# 15-441 Computer Networking

Lecture 16 – Transport Protocols

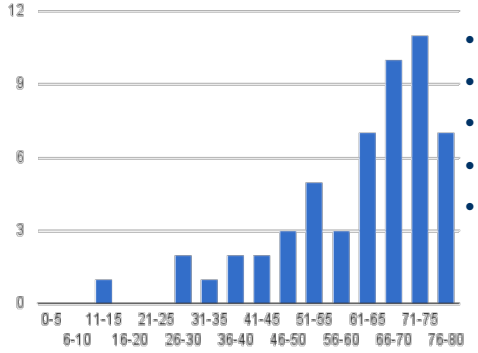


## Announcements

- Mid-semester grades
  - Based on (ckpt 1 & ckpt2) + midterm + HW1 + HW2
    - **NOTE: GRADES DO NOT REFLECT LATE PENALTIES!**
    - 25.4% of class
  - If you got a D+,D, or F → must meet with Roger or me
- Worry but don't panic
  - 74.6% of class grade remains!
  - Grading is likely a bit harsher than end-of-semester
- Project 1 grades – coming soon – lots of handin issues



## Midterm




- Avg: 62
- Med: 67
- STD: 13.5
- Max: 79
- Min: 28



## What was hard…

| | A | B | C | D | E |
|---|---|---|---|---|---|
| Perfect | 15 | 24 | 9 | 14 | 17 |
| Average | 12.8 | 18.4 | 6.3 | 11 | 12.5 |
| | | | Crypto | | Bridging & Routing |

## Feedback (positive)

**Likes**

- 12 project
- 8 recitations
- 7 HW
- 6 TA
- 2 IRC
- Slides
- **Jokes!**

**More**

- 2 lab/tool assignments
- 2 examples



## Feedback (negative)

**Project/HW**

- 10 release all at start/ clarity/changes
- 2 Due date conflicts
- Smaller HWs
- HW clarity
- Project open-ended
- Recitations run over time

**Lectures**

- 4 Integration with project/HW
- 3 not enough detail/too much material
- Need less repetition
- First HW date vs. lectures

**Other**

- 2 Study guide for exam/ practice
- 2 3-free points
- more office hours
- Use bboard more



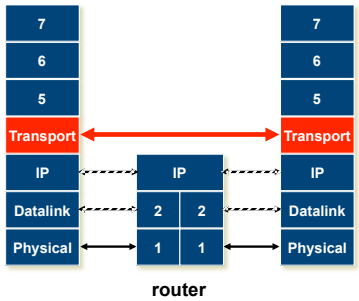
## Outline

- Transport introduction
- Error recovery & flow control



## Transport Protocols

- Lowest level end-to-end protocol.
  - Header generated by sender is interpreted only by the destination
  - Routers view transport header as part of the payload



## Functionality Split

- Network provides best-effort delivery
- End-systems implement many functions
  - Reliability
  - In-order delivery
  - Demultiplexing
  - Message boundaries
  - Connection abstraction
  - Congestion control
  - …



## Transport Protocols

- UDP provides just integrity and demux
- TCP adds…
  - Connection-oriented
  - Reliable
  - Ordered
  - Point-to-point
  - Byte-stream
  - Full duplex
  - Flow and congestion controlled



## UDP: User Datagram Protocol [RFC 768]

- "No frills," "bare bones" Internet transport protocol
- "Best effort" service, UDP segments may be:
  - Lost
  - Delivered out of order to app
- *Connectionless:*
  - No handshaking between UDP sender, receiver
  - Each UDP segment handled independently of others

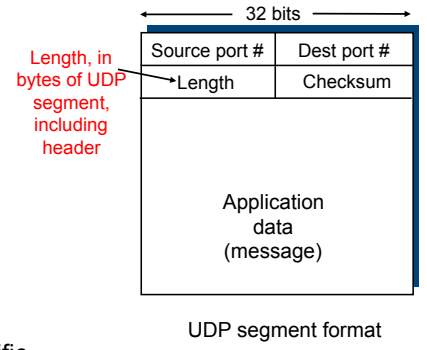
Why is there a UDP?

- No connection establishment (which can add delay)
- Simple: no connection state at sender, receiver
- Small header
- No congestion control: UDP can blast away as fast as desired



## UDP, cont.

- Often used for streaming multimedia apps
  - Loss tolerant
  - Rate sensitive
- Other UDP uses (why?):
  - DNS, SNMP
- Reliable transfer over UDP
  - Must be at application layer
  - Application-specific error recovery




UDP segment format

## UDP Checksum

Goal: detect "errors" (e.g., flipped bits) in transmitted segment – optional use!

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

**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?*



## High-Level TCP Characteristics

- Protocol implemented entirely at the ends
  - Fate sharing
- Protocol has evolved over time and will continue to do so
  - Nearly impossible to change the header
  - Use options to add information to the header
    - These do change sometimes
  - Change processing at endpoints
  - Backward compatibility is what makes it TCP



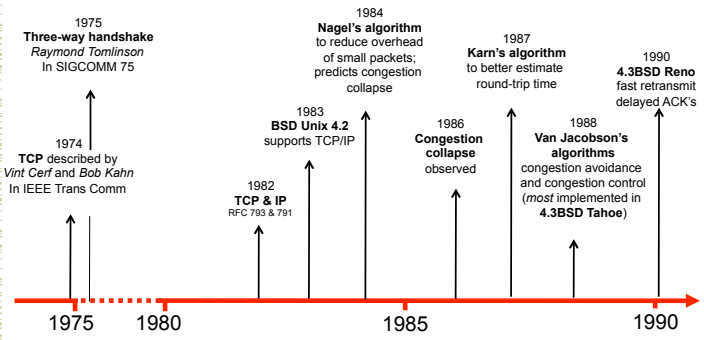
## TCP Header

Flags: SYN
FIN
RESET
PUSH
URG
ACK

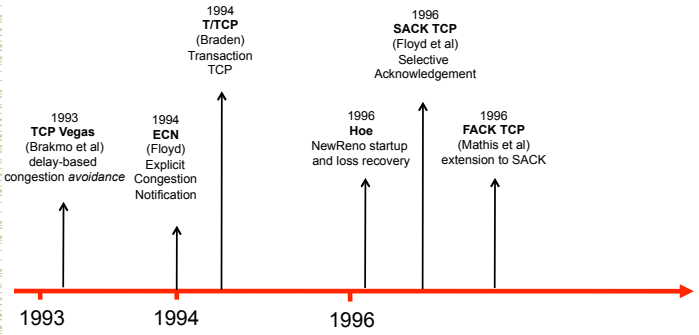
| | | | |
|---|---|---|---|
| Source port | | | Destination port |
| Sequence number | | | |
| Acknowledgement | | | |
| HdrLen | 0 | Flags | Advertised window |
| Checksum | | | Urgent pointer |
| Options (variable) | | | |
| Data | | | |



## Evolution of TCP



## TCP Through the 1990s

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## Outline

- Transport introduction
- Error recovery & flow control

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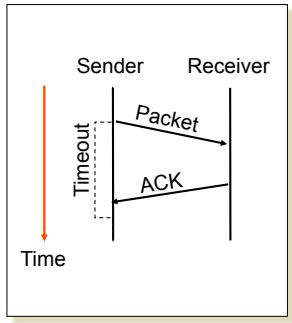
## Stop and Wait

- ARQ
  - Receiver sends acknowledgement (ACK) when it receives packet
  - Sender waits for ACK and timeouts if it does not arrive within some time period
- Simplest ARQ protocol
- Send a packet, stop and wait until ACK arrives

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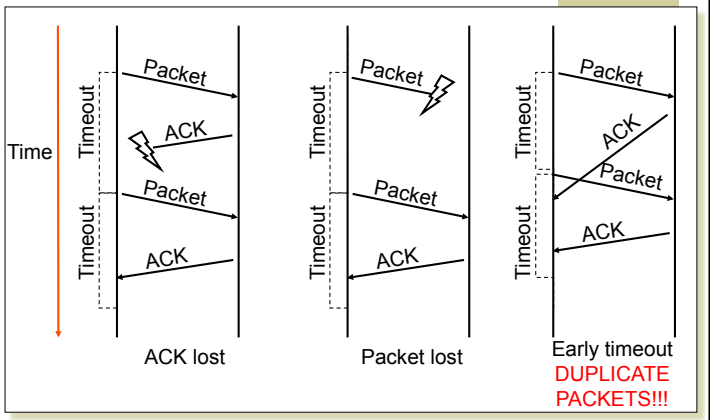
## Recovering from Error

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## Problems with Stop and Wait

- How to recognize a duplicate
- Performance
  - Can only send one packet per round trip

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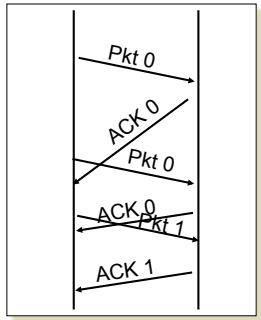
## How to Recognize Resends?

- 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

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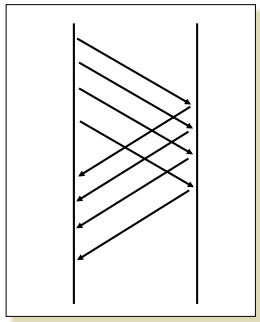
## How to Keep the Pipe Full?

- Send multiple packets without waiting for first to be acked
  - Number of pkts in flight = window
- Reliable, unordered delivery
  - Several parallel stop & waits
  - Send new packet after each ack
  - Sender keeps list of unack'ed packets; resends after timeout
  - Receiver same as stop & wait
- How large a window is needed?
  - Suppose 10Mbps link, 4ms delay, 500byte pkts
    - 1? 10? 20?
  - Round trip delay * bandwidth = capacity of pipe



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## Sliding Window

- Reliable, ordered delivery
- Receiver has to hold onto a packet until all prior packets have arrived
  - Why might this be difficult for just parallel stop & wait?
  - Sender must prevent buffer overflow at receiver
- Circular buffer at sender and receiver
  - Packets in transit ≤ buffer size
  - Advance when sender and receiver agree packets at beginning have been received

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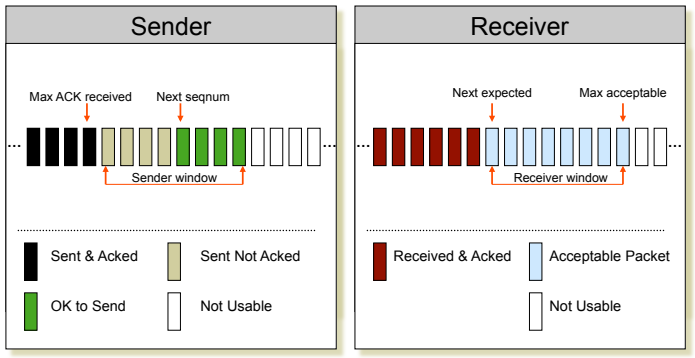
## Sender/Receiver State

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## Sequence Numbers

- How large do sequence numbers need to be?
  - Must be able to detect wrap-around
  - Depends on sender/receiver window size
- E.g.
  - Max seq = 7, send win=recv win=7
  - If pkts 0..6 are sent succesfully and all acks lost
    - Receiver expects 7,0..5, sender retransmits old 0..6!!!
- Max sequence must be ≥ send window + recv window

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## Window Sliding – Common Case

- On reception of new ACK (i.e. ACK for something that was not acked earlier)
  - Increase sequence of max ACK received
  - Send next packet
- On reception of new in-order data packet (next expected)
  - Hand packet to application
  - Send cumulative ACK – acknowledges reception of all packets up to sequence number
  - Increase sequence of max acceptable packet

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## Loss Recovery

- On reception of out-of-order packet
  - Send nothing (wait for source to timeout)
  - Cumulative ACK (helps source identify loss)
- Timeout (Go-Back-N recovery)
  - Set timer upon transmission of packet
  - Retransmit all unacknowledged packets
- Performance during loss recovery
  - No longer have an entire window in transit
  - Can have much more clever loss recovery

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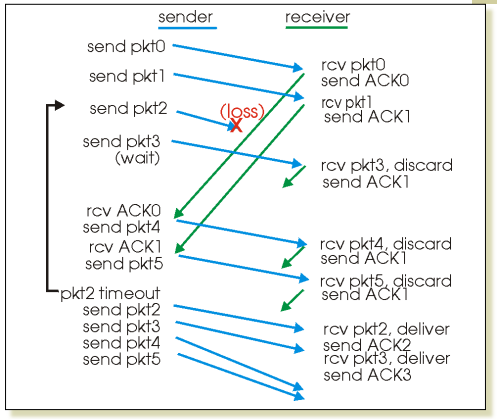
## Go-Back-N in Action



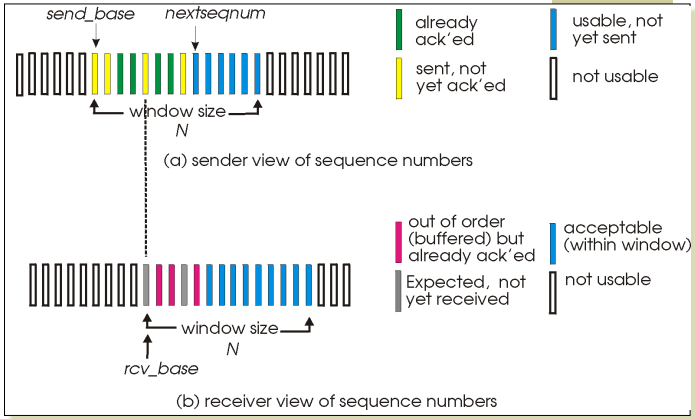



## Selective Repeat

- Receiver *individually* acknowledges all correctly received pkts
  - Buffers packets, as needed, for eventual in-order delivery to upper layer
- Sender only resends packets for which ACK not received
  - Sender timer for each unACKed packet
- Sender window
  - N consecutive seq #'s
  - Again limits seq #s of sent, unACKed packets



## Selective Repeat: Sender, Receiver Windows






## Important Lessons

- Transport service
  - UDP → mostly just IP service
  - TCP → congestion controlled, reliable, byte stream
- Types of ARQ protocols
  - Stop-and-wait → slow, simple
  - Go-back-n → can keep link utilized (except w/ losses)
  - Selective repeat → efficient loss recovery
- Sliding window flow control
  - Addresses buffering issues and keeps link utilized

## Next Lecture

- Congestion control
- TCP Reliability

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