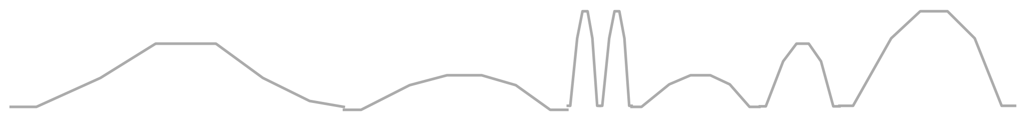
15-441 Computer Networking

Lecture 4 - Coding and Error Control

From Signals to Frames

Analog Signal



“Digital” Signal

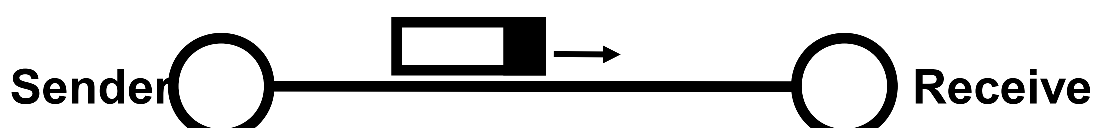
Bit Stream **0 0 1 0 1 1 1 0 0 0 1**

Packets

0100010101011100101010101011101110000001111010101110101010101101011010111001

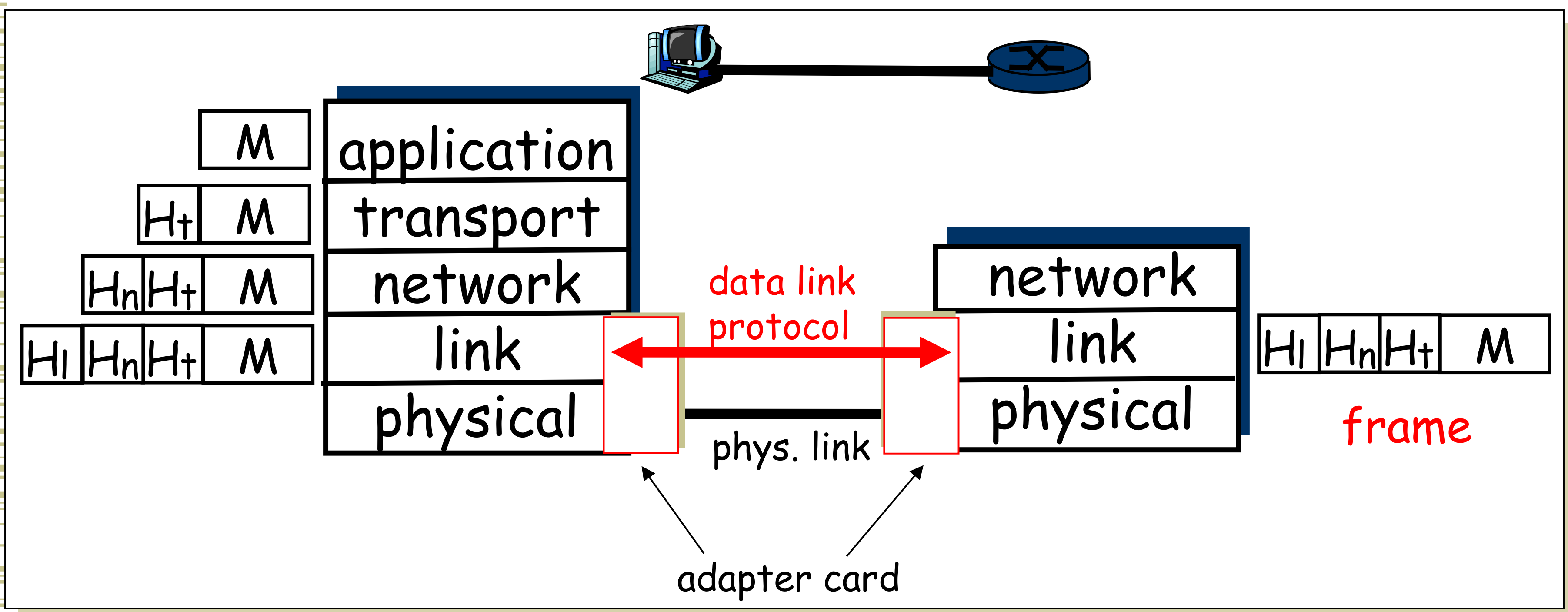
Header/Body **Header/Body** **Header/Body**

Packet Transmission



Link Layer: Implementation

- Implemented in "adapter"
  - E.g., PCMCIA card, Ethernet card
  - Typically includes: RAM, DSP chips, host bus interface, and link interface



Datalink Functions

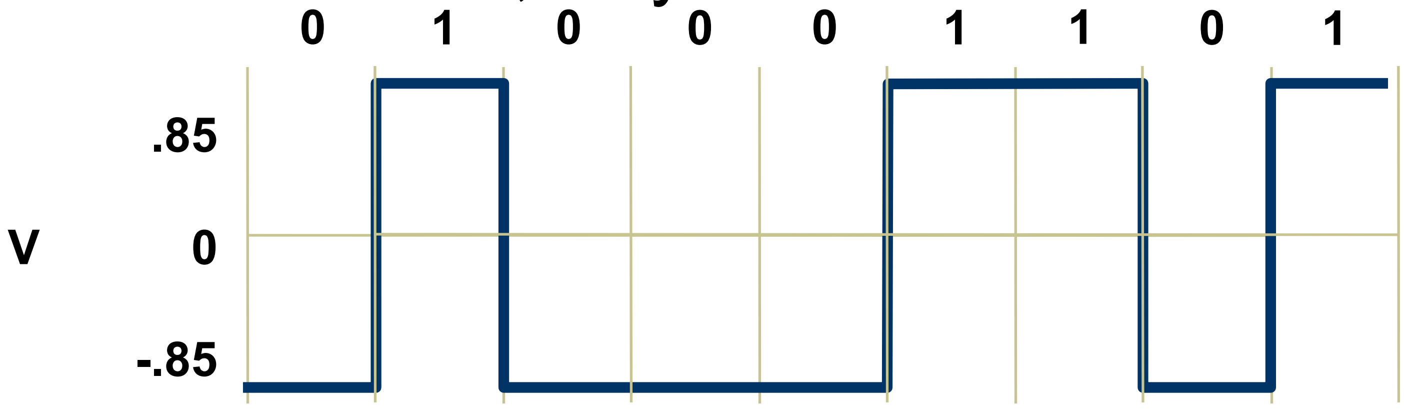
- Framing: encapsulating a network layer datagram into a bit stream.
  - Add header, mark and detect frame boundaries
- Media access: controlling which frame should be sent over the link next.
- Error control: error detection and correction to deal with bit errors.
  - May also include other reliability support, e.g. retransmission
- Flow control: avoid that the sender outruns the receiver
- Hubbing, bridging: extend the size of the network

Outline

- Encoding
  - Digital signal to bits
- Framing
  - Bit stream to packets
- Packet loss & corruption
  - Error detection
  - Flow control
  - Loss recovery

How Encode?

- Seems obvious, why take time with this?



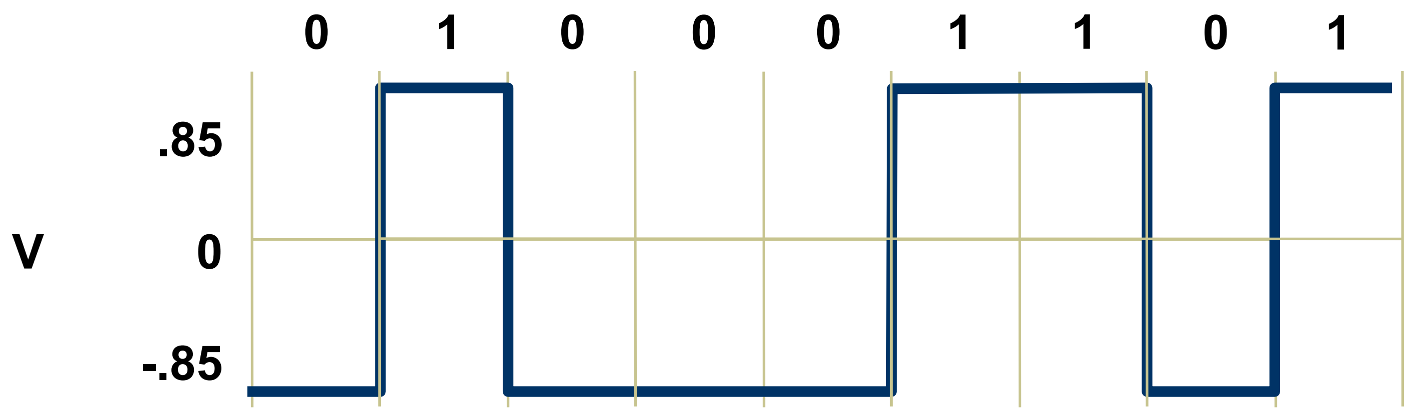
Why Encode?

0 1 0 1 How many more ones?

Why Do We Need Encoding?

- Keep receiver synchronized with sender.
- Create control symbols, in addition to regular data symbols.
  - E.g. start or end of frame, escape, ...
- Error detection or error corrections.
  - Some codes are illegal so receiver can detect certain classes of errors
  - Minor errors can be corrected by having multiple adjacent signals mapped to the same data symbol
- Encoding can be done one bit at a time or in multi-bit blocks, e.g., 4 or 8 bits.
- Encoding can be very complex, e.g. wireless.

Non-Return to Zero (NRZ)

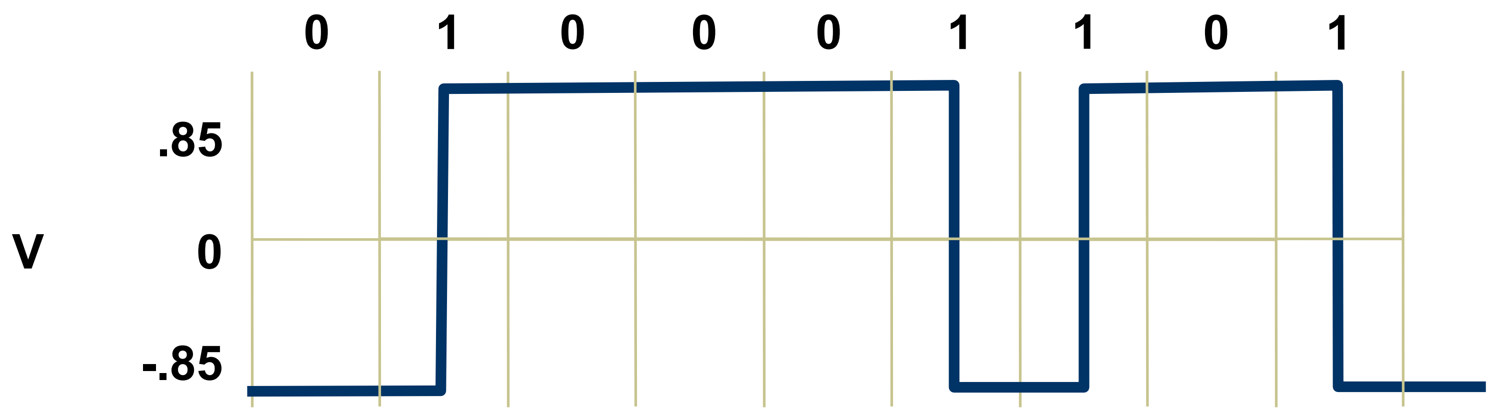


- 1 → high signal; 0 → low signal
- Used by Synchronous Optical Network (SONET)
- Long sequences of 1's or 0's can cause problems:
  - Sensitive to clock skew, i.e. hard to recover clock
  - DC bias hard to detect – low and high detected by difference from average voltage

Clock Recovery

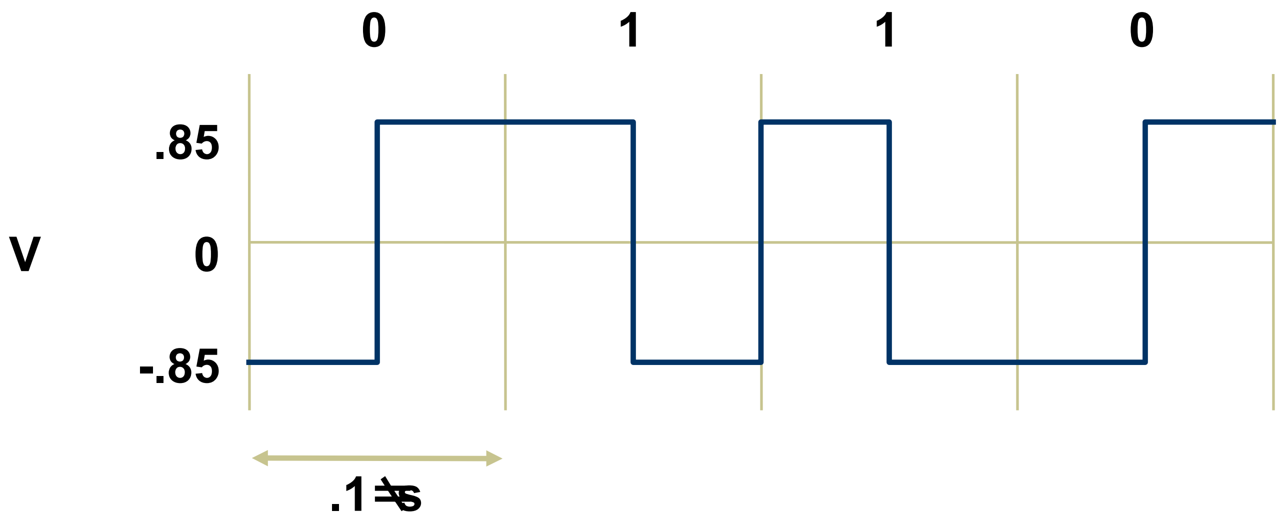
- When to sample voltage?
- Synchronized sender and receiver clocks
- Need easily detectible event at both ends
  - Signal transitions help resync sender and receiver
  - Need frequent transitions to prevent clock skew
  - SONET XOR's bit sequence to ensure frequent transitions

Non-Return to Zero Inverted (NRZI)



- 1 → make transition; 0 → signal stays the same
- Solves the problem for long sequences of 1's, but not for 0's.

Manchester Encoding



- Used by Ethernet
- 0=low to high transition, 1=high to low transition
- Transition for every bit simplifies clock recovery
- DC balance has good electrical properties
- Not very efficient
  - Doubles the number of transitions
  - Circuitry must run twice as fast

4B/5B Encoding

- Data coded as symbols of 5 line bits → 4 data bits, so 100 Mbps uses 125 MHz.
  - Uses less frequency space than Manchester encoding
- Encoding ensures no more than 3 consecutive 0's
- Uses NRZI to encode resulting sequence
- 16 data symbols, 8 control symbols
  - Data symbols: 4 data bits
  - Control symbols: idle, begin frame, etc.
- Example: FDDI.

4B/5B Encoding

Data	Code
0000	11110
0001	01001
0010	10100
0011	10101
0100	01010
0101	01011
0110	01110
0111	01111

Data	Code
1000	10010
1001	10011
1010	10110
1011	10111
1100	11010
1101	11011
1110	11100
1111	11101

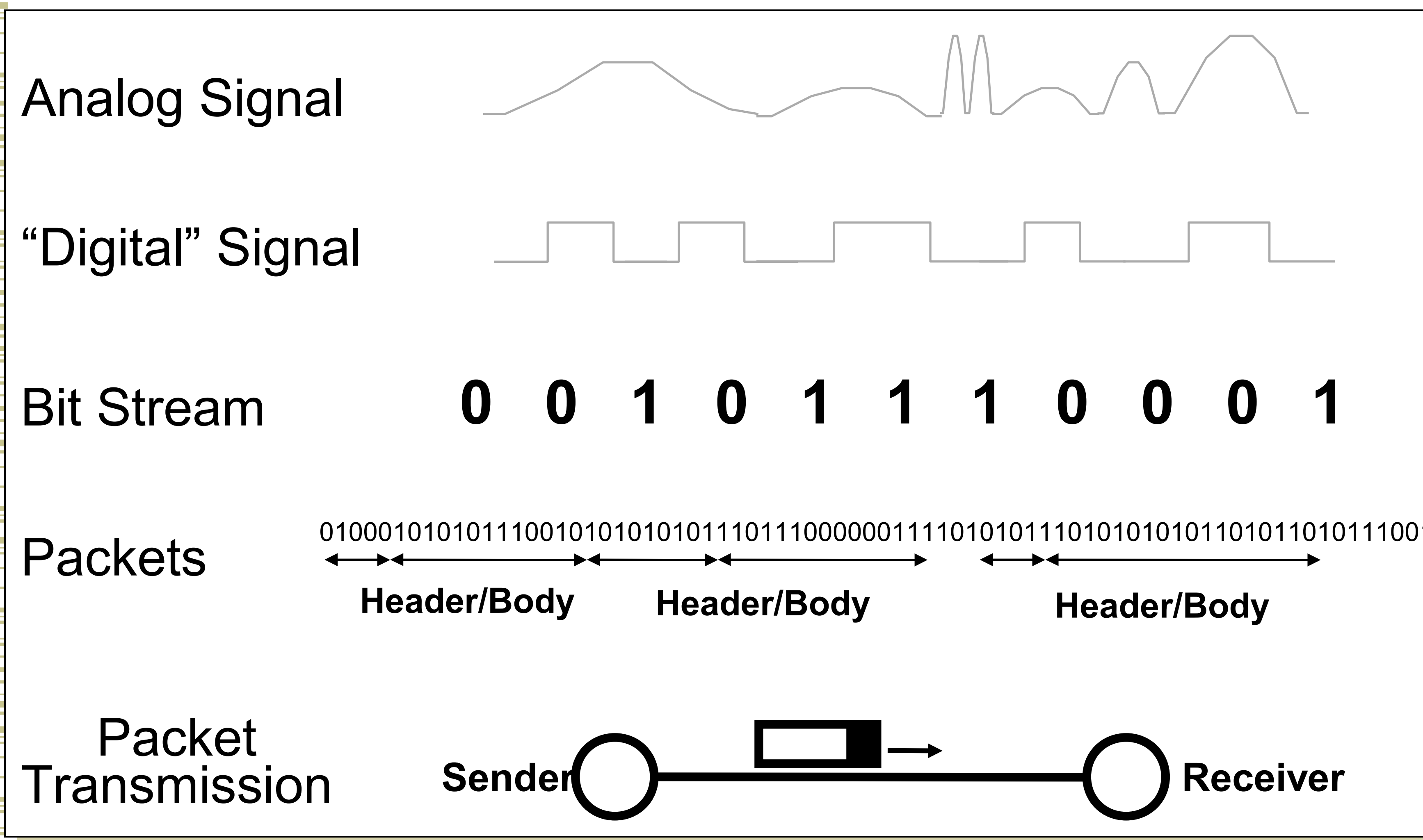
Other Encodings

- 8B/10B: Fiber Channel and Gigabit Ethernet
- 64B/66B: 10 Gbit Ethernet
- B8ZS: T1 signaling (bit stuffing)

Things to Remember

- Encoding necessary for clocking
- Lots of approaches
- Rule of thumb:
  - Little bandwidth → complex encoding
  - Lots of bandwidth → simple encoding

From Signals to Packets



Outline

- Encoding
  - Digital signal to bits
- Framing
  - Bit stream to packets
- Packet loss & corruption
  - Error detection
  - Flow control
  - Loss recovery

Framing

- How do we differentiate the stream of bits into frames?

010001010101110010101010101110111000000111101010111010101010101101010101101011100
1

Framing

- A link layer function, defining which bits have which function.
- Minimal functionality: mark the beginning and end of packets (or frames).
- Some techniques:
  - out of band delimiters (e.g. FDDI 4B/5B control symbols)
  - frame delimiter characters with character stuffing
  - frame delimiter codes with bit stuffing
  - synchronous transmission (e.g. SONET)

Out-of-band: E.g., 802.5

- 802.5/token ring uses 4b/5b
- Start delim & end delim are “illegal” codes

Start delim	Access ctrl	Frame ctrl	Dest adr	Src adr	Body	checksum	End delim	Frame status

Delimiter Based

- SYN: sync character
- SOH: start of header
- STX: start of text
- ETX: end of text

- What happens when ETX is in Body?

Character and Bit Stuffing

- Mark frames with special character.
  - What happens when the user sends this character?
  - Use escape character when controls appear in data:
  - *abc*def → *abc*def
  - Very common on serial lines, in editors, etc.
- Mark frames with special bit sequence
  - must ensure data containing this sequence can be transmitted
  - example: suppose 11111111 is a special sequence.
  - transmitter inserts a 0 when this appears in the data:
  - 11111111 → 111111101
  - must stuff a zero any time seven 1s appear:
  - 11111110 → 111111100
  - receiver unstuffs.

Ethernet Framing

- Preamble is 7 bytes of 10101010 (5 MHz square wave) followed by one byte of 10101011
- Allows receivers to recognize start of transmission after idle channel

Clock-Based Framing

- Used by SONET
- Fixed size frames (810 bytes)
- Look for start of frame marker that appears every 810 bytes
- Will eventually sync up

How avoid clock skew?

- Special bit sequences sent in first two chars of frame
  - But no bit stuffing. Hmmm?
- Lots of transitions by xoring with special pattern (and hope for the best)

Outline

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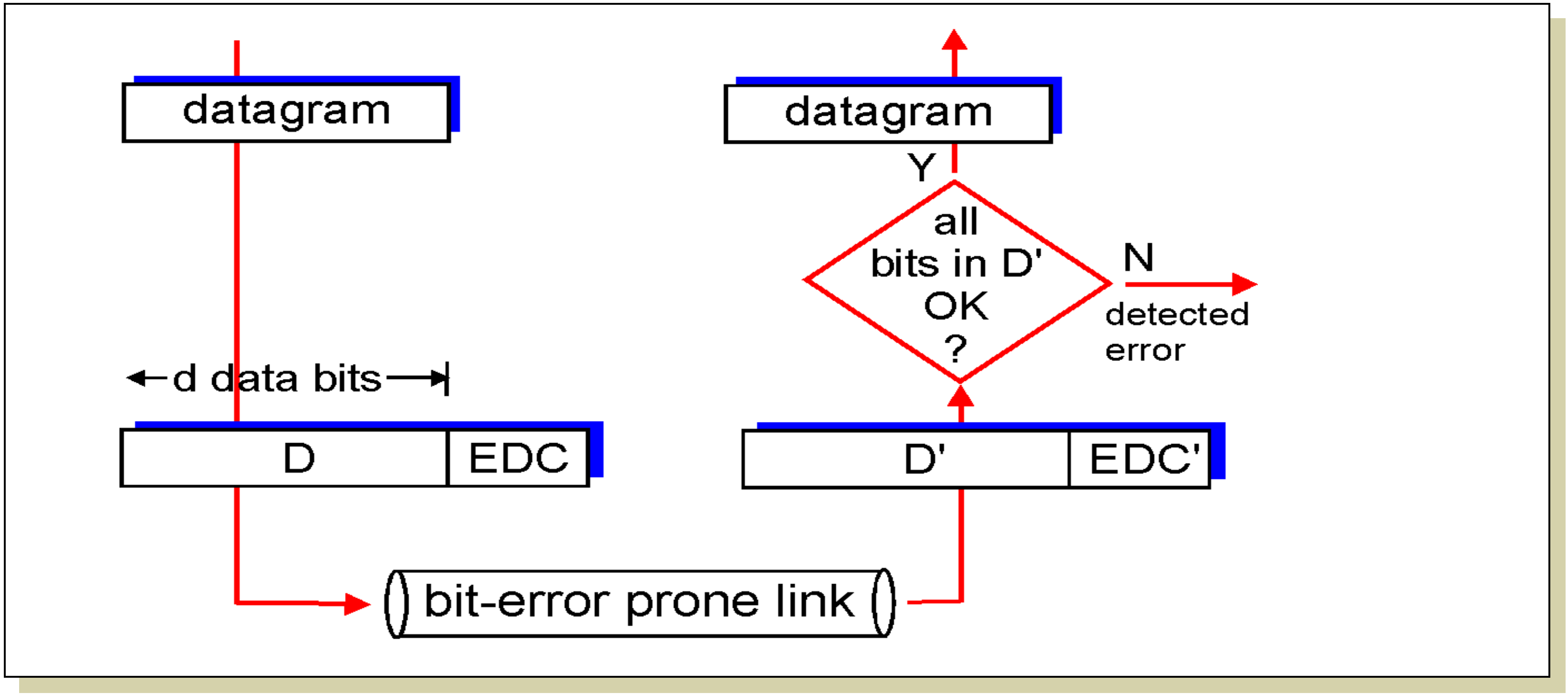
Error Coding

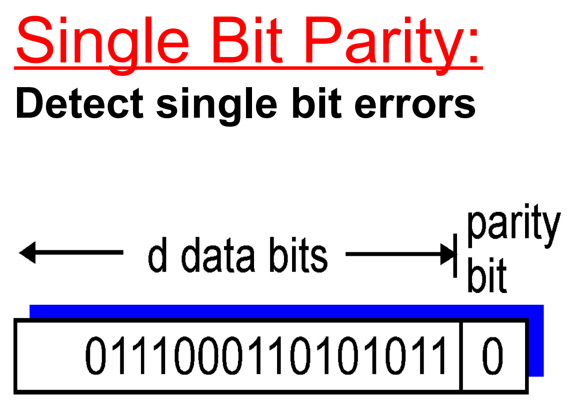
- Transmission process may introduce errors into a message.
  - Single bit errors versus burst errors
- Detection:
  - Requires a convention that some messages are invalid
  - Hence requires extra bits
  - An (n,k) code has codewords of n bits with k data bits and r = (n-k) redundant check bits
- Correction
  - Forward error correction: many related code words map to the same data word
  - Detect errors and retry transmission

Error Detection

- EDC= Error Detection and Correction bits (redundancy)
- D = Data protected by error checking, may include header fields
- Error detection not 100% reliable!
  - Protocol may miss some errors, but rarely
  - Larger EDC field yields better detection and correction



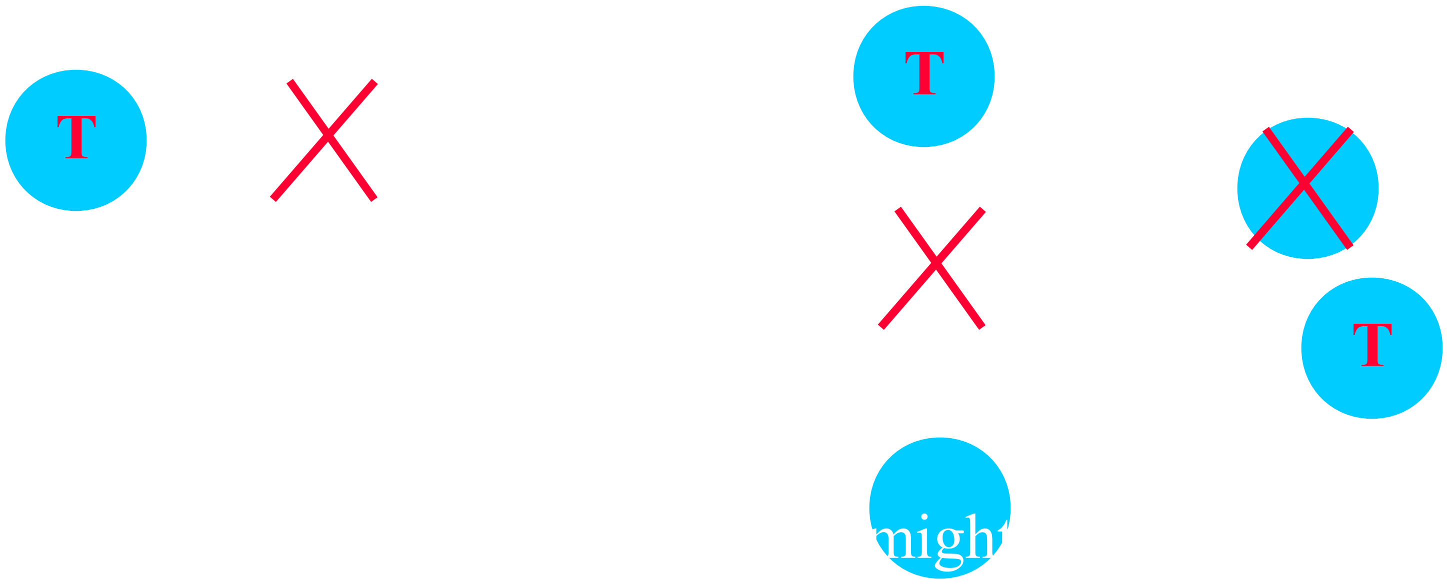
Parity Checking



Close Enough?

- Consider the following code:
  - 0 = jump
  - 1 = run
  - If 1 bit is in error, the message will be incorrect – and misleading
- Now, consider the following code:
  - 00 = jump
  - 11 = run
  - Now, if only 1 bit is in error, the message won't make sense, but we know that there is an error.
- Okay, one more code:
  - 000 = jump
  - 111 = run
  - Now, if only 1 bit is in error, we can figure out which one it should be. If 2 bits are in error, we know that the codeword is defective, but don't know which bits are wrong.

Thinking about Error Detection and Correction



Hamming Distance

- The *Hamming Distance* between two codewords is the number of bits that one would need to change to convert one into the other.
- The (minimum) Hamming distance of a code is the minimum Hamming Distance between any pair of codewords within the code.
- Hamming distance is important, because it gives us a way of determining how much error detection and how much error correction is possible for a given code.

Hamming Distance and EC/ED

- Like the example on the previous slide, Hamming distance measures how far two things (codewords) are apart.
- Remember that Hamming Distance measures the distance between two codewords by the number of bits that would need to change to convert one into another.
- This is a useful measure, because as long as the number of bits in error is less than the Hamming Distance, the error will be detected -- the codeword will be invalid.
- Similarly, if the Hamming distance between the codewords is more than double the number of bits in the error, the defective codeword will be closer to the correct one than to any other.

How Many Check Bits?

- If we have a dense code with m message bits, we will need to add some r check bits to the message to put distance between the code words
- The total number of bits in the codeword

  $n = m + r$
- If we do this, each codeword will have n illegal codewords within 1 bit. (Flip each bit).
- To be able to correct an error, we need 1 more bit than this, (n + 1) bits to make sure that 1-bit errors will fall closer to one codeword than any other.

Hamming's Code

- Label the bits of the codeword from left-to-right, from 1 through n.
- Check bits are stored in power of two bit positions.
- Data bits are stored in other positions
- Each parity bit is used to force the sum of itself and the bits that it checks to an even number (or odd)
- Each bit is checked by one or more parity bits. Specifically, let's consider a bit index i. If we rewrite in terms of powers of 2, it is checked by those powers of two that contribute to the addition
- For example, 7 = 4 + 2 + 1 so bit 7 contributes to parity bits 4, 2, and 1

Hamming's Code (Example)

- a = _ _ 1 _ 1 0 0 _ 0 0 1
  1 2 3 4 5 6 7 8 9 10 11

- 1 checks 3, 5, 7, 9, 11
  1 + 1 + 0 + 0 + 1= 3; set parity bit on to force even parity

- 2 checks 6, 7, 10, 11
  0 + 0 + 0 + 1= 1; set parity bit on to force even parity

- 4 checks 5, 6, 7
  1 + 0 + 0 = 1; set parity bit on to force even parity

- 8 checks 9, 10, 11
  0 + 0 + 1= 1; set parity bit on to force even parity

- a = 1 1 1 1 1 0 0 1 0 0 1
  1 2 3 4 5 6 7 8 9 10 1

Hamming's Code (Ex.), cont.

- 1 checks 3, 5, 7, 9, 11

  1 + 1 + 1 + 0 + 1 = 4; parity should be 0, but it is 1. Count = 1

- 2 checks 6, 7, 10, 11

  0 + 1 + 0 + 1 = 2; parity bit should be 0, but isn't. Count +=2, so count is 3

- 4 checks 5, 6, 7

  1 + 0 + 1 = 2; parity bit should be 0, but isn't. Count += 4, so count=7

- 8 checks 9, 10, 11

  0 + 0 + 1= 1; parity bit should be 1 and is. Don't change count. Count is still 7

- So, if only 1 bit is in error, it is bit 7.

1 2 3 4 5 6 7 8 9 10 11

Hamming's Code (Ex.), cont.

- 1 checks 3, 5, 7, 9, 11

  1 + 1 + 1 + 0 + 1= 4; parity should be 0, but it is 1. Count = 1

- 2 checks 6, 7, 10, 11

  0 + 1 + 0 + 1= 2; parity bit should be 0, but isn't. Count +=2, so count is 3

- 4 checks 5, 6, 7

  1 + 0 + 1 = 2; parity bit should be 0, but isn't. Count += 4, so count=7

- 8 checks 9, 10, 11

  0 + 0 + 1= 0; parity bit should be 1 but is 0. Count +=8, so count=15.

- This makes no sense! More than 1 bit is in error. We can't fix it.

Checksums

- Checksums are based on dividing binary polynomials, modulus 2.
- Both addition and subtraction are equal to XOR in modulus 2 arithmetic
-
```
     10011011         11110000
   + 11001010       + 10101111
     01010001          01011111
```
- This can be used to perform long division.

Checksums, cont.

- Given a message, we will add checksum bits
- These bits will be computed by dividing the message by a *generator polynomial* modulus 2.
- The remainder is the checksum
- The checksum is one bit smaller than the generator polynomial.
- Good polynomials won’t divide the types of errors common in a particular channel

Checksum, cont.

- CRC-12: $x^{12} + x^{11} + x^3 + x^2 + x^1 + 1$
- CRC-16: $x^{16} + x^{15} + x^2 + 1$
- CRC-CCITT: $x^{16} + x^{12} + x^5 + 1$

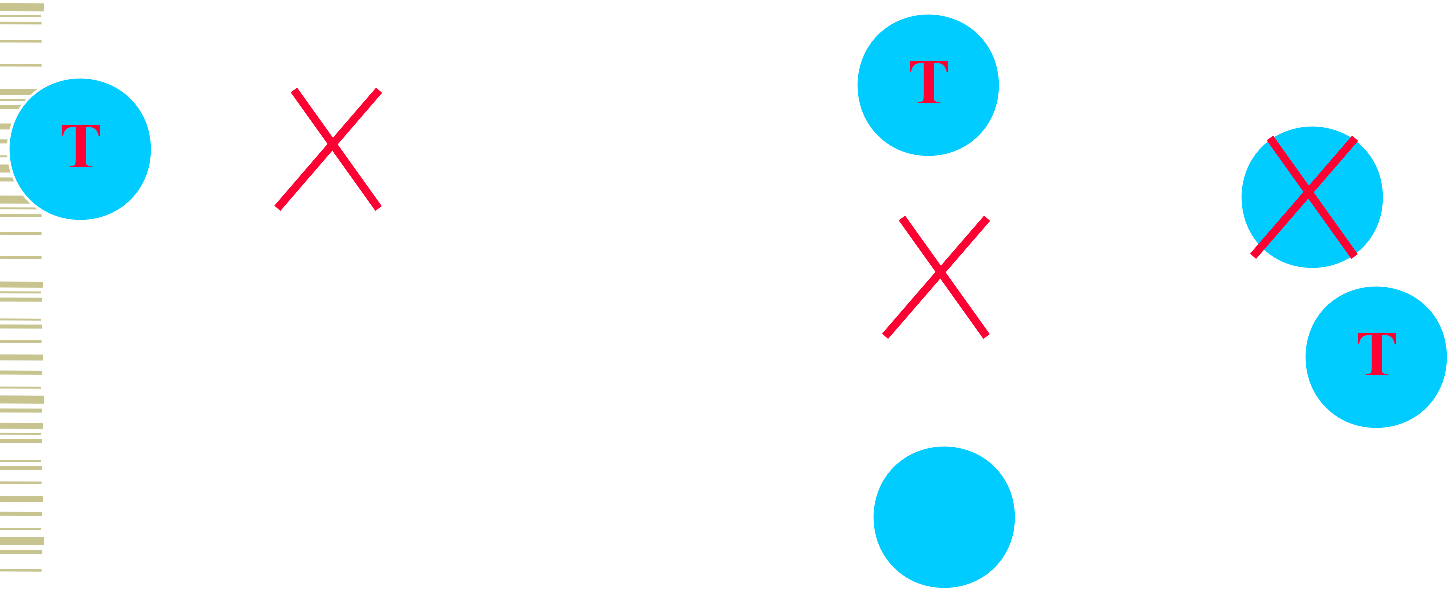
- These can be represented as polynomials. For example, consider CRC-12:

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

Checksum, cont.

```
                     1 1 0 0 0 0 1 0 1 0
            ____________________________
1 0 0 1 1 | 1 1 0 1 0 1 1 0 1 1 0 0 0 0
            1 0 0 1 1
              1 0 0 1 1
              1 0 0 1 1
                        1 0 1 1 0
                        1 0 0 1 1
                            1 0 1 0 0
                            1 0 0 1 1
                                1 1 1 0
```

Thinking about Error Detection and Correction



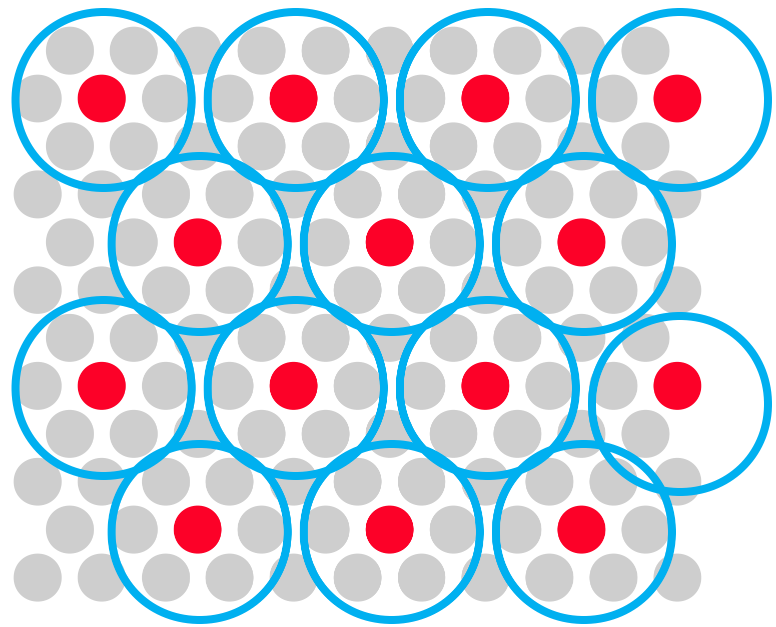
Basic Concept: Hamming Distance

- Hamming distance of two bit strings = number of bit positions in which they differ.
- If the valid words of a code have minimum Hamming distance D, then D-1 bit errors can be detected.
- If the valid words of a code have minimum Hamming distance D, then [(D-1)/2] bit errors can be corrected.

1	0	1	1	0
1	1	0	1	0

HD=2

HD=3



Examples

- A (4,3) parity code has D=2:
  - 0001 0010 0100 0111 1000 1011 1101 1110
  - (last bit is binary sum of previous 3, inverted - “odd parity”)
- A (7,4) code with D=3 (2ED, 1EC):
  - 0000000 0001101 0010111 0011010
  - 0100011 0101110 0110100 0111001
  - 1000110 1001011 1010001 1011100
  - 1100101 1101000 1110010 1111111
- 1001111 corrects to 1001011
- Note the inherent risk in correction; consider a 2-bit error resulting in 1001011 → 1111011.
- There are formulas to calculate the number of extra bits that are needed for a certain D.

Hamming Distance and EC/ED

- Review:
  - d bit errors can be detected if the Hamming Distance of the code is greater than d
  - d bit errors can be corrected if the Hamming Distance of the code is greater than 2*d

How Many Check Bits?

- If we have a dense code with m message bits, we will need to add some r check bits to the message to put distance between the code words
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Internet Checksum

- Goal: detect "errors" (e.g., flipped bits) in transmitted segment

Sender

- Treat segment contents as sequence of 16-bit integers
- Checksum: addition (1's complement sum) of segment contents
- Sender puts checksum value into checksum field in header

Receiver

- Compute checksum of received segment
- Check if computed checksum equals checksum field value:
  - NO - error detected
  - YES - no error detected. But maybe errors nonethless?

Cyclic Redundancy Codes (CRC)

- Commonly used codes that have good error detection properties.
  - Can catch many error combinations with a small number of redundant bits
- Based on division of polynomials.
  - Errors can be viewed as adding terms to the polynomial
  - Should be unlikely that the division will still work
- Can be implemented very efficiently in hardware.
- Examples:
  - CRC-32: Ethernet
  - CRC-8, CRC-10, CRC-32: ATM

CRC: Basic idea

- Treat bit strings as polynomials:

  1 0 1 1 1

  $$X^{4}+\quad X^{2}+X^{1}+X^{0}$$

- Sender and Receiver agree on a *divisor* polynomial of degree k
- Message of M bits → send M+k bits
- No errors if M+k is divisible by divisor polynomial
- If you pick the right divisor you can:
  - Detect all 1 & 2-bit errors
  - Any odd number of errors
  - All Burst errors of less than k bits
  - Some burst errors >= k bits

Outline

- Encoding
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- Framing
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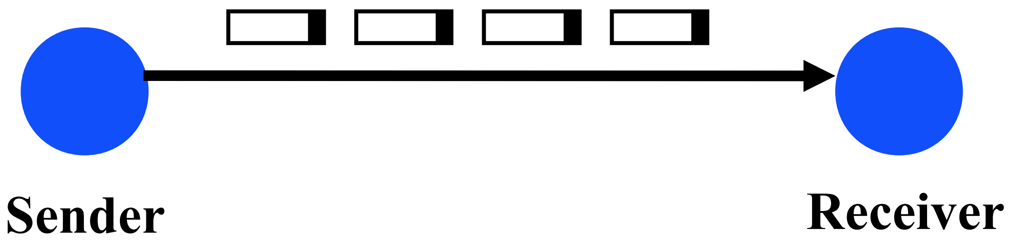
- Packet loss & corruption
  - Error detection
  - Flow control
  - Loss recovery

Link Flow Control and Error Recovery

- Dealing with receiver overflow: flow control.
- Dealing with packet loss and corruption: error control.
- Meta-comment: these issues are relevant at many layers.
  - Link layer: sender and receiver attached to the same “wire”
  - End-to-end: transmission control protocol (TCP) - sender and receiver are the end points of a connection
- How can we implement flow control?
  - “You may send” (windows, stop-and-wait, etc.)
  - “Please shut up” (source quench, 802.3x pause frames, etc.)
  - Where are each of these appropriate?

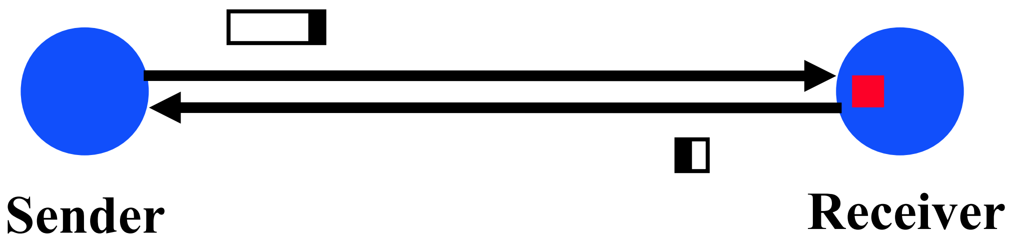
A Naïve Protocol

- Sender simply sends to the receiver whenever it has packets.
- Potential problem: sender can outrun the receiver.
  - Receiver too slow, buffer overflow, ..
- Not always a problem: receiver might be fast enough.

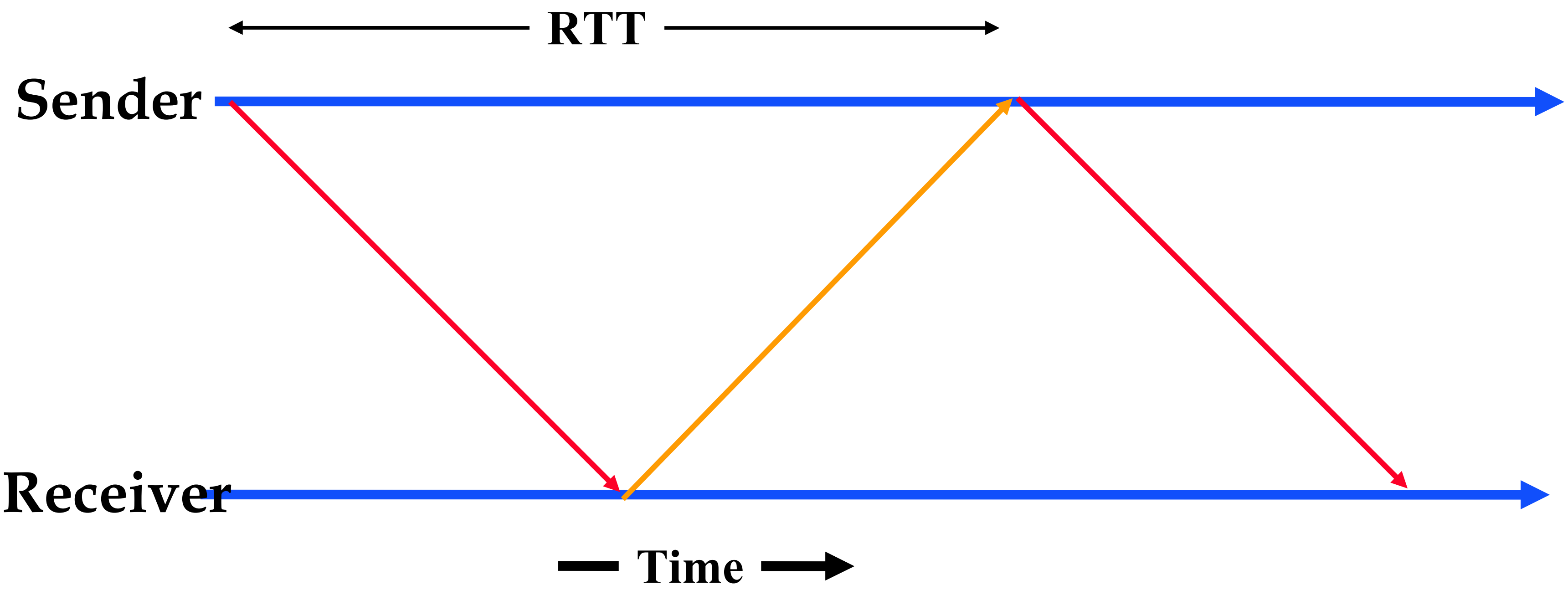


Adding Flow Control

- Stop and wait flow control: sender waits to send the next packet until the previous packet has been acknowledged by the receiver.
  - Receiver can pace the receiver



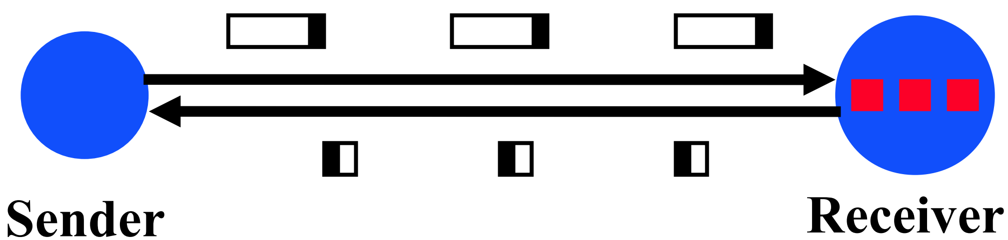
Drawback: Performance



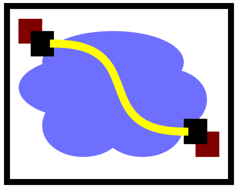
$$\text{Max Throughput} = \frac{\text{1 pkt}}{\text{Roundtrip Time}}$$

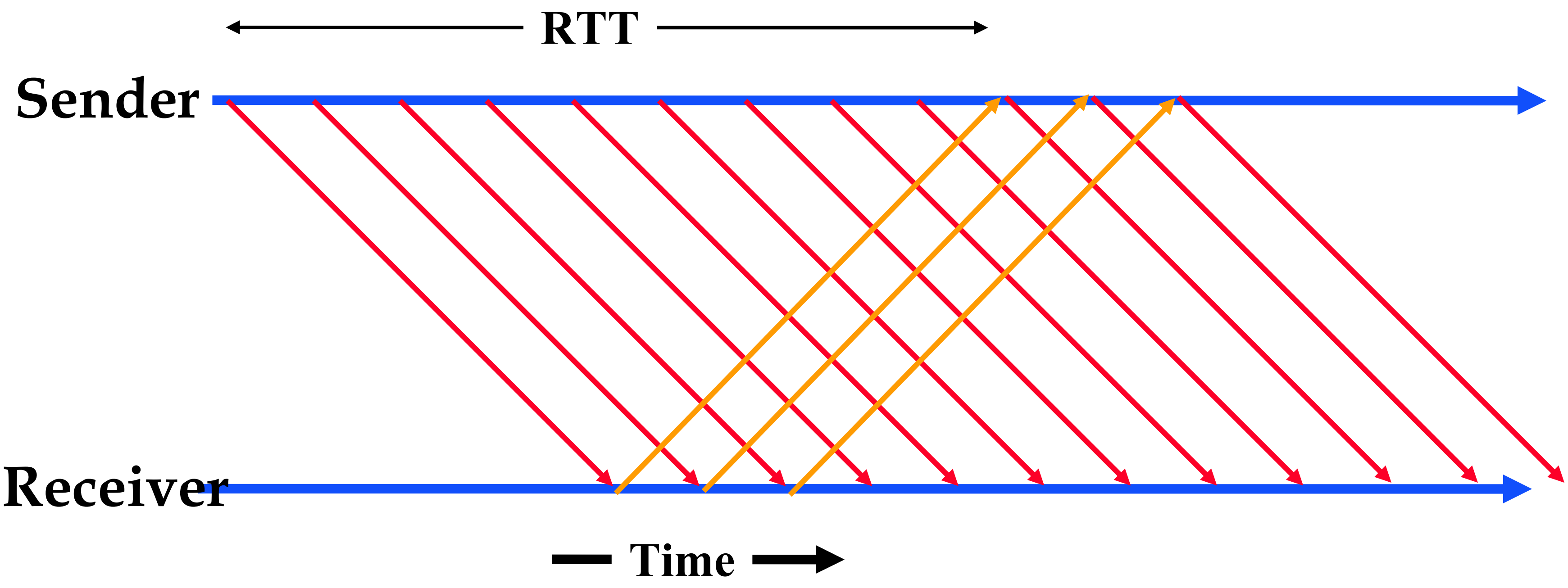
Window Flow Control

- Stop and wait flow control results in poor throughput for long-delay paths: packet size/ roundtrip-time.
- Solution: receiver provides sender with a window that it can fill with packets.
  - The window is backed up by buffer space on receiver
  - Receiver acknowledges the a packet every time a packet is consumed and a buffer is freed



Bandwidth-Delay Product





$$\text{Max Throughput} = \frac{\text{Window Size}}{\text{Roundtrip Time}}$$

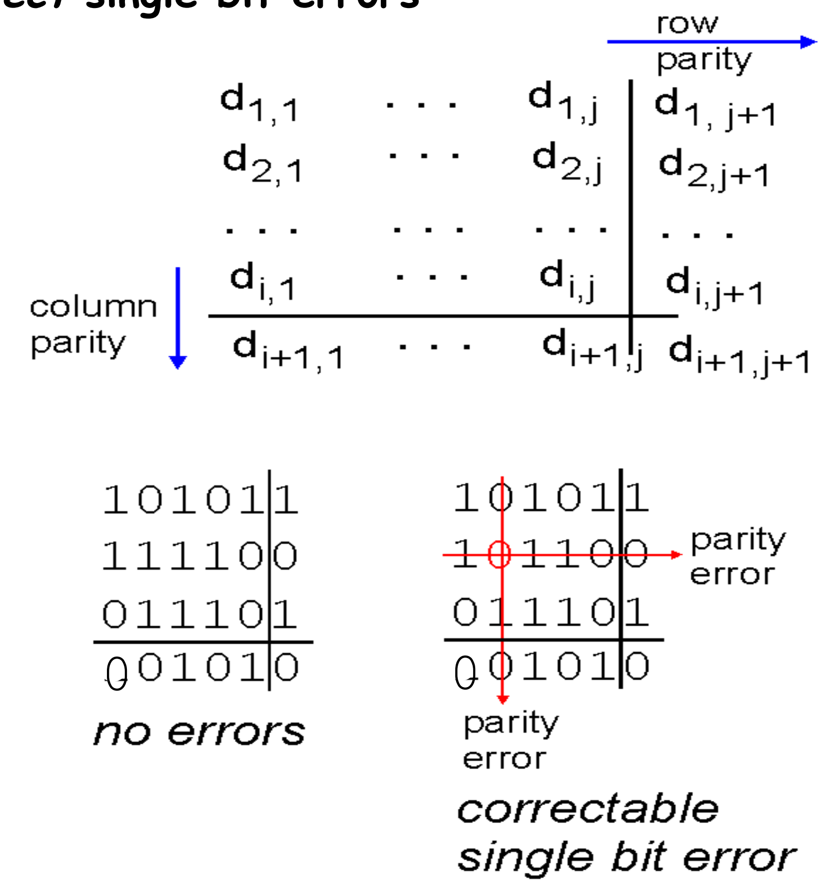
Error Recovery

- Two forms of error recovery
  - Error Correcting Codes (ECC)
  - Automatic Repeat Request (ARQ)
- ECC
  - Send extra redundant data to help repair losses
- ARQ
  - Receiver sends acknowledgement (ACK) when it receives packet
  - Sender uses ACKs to identify and resend data that was lost
- Which should we use? Why? When?

Error Recovery Example: Error Correcting Codes (ECC)

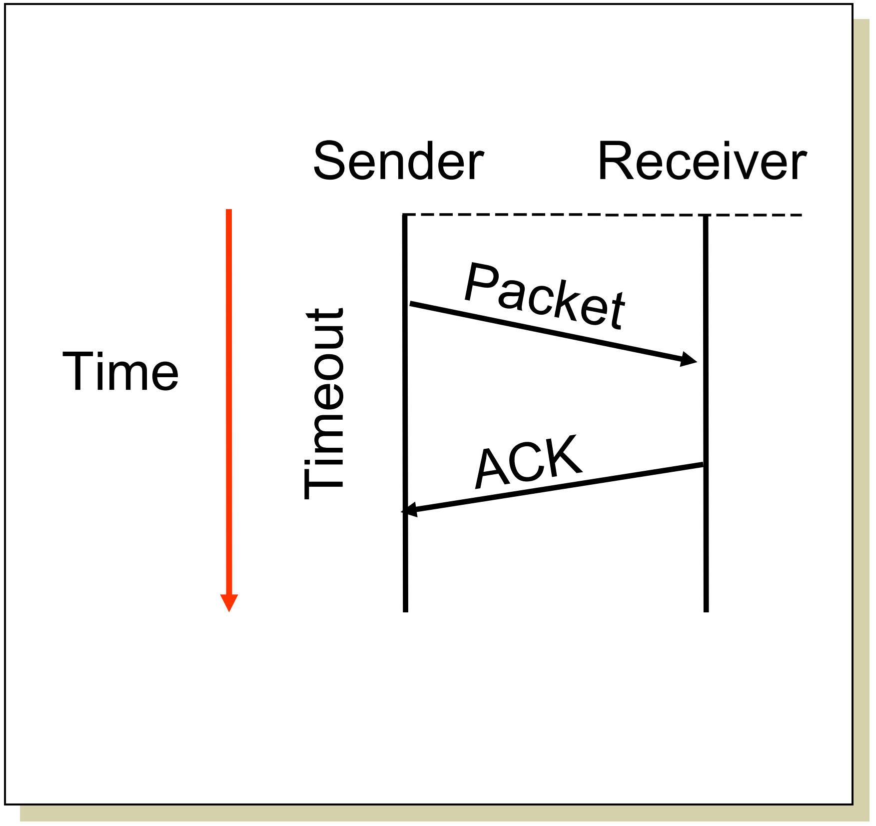
Two Dimensional Bit Parity:

Detect *and correct* single bit errors

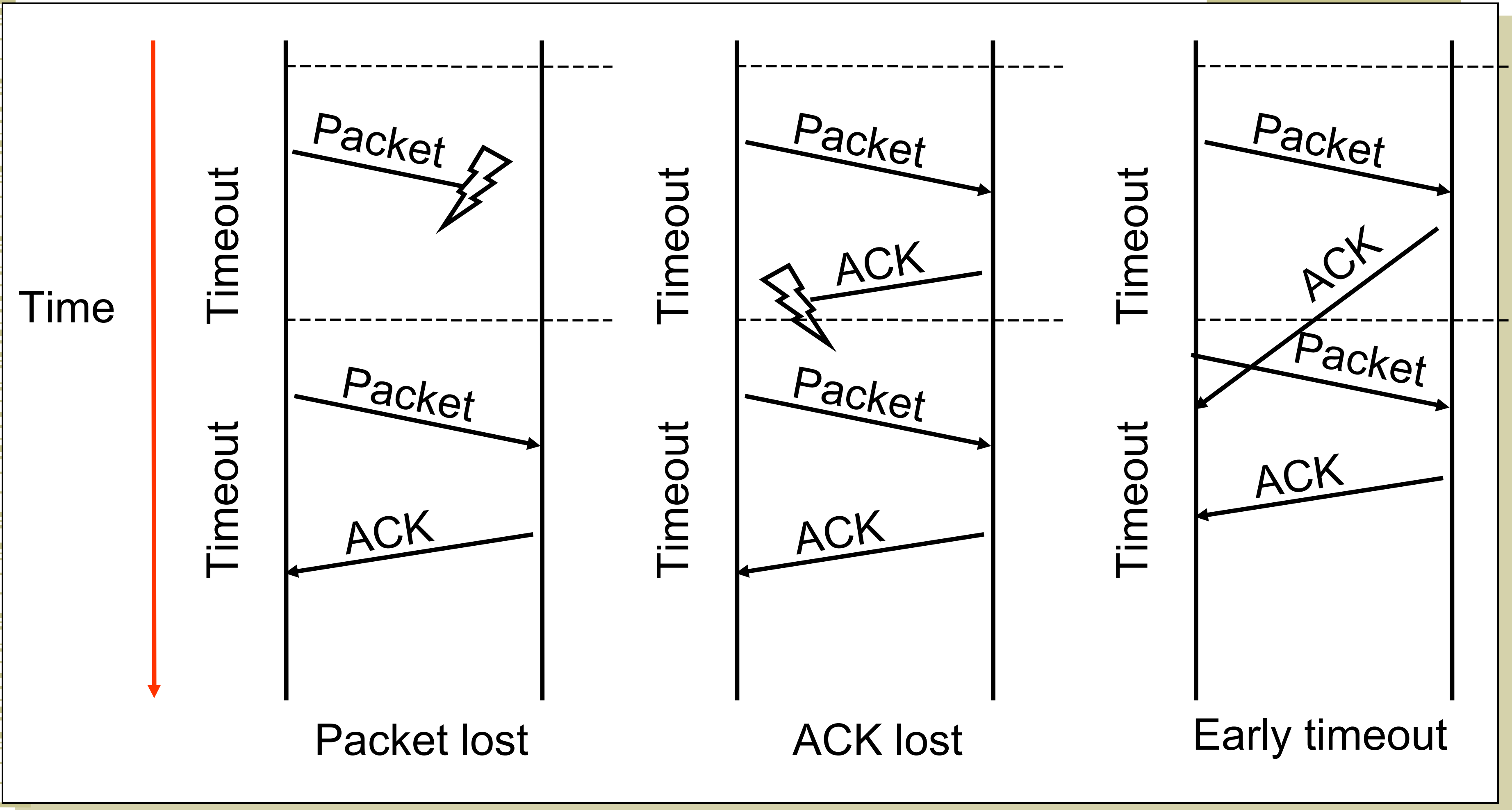


Stop and Wait

- Simplest ARQ protocol
- Send a packet, stop and wait until acknowledgement arrives
- Will examine ARQ issues later in semester

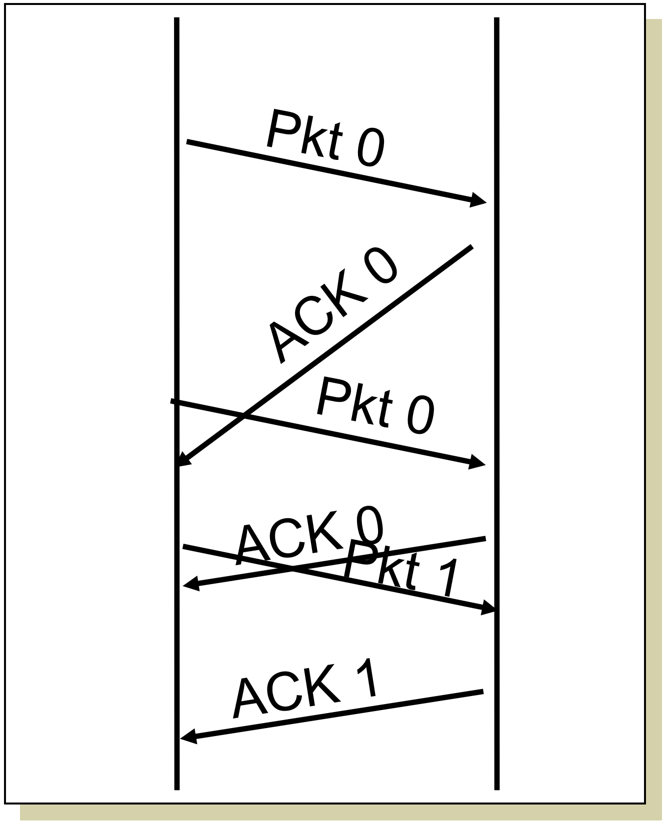


Recovering from Error



How to Recognize Retransmissions?

- Use sequence numbers
  - both packets and acks
- Sequence # in packet is finite → How big should it be?
  - For stop and wait?
- One bit – won't send seq #1 until received ACK for seq #0



Issues with Window-based Protocol

- Receiver window size: # of out-of-sequence packets that the receiver can receive
- Sender window size: # of total outstanding packets that sender can send without acknowledged
- How to deal with sequence number wrap around?

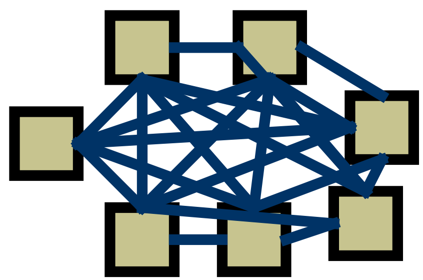
What is Used in Practice?

- No flow or error control.
  - E.g. regular Ethernet, just uses CRC for error detection
- Flow control only.
  - E.g. Gigabit Ethernet
- Flow and error control.
  - E.g. X.25 (older connection-based service at 64 Kbs that guarantees reliable in order delivery of data)

So far …

Can connect two nodes

- … But what if we want more nodes?

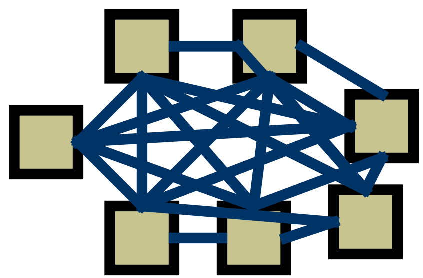


Wires for everybody!

So far …

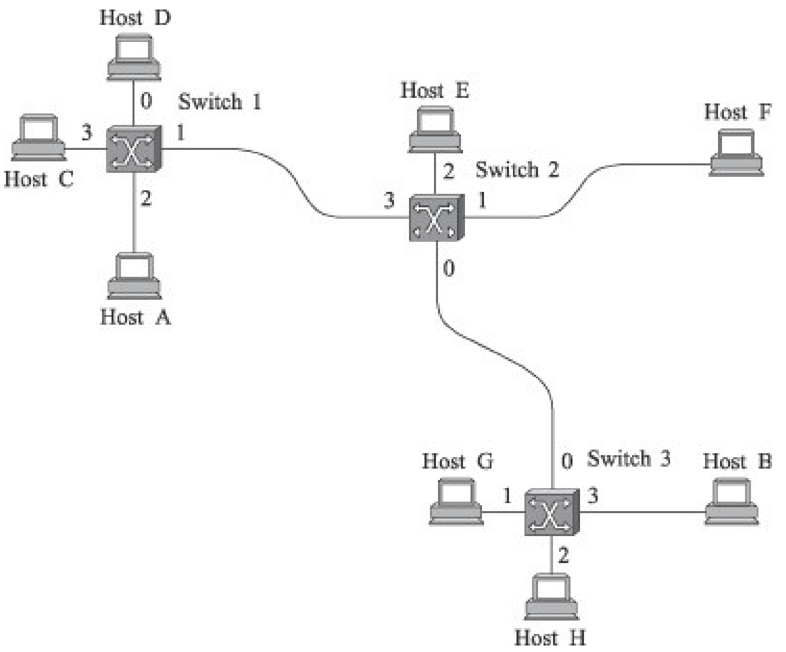
Can connect two nodes

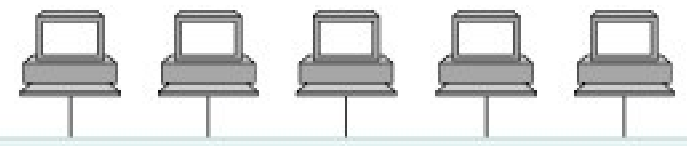
- … But what if we want more nodes?



Wires for everybody!

Better Solutions: Datalink Architectures





- Point-Point with switches
- Media access control.

EXTRA SLIDES

Clock Based Framing: SONET

- SONET is the Synchronous Optical Network standard for data transport over optical fiber.
- One of the design goals was to be backwards compatible with many older telco standards.
- Beside minimal framing functionality, it provides many other functions:
  - operation, administration and maintenance (OAM) communications
  - synchronization
  - multiplexing of lower rate signals
  - multiplexing for higher rates
- In otherwords, really complicated!

Standardization History

- Process was started by divestiture in 1984.
  - Multiple telephone companies building their own infrastructure
- SONET concepts originally developed by Bellcore.
- First standardized by ANSI T1X1 group for US.
- Later by CCITT and developed its own version.
- SONET/SDH standards approved in 1988.

A Word about Data Rates

- Bandwidth of telephone channel is under 4KHz, so when digitizing:

  8000 samples/sec * 8 bits = 64Kbits/second

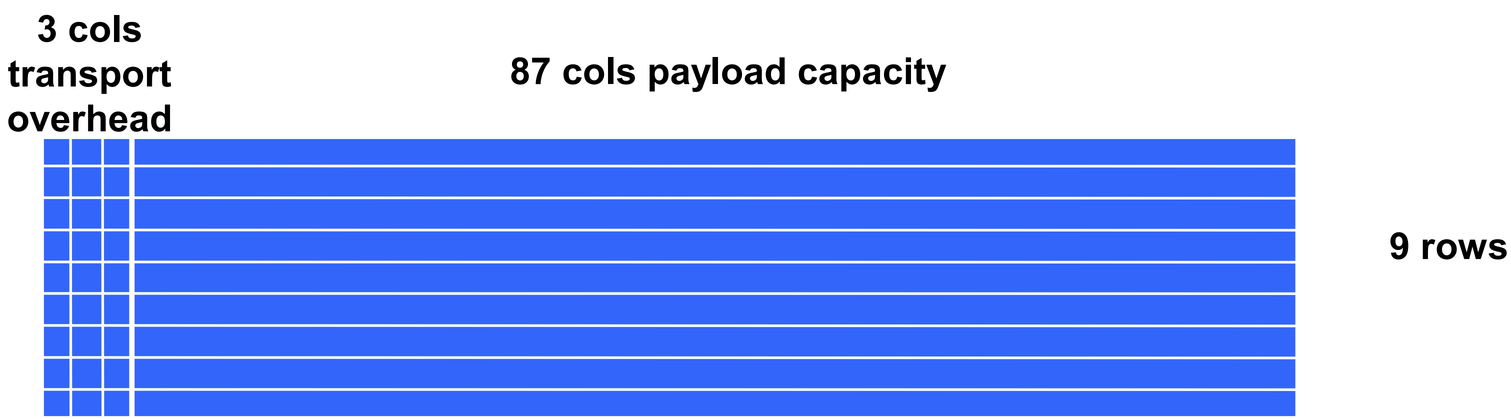
- Common data rates supported by telcos in North America:
  - Modem: rate improved over the years
  - T1/DS1: 24 voice channels plus 1 bit per sample

    (24 * 8 + 1) * 8000 = 1.544 Mbits/second
  - T3/DS3: 28 T1 channels:

    7 * 4 * 1.544 = 44.736 Mbits/second

Synchronous Data Transfer

- Sender and receiver are always synchronized.
  - Frame boundaries are recognized based on the clock
  - No need to continuously look for special bit sequences
- SONET frames contain room for control and data.
  - Data frame multiplexes bytes from many users
  - Control provides information on data, management, …

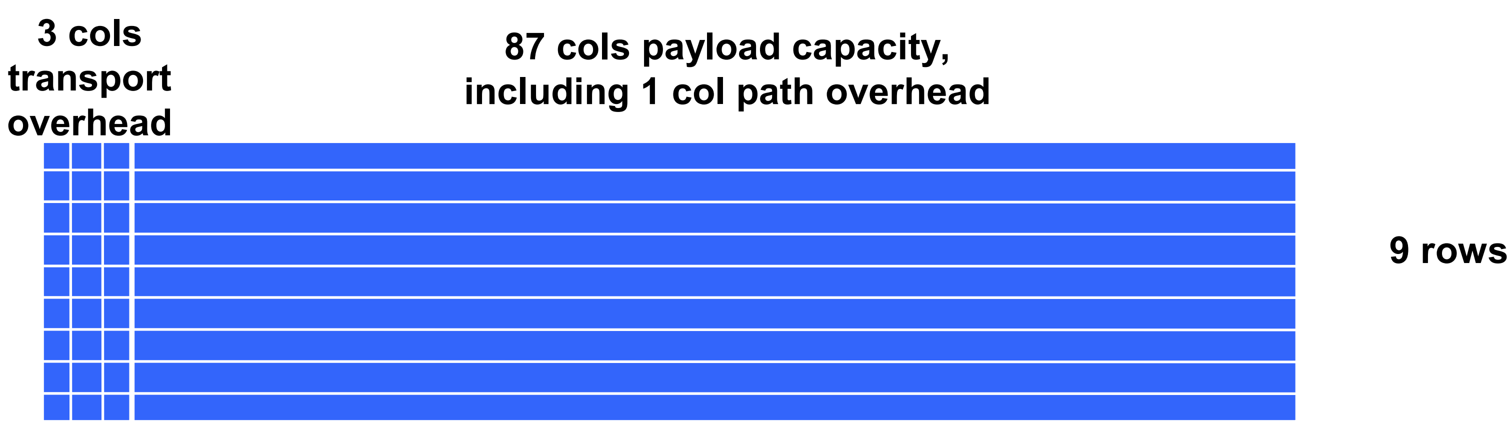


How avoid clock skew?

- Special bit sequences sent in first two chars of frame
  - But no bit stuffing. Hmmm?
- Lots of transitions by xoring with special pattern (and hope for the best)

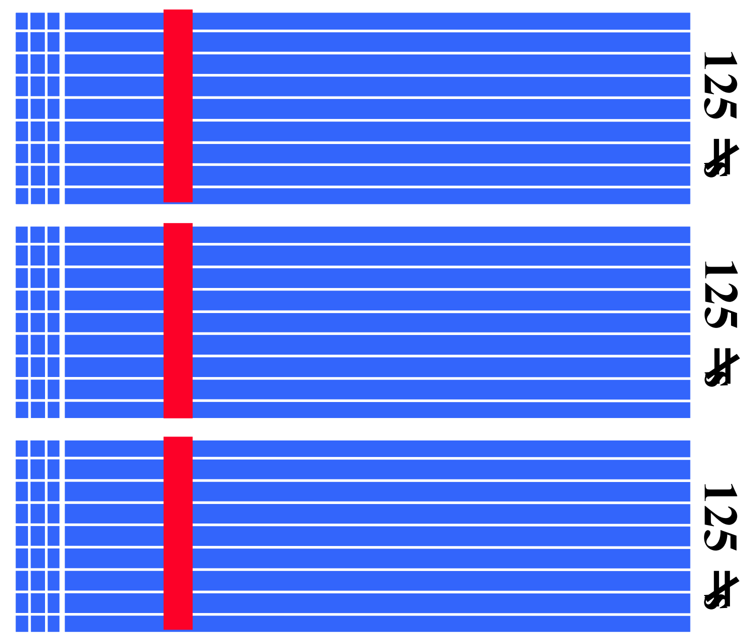
SONET Framing

- Base channel is STS-1 (Synchronous Transport System).
  - Takes 125 ≒sec and corresponds to 51.84 Mbps
  - 1 byte/frame corresponds to a 64 Kbs channel (voice)
  - Transmitted on an OC-1 optical carrier (fiber link)
- Standard ways of supporting slower and faster channels.
  - Support both old standards and future (higher) data rates



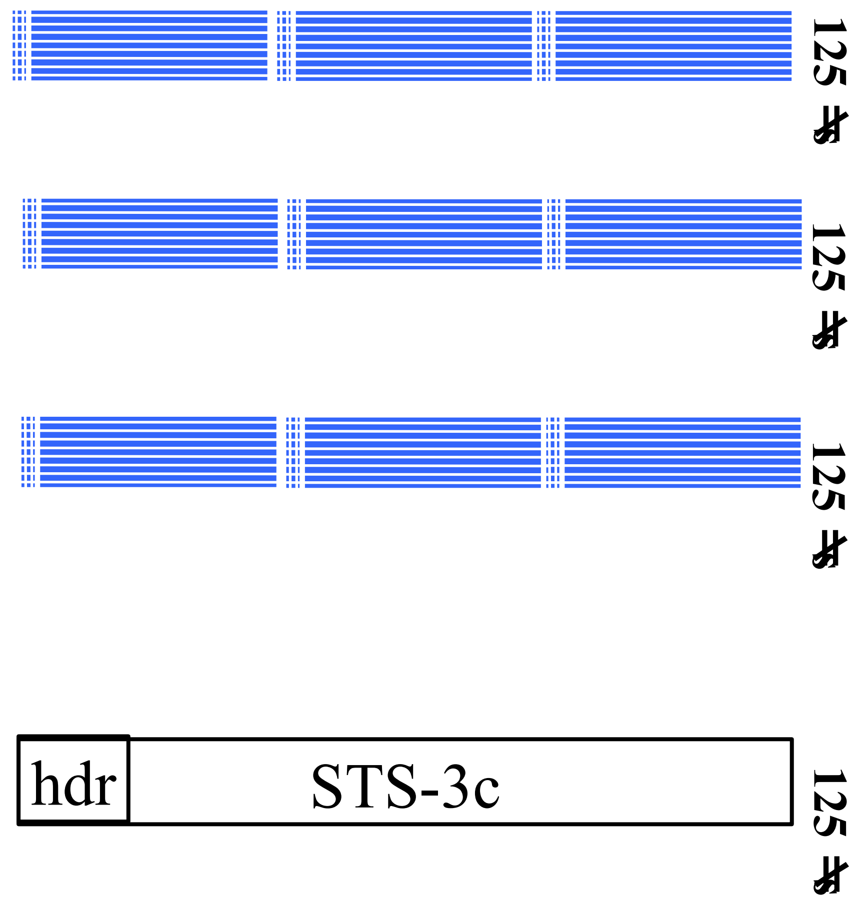
How Do We Support Lower Rates?

- 1 Byte in every consecutive frame corresponds to a 64 Kbit/second channel.
  - 1 voice call.
- Higher bandwidth channels hold more bytes per frame.
  - Multiples of 64 Kbit/second
- Channels have a “telecom” flavor.
  - Fixed bandwidth
  - Just data – no headers
  - SONET multiplexers remember how bytes on one link should be mapped to bytes on the next link
    - Byte 33 on incoming link 1 is byte 97 on outgoing link 7



How Do We Support Higher Rates?

- Send multiple frames in a 125 μsec time slot.
- The properties of a channel using a single byte/ST-1 frame are maintained!
  - Constant 64 Kbit/second rate
  - Nice spacing of the byte samples
- Rates typically go up by a factor of 4.
- Two ways of doing interleaving.
  - Frame interleaving
  - Column interleaving
    - concatenated version, i.e. OC-3c



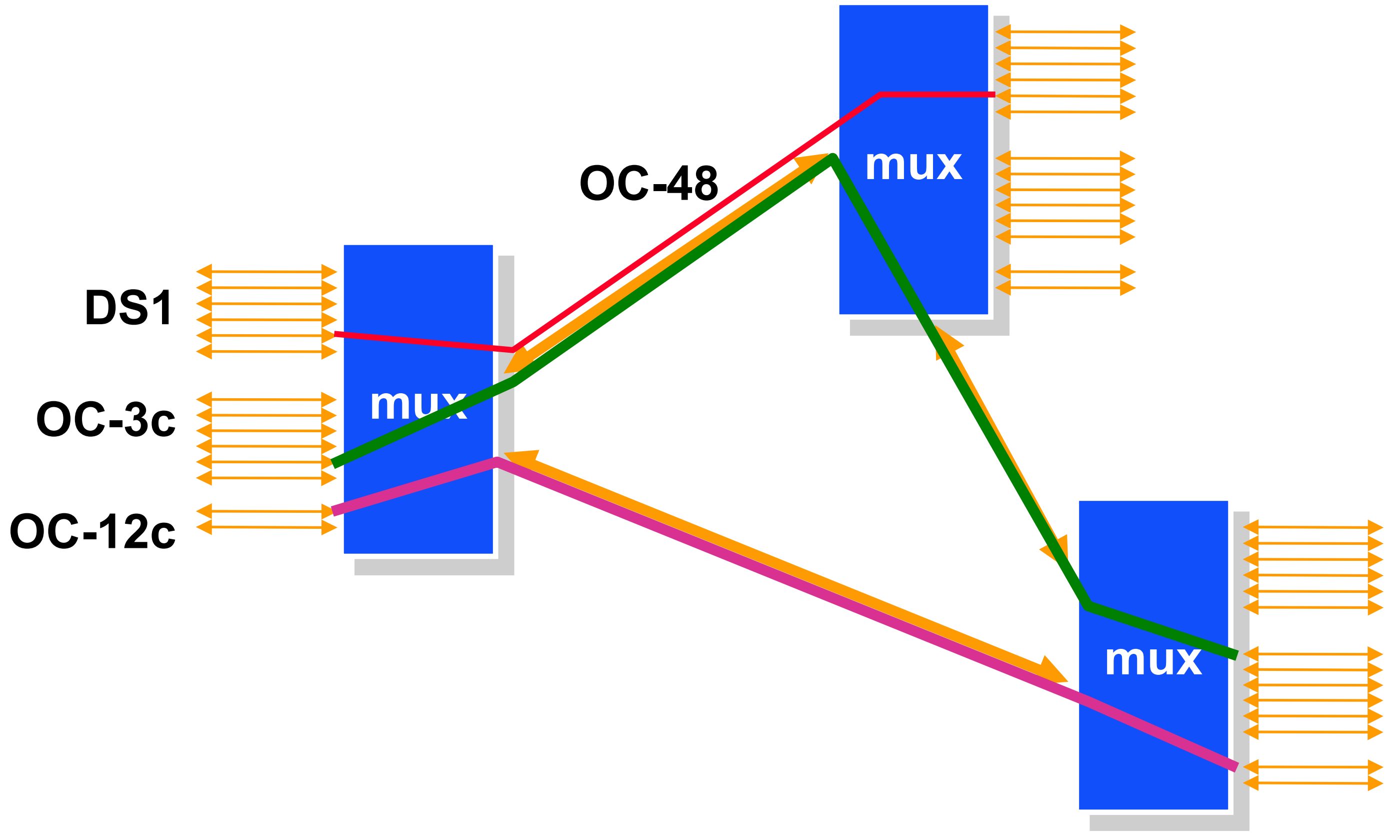
The SONET Signal Hierarchy

STS-1 carries one DS-3 plus overhead

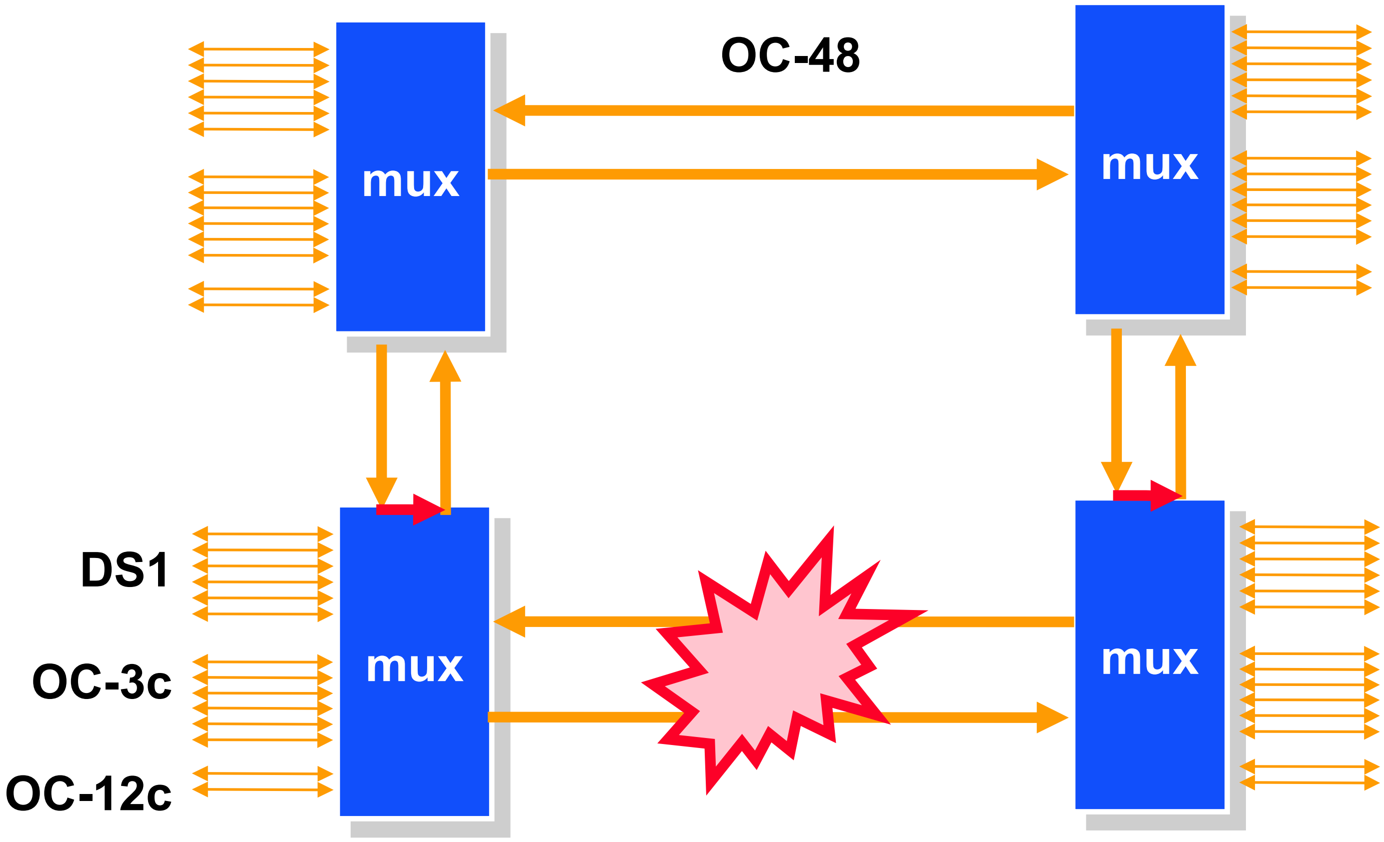
Signal Type	line rate	# of DS0
DS0 (POTS)	64 Kbs	1
DS1	1.544 Mbs	24
DS3	44.736 Mbs	672
OC-1	51.84 Mbs	672
OC-3	155 Mbs	2,016
OC-12	622 Mbs	8,064
STS-48	2.49 Gbs	32,256
STS-192	9.95 Gbs	129,024
STS-768	39.8 Gbs	516,096

Using SONET in Networks

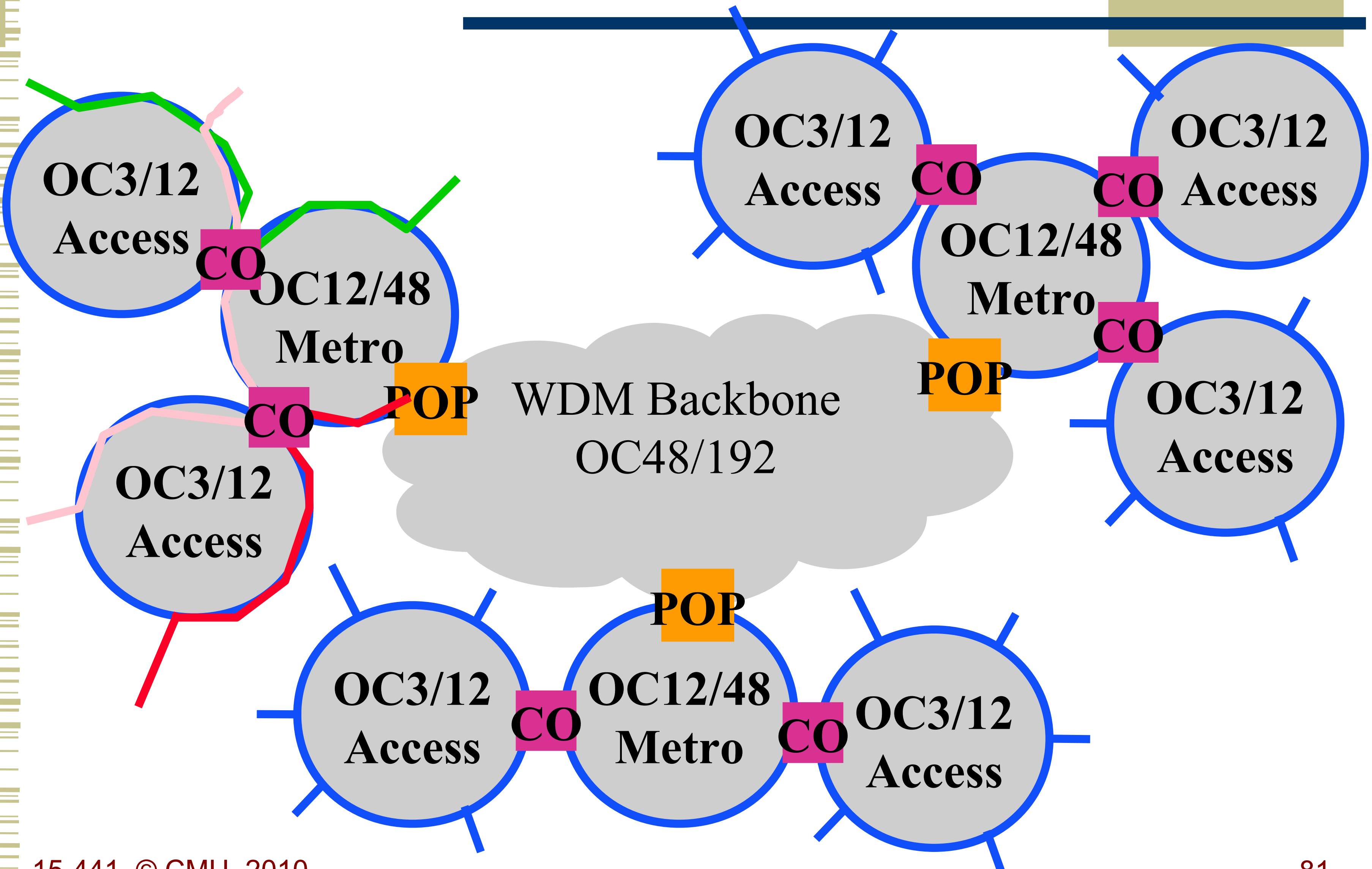
Add-drop capability allows soft configuration of networks, usually managed manually.



Self-Healing SONET Rings

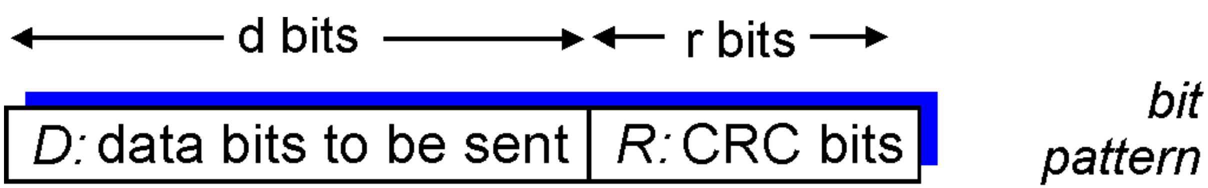


SONET as Physical Layer



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 (ATM, HDCL)



$$D * 2^r \text{ XOR } R$$

mathematical formula

CRC Example

Want:

D·2r XOR R = nG

equivalently:

D·2r = nG XOR R

equivalently:

if we divide D·2r by G, want reminder Rb

$$R = \text{remainder}\left[\frac{D \cdot 2r}{G}\right]$$