CS4450

Computer Networks:
Architecture and Protocols

Lecture 24
Critical Analysis of TCP

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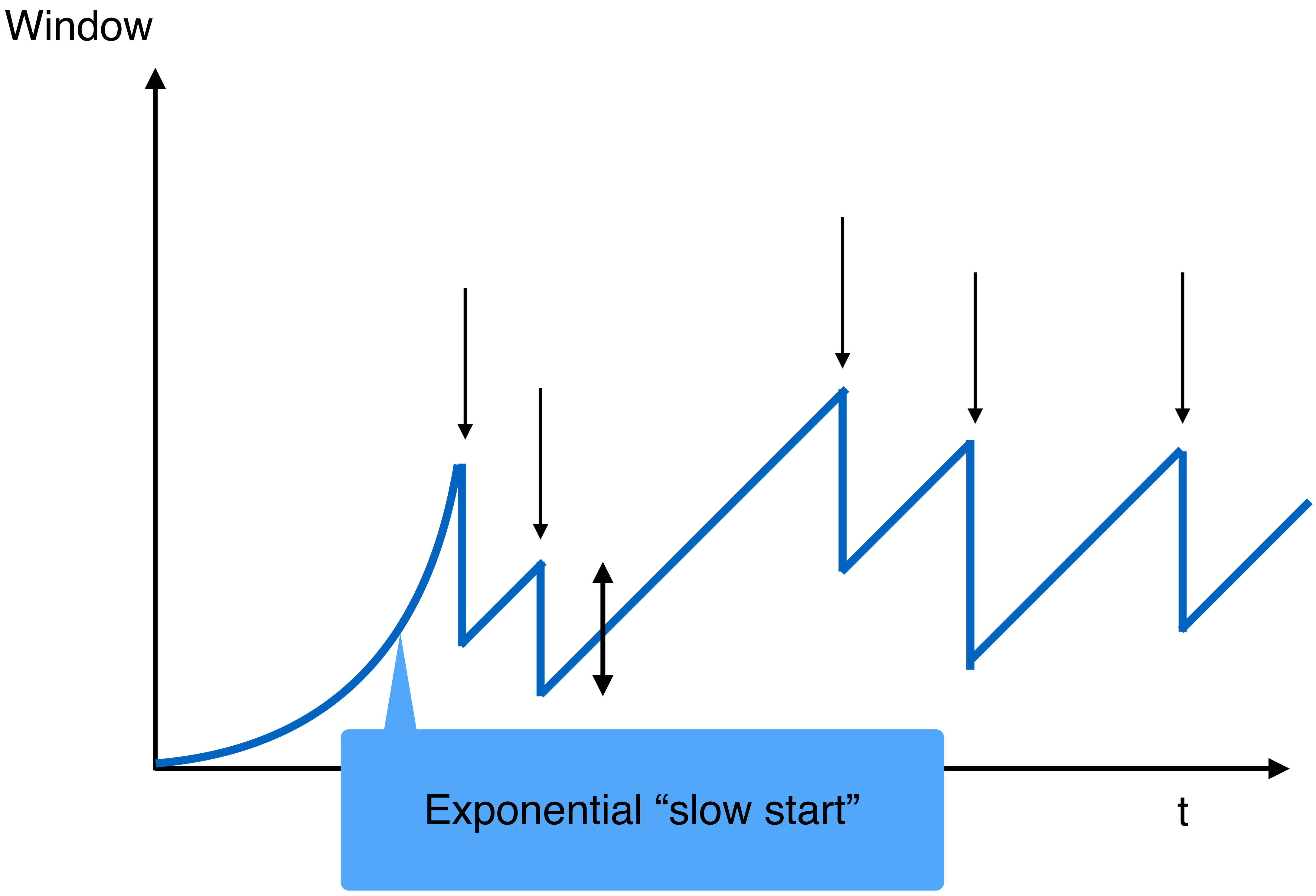
Cornell University Founded A.D. 1865

Purpose of Today

- The **conceptual parts of congestion control** are the main point
  - TCP is just a **specific implementation for a specific context** (Internet)
  - **Need to understand what TCP does and does not achieve**

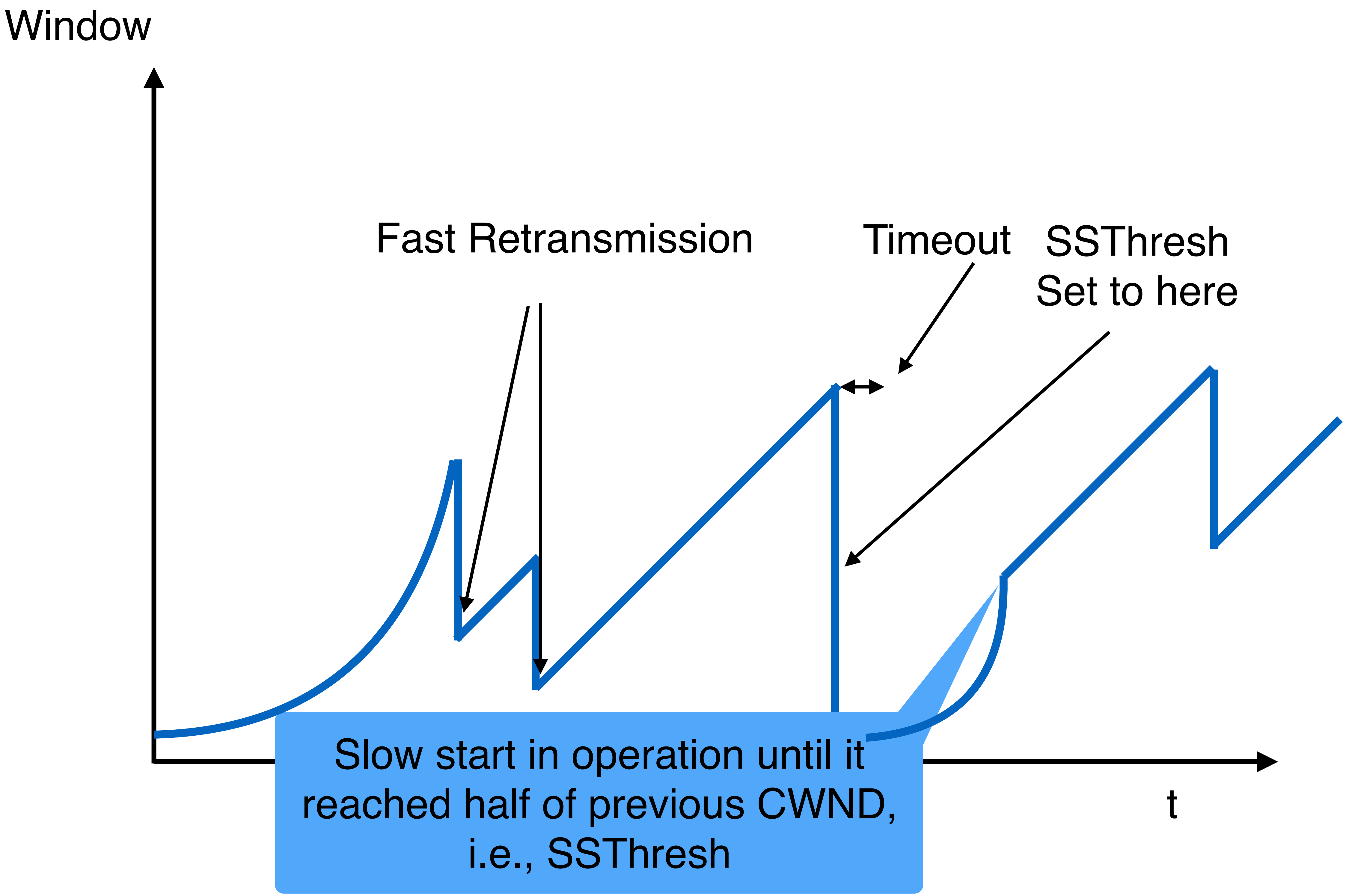
- But the conceptual parts let you think more generally
  - Beyond specific TCP congestion control details
  - How would I design a congestion control mechanism
    - **Given my specific context…?**
    - **Congestion control mechanisms depend on the context**
      - Different implementations for different contexts
      - One example: datacenter networks (next lecture)
      - Another example: wireless networks

Recap: Slow Start and the TCP Sawtooth (no timeouts)



Exponential “slow start”

Recap: TCP Time Diagram (with timeouts)



Slow start in operation until it reached half of previous CWND, i.e., SSThresh

Any Questions?

TCP and fairness guarantees

Consider A Simple Model

- Flows **ask** for an amount of bandwidth r_i
  - In reality, this request is implicit (the amount they send)

- The link gives them an amount a_i
  - Again, this is implicit (by how much is forwarded)
  - $a_i <= r_i$

- There is some total capacity C
  - Sum $a_i <= C$

Fairness

- When all flows want the same rate, fair is easy
    - Fair share = C/N
    - C = capacity of link
    - N = number of flows
- Note:
    - This is fair share per link. This is not a global fair share
- When not all flows have the same demand?
    - What happens here?

Example 1

- Requests: r_i Allocations: a_i
- C = 20
    - Requests: $r_1 = 6$, $r_2 = 5$, $r_3 = 4$
- Solution
    - $a_1 = 6$, $a_2 = 5$, $a_3 = 4$
- When bandwidth is plentiful, everyone gets their request
- This is the easy case

Example 2

- Requests: r_i Allocations: a_i
- $C = 12$
  - Requests: $r_1 = 6$, $r_2 = 5$, $r_3 = 4$
- One solution
  - $a_1 = 4$, $a_2 = 4$, $a_3 = 4$
  - Everyone gets the same
- Why not proportional to their demands?
  - $a_i = (12/15)\, r_i$
- Asking for more gets you more!
  - Not incentive compatible (i.e., cheating works!)
  - You can’t have that and invite innovation!

Example 3

- Requests: r_i Allocations: a_i
- C = 14
  - Requests: $r_1 = 6$, $r_2 = 5$, $r_3 = 4$
- $a_3 = 4$ (can’t give more than a flow wants)
- Remaining bandwidth is 10, with demands 6 and 5
  - From previous example, if both want more than their share, they both get half
  - $a_1 = a_2 = 5$

Max-Min Fairness

- Given a set of bandwidth demands r_i and total bandwidth C, max-min bandwidth allocations are $a_i = \min(f, r_i)$
  - Where f is the unique value such that $\mathrm{Sum}(a_i) = C$ or set f to be infinite if no such value exists

- **This is what round-robin service gives**
  - If all packets are MTU

- Property:
  - If you don't get full demand, no one gets more than you

Computing Max-Min Fairness

- Assume demands are in increasing order…
- If $C/N <= r_1$, then $a_i = C/N$ for all i
- Else, a_1 = r1, set $C = C - a_1$ and $N = N-1$
- Repeat
- Intuition: all flows requesting less than fair share get their request. Remaining flows divide equally

Example

- Assume link speed C is 10Mbps

- Have three flows:
    - Flow 1 is sending at a rate 8 Mbps
    - Flow 2 is sending at a rate 6 Mbps
    - Flow 3 is sending at a rate 2 Mbps

- How much bandwidth should each get?
    - According to max-min fairness?

- Work this out, talk to your neighbors

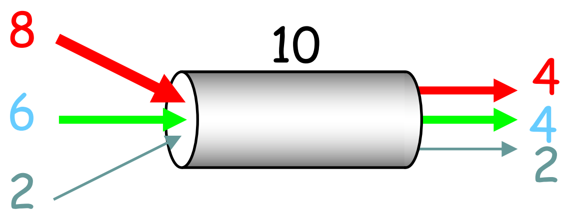
Example

- Requests: r_i Allocations: a_i

- Requests: $r_1 = 8$, $r_2 = 6$, $r_3 = 2$

- $C = 10$, $N = 3$, $C/N = 3.33$
  - Can serve all for r_3
  - Remove r_3 from the accounting: $C = C - r_3 = 8$, $N = 2$

- $C/2 = 4$
  - Can't service all for r_1 or r_2
  - So hold them to the remaining fair share: $f = 4$



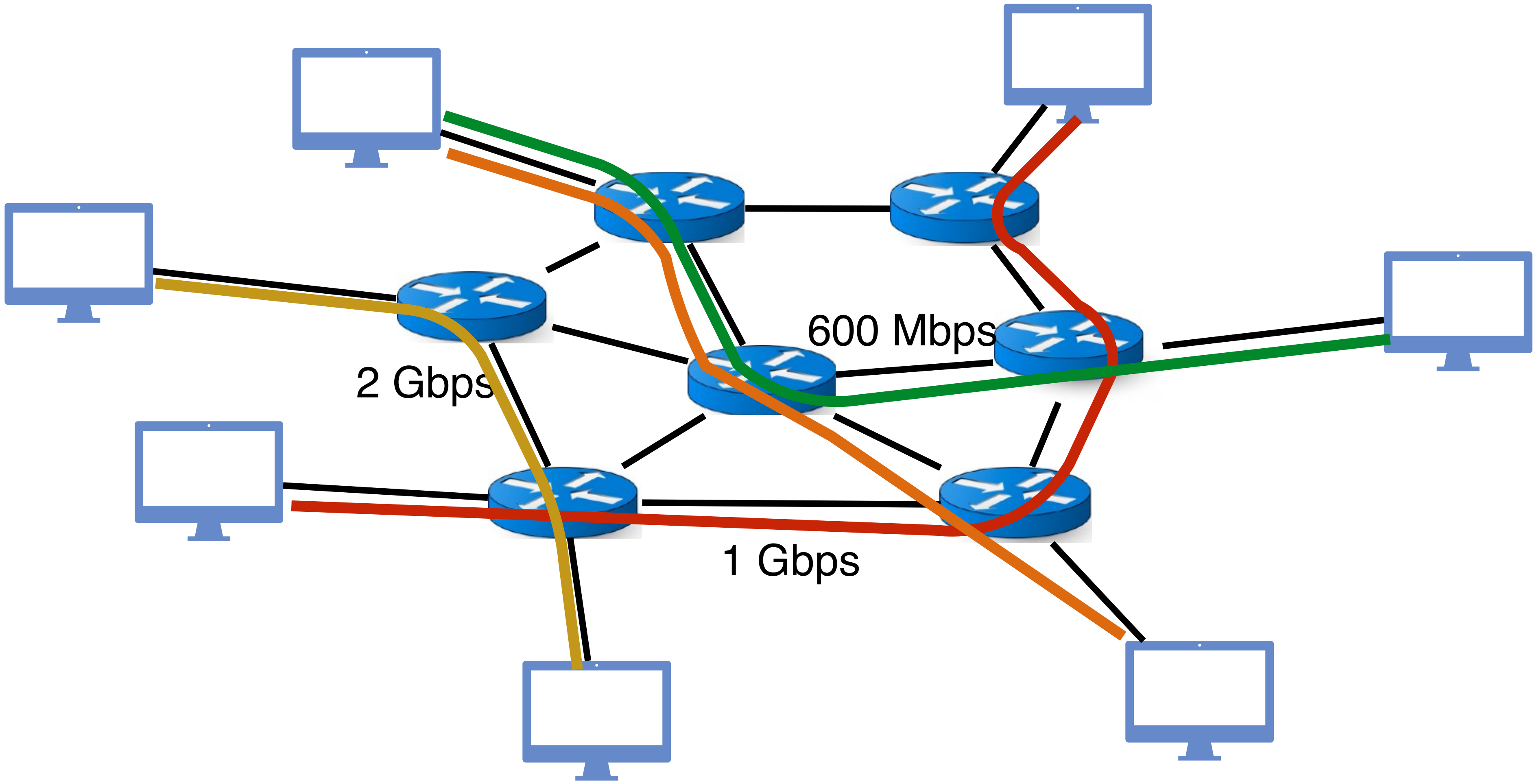
$f = 4$:
min(8, 4) = 4
min(6, 4) = 4
min(2, 4) = 2

Max-Min Fairness

- Max-min fairness the natural per-link fairness

- Only one that is
    - Symmetric
    - Incentive compatible (asking for more doesn’t help)

Reality of Congestion Control



Congestion control is a resource allocation problem involving many flows, many links and complicated global dynamics

Classical result:

In a stable state
(no dynamics; all flows are infinitely long; no failures; etc.)

TCP guarantees max-min fairness

Any Questions?

The Many Failings of TCP Congestion Control

1. Fills up queues (large queueing delays)
2. Every segment not ACKed is a loss (non-congestion related losses)
3. Produces irregular saw-tooth behavior
4. Biased against long RTTs (unfair)
5. Not designed for short flows
6. Easy to cheat

(1) TCP Fills Up Queues

- TCP only slows down when queues fill up
    - High queueing delays
- Means that it is not optimized for latency
    - What is it optimized for then?
        - **Answer: Fairness (discussion in next few slides)**
- And many packets are dropped when buffer fills
- Alternative 1: Use small buffers
    - Is this a good idea?
    - Answer: No, bursty traffic will lead to reduced utilization
- Alternative: **Random Early Drop (RED)**
    - Drop packets on purpose **before** queue is full
    - A very clever idea

Random Early Drop (or Detection)

- Measure average queue size A with exponential weighting
    - Average: Allows for short bursts of packets without over-reacting

- Drop probability is a function of A
    - No drops if A is very small
    - Low drop rate for moderate A’s
    - Drop everything if A is too big

- Drop probability applied to incoming packets

- Intuition: link is fully utilized well before buffer is full

Advantages of RED

- Keeps queues smaller, while allowing bursts
  - Just using small buffers in routers can’t do the latter

- Reduces synchronization between flows
  - Not all flows are dropping packets at once
  - Increases/decreases are more gentle

- Problem
  - Turns out that RED does not guarantee fairness

(2) Non-Congestion-Related Losses?

- For instance, RED drops packets intentionally
    - TCP would think the network is congested

- Can use **Explicit Congestion Notification (ECN)**

- Bit in IP packet header (actually two)
    - TCP receiver returns this bit in ACK

- When RED router would drop, it sets bit instead
    - Congestion semantics of bit exactly like that of drop

- Advantages
    - Doesn’t confuse corruption with congestion

(3) Sawtooth Behavior Uneven

- TCP throughput is “choppy"
  - Repeated swings between W/2 to W

- Some apps would prefer sending at a steady rate
  - E.g., streaming apps

- A solution: “Equation-based congestion control”
  - Ditch TCP’s increase/decrease rules and just follow the equation:
  - **[Matthew Mathis, 1997] TCP Throughput = MSS/RTT sqrt(3/2p)**
    - **Where p is drop rate**
  - Measure drop percentage p and set rate accordingly

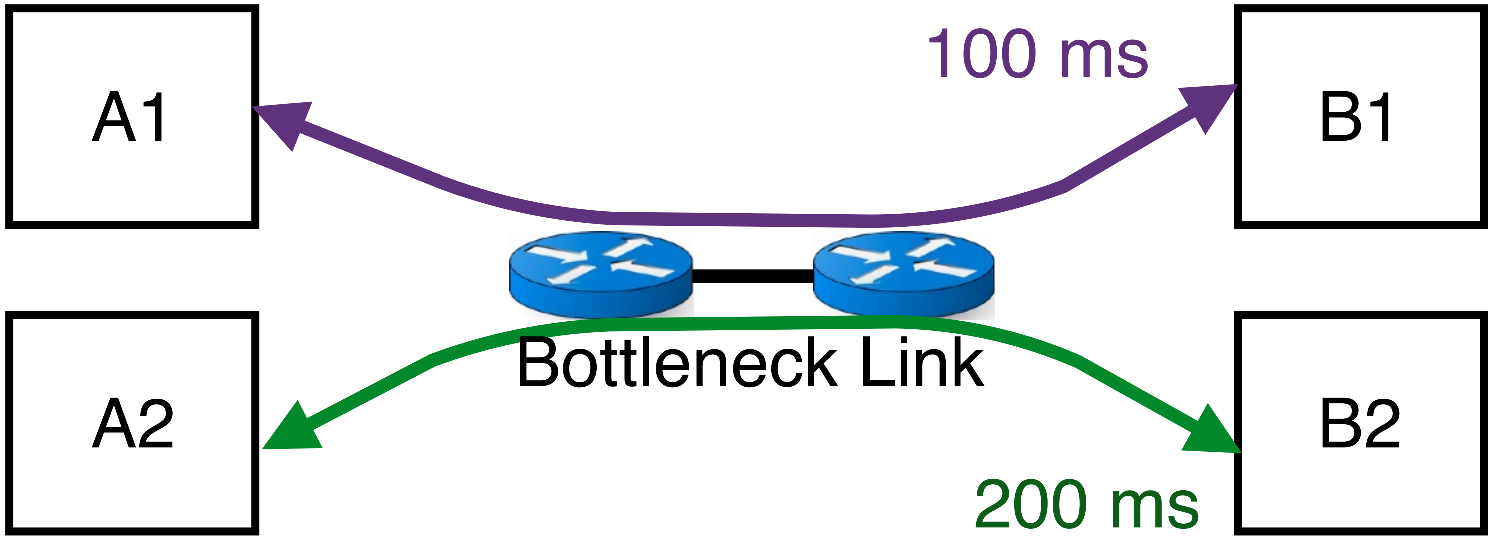
- Following the TCP equation ensures we’re TCP friendly
  - I.e., use no more than TCP does in similar setting

Any Questions?

(4) Bias Against Long RTTs

- Flows get throughput inversely proportional to RTT
- **TCP unfair in the face of heterogeneous RTTs!**
- [Matthew Mathis, 1997] TCP Throughput = MSS/RTT sqrt(3/2p)
  - Where p is drop rate

- Flows with long RTT will achieve lower throughput



Possible Solutions

- Make additive constant proportional to RTT

- But people don’t really care about this…

(5) How Short Flows Fare?

- Internet traffic:
  - Elephant and mice flows
  - Elephant flows carry most bytes (>95%), but are very few (<5%)
  - Mice flows carry very few bytes, but most flows are mice
    - 50% of flows have < 1500B to send (1 MTU);
    - 80% of flows have < 100KB to send

- Problem with TCP?
  - Mice flows do not have enough packets for duplicate ACKs!!
  - Drop ~=~ Timeout (unnecessary high latency)
  - These are precisely the flows for which latency matters!!!

- Another problem:
  - Starting with small window size leads to high latency

Possible Solutions?

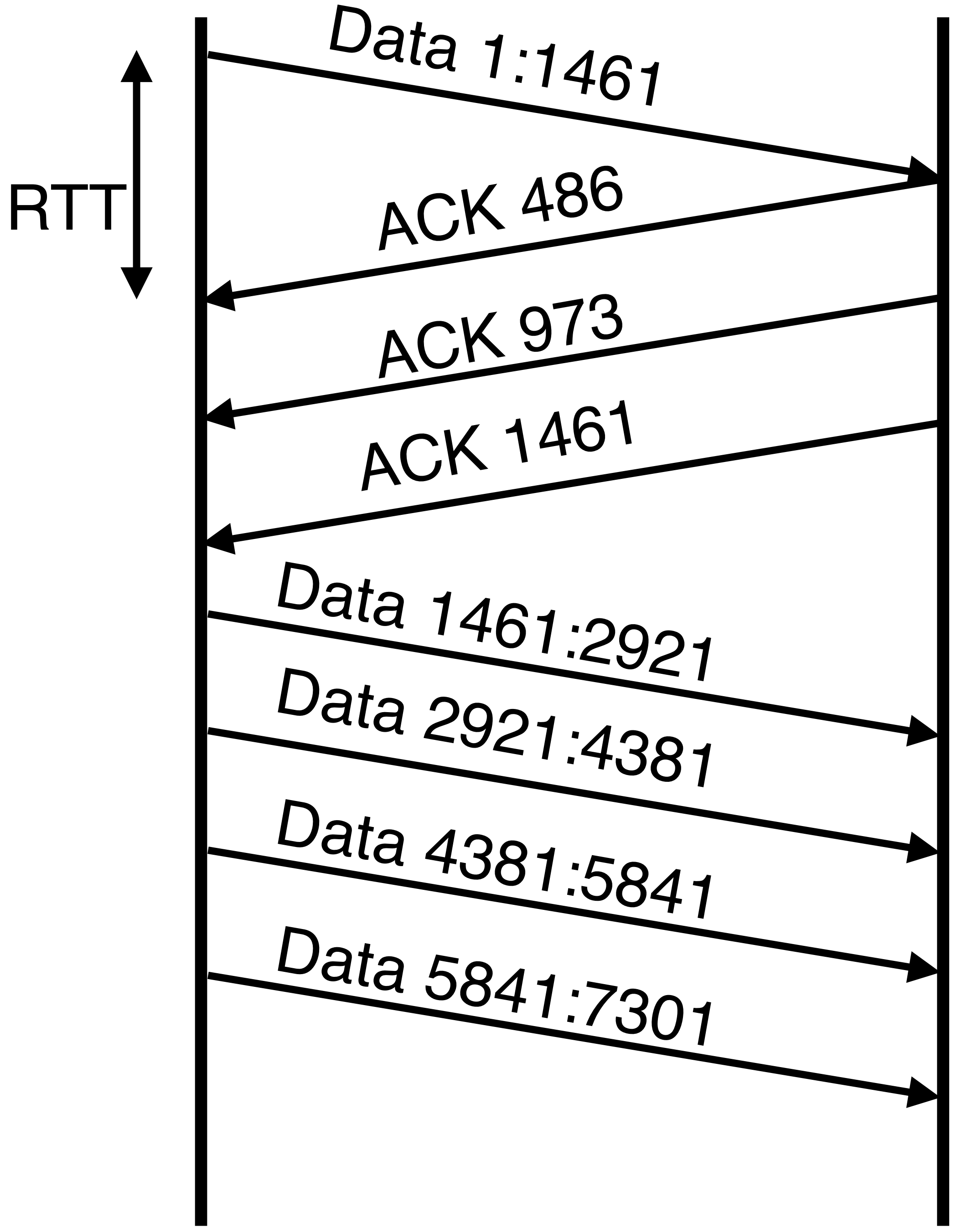
- Larger initial window?
    - Google proposed moving from ~4KB to ~15KB
    - Covers ~90% of HTTP Web
    - Decreases delay by 5%
- Many recent research papers on the timeout problem
    - Require network support

(6) Cheating

- TCP was designed assuming a cooperative world
- No attempt was made to prevent cheating
- Many ways to cheat, will present three

Cheating #1: ACK-splitting (receiver)

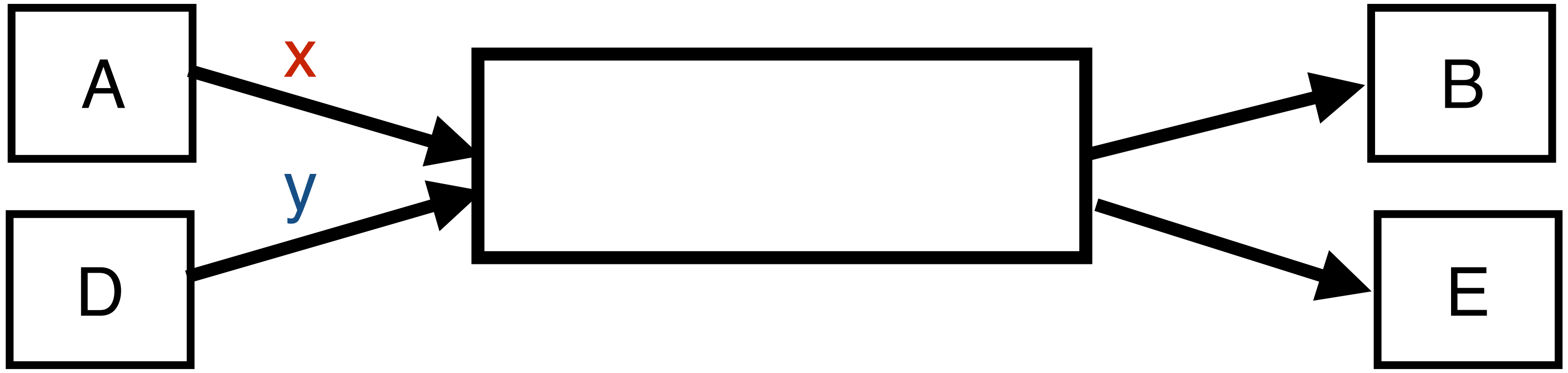
- TCP Rule: grow window by one MSS for each valid ACK received
- Send **M** (distinct) ACKs for one MSS
- Growth factor proportional to **M**



Cheating #2: Increasing CWND Faster (source)

- TCP Rule: increase window by one MSS for each valid ACK received
- Increase window by **M** per ACK
- Growth factor proportional to **M**

Cheating #3: Open Many Connections (source/receiver)



- Assume
    - A start 10 connections to B
    - D starts 1 connection to E
    - Each connection gets about the same throughput
- Then A gets 10 times more throughput than D

Cheating

- Either sender or receiver can independently cheat!

- **Why hasn't Internet suffered congestion collapse yet?**
    - Individuals don't hack TCP (not worth it)
    - Companies need to avoid TCP wars

- How can we prevent cheating
    - Verify TCP implementations
    - Controlling end points is hopeless

- Nobody cares, really

Any Questions?

How Do You Solve These Problems?

- Bias against long RTTs
- Slow to ramp up (for short-flows)
- Cheating
- Need for uniformity

Next lecture: Datacenter networks

Where it matters,
And where people have tried to solve these problems!