CSCI-1680
Link Layer Reliability

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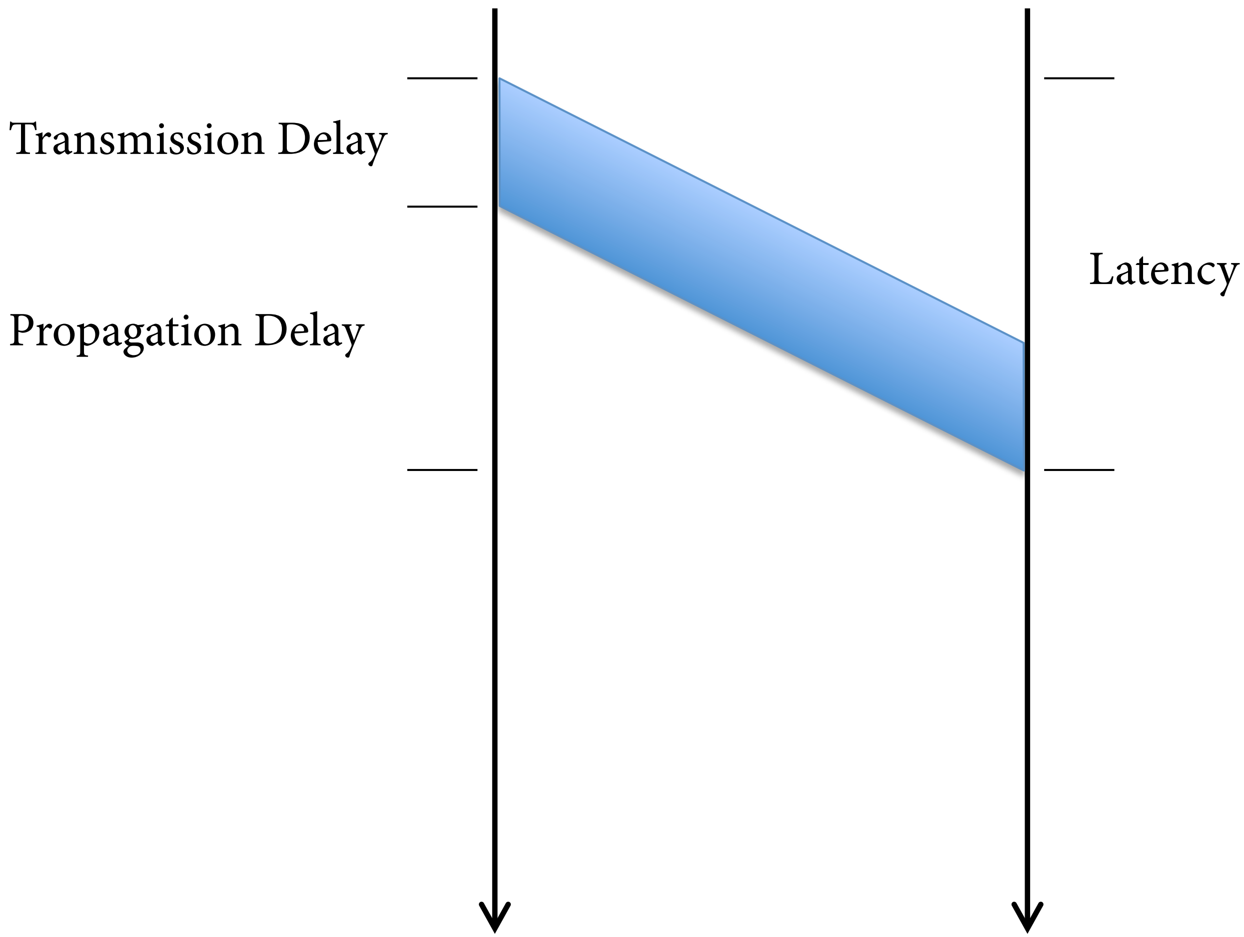
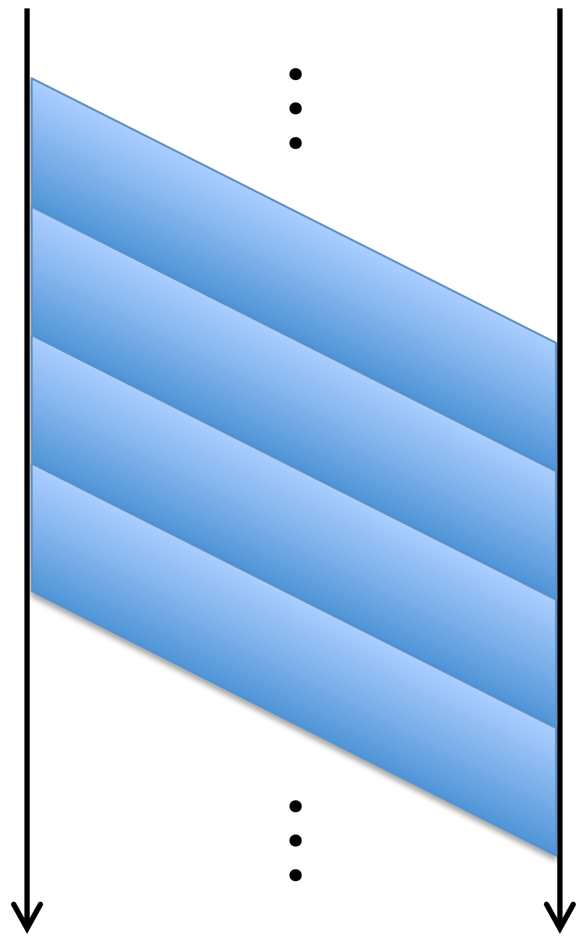
Based partly on lecture notes by David Mazières, Phil Levis, John Jannotti

- **Last time**
  - Physical layer: encoding, modulation
  - Link layer framing
- **Today**
  - Getting frames across: reliability, performance

Sending Frames Across



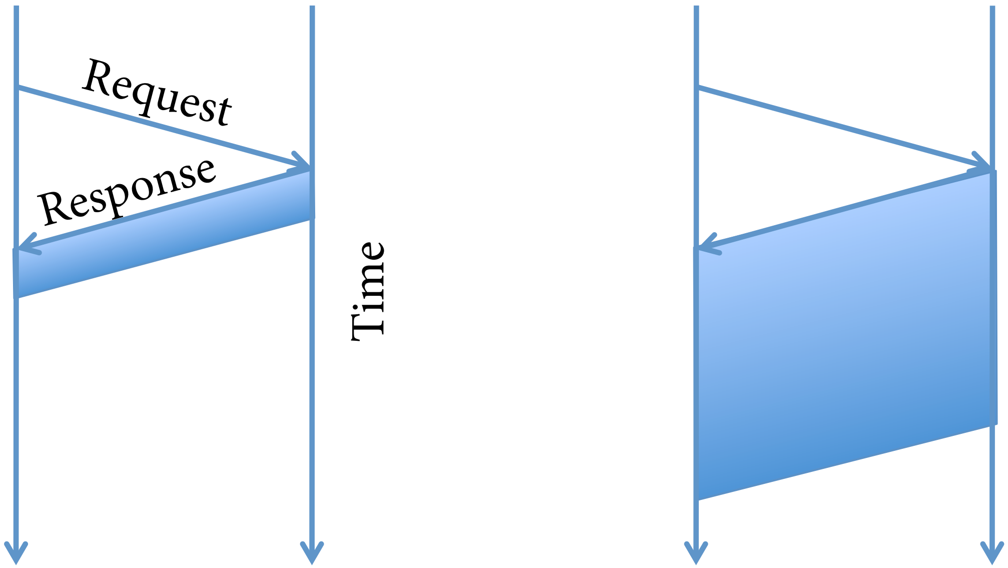
Sending Frames Across



Throughput: bits / s

Which matters most, bandwidth or delay?

- How much data can we send during one RTT?
- *E.g.*, send request, receive file



- For small transfers, latency more important, for bulk, throughput more important

Performance Metrics

- **Throughput - Number of bits received/unit of time**
  - *e.g.* 10Mbps
- **Goodput -** ***Useful*** **bits received per unit of time**
- **Latency – How long for message to cross network**
  - Process + Queue + Transmit + Propagation
- **Jitter – Variation in latency**

Latency

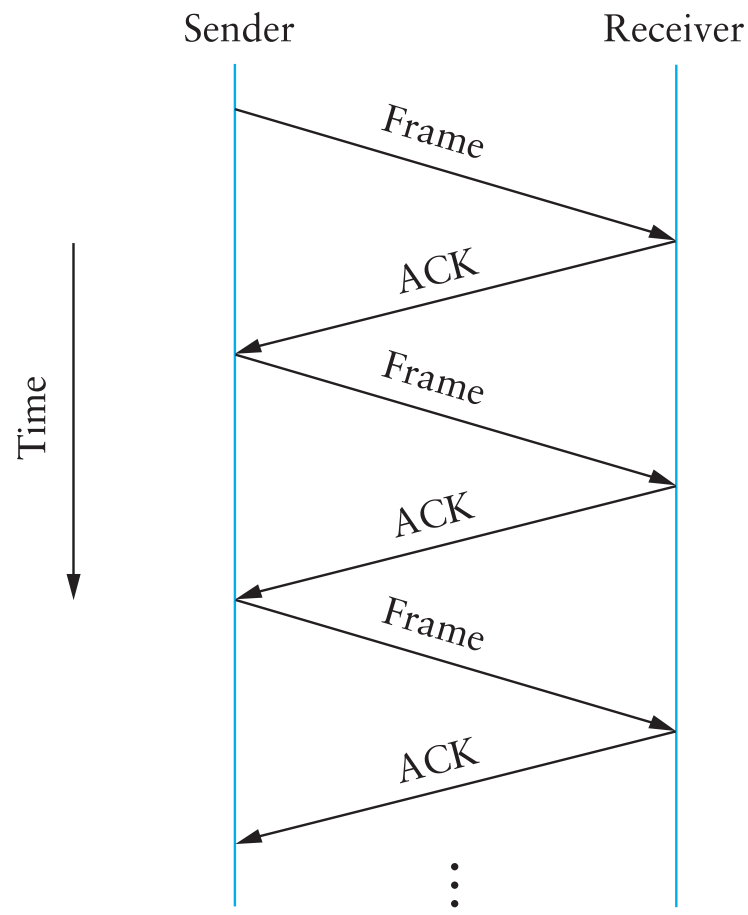
- **Processing**
  - Per message, small, limits throughput
  - *e.g.* $\frac{100Mb}{s} \times \frac{pkt}{1500B} \times \frac{B}{8b} \approx 8{,}333 pkt/s$ or 120µs/pkt
- **Queue**
  - Highly variable, offered load vs outgoing b/w
- **Transmission**
  - Size/Bandwidth
- **Propagation**
  - Distance/Speed of Light

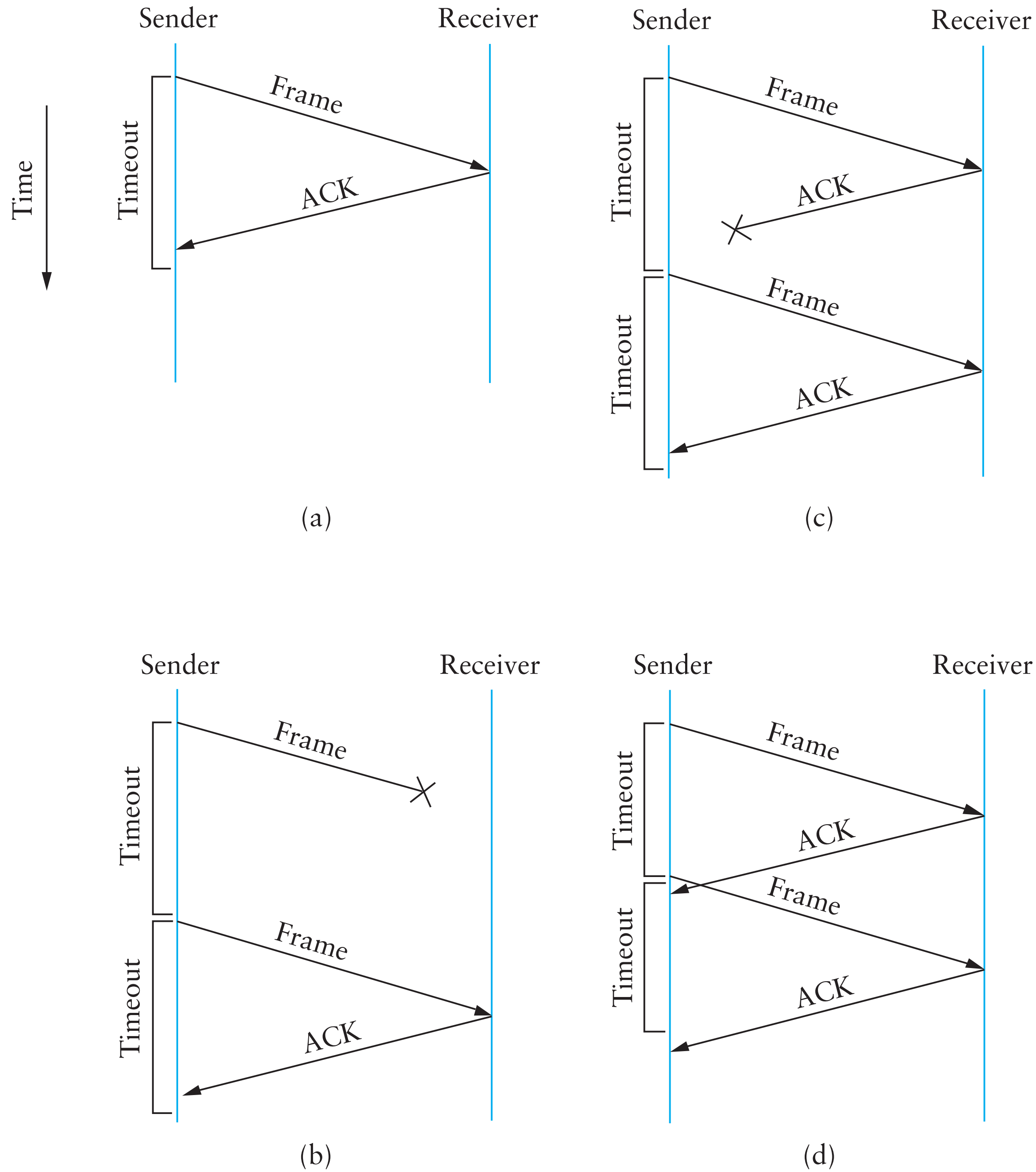
Reliable Delivery

- **Several sources of errors in transmission**
- **Error detection can discard bad frames**
- **Problem: if bad packets are lost, how can we ensure reliable delivery?**
  - Exactly-once semantics = at least once + at most once

At Least Once Semantics

- **How can the sender know packet arrived *at least once*?**
  - Acknowledgments + Timeout
- **Stop and Wait Protocol**
  - S: Send packet, wait
  - R: Receive packet, send ACK
  - S: Receive ACK, send next packet
  - S: No ACK, timeout and retransmit

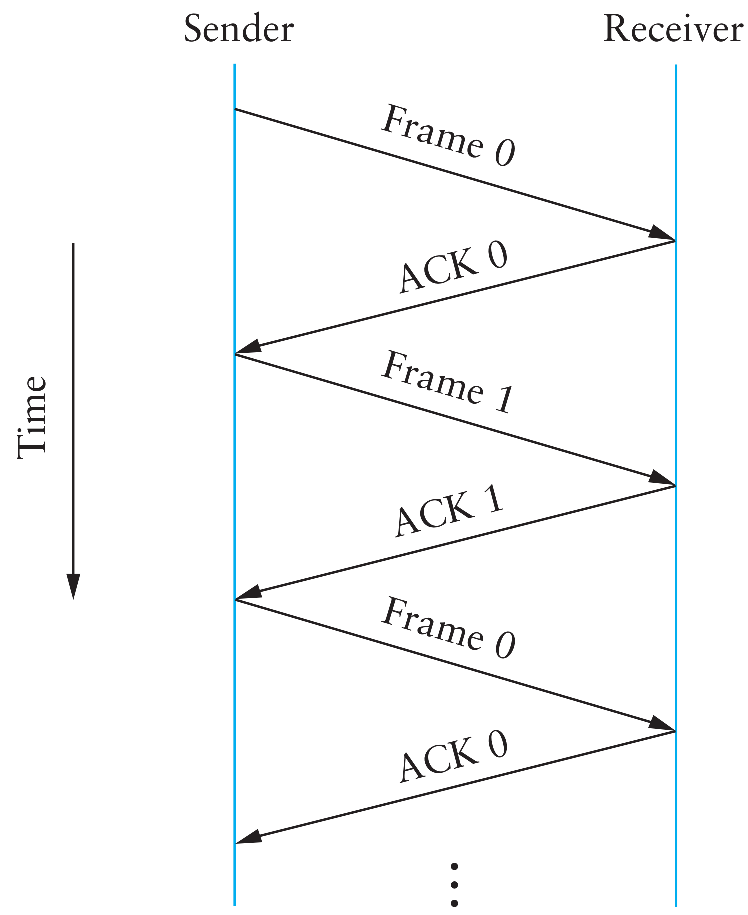

Sender
Receiver
Frame
ACK
Frame
ACK
Frame
ACK
Time


Time
Sender
Receiver
Timeout
Frame
ACK
(a)
(b)
(c)
(d)

Stop and Wait Problems

- Duplicate data
- Duplicate acks
- Slow (channel idle most of the time!)
- May be difficult to set the timeout value

Duplicate data: adding sequence numbers

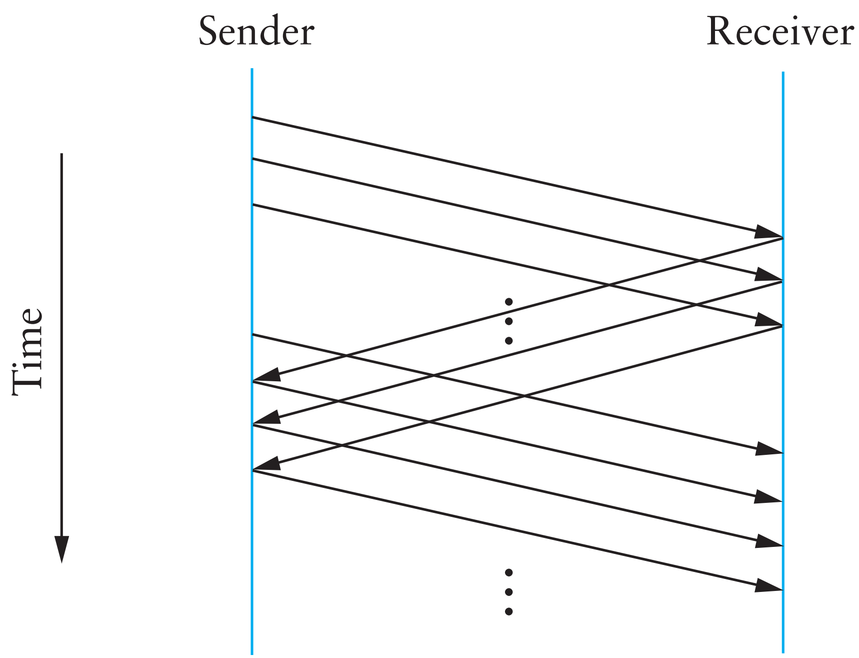


At Most Once Semantics

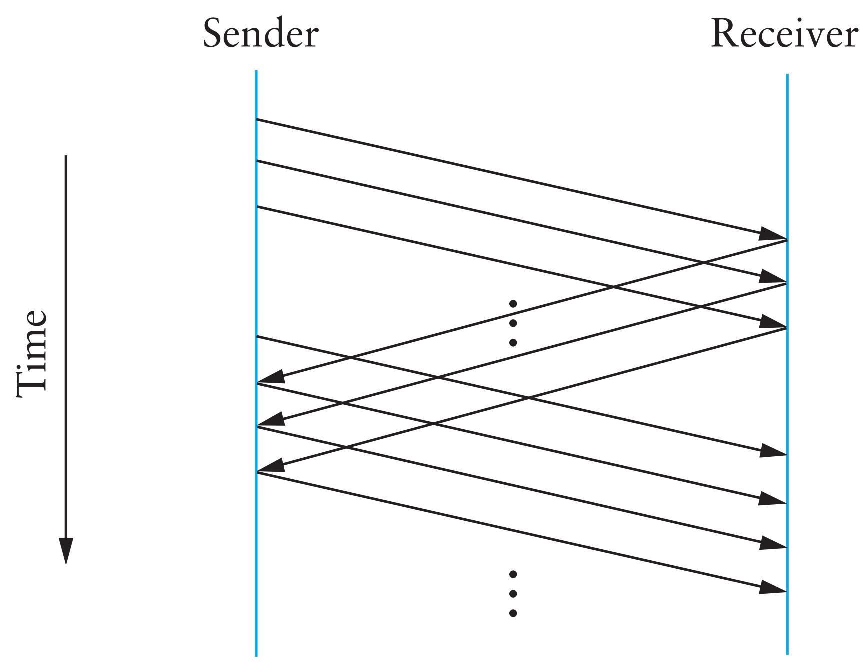
- **How to avoid duplicates?**
  - Uniquely identify each packet
  - Have receiver and sender remember
- **Stop and Wait: add 1 bit to the header**
  - Why is it enough?

Going faster: sliding window protocol

- **Still have the problem of keeping pipe full**
  - Generalize approach with > 1-bit counter
  - Allow multiple outstanding (unACKed) frames
  - Upper bound on unACKed frames, called *window*



How big should the window be?



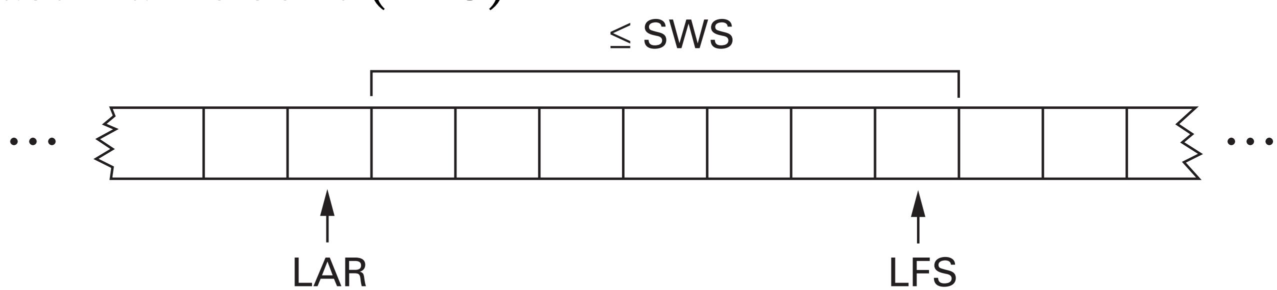
- **How many bytes can we transmit in one RTT?**
  - BW B/s x RTT s => "Bandwidth-Delay Product"

Maximizing Throughput

- **Can view network as a pipe**
  - For full utilization want bytes in flight ≥ bandwidth × delay
  - But don't want to overload the network (future lectures)
- **What if protocol doesn't involve bulk transfer?**
  - Get throughput through concurrency – service multiple clients simultaneously

Sliding Window Sender

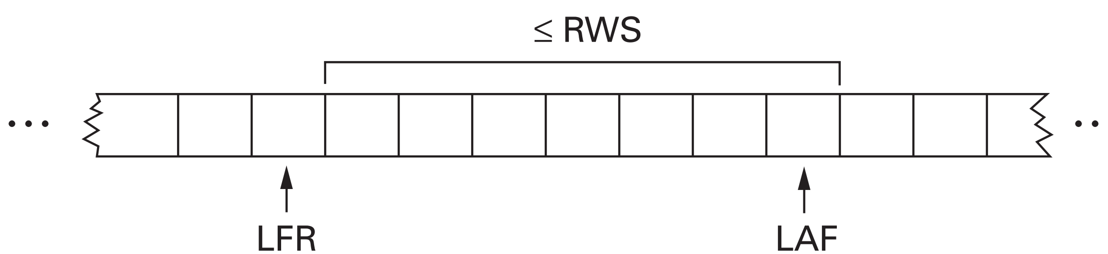
- **Assign sequence number (SeqNum) to each frame**
- **Maintain three state variables**
  - send window size (SWS)
  - last acknowledgment received (LAR)
  - last frame sent (LFS)



- **Maintain invariant: LFS – LAR ≤ SWS**
- **Advance LAR when ACK arrives**
- **Buffer up to SWS frames**

Sliding Window Receiver

- **Maintain three state variables:**
  - receive window size (RWS)
  - largest acceptable frame (LAF)
  - last frame received (LFR)



- **Maintain invariant: LAF – LFR ≤ RWS**
- **Frame SeqNum arrives:**
  - if LFR < SeqNum ≤ LAF, accept
  - if SeqNum ≤ LFR or SeqNum > LAF, discard
- **Send *cumulative* ACKs**

Tuning Send Window

- **How big should SWS be?**
  - "Fill the pipe"
- **How big should RWS be?**
  - $1 \leq RWS \leq SWS$
- **How many distinct sequence numbers needed?**
  - SWS can't be more than half of the space of valid seq#s.

Example

- SWS = RWS = 5. Are 6 seq #s enough?
- Sender sends 0,1,2,3,4
- All acks are lost
- Sender sends 0,1,2,3,4 again
- …

Summary

- **Want exactly once**
  - At least once: acks + timeouts + retransmissions
  - At most once: sequence numbers
- **Want efficiency**
  - Sliding window

Error Detection

- **Idea: have some codes be *invalid***
  - Must add bits to catch errors in packet
- **Sometimes can also *correct* errors**
  - If enough redundancy
  - Might have to retransmit
- **Used in multiple layers**
- **Three examples today:**
  - Parity
  - Internet Checksum
  - CRC

Simplest Schemes

- **Repeat frame *n* times**
  - Can we detect errors?
  - Can we correct errors?
    - Voting
  - Problem: high redundancy : *n*
- **Example: send each bit 3 times**
  - Valid codes: 000 111
  - Invalid codes : 001 010 011 100 101 110
  - Corrections : 0 0 1 0 1 1

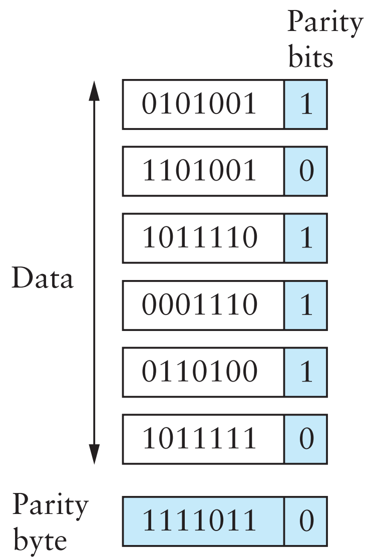
Parity

- **Add a parity bit to the end of a word**
- **Example with 2 bits:**
  - Valid: 000 011 011 110
  - Invalid: 001 010 010 111
  - Can we correct?
- **Can detect odd number of bit errors**
  - No correction

In general

- **Hamming distance: number of bits that are different**
  - E.g.: HD (00001010, 01000110) = 3
- **If min HD between valid codewords is *d*:**
  - Can detect *d*-1 bit error
  - Can correct $\lfloor (d\text{-}1)/2 \rfloor$ bit errors
- **What is *d* for parity and 3-voting?**

2-D Parity



- **Add 1 parity bit for each 7 bits**
- **Add 1 parity bit for each bit position across the frame)**
  - Can correct single-bit errors
  - Can detect 2- and 3-bit errors, most 4-bit errors
- **Find a 4-bit error that can't be corrected**

IP Checksum

- **Fixed-length code**
  - n-bit code should capture all but 2^{-n} fraction of errors
    - Why?
  - Trick is to make sure that includes all *common* errors
- **IP Checksum is an example**
  - 1's complement of 1's complement sum of every 2 bytes

```
uint16 cksum(uint16 *buf, int count) {
    uint32 sum = 0;
    while (count--)
        if ((sum += *buf++) & 0xffff0000) // carry
            sum = (sum & 0xffff) + 1;
    return ~(sum & 0xffff);
}
```

How good is it?

- **16 bits not very long: misses how many errors?**
  - 1 in 2^{16}, or 1 in 64K errors
- **Checksum does catch all 1-bit errors**
- **But not all 2-bit errors**
  - E.g., increment word ending in 0, decrement one ending in 1
- **Checksum also optional in UDP**
  - All 0s means no checksums calculated
  - If checksum word gets wiped to 0 as part of error, bad news

From rfc791 (IP)

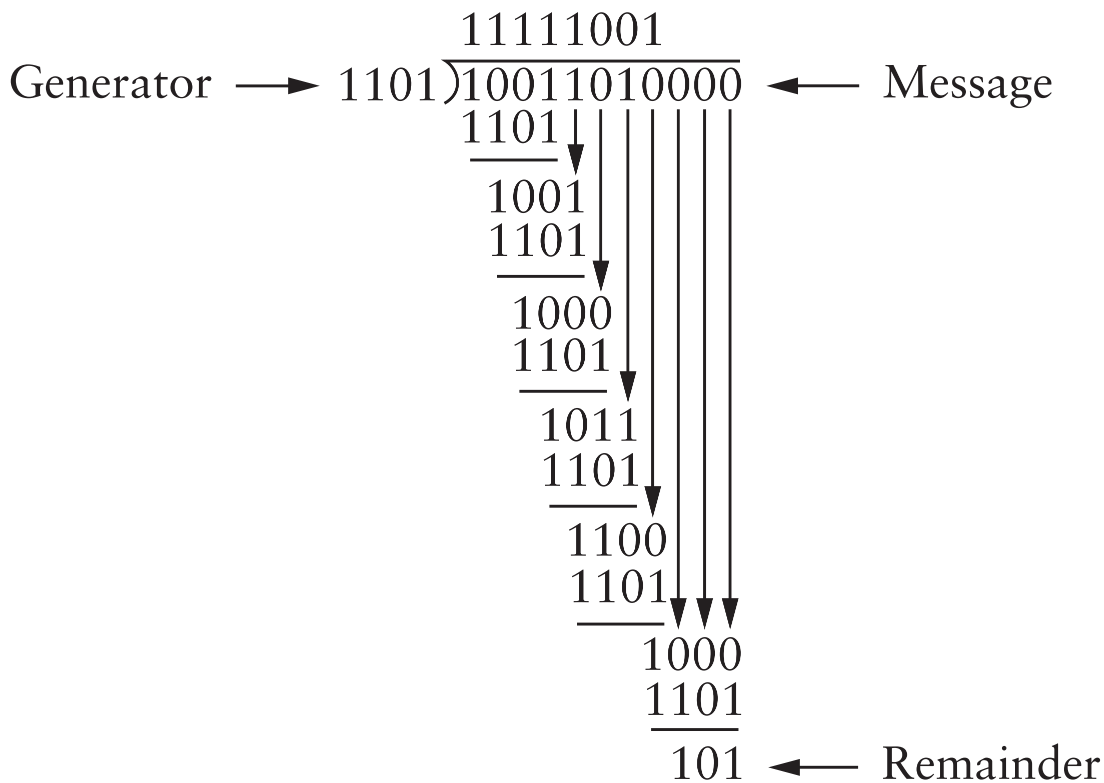
"This is a simple to compute checksum and experimental evidence indicates it is adequate, but it is provisional and may be replaced by a CRC procedure, depending on further experience."

CRC – Error Detection with Polynomials

- **Goal: maximize protection, minimize bits**
- **Consider message to be a polynomial in $Z_2[x]$**
  - Each bit is one coefficient
  - E.g., message 10101001 -> $m(x) = x^7 + x^5 + x^3 + 1$
- **Can reduce one polynomial modulo another**
  - Let $n(x) = m(x)x^3$. Let $C(x) = x^3 + x^2 + 1$.
  - $n(x)$ "**mod**" $C(x)$: $r(x)$
  - Find $q(x)$ and $r(x)$ s.t. $n(x) = q(x)C(x) + r(x)$ and degree of $r(x)$ < degree of $C(x)$
  - Analogous to taking 11 **mod** 5 = 1

Polynomial Division Example

- **Just long division, but addition/subtraction is XOR**



CRC

- **Select a divisor polynomial C(x), degree k**
  - C(x) should be *irreducible* – not expressible as a product of two lower-degree polynomials in $Z_2[x]$
- **Add k bits to message**
  - Let $n(x) = m(x)x^k$ (add k 0's to m)
  - Compute $r(x) = n(x) \bmod C(x)$
  - Compute $n(x)$ = n(x) – r(x) (will be divisible by C(x)) (subtraction is XOR, just set k lowest bits to r(x)!)
- **Checking CRC is easy**
  - Reduce message by C(x), make sure remainder is 0

Why is this good?

- **Suppose you send m(x), recipient gets m'(x)**
  - E(x) = m'(x) – m(x) (all the incorrect bits)
  - If CRC passes, C(x) divides m'(x)
  - Therefore, C(x) must divide E(x)
- **Choose C(x) that doesn't divide any common errors!**
  - All single-bit errors caught if x^k, x^0 coefficients in C(x) are 1
  - All 2-bit errors caught if at least 3 terms in C(x)
  - Any odd number of errors if last two terms (x + 1)
  - Any error burst less than length k caught

Common CRC Polynomials

- **Polynomials not trivial to find**
  - Some studies used (almost) exhaustive search
- **CRC-8: $x^8 + x^2 + x^1 + 1$**
- **CRC-16: $x^{16} + x^{15} + x^2 + 1$**
- **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 easily computable in hardware**

An alternative for reliability

- **Erasure coding**
  - Assume you can detect errors
  - Code is designed to tolerate entire missing frames
    - Collisions, noise, drops because of bit errors
  - Forward error correction
- **Examples: Reed-Solomon codes, LT Codes, Raptor Codes**
- **Property:**
  - From K source frames, produce B > K encoded frames
  - Receiver can reconstruct source with *any* K' frames, with K' *slightly* larger than K
  - Some codes can make B as large as needed, on the fly

LT Codes

- **Luby Transform Codes**
  - Michael Luby, circa 1998
- **Encoder: repeat B times**
  1. Pick a degree d
  2. Randomly select d source blocks. Encoded block t_n= XOR or selected blocks

LT Decoder

- **Find an encoded block t_n with d=1**
- **Set $s_n = t_n$**
- **For all other blocks $t_{n'}$ that include s_n ,**

  set $t_{n'}=t_{n'}$ XOR s_n
- **Delete s_n from all encoding lists**
- **Finish if**
  1. You decode all source blocks, or
  2. You run out out blocks of degree 1

Next class

- **Link Layer II**
  - Ethernet: dominant link layer technology
    - Framing, MAC, Addressing
  - Switching