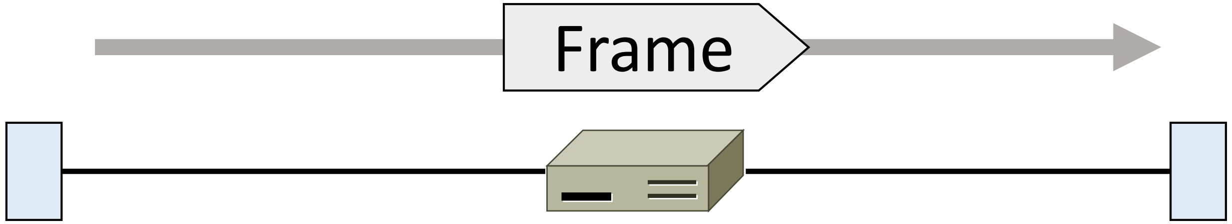
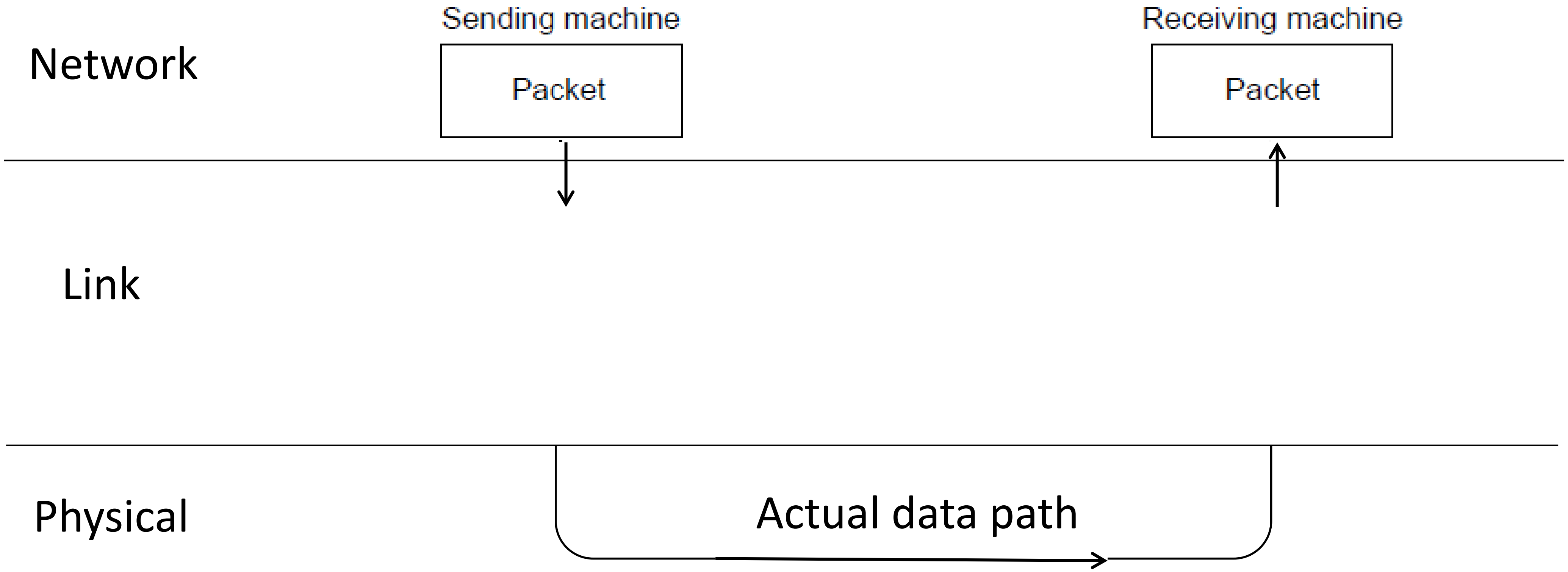
Link Layer

Scope of the Link Layer

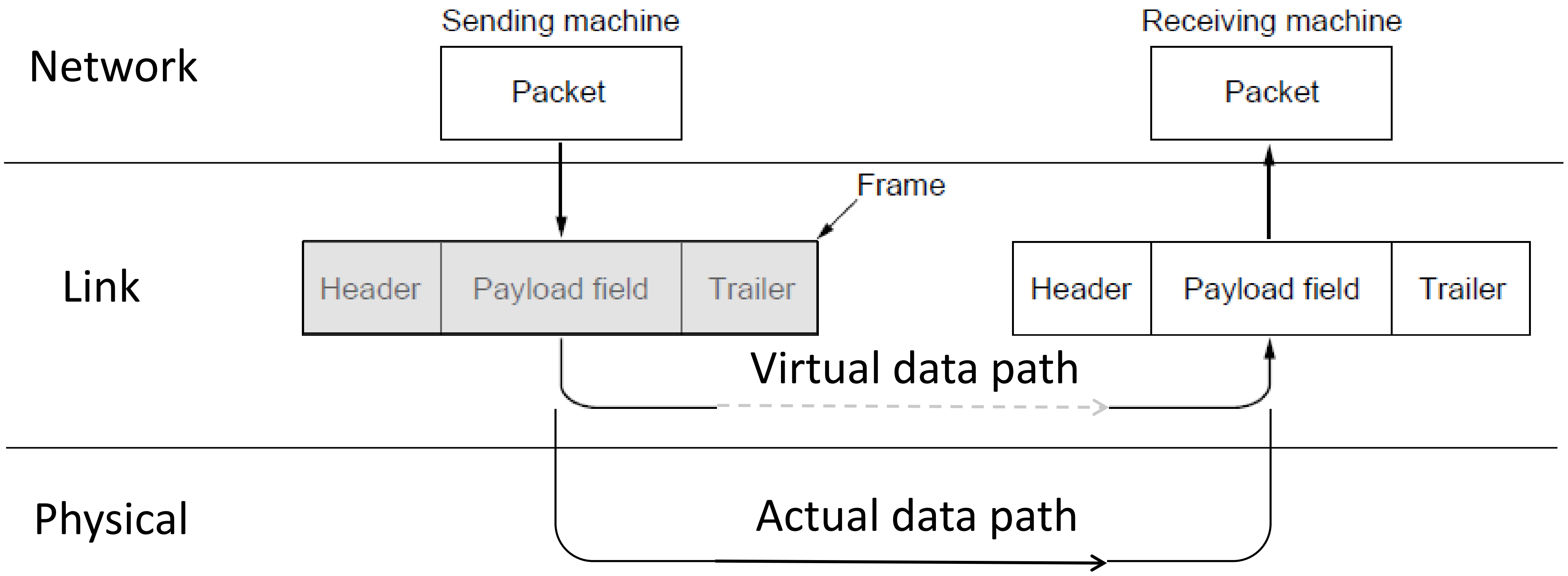
- Concerns how to transfer messages over one or more connected links
  - Messages are frames, of limited size
  - Builds on the physical layer



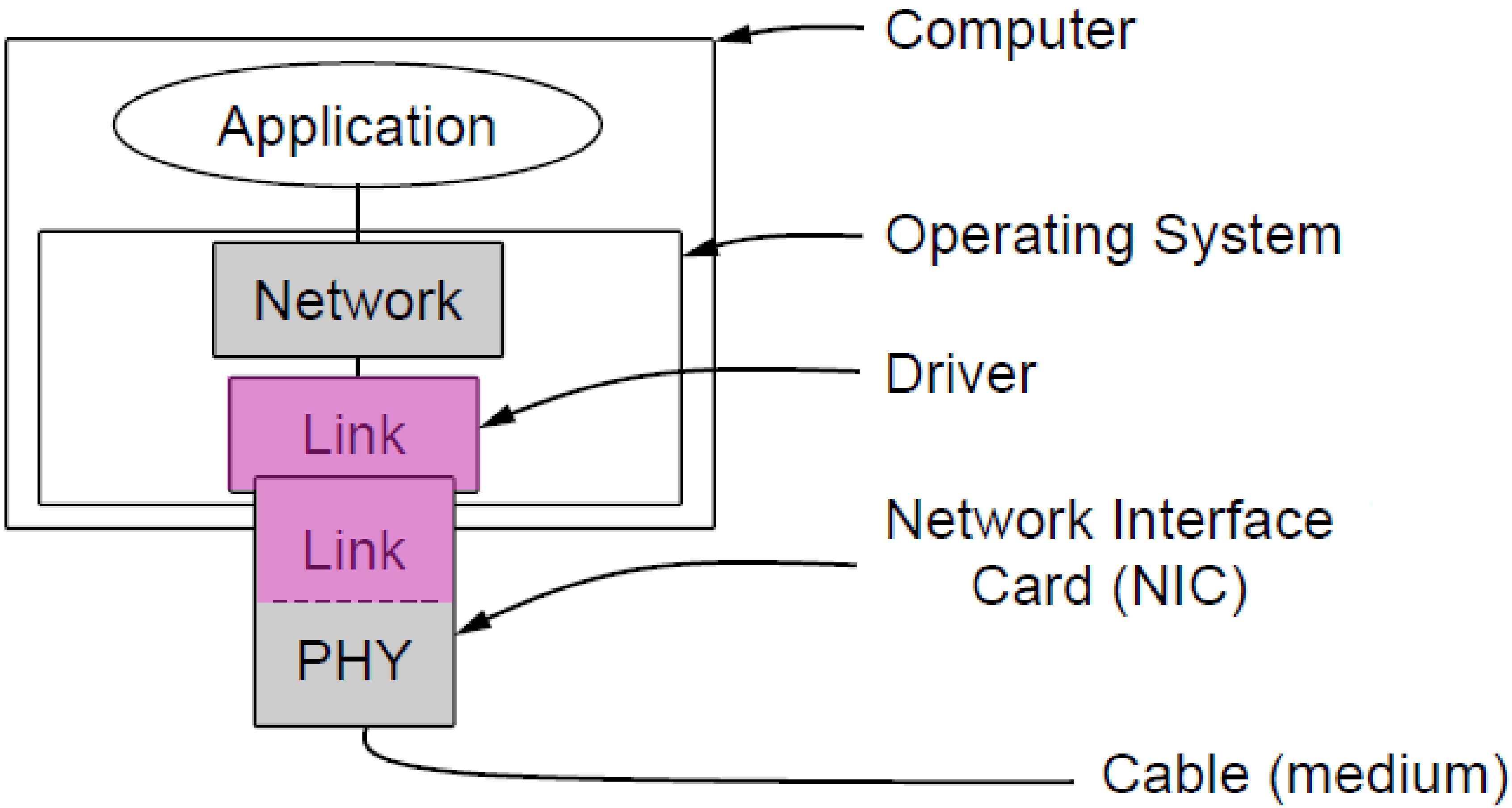
In terms of layers …



In terms of layers (2)



Typical Implementation of Layers (2)



Topics

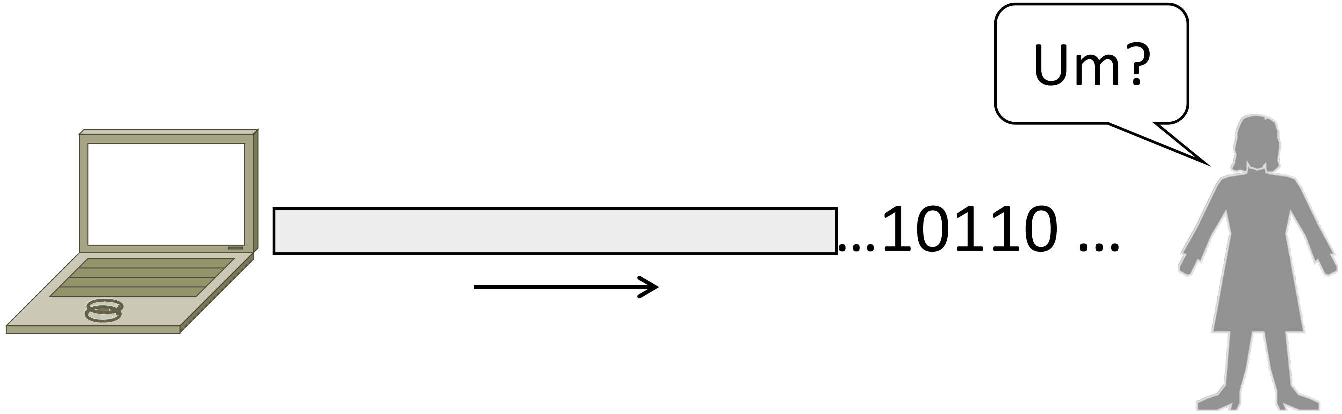
1. Framing
   - Delimiting start/end of frames
2. Error detection and correction
   - Handling errors
3. Retransmissions
   - Handling loss
4. Multiple Access
   - 802.11, classic Ethernet
5. Switching
   - Modern Ethernet

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

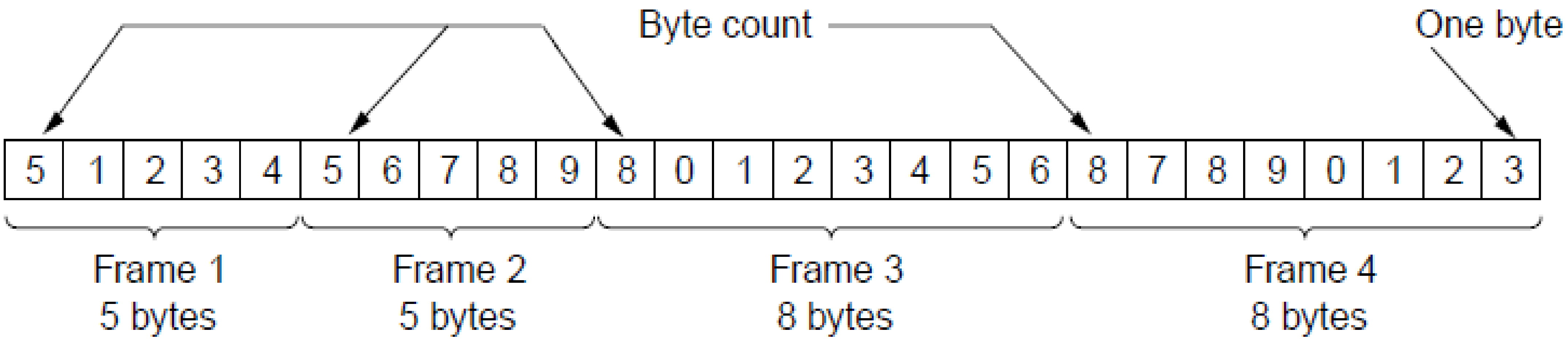
- We'll look at:
  - Byte count (motivation)
  - Byte stuffing
  - Bit stuffing

- 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 …

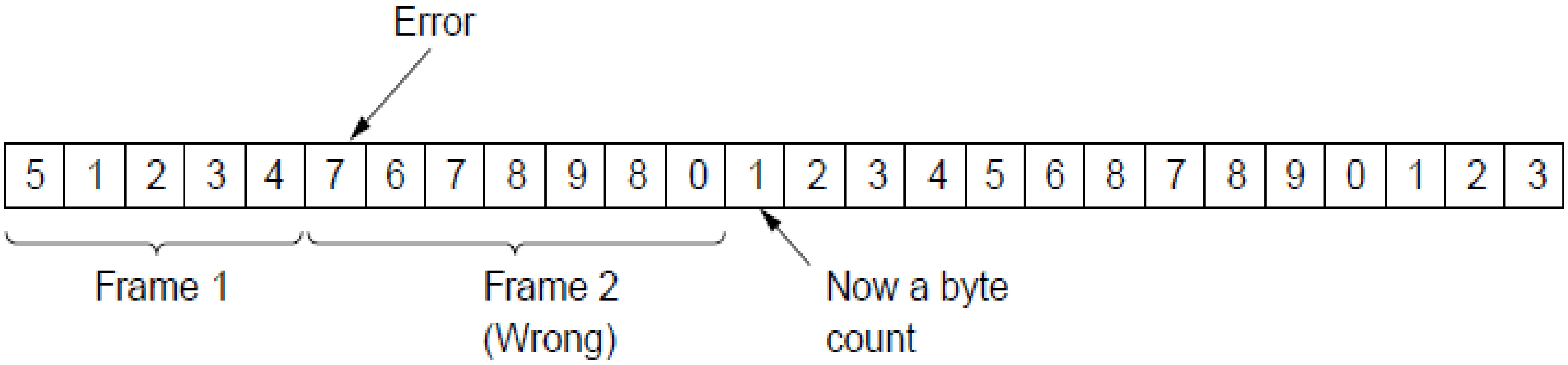
Byte Count (2)



- 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



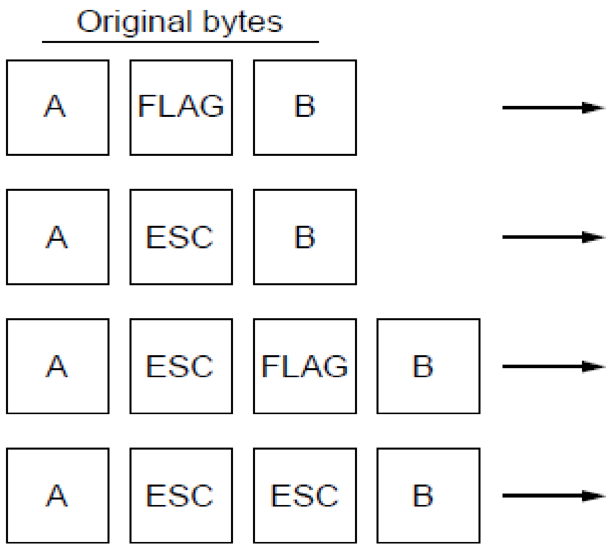
5	1	2	3	4	7	6	7	8	9	8	0	1	2	3	4	5	6	8	7	8	9	0	1	2	3

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!

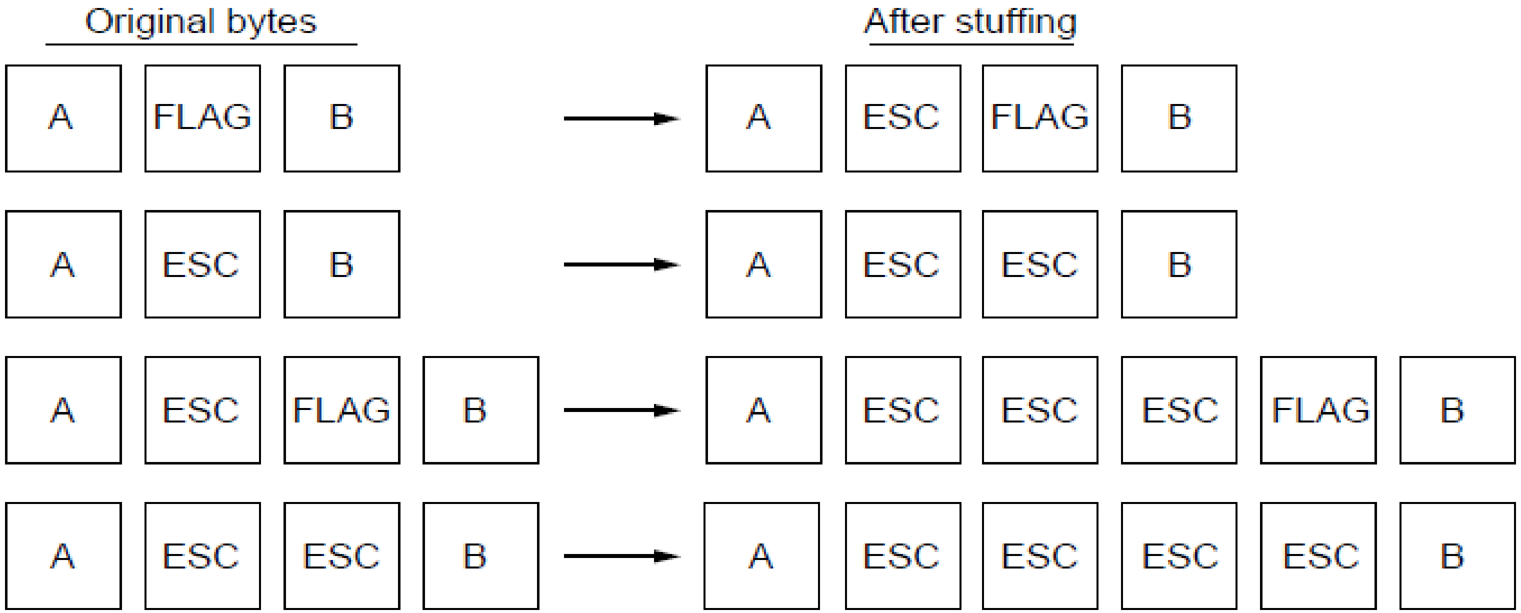
Byte Stuffing (2)

- 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

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)

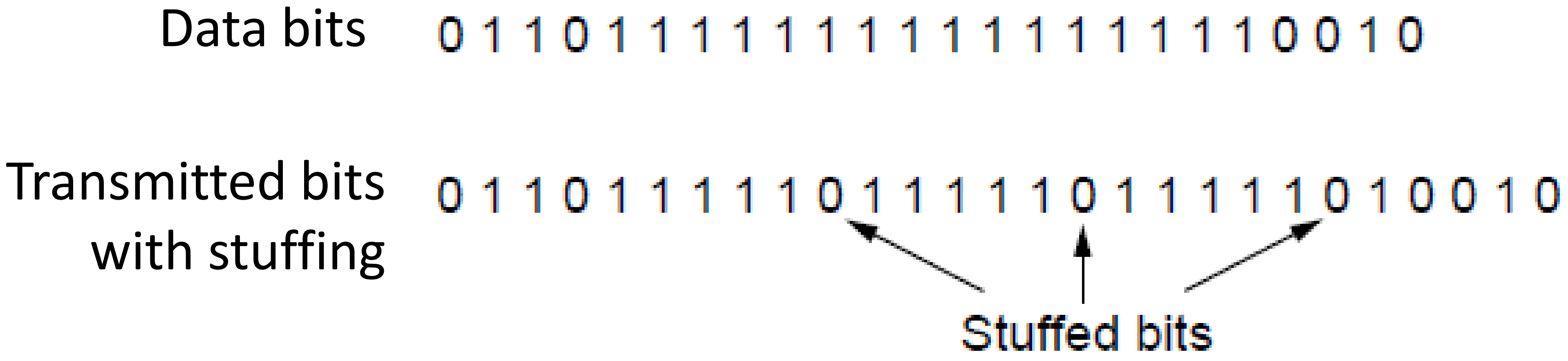
- Example:

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 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 0 1 1 0 1 1 1 1 1 0 1 1 1 1 1 0 1 1 1 1 1 0 1 0 0 1 0

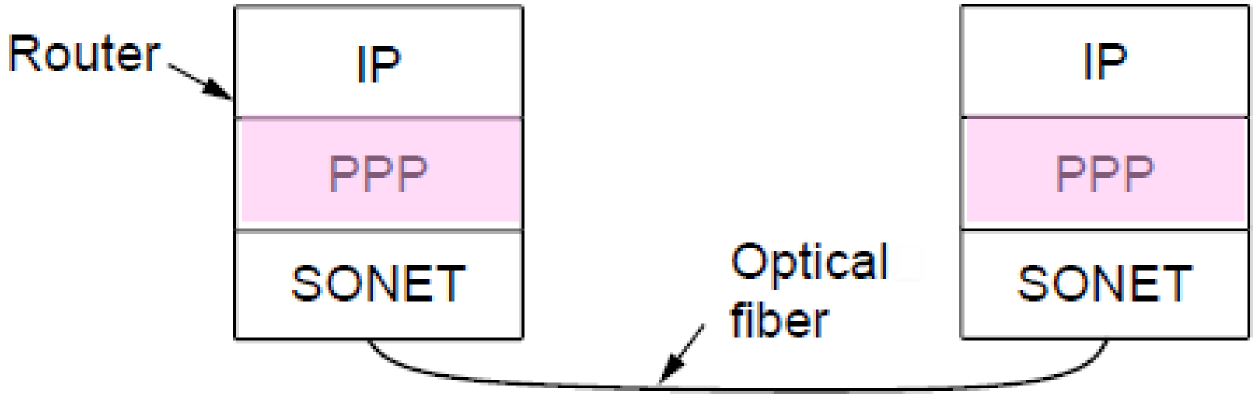
Stuffed bits

Link Example: PPP over SONET

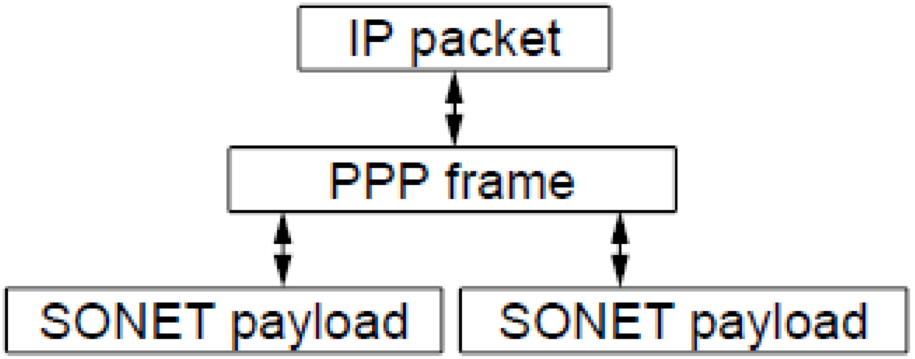
- PPP is Point-to-Point Protocol
- Widely used for link framing
  - E.g., it is used to frame IP packets that are sent over SONET optical links

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



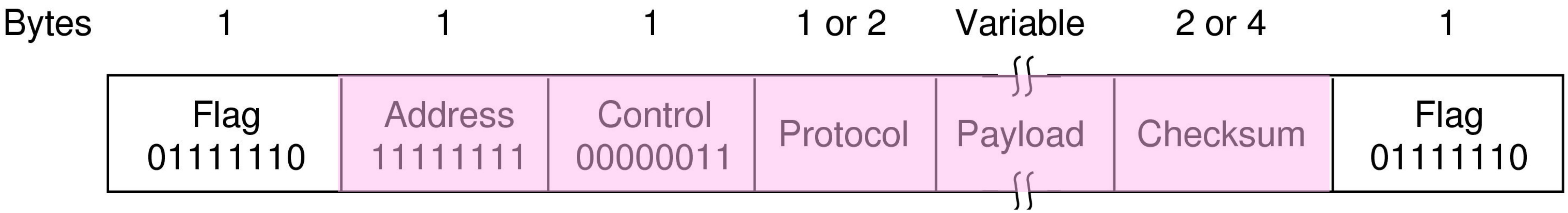
Protocol stacks



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

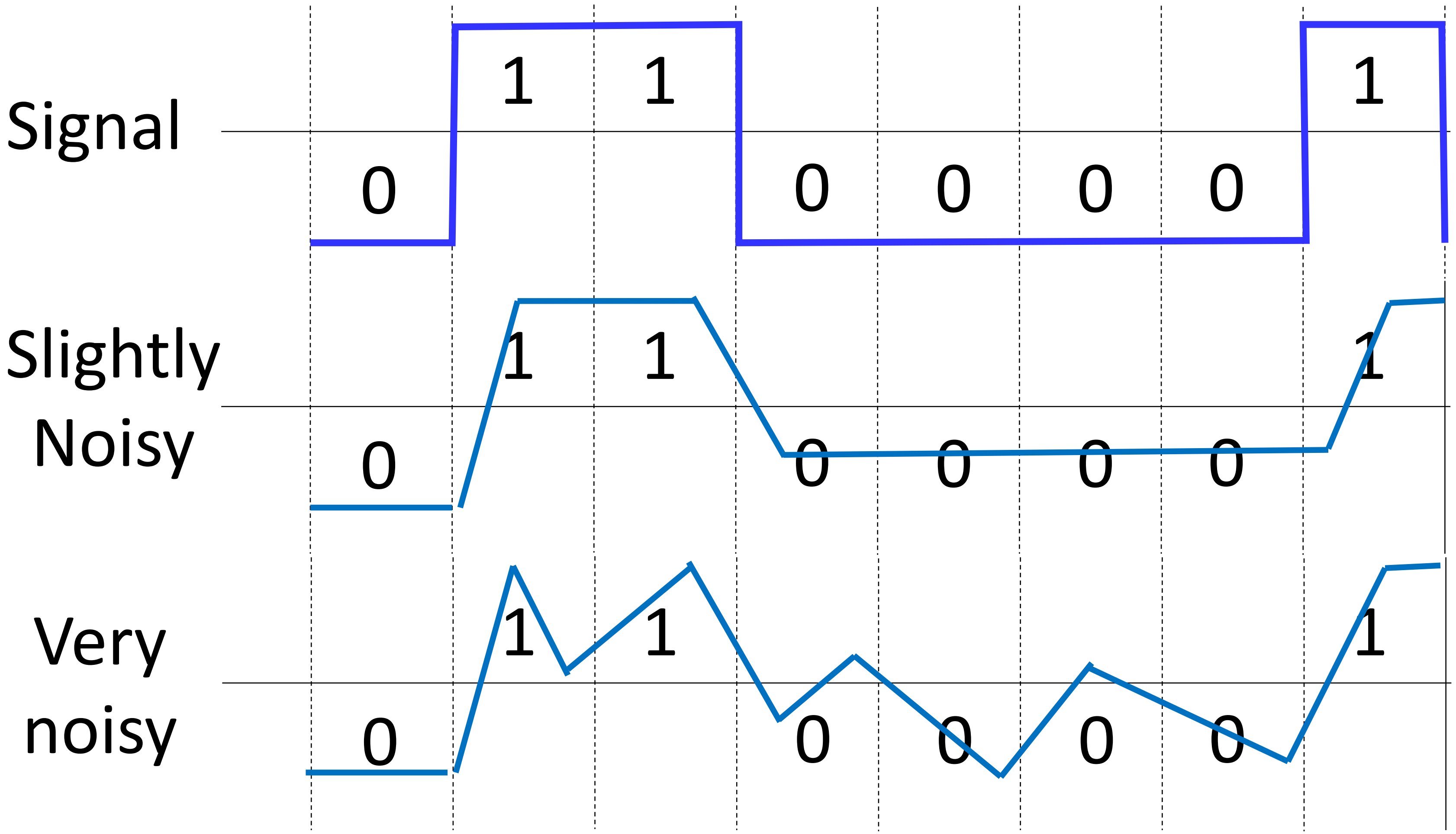
Error detection and correction

Handling errors

Topic

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

Motivating Example

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

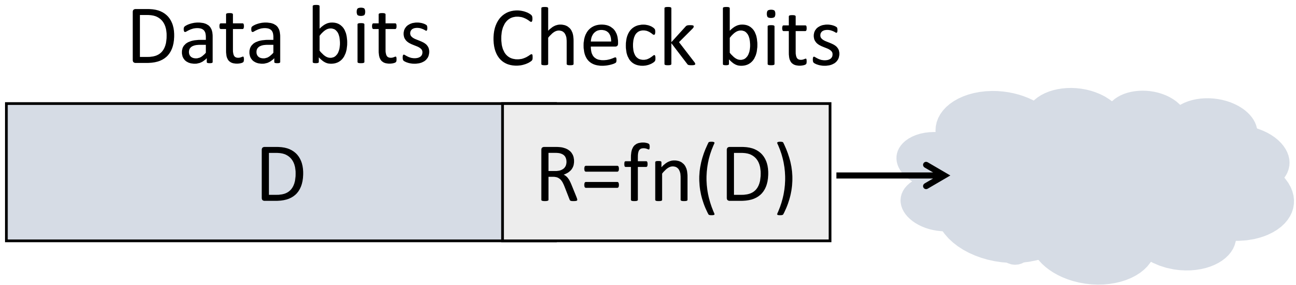
- How good is this code?
  - How many errors can it detect/correct?
  - How many errors will make it fail?

Motivating Example (2)

- We want to handle more errors with less overhead
  - Will look at better codes
  - But, they can’t handle all errors
  - And they focus on accidental (random) errors
    - Not adversaries

Using Error Codes

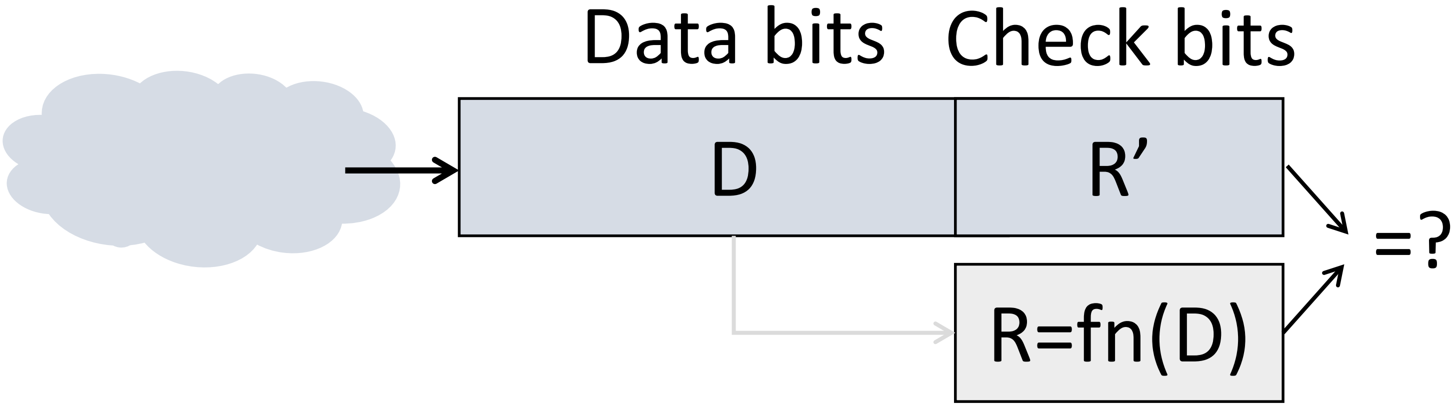
- Codeword consists of D data plus R check bits (=systematic block code)



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

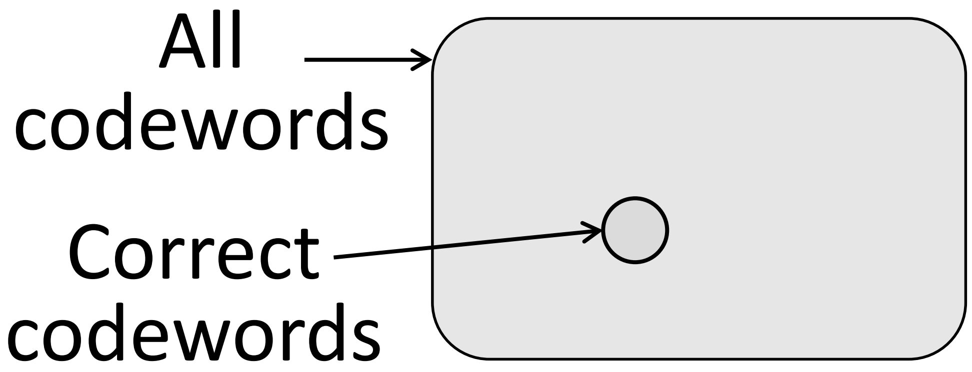
Using Error Codes (2)

- 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:



All codewords

Correct codewords

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

Hamming Distance

- Distance between codewords D_1 and D_2 is the number of bit flips needed to change D_1 to D_2
- The Hamming distance of a coding is the minimum distance between any pair of valid 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 (XOR)

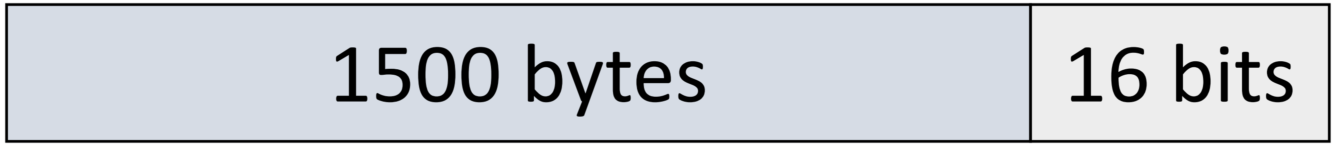
Parity Bit (2)

- 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



1500 bytes

16 bits

- 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
- 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:

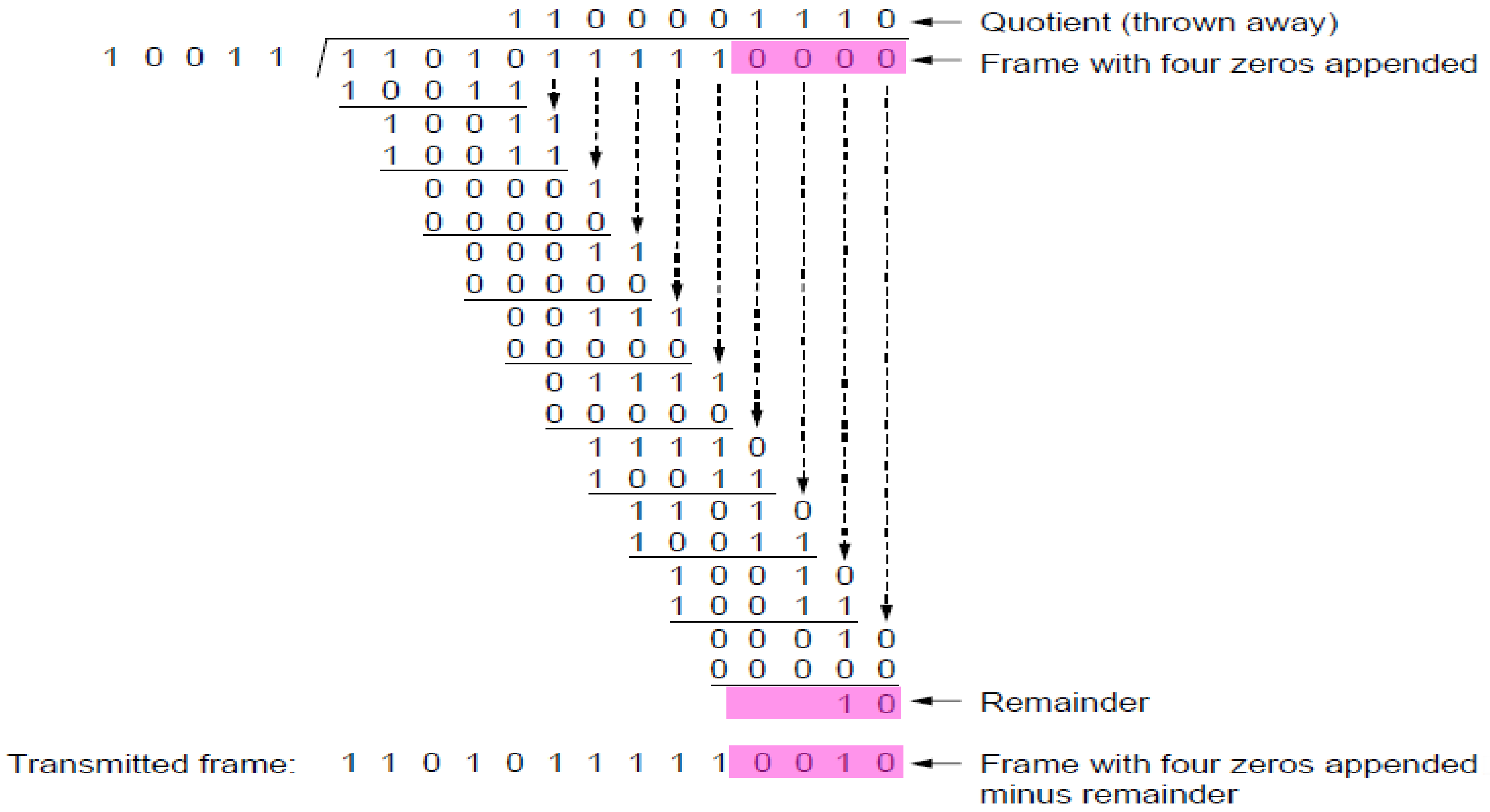
$C(x)=x^4+x^1+1$

$C = 10011$

$k = 4$

$$1\ 0\ 0\ 1\ 1\,\overline{\big)\,1\ \ 1\ \ 0\ \ 1\ \ 0\ \ 1\ \ 1\ \ 1\ \ 1\ \ 1\qquad}$$

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
```

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