Where we are in the Course

• Moving on to the Link Layer!

```
   Application
       Transport
       Network
    Link
   Physical
```
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
Typical Implementation of Layers (2)
Functions of the Link Layer

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

...10110 ...

Um?
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 ...
• 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 that means start/end of frame
  – Replace (“stuff”) the flag inside the frame 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
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 0 0 1 0

Transmitted bits with stuffing

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Bit Stuffing (3)

• So how does it compare with byte stuffing?

Data bits: 011011111111111111111110010

Transmitted bits with stuffing: 011011111101111111011111101010010

Stuffed bits
Error Correction and Detections

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

• Reliability is a concern that cuts across the layers – we’ll see it again
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; 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:

  All codewords

  Correct codewords

• 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

- See also:
  - “You and Your Research”, 1986

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Hamming Distance

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

• Hamming distance of a code is the minimum distance between any pair of codewords
Hamming Distance (2)

• Error detection:
  – For a code of distance $d+1$, up to $d$ errors will always be detected
Hamming Distance (3)

• Error correction:
  – For a code of distance $2d+1$, up to $d$ errors can always be corrected by mapping to the closest codeword