Link Layer

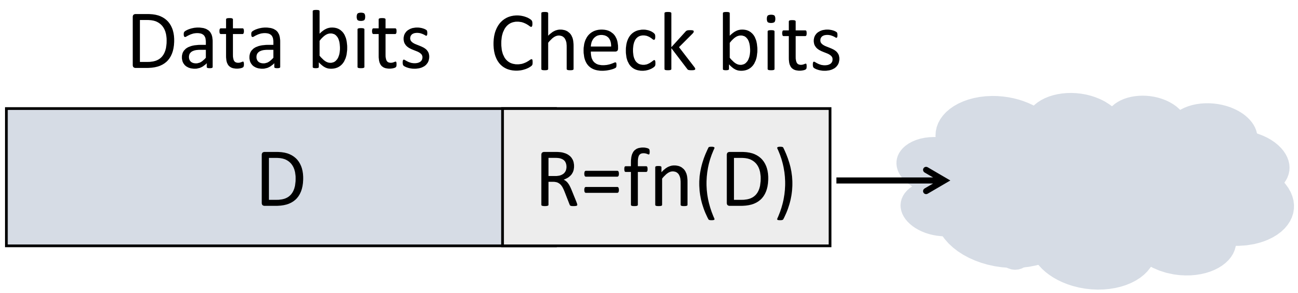
(continued)

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

Using Error Codes

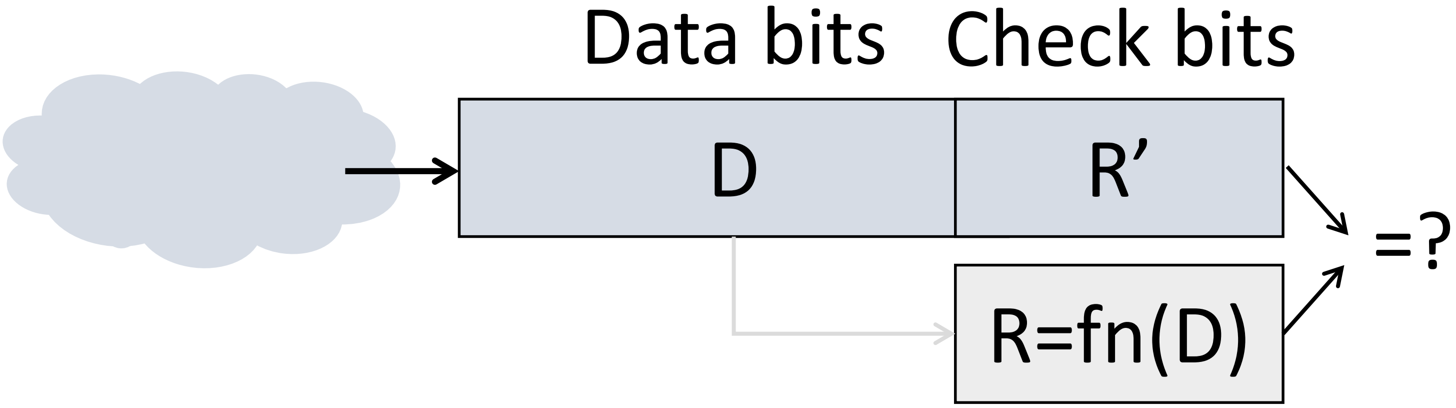
- Codeword consists of D data plus R check bits (=systematic block code)



- 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'



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
```

Why Error Correction is Hard

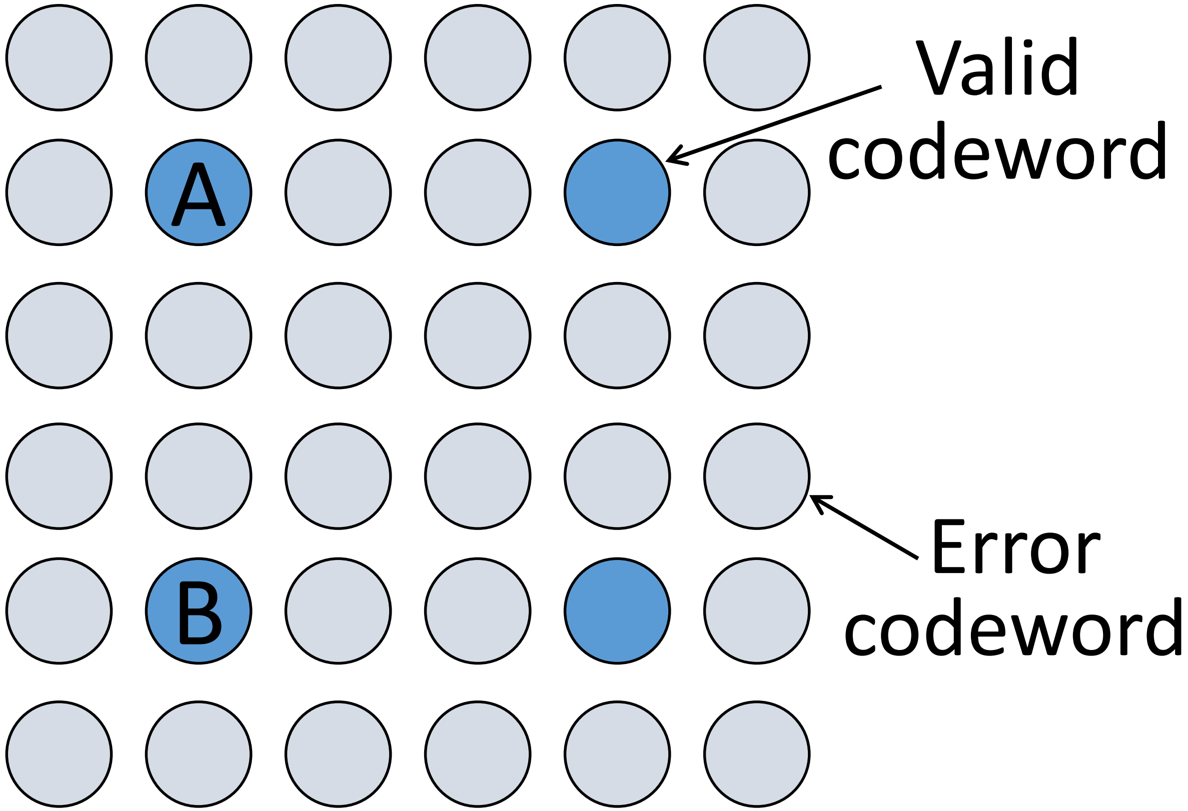
- If we had reliable check bits we could use them to narrow down the position of the error
  - Then correction would be easy
- But error could be in the check bits as well as the data bits!
  - Data might even be correct

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
  - There will be a unique valid codeword that is closest to a received word with a single bit error
- If we assume errors are only 1 bit, we can correct them by mapping an error to the closest valid codeword
  - Works for up to d errors if HD ≥ 2d + 1
  - (We just assume that no more than d errors occur. We have no way to verify that.)

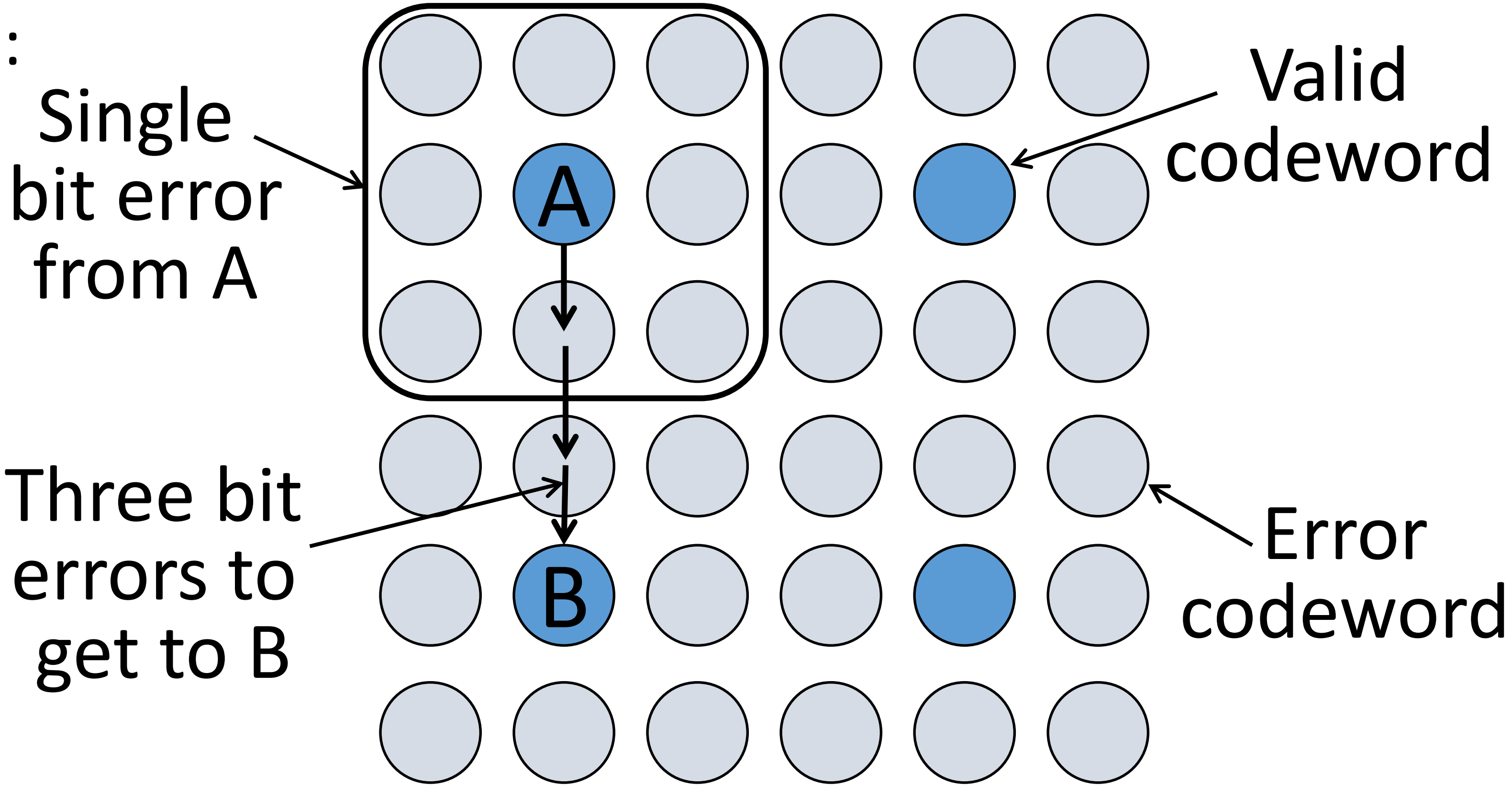
Intuition (2)

- Visualization of code:



Intuition (3)

- Visualization of code:



Hamming Code

- Gives a method for constructing a code with a distance of, say, 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
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  - Check 2 covers positions 2, 3, 6, 7
  - Check 4 covers positions 4, 5, 6, 7

<u>0</u>	<u>1</u>	0	<u>0</u>	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!)