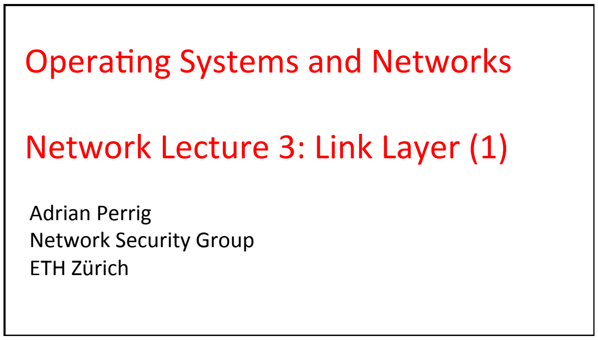

Operating Systems and Networks

Network Lecture 3: Link Layer (1)

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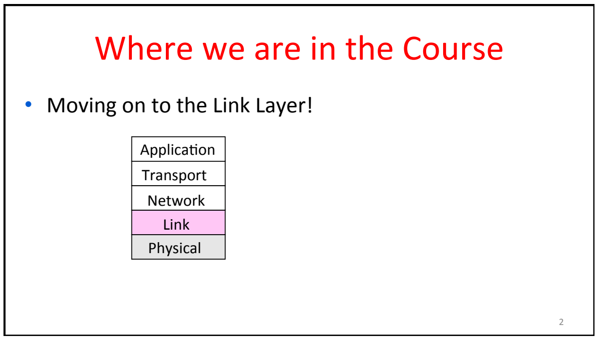
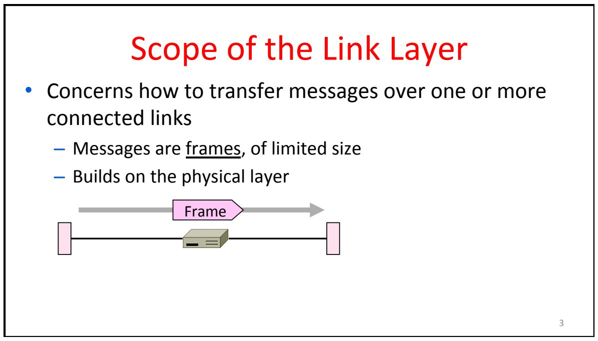


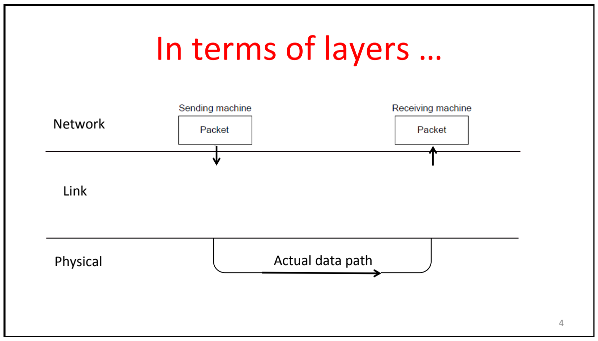
Where we are in the Course

- Moving on to the Link Layer!

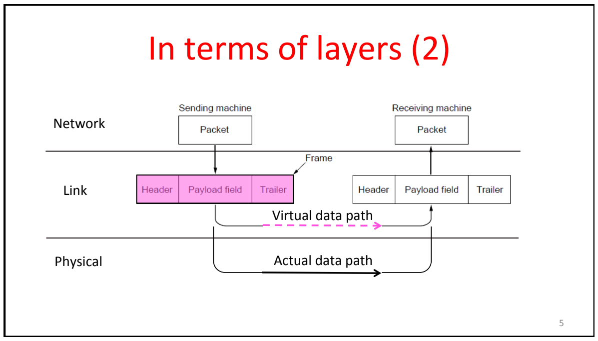


Scope of the Link Layer

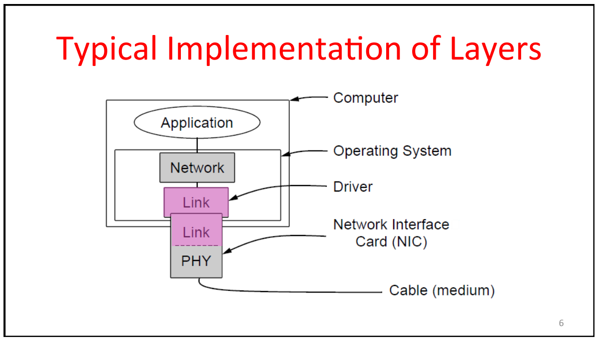
- Concerns how to transfer messages over one or more connected links
  - Messages are frames, of limited size
  - Builds on the physical layer



In terms of layers …



In terms of layers (2)



Typical Implementation of Layers

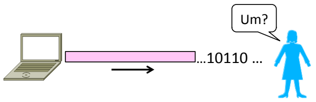
Topics

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

Later

Framing (§3.1.2)

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



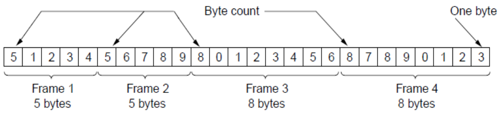
Framing Methods

- 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 ...

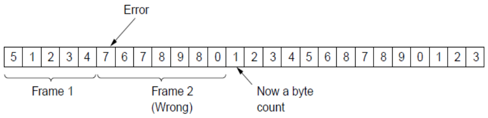
Byte Count (2)

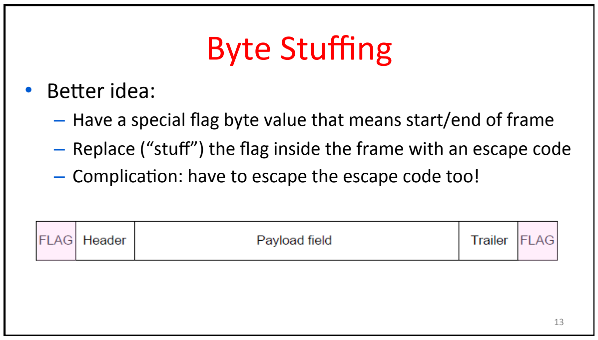


- How well do you think it works?

Byte Count (3)

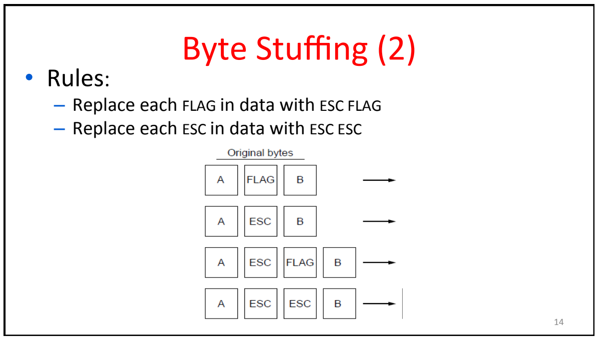
- Difficult to re-synchronize after framing error
  - Want a way to scan for a start of frame





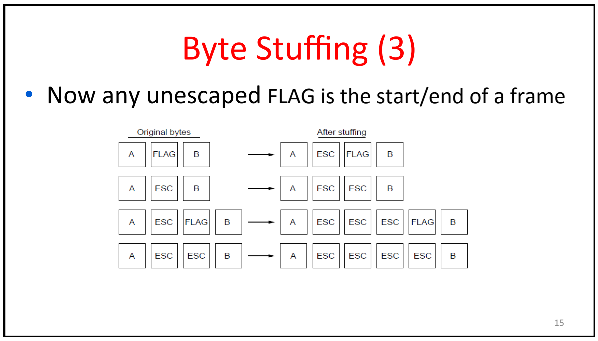
Byte Stuffing

- Better idea:
  - Have a special flag byte value 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!



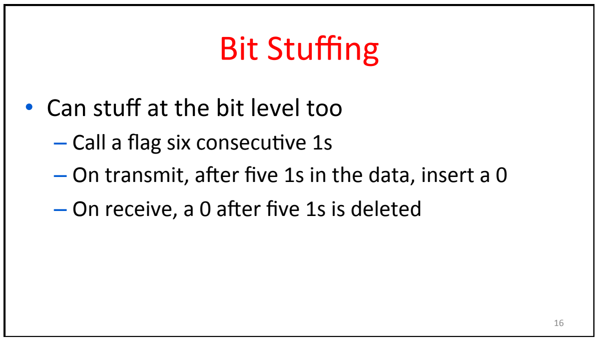
Byte Stuffing (2)

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



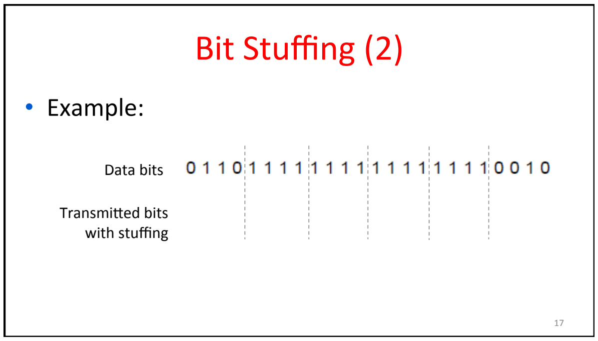
Byte Stuffing (3)

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



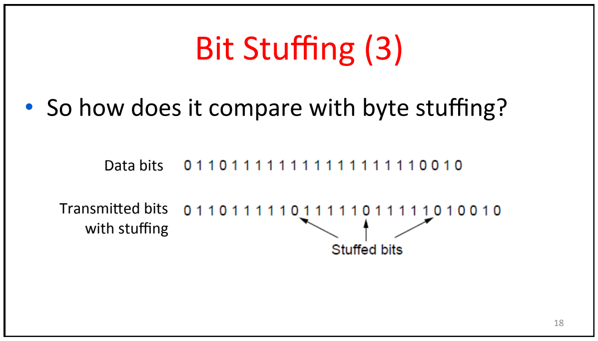
Bit Stuffing

- 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:



Bit Stuffing (3)

- So how does it compare with byte 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

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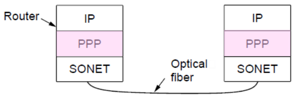
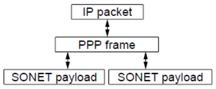
Link Example: PPP over SONET (2)

- 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 Coding Overview (§3.2)

- 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

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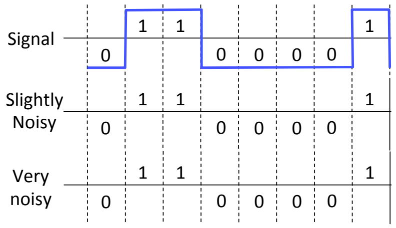
Problem – Noise may flip received bits



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

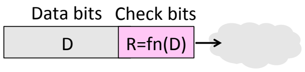
- A simple code to handle errors:
  - Send two copies! Error if different.
- How good is this code?
  - How many errors can it detect/correct?
  - How many errors will make it fail?

Motivating Example (2)

- We want to handle more errors with less overhead
  - Will look at better codes; they are applied mathematics
  - But, they can't handle all errors
  - And they focus on accidental errors

Using Error Codes

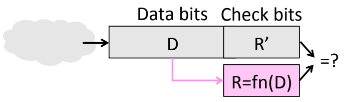
- Codeword consists of D data plus R check bits (=systematic block code)



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

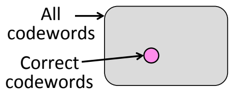
Using Error Codes (2)

- 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

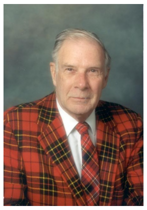
- For D data bits, R check bits:



- 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



Source: IEEE GHN, © 2009 IEEE

Hamming Distance

- Distance is the number of bit flips needed to change $D+R_1$ to $D+R_2$
- Hamming distance of a code is the minimum distance between any pair of codewords

Hamming Distance (2)

- Error detection:
  - For a code of Hamming distance d+1, up to d errors will always be detected

Hamming Distance (3)

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

Error Detection (§3.2.2)

- Some bits may be received in error due to noise. How do we detect this?
  - Parity
  - Checksums
  - CRCs
- Detection will let us fix the error, for example, by retransmission (later)

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

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 bit
4. Negate (complement) to get sum

```
0001
f203
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
      f203
      f4f5
      f6f7
  + (0000)
   ------
     2ddf0
       ↓
      ddf0
  +      2
   ------
      ddf2
       ↓
      220d
```

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
   f203
   f4f5
   f6f7
+  220d
------
```

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
  f203
  f4f5
  f6f7
+ 220d
------
 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:
  - Message = 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

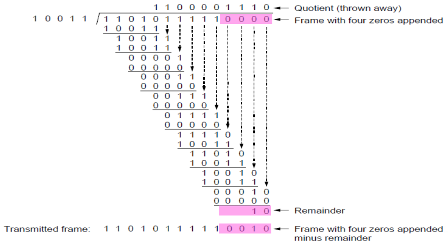
CRCs (4)

Data bits:
1101011111

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

```
         ___________________
1 0 0 1 1|1 1 0 1 0 1 1 1 1 1
```

CRCs (5)



CRCs (6)

- Protection depend on generator
  - Standard CRC-32 is 1 0000 0100 1100 0001 0001 1101 1011 0111
- 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 (i.e., moving data around) like checksums

Error Detection in Practice

- CRCs are widely used on links
  - Ethernet, 802.11, ADSL, Cable …
- Checksum used in Internet
  - IP, TCP, UDP … but it is weak
- Parity
  - Is little used

Error Correction (§3.2.1)

- Some bits may be received in error due to noise. How do we fix them?
  - Hamming code
  - Other codes
- And why should we use detection when we can use correction?

Why Error Correction is Hard

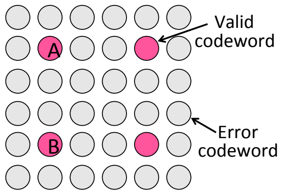
- If we had reliable check bits we could use them to narrow down the position of the error
  - Then correction would be easy
- But error could be in the check bits as well as the data bits!
  - Data might even be correct

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

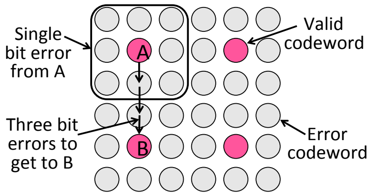
Intuition (2)

- 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

0 1 0 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

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

p_1= p_2=
p_4=

Syndrome =
Data =

Hamming Code (6)

- Example, continued

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

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

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

p_1= p_2=
p_4=

Syndrome =
Data =

Hamming Code (8)

- Example, continued

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

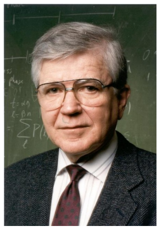
p_1= 0+0+1+1 = 0, p_2= 1+0+1+1 = 1,
p_4= 0+1+1+1 = 1

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

Other Error Correction Codes

- Codes used in practice are much more involved than Hamming
- Convolutional codes (§3.2.3)
  - Take a stream of data and output a mix of the recent input bits
  - Makes each output bit less fragile
  - Decode using Viterbi algorithm (which can use bit confidence values)

Other Codes (2) – LDPC



Source: IEEE GHN, © 2009 IEEE

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

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 depends! We need to know more about the errors

Detection vs. Correction (2)

1. Assume bit errors are random
   - Messages have 0 or maybe 1 error

- Error correction:
  - Need ~10 check bits per message
  - Overhead:
- Error detection:
  - Need ~1 check bit per message plus 1000 bit retransmission 1/10 of the time
  - Overhead:

Detection vs. Correction (3)

2. Assume errors come in bursts of 100 consecutively garbled bits
   - Only 1 or 2 messages in 1000 have errors

- Error correction:
  - Need >>100 check bits per message
  - Overhead:
- Error detection:
  - Can use 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
    - Small number of errors are correctable
  - 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, LTE, power-line, …
  - Convolutional codes widely used in practice
- Error detection (with 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 (entire packets are lost)
  - E.g., Reed-Solomon (CDs, DVDs, etc.)