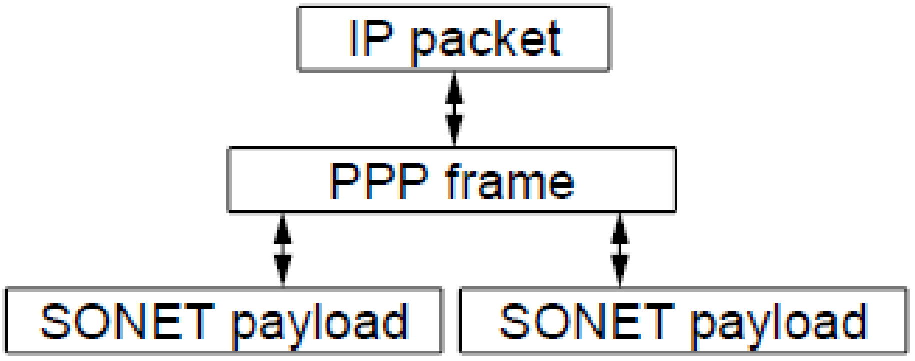
- PPP is Point-to-Point Protocol
- Widely used for link framing
    - E.g., it is used to frame IP packets that are sent over SONET optical links

Link Example: PPP over SONET (2)

- Think of SONET as a bit stream, and PPP as the framing that carries an IP packet over the link



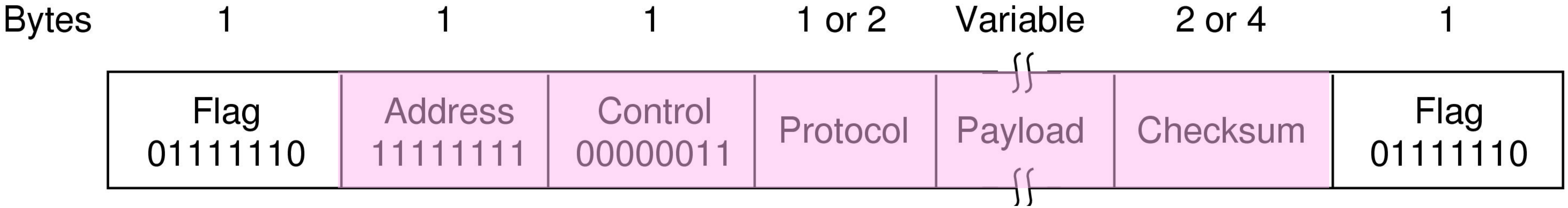
Protocol stacks



PPP frames may be split over SONET payloads

Link Example: PPP over SONET (3)

- Framing uses byte stuffing
  - FLAG is 0x7E and ESC is 0x7D



Bytes	1	1	1	1 or 2	Variable	2 or 4	1
	Flag 01111110	Address 11111111	Control 00000011	Protocol	Payload	Checksum	Flag 01111110

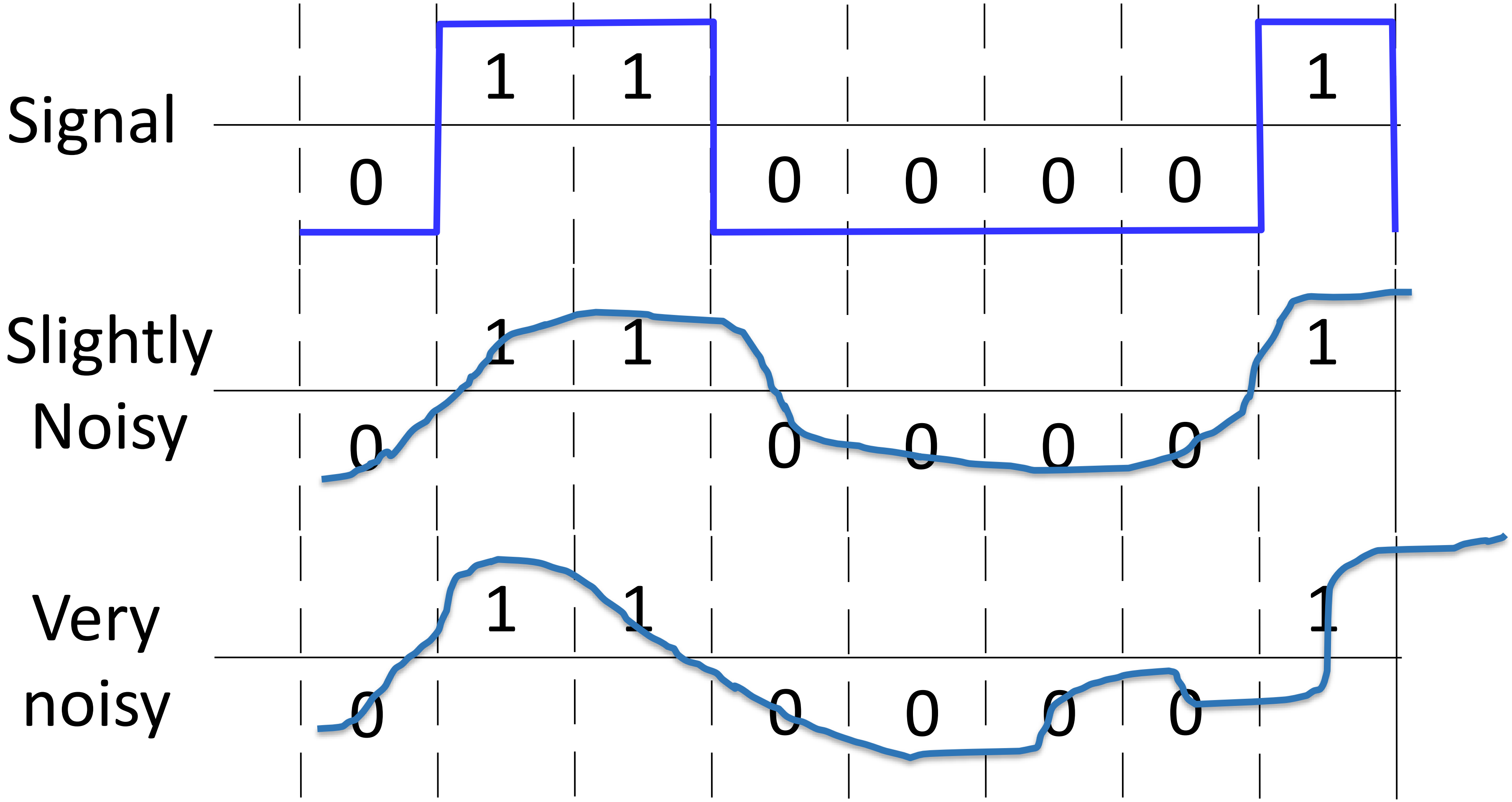
Link Layer: Error detection and correction

Topic

- Some bits will be received in error due to noise. What can we do?
  - Detect errors with codes
  - Retransmit lost frames ← Later
  - Correct errors with codes

- Reliability is a concern that cuts across the layers

Problem – Noise may flip received bits



Approach – Add Redundancy

- Error detection codes
  - Add check bits to the message bits to let some errors be detected
- Error correction codes
  - Add more check bits to let some errors be corrected
- Key issue is now to structure the code to detect many errors with few check bits and modest computation

- Ideas?

Motivating Example

- A simple code to handle errors:
  - Send two copies! Error if different.

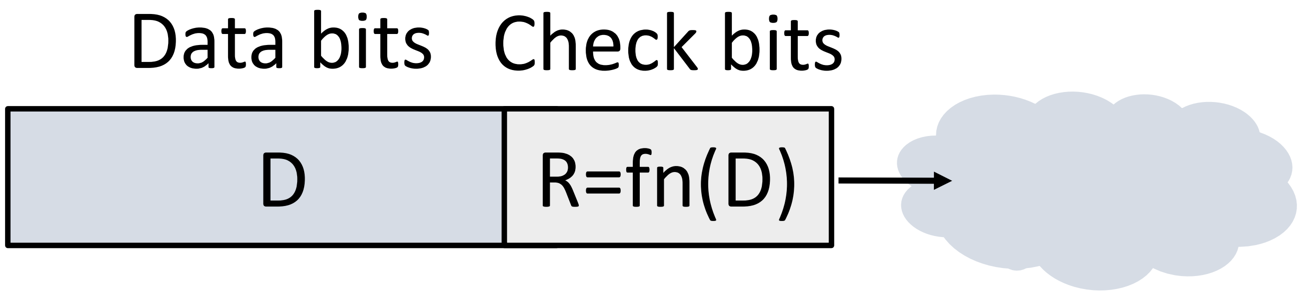
- How good is this code?
  - How many errors can it detect/correct?
  - How many errors will make it fail?

Motivating Example (2)

- We want to handle more errors with less overhead
  - Will look at better codes; they are applied mathematics
  - But, they can’t handle all errors
  - And they focus on accidental errors (will look at secure hashes later)

Using Error Codes

- Codeword consists of D data plus R check bits (=systematic block code)



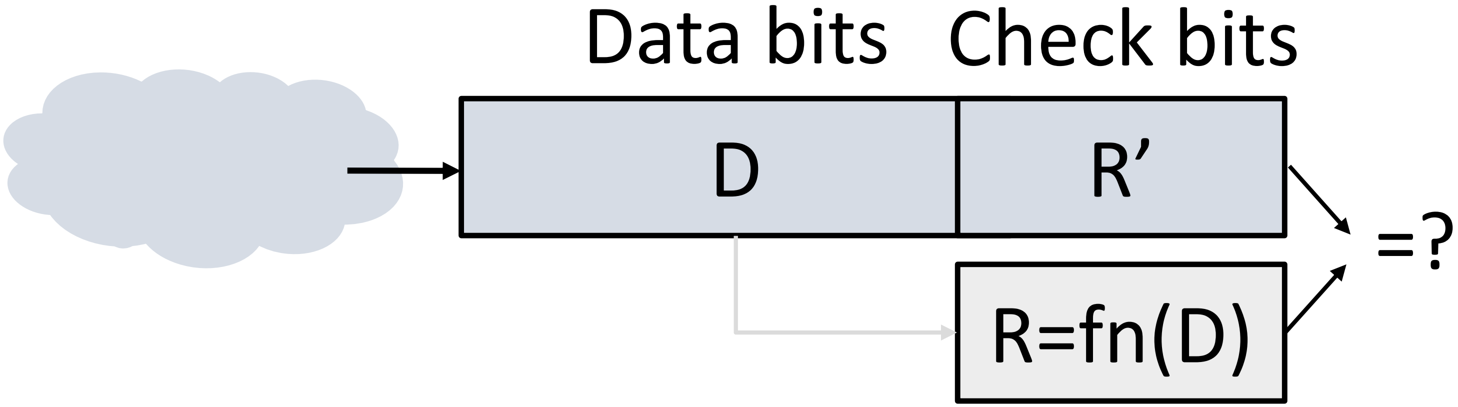
Data bits Check bits

D R=fn(D)

- Sender:
  - Compute R check bits based on the D data bits; send the codeword of D+R bits

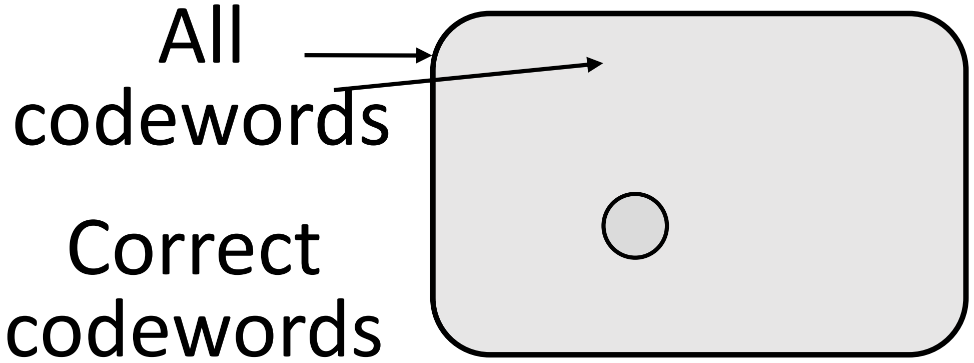
Using Error Codes (2)

- Receiver:
  - Receive D+R bits with unknown errors
  - Recompute R check bits based on the D data bits; error if R doesn't match R'



Intuition for Error Codes

- For D data bits, R check bits:

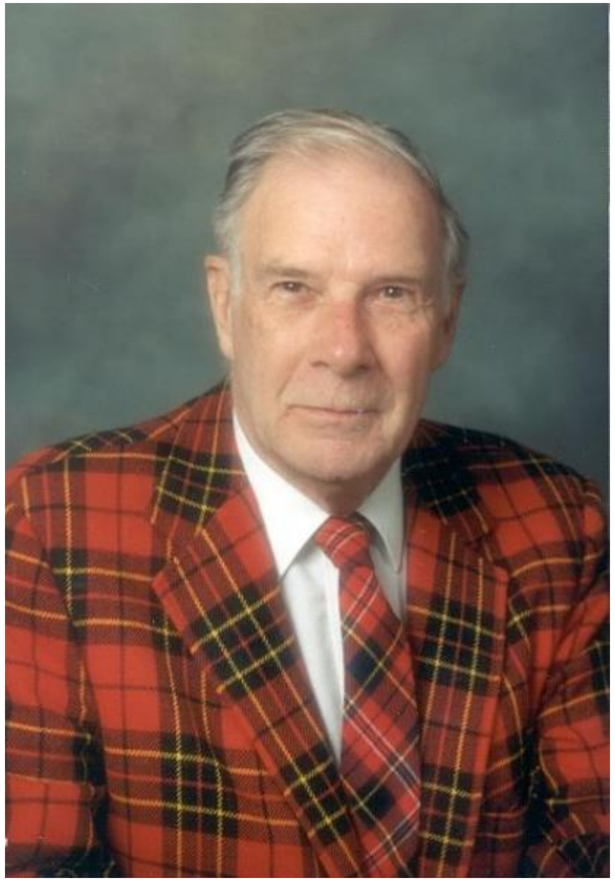


- Randomly chosen codeword is unlikely to be correct; overhead is low

R.W. Hamming (1915-1998)

- Much early work on codes:
  - “Error Detecting and Error Correcting Codes”, BSTJ, 1950

- *“If the computer can tell when an error has occurred, surely there is a way of telling where the error is so the computer can correct the error itself”* - Hamming



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Hamming Distance

- Hamming distance between two codes (D_1 D_2) is the number of bit flips needed to change D_1 to D_2

- Hamming distance of a coding is the minimum error distance between any pair of codewords (bit-strings) that cannot be detected

Hamming Distance (2)

- Error detection:
  - For a coding of distance d+1, up to d errors will always be detected
- Error correction:
  - For a coding of distance 2d+1, up to d errors can always be corrected by mapping to the closest valid codeword

Simple Error Detection – Parity Bit

- Take D data bits, add 1 check bit that is the sum of the D bits
  - Sum is modulo 2 or XOR

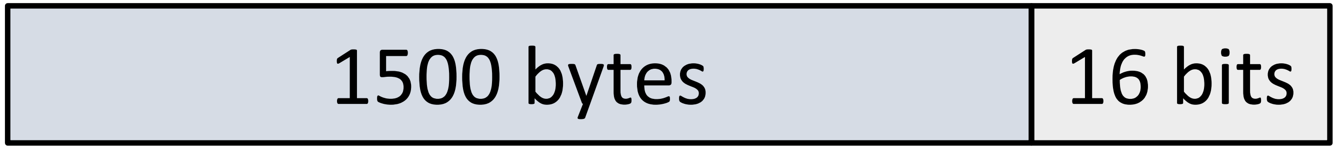
Parity Bit (2)

- How well does parity work?
  - What is the distance of the code?
  - How many errors will it detect/correct?

- What about larger errors?

Checksums

- Idea: sum up data in N-bit words
  - Widely used in, e.g., TCP/IP/UDP



- Stronger protection than parity

Internet Checksum

- Sum is defined in 1s complement arithmetic (must add back carries)
  - And it's the negative sum
- "*The checksum field is the 16 bit one's complement of the one's complement sum of all 16 bit words …*" – RFC 791

Internet Checksum (2)

Sending:

1. Arrange data in 16-bit words
2. Put zero in checksum position, add
3. Add any carryover back to get 16 bits
4. Negate (complement) to get sum

```
0001
f204
f4f5
f6f7
```

Internet Checksum (3)

Sending:

1. Arrange data in 16-bit words
2. Put zero in checksum position, add
3. Add any carryover back to get 16 bits
4. Negate (complement) to get sum

```
   0001
   f204
   f4f5
   f6f7
+(0000)
------
  2ddf1
    ↓
   ddf1
+     2
------
   ddf3
    ↓
   220c
```

Internet Checksum (4)

Receiving:

1. Arrange data in 16-bit words
2. Checksum will be non-zero, add
3. Add any carryover back to get 16 bits
4. Negate the result and check it is 0

```
  0001
  f204
  f4f5
  f6f7
+ 220c
------
```

Internet Checksum (5)

Receiving:

1. Arrange data in 16-bit words
2. Checksum will be non-zero, add
3. Add any carryover back to get 16 bits
4. Negate the result and check it is 0

```
  0001
  f204
  f4f5
  f6f7
+ 220c
------
 2fffd
   ↓
  fffd
+    2
------
  ffff
   ↓
  0000
```

Internet Checksum (6)

- How well does the checksum work?
  - What is the distance of the code?
  - How many errors will it detect/correct?

- What about larger errors?

Cyclic Redundancy Check (CRC)

- Even stronger protection
  - Given n data bits, generate k check bits such that the n+k bits are evenly divisible by a generator C
- Example with numbers:
  - n = 302, k = one digit, C = 3

CRCs (2)

- The catch:
  - It’s based on mathematics of finite fields, in which “numbers” represent polynomials
  - e.g, 10011010 is $x^7 + x^4 + x^3 + x^1$

- What this means:
  - We work with binary values and operate using modulo 2 arithmetic

CRCs (3)

- Send Procedure:

1. Extend the n data bits with k zeros
2. Divide by the generator value C
3. Keep remainder, ignore quotient
4. Adjust k check bits by remainder

- Receive Procedure:

1. Divide and check for zero remainder

CRCs (4)

Data bits:

1101011111

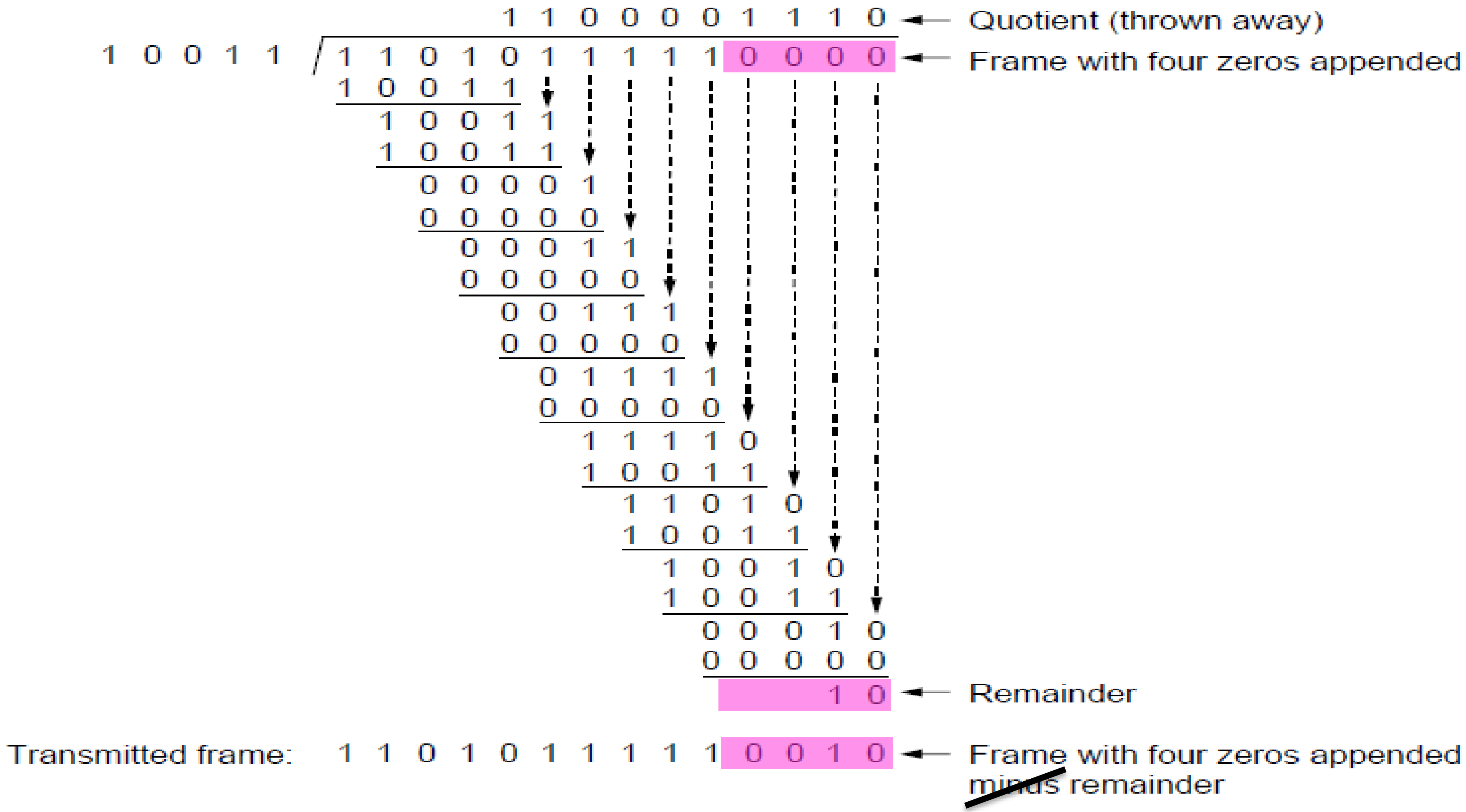
Check bits:

$C(x)=x^4+x^1+1$

C = 10011

k = 4

CRCs (5)



```
                    1 1 0 0 0 0 1 1 1 0  ← Quotient (thrown away)
1 0 0 1 1 / 1 1 0 1 0 1 1 1 1 1 0 0 0 0  ← Frame with four zeros appended
            1 0 0 1 1
              1 0 0 1 1
              1 0 0 1 1
                0 0 0 0 1
                0 0 0 0 0
                  0 0 0 1 1
                  0 0 0 0 0
                    0 0 1 1 1
                    0 0 0 0 0
                      0 1 1 1 1
                      0 0 0 0 0
                        1 1 1 1 0
                        1 0 0 1 1
                          1 1 0 1 0
                          1 0 0 1 1
                            1 0 0 1 0
                            1 0 0 1 1
                              0 0 0 1 0
                              0 0 0 0 0
                                    1 0  ← Remainder

Transmitted frame: 1 1 0 1 0 1 1 1 1 1 0 0 1 0  ← Frame with four zeros appended
                                                   ~~minus~~ remainder
```

Plus

CRCs (6)

- Protection depend on generator
  - Standard CRC-32 is 10000010 01100000 10001110 110110111

- Properties:
  - HD=4, detects up to triple bit errors
  - Also odd number of errors
  - And bursts of up to k bits in error
  - Not vulnerable to systematic errors like checksums

Why Error Correction is Hard

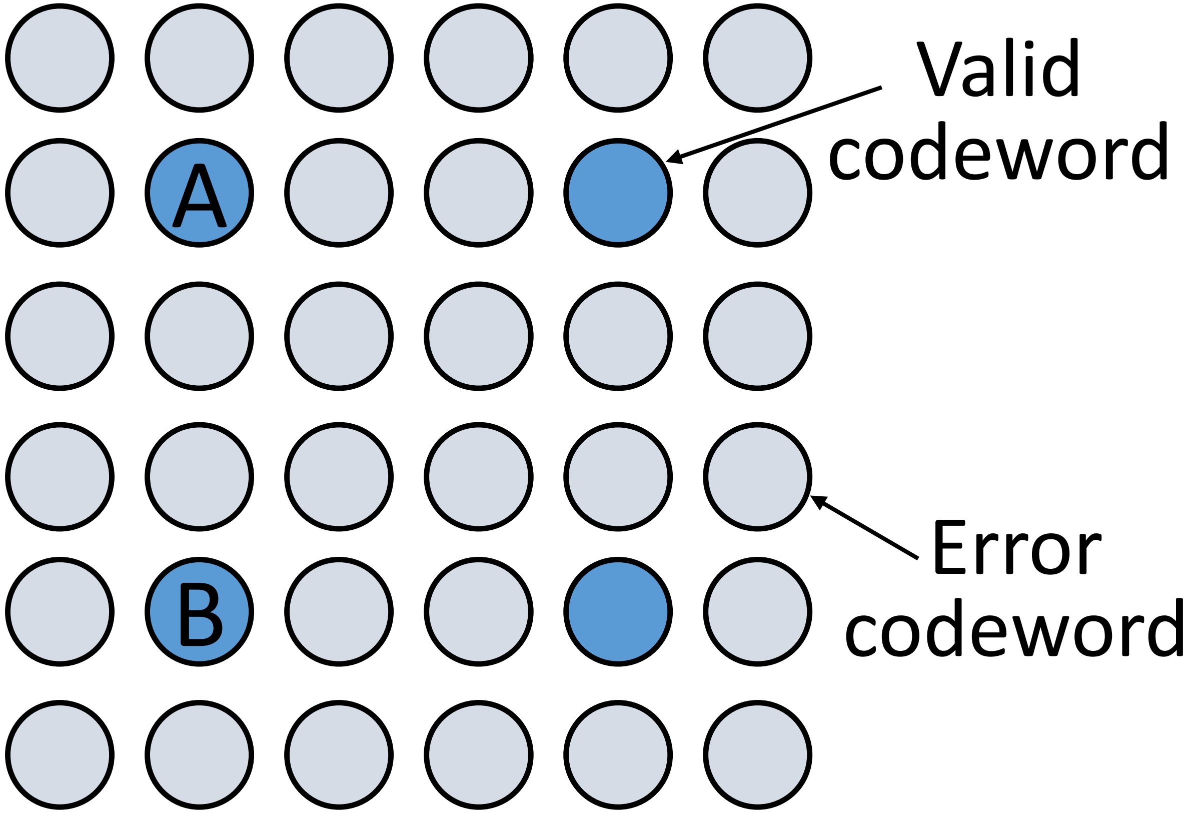
- If we had reliable check bits we could use them to narrow down the position of the error
    - Then correction would be easy
- But error could be in the check bits as well as the data bits!
    - Data might even be correct

Intuition for Error Correcting Code

- Suppose we construct a code with a Hamming distance of at least 3
    - Need ≥3 bit errors to change one valid codeword into another
    - Single bit errors will be closest to a unique valid codeword
- If we assume errors are only 1 bit, we can correct them by mapping an error to the closest valid codeword
    - Works for d errors if HD ≥ 2d + 1

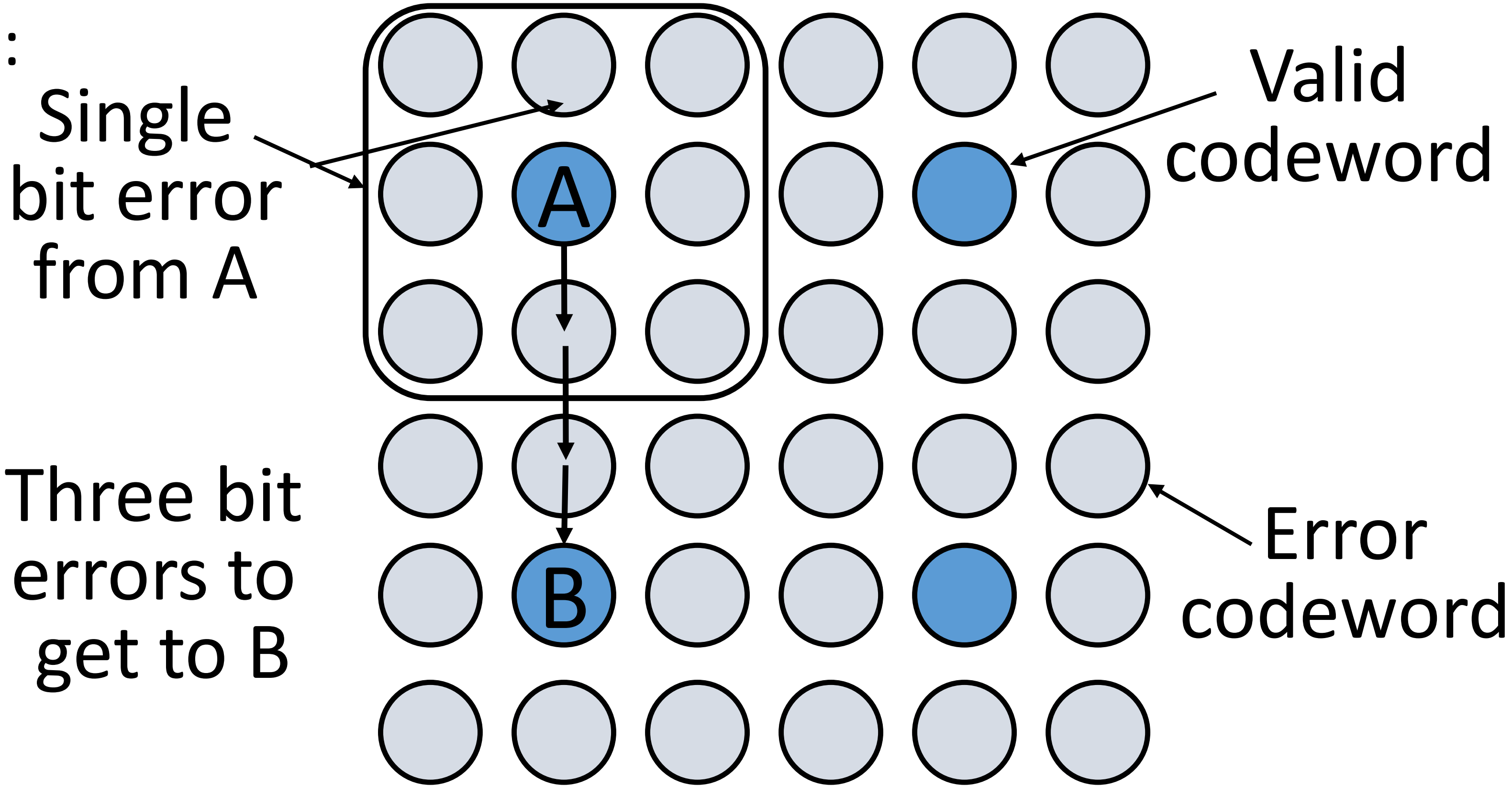
Intuition (2)

- Visualization of code:



Intuition (3)

- Visualization of code:



Hamming Code

- Gives a method for constructing a code with a distance of 3
  - Uses $n = 2^k - k - 1$, e.g., n=4, k=3
  - Put check bits in positions p that are powers of 2, starting with position 1
  - Check bit in position p is parity of positions with a p term in their values
- Plus an easy way to correct [soon]

Hamming Code (2)

- Example: data=0101, 3 check bits
  - 7 bit code, check bit positions 1, 2, 4
  - Check 1 covers positions 1, 3, 5, 7
  - Check 2 covers positions 2, 3, 6, 7
  - Check 4 covers positions 4, 5, 6, 7

_ _ _ _ _ _ _
1 2 3 4 5 6 7

Hamming Code (3)

- Example: data=0101, 3 check bits
  - 7 bit code, check bit positions 1, 2, 4
  - Check 1 covers positions 1, 3, 5, 7
  - Check 2 covers positions 2, 3, 6, 7
  - Check 4 covers positions 4, 5, 6, 7

$\underline{0}$	$\underline{1}$	0	$\underline{0}$	1	0	1	⟶
1	2	3	4	5	6	7	

p_1= 0+1+1 = 0, p_2= 0+0+1 = 1, p_4= 1+0+1 = 0

Hamming Code (4)

- To decode:
  - Recompute check bits (with parity sum including the check bit)
  - Arrange as a binary number
  - Value (syndrome) tells error position
  - Value of zero means no error
  - Otherwise, flip bit to correct

Hamming Code (5)

- Example, continued

$$\longrightarrow \quad \underline{0}\ \ \underline{1}\ \ 0\ \ \underline{0}\ \ 1\ \ 0\ \ 1$$

1 2 3 4 5 6 7

p_1= p_2=

p_4=

Syndrome =

Data =

Hamming Code (6)

- Example, continued

$$\longrightarrow \quad \begin{array}{ccccccc} \underline{0} & \underline{1} & 0 & \underline{0} & 1 & 0 & 1 \\ 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{array}$$

p_1= 0+0+1+1 = 0, p_2= 1+0+0+1 = 0,
p_4= 0+1+0+1 = 0

Syndrome = 000, no error
Data = 0 1 0 1

Hamming Code (7)

- Example, continued

$$\longrightarrow \quad \begin{array}{ccccccc} \underline{0} & \underline{1} & 0 & \underline{0} & 1 & 1 & 1 \\ 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{array}$$

p_1= p_2=

p_4=

Syndrome =

Data =

Hamming Code (8)

- Example, continued

$$\longrightarrow \quad \underline{0}\quad \underline{1}\quad 0\quad \underline{0}\quad 1\quad 1\quad 1$$

$$1\quad 2\quad 3\quad 4\quad 5\quad 6\quad 7$$

p_1= 0+0+1+1 = 0, p_2= 1+0+1+1 = 1,
p_4= 0+1+1+1 = 1

Syndrome = 1 1 0, flip position 6
Data = 0 1 0 1 (correct after flip!)

Hamming Code (3)

- Example: bad message 0100111
  - 7 bit code, check bit positions 1, 2, 4
  - Check 1 covers positions 1, 3, 5, 7
  - Check 2 covers positions 2, 3, 6, 7
  - Check 4 covers positions 4, 5, 6, 7

0 1 0 0 1 1 1 →

1 2 3 4 5 6 7

p_1= 0+0+1+1 = 0, p_2= 1+0+1+1 = 1, p_4= 0+1+1+1 = 1

Hamming Code (3)

- Example: bad message 0100111
  - 7 bit code, check bit positions 1, 2, 4
  - Check 1 covers positions 1, 3, 5, 7
  - Check 2 covers positions 2, 3, 6, 7
  - Check 4 covers positions 4, 5, 6, 7

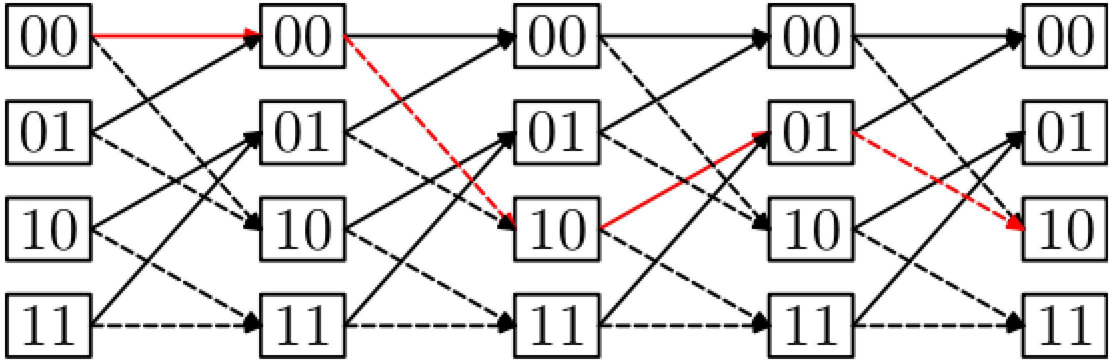
0 1 0 0 1 1 1 →

1 2 3 4 5 6 7

p_1= 0+0+1+1 = 0, p_2= 1+0+1+1 = 1, p_4= 0+1+1+1 = 1

Other Error Correction Codes

- Real codes are more involved than Hamming
- E.g., Convolutional codes (§3.2.3)
  - Take a stream of data and output a mix of the input bits
  - Makes each output bit less fragile
  - Decode using Viterbi algorithm (which can use bit confidence values)



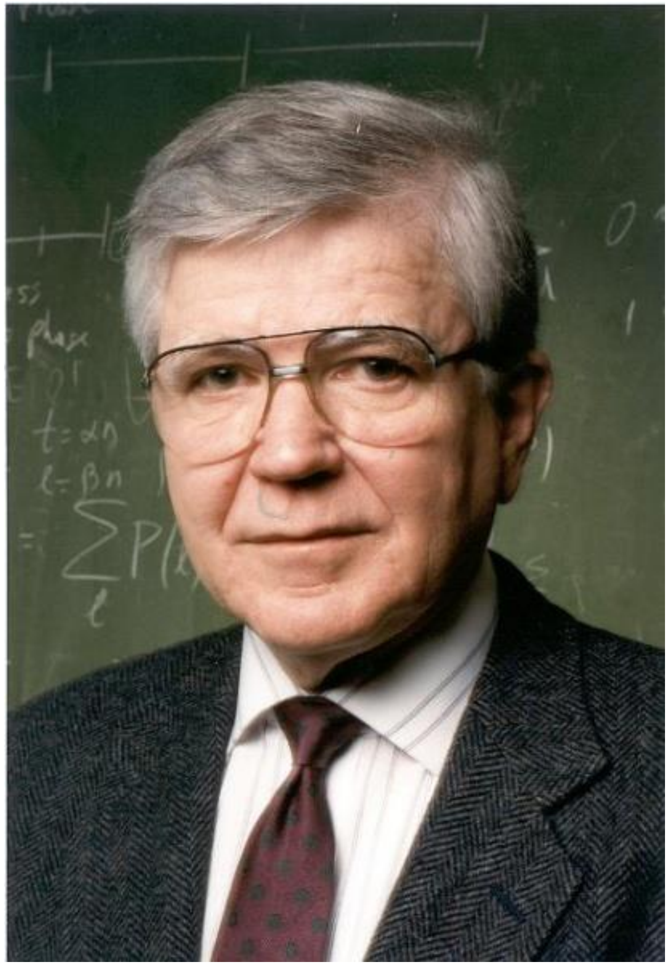
Other Codes (2) – Turbo Codes

- Turbo Codes
  - Evolution of convolutional codes
  - Sends multiple sets of parity bits with payload
  - Decodes sets together (e.g. Sudoku)
  - Used in 3G and 4G cellular technologies

- Invented and patented by Claude Berrou
  - Professor at École Nationale Supérieure des Télécommunications de Bretagne

Other Codes (3) – LDPC

- Low Density Parity Check (§3.2.3)
  - LDPC based on sparse matrices
  - Decoded iteratively using a belief propagation algorithm
- Invented by Robert Gallager in 1963 as part of his PhD thesis
  - Promptly forgotten until 1996 …



Source: IEEE GHN, © 2009 IEEE

More coding theory

- This is a **huge** field.
- See EE 505, 514, 515 for more info
  - These are graduate classes
- Key points:
  - Coding allows us to detect and correct bit errors received from the PHY
  - It is very complicated. Abstract away with Hamming Distance

Detection vs. Correction

- Which is better will depend on the pattern of errors. For example:
  - 1000 bit messages with a bit error rate (BER) of 1 in 10000

- Which has less overhead?

Detection vs. Correction

- Which is better will depend on the pattern of errors. For example:
  - 1000 bit messages with a bit error rate (BER) of 1 in 10000

- Which has less overhead?
  - It still depends! We need to know more about the errors

Detection vs. Correction (2)

Assume bit errors are random

- Messages have 0 or maybe 1 error (1/10 of the time)

Error correction:

- Need ~10 check bits per message
- Overhead:

Error detection:

- Need ~1 check bits per message plus 1000 bit retransmission
- Overhead:

Detection vs. Correction (3)

Assume errors come in bursts of 100

- Only 1 or 2 messages in 1000 have significant (multi-bit) errors

Error correction:

- Need >>100 check bits per message
- Overhead:

Error detection:

- Need 32 check bits per message plus 1000 bit resend 2/1000 of the time
- Overhead:

Detection vs. Correction (4)

- Error correction:
  - Needed when errors are expected
  - Or when no time for retransmission

- Error detection:
  - More efficient when errors are not expected
  - And when errors are large when they do occur

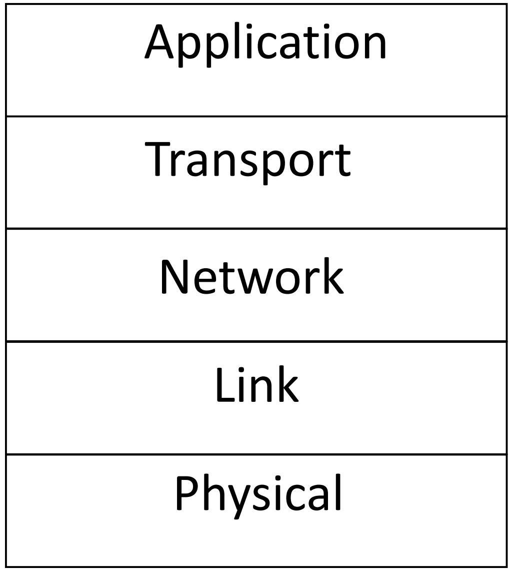
Error Correction in Practice

- Heavily used in physical layer
  - LDPC is the future, used for demanding links like 802.11, DVB, WiMAX, power-line, …
  - Convolutional codes widely used in practice
- Error detection (w/ retransmission) is used in the link layer and above for residual errors
- Correction also used in the application layer
  - Called Forward Error Correction (FEC)
  - Normally with an erasure error model
  - E.g., Reed-Solomon (CDs, DVDs, etc.)

Link Layer: Retransmissions

Context on Reliability

- Where in the stack should we place reliability functions?



Application

Transport

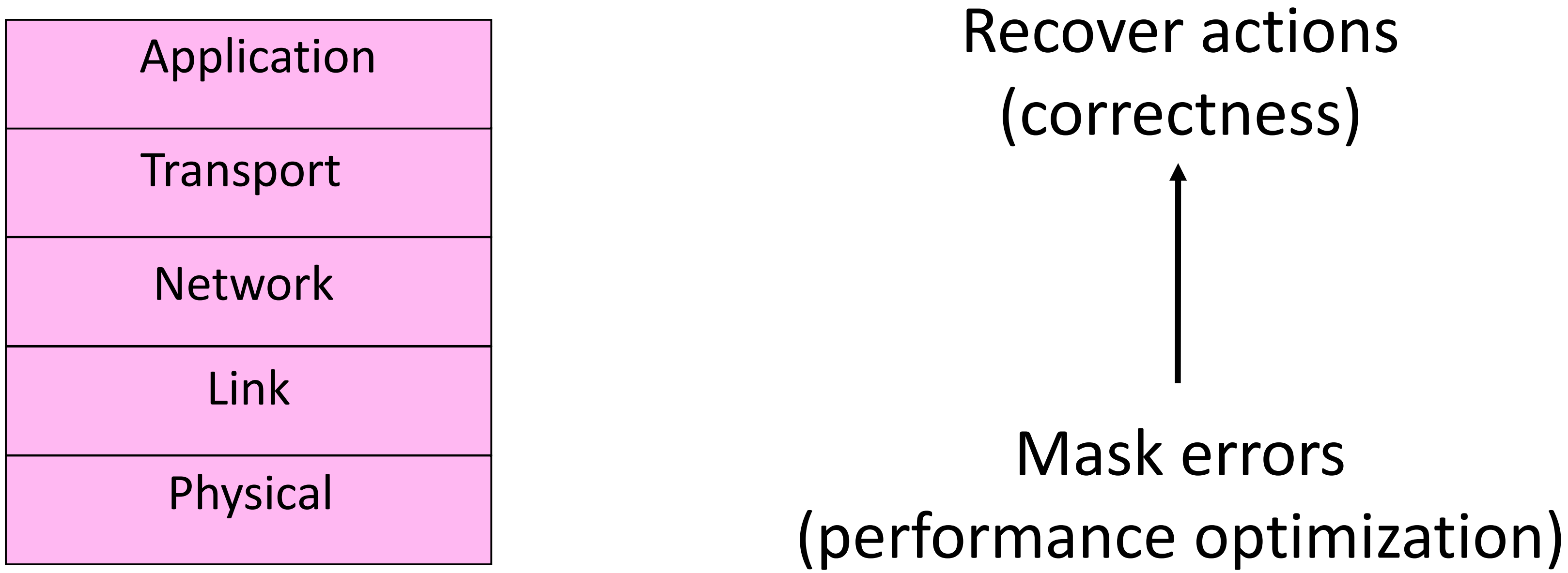
Network

Link

Physical

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?

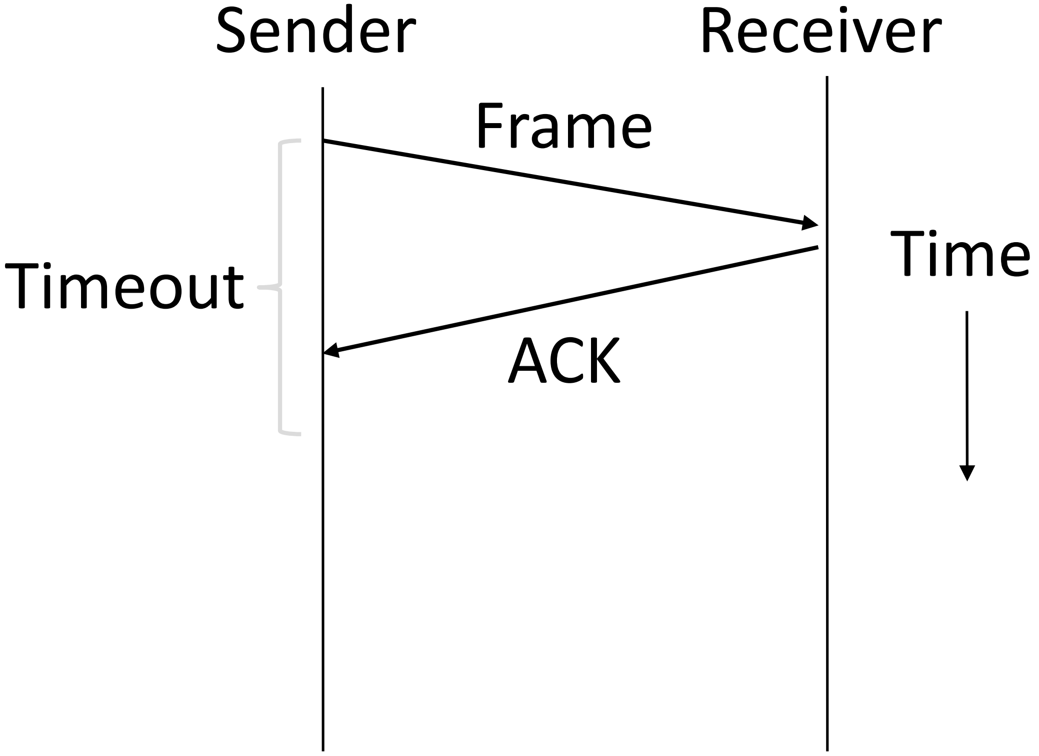
ARQ (Automatic Repeat reQuest)

- 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

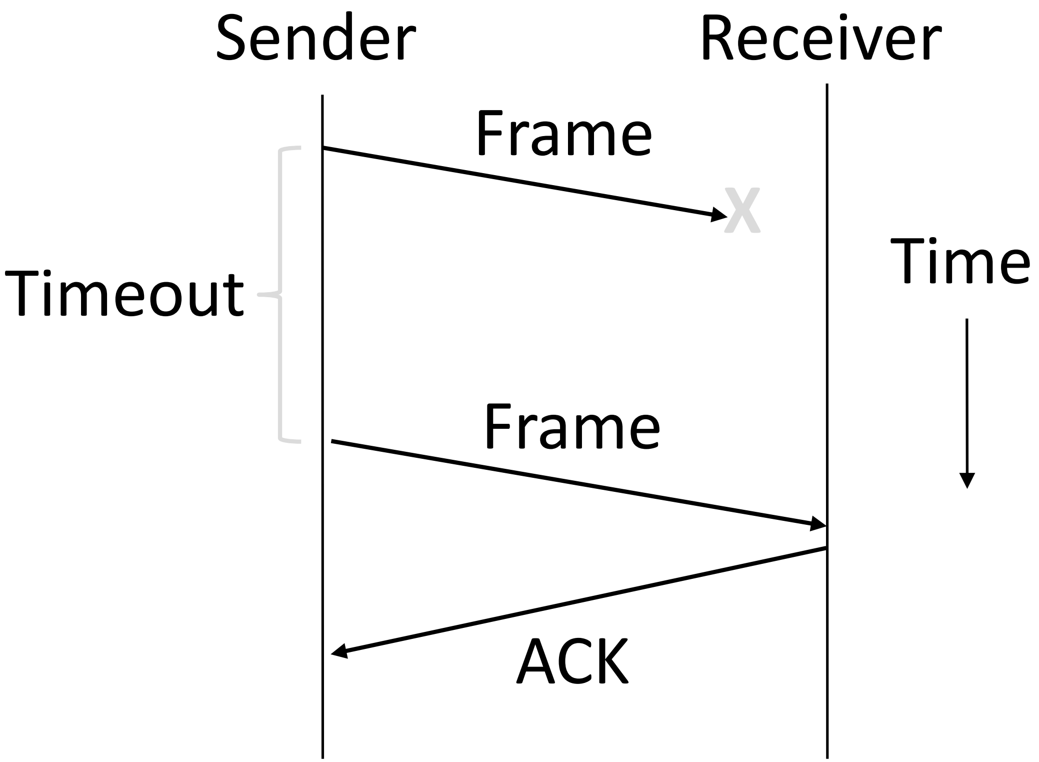
ARQ (2)

- Normal operation (no loss)



ARQ (3)

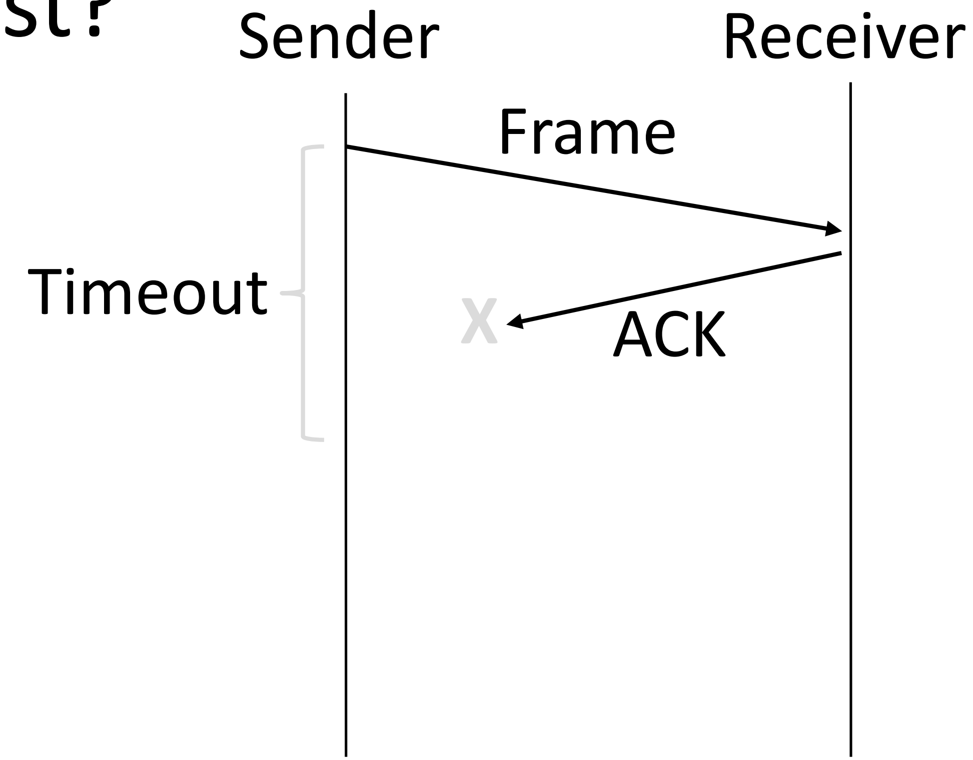
- Loss and retransmission



So What’s Tricky About ARQ?

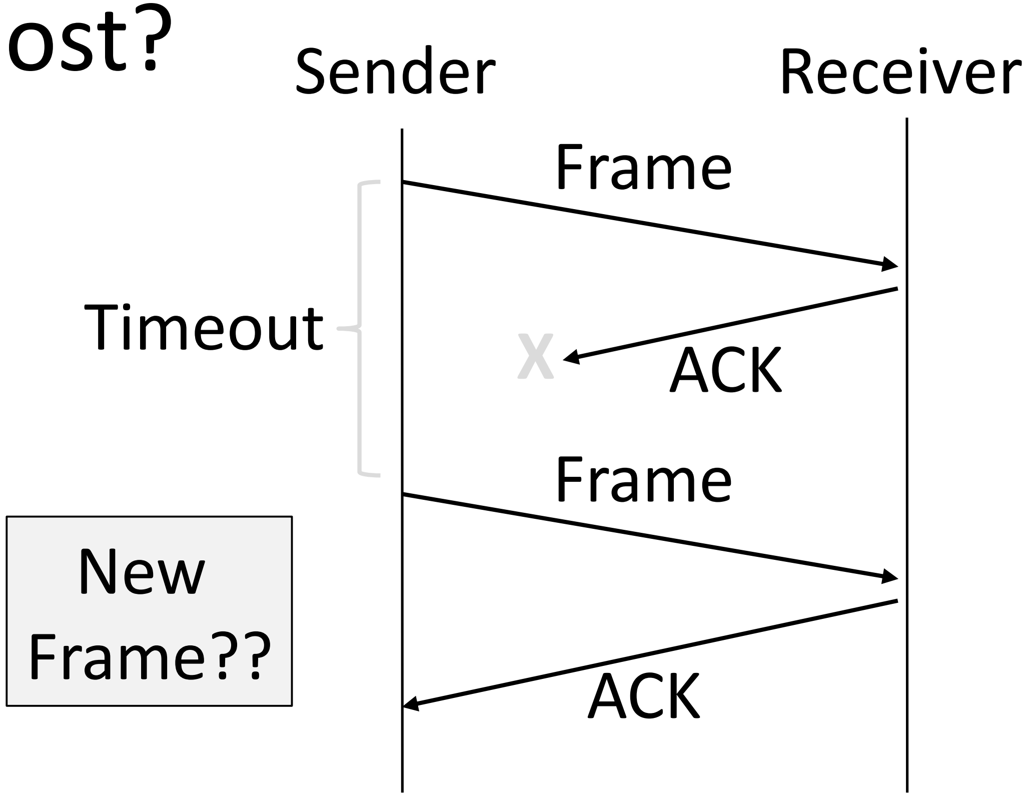
Duplicates

- What happens if an ACK is lost?



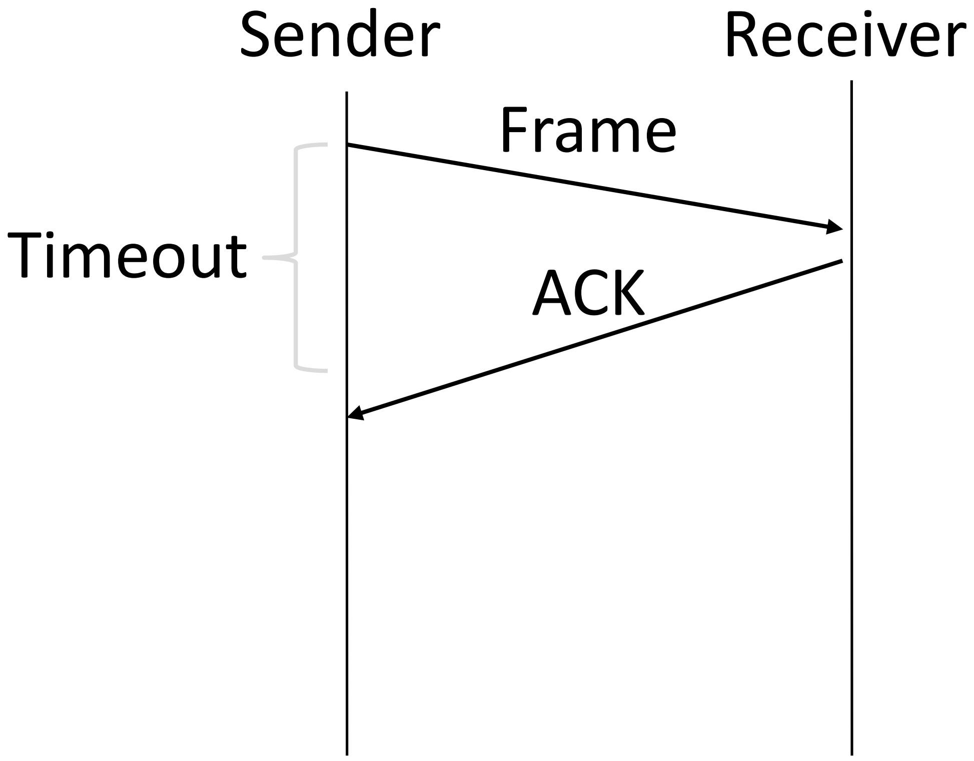
Duplicates (2)

- What happens if an ACK is lost?



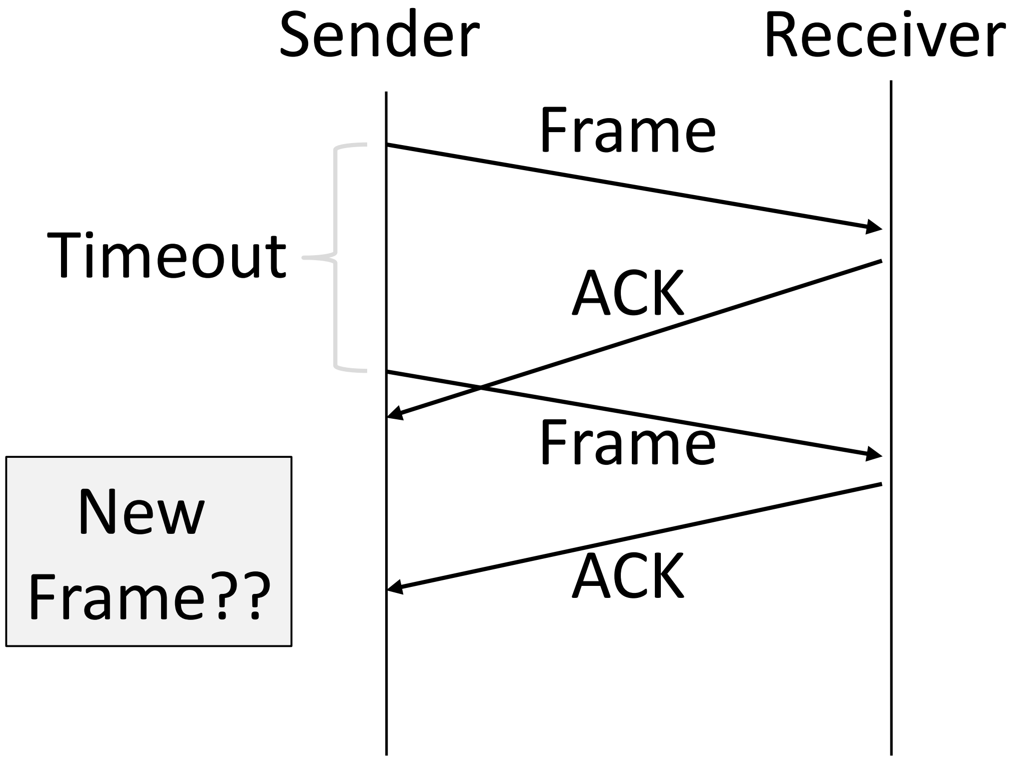
Duplicates (3)

- 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)

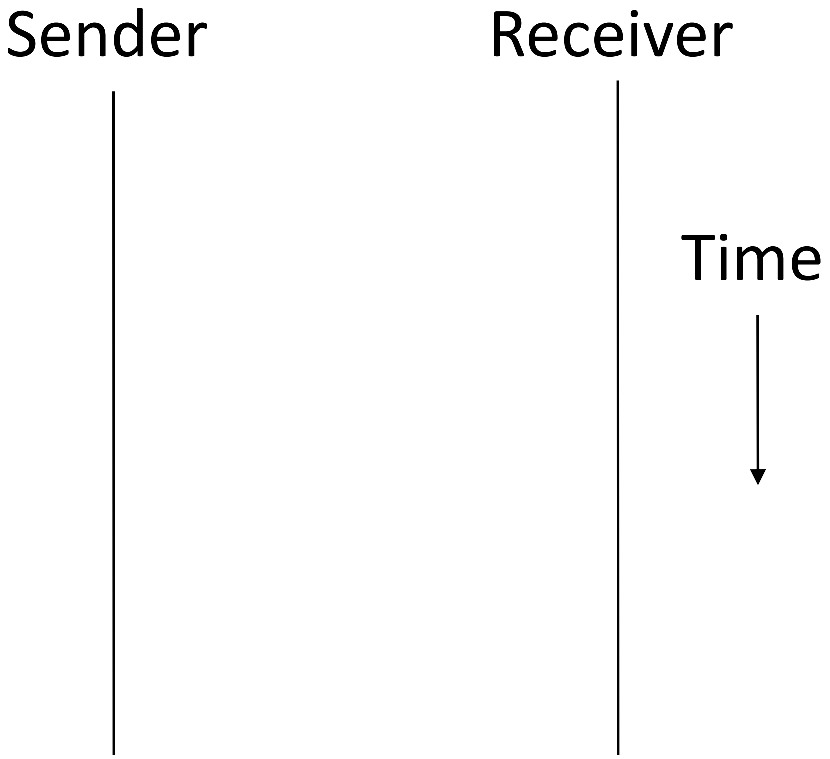
Sequence Numbers

- 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>

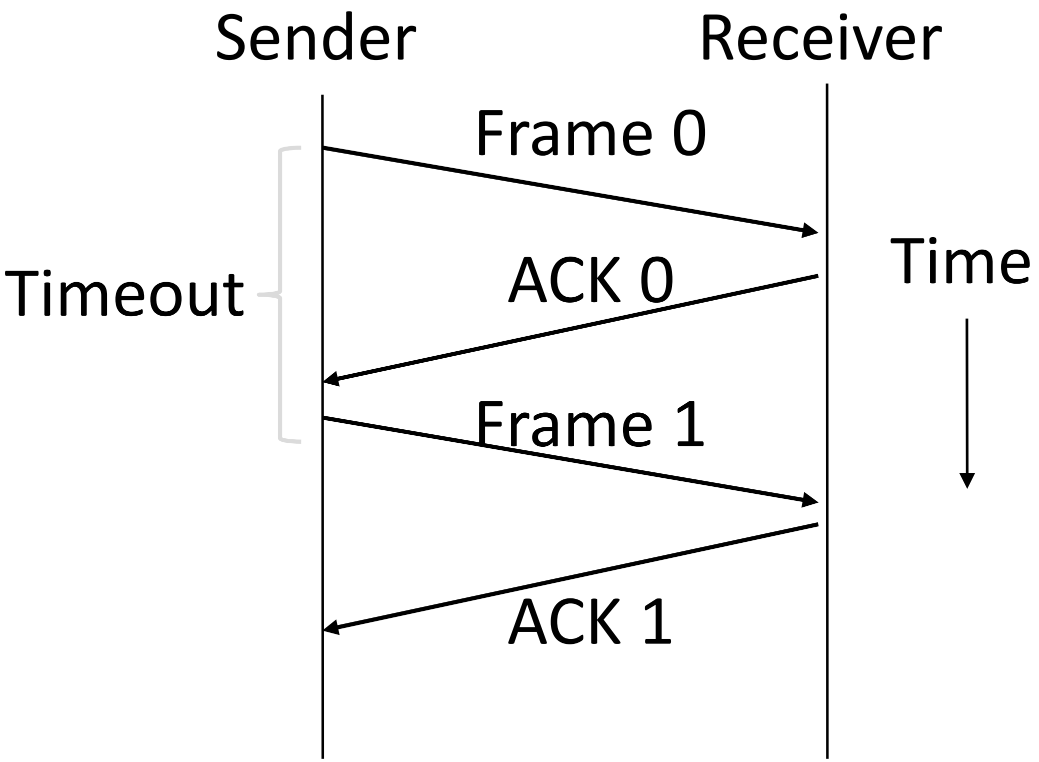
Stop-and-Wait

- In the normal case:



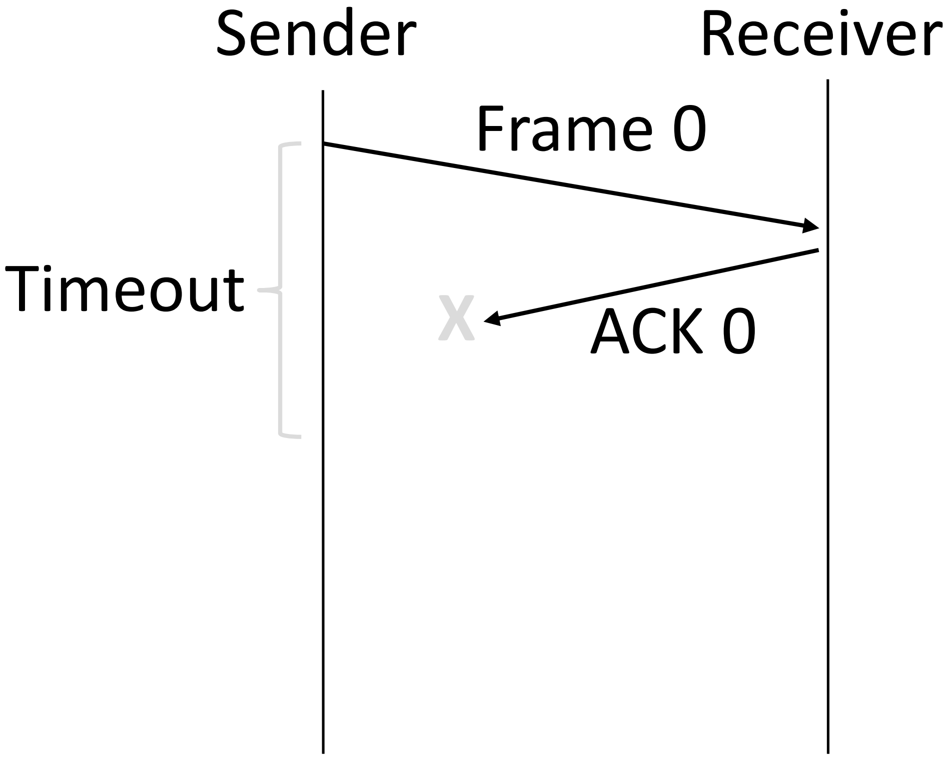
Stop-and-Wait (2)

- In the normal case:



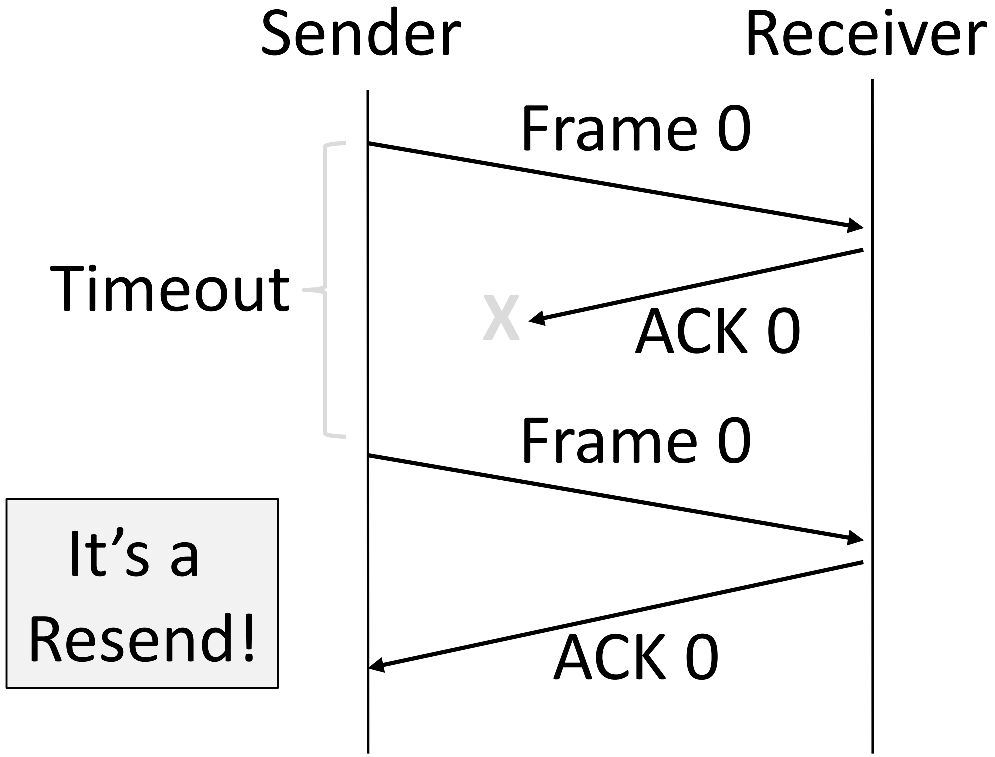
Stop-and-Wait (3)

- With ACK loss:



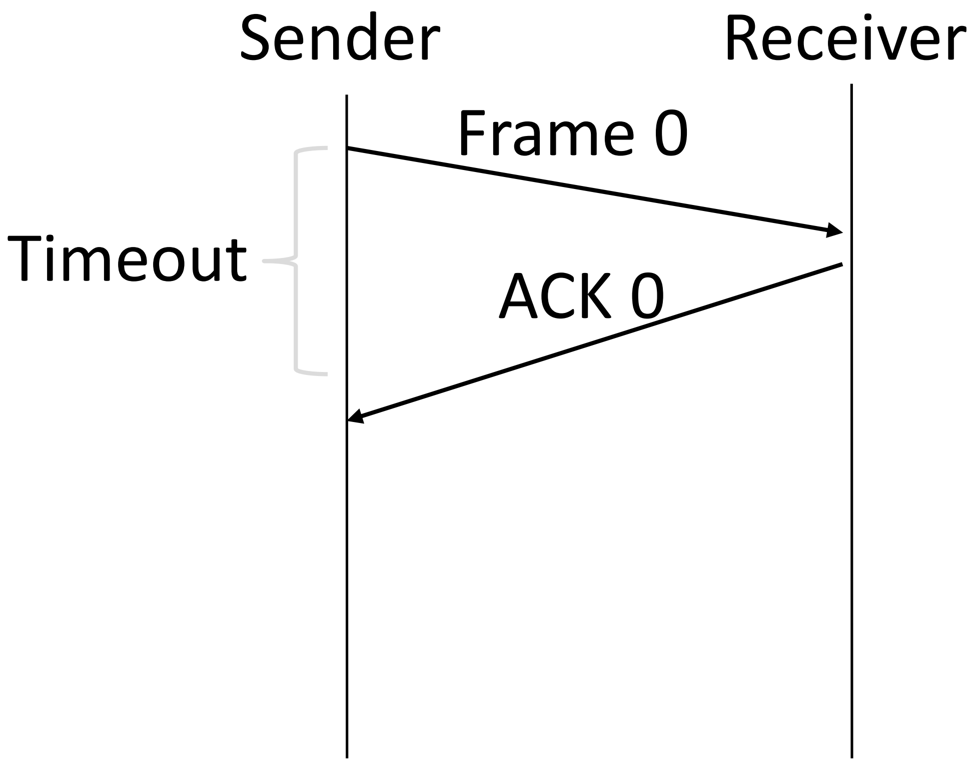
Stop-and-Wait (4)

- With ACK loss:



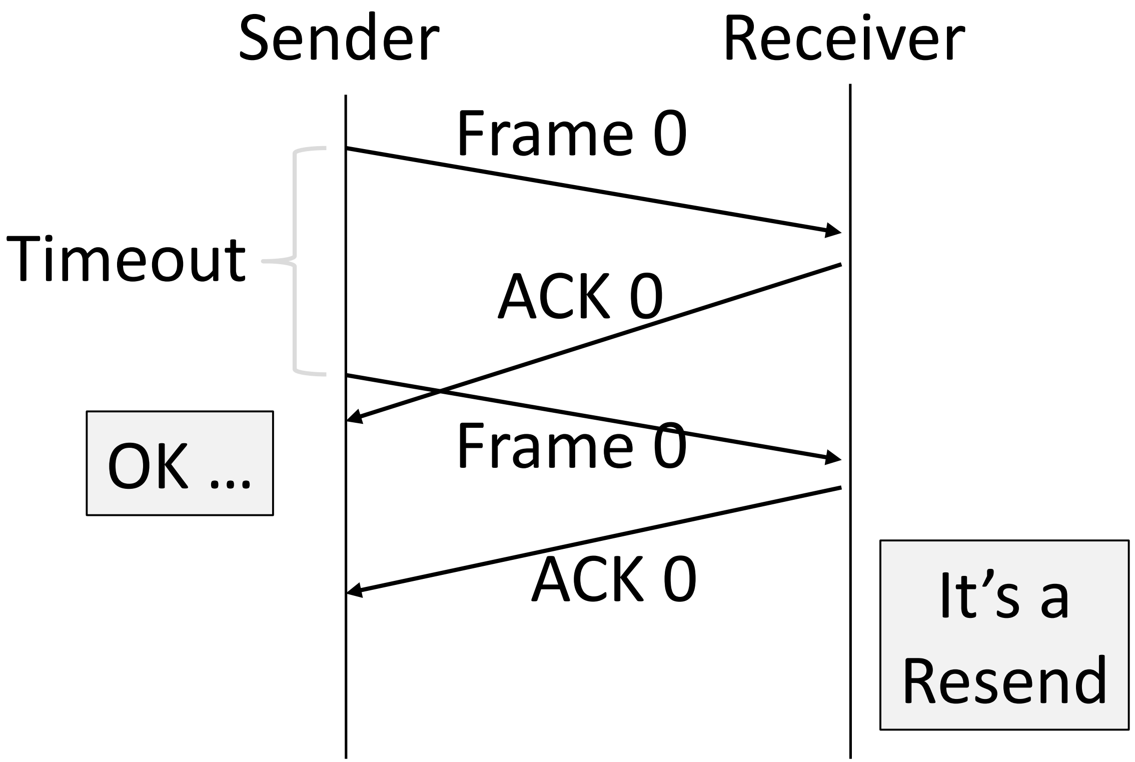
Stop-and-Wait (5)

- With early timeout:



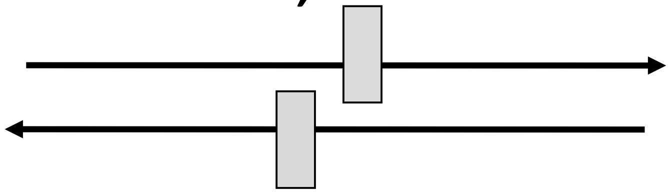
Stop-and-Wait (6)

- With early timeout:



Limitation of Stop-and-Wait

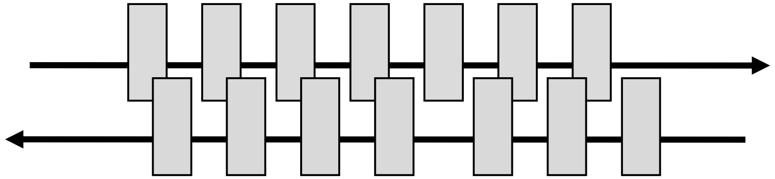
- It allows only a single frame to be outstanding from the sender:
  - Good for LAN, not efficient for high BD



- 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?

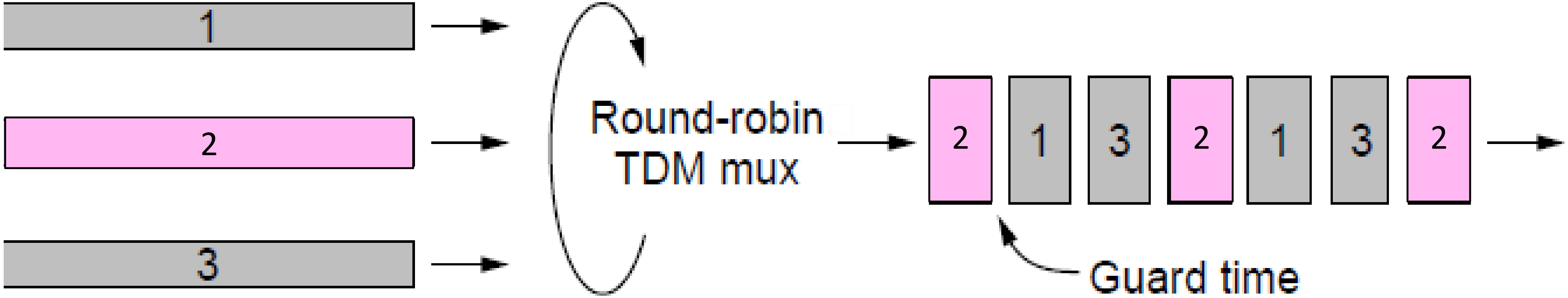
Topic

- 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)

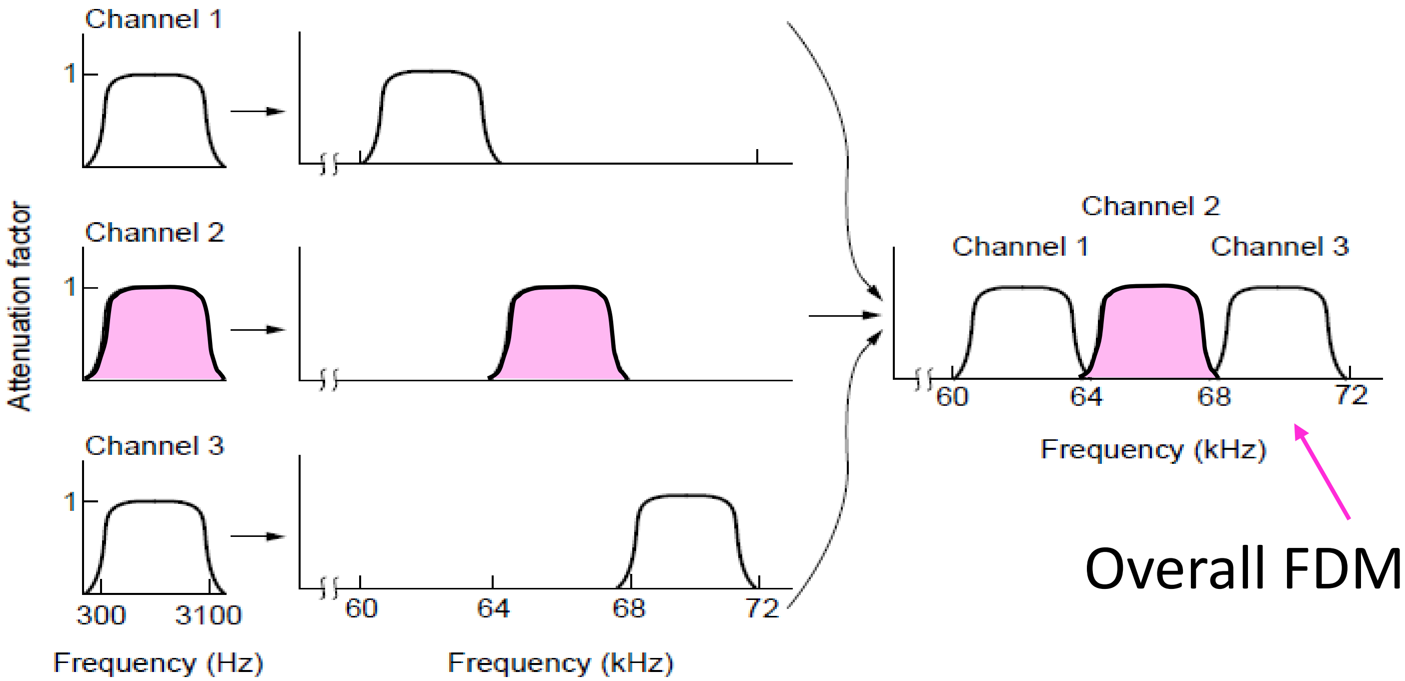
Time Division Multiplexing (TDM)

- Users take turns on a fixed schedule



Frequency Division Multiplexing (FDM)

- Put different users on different frequency bands



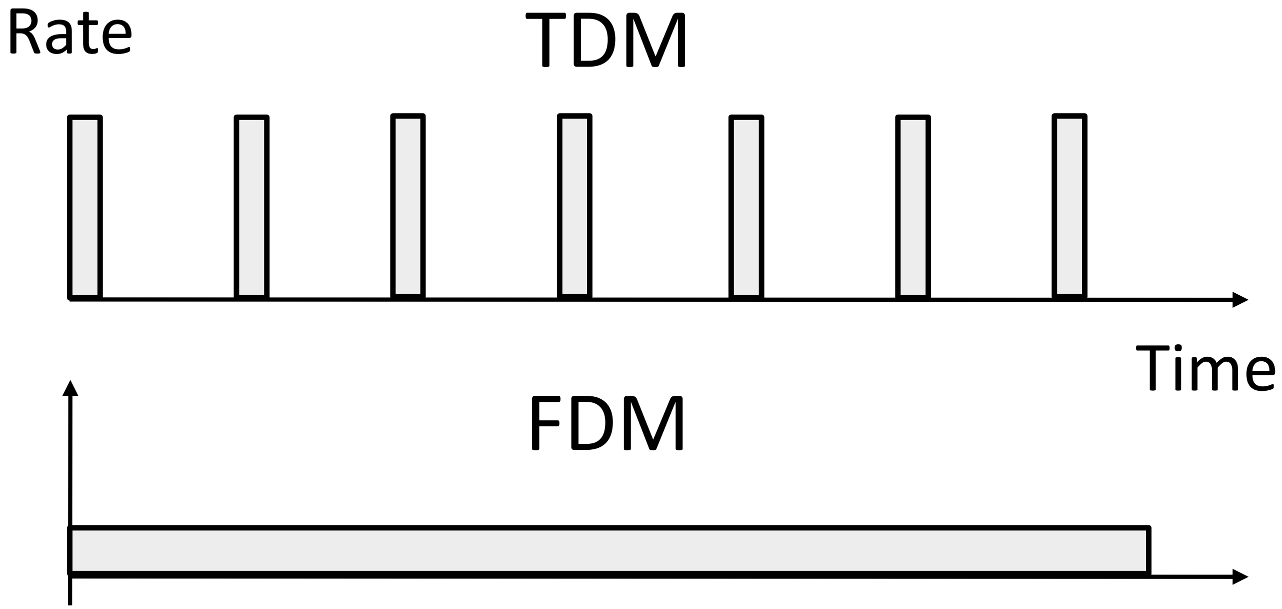
Overall FDM channel

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

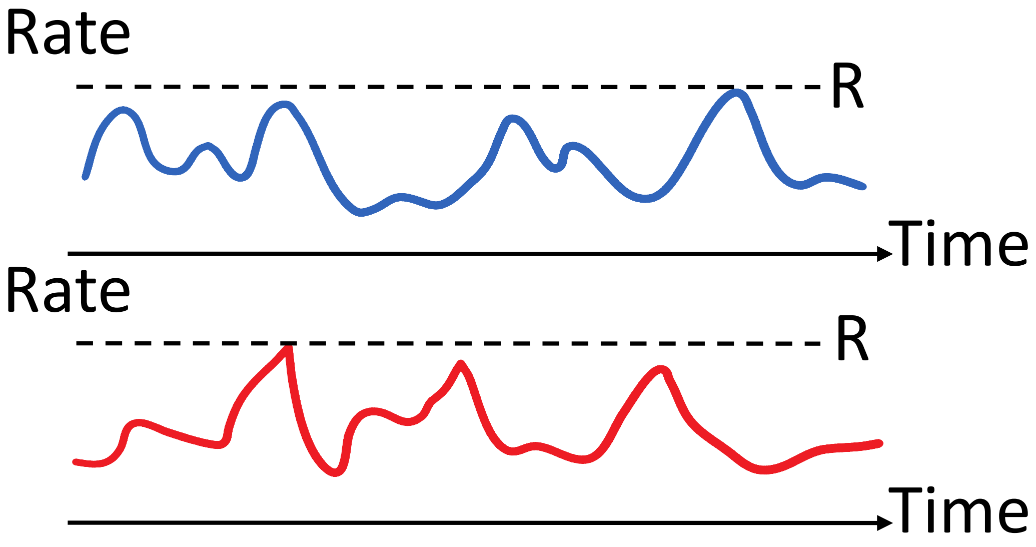


TDM/FDM Usage

- 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

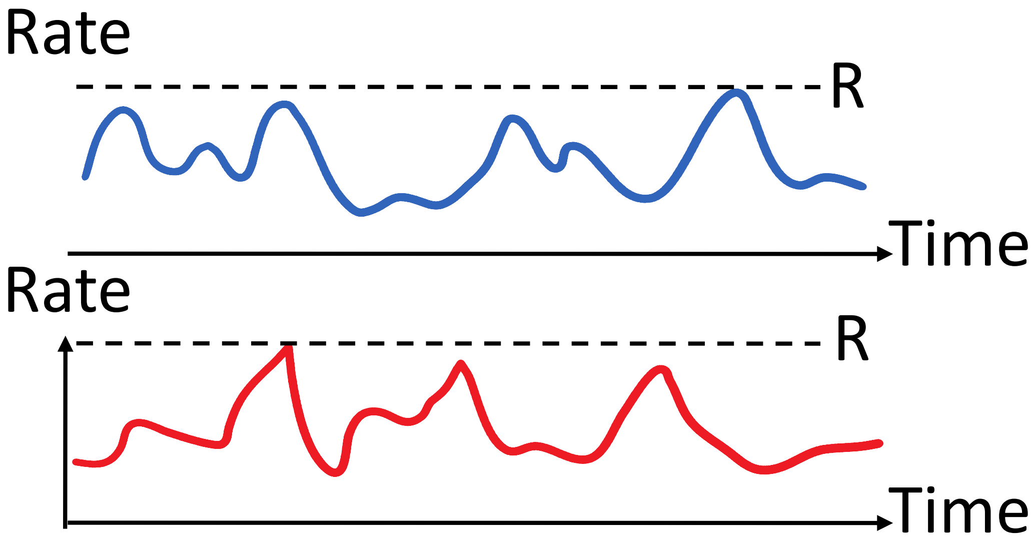
Multiplexing Network Traffic

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



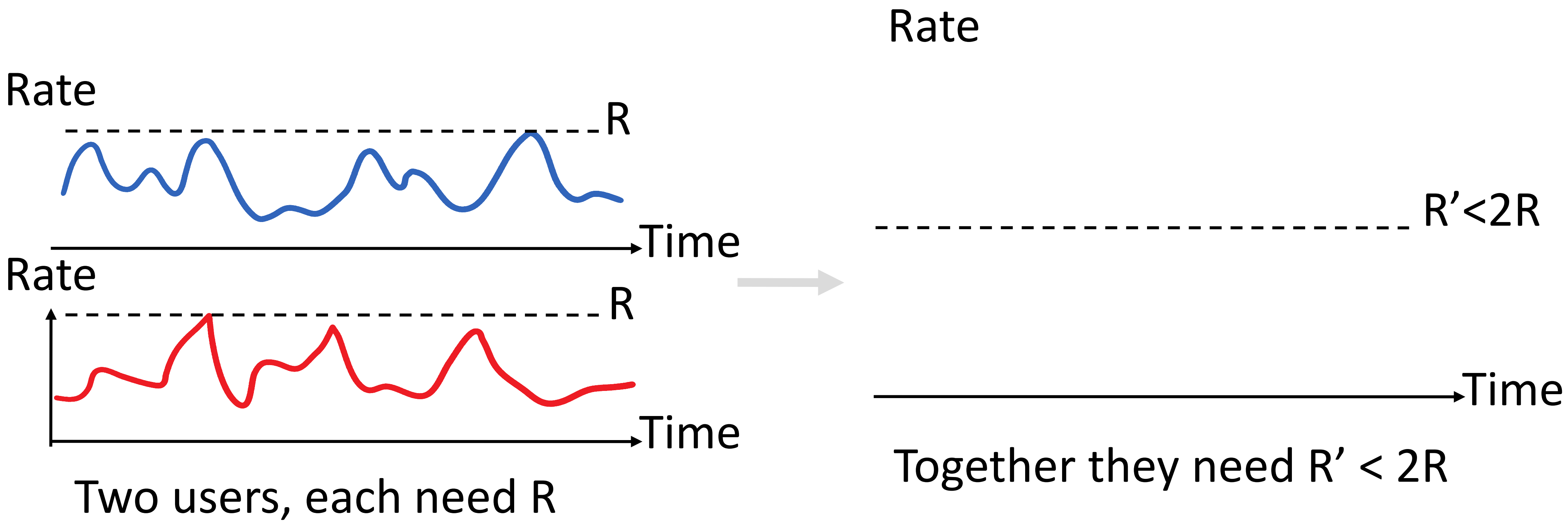
Multiplexing Network Traffic (2)

- Network traffic is bursty
  - 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

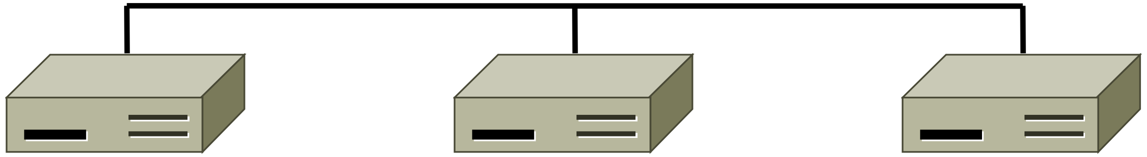
How to control?

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

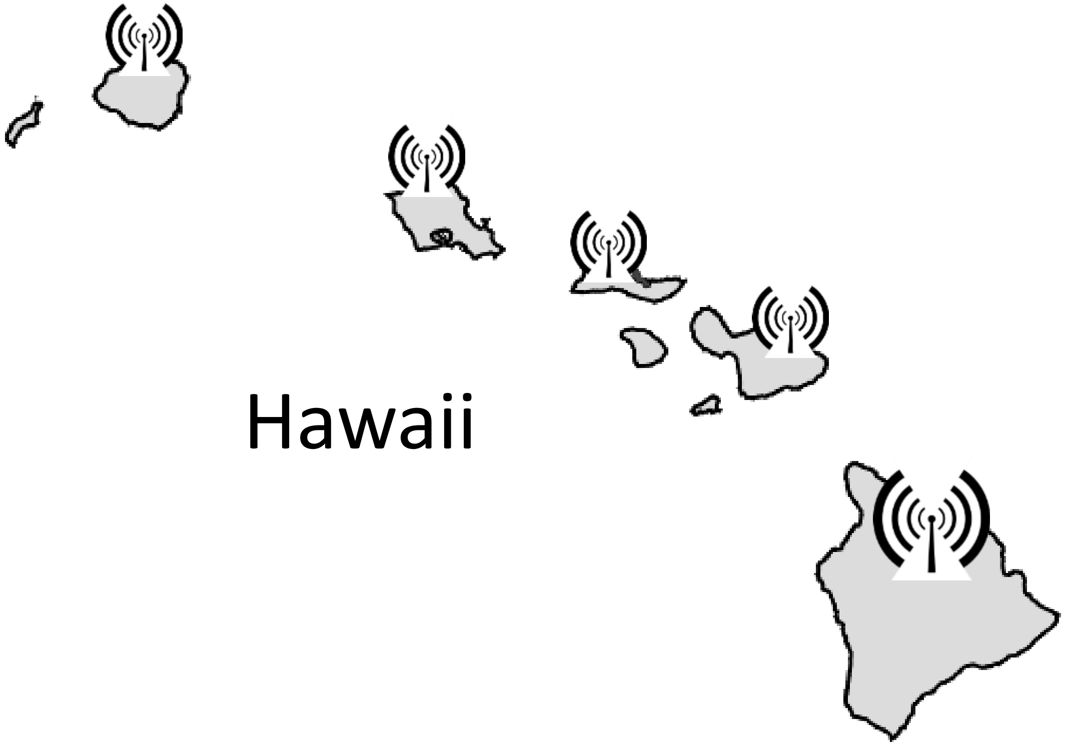
Distributed (random) Access (2)

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

Busy!
Zzzz..
Ho hum

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 …



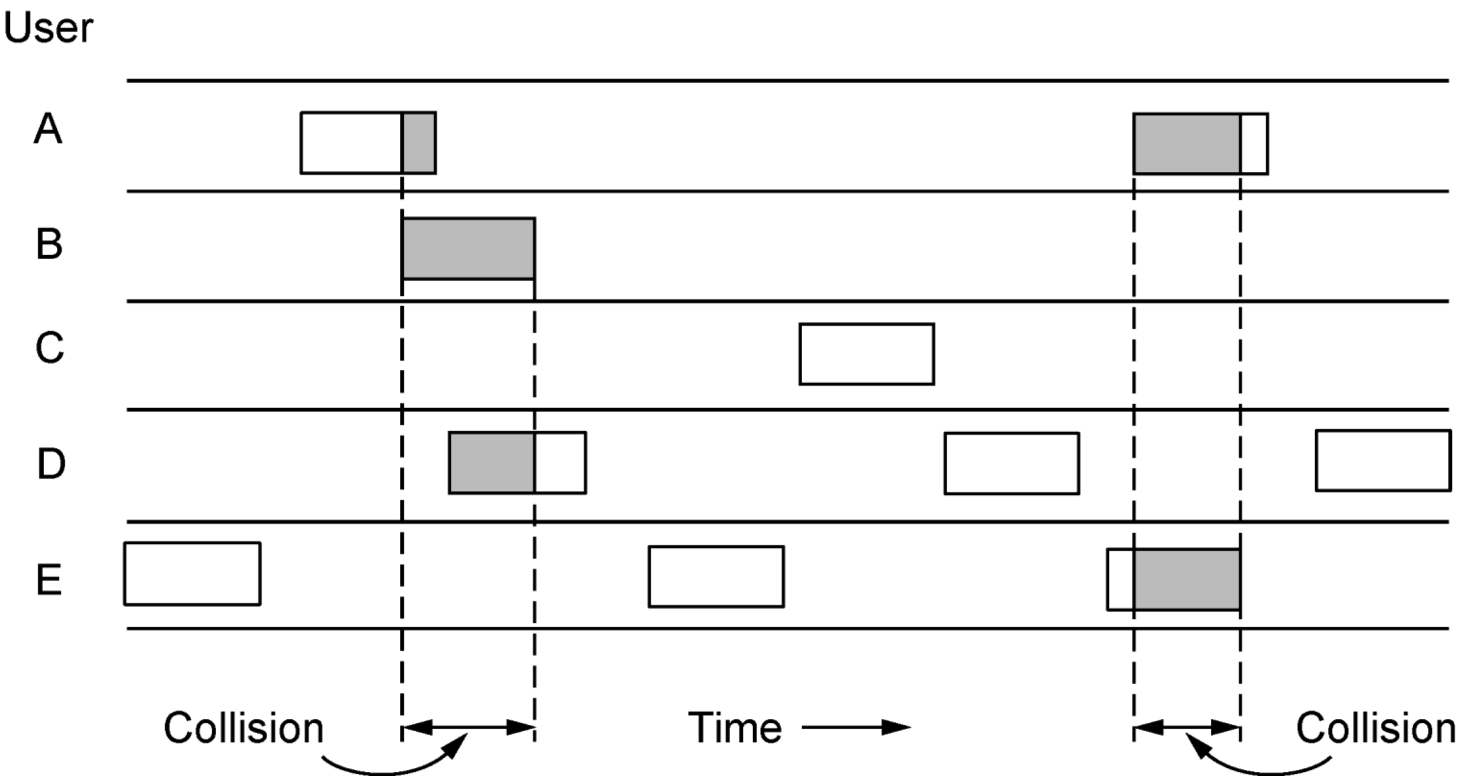
ALOHA Protocol

- 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)

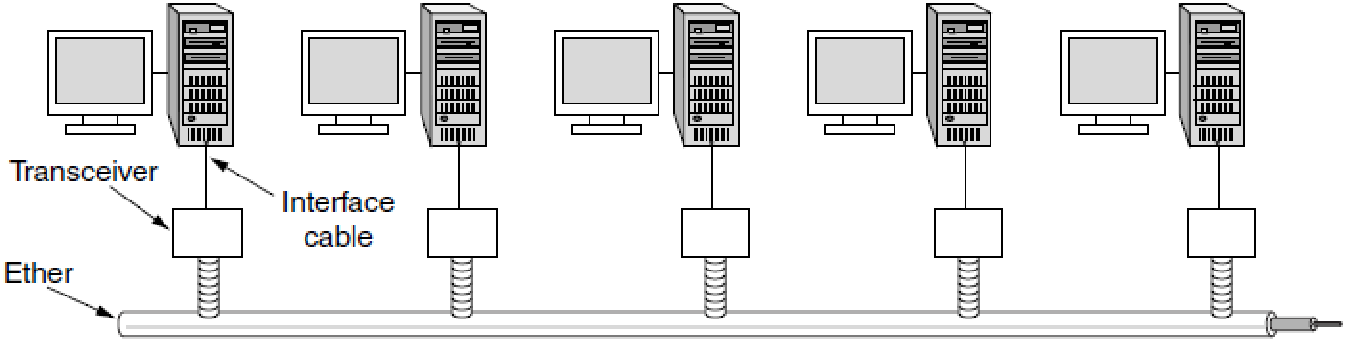
- Simple, decentralized protocol that works well under low load!

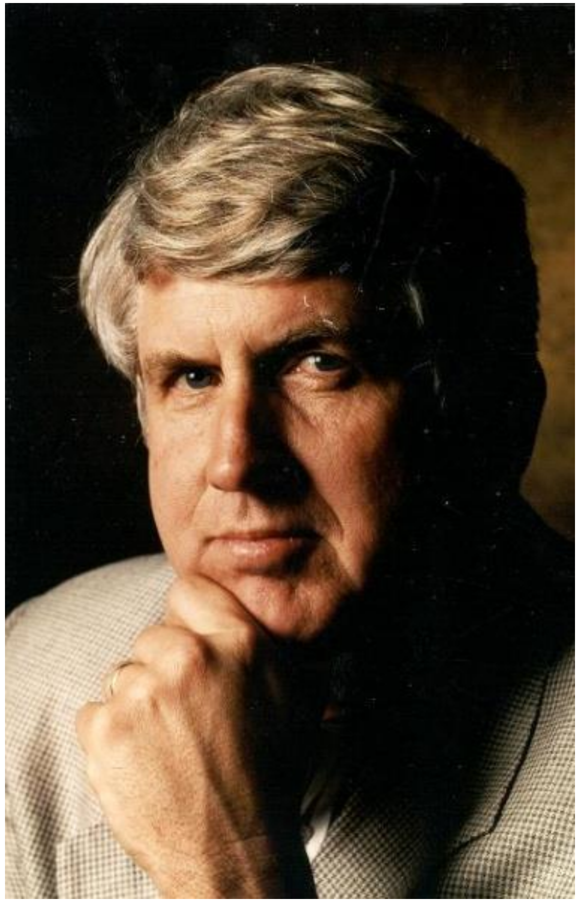
- Not efficient under high load
  - Analysis shows at most 18% efficiency
  - Improvement: divide time into slots and efficiency goes up to 36%

- 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

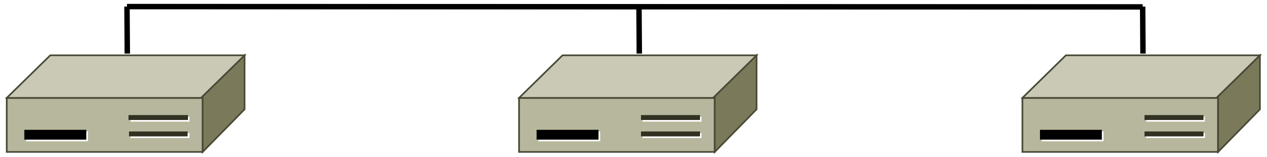
CSMA (Carrier Sense Multiple Access)

- 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?

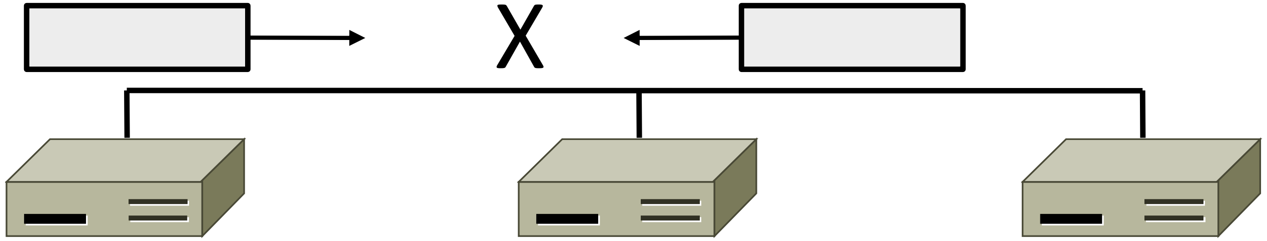
CSMA (2)

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



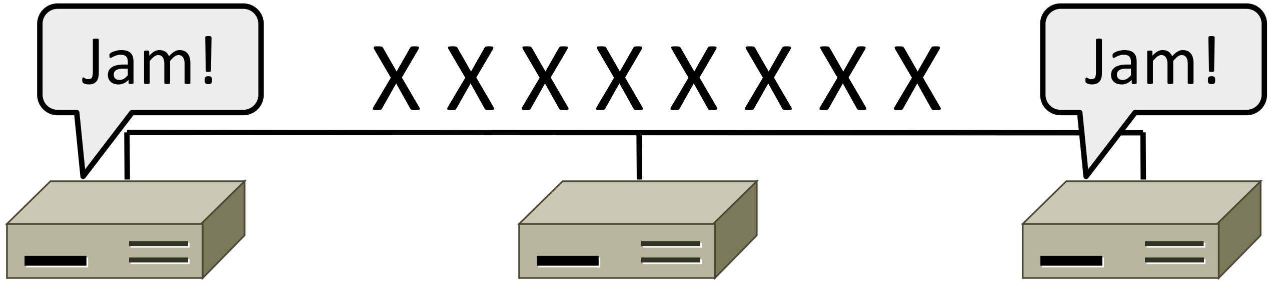
CSMA (3)

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



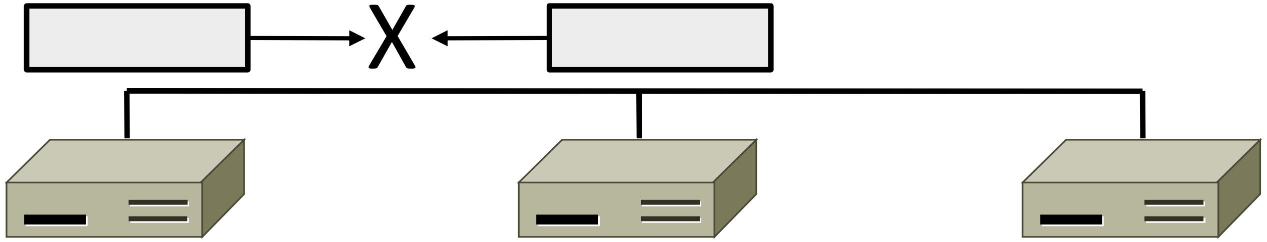
CSMA/CD (with Collision Detection)

- 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



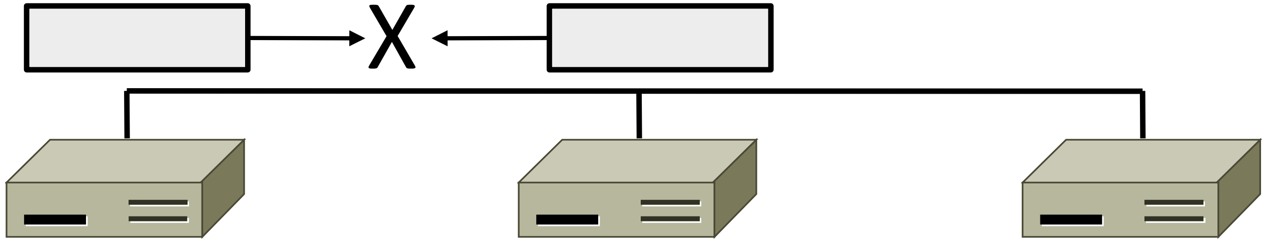
CSMA/CD Complications

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



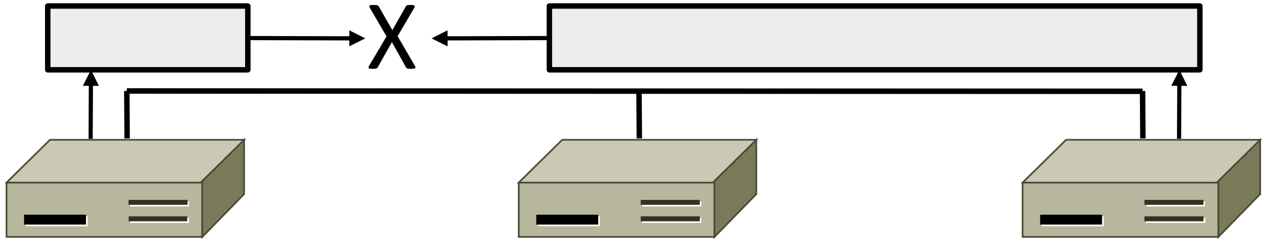
CSMA/CD Complications

- 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



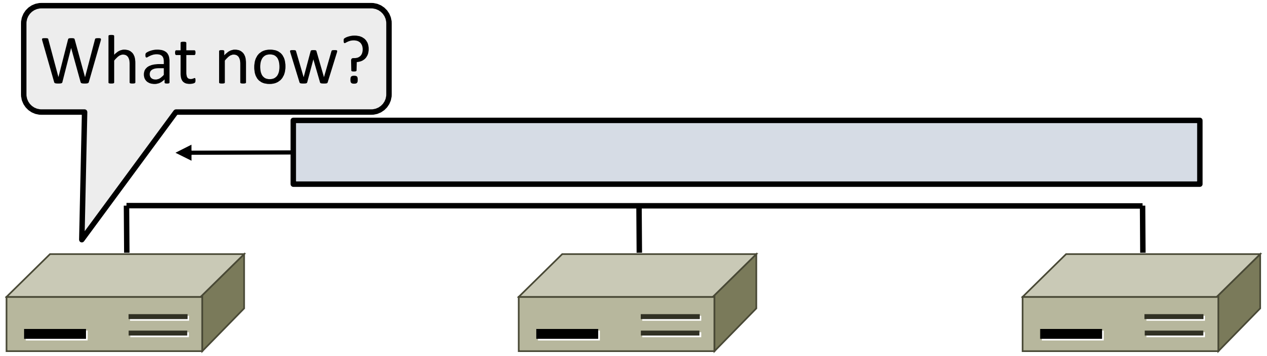
CSMA/CD Complications (2)

- 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"

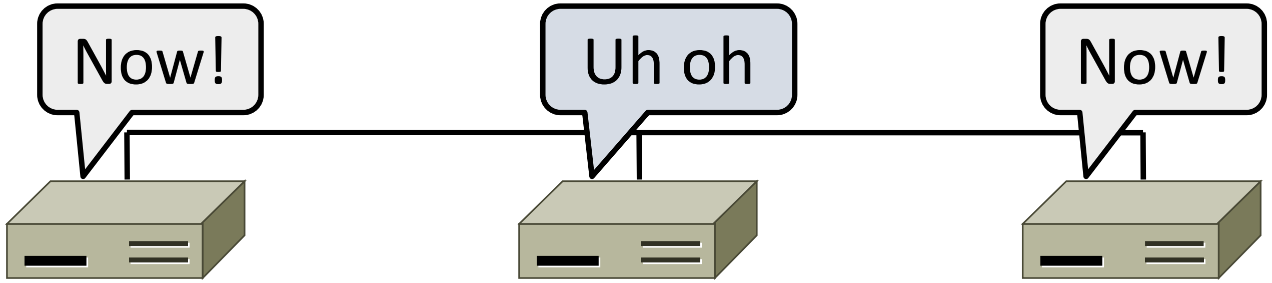
- What should a node do if another node is sending?



- Idea: Wait until it is done, and send

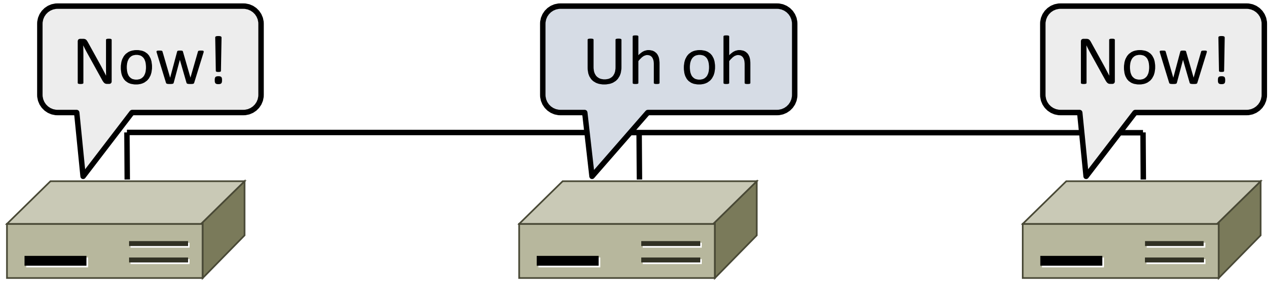
CSMA “Persistence” (2)

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



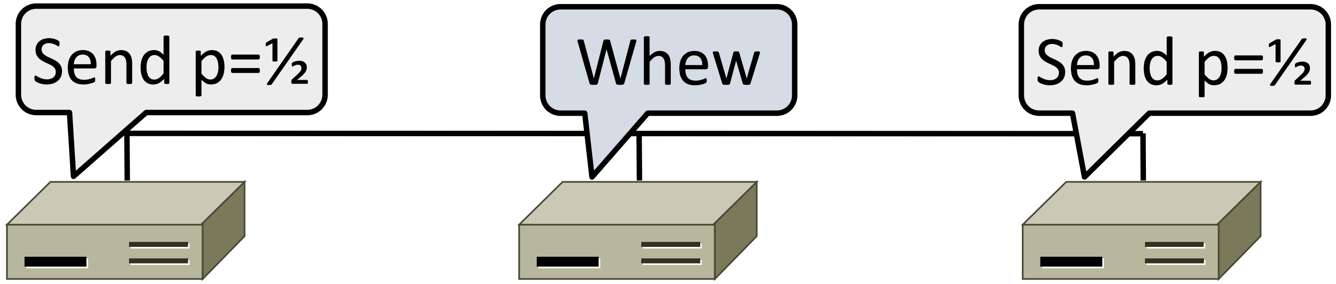
CSMA "Persistence" (2)

- 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

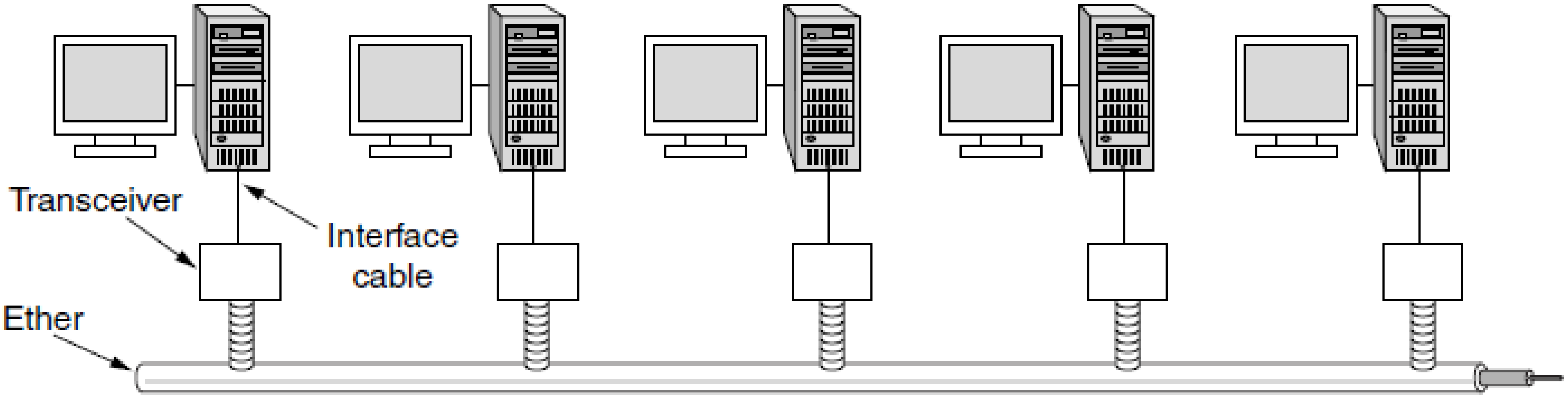


Binary Exponential Backoff (BEB)

- 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

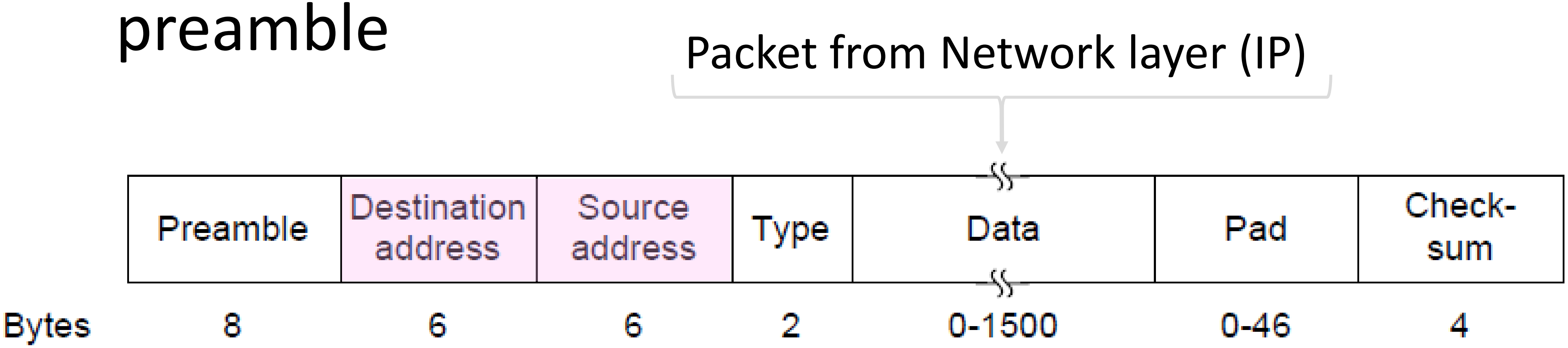
Classic Ethernet, or IEEE 802.3

- 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

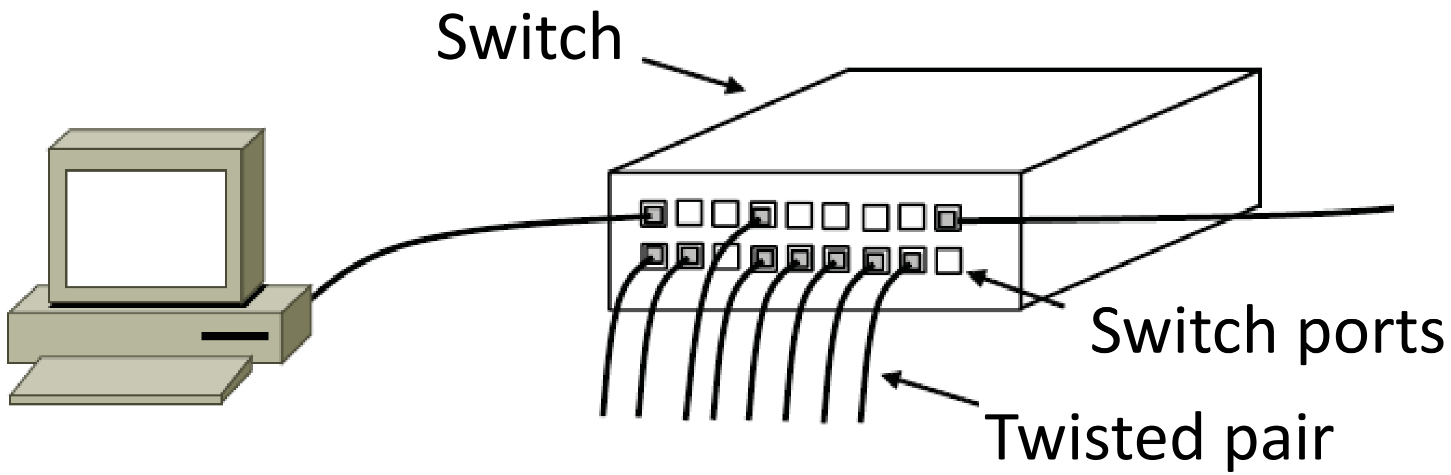


Packet from Network layer (IP)

	Preamble	Destination address	Source address	Type	Data	Pad	Check-sum
Bytes	8	6	6	2	0-1500	0-46	4

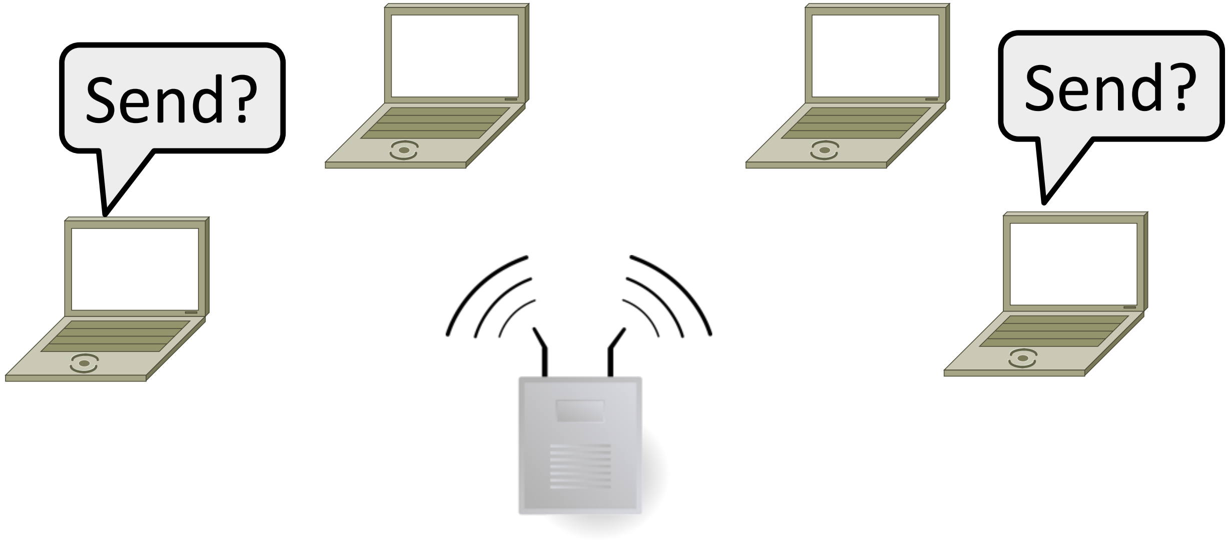
Modern Ethernet

- 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



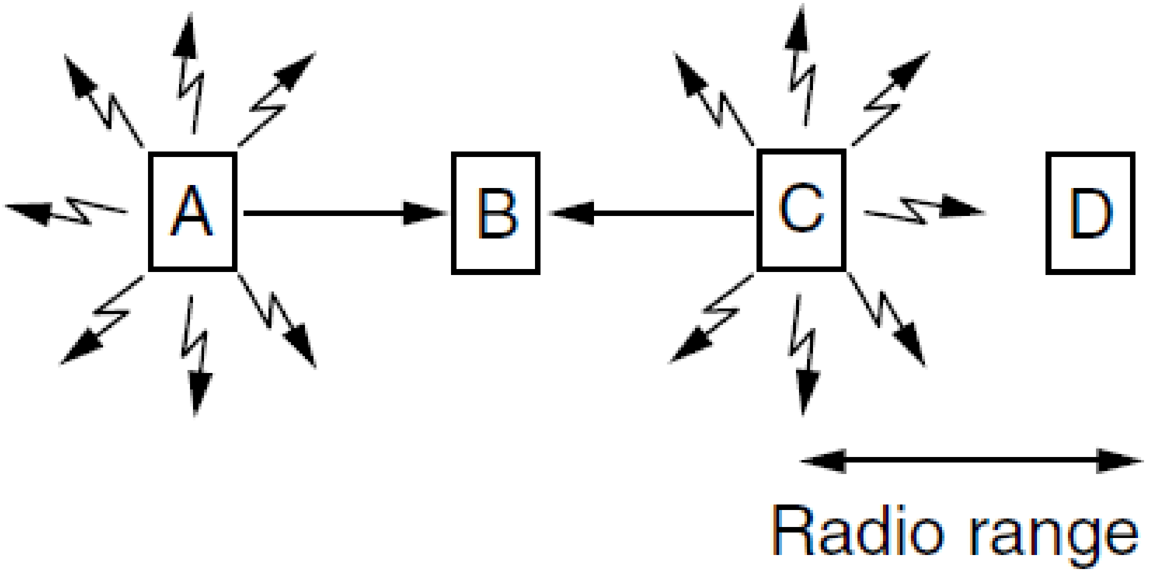
Wireless Complications

- 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

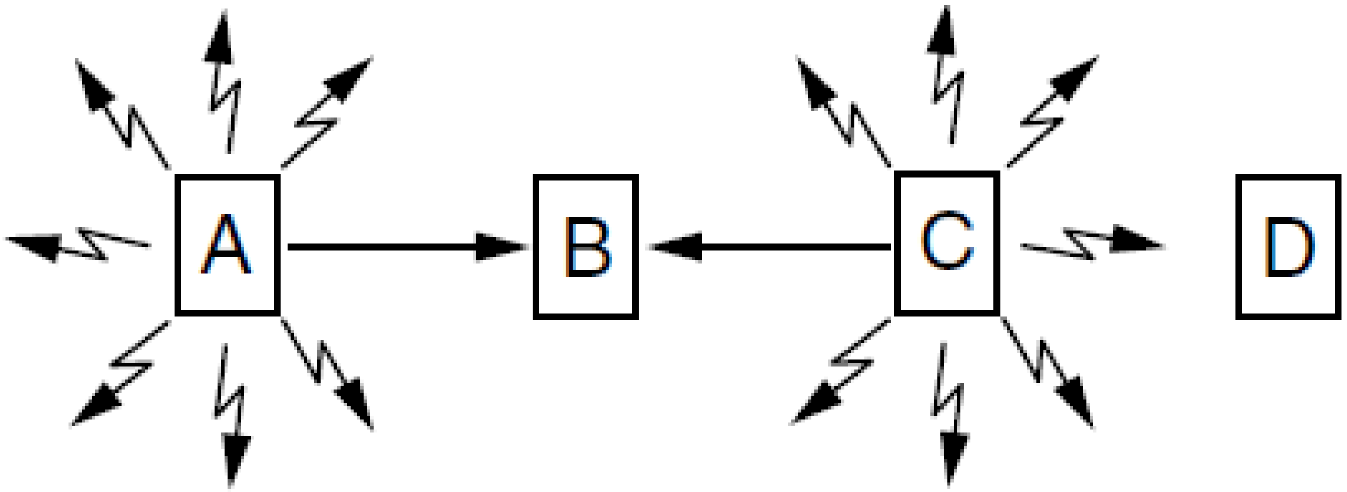
No CS: Different Coverage Areas

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



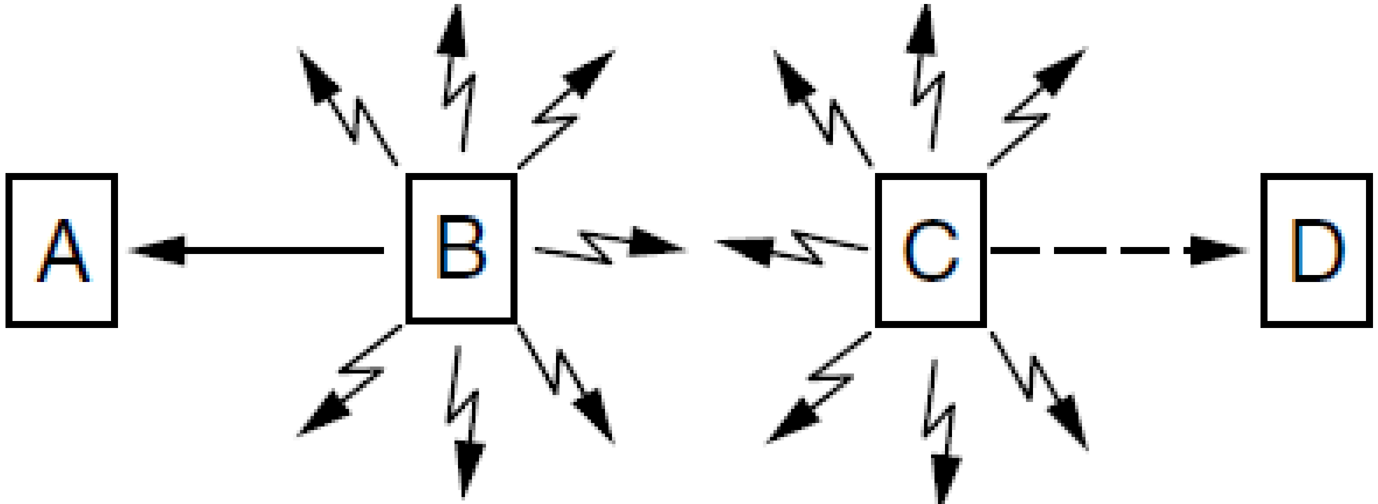
No CS: Hidden Terminals

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



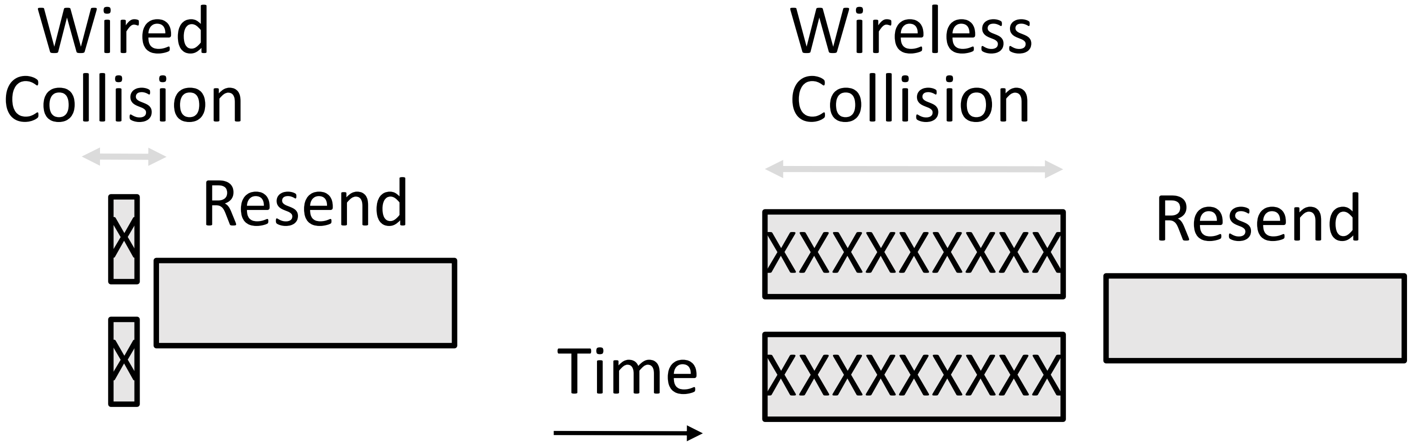
No CS: Exposed Terminals

- 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?

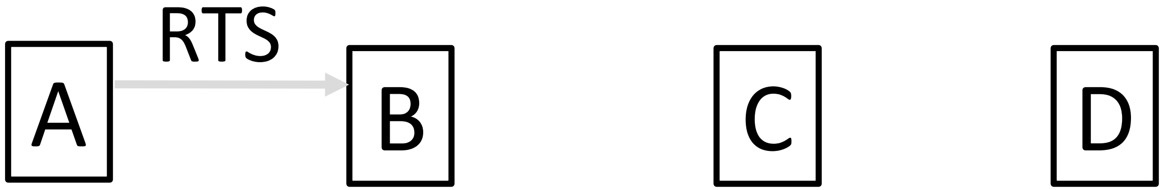
MACA (Multiple Access with Collision Avoidance)

- 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

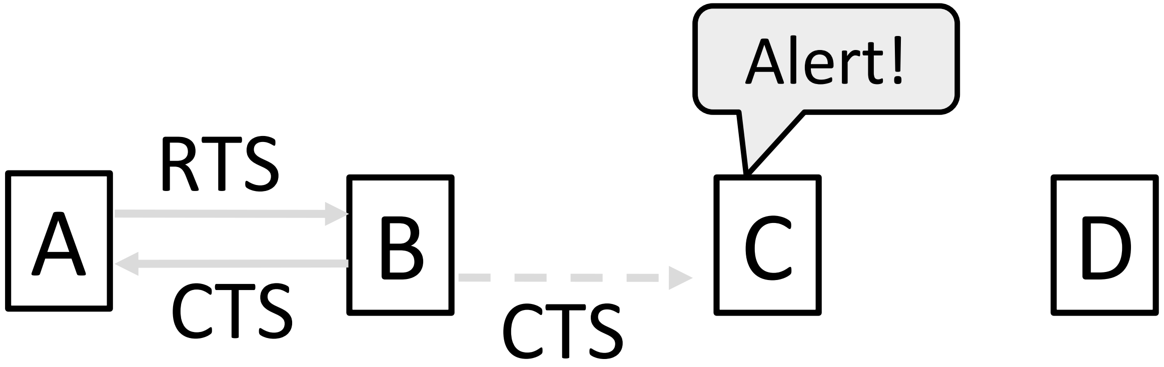
MACA – Hidden Terminals

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



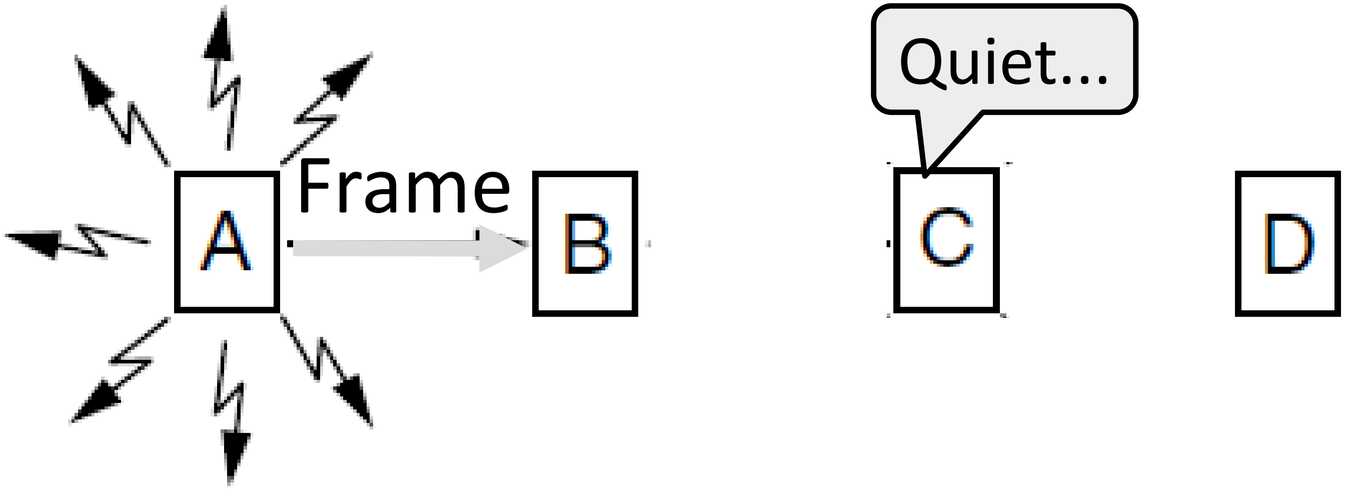
MACA – Hidden Terminals (2)

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



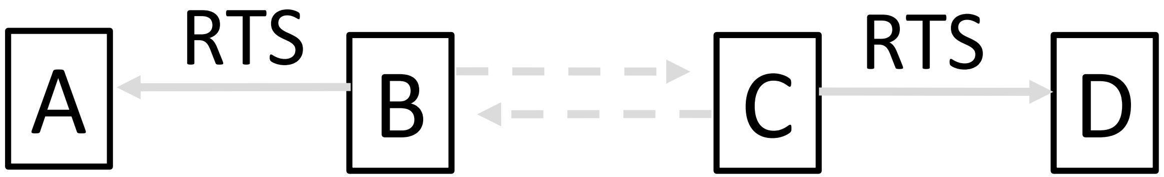
MACA – Hidden Terminals (3)

- A → B with hidden terminal C
    3. A sends frame while C defers



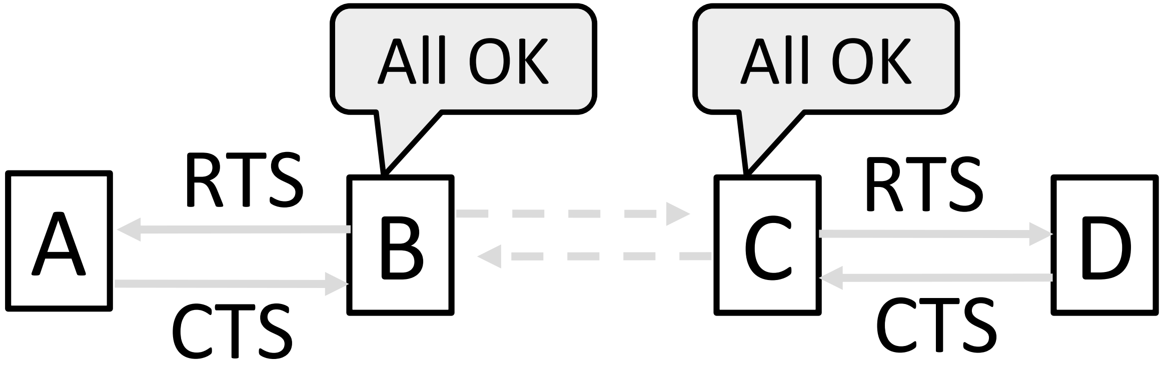
MACA – Exposed Terminals

- B → A, C → D as exposed terminals
  - B and C send RTS to A and D



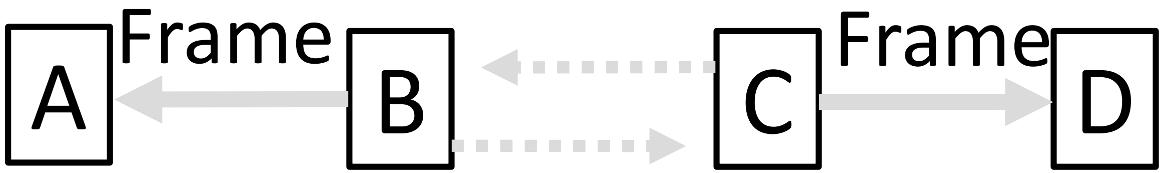
MACA – Exposed Terminals (2)

- B → → A, C D as exposed terminals
  - A and D send CTS to B and C



MACA – Exposed Terminals (3)

- B → → A, C D as exposed terminals
  - A and D send CTS to B and C

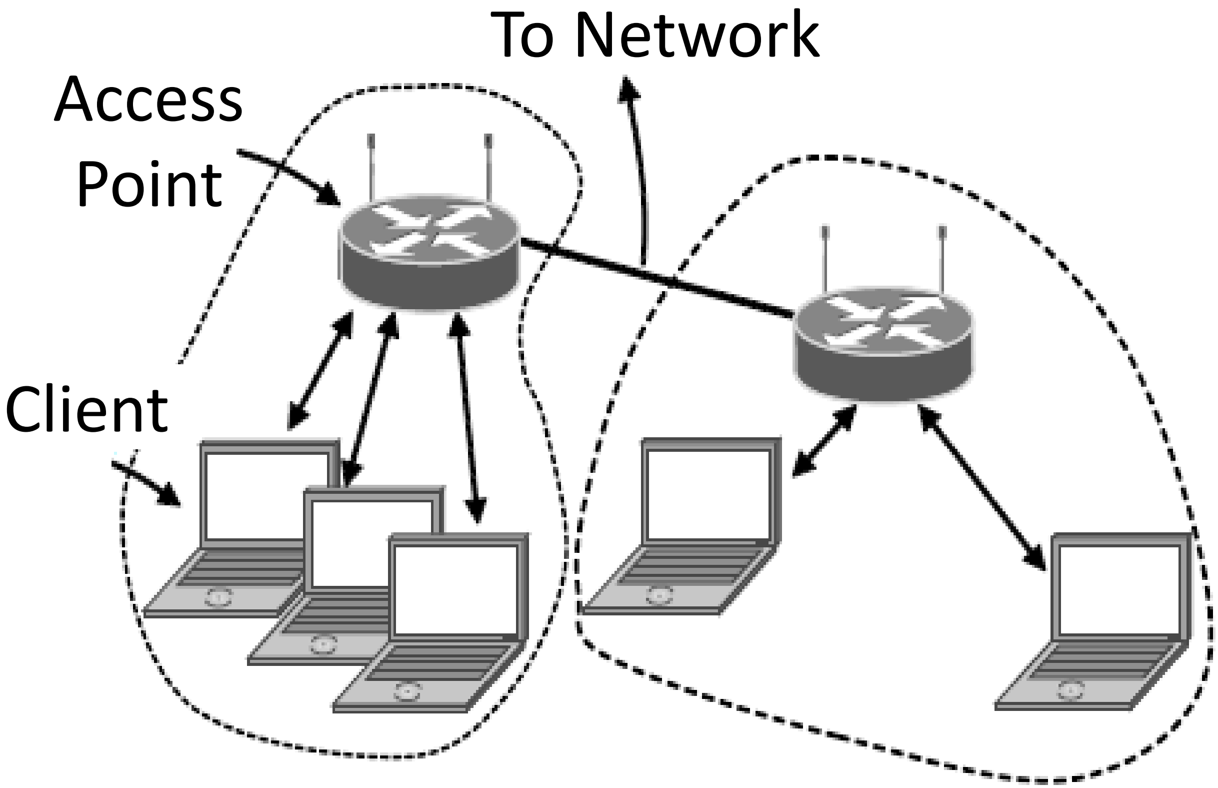


MACA

- 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

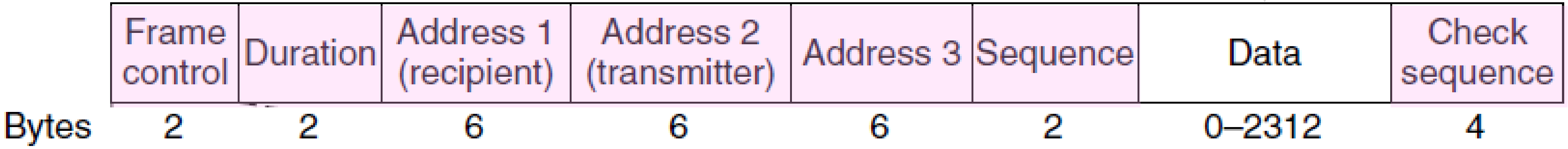
- Uses 20/40 MHz channels on ISM (unlicensed) bands
  - 802.11b/g/n on 2.4 GHz
  - 802.11 a/n on 5 GHz

- 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)

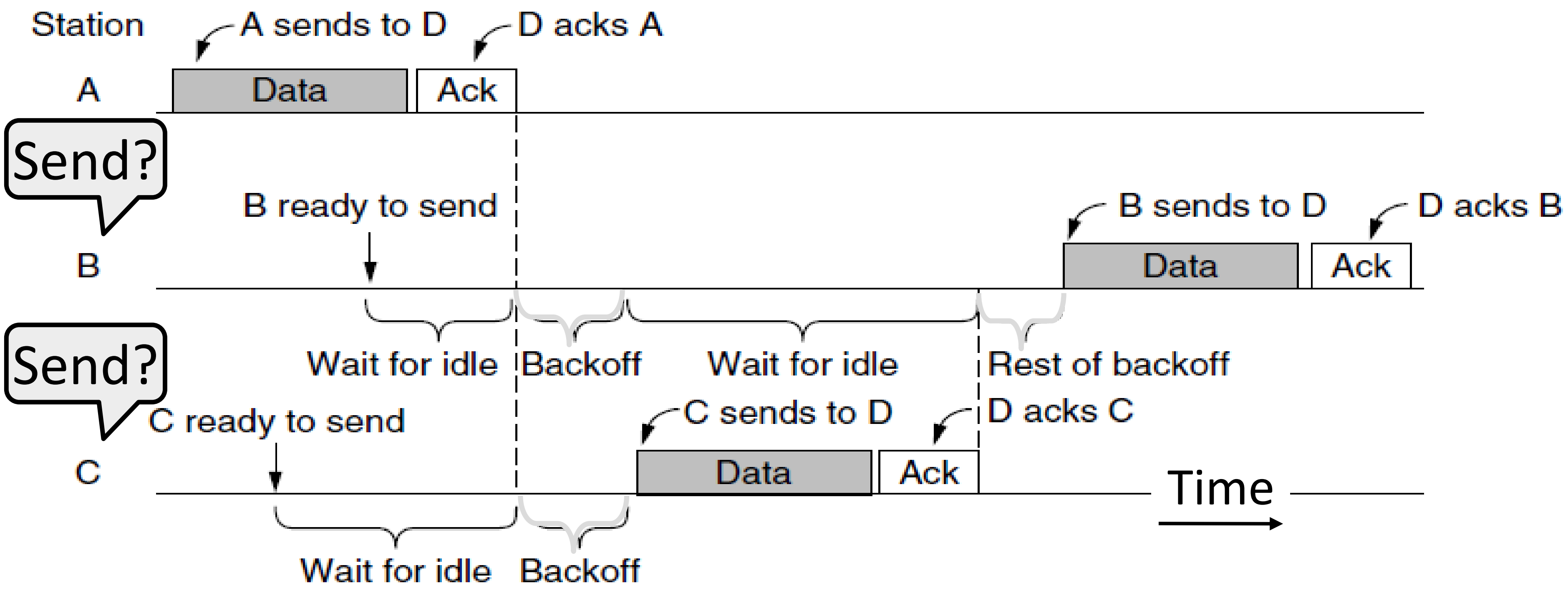
Packet from Network layer (IP)



	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!

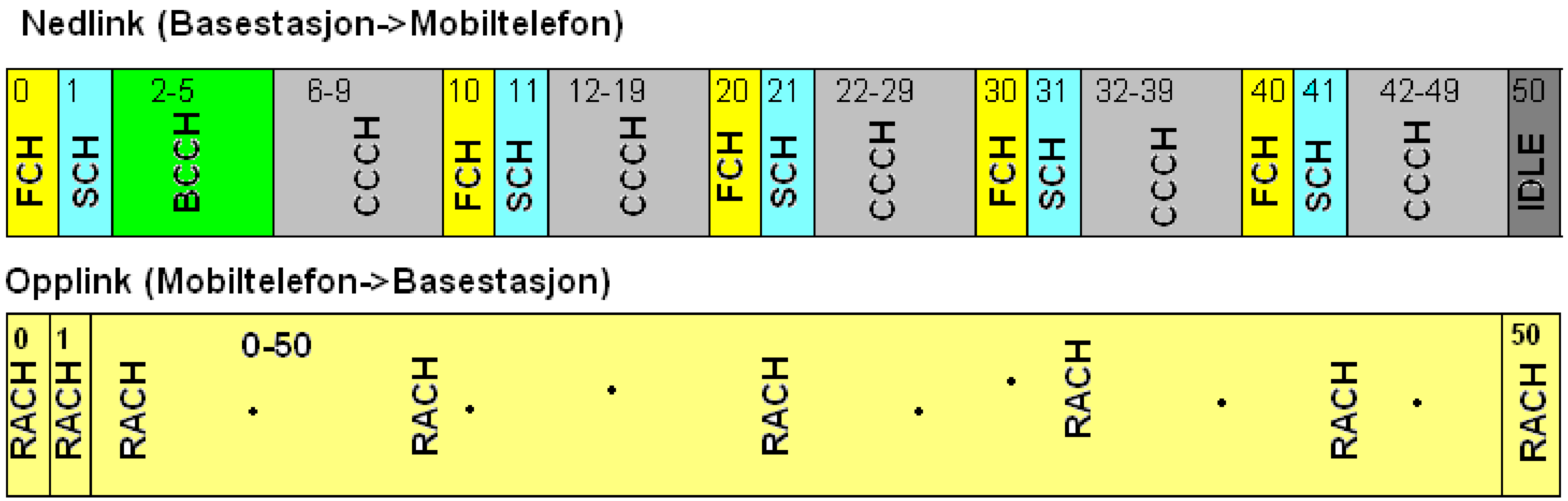


Centralized MAC: Cellular

- 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

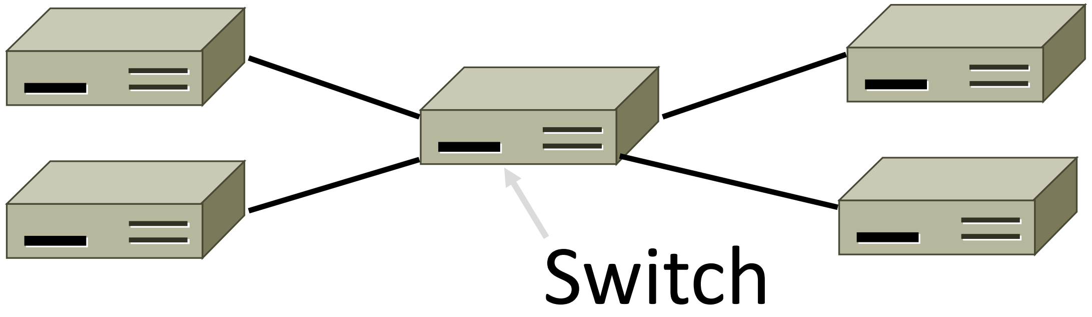
- FDMA/TDMA
- Use one channel for coordination – Random access w/BEB (no CSMA, can’t detect)
- Use other channels for traffic
  - Dedicated channel for QoS



Link Layer: Switching

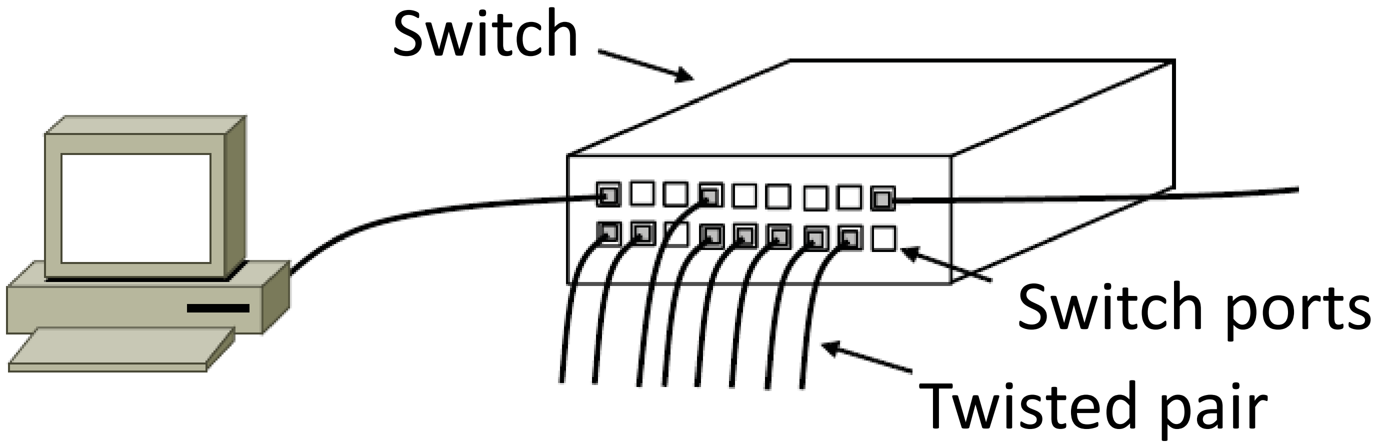
Topic

- How do we connect nodes with a switch 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



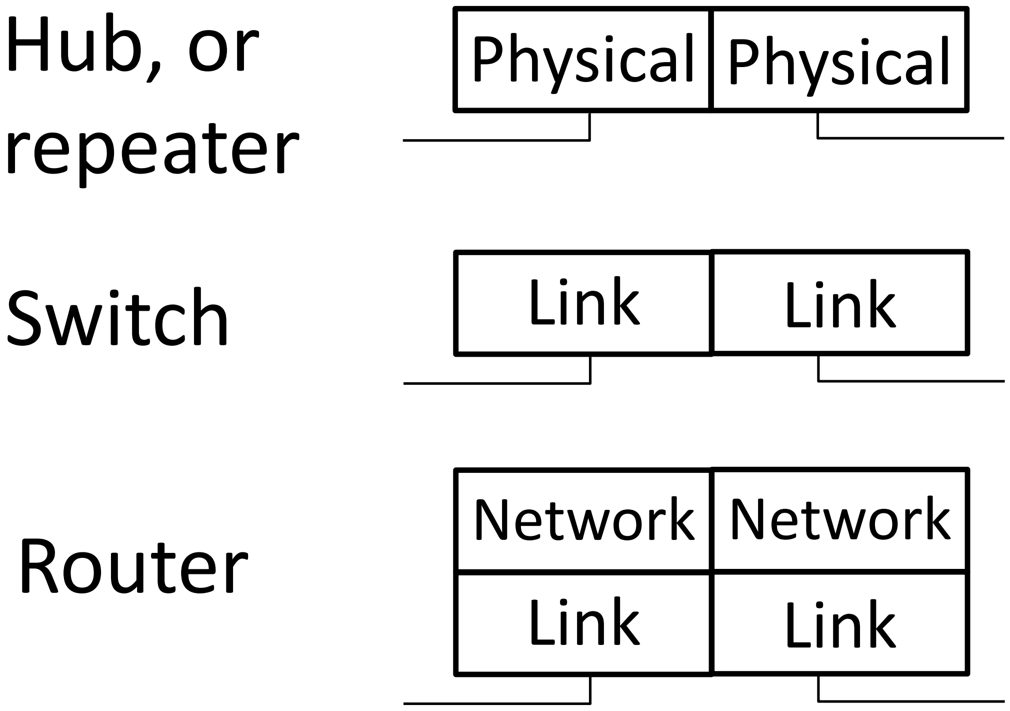
Switch

Switch ports

Twisted pair

What's in the box?

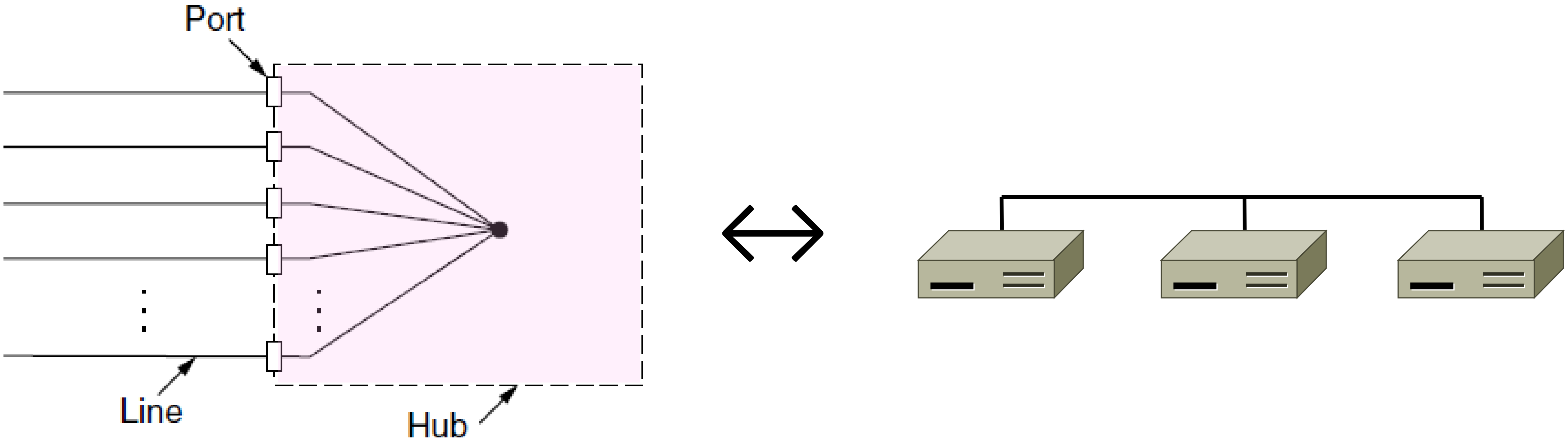
- Remember from protocol layers:



All look like this:

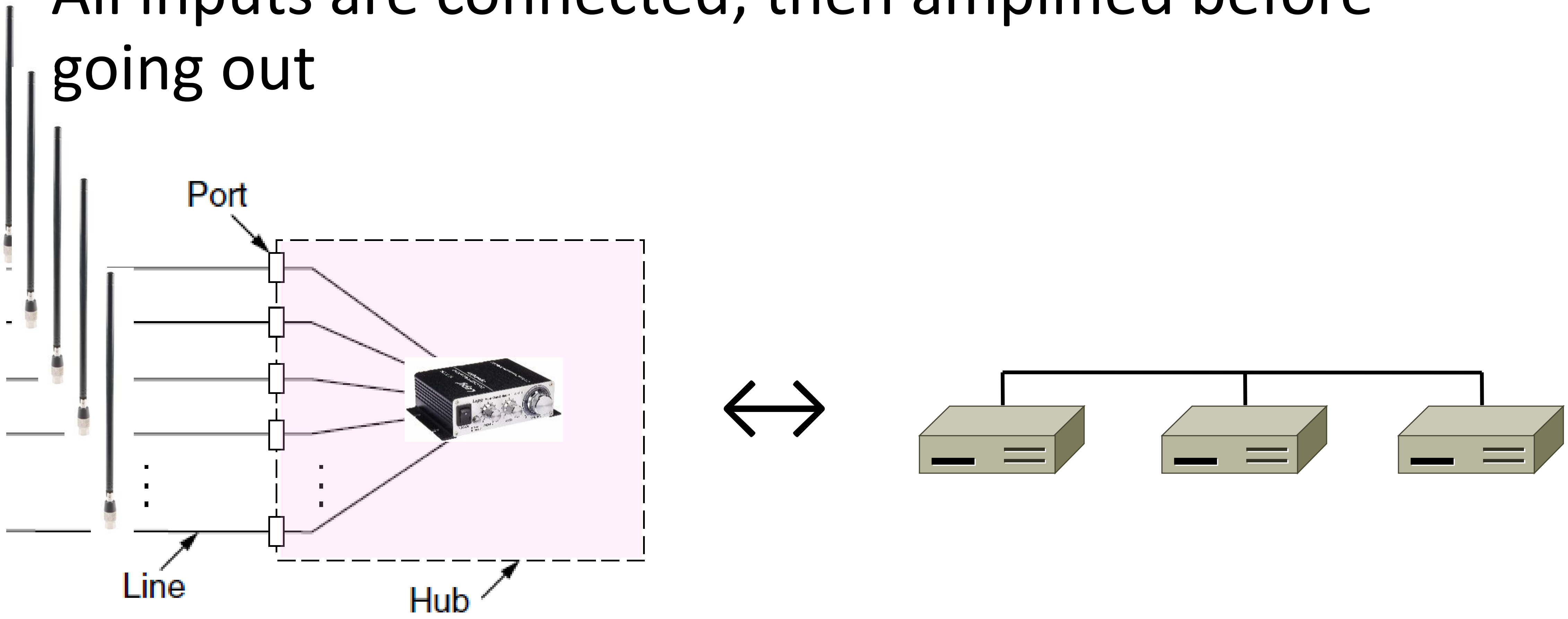
Inside a Hub

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



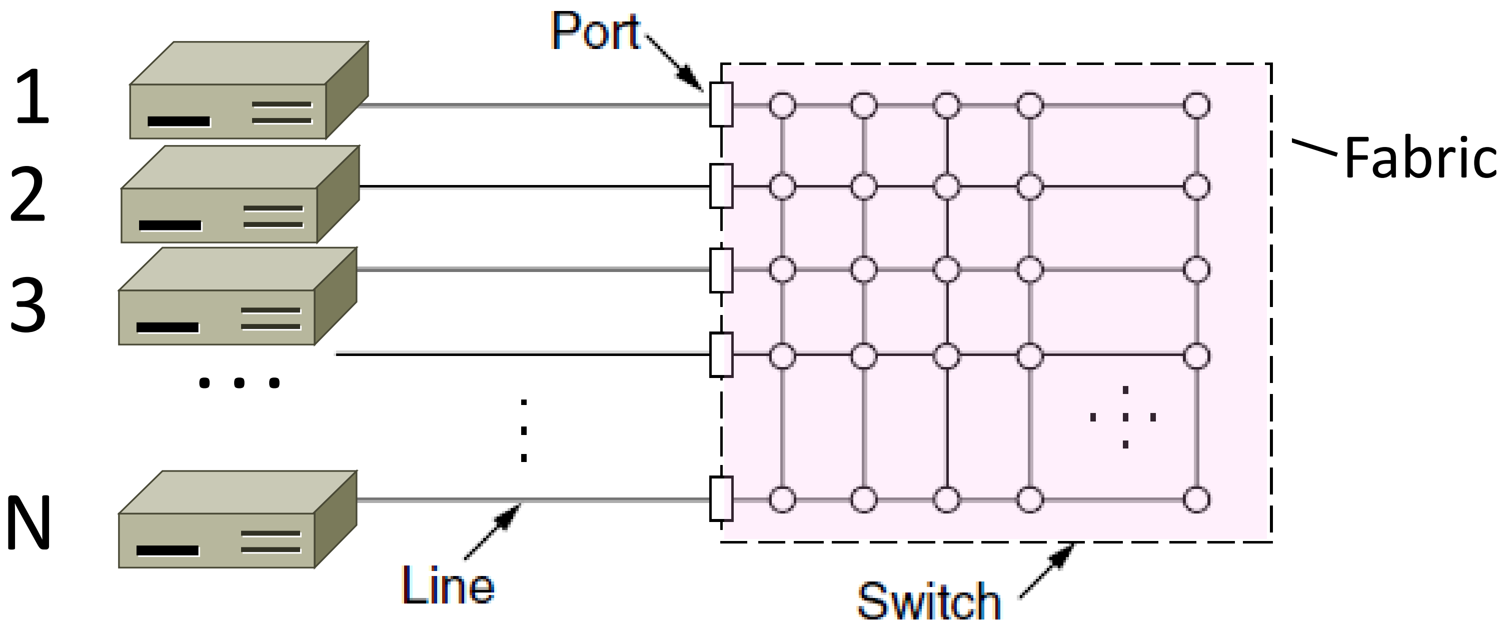
Inside a Repeater

- All inputs are connected; then amplified before going out



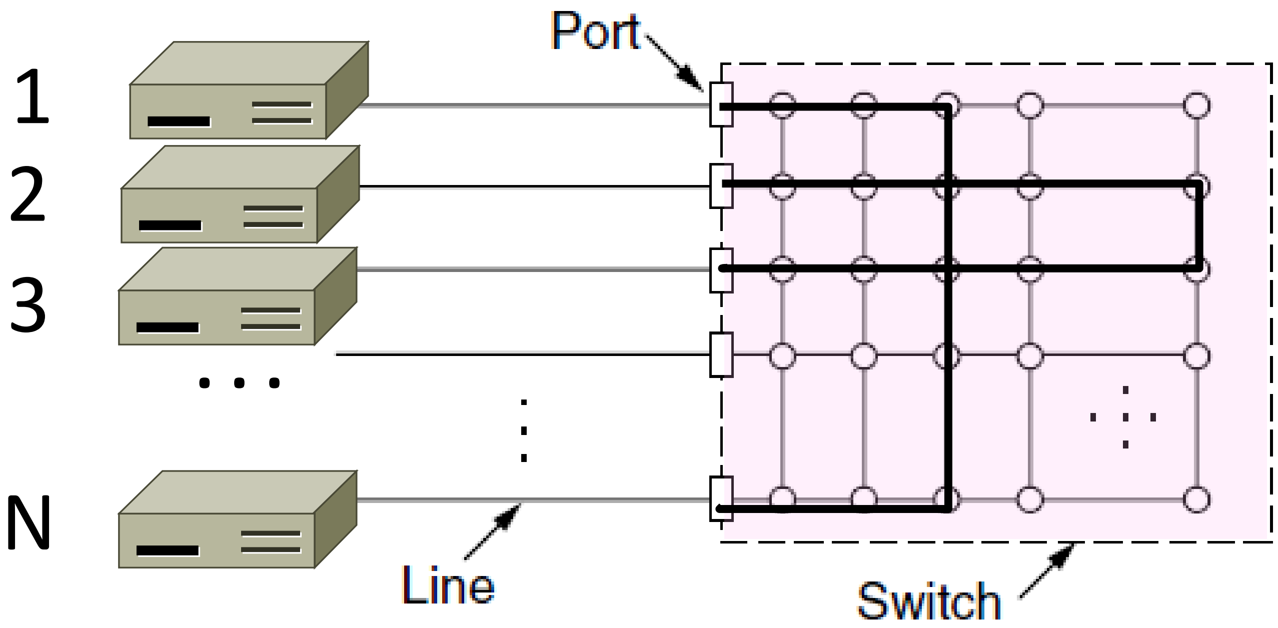
Inside a Switch

- 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)

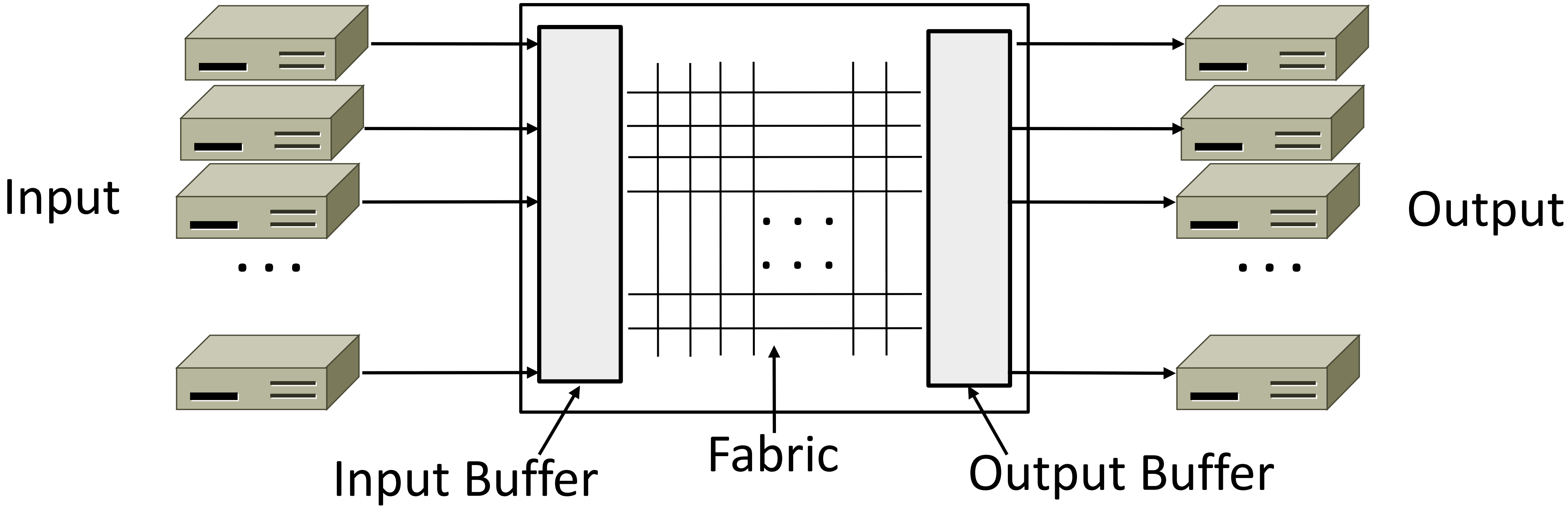
- Port may be used for both input and output (full-duplex)
  - Just send, no multiple access protocol



1 → 4
and
2 → 3

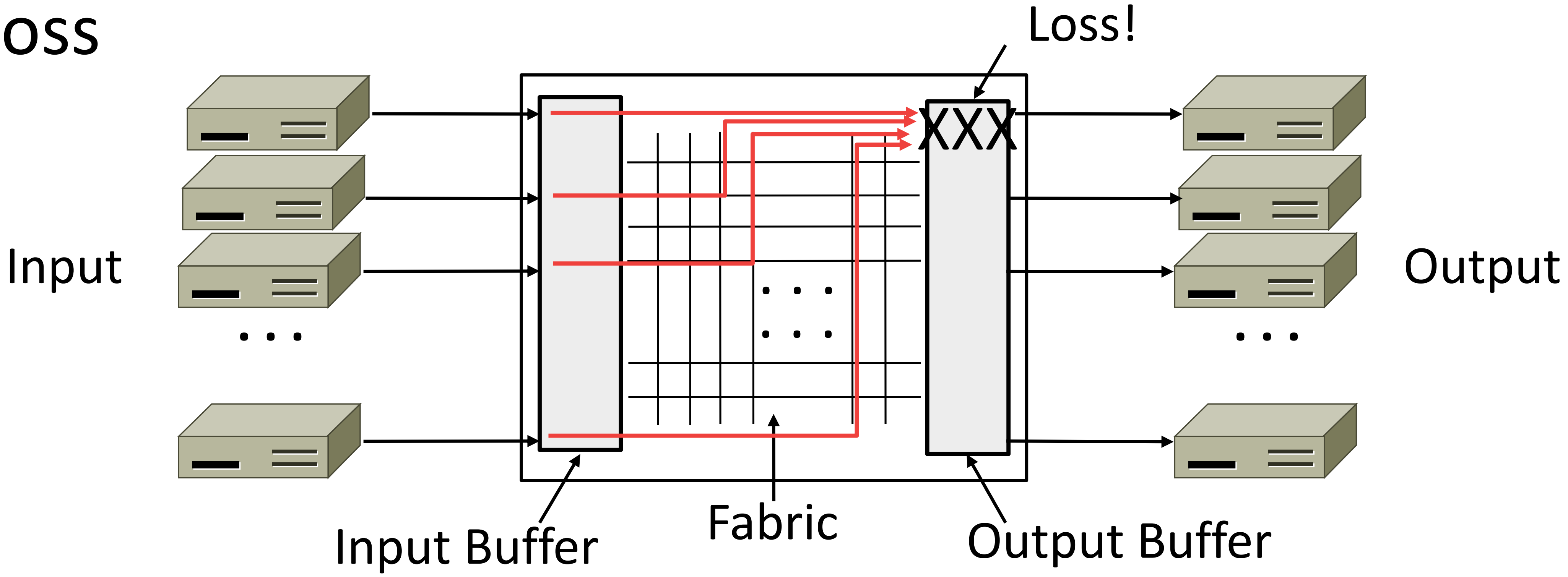
Inside a Switch (3)

- Need buffers for multiple inputs to send to one output



Inside a Switch (4)

- Sustained overload will fill buffer and lead to frame loss



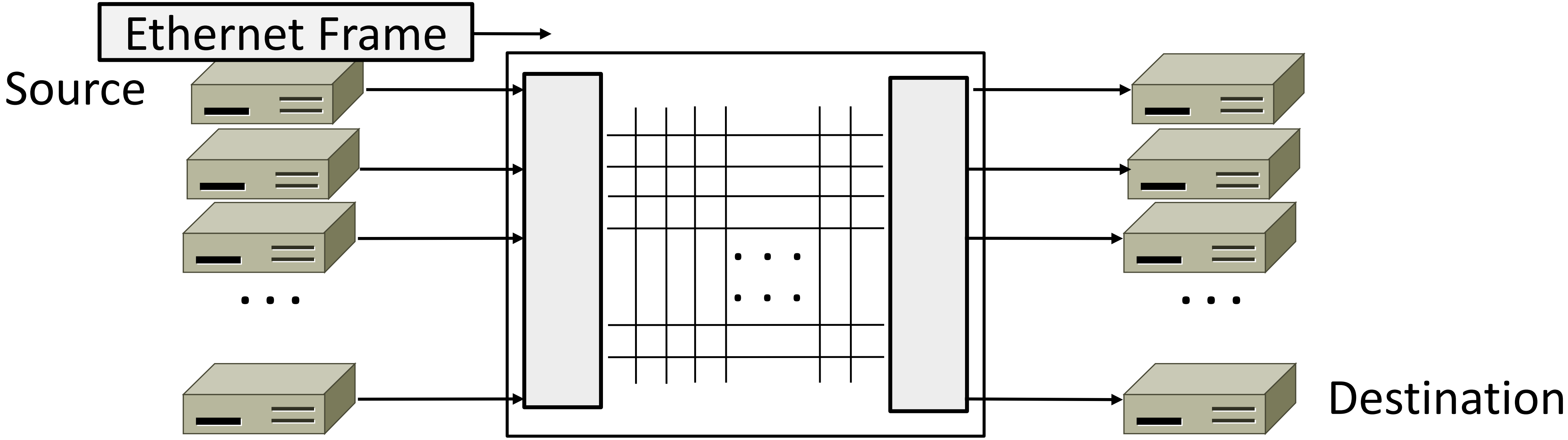
Advantages of Switches

- 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

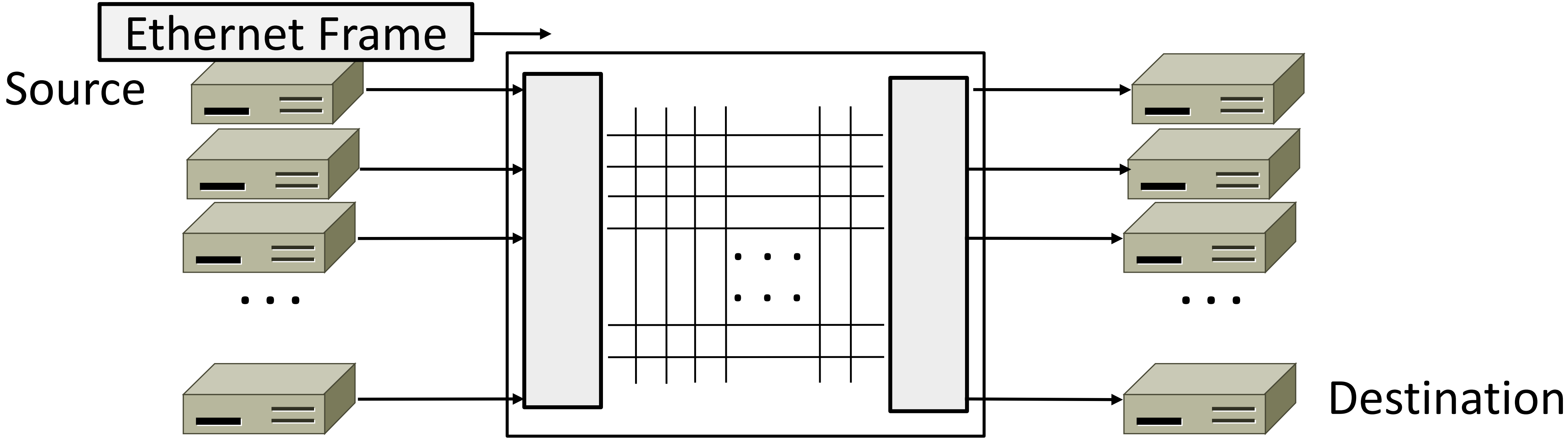
Switch Forwarding

- 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?

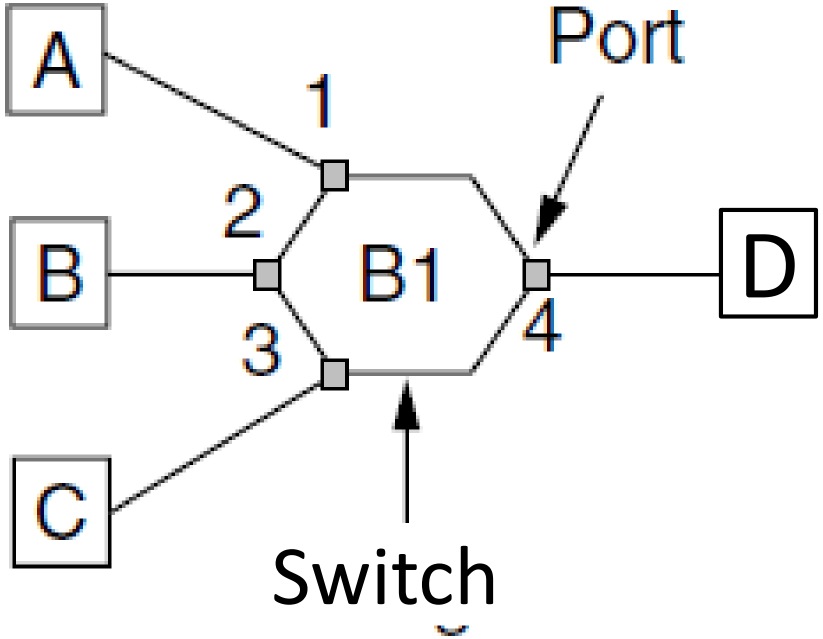


Backward Learning

- 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)

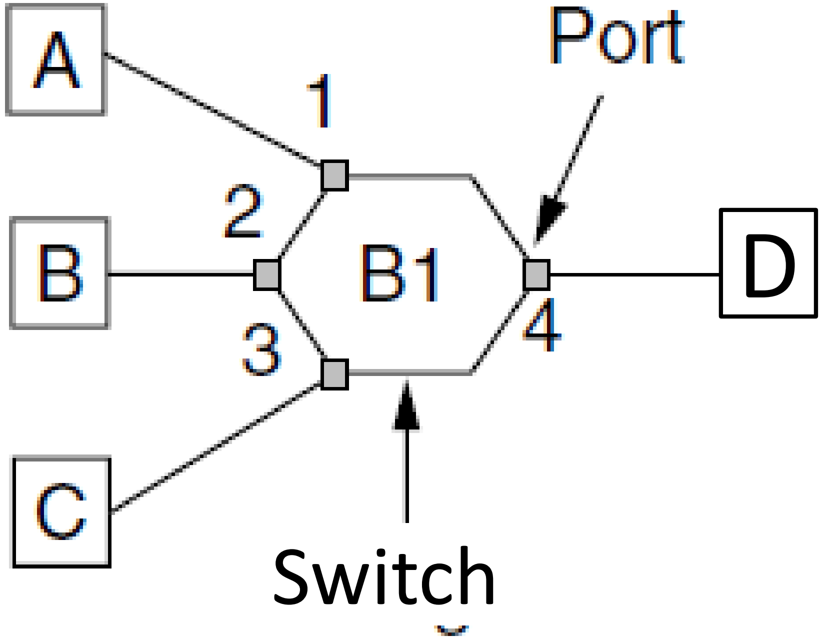
- 1: A sends to D



Address	Port
A	
B	
C	
D	

Backward Learning (3)

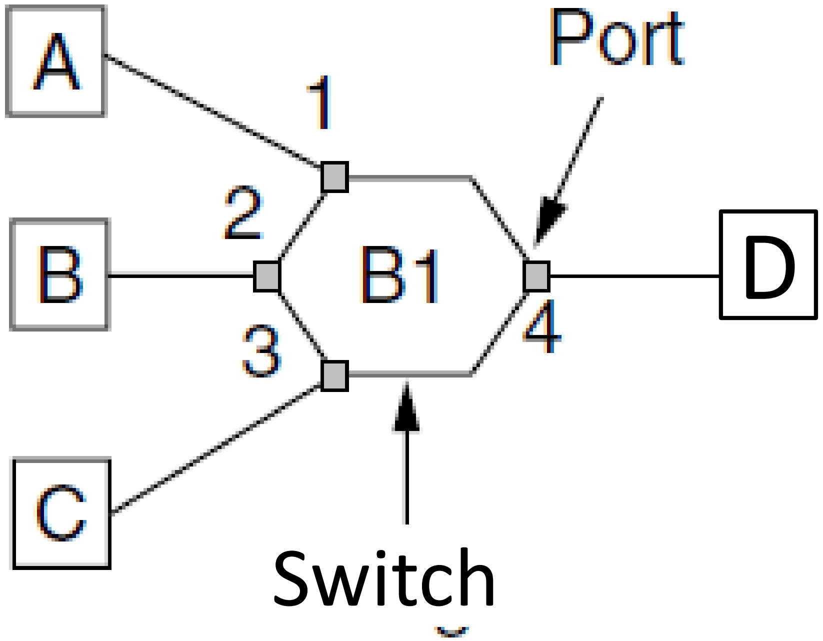
- 2: D sends to A



Address	Port
A	1
B	
C	
D	

Backward Learning (4)

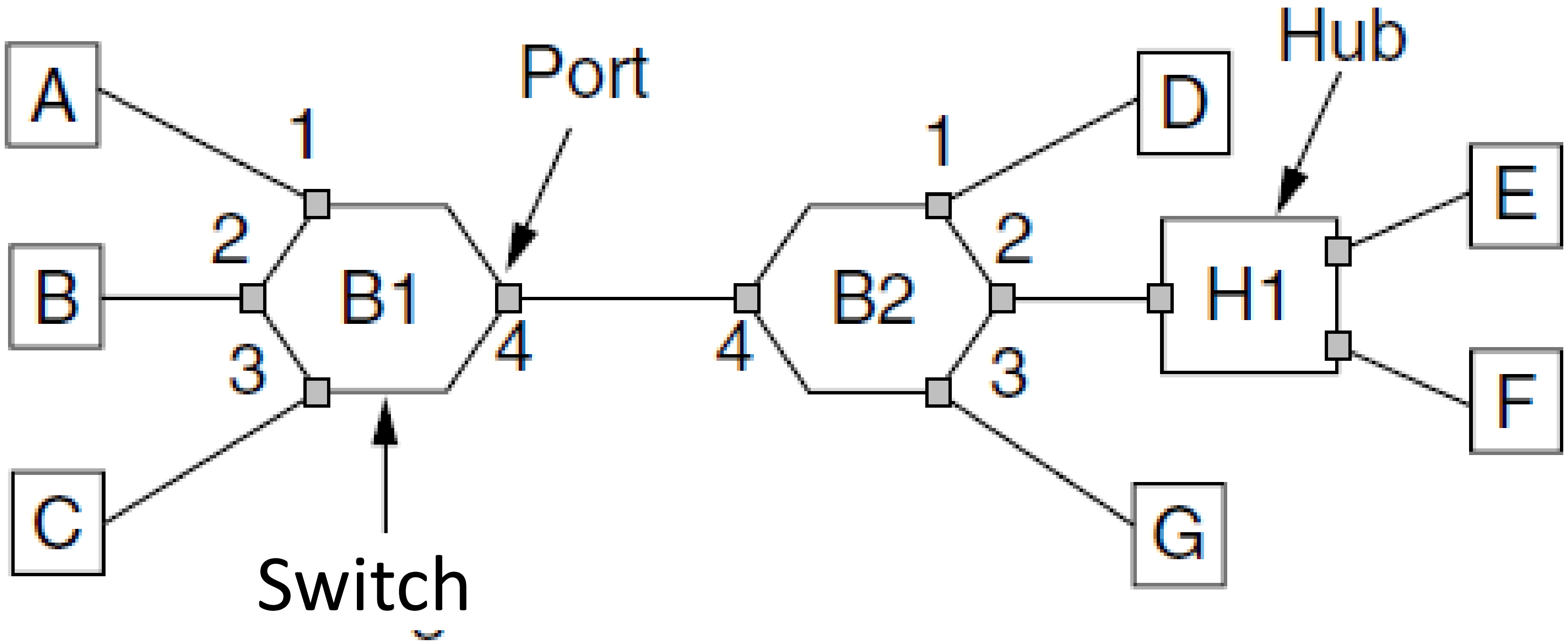
- 3: A sends to D



Address	Port
A	1
B	
C	
D	4

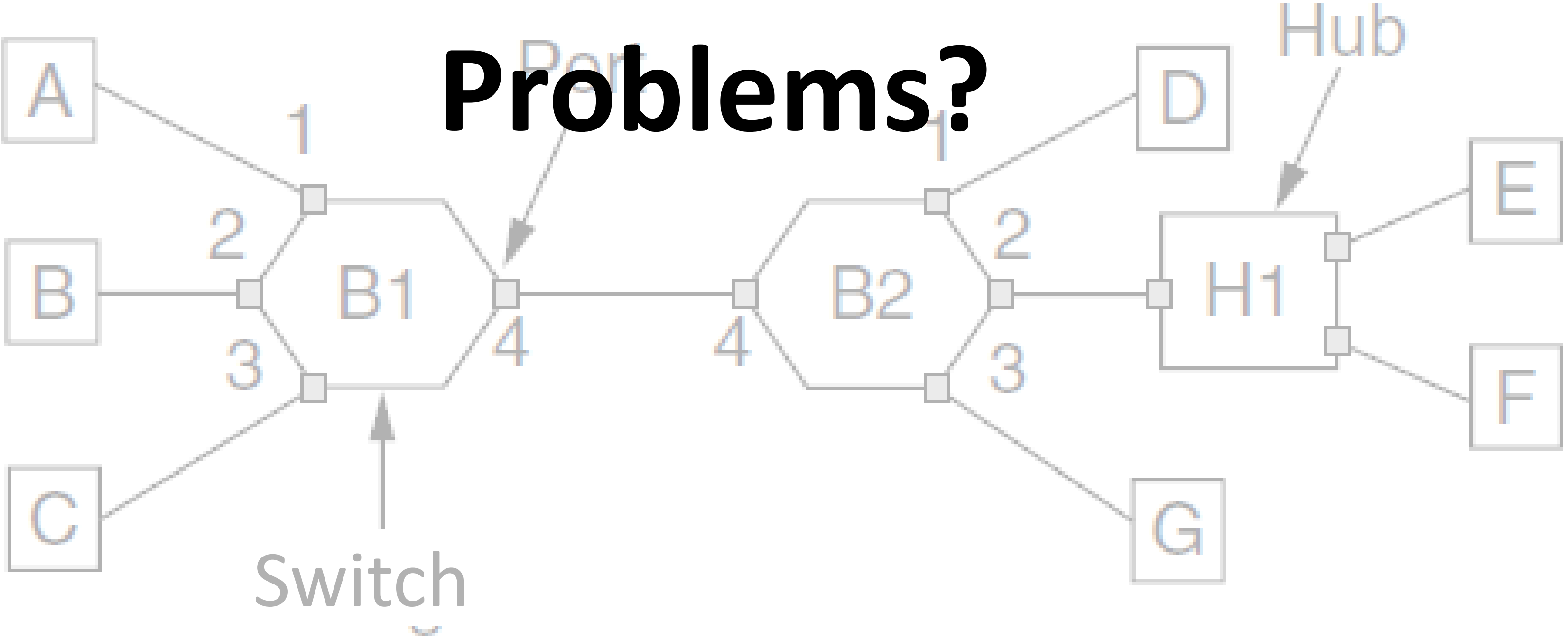
Learning with Multiple Switches

- 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

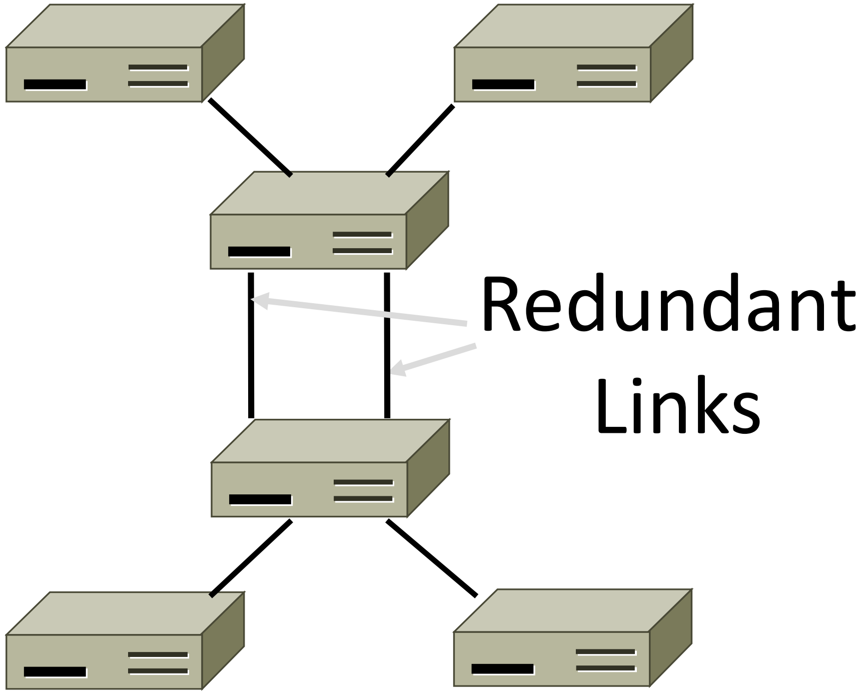


Problems?

Problem – Forwarding Loops

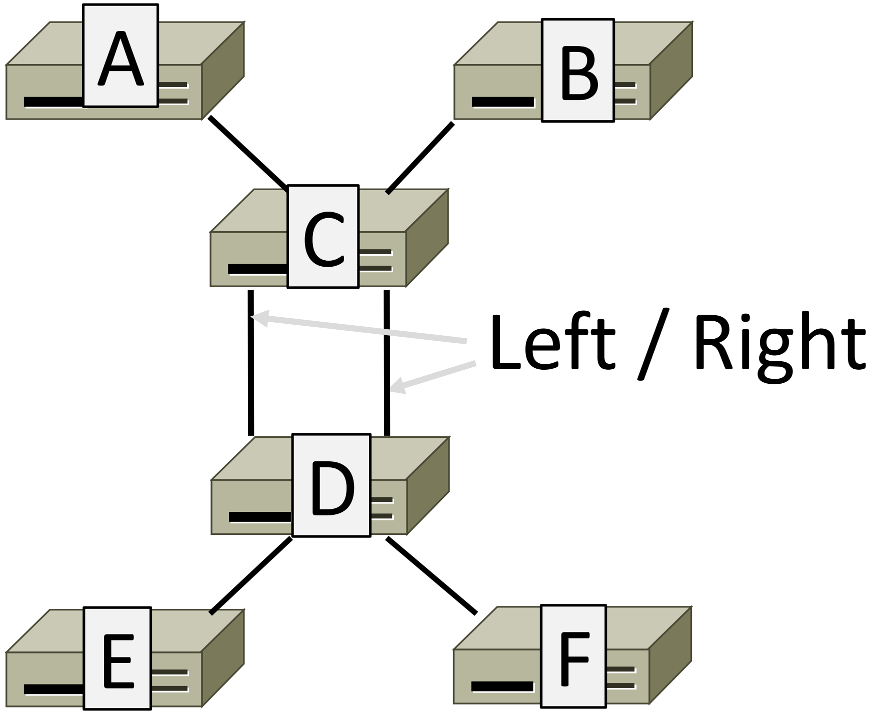
- May have a loop in the topology
  - Redundancy in case of failures
  - Or a simple mistake

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



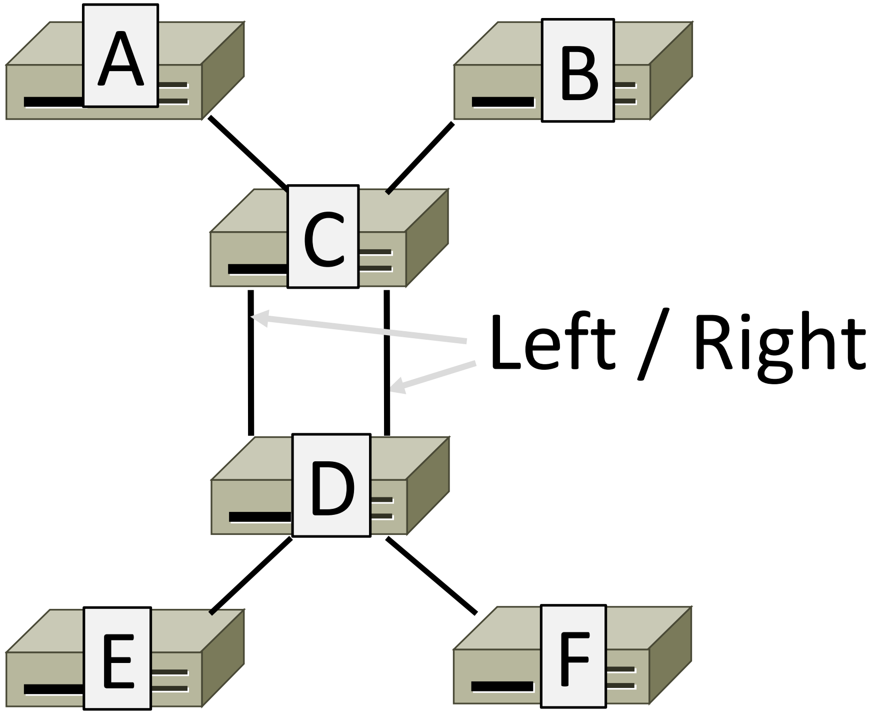
Forwarding Loops (2)

- 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 → …

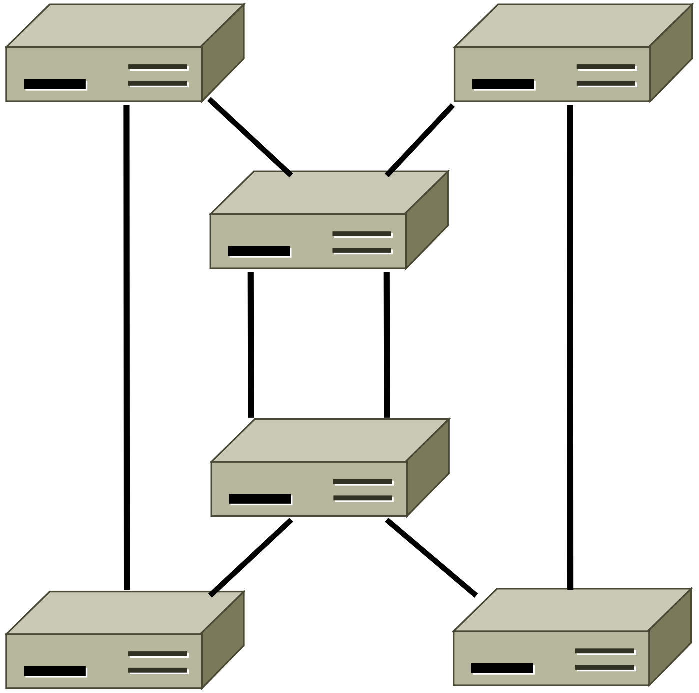


Spanning Tree Solution

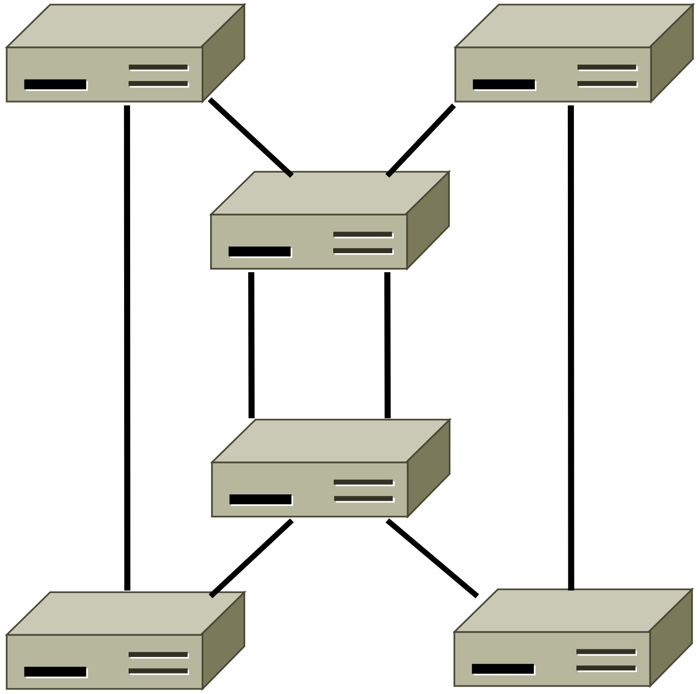
- Switches collectively find a spanning tree for the topology
  - A subset of links that is a tree (no loops) and reaches all switches
  - They switches forward as normal on the spanning tree
  - Broadcasts will go up to the root of the tree and down all the branches

Spanning Tree (2)

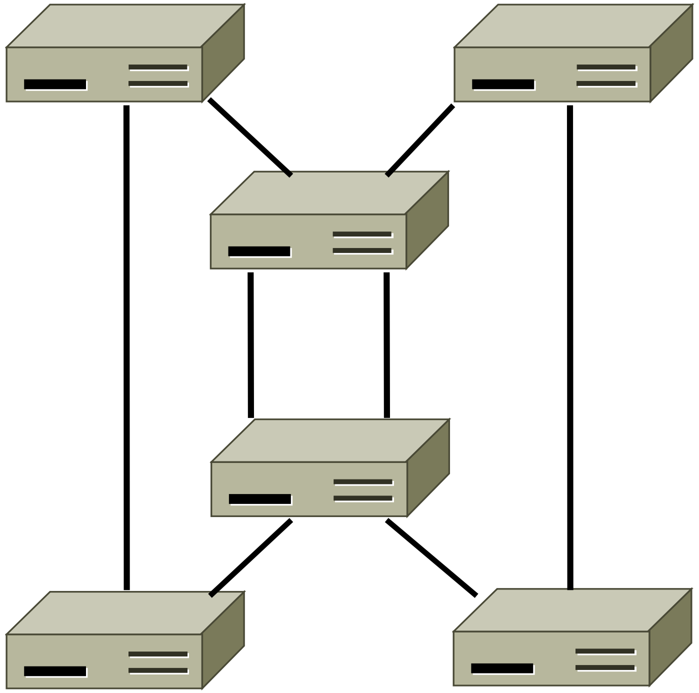
Topology



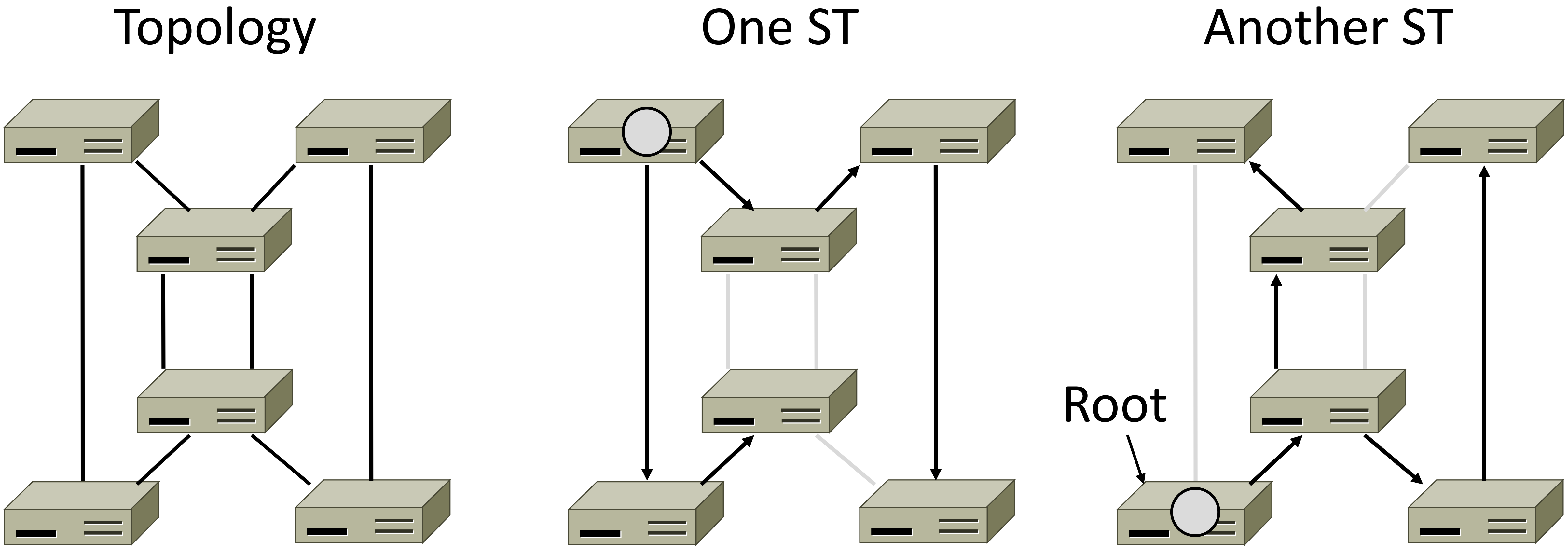
One ST



Another ST



Spanning Tree (3)



Topology

One ST

Another ST

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)

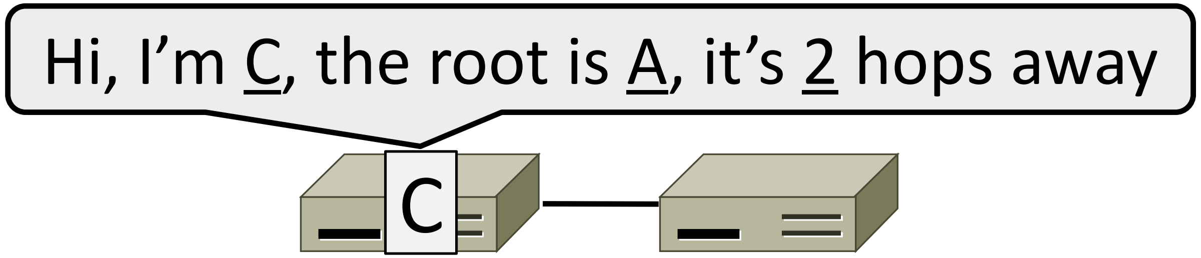
- Now focused on network security

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)

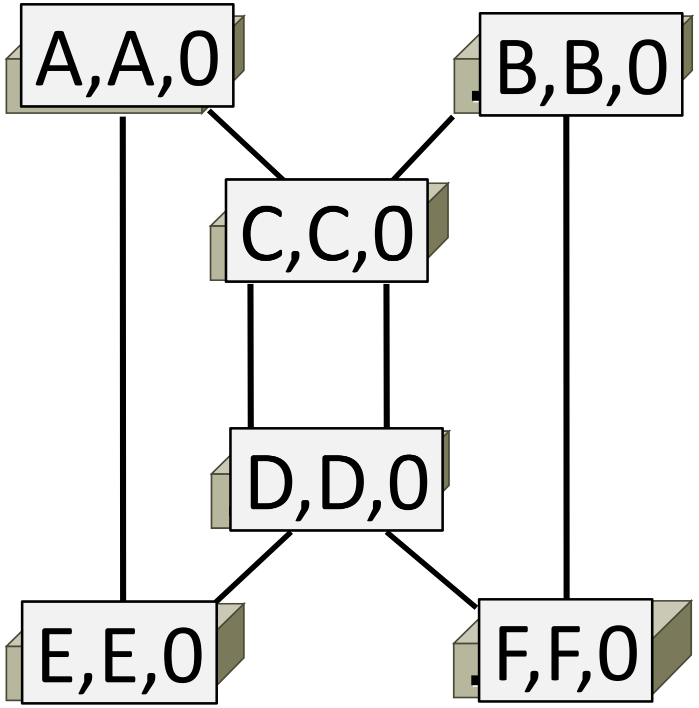
- Details:
  - Each switch initially believes it is the root of the tree
  - Each switch sends periodic updates to neighbors with:
    - Its address, address of the root, and distance (in hops) to root
    - Short-circuit when topology changes
  - Switches favors ports with shorter distances to lowest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



or (C, A, 2)

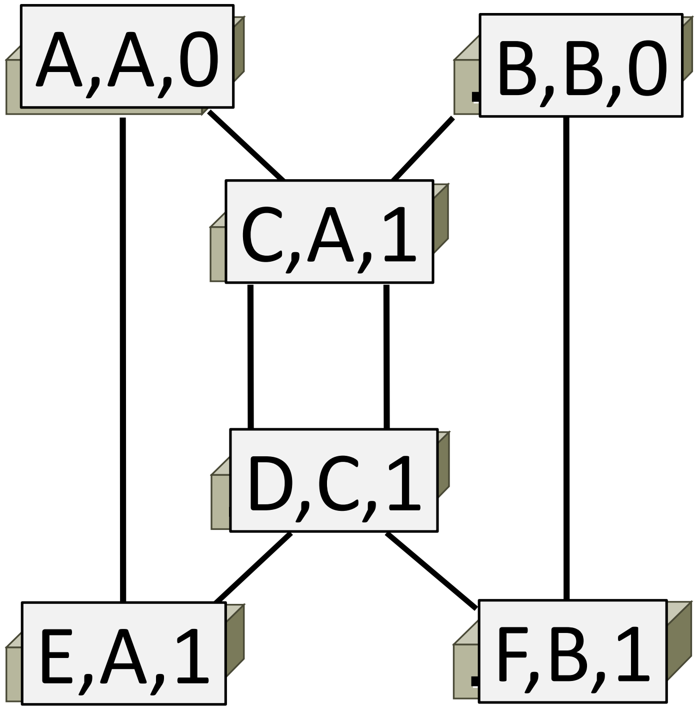
Spanning Tree Example

- 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)



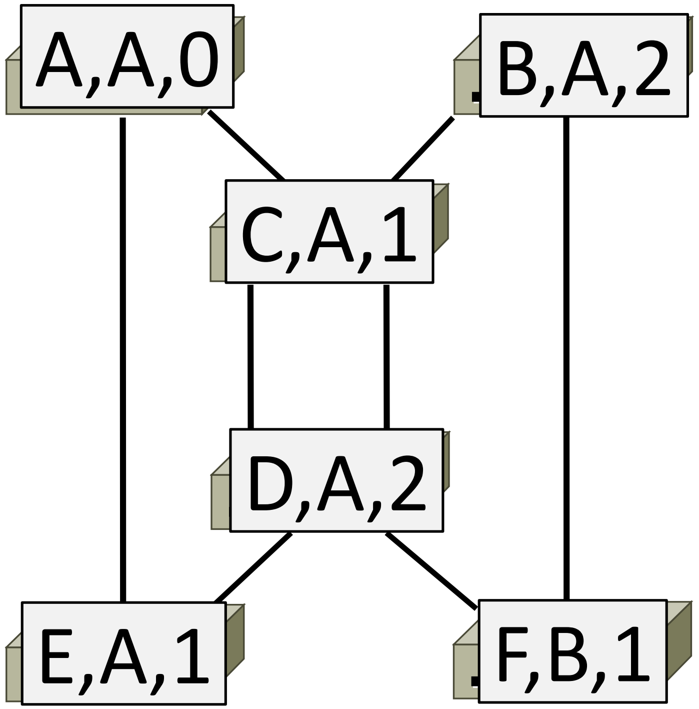
Spanning Tree Example (2)

- 2^{nd} round, sending
  - Nodes send their updated state
- 2^{nd} 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)

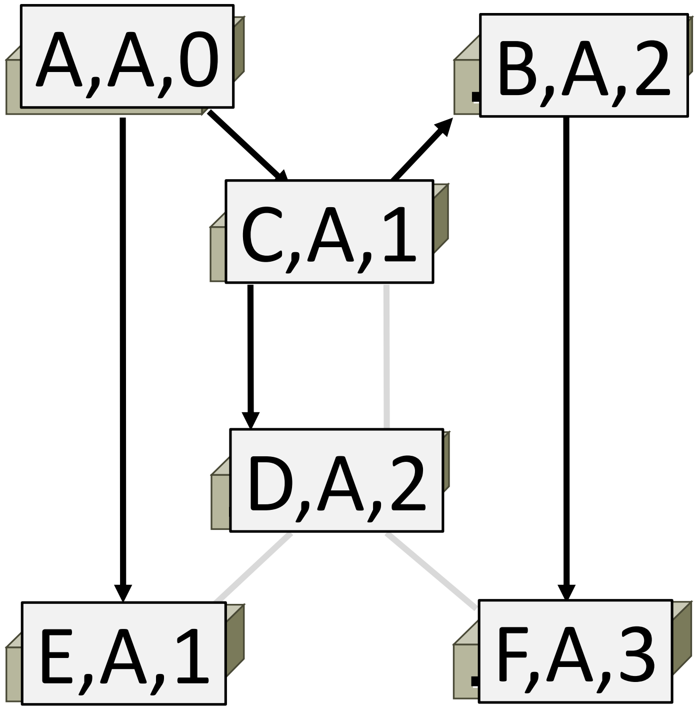
- 3rd round, sending
  - Nodes send their updated state
- 3rd round receiving:
  - A remains (A, A, 0)
  - B remains (B, A, 2) via C
  - C remains (C, A, 1)
  - D remains (D, A, 2) via C-left
  - E remains (E, A, 1)
  - F updates to (F, A, 3) via B



Spanning Tree Example (4)

- 4th round
  - Steady-state has been reached
  - Nodes turn off forwarding that is not on the spanning tree

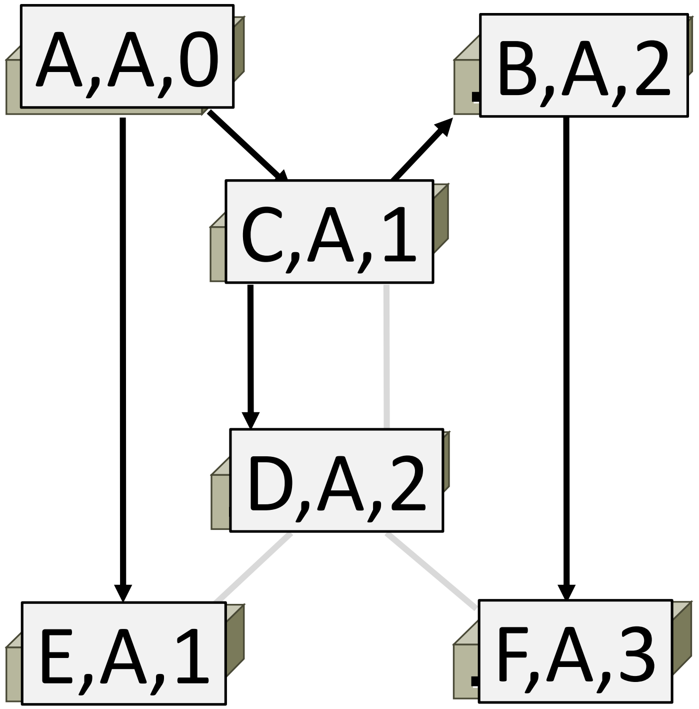
- Algorithm continues to run
  - Adapts by timing out information
  - E.g., if A fails, other nodes forget it, and B will become the new root



Spanning Tree Example (5)

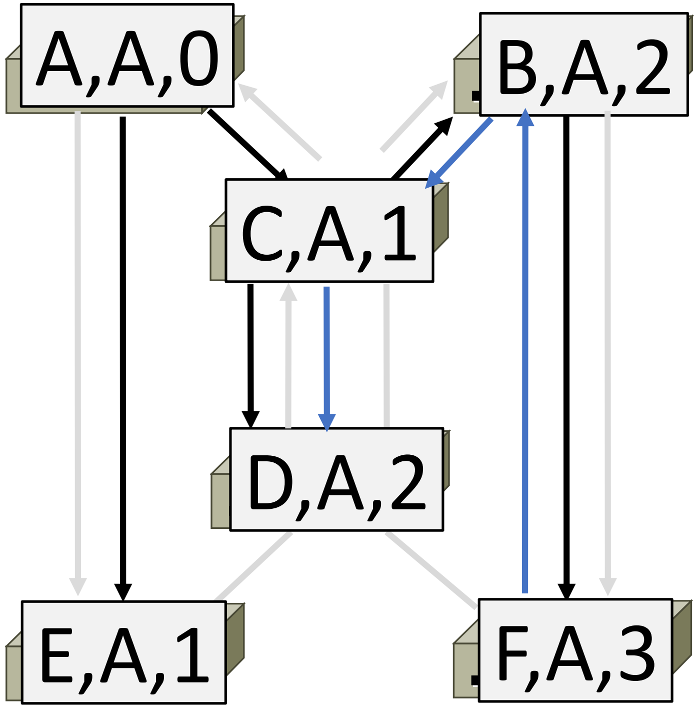
- Forwarding proceeds as usual on the ST
- Initially D sends to F:

- And F sends back to D:



Spanning Tree Example (6)

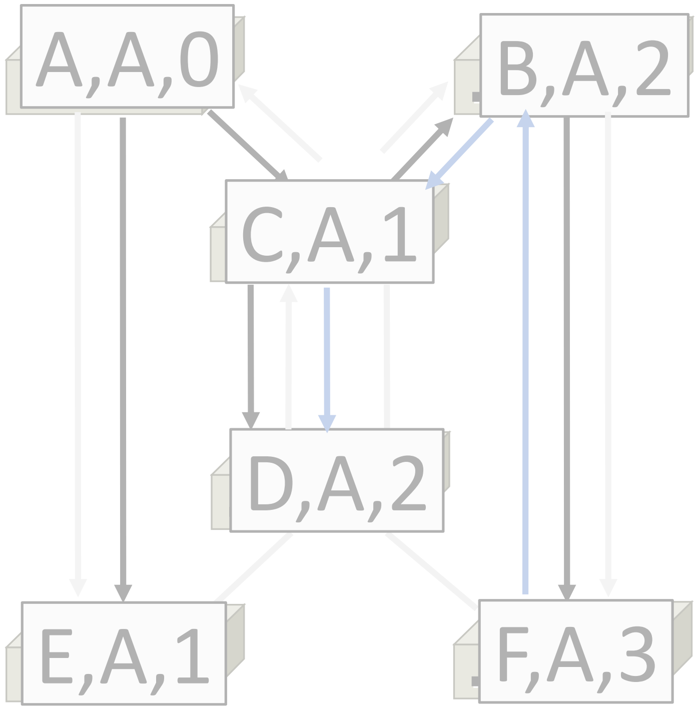
- Forwarding proceeds as usual on the ST
- Initially D sends to F:
  - D → C-left
  - C →   A, B
  - A →   E
  - B →   F
- And F sends back to D:
  - F →   B
  - B →   C
  - C →   D



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

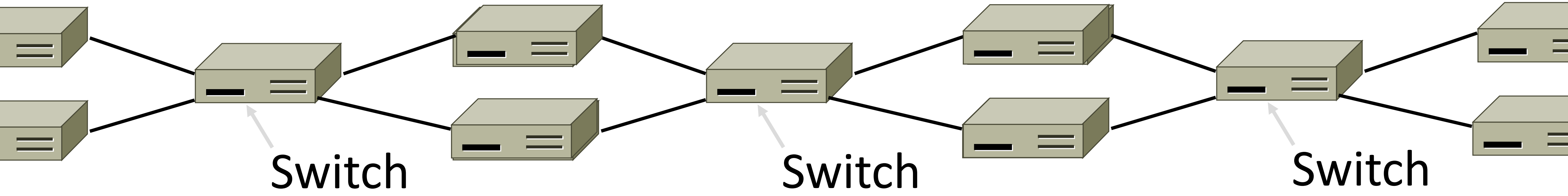
Problems?



Link Layer: Software Defined Networking

Topic

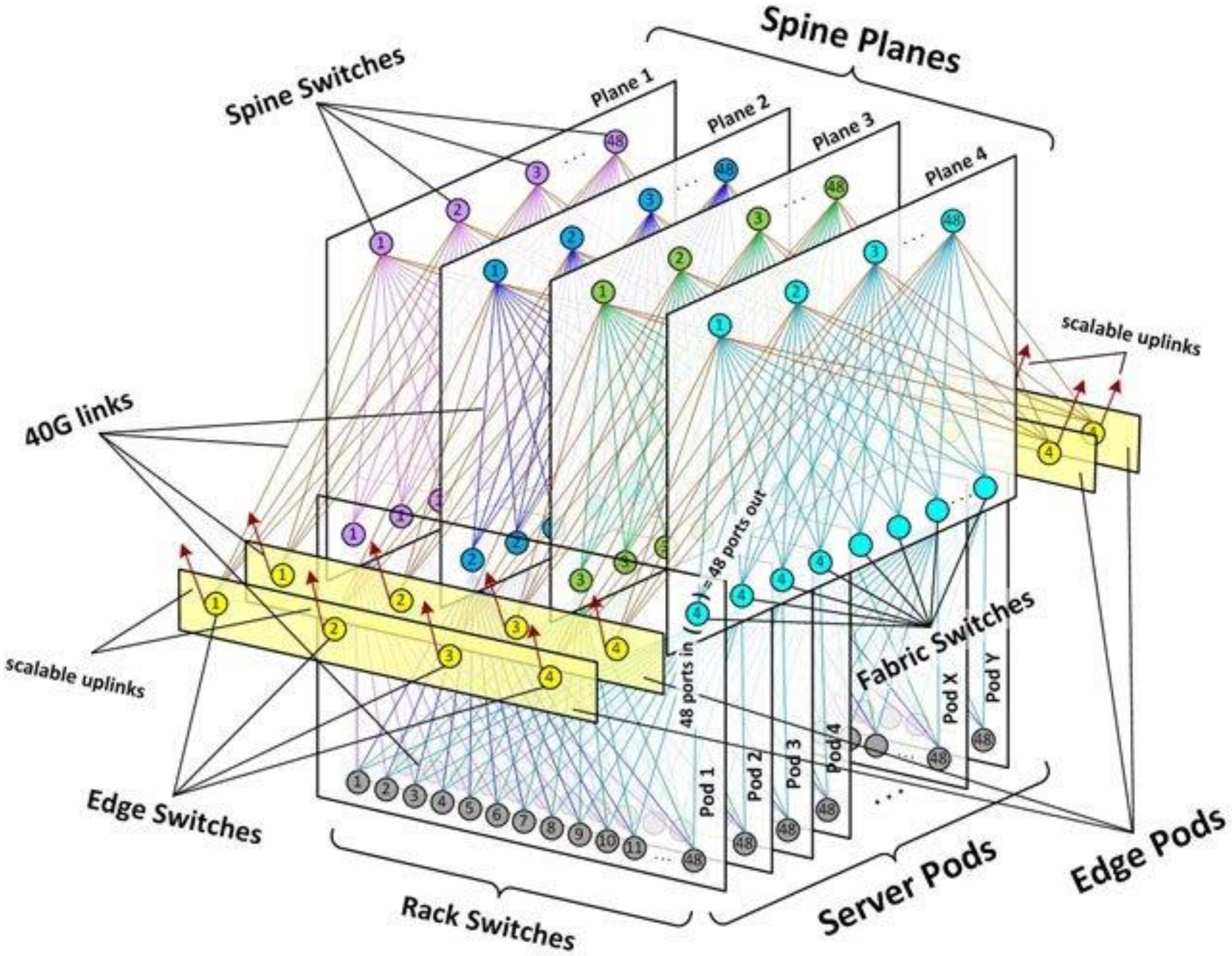
- How do we scale these networks up?
  - Answer 1: Network of networks, a.k.a. The Internet
  - Answer 2: Ah, just kinda hope spanning tree works?



Rise of the Datacenter

The Original Googl
In 1996 Larry Page and Serge
students in Stanford CSD,
Digital Library Project, nee
amount of diskspace to tes
Pagerank™ algorithm on a
wide-web data. At that tim
hard disks were the largest
they assembled 10 of these
low-cost cabinet.
In Nov 1999, Google Inc, by the
one of the primary search e
web, provided replacement
capacity to the Digital Librar
that we could move this orig
assembly into our history di
As of September 2000, Google,
in Mountain View, operated
searching and web crawling,
LINUX operating system.

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)

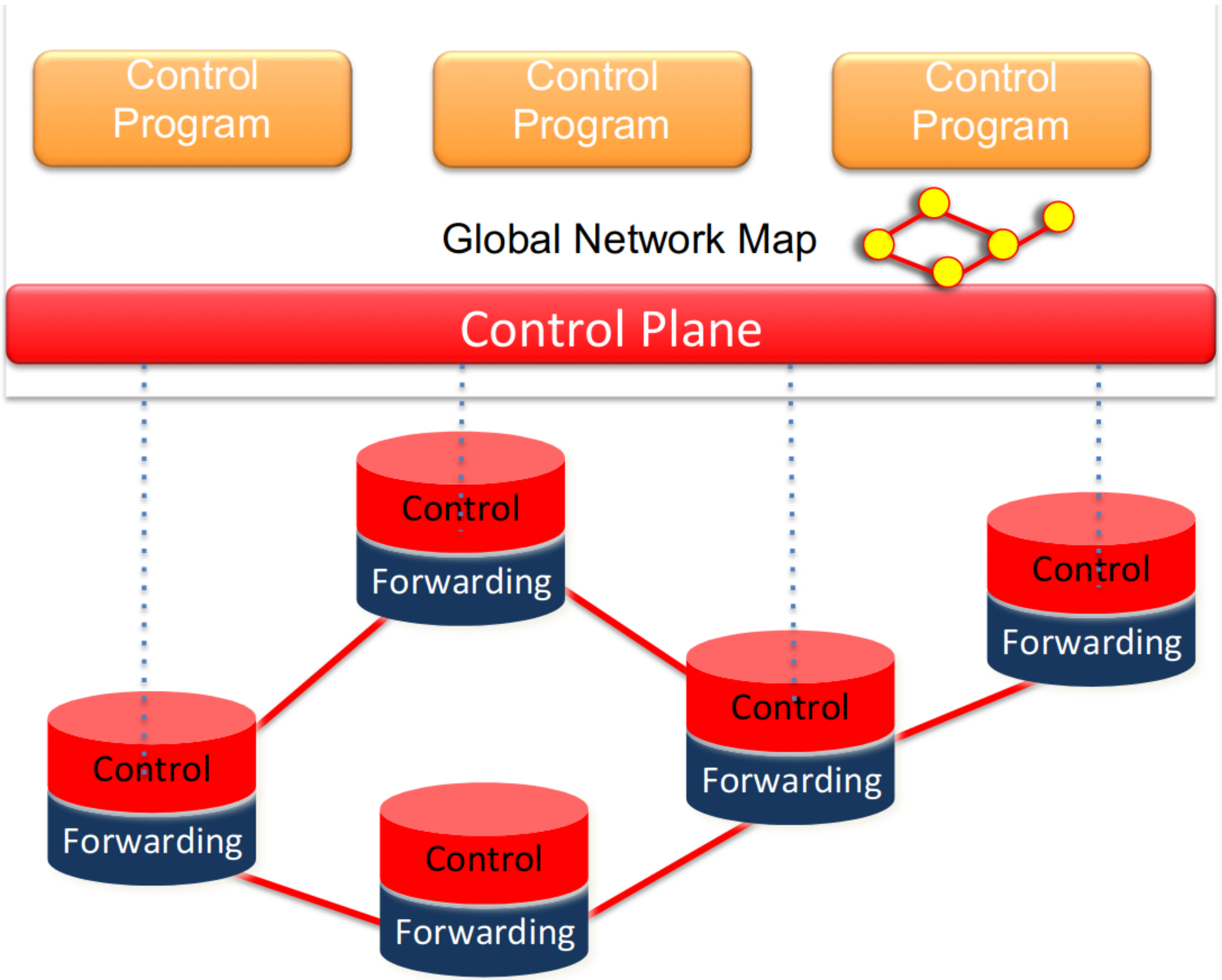
- Core idea: **stop being a distributed system**
  - Centralize the operation of the network
    - Create a “controller” that manages the network
  - Push new code, state, and configuration from “controller” to switches
    - Run link state with a global view of the network rather than in a distributed 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

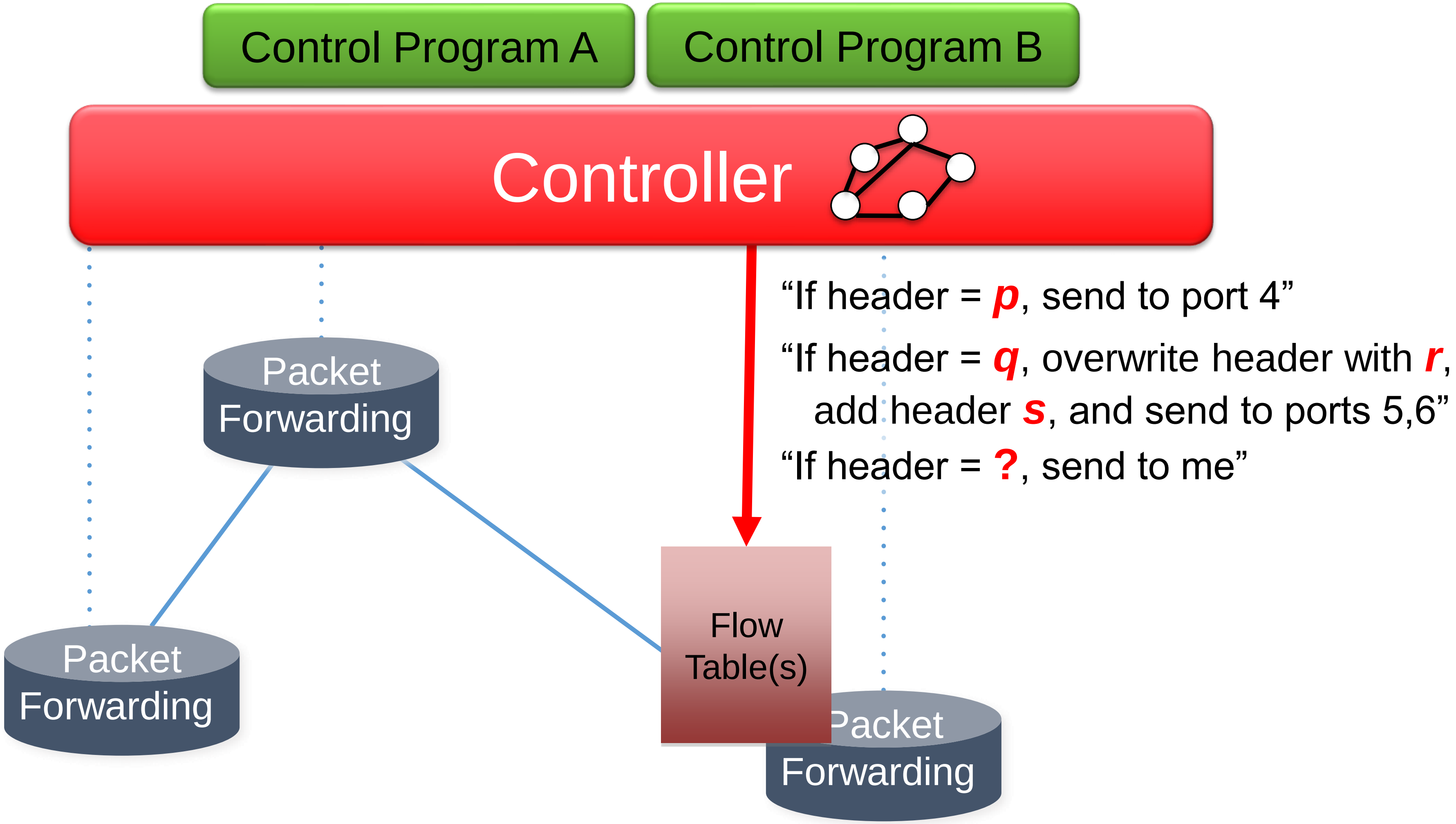


SDN – Problem 2

- 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"

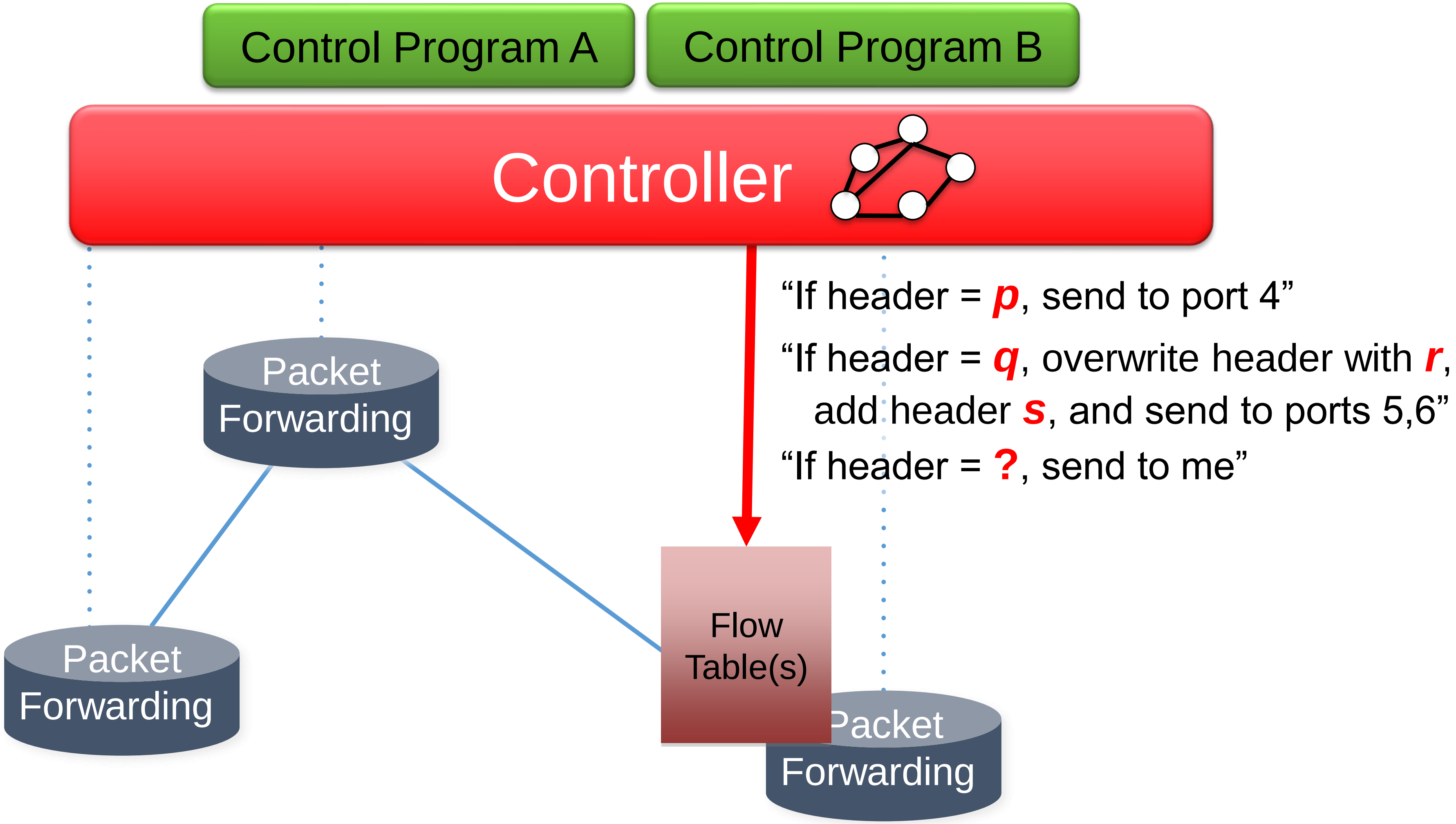
SDN – OpenFlow

- 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