15-441 Computer Networking

Lecture 17 – TCP & Congestion Control

Good Ideas So Far…

- Flow control
  - Stop & wait
  - Parallel stop & wait
  - Sliding window
- Loss recovery
  - Timeouts
  - Acknowledgement-driven recovery (selective repeat or cumulative acknowledgement)

Outline

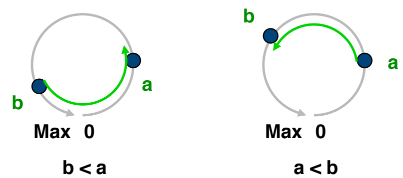
- TCP flow control
- Congestion sources and collapse
- Congestion control basics

Sequence Numbers (reminder)

- 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

Sequence Numbers

- 32 Bits, Unsigned → for bytes not packets!
  - Circular Comparison

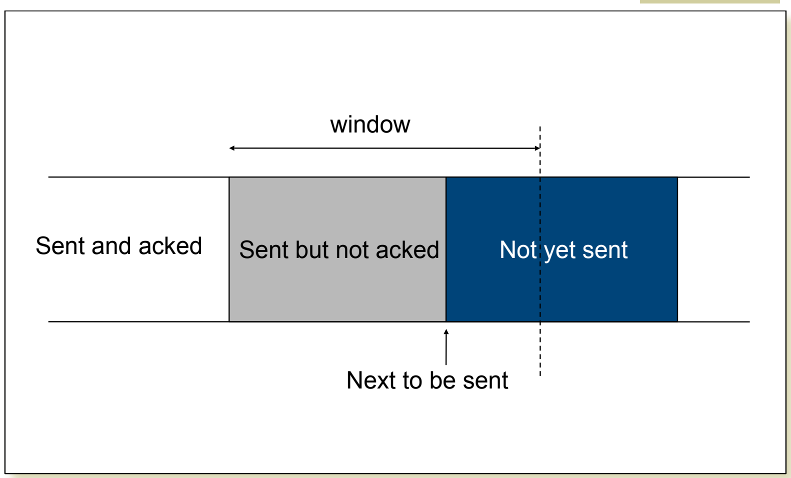


- Why So Big?
  - For sliding window, must have
    |Sequence Space| > |Sending Window| + |Receiving Window|
    - No problem
  - Also, want to guard against stray packets
    - With IP, packets have maximum lifetime of 120s
    - Sequence number would wrap around in this time at 286MB/s =~ 2.3Gbit/s (hmm!)

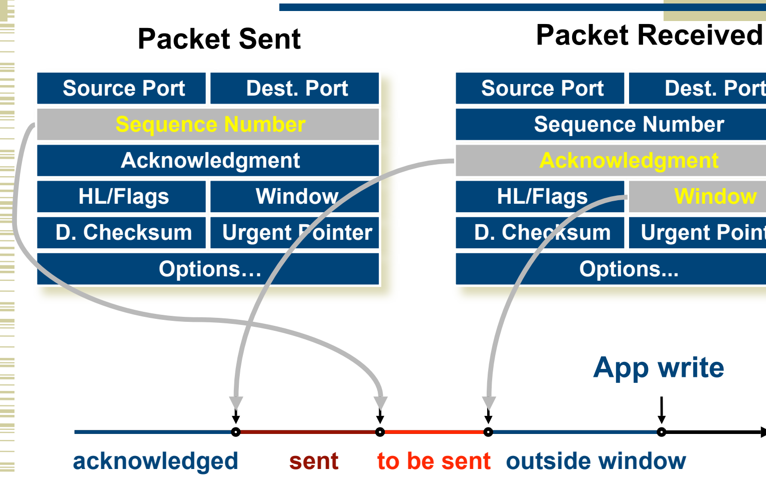
TCP Flow Control

- TCP is a sliding window protocol
  - For window size *n*, can send up to *n* bytes without receiving an acknowledgement
  - When the data is acknowledged then the window slides forward
- Each packet advertises a window size
  - Indicates number of bytes the receiver has space for
- Original TCP always sent entire window
  - But receiver buffer space != available net. capacity!
    - Congestion control now limits this
    - window = min(receiver window, congestion window)

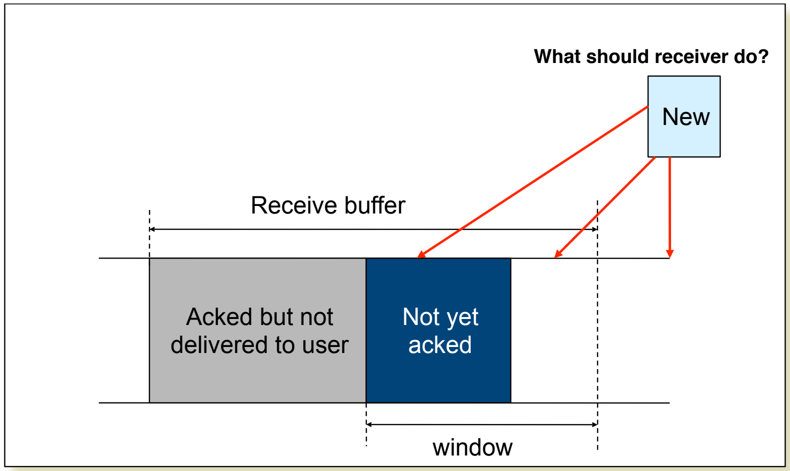
Window Flow Control: Send Side



Window Flow Control: Send Side



Window Flow Control: Receive Side



TCP Persist

- What happens if window is 0?
  - Receiver updates window when application reads data
  - What if this update is lost?
- TCP Persist state
  - Sender periodically sends 1 byte packets
  - Receiver responds with ACK even if it can't store the packet

Performance Considerations

- The window size can be controlled by receiving application
  - Can change the socket buffer size from a default (e.g. 8-64Kbytes) to some maximum value
- Modern TCPs (linux, bsd, os x) may auto-tune
  - Historical source of performance problems on fast nets
- The window size field in the TCP header limits the window that the receiver can advertise
  - 16 bits → 64 KBytes
  - 10 msec RTT → 51 Mbit/second
  - 100 msec RTT → 5 Mbit/second
  - TCP options to get around 64KB limit → increases above limit

Outline

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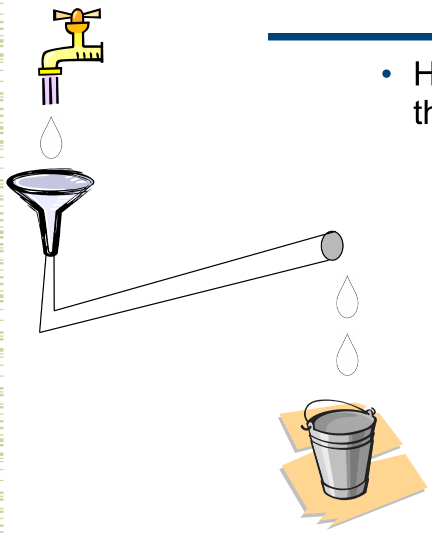
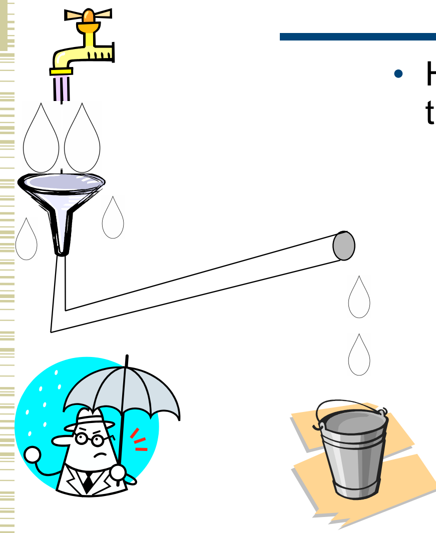
Internet Pipes?



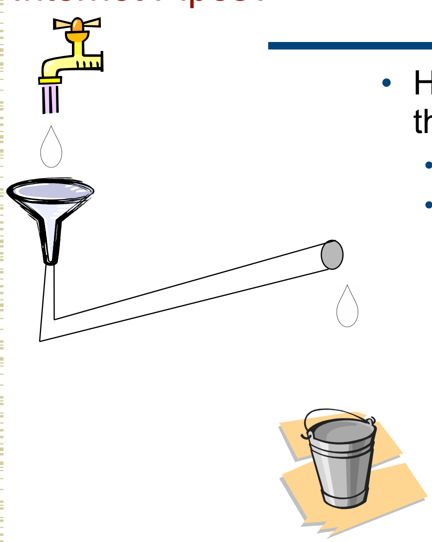
- How should you control the faucet?

Internet Pipes?



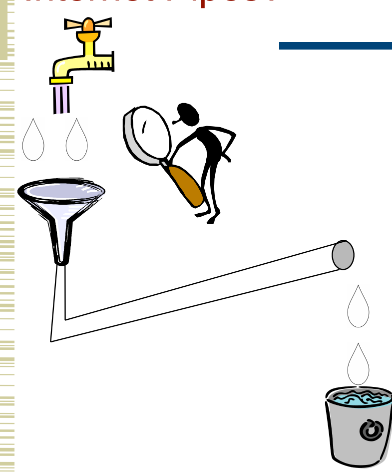
- How should you control the faucet?
  - Too fast – sink overflows!

Internet Pipes?



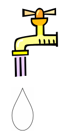
- How should you control the faucet?
  - Too fast – sink overflows!
  - Too slow – what happens?

Internet Pipes?

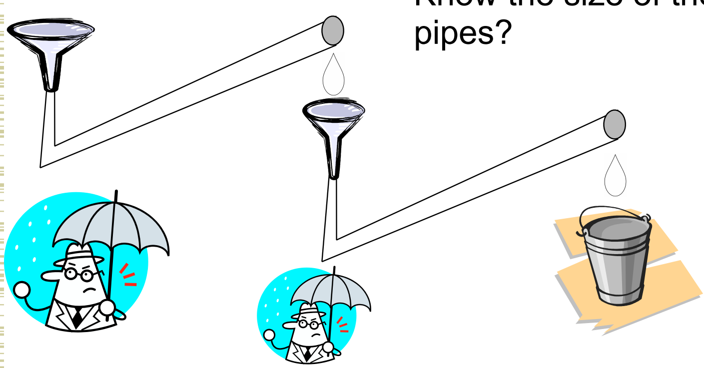


- How should you control the faucet?
  - Too fast – sink overflows
  - Too slow – what happens?
- Goals
  - Fill the bucket as quickly as possible
  - Avoid overflowing the sink
- Solution – watch the sink

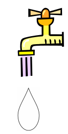
Plumbers Gone Wild!



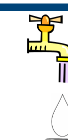
- How do we prevent water loss?
- Know the size of the pipes?

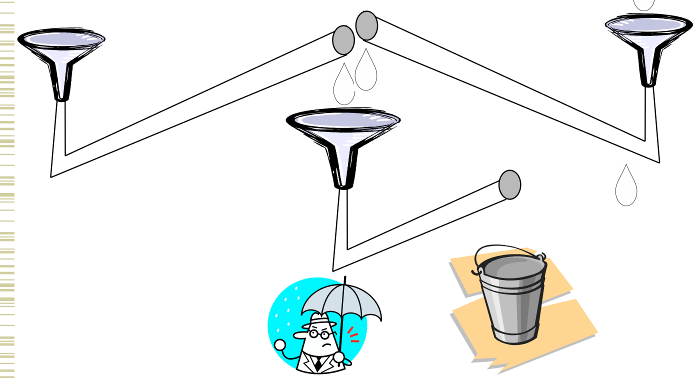


Plumbers Gone Wild 2!

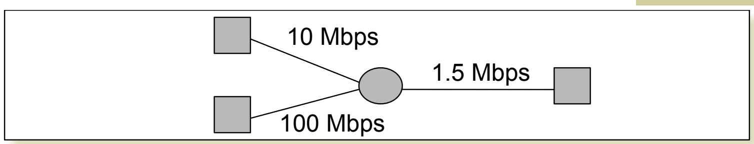


- Now what?
- Feedback from the bucket or the funnels?





Congestion

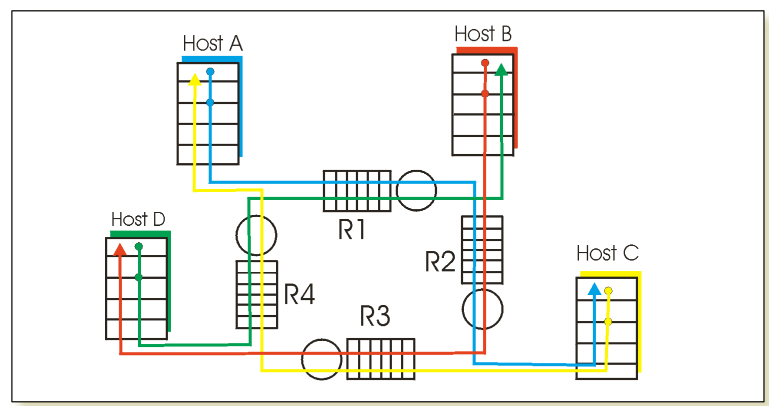


- Different sources compete for resources inside network
- Why is it a problem?
  - Sources are unaware of current state of resource
  - Sources are unaware of each other
- Manifestations:
  - Lost packets (buffer overflow at routers)
  - Long delays (queuing in router buffers)
  - Can result in throughput less than bottleneck link (1.5Mbps for the above topology) → a.k.a. congestion collapse

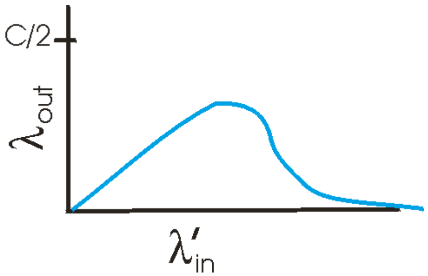
Causes & Costs of Congestion

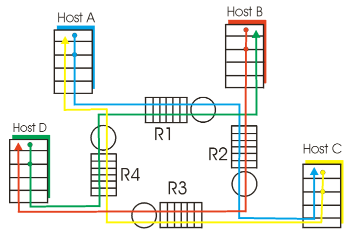
- Four senders – multihop paths
- Timeout/retransmit

Q: What happens as rate increases?



Causes & Costs of Congestion





- When packet dropped, any "upstream transmission capacity used for that packet was wasted!

Congestion Collapse

- Definition: *Increase in network load results in decrease of useful work done*
- Many possible causes
  - Spurious retransmissions of packets still in flight
    - Classical congestion collapse
    - How can this happen with packet conservation? RTT increases!
    - Solution: better timers and TCP congestion control
  - Undelivered packets
    - Packets consume resources and are dropped elsewhere in network
    - Solution: congestion control for ALL traffic

Congestion Control and Avoidance

- A mechanism that:
  - Uses network resources efficiently
  - Preserves fair network resource allocation
  - Prevents or avoids collapse
- Congestion collapse is not just a theory
  - Has been frequently observed in many networks

Approaches Towards Congestion Control

- Two broad approaches towards congestion control:

- End-end congestion control:
  - No explicit feedback from network
  - Congestion inferred from end-system observed loss, delay
  - Approach taken by TCP

- Network-assisted congestion control:
  - Routers provide feedback to end systems
    - Single bit indicating congestion (SNA, DECbit, TCP/IP ECN, ATM)
    - Explicit rate sender should send at
  - Problem: makes routers complicated

Example: TCP Congestion Control

- Very simple mechanisms in network
  - FIFO scheduling with shared buffer pool
  - Feedback through packet drops
- TCP interprets packet drops as signs of congestion and slows down
  - This is an assumption: packet drops are not a sign of congestion in all networks
    - E.g. wireless networks
- Periodically probes the network to check whether more bandwidth has become available.

Outline

- TCP flow control
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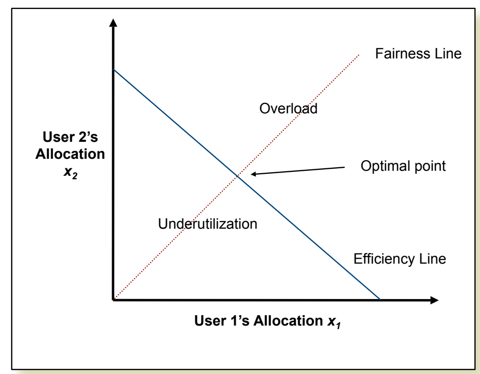
- Congestion control basics

Objectives

- Simple router behavior
- Distributedness
- Efficiency: $X = \Sigma x_i(t)$
- Fairness: $(\Sigma x_i)^2/n(\Sigma x_i^2)$
  - What are the important properties of this function?
- Convergence: control system must be stable

Phase Plots

- What are desirable properties?
- What if flows are not equal?



Basic Control Model

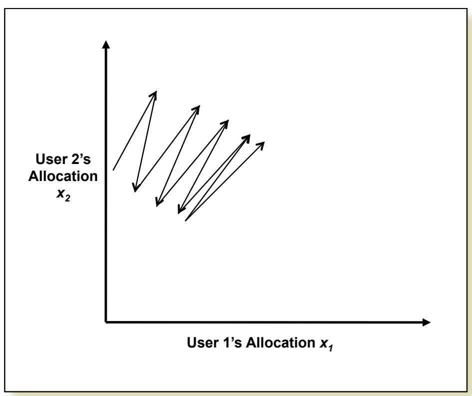
- Reduce speed when congestion is perceived
  - How is congestion signaled?
    - Either mark or drop packets
  - How much to reduce?
- Increase speed otherwise
  - Probe for available bandwidth – how?

Linear Control

- Many different possibilities for reaction to congestion and probing
  - Examine simple linear controls
    - Window(t + 1) = a + b Window(t)
    - Different a_i/b_i for increase and a_d/b_d for decrease
- Supports various reaction to signals
  - Increase/decrease additively
  - Increased/decrease multiplicatively
  - Which of the four combinations is optimal?

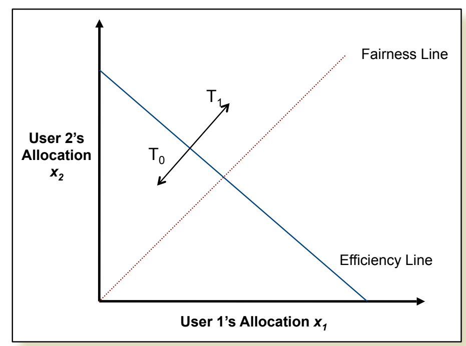
Phase Plots

- Simple way to visualize behavior of competing connections over time



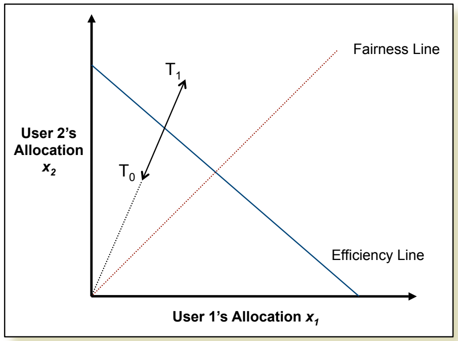
Additive Increase/Decrease

- Both X_1 and X_2 increase/ decrease by the same amount over time
  - Additive increase improves fairness and additive decrease reduces fairness

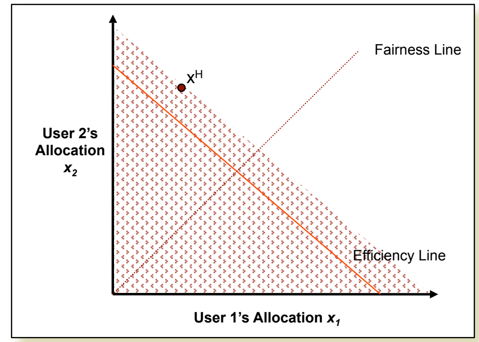


Muliplicative Increase/Decrease

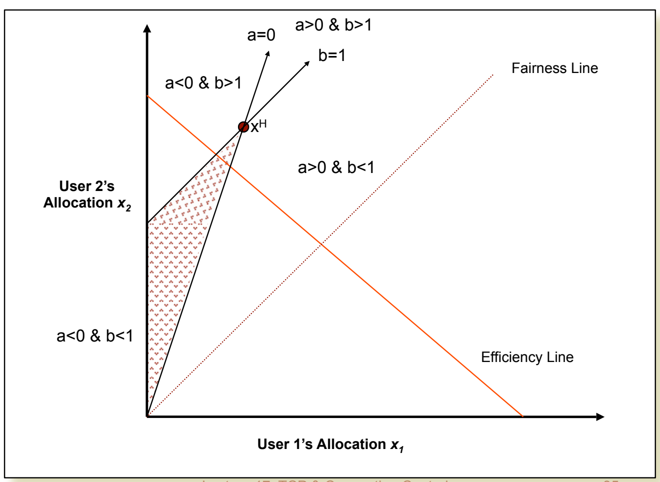
- Both X_1 and X_2 increase by the same factor over time
  - Extension from origin – constant fairness



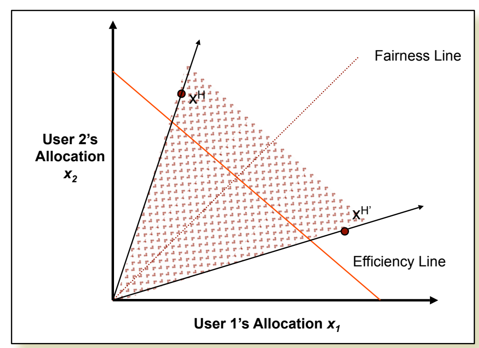
Convergence to Efficiency



Distributed Convergence to Efficiency

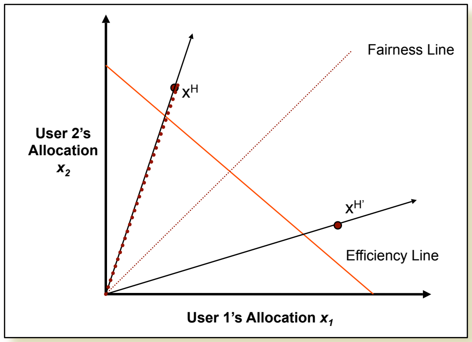


Convergence to Fairness



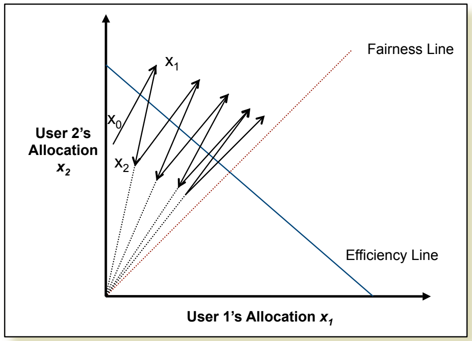
Convergence to Efficiency & Fairness

- Intersection of valid regions
- For decrease: a=0 & b < 1



What is the Right Choice?

- Constraints limit us to AIMD
  - Can have multiplicative term in increase (MAIMD)
  - AIMD moves towards optimal point



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
- TCP flow control
  - Sliding window → mapping to packet headers
  - 32bit sequence numbers (bytes)

Important Lessons

- Why is congestion control needed?
- How to evaluate congestion control algorithms?
  - Why is AIMD the right choice for congestion control?
- TCP flow control
  - Sliding window → mapping to packet headers
  - 32bit sequence numbers (bytes)

Good Ideas So Far…

- Flow control
  - Stop & wait
  - Parallel stop & wait
  - Sliding window (e.g., advertised windows)
- Loss recovery
  - Timeouts
  - Acknowledgement-driven recovery (selective repeat or cumulative acknowledgement)
- Congestion control
  - AIMD → fairness and efficiency
- Next Lecture: How does TCP actually implement these?

Pipes…Tubes…Let's call the whole thing off

- An alternate way to look at congestion?