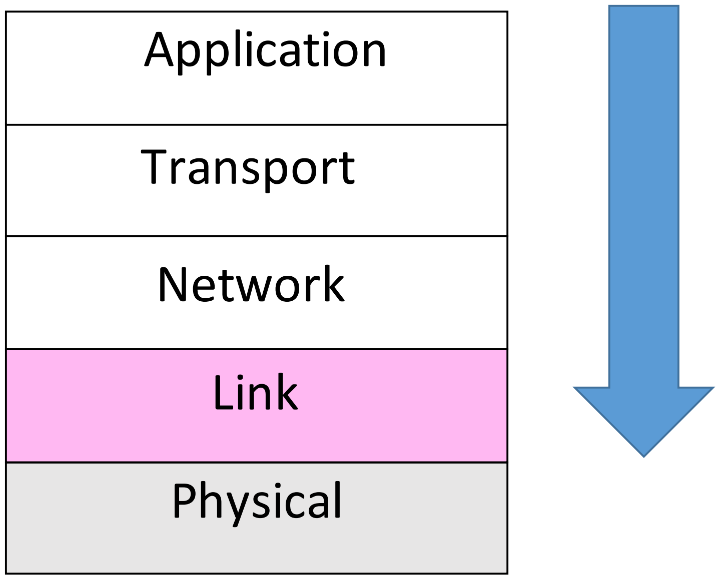
Link Layer

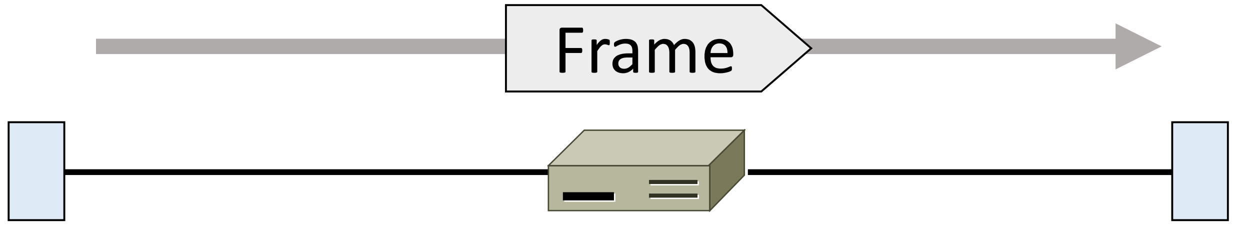
Where we are in the Course

- Moving on up to the Link Layer!

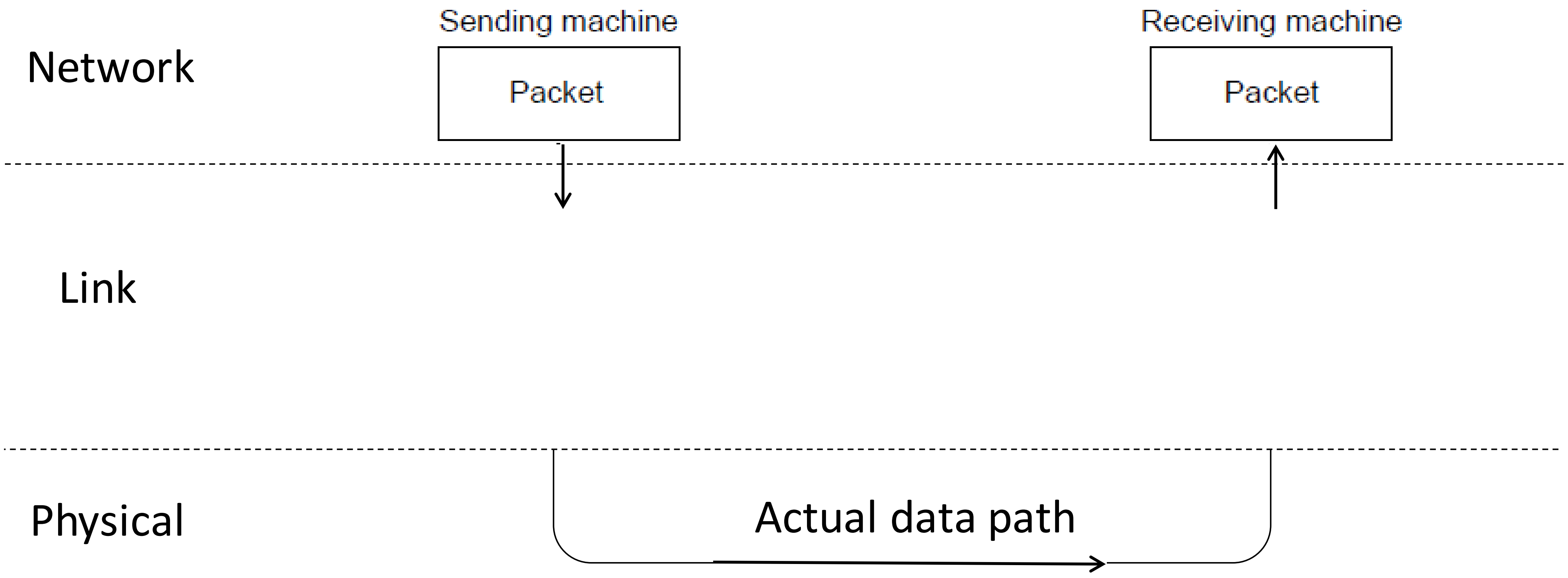


Scope of the Link Layer

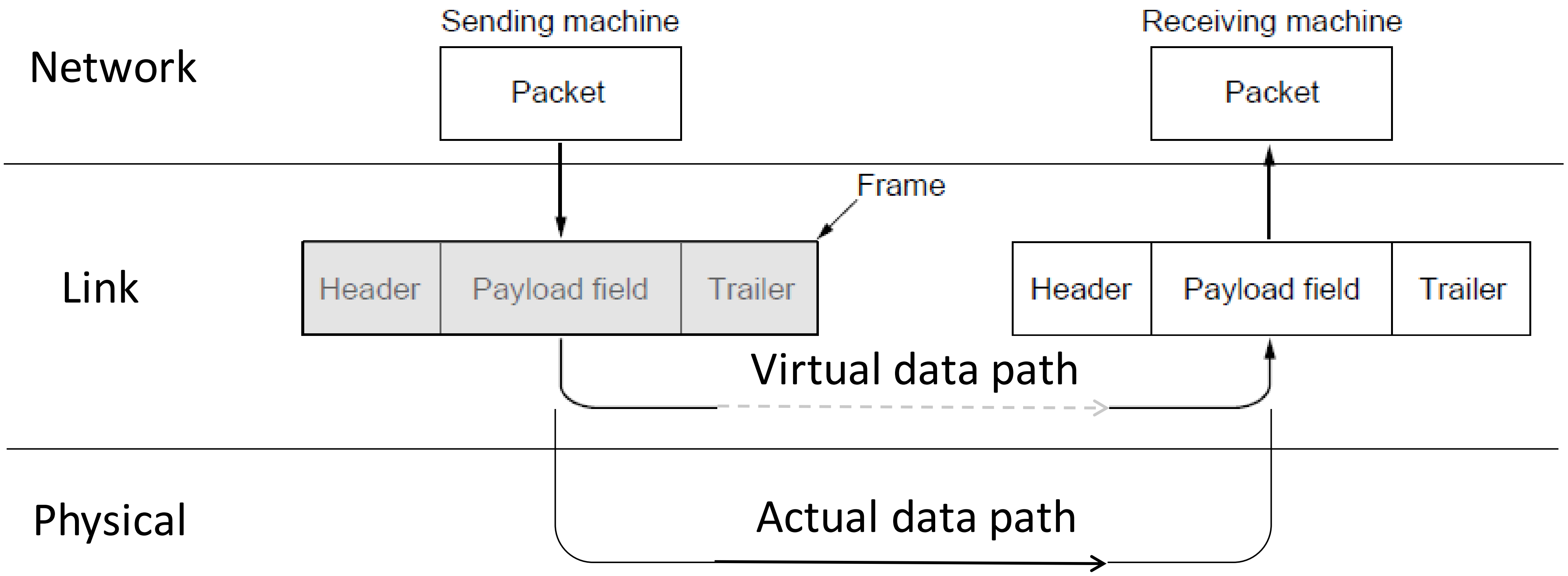
- Concerns how to transfer messages over one or more connected links
  - Messages are frames, of limited size
  - Builds on the physical layer
    - How to transfer bits



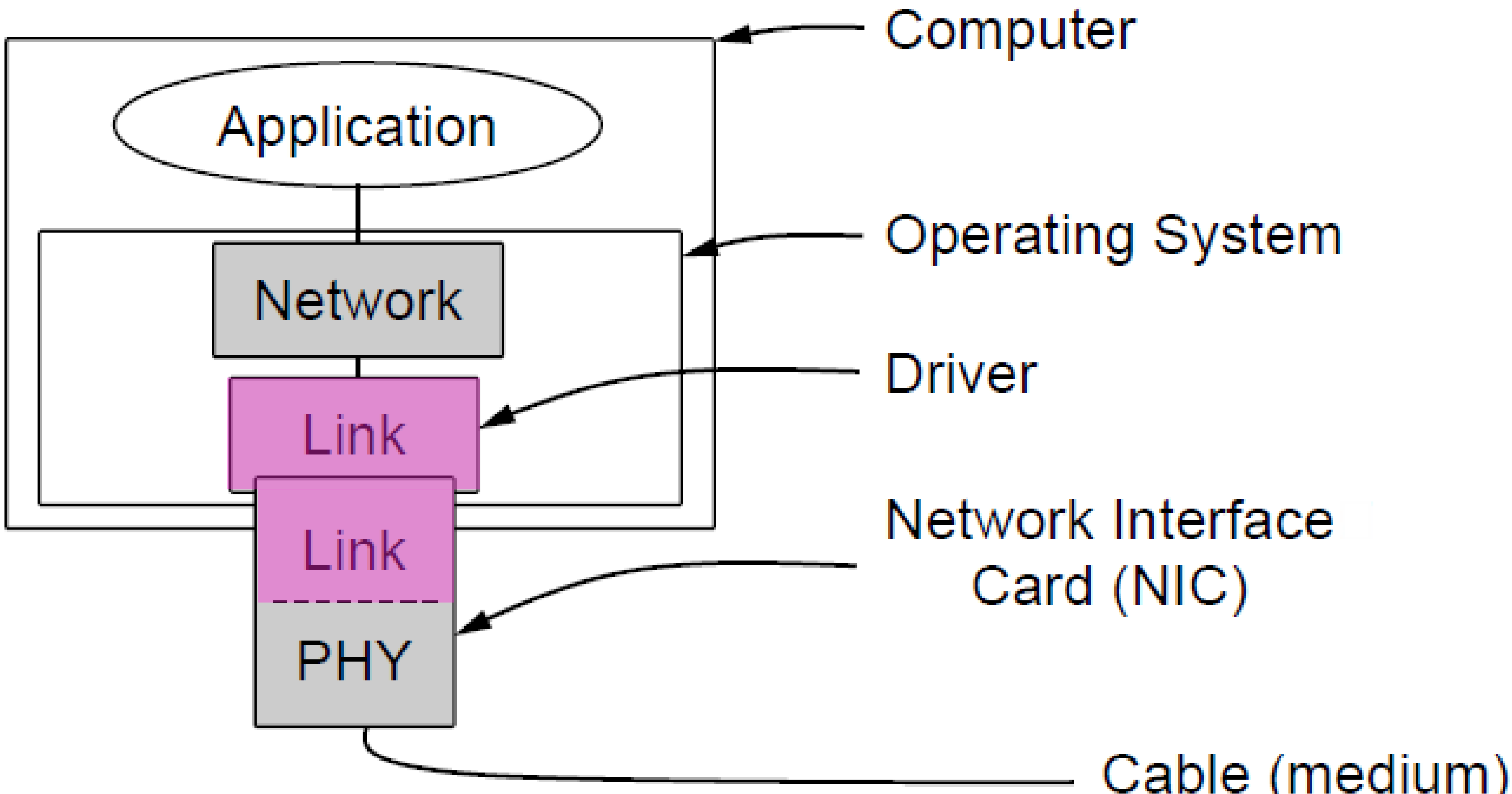
In terms of layers …



In terms of layers (2)



Typical Implementation of Layers (2)



Topics

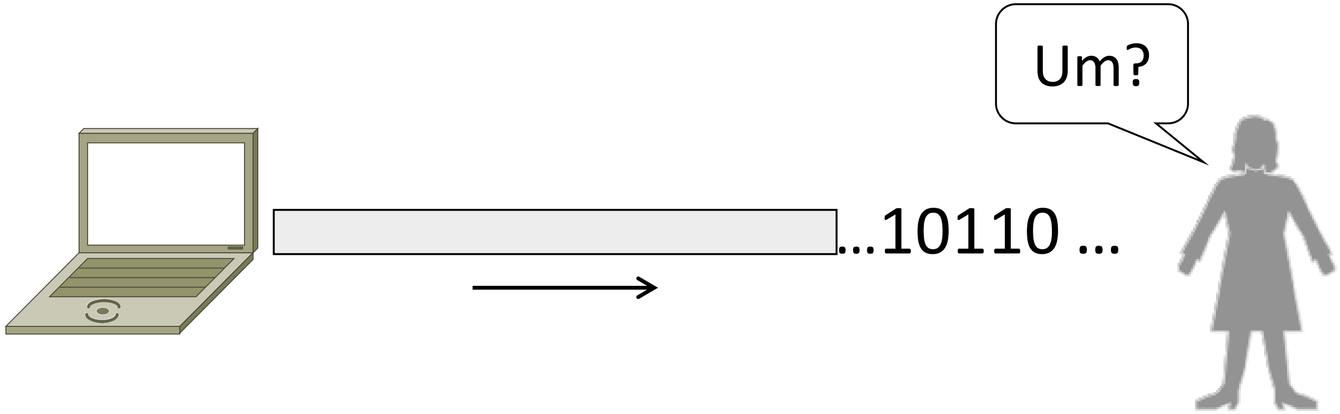
1. Framing
   - Delimiting start/end of frames
2. Error detection and correction
   - Handling errors
3. Retransmissions
   - Handling loss
4. Multiple Access
   - 802.11, classic Ethernet
5. Switching
   - Modern Ethernet

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

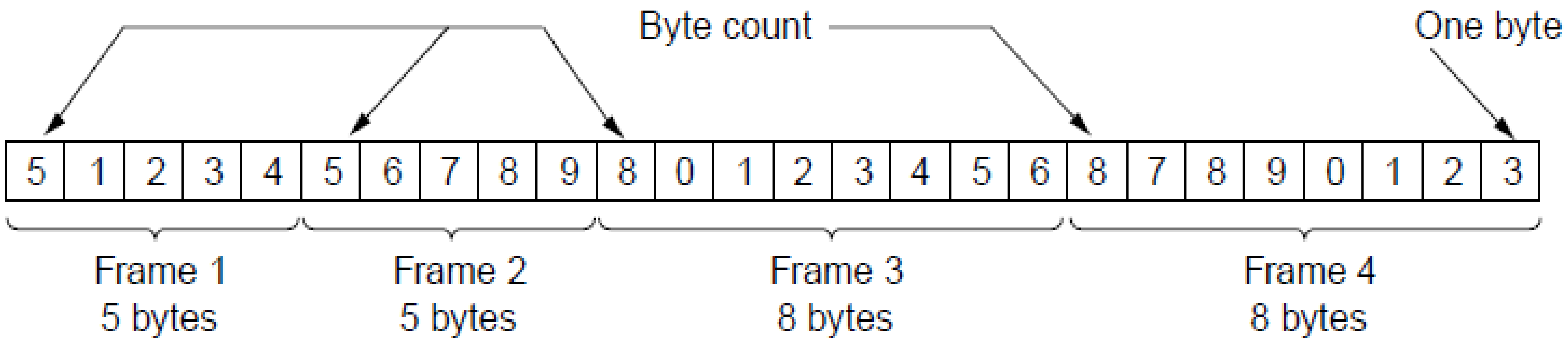
- We'll look at:
  - Byte count (motivation)
  - Byte stuffing
  - Bit stuffing

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

Byte Count

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

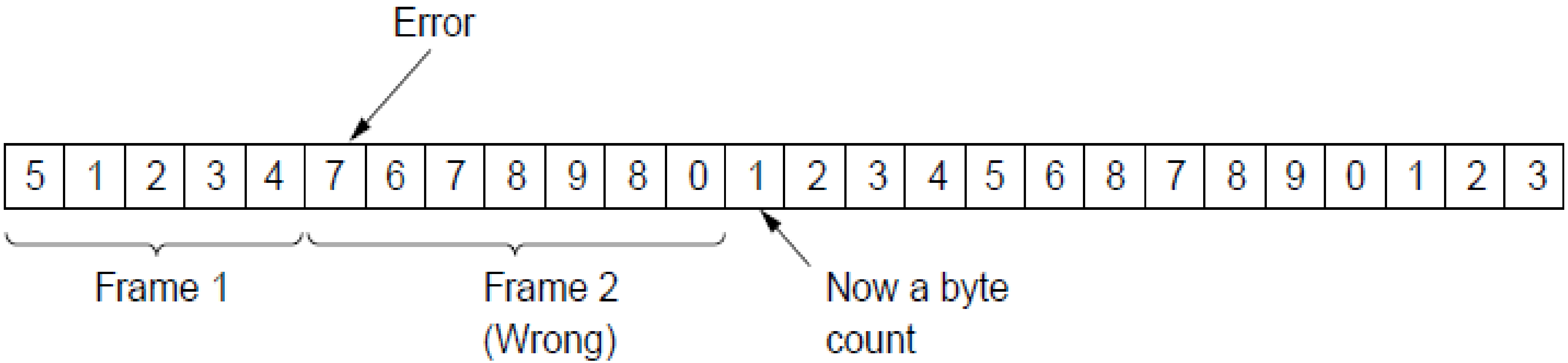
Byte Count (2)



- How well do you think it works?

Byte Count (3)

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

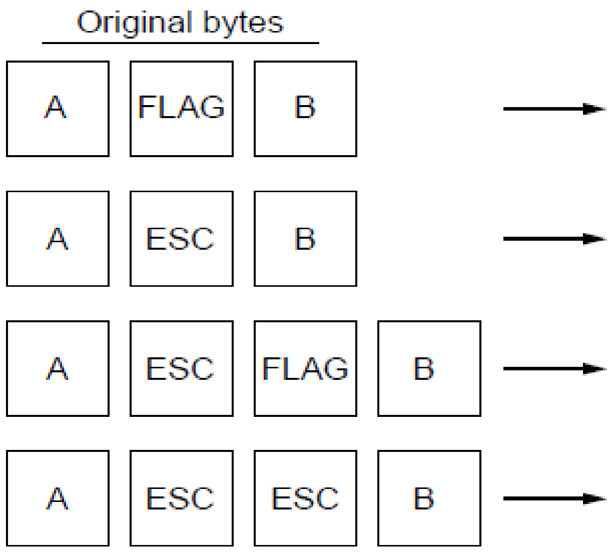


Byte Stuffing

- 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!

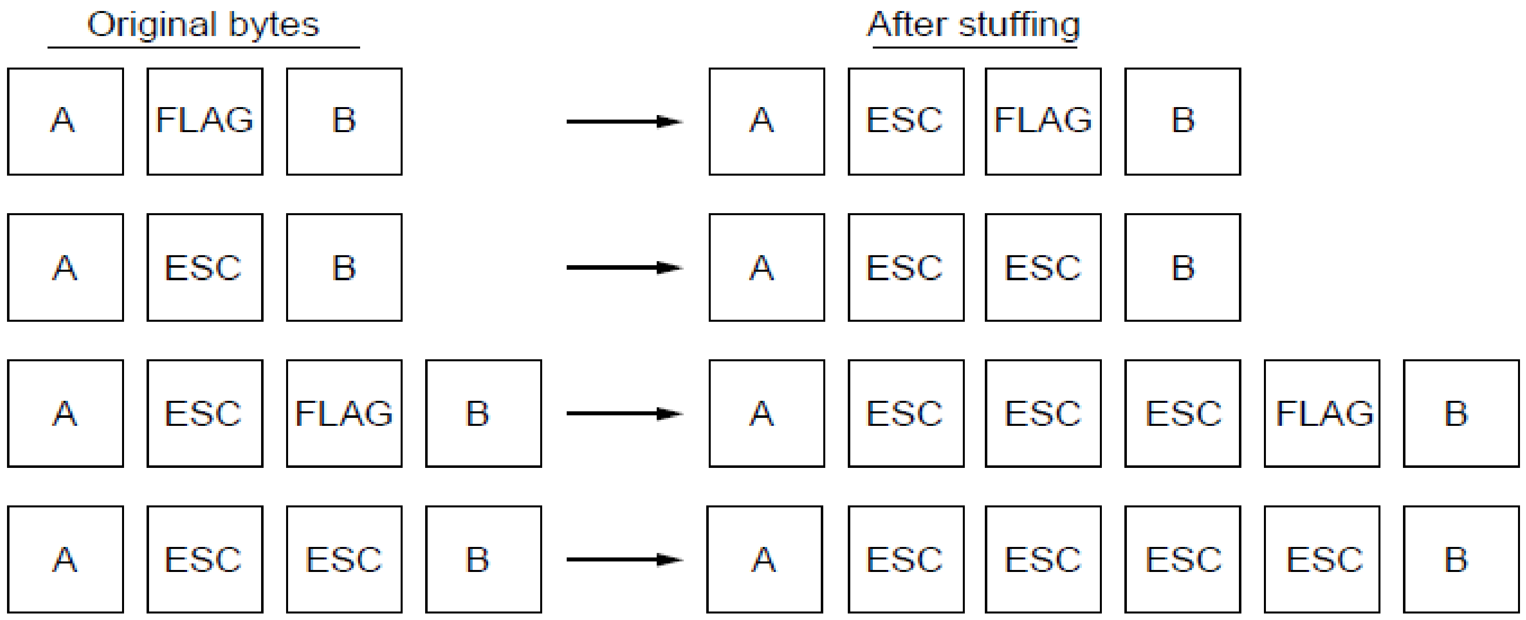
Byte Stuffing

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



Byte Stuffing

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



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

- 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

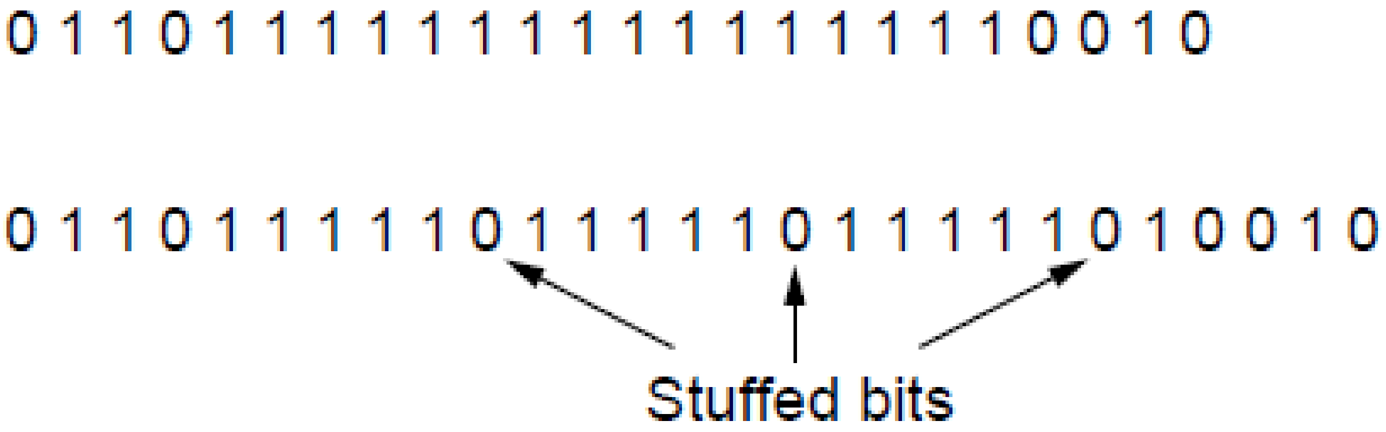
Transmitted bits with stuffing:

Bit Stuffing

- So how does it compare with byte stuffing?

Data bits

Transmitted bits
with stuffing

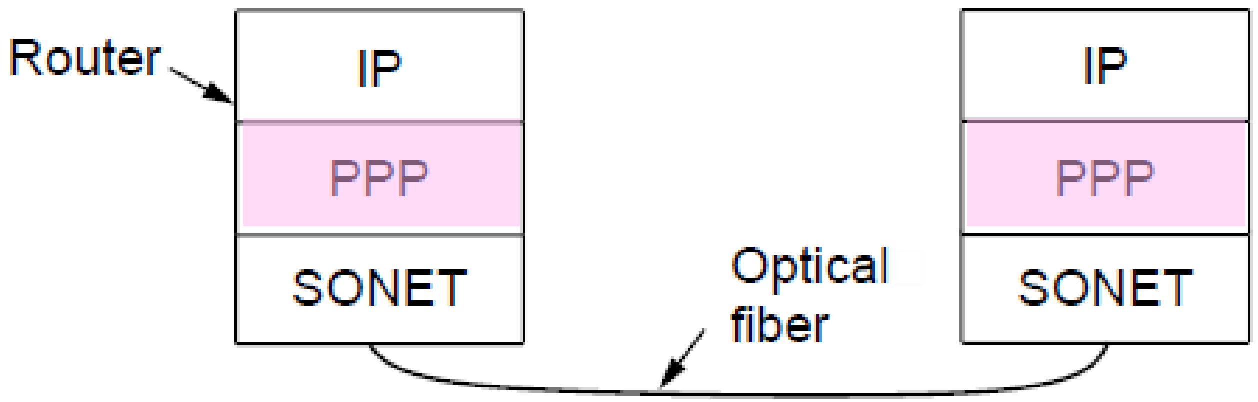


Link Example: PPP over SONET

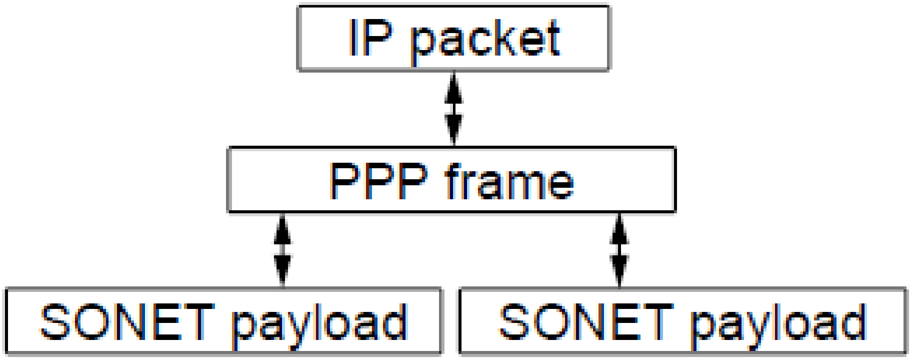
- PPP is Point-to-Point Protocol
- Widely used for link framing
  - E.g., it is used to frame IP packets that are sent over SONET optical links

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 Example: PPP over SONET (4)

- Byte stuffing method:
  - To stuff (unstuff) a byte
    - add (remove) ESC (0x7D)
    - and XOR byte with 0x20
  - Removes FLAG from the contents of the frame

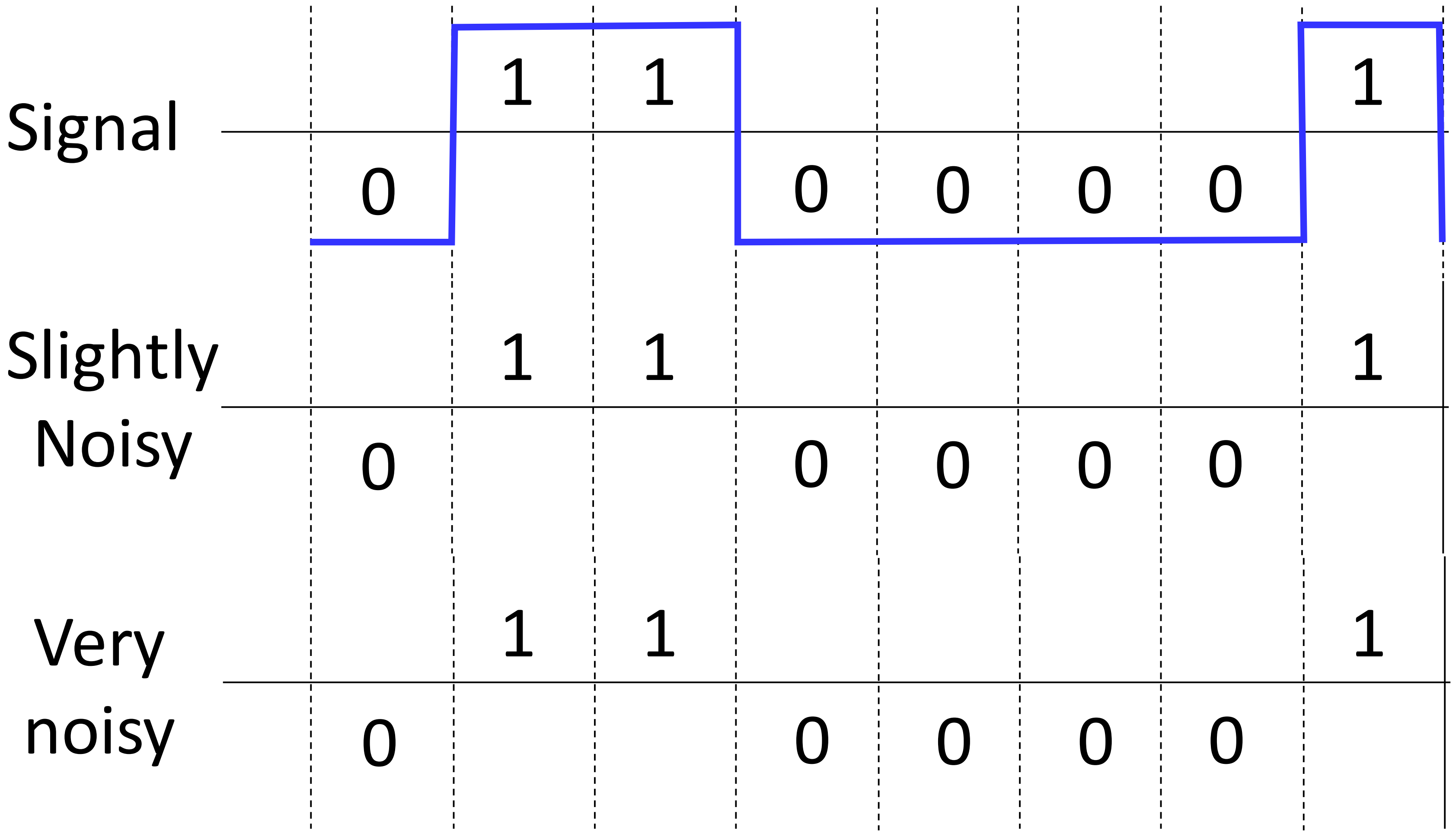
Error detection and correction

Handling errors

Topic

- Some bits will be received in error due to noise. What can we do?
  - Detect errors with codes
  - 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 allow correction of some errors

- 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 differ from each other.

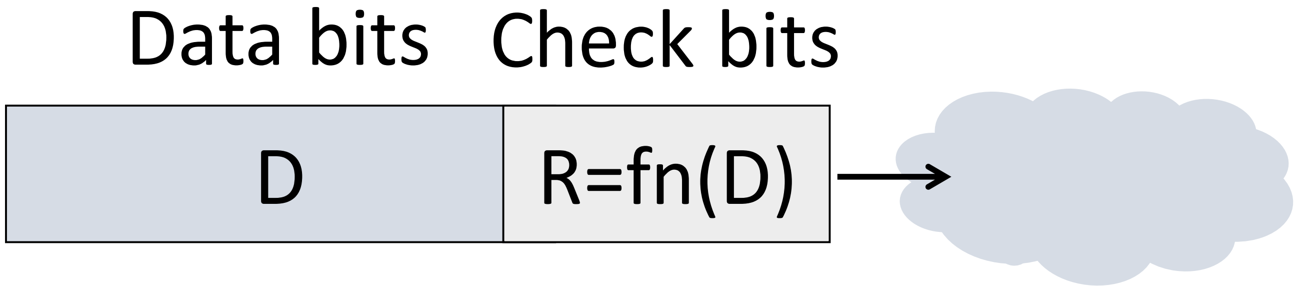
- How good is this code?
  - How many bit errors can it detect?
    - What is the minimum number of bit errors that could cause it to make a mistake?
  - How many bit errors can it correct?

Motivating Example

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

Using Error Codes

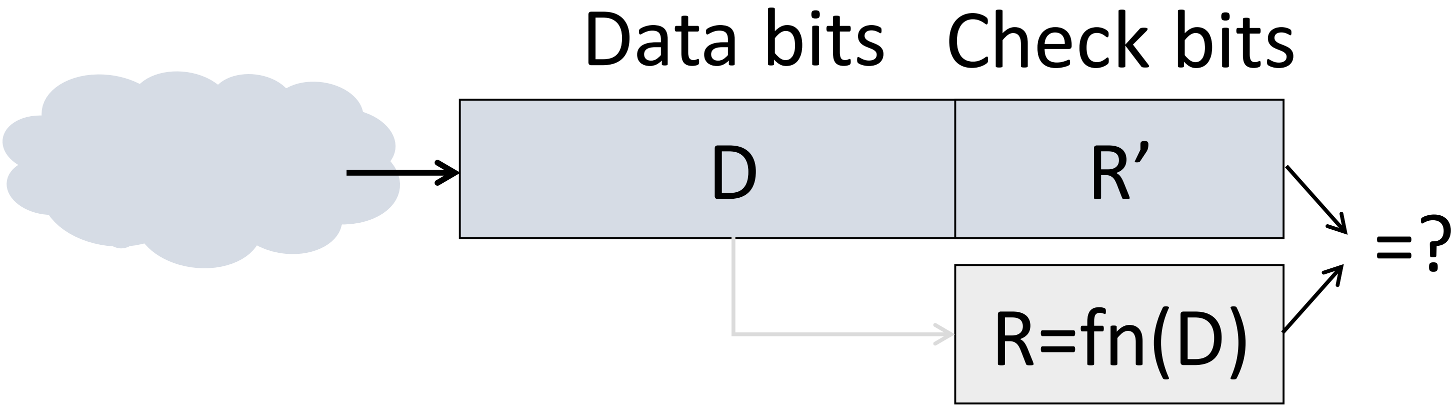
- Codeword consists of D data plus R check bits (=systematic block code)



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

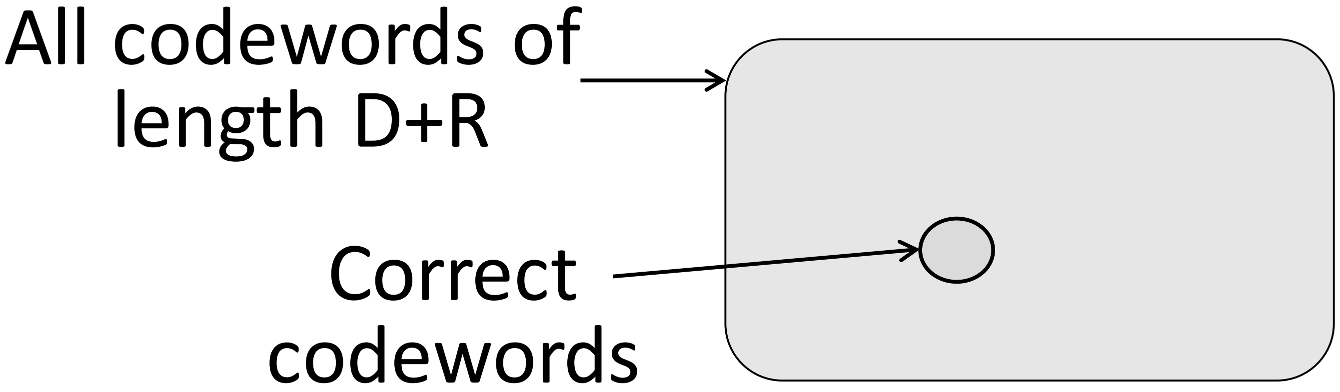
Using Error Codes

- 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

Hamming Distance

- Distance is the number of bit flips needed to change D_1 to D_2

- Hamming distance of a coding is the minimum distance between any pair of valid codewords
  - How many bits must be flipped to turn one legal codeword into another?

Hamming Distance

- 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
    - map to the closest valid codeword (there can be only one)

Parity Bit - Simple Error Detection

- Take D data bits, add 1 check bit that is the sum of the D bits
  - “Sum” is modulo 2 or XOR
  - This is called even parity
- Overhead is one bit, not matter how big D is

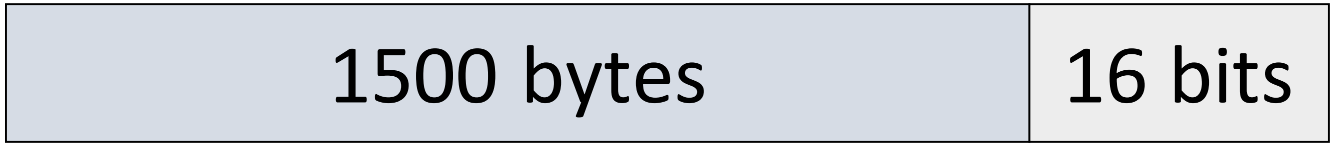
Parity Bit

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

- What happen if there are more errors?

Checksums

- Like parity, number of check bits is independent of the amount of data



- 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

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

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

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

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

- 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

- The catch:
  - It's based on mathematics of finite fields, in which bit strings 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

- 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

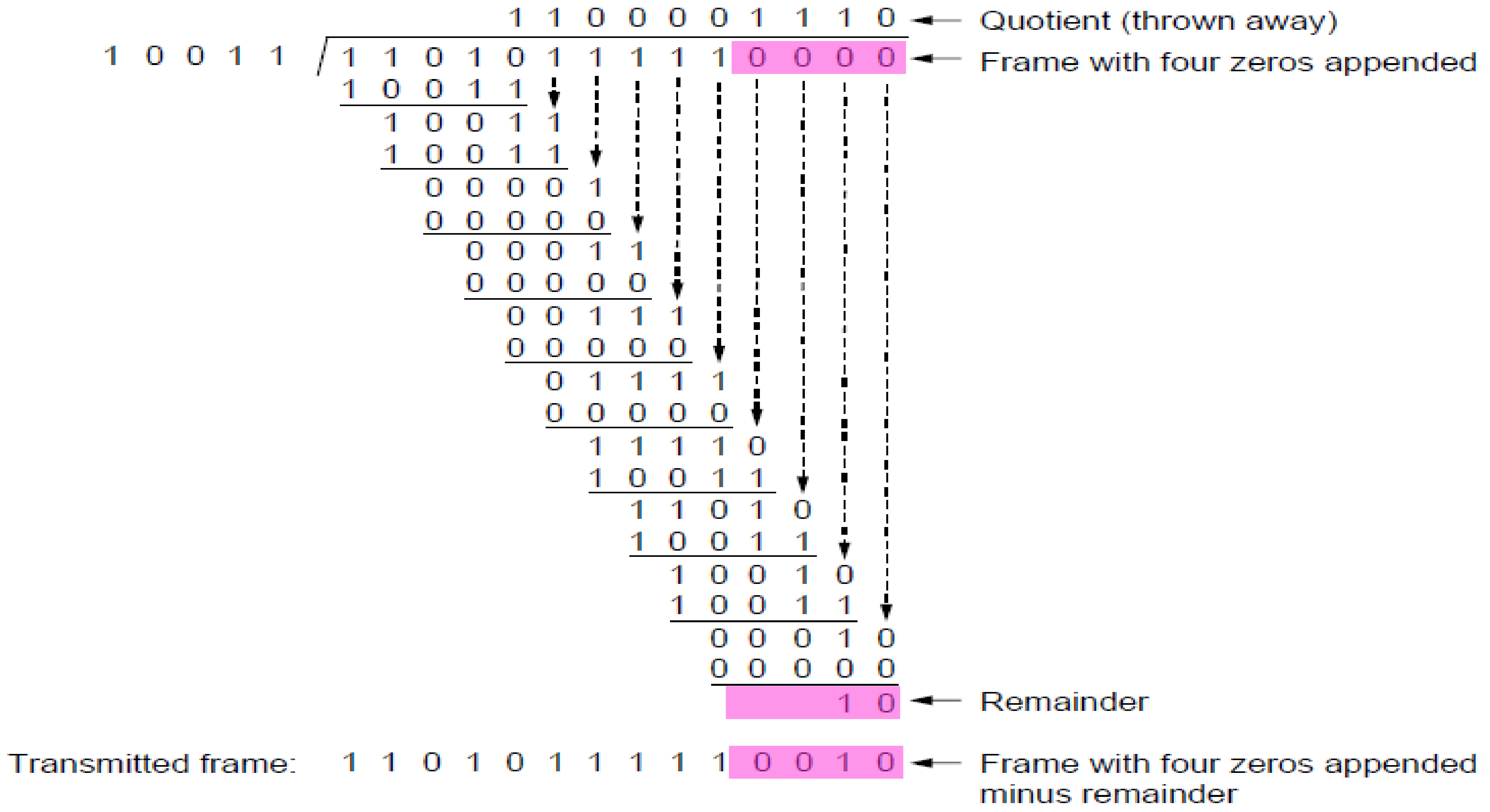
CRCs

Data bits:
1101011111

Check bits:
$C(x)=x^4+x^1+1$
C = 10011
k = 4

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

CRCs


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

CRCs

- 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