Lecture 3:
Framing and Error Detection

CSE 123: Computer Networks
Stefan Savage

UCSDCSE

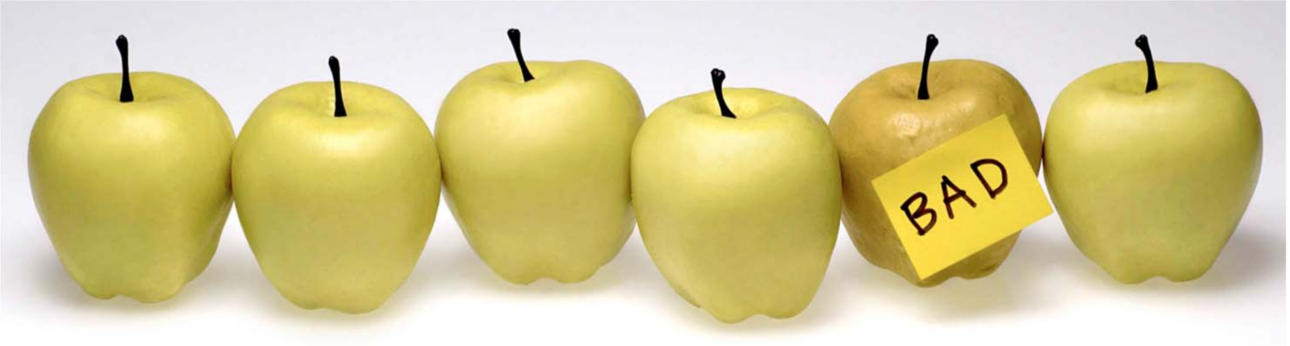
Last time: Physical link layer

- Tasks
  - Encode binary data from source node into signals that physical links carry
  - Signal is decoded back into binary data at receiving node
  - Work performed by network adapter at sender and receiver
- Synchronous encoding algorithms
  - NRZ, NRZI, Manchester, 4B/5B

Today: Data-link layer

- **Framing (2.3)**

- **Error detection (2.4)**



Recall: (Data) Link Layer

- Framing
  - Break stream of bits up into discrete chunks
- Error handling
  - Detect and/or correct errors in received frames
- Media access
  - Arbitrate which nodes can send frames at any point in time
  - Not always necessary; e.g. point-to-point duplex links
- Multiplexing
  - Determine appropriate destination for a given frame
  - Also not always required; again, point-to-point

Framing

- Break down a stream of bits into smaller, digestible chunks called frames

- Allows the physical media to be shared
  - Multiple senders and/or receivers can time multiplex the link
  - Each frame can be separately addressed

- Provides manageable unit for error handling
  - Easy to determine whether something went wrong
  - And perhaps even to fix it if desired

What's a Frame?

- Wraps payload up with some additional information
  - Header usually contains addressing information
  - Maybe includes a trailer (w/checksum—to be explained)
- Basic unit of reception
  - Link either delivers entire frame payload, or none of it
  - Typically some maximum transmission unit (MTU)
- Some link layers require absence of frames as well
  - I.e., minimum gaps between frames

Identifying Frames

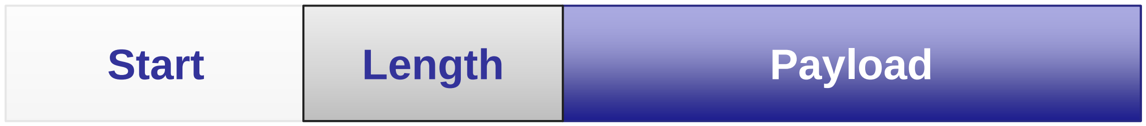
- First task is to delineate frames
  - Receiver needs to know when a frame **starts** and **ends**
  - Otherwise, errors from misinterpretation of data stream

- Several different alternatives
  - Fixed length (bits) frames
  - Explicitly delimited frames
    - Length-based framing
    - Sentinel-based framing
  - Fixed duration (seconds) frames

Fixed-Length Frames

- Easy to manage for receiver
  - Well understood buffering requirements
- Introduces inefficiencies for variable length payloads
  - May waste space (padding) for small payloads
  - Larger payloads need to be fragmented across many frames
- Requires explicit design tradeoff
  - ATM uses 53-byte frames (cells)
  - Aside: why 53 bytes?

Length-Based Framing



- To avoid overhead, we'd like variable length frames
  - Each frame declares how long it is
  - E.g. DECNet DDCMP

- Issues?
  - What if you decode it wrong?
    - Remember, need to decode *while* receiving
  - Still need to identify the frame beginning correctly…

Sentinel-based Framing

- Idea: mark start/end of frame with special “marker”
  - Byte pattern, bit pattern, signal pattern

- But… must make sure marker doesn’t appear in data

- Two solutions
  - Special non-data physical-layer symbol (e.g., 00000 in 4B/5B)
    - » Impact on efficiency (can’t use symbol for data) and utility of code (now can have long strings of 000’s sometimes)
  - Stuffing
    - » Dynamically remove market bit patterns from data stream
    - » Receiver “unstuffs” data stream to reconstruct original data

Bit-level Stuffing

- Avoid sentinel bit pattern in payload data
  - Commonly, sentinel is bit pattern 01111110 (0x7E)
  - Invented for SDLC/HDLC, now standard pattern
- Sender: any time five ones appear in outgoing data, insert a zero, resulting in 01111101

Stuffed bits

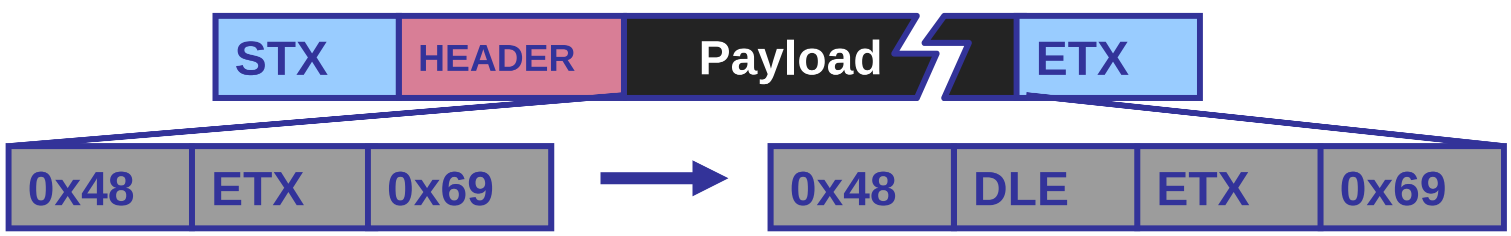
0111111000011101110111110111111001

011111**0**1000001110111011111**0**011111**0**001

- Receiver: any time five ones appear, removes next zero
  - If there is no zero, there will either be six ones (sentinel) or
  - It declares an error condition!
  - Note bit pattern that cannot appear is 01111111 (0x7F)
- What’s bad case?

Byte Stuffing

- Same as bit stuffing, except at byte (character) level
  - Generally have two different flags, STX and ETX
  - Found in PPP, DDCMP, BISYNC, etc.
- Need to stuff if either appears in the payload
  - Prefix with another special character, DLE (data-link escape)
  - New problem: what if DLE appears?
- Stuff DLE with DLE!
  - Could be as bad as 50% efficient to send all DLEs



Consistent-Overhead BS

- Control expansion of payload size due to stuffing
  - Important for low-bandwidth links or fixed-sized buffers
- Idea is to use 0x00 as a sentinel, and replace all zeros in data stream with *distance* to next 0x00.
  - Break frame up into runs without zeros, encode by pre-pending each run with length (including length byte)
  - Pretend frame ends in 0x00. Max run is 254; if no zeros pre-pend with 255 (0xFF)

45	00	00	2C	4C	79	00	00	40	06	4F	37		
02	45	**01**	**04**	2C	4C	79	**01**	**05**	40	06	4F	37	00

Consistent-Overhead Byte Stuffing (COBS)

- Sentinel based framing
- Run length encoding applied to byte stuffing
  - Add implied 0 to end of frame
  - Each 0 is replaced with (number of bytes to next 0) + 1
  - What if no 0 within 255 bytes? – 255 value indicates 254 bytes followed by no zero
  - Worst case – no 0's in packet – 1/254 overhead
- Appropriate for very low-bandwidth links

Code	Followed by	Meaning
`0x00`	(not applicable)	(not allowed)
`0x01`	No data bytes	A single zero byte
n	*(n-1)* data bytes	Data followed by 0
`0xFF`	254 data bytes	Data, no following 0

Clock-Based Framing

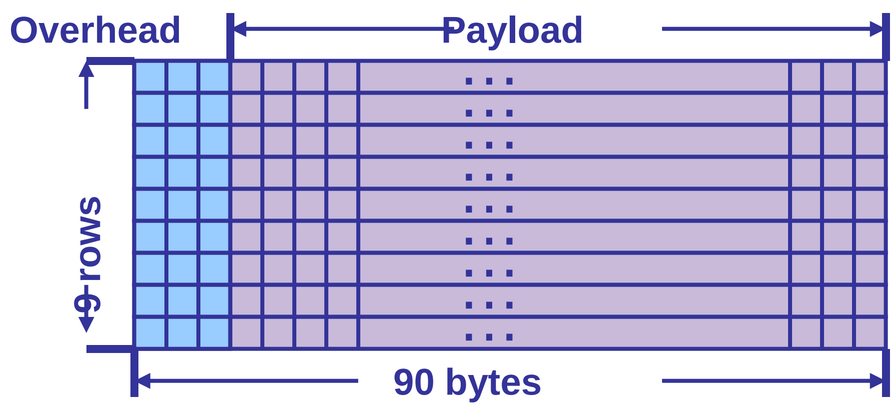
- So far, we've based framing on what's on the wire
  - Any bit errors may throw off our framing
  - What happens with missed flag? Spurious flag?
- An alternative is to base framing on external clock
  - Kind of like Phy-layer signaling: sample at specific intervals
  - This is what SONET does, among others
- Significant engineering tradeoffs
  - No extra bits needed in the data stream itself, but…
  - Need tight clock synchronization between sender and receiver

SONET

- Synchronous Optical NETwork
  - Engineering goal to reduce delay and buffering
- All frames take same amount of time
  - Independent of bit rate!
- Each frame starts with signal bits
  - Can synch clock just like PLL—look for periodic signal bits
  - No need to stuff; signal pattern is unlikely, so won't be periodic in data
- Keep sync within frames with transitions
  - Encoded using NRZ, but
  - Data is XORed with special 127-bit pattern
  - Creates lots of transitions, makes signal pattern unlikely

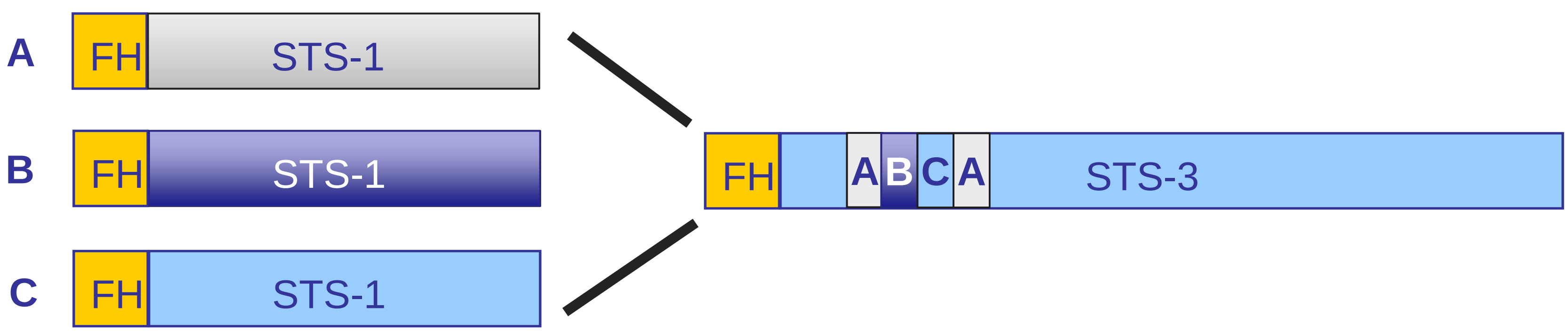
SONET Frame

- Every STS frame is 125 us long
- Supports multiple bit rates in same network
- STS-1 is base (slowest) speed: 51.84 Mbps
  - Frame contains 9 rows of 90 bytes each (810 bytes)
  - First 3 bytes of each row are header
    - » 2-byte sync pattern, one byte for “flags”

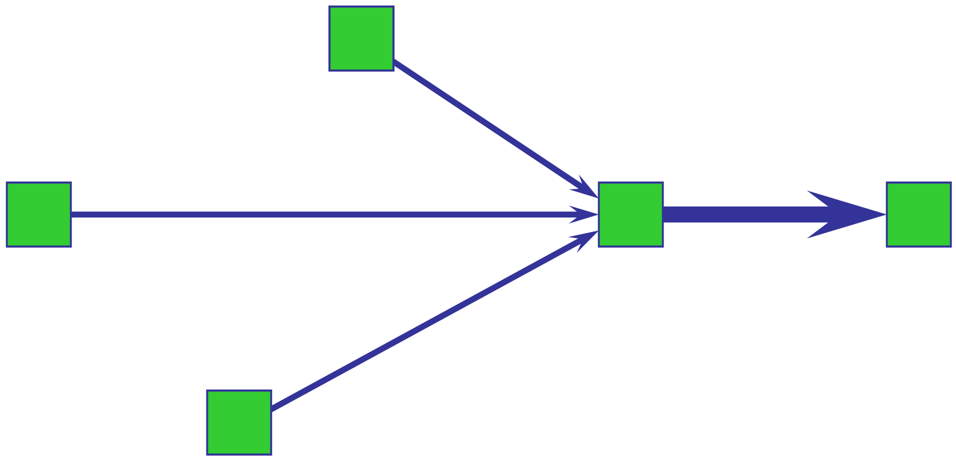


Multiplexed SONET Links

- SONET actually defines networking functionality
  - Conflates layers; we'll talk more in future lectures
  - Thinks about how to move frames between links
- Higher-speed links are multiples of STS-1 frames
  - E.g., STS-3 is three times as fast as STS-1
- Frames are byte-wise interleaved
  - Ensures pace of embedded STS-1 frames remains same

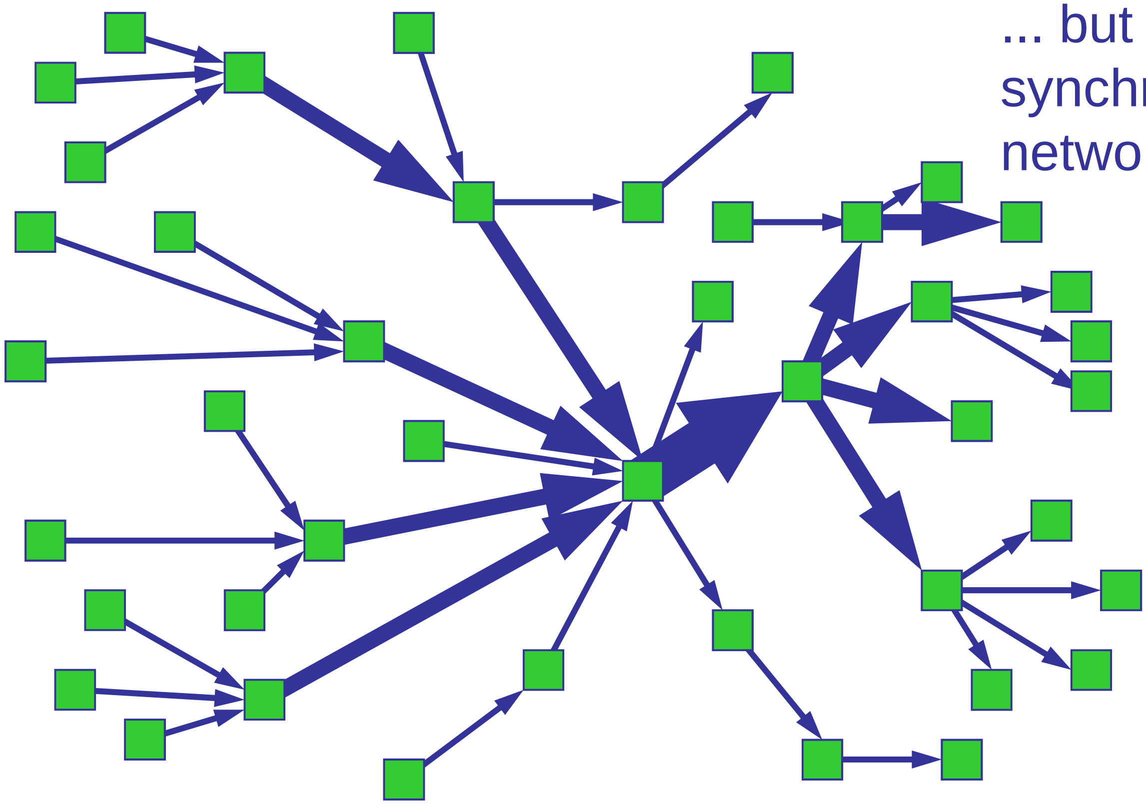


Synchronization…



Not too difficult to synchronize clocks such that first byte of all incoming flows arrives just before sending first 3 bytes of outgoing flow

Synchronization…



... but now try to synchronize this network's clocks

Framing: When Things Go Wrong

- May misinterpret frame boundaries
  - Length corrupted
  - Sentinel corrupted
  - Clock drift confuses frame boundaries

- Data in frame may be corrupted
  - Bit errors from noise, hardware failures, software errors

- In general, need to make sure we don’t accept bad data
  - Error detection (and perhaps correction)

Error Handling

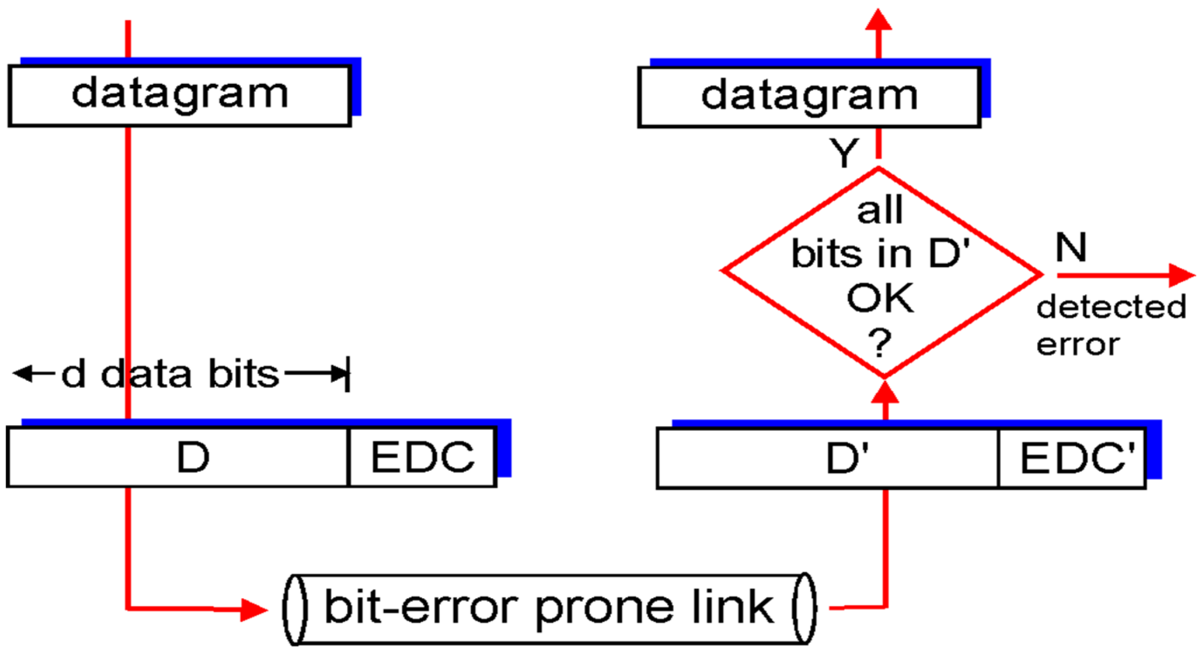
- Error handling through redundancy
  - Adding extra bits to the frame to check for errors

- Hamming Distance
  - When we can detect
  - When we can correct

- Simple schemes: parity, voting, 2d-parity
- Checksum
- Cyclic Remainder Check (CRC)

Error Detection

- Implemented at many layers (link-layer today)
  - D = Data, EDC = Error Detection Code (redundancy)



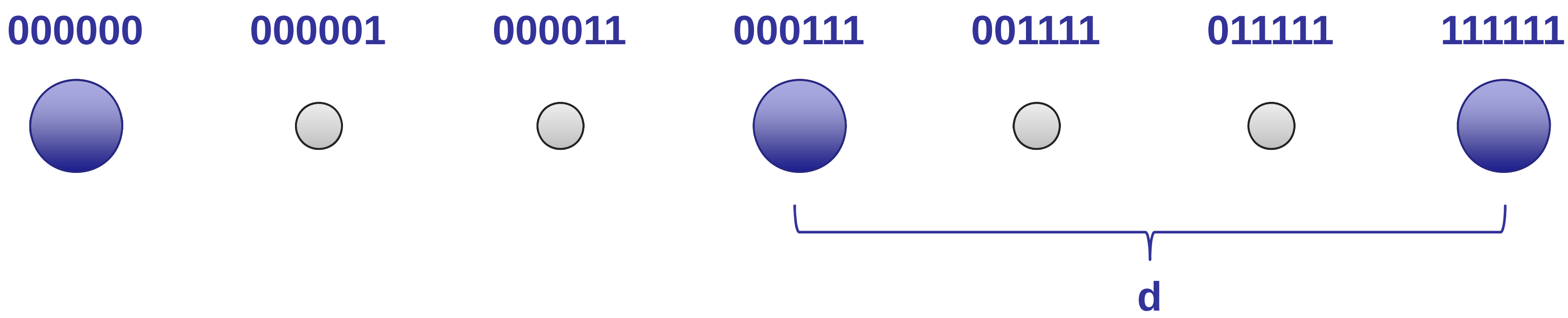
Basic Idea

- The problem is data itself is not self-verifying
  - Every string of bits is potentially legitimate
  - Hence, any errors/changes in a set of bits are equally legit
- The solution is to reduce the set of potential bitstrings
  - Not every string of bits is allowable
  - Receipt of a disallowed string of bits means the original bits were garbled in transit
- Key question: which bitstrings are allowed?

Codewords

- Let’s start simple, and consider fixed-length bitstrings
  - Reduce our discussion to *n*-bit substrings
  - E.g., 7-bits at a time, or 4 bits at a time (4B/5B)
  - Or even a frame at a time
- We call an allowable sequence of *n* bits a codeword
  - Not all strings of *n* bits are codewords!
  - The remaining *n*-bit strings are “space” between codewords
- We’re going to encode data in terms of codewords (just like 4B/5B)
  - Non-codewords indicate an error (just like 4B/5B)
- How many codewords with how much space between them?

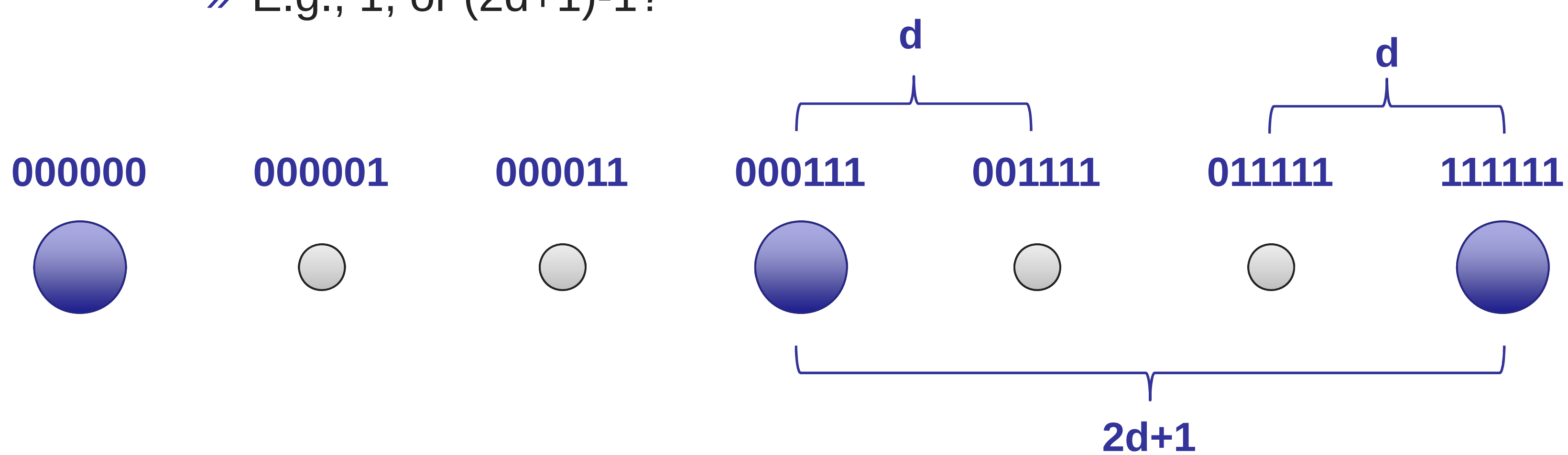
Hamming Distance



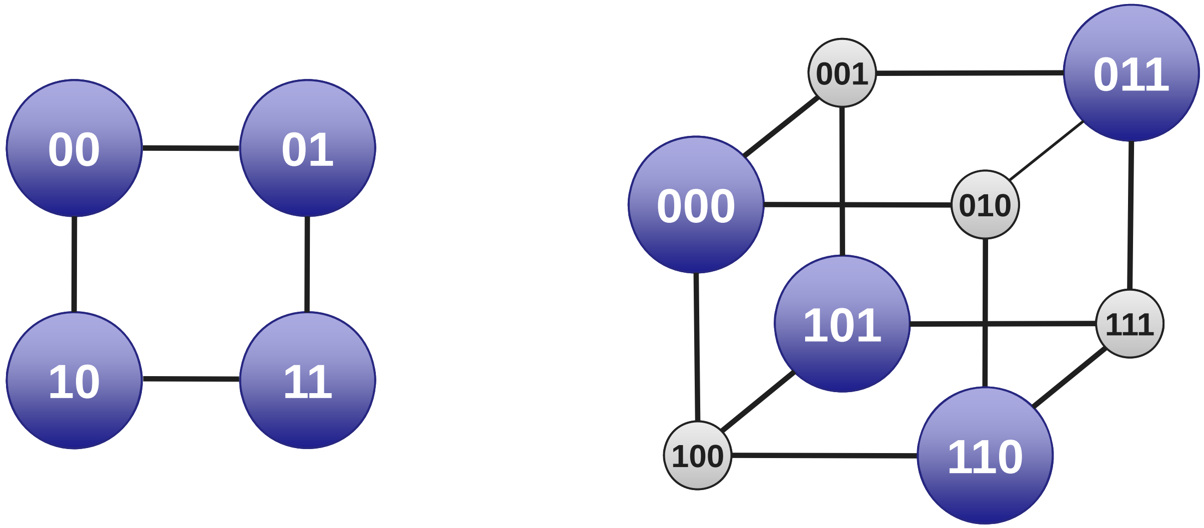
- Distance between legal codewords
  - Measured in terms of number of bit flips
- Efficient codes are of uniform Hamming Distance
  - All codewords are equidistant from their neighbors

2d+1 Hamming Distance

- Can detect up to *2d* bit flips
  - The next codeword is always *2d+1* bit flips away
  - Any fewer is guaranteed to land in the middle
- Can correct up to *d* bit flips
  - We just move to the closest codeword
  - Unfortunately, no way to tell how many bit flips
    - E.g., 1, or (2d+1)-1?

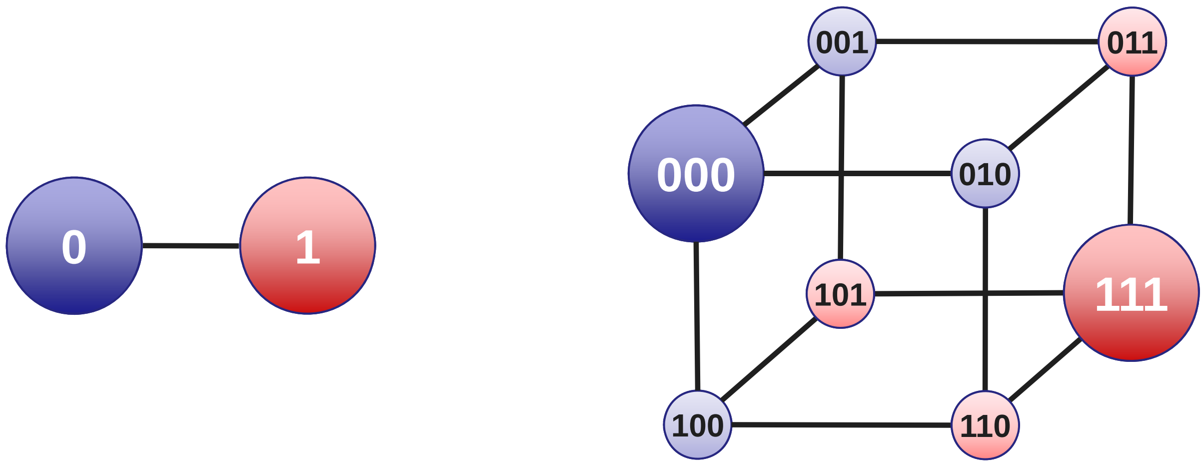


Simple Embedding: Parity



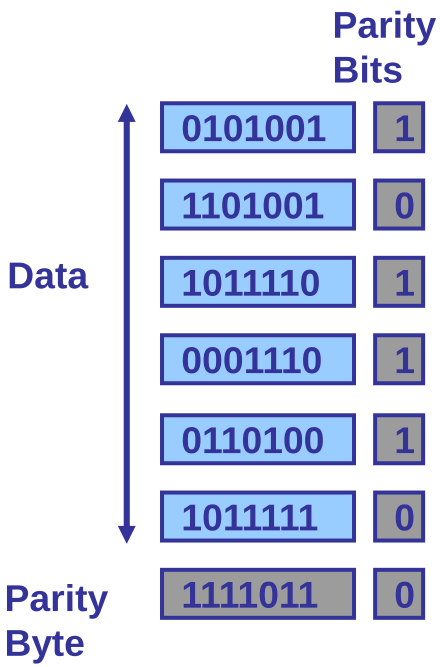
- Add extra bit to ensure odd(even) number of ones
  - Can **detect** any single bit flip (hamming distance 2)
  - Code is 66% efficient (need three bits to encode two)
    - Note: Even parity is simply XOR

Simple Correction: Voting



- Simply send each bit *n times* (3 in this example)
  - Majority voting
  - Can detect any 2 bit flips and correct any 1 flip (d=1)
- Straightforward duplication is extremely inefficient
  - We can be much smarter about this

Two-Dimensional Parity



- Start with normal parity
  - *n* data bits, 1 one parity bit
- Do the same across rows
  - *m* data bytes, 1 parity byte
- Can detect up to 3 bit errors
  - Even most 4-bit errors
- Can correct any 1 bit error
  - Why?

Per-Frame
Error Detection Codes

- Want to add an error detection code per frame
  - Frame is unit of transmission; all or nothing.
  - Computed over the entire frame—including header! Why?
- Receiver *recomputes* EDC over frame and checks against received EDC value
  - If frame fails check, throw it away
- We *could* use error-correcting codes
  - But they are less efficient, and *we expect errors to be rare*

Checksums

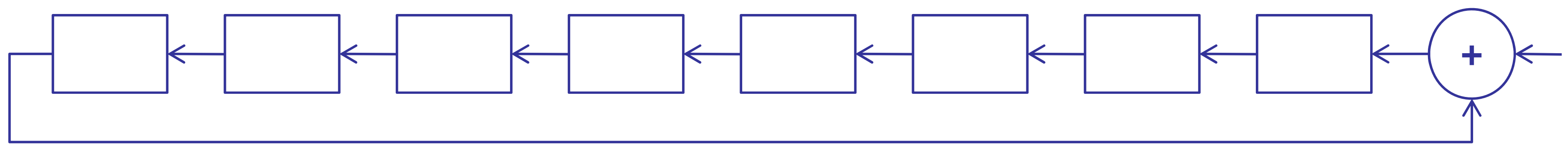
- Simply sum up all of the data in the frame
  - Transmit that sum as the EDC
- Extremely lightweight
  - Easy to compute fast in hardware
  - Fragile: Hamming Distance of 2
- Also easy to modify if frame is modified in flight
  - Happens a lot to packets on the Internet
- IP packets include a 1’s compliment checksum

IP Checksum Example

- 1's compliment of sum of *words* (not bytes)
  - Final 1's compliment means all-zero frame is not valid

```
u_short cksum(u_short *buf, int count) {
   register u_long sum = 0;
   while (count--) {
        sum += *buf++;
        if (sum & 0xFFFF0000) {
        /* carry occurred, so wrap around */
                sum &= 0xFFFF;
                sum++;
        }
   }
   return ~(sum & 0xFFFF);
}
```

Checksum in Hardware

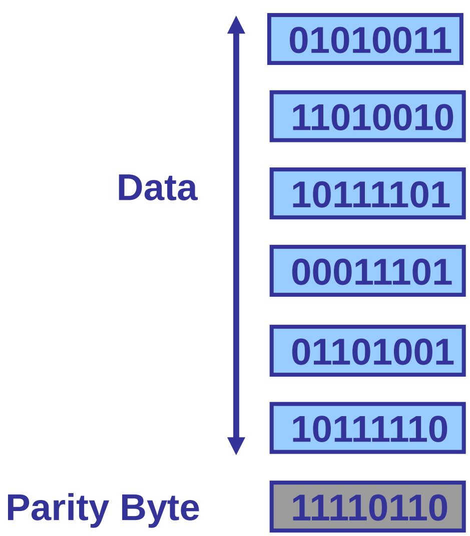


- Compute checksum in Modulo-2 Arithmetic
  - Addition/subtraction is simply XOR operation
  - Equivalent to vertical parity computation

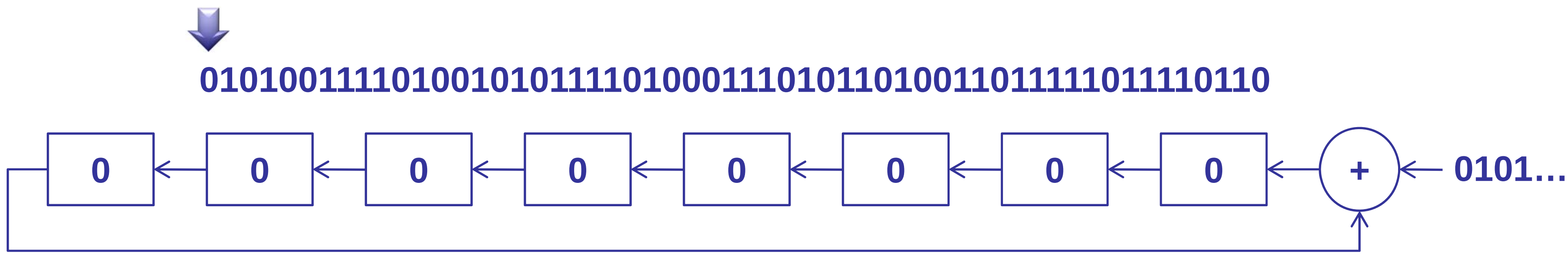
- Need only a word-length shift register and XOR gate
  - Assuming data arrives serially
  - All registers are initially 0

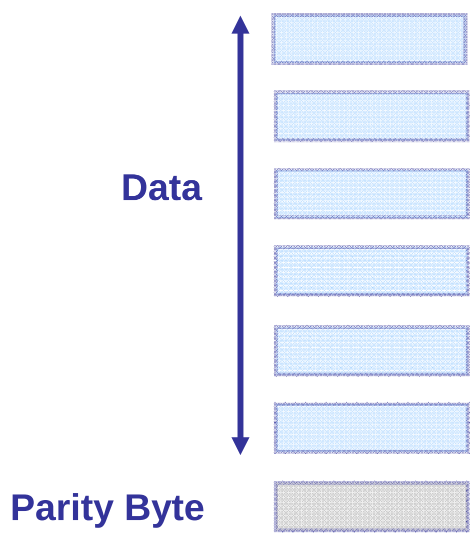
Checksum Example

01010011110100101011110100011101011010011011111011110110

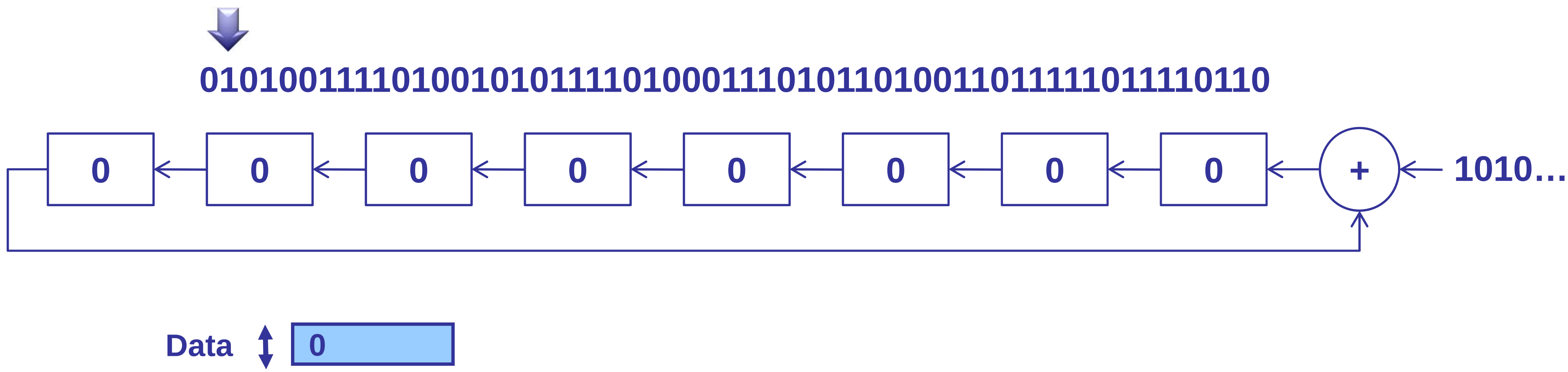


Checksum Example

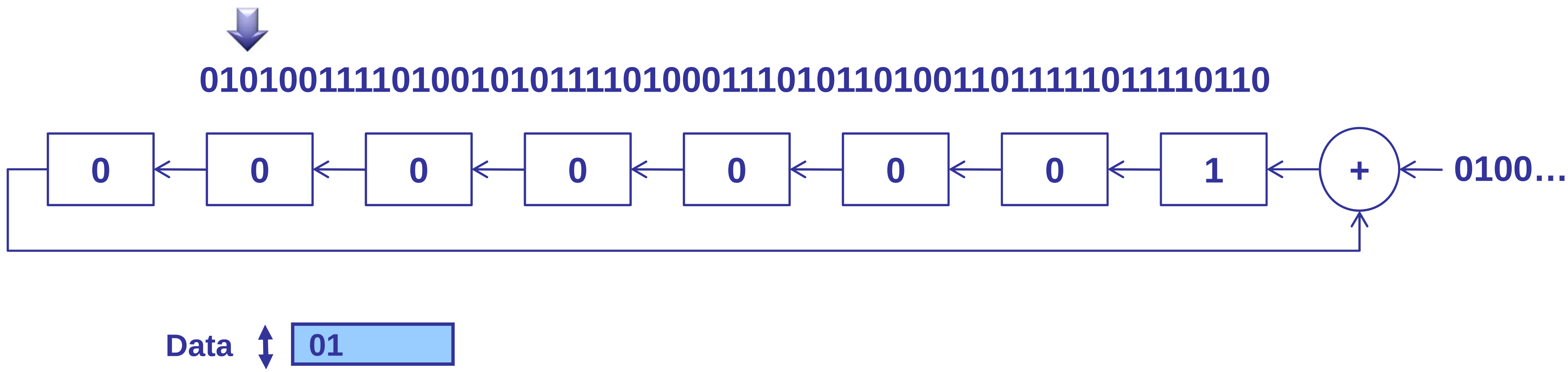




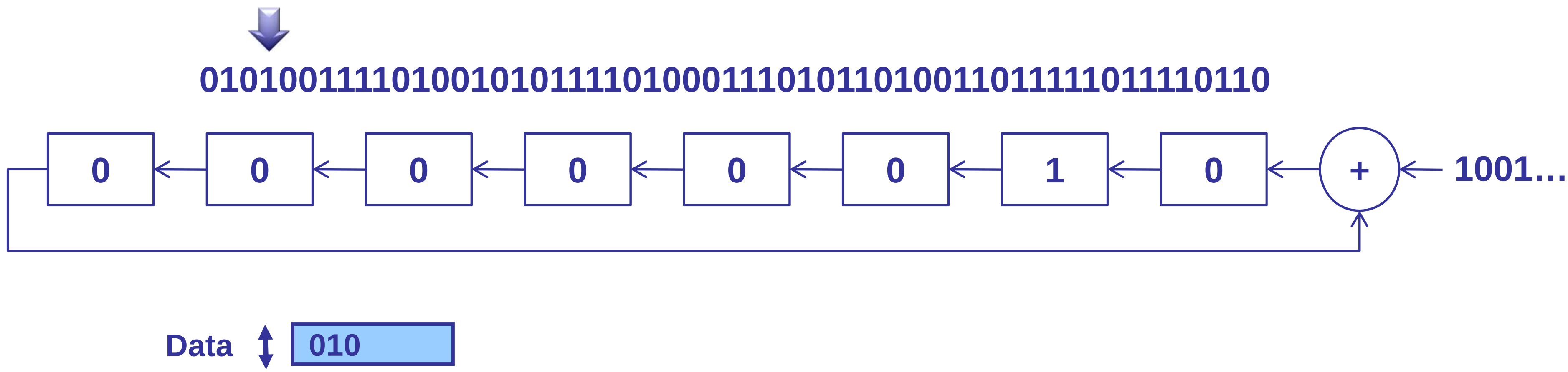
Checksum Example



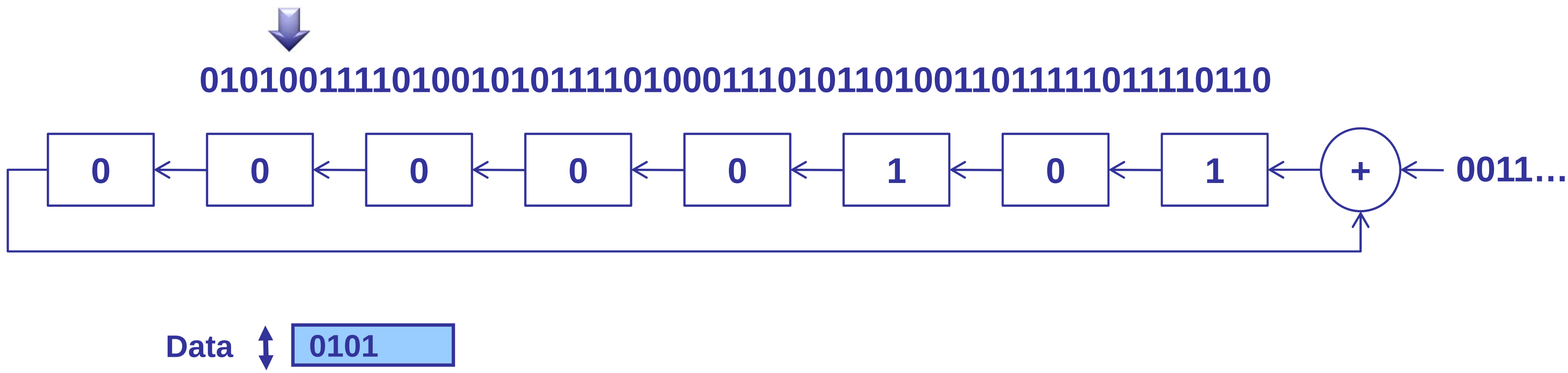
Checksum Example



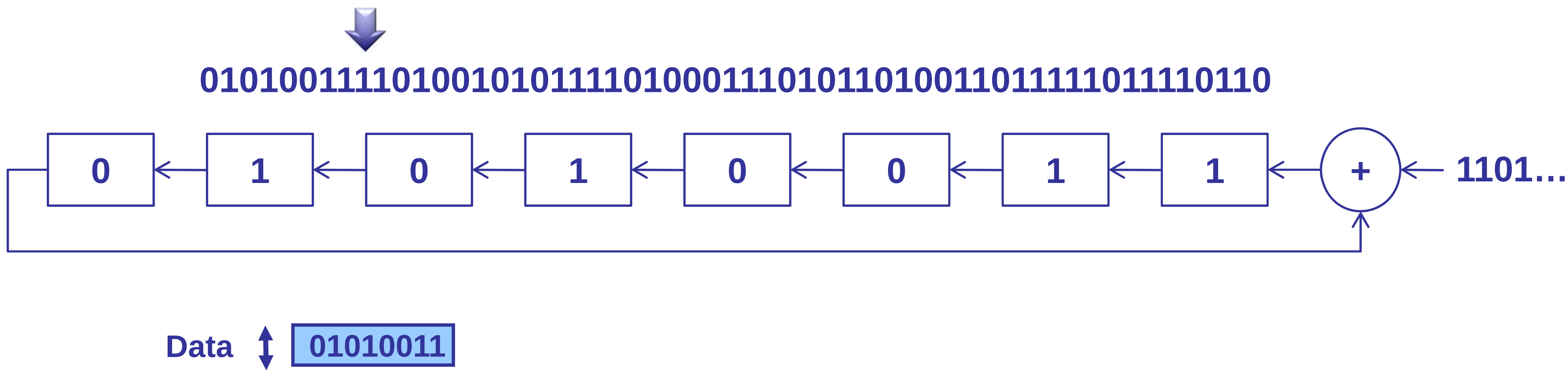
Checksum Example



Checksum Example

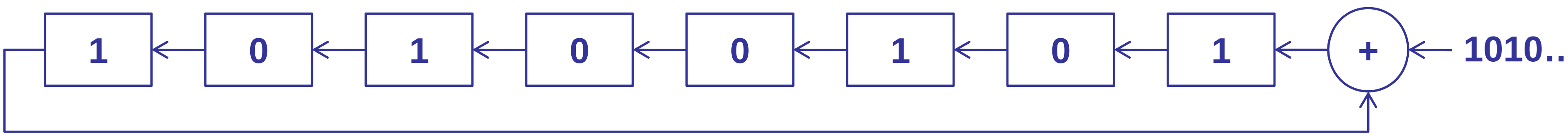


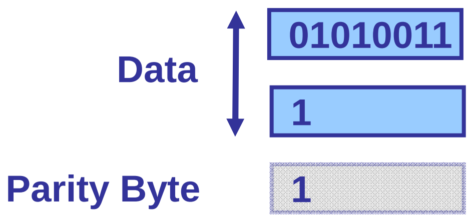
Checksum Example



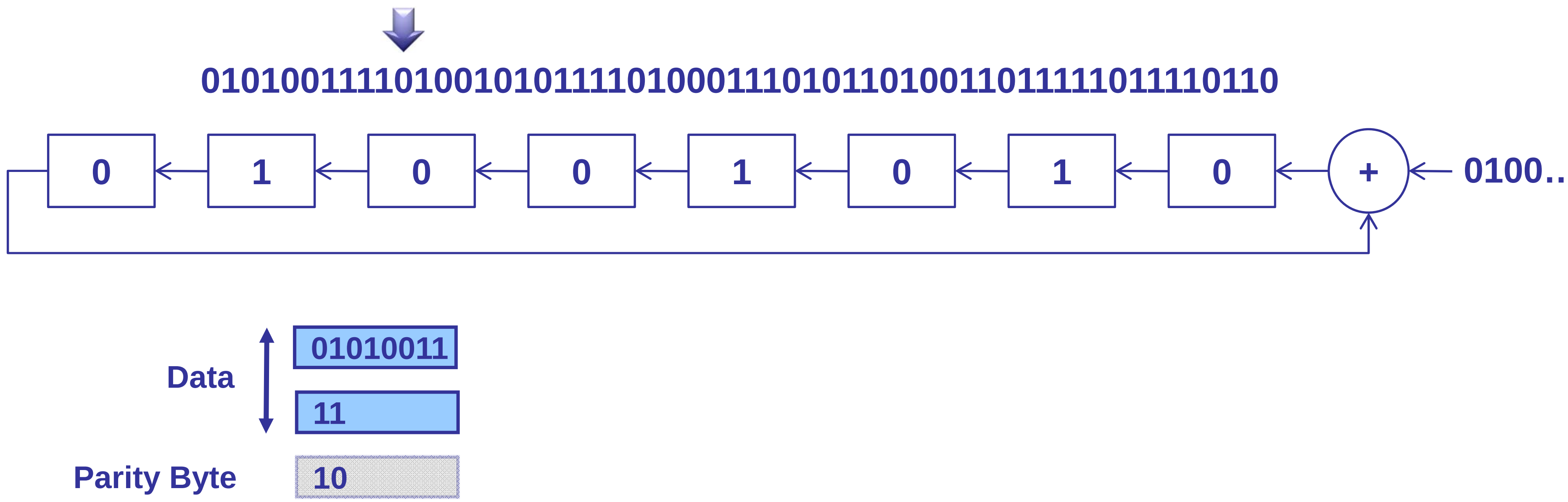
Checksum Example

0101001111010010101111010001110101101001101111011110110

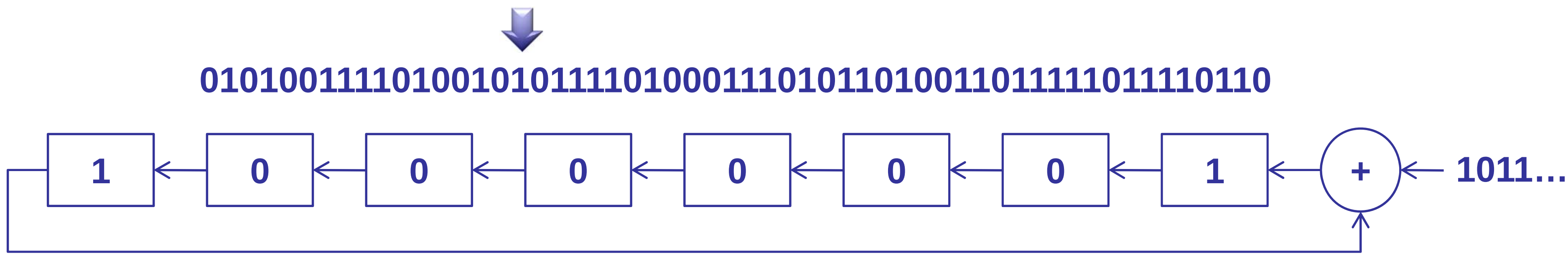




Checksum Example

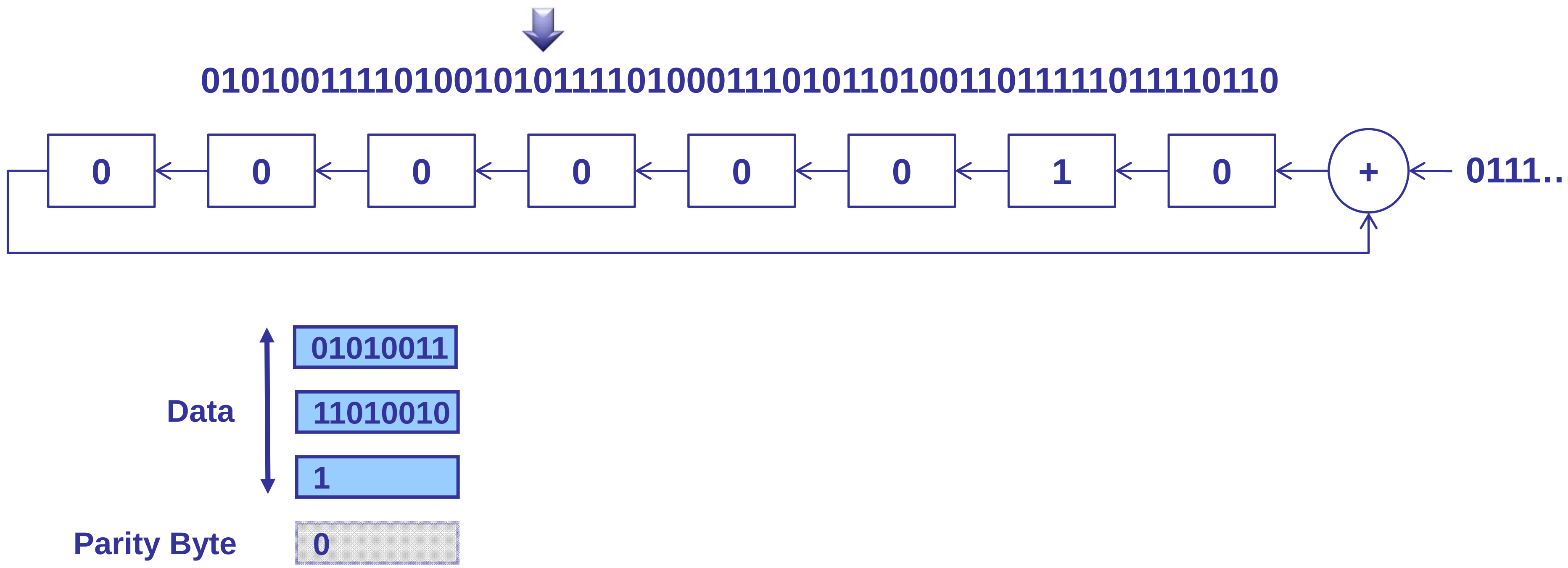


Checksum Example

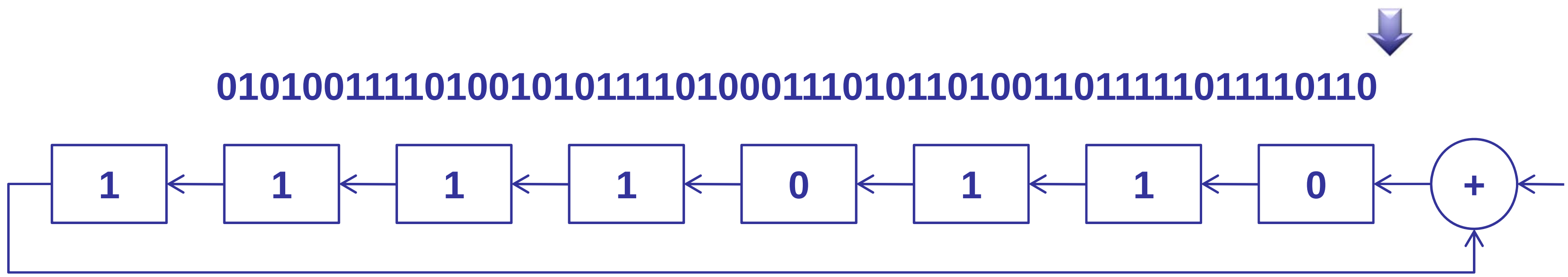


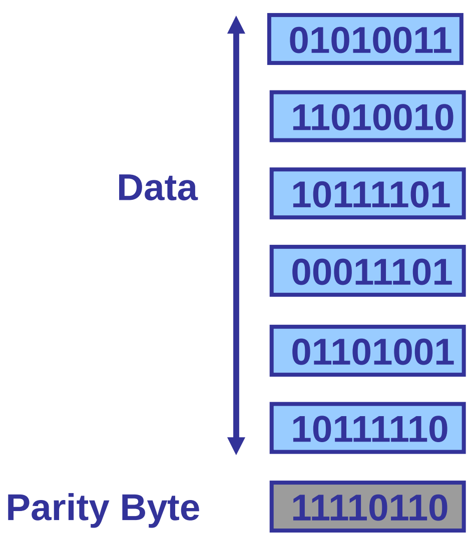
Data		01010011
		11010010
Parity Byte		10000001

Checksum Example



Checksum Example





From Sums to Remainders

- Checksums are easy to compute, but very fragile
  - In particular, burst errors are frequently undetected (yet common)
  - We'd rather have a scheme that "smears" parity
- Need to remain easy to implement in hardware
  - So far just shift registers and an XOR gate
- We'll stick to Modulo-2 arithmetic
  - Multiplication and division are XOR-based as well

Cyclic Remainder Check (CRC)

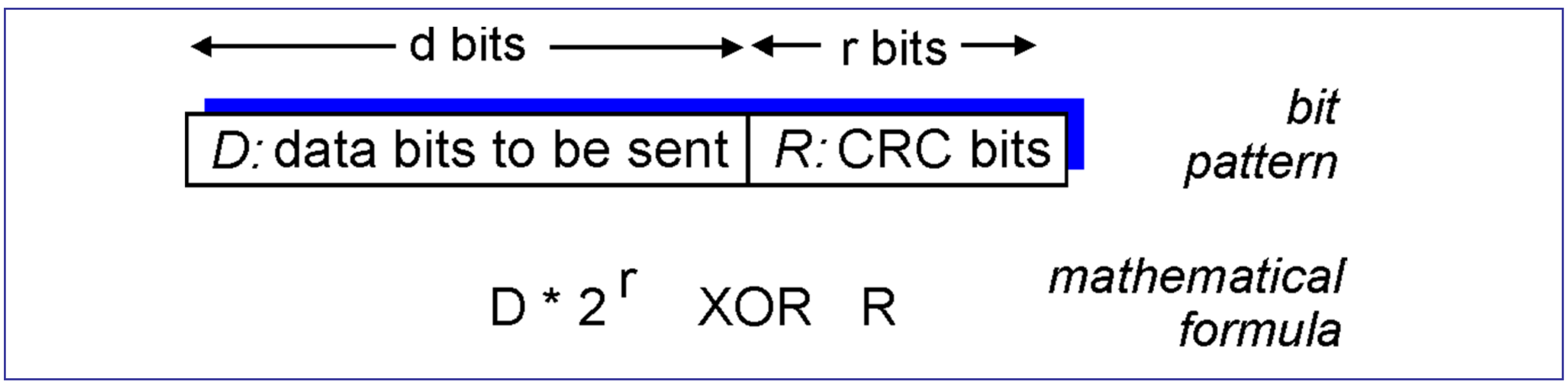
- Also called Cyclic Redundancy Check
- Polynomial code
  - Treat packet bits as coefficients of n-bit polynomial
    - Message = 10011010
    - Generator polynomial

      $= 1 * x^7 + 0 * x^6 + 0 * x^5 + 1 * x^4 + 1 * x^3 + 0 * x^2 + 1 * x + 0$

      $= x^7 + x^4 + x^3 + x$
  - Choose r+1 bit generator polynomial
    (well known – chosen in advance… handles burst errors of size r)
  - Add r bits to packet such that message is divisible by generator polynomial (these bits are the EDC)
  - Note: easy way to think of polynomial arithmetic mod 2
    - Multiplication: binary addition without carries
    - Division: binary subtraction without carries
- Better loss detection properties than checksums

Error Detection – CRC

- View data bits, D, as a binary number
- Choose r+1 bit pattern (generator), G
- Goal: choose r CRC bits, R, such that
  - <D,R> exactly divisible by G (modulo 2)
  - Receiver knows G, divides <D,R> by G. If non-zero remainder: error detected!
  - Can detect all burst errors less than r+1 bits
- Widely used in practice (Ethernet, FDDI, ATM)



Common Generator Polynomials

CRC-8	$x^8 + x^2 + x^1 + 1$
CRC-10	$x^{10} + x^9 + x^5 + x^4 + x^1 + 1$
CRC-12	$x^{12} + x^{11} + x^3 + x^2 + x^1 + 1$
CRC-16	$x^{16} + x^{15} + x^2 + 1$
CRC-CCITT	$x^{16} + x^{12} + x^5 + 1$
CRC-32	$x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x^1 + 1$

CRC Example Encoding

$x^3 + x^2 + 1$ = 1101 Generator

$x^7 + x^4 + x^3 + x$ = 10011010 Message

```
1101 | 10011010000
       1101
       ----
        1001
        1101
        ----
         1000
         1101
         ----
          1011
          1101
          ----
           1100
           1101
           ----
            1000
            1101
            ----
             101
```

Message plus r zeros (*2^k)

r + *1* bit check sequence *g*, equivalent to a degree-r polynomial

Remainder

D mod *g*

Result:

Transmit message followed by remainder:

10011010101

CRC Example Decoding

$x^3 + x^2 + 1$	= 1101	**Generator**
$x^{10} + x^7 + x^6 + x^4 + x^2 + 1$	= 10011010101	**Received Message**

```
1101 | 10011010101
       1101
       ----
        1001
        1101
        ----
         1000
         1101
         ----
          1011
          1101
          ----
           1100
           1101
           ----
            1101
            1101
            ----
               0
```

Received message, no errors

r + 1 **bit check sequence** ***g*****, equivalent to a degree-r polynomial**

Remainder

D **mod** ***g***

Result:

CRC test is passed

CRC Example Failure

$x^3 + x^2 + 1$	= 1101	Generator
$x^{10} + x^7 + x^5 + x^4 + x^2 + 1$	= 10010110101	Received Message

```
1101 | 10010110101
       1101
       ----
        1000
        1101
        ----
         1011
         1101
         ----
          1101
          1101
          ----
           0101
```

Received message

Two bit errors

r + 1 bit check sequence *g*, equivalent to a degree-r polynomial

Remainder

D mod *g*

Result:

CRC test failed

Summary

- Data Link Layer provides four basic services
  - Framing, multiplexing, error handling, and MAC
- Framing determines when payload starts/stops
  - Lots of different ways to do it, various efficiencies
    - Sentinels: increase size of packet, allow variable length frames
      - Stuffing
    - Clock-based
- Error detection
  - Add redundant bits to detect error
  - Strength of code depends on Hamming distance
  - Checksums & CRCs commonly used
    - CRC's stronger, but somewhat more computational complexity

For Next Class

- Reliable transmission
  - Read 2.5 in P&D
- Geoff Voelker will be lecturing

- Reminder:
  Homework #1 due at the beginning of class