Project 2: Traceroute

- Project 2 (Traceroute) is out
- Due Friday, March 22nd at 11:59 PM PST
- Project 2 is hard(er)
  - Start Early
  - Don’t expect a perfect score
- Ethan Jackson is the lead TA.
- See the website for his office hours.
TCP Congestion Control (contd.)

CS 168
http://cs168.io

Sylvia Ratnasamy
TCP Congestion Control (contd.)

CS 168
http://cs168.io

Sylvia Ratnasamy
Today

- The TCP state machine
- Modeling TCP throughput
- Critiquing TCP
- Router-assisted CC (briefly)
TCP Implementation
TCP Implementation
TCP Implementation

- **State at sender**
  - CWND (initialized to a 1 MSS)
  - SSTHRESH (initialized to a large constant)
  - dupACKcount (initialized to zero, as before)
  - Timer (as before)
TCP Implementation

- **State at sender**
  - CWND (initialized to a 1 MSS)
  - SSTHRESH (initialized to a large constant)
  - dupACKcount (initialized to zero, as before)
  - Timer (as before)

- **Events at sender**
  - ACK (for new data)
  - dupACK (duplicate ACK for old data)
  - Timeout
TCP Implementation

- **State at sender**
  - CWND (initialized to a 1 MSS)
  - SSTHRESH (initialized to a large constant)
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- **Events at sender**
  - ACK (for new data)
  - dupACK (duplicate ACK for old data)
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- **What about receiver?**
  - Just send ACKs like before
Event: ACK (new data)

- If in slow start
  - CWND += 1 (MSS)
Event: ACK (new data)

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- CWND packets per RTT
- Hence after one RTT with no drops:
  \[ \text{CWND} = 2 \times \text{CWND} \]
Event: ACK (new data)

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  - CWND += 1 (MSS)

Slow start phase
Event: ACK (new data)

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- Else
  - CWND = CWND + 1/CWND
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Slow start phase

- CWND packets per RTT
- Hence after one RTT with no drops:
  \[ CWND = CWND + 1 \]
Event: ACK (new data)

- If in slow start
  - CWND += 1 (MSS)

- Else
  - CWND = CWND + 1/CWND

Slow start phase

“Congestion Avoidance” phase (additive increase)
Event: ACK (new data)

- If in slow start
  - CWND += 1 (MSS)

- Else
  - CWND = CWND + 1/CWND

- Plus the usual ...
  - Reset timer, dupACKcount
  - Send new data packets (if CWND allows)

---

Slow start phase

“Congestion Avoidance” phase (additive increase)
Event: TimeOut

- On Timeout
  - SSTHRESH $\leftarrow$ CWND/2
  - CWND $\leftarrow$ 1
  - And retransmit packet (as always)
Event: TimeOut

- On Timeout
  - SSTHRESH $\leftarrow$ CWND/2
  - CWND $\leftarrow$ 1
  - And retransmit packet (as always)
Event: dupACK
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- dupACKcount ++
**Event: dupACK**

- dupACKcount ++

- If dupACKcount = 3 /* fast retransmit */
  - SSTHRESH = CWND/2
  - CWND = CWND/2 (but never less than 1)
  - And retransmit packet (as always)
Event: dupACK

- dupACKcount ++

- If dupACKcount = 3 /* fast retransmit */
  - SSTHRESH = CWND/2
  - CWND = CWND/2 (but never less than 1)
  - And retransmit packet (as always)

Remain in AIMD after fast retransmission…
Any Questions?
Any Questions?
Time Diagram

Window
Time Diagram

Window
Time Diagram

Window

Fast Retransmission
Time Diagram

Window

Fast Retransmission

Timeout
Time Diagram

Window

Fast Retransmission

Timeout
Time Diagram

Window

- Fast Retransmission
- Timeout
- SSThresh Set to Here

$t$
Window

Time Diagram

Slow start in operation until CWND crosses SSTHRESH
Time Diagram

Window

Fast Retransmission

Timeout

SSThresh Set to Here

Slow start in operation until CWND crosses SSTHRESH
One Final Phase: Fast Recovery
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- The problem: congestion avoidance too slow in recovering from an isolated loss
One Final Phase: Fast Recovery

- The problem: congestion avoidance too slow in recovering from an isolated loss

- This last feature is an optimization to improve performance
  - Bit of a hack, but effective
Example
Example
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- Again: counting packets, not bytes
  - If you want example in bytes, assume MSS=1000 and add three zeros to all sequence numbers
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  - If you want example in bytes, assume MSS=1000 and add three zeros to all sequence numbers

- Consider a TCP connection with:
  - CWND=10 packets
  - Last ACK was for packet # 101
    - i.e., receiver expecting next packet to have seq. no. 101

- 10 packets [101, 102, 103, ..., 110] are in flight
  - Packet 101 is dropped
  - What ACKs do they generate and how does the sender respond?
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110
Timeline (at sender)

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Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1 (no xmit)
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1 (no xmit)
- ACK 101 (due to 103) cwnd=10 dupACK#2 (no xmit)
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1 (no xmit)
- ACK 101 (due to 103) cwnd=10 dupACK#2 (no xmit)
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In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

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- ACK 101 (due to 103) cwnd=10 dupACK#2 (no xmit)
- ACK 101 (due to 104) cwnd=10 dupACK#3 (no xmit)
- RETRANSMIT 101 ssthresh=5 cwnd= 5
Timeline (at sender)

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- ACK 101 (due to 102) cwnd=10 dupACK#1 (no xmit)
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- RETRANSMIT 101 ssthresh=5 cwnd=5
- ACK 101 (due to 105) cwnd=5 (no xmit)
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- ACK 101 (due to 104) cwnd=10  dupACK#3 (no xmit)
- RETRANSMIT 101 ssthresh=5  cwnd= 5
- ACK 101 (due to 105) cwnd=5 (no xmit)
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- RETRANSMIT 101 ssthresh=5 cwnd=5
- ACK 101 (due to 105) cwnd=5 (no xmit)
- ACK 101 (due to 106) cwnd=5 (no xmit)
- ACK 101 (due to 107) cwnd=5 (no xmit)

Note that you do not restart dupACK counter on same packet!
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- ACK 101 (due to 109) cwnd=5 (no xmit)
- ACK 101 (due to 110) cwnd=5 (no xmit)
Timeline (at sender)

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- RETRANSMIT 101 ssthresh=5 cwnd=5
- ACK 101 (due to 105) cwnd=5 (no xmit)
- ACK 101 (due to 106) cwnd=5 (no xmit)
- ACK 101 (due to 107) cwnd=5 (no xmit)
- ACK 101 (due to 108) cwnd=5 (no xmit)
- ACK 101 (due to 109) cwnd=5 (no xmit)
- ACK 101 (due to 110) cwnd=5 (no xmit)
- ACK 111 (due to 101) ➔ only now can we transmit new packets
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1 (no xmit)
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- ACK 101 (due to 104) cwnd=10 dupACK#3 (no xmit)
- RETRANSMIT 101 ssthresh=5 cwnd=5
- ACK 101 (due to 105) cwnd=5 (no xmit)
- ACK 101 (due to 106) cwnd=5 (no xmit)
- ACK 101 (due to 107) cwnd=5 (no xmit)
- ACK 101 (due to 108) cwnd=5 (no xmit)
- ACK 101 (due to 109) cwnd=5 (no xmit)
- ACK 101 (due to 110) cwnd=5 (no xmit)
- ACK 111 (due to 101) only now can we transmit new packets
- Plus no packets in flight so no additional ACKs for another RTT
Two Questions
Two Questions
Two Questions

- Do you understand the problem?
  - Have to wait a long time before sending again
  - When you finally send, you have to send full window
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- How would you fix it?
Solution: Fast Recovery
Solution: Fast Recovery
Solution: Fast Recovery

Idea: Grant the sender temporary “credit” for each dupACK so as to keep packets in flight
Solution: Fast Recovery

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- If dupACKcount = 3
  - SSTHRESH = CWND/2
  - CWND = SSTHRESH + 3
Solution: Fast Recovery

Idea: Grant the sender temporary “credit” for each dupACK so as to keep packets in flight

- If dupACKcount = 3
  - SSTHRESH = CWND/2
  - CWND = SSTHRESH + 3

- While in fast recovery
  - CWND = CWND + 1 (MSS) for each additional duplicate ACK
  - This allows source to send an additional packet…
  - …to compensate for the packet that arrived (generating dupACK)
Solution: Fast Recovery

Idea: Grant the sender temporary “credit” for each dupACK so as to keep packets in flight

- If dupACKcount = 3
  - SSTHRESH = CWND/2
  - CWND = SSTHRESH + 3

- While in fast recovery
  - CWND = CWND + 1 (MSS) for each additional duplicate ACK
  - This allows source to send an additional packet…
  - …to compensate for the packet that arrived (generating dupACK)

- Exit fast recovery after receiving new ACK
  - set CWND = SSTHRESH
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1
- ACK 101 (due to 103) cwnd=10 dupACK#2
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1
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Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1
- ACK 101 (due to 103) cwnd=10 dupACK#2
- ACK 101 (due to 104) cwnd=10 dupACK#3
- REXMIT 101 ssthresh=5 cwnd= 8 (5+3)
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1
- ACK 101 (due to 103) cwnd=10 dupACK#2
- ACK 101 (due to 104) cwnd=10 dupACK#3
- REXMIT 101 ssthresh=5 cwnd= 8 (5+3)
- ACK 101 (due to 105) cwnd= 9 (no xmit)
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10  dupACK#1
- ACK 101 (due to 103) cwnd=10  dupACK#2
- ACK 101 (due to 104) cwnd=10  dupACK#3
- REXMIT 101 ssthresh=5  cwnd=8 (5+3)
- ACK 101 (due to 105) cwnd=9 (no xmit)
- ACK 101 (due to 106) cwnd=10 (no xmit)
Timeline (at sender)

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- ACK 101 (due to 103) cwnd=10 dupACK#2
- ACK 101 (due to 104) cwnd=10 dupACK#3
- REXMIT 101 ssthresh=5 cwnd= 8 (5+3)
- ACK 101 (due to 105) cwnd= 9 (no xmit)
- ACK 101 (due to 106) cwnd=10 (no xmit)
- ACK 101 (due to 107) cwnd=11 (xmit 111)
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1
- ACK 101 (due to 103) cwnd=10 dupACK#2
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- REXMIT 101 ssthresh=5 cwnd=8 (5+3)
- ACK 101 (due to 105) cwnd=9 (no xmit)
- ACK 101 (due to 106) cwnd=10 (no xmit)
- ACK 101 (due to 107) cwnd=11 (xmit 111)
- ACK 101 (due to 108) cwnd=12 (xmit 112)
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

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- ACK 101 (due to 103) cwnd=10 dupACK#2
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- ACK 101 (due to 105) cwnd= 9 (no xmit)
- ACK 101 (due to 106) cwnd=10 (no xmit)
- ACK 101 (due to 107) cwnd=11 (xmit 111)
- ACK 101 (due to 108) cwnd=12 (xmit 112)
- ACK 101 (due to 109) cwnd=13 (xmit 113)
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1
- ACK 101 (due to 103) cwnd=10 dupACK#2
- ACK 101 (due to 104) cwnd=10 dupACK#3
- REXMIT 101 ssthresh=5 cwnd= 8 (5+3)
- ACK 101 (due to 105) cwnd= 9 (no xmit)
- ACK 101 (due to 106) cwnd=10 (no xmit)
- ACK 101 (due to 107) cwnd=11 (xmit 111)
- ACK 101 (due to 108) cwnd=12 (xmit 112)
- ACK 101 (due to 109) cwnd=13 (xmit 113)
- ACK 101 (due to 110) cwnd=14 (xmit 114)
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10  dupACK#1
- ACK 101 (due to 103) cwnd=10  dupACK#2
- ACK 101 (due to 104) cwnd=10  dupACK#3
- REXMIT 101 ssthresh=5  cwnd= 8 (5+3)
- ACK 101 (due to 105) cwnd= 9 (no xmit)
- ACK 101 (due to 106) cwnd=10 (no xmit)
- ACK 101 (due to 107) cwnd=11 (xmit 111)
- ACK 101 (due to 108) cwnd=12 (xmit 112)
- ACK 101 (due to 109) cwnd=13 (xmit 113)
- ACK 101 (due to 110) cwnd=14 (xmit 114)
- ACK 111 (due to 101) cwnd = 5 (xmit 115) ➞ exiting fast recovery

✗ 101 111, 112, ...
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1
- ACK 101 (due to 103) cwnd=10 dupACK#2
- ACK 101 (due to 104) cwnd=10 dupACK#3
- REXMIT 101 ssthresh=5 cwnd=8 (5+3)
- ACK 101 (due to 105) cwnd=9 (no xmit)
- ACK 101 (due to 106) cwnd=10 (no xmit)
- ACK 101 (due to 107) cwnd=11 (xmit 111)
- ACK 101 (due to 108) cwnd=12 (xmit 112)
- ACK 101 (due to 109) cwnd=13 (xmit 113)
- ACK 101 (due to 110) cwnd=14 (xmit 114)
- ACK 111 (due to 101) cwnd = 5 (xmit 115) ➜ exiting fast recovery
- Packets 111-114 already in flight (and now sending 115)
Timeline (at sender)

In flight: 101, 102, 103, 104, 105, 106, 107, 108, 109, 110

- ACK 101 (due to 102) cwnd=10 dupACK#1
- ACK 101 (due to 103) cwnd=10 dupACK#2
- ACK 101 (due to 104) cwnd=10 dupACK#3
- REXMIT 101 ssthresh=5 cwnd= 8 (5+3)
- ACK 101 (due to 105) cwnd= 9 (no xmit)
- ACK 101 (due to 106) cwnd=10 (no xmit)
- ACK 101 (due to 107) cwnd=11 (xmit 111)
- ACK 101 (due to 108) cwnd=12 (xmit 112)
- ACK 101 (due to 109) cwnd=13 (xmit 113)
- ACK 101 (due to 110) cwnd=14 (xmit 114)
- ACK 111 (due to 101) cwnd = 5 (xmit 115) ← exiting fast recovery
- Packets 111-114 already in flight (and now sending 115)
- ACK 112 (due to 111) cwnd = 5 + 1/5 ← back in congestion avoidance
Updated Event-Actions
Updated Event-Actions
Event: ACK (new data)

- If in slow start
  - CWND += 1 (MSS)

- If in fast recovery
  - CWND = SSTHRESH

- Else
  - CWND = CWND + 1/CWND

- Plus the usual...

  Slow start phase

  Leaving Fast Recovery

  “Congestion Avoidance” phase (additive increase)
Event: ACK (new data)

- If in slow start
  - CWND += 1 (MSS)

- If in fast recovery
  - CWND = SSTHRESH

- Else
  - CWND = CWND + 1/CWND

- Plus the usual...

---

- Slow start phase
- Leaving Fast Recovery
- “Congestion Avoidance” phase (additive increase)
Event: dupACK

- dupACKcount ++

- If dupACKcount = 3 /* fast retransmit */
  - ssthresh = CWND/2
  - CWND = CWND/2 +3
  - And retransmit packet

- If dupACKcount > 3 /* fast recovery */
  - CWND = CWND + 1 (MSS)
Event: dupACK

- dupACKcount ++

- If dupACKcount = 3 /* fast retransmit */
  - ssthresh = CWND/2
  - CWND = CWND/2 + 3
  - And retransmit packet

- If dupACKcount > 3 /* fast recovery */
  - CWND = CWND + 1 (MSS)
Next: TCP State Machine
Next: TCP State Machine
TCP State Machine

slow start

congestion avoidance

fast recovery
TCP State Machine

- slow start
- fast recovery
- congestion avoidance
TCP State Machine

slow start

fast recovery

congestion avoidance

timeout
TCP State Machine

- **Slow Start**:
  - Transition to Congestion Avoidance with CWND > SSTHRESH
  - Transition to Fast Recovery with timeout
  - Transition to itself with new ACK
  - Transition to itself with timeout

- **Congestion Avoidance**:
  - Transition to Slow Start with timeout

- **Fast Recovery**:
  - Transition to Slow Start with timeout
TCP State Machine

- **slow start**
  - dupACK
  - new ACK
  - timeout

- **fast recovery**
  - timeout

- **congestion avoidance**
  - CWND > SSTHRESH
  - timeout
TCP State Machine

- **Slow Start**
  - Transition on **dupACK**
  - Transition on **new ACK**
  - Transition on **dupACK=3**
  - Transition on **timeout**

- **Fast Recovery**
  - Transition on **CWND > SSTHRESH**
  - Transition on **timeout**

- **Congestion Avoidance**
  - Transition on **timeout**
TCP State Machine

- **slow start**: CWND > SSTHRESH → congestion avoidance
- **congestion avoidance**: new ACK → fast recovery
- **fast recovery**: timeout → slow start
- **slow start**: dupACK → slow start
- **congestion avoidance**: timeout → slow start
- **fast recovery**: timeout → slow start
- **new ACK**: congestion avoidance
- **dupACK**: congestion avoidance
TCP State Machine

- **slow start**: CWND > SSTHRESH
- **congestion avoidance**: timeout
- **fast recovery**: dupACK=3
- **new ACK**: timeout
- **dupACK**: timeout
- **dupACK=3**: timeout

States:
- slow start
- congestion avoidance
- fast recovery
TCP State Machine

- **Slow Start**
  - CWND > SSTHRESH
  - timeout
  - new ACK
  - dupACK
  - dupACK=3

- **Congestion Avoidance**
  - timeout
  - new ACK
  - dupACK
  - dupACK=3

- **Fast Recovery**
  - timeout
  - dupACK
  - dupACK
TCP State Machine

dupACK

dupACK=3

cWND > SSTHRESH

timeout

dupACK

dupACK=3

new ACK

timeout

dupACK

dupACK=3

new ACK

timeout

dupACK

dupACK
Many variants
Many variants
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- TCP-Tahoe
  - CWND = 1 on triple dupACK
Many variants

- TCP-Tahoe
  - $\text{CWND} = 1$ on triple dupACK
- TCP-Reno
  - $\text{CWND} = 1$ on timeout
  - $\text{CWND} = \text{CWND}/2$ on triple dupack
Many variants

- **TCP-Tahoe**
  - CWND = 1 on triple dupACK
- **TCP-Reno**
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  - TCP-Reno + improved fast recovery
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  - incorporates “selective acknowledgements”
  - ACKs describe byte ranges received
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Interoperability
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- How can all these algorithms coexist? Don’t we need a single, uniform standard?
Interoperability

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- What happens if I’m using Reno and you are using Tahoe, and we try to communicate?
Interoperability

- How can all these algorithms coexist? Don’t we need a single, uniform standard?

- What happens if I’m using Reno and you are using Tahoe, and we try to communicate?

- What happens if I’m using Tahoe and you are using SACK?
TCP Throughput Equation
TCP Throughput
TCP Throughput

- Given a path, what TCP throughput can we expect?
TCP Throughput

- Given a path, what TCP throughput can we expect?

- We’ll derive a simple model that expresses TCP throughput in terms of path properties:
  - RTT
  - Loss rate, $p$
A Simple Model for TCP Throughput

cwnd

Loss

time
A Simple Model for TCP Throughput
A Simple Model for TCP Throughput

- Assume loss occurs whenever CWND reaches $W_{max}$
A Simple Model for TCP Throughput

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A Simple Model for TCP Throughput

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- Hence, evolution of window size:
  
  - $\frac{1}{2}W_{max}$ (after detecting loss)
  - $\frac{1}{2}W_{max} + 1$ (one RTT later)
  - $\frac{1}{2}W_{max} + 2$ (two RTTs later)
  - $\frac{1}{2}W_{max} + 3$ (three RTTs later)
  - ...
  - $W_{max}$ [drop]
  - $\frac{1}{2}W_{max}$
  - $\frac{1}{2}W_{max} + 1$
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A Simple Model for TCP Throughput

- Assume loss occurs whenever CWND reaches $W_{max}$
- And is detected by duplicate ACKs (i.e., no timeouts)

- Hence, evolution of window size:
  - Increase by 1 for $\frac{1}{2} W_{max}$ RTTs, then drop, then repeat
  - Average window size per RTT = $\frac{3}{4} W_{max}$
  - Average throughput = $\frac{3}{4} W_{max} \times \frac{MSS}{RTT}$

- Remaining step: express $W_{max}$ in terms of loss rate $p$
A Simple Model for TCP Throughput

cwnd

Loss

time
A Simple Model for TCP Throughput

cwnd

Loss

A

time
A Simple Model for TCP Throughput

On average, one of all packets in shaded region is lost (i.e., loss rate is $1/A$, where $A$ is the number of packets in the shaded region).
A Simple Model for TCP Throughput

Packet drop rate, $p = \frac{1}{A}$
A Simple Model for TCP Throughput

Packet drop rate, \( p = \frac{1}{A} \)

\( cwnd \)

Loss

\( \frac{1}{2} W_{\text{max}} \) RTTs between drops

\( \begin{align*} p &= \frac{1}{A} \\ \text{Packet drop rate,} \quad \frac{1}{A} \end{align*} \)
A Simple Model for TCP Throughput

Packet drop rate, \( p = \frac{1}{A} \)

\( A \) is the area under the curve, representing the total loss over \( \frac{1}{2} W_{max} \) RTTs between drops.
A Simple Model for TCP Throughput

Packet drop rate, \( p = \frac{1}{A} \)

Avg. \( \frac{3}{4} W_{\text{max}} \) packets per RTT

\( \frac{1}{2} W_{\text{max}} \) RTTs between drops
A Simple Model for TCP Throughput

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A Simple Model for TCP Throughput

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\[ A = \frac{3}{8} W_{\text{max}}^2 \]

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\( \text{cwnd} \)
A Simple Model for TCP Throughput

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\[ W_{\text{max}} = \frac{2\sqrt{2}}{\sqrt{3p}} \]
A Simple Model for TCP Throughput

Packet drop rate, \( p = \frac{1}{A} \)

Average Throughput = \( \frac{\frac{3}{4} W_{\text{max}} \times MSS}{RTT} \)

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\( \Rightarrow W_{\text{max}} = \frac{2\sqrt{2}}{\sqrt{3p}} \)

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- RTT is path round-trip time and $p$ is the packet loss rate
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- Model makes many simplifying assumptions
  - Ignores slow-start, assumes fixed RTT, isolated loss, etc.
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- But leads to some insights (coming up)
Taking Stock: TCP CC
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- (Sender) host based
Taking Stock: TCP CC

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- Loss based
Taking Stock: TCP CC

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- Loss based
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- Starts out in slow start (start small, double every RTT)
- Adapts based on AIMD (gentle increase, rapid decrease)
- TCP throughput depends on path RTT and loss rate

\[
\text{Throughput} = \sqrt{\frac{3}{2}} \frac{\text{MSS}}{\text{RTT} \sqrt{p}}
\]
Implications (1): Different RTTs

Throughput = \sqrt{\frac{3}{2}} \frac{\text{MSS}}{\text{RTT}} \sqrt{p}
Implications (1): Different RTTs

Throughput = \sqrt{\frac{3}{2}} \frac{MSS \times \sqrt{p}}{RTT}

A1

A2

bottleneck link

100ms

B1

200ms

B2
Implications (1): Different RTTs

- Flows get throughput inversely proportional to RTT
- TCP unfair in the face of heterogeneous RTTs!

\[
\text{Throughput} = \sqrt{\frac{3}{2}} \frac{\text{MSS}}{\text{RTT} \sqrt{p}}
\]
Implications (2): Rate-based CC [RFC 5348]

Throughput = \sqrt{\frac{3}{2} \frac{1}{\text{RTT}\sqrt{p}}}
Implications (2): *Rate*-based CC [RFC 5348]

- TCP throughput is “choppy”
  - repeated swings between $W/2$ to $W$

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  - ditch TCP’s increase/decrease rules and just follow the equation
  - measure RTT and drop percentage $p$, and set rate accordingly

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

\[
\text{Throughput} = \sqrt{\frac{3}{2}} \frac{1}{\text{RTT} \sqrt{p}}
\]
(3) Loss not due to congestion?

- TCP will confuse corruption with congestion
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- TCP will confuse corruption with congestion
- Flow will cut its rate
  - Throughput $\sim \frac{1}{\sqrt{p}}$ even for non-congestion losses!
(4) How do short flows fare?
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- 50% of flows have < 1500B to send; 80% < 100KB
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  - In fact, short flows are likely to suffer unduly long transfer times
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- A partial fix: use a higher initial CWND [RFC IW10]
(5) TCP fills up queues → long delays
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- Recall: loss follows delay (i.e., queue *must* fill up)
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Means that delays are large, for *everyone*.
  - Consider a flow transferring a 10GB file sharing a bottleneck link with 10 flows transferring 100B.
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  - Consider a flow transferring a 10GB file sharing a bottleneck link with 10 flows transferring 100B.

- Problem exacerbated by the trend towards adding large amounts of memory on routers (a.k.a. “bufferbloat”).
(5) TCP fills up queues → long delays

- Focus of Google’s BBR algorithm\(^1\)

\(^1\) [BBR: Congestion-Based Congestion Control; Cardwell et al, ACM Queue 2016]
(5) TCP fills up queues $\Rightarrow$ long delays

- Focus of Google’s BBR algorithm\(^1\)

- Basic idea (simplified):
  - Sender learns its minimum RTT ($\sim$ propagation RTT)
  - Decreases its rate when the observed RTT exceeds the minimum RTT

\(^1\) BBR: Congestion-Based Congestion Control; Cardwell et al, ACM Queue 2016
(6) Cheating
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- Three easy ways to cheat
  - Increasing CWND faster than +1 MSS per RTT
Increasing CWND Faster

\[ x = 2y \]

- $x$ increases by 2 per RTT
- $y$ increases by 1 per RTT

Limit rates:
\[ x = 2y \]
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• Three easy ways to cheat
  • Increasing CWND faster than +1 MSS per RTT
  • Opening many connections
Open Many Connections

Assume
• A starts 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
(6) Cheating
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- Three easy ways to cheat
  - Increasing CWND faster than +1 MSS per RTT
  - Opening many connections
  - Using large initial CWND
Why hasn’t the Internet suffered another congestion collapse?
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- Even “cheaters” do back off!
  - Leads to unfairness, not necessarily collapse
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Google’s Network Congestion Algorithm Isn’t Fair, Researchers Say
Why hasn’t the Internet suffered another congestion collapse?

- Even “cheaters” do back off!
  - Leads to unfairness, not necessarily collapse

- Hard to say whether unfair behavior is common

Google’s Network Congestion Algorithm Isn’t Fair, Researchers Say
(7) CC intertwined with reliability
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- Mechanisms for CC and reliability are tightly coupled
  - CWND adjusted based on ACKs and timeouts
  - Cumulative ACKs and fast retransmit/recovery rules
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  - Consider changing from cumulative to selective ACKs
  - A failure of modularity, not layering
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  - e.g., real-time audio/video
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Recap: TCP problems
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- Misled by non-congestion losses
- Fills up queues leading to high delays
- Short flows complete before discovering available capacity
- Sawtooth discovery too choppy for some apps
- Unfair under heterogeneous RTTs
- Tight coupling with reliability mechanisms
- Endhosts can cheat
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Could fix many of these with some help from routers!
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Routers enforce fair sharing

Could fix many of these with some help from routers!
Router-Assisted Congestion Control

- Three ways routers can help
  - Enforce fairness
  - More precise rate adaptation
  - Detecting congestion
How can routers ensure each flow gets its “fair share”? 
Fairness: General Approach
Fairness: General Approach

● Consider a single router’s actions
Fairness: General Approach

- Consider a single router’s actions

- Router classifies incoming packets into “flows”
  - (For now) let’s assume flows are TCP connections
Fairness: General Approach

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- Each flow has its own FIFO queue in router

- Router picks a queue (i.e., flow) in a fair order; transmits packet from the front of the queue
Fairness: General Approach

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- What does “fair” mean exactly?
Max-Min Fairness
Max-Min Fairness

- Total available bandwidth $C$
Max-Min Fairness

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- Max-min bandwidth allocations are:
  \[ a_i = \min(f, r_i) \]
Max-Min Fairness

- Total available bandwidth $C$
- Each flow $i$ has bandwidth demand $r_i$
- What is a fair allocation $a_i$ of bandwidth to each flow $i$?
- Max-min bandwidth allocations are:
  $$a_i = \min(f, r_i)$$

where $f$ is the unique value such that $\sum a_i = C$
Example
Example

- $C = 10; \ N = 3; \ r_1 = 8, \ r_2 = 6, \ r_3 = 2$
Example

- $C = 10; \ N = 3; \ r_1 = 8, \ r_2 = 6, \ r_3 = 2$

- $C/N = 10/3 = 3.33 \rightarrow$
  - But $r_3$’s need is only 2
  - Can service all of $r_3$
  - Allocate 2 to $r_3$ and remove it from accounting: $C = C - r_3 = 8; \ N = 2$
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- $C/2 = 4 \rightarrow$
  - Can’t service all of $r_1$ or $r_2$
  - So hold them to the remaining fair share: $f = 4$
Example

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\[\begin{align*}
  f &= 4: \\
  \min(8, 4) &= 4 \\
  \min(6, 4) &= 4 \\
  \min(2, 4) &= 2
\end{align*}\]
Max-Min Fairness

- Property:
  - If you don’t get full demand, no one gets more than you
Max-Min Fairness

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

- This is what round-robin service gives if all packets are the same size
How do we deal with packets of different sizes?
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- Mental model: Bit-by-bit round robin ("fluid flow")
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How do we deal with packets of different sizes?

- Mental model: Bit-by-bit round robin ("fluid flow")
- Cannot do this in practice!
- But we can approximate it
  - This is what "fair queuing" routers do
Fair Queuing (FQ)
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- For each packet, compute the time at which the last bit of a packet would have left the router if flows are served bit-by-bit (called “deadlines”)
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- Then serve packets in increasing order of their deadlines
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- Then serve packets in increasing order of their deadlines

- Think of it as an implementation of round-robin extended to the case where not all packets are equal sized
Fair Queuing (FQ)

- For each packet, compute the time at which the last bit of a packet would have left the router if flows are served bit-by-bit (called “deadlines”)

- Then serve packets in increasing order of their deadlines

- Think of it as an implementation of round-robin extended to the case where not all packets are equal sized
Example

Flow 1
(arrival traffic)

Flow 2
(arrival traffic)
Example

Flow 1 (arrival traffic)

Flow 2 (arrival traffic)

Service in fluid system
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Flow 1 (arrival traffic)

Flow 2 (arrival traffic)

Service in fluid system

FQ Packet system
FQ vs. FIFO
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- FQ advantages:
  - Isolation: cheating flows don’t benefit
  - Bandwidth share does not depend on RTT
  - Flows can pick any rate adjustment scheme they want
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- FQ advantages:
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- Disadvantages:
  - More complex than FIFO: per flow queue/state, additional per-packet book-keeping
  - Still only a partial solution (coming up)
Fair Queuing In Practice
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- “Pure” FQ too complex to implement at high speeds
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- But several approximations exist
  - E.g., Deficit Round Robin (DRR)
Fair Queuing In Practice

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- Today:
  - Routers typically implement approximate FQ (e.g., DRR)
  - For a small number of queues
  - Commonly used for coarser-grained isolation (e.g., for select customer prefixes) rather than per-flow isolation
FQ in the big picture

- FQ does not eliminate congestion → it just manages the congestion
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Blue and Green get 0.5Gbps; any excess will be dropped
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Will drop an additional 400Mbps from the green flow
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Will drop an additional 400Mbps from the green flow

If the green flow doesn’t drop its sending rate to 100Mbps, we’re wasting 400Mbps that could be usefully given to the blue flow
FQ in the big picture

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- FQ’s benefit is its resilience (to cheating, variations in RTT, details of delay, reordering, etc.)
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- FQ’s benefit is its resilience (to cheating, variations in RTT, details of delay, reordering, etc.)

- But congestion and packet drops still occur

- And we still want end-hosts to discover/adapt to their fair share!
Per-flow fairness is a controversial goal
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- What if you have 8 flows, and I have 4?
  - Why should you get twice the bandwidth
Per-flow fairness is a controversial goal

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- What if your flow goes over 4 congested hops, and mine only goes over 1?
  - Shouldn’t you be penalized for using more of scarce bandwidth?

- And at what granularity do we really want fairness?
  - TCP connection? Source-Destination pair? Source?
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- Nonetheless, FQ/DRR is a great way to ensure isolation
  - Avoiding starvation even in the worst cases
Router-Assisted Congestion Control

- Three ways routers can help
  - Enforce fairness
  - More precise rate adaptation
  - Detecting congestion
Why not just let routers tell endhosts what rate they should use?
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- Packets carry “rate field”
- Routers insert a flow’s fair share $f$ in packet header
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- Packets carry “rate field”
- Routers insert a flow’s fair share $f$ in packet header
- End-hosts set sending rate (or window size) to $f$
Router-Assisted Congestion Control

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Explicit Congestion Notification (ECN)
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  - If data packet has bit set, then ACK has ECN bit set
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  - Early indicator of congestion → avoid delays
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- Today:
  - Widely implemented in routers
  - Commonly used in datacenters (e.g., Azure)
Recap: Router-Assisted CC

- **FQ**: routers *enforce* per-flow fairness
- **RCP**: routers *inform* endhosts of their fair share
- **ECN**: routers set “I’m congested” bit in packets
Perspective: Router-Assisted CC
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- Can be highly effective, approaching optimal perf.
Perspective: Router-Assisted CC

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- But deployment is more challenging
  - Need support at hosts and routers
  - Some require more complex book-keeping at routers
  - Some require deployment at every router
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- But deployment is more challenging
  - Need support at hosts and routers
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- Though worth revisiting in datacenter contexts
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- Though datacenters are the CC agenda
  - different needs and constraints (future lecture)