CS162
Operating Systems and Systems Programming
Lecture 17
TCP, Flow Control, Reliability

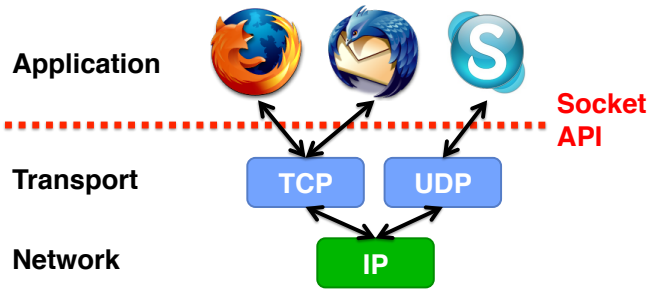
October 29, 2012
Ion Stoica
http://inst.eecs.berkeley.edu/~cs162

Goals for Today

- Reliable Transfer & flow control
- TCP
  - Open connection (3-way handshake)
  - Tear-down connection
  - Flow control

Socket API

- Socket API: Network programming interface



BSD Socket API

- Created at UC Berkeley (1980s)
- Most popular network API
- Ported to various OSes, various languages
  - Windows Winsock, BSD, OS X, Linux, Solaris, …
  - Socket modules in Java, Python, Perl, …
- Similar to Unix file I/O API
  - In the form of *file descriptor* (sort of handle).
  - Can share same `read()`/`write()`/`close()` system calls

TCP: Transport Control Protocol

- Reliable, in-order, and at most once delivery
- Stream oriented: messages can be of arbitrary length
- Provides multiplexing/demultiplexing to IP
- Provides congestion and flow control
- Application examples: file transfer, chat

TCP Service

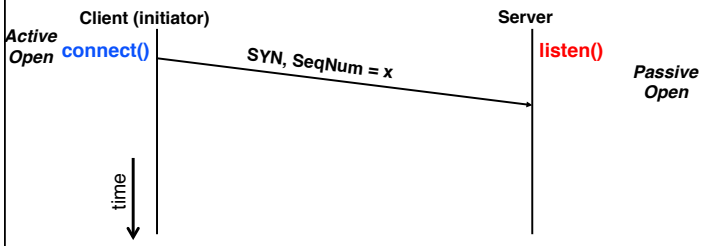
1) Open connection: 3-way handshaking
2) Reliable byte stream transfer from (IPa, TCP_Port1) to (IPb, TCP_Port2)
   - Indication if connection fails: Reset
3) Close (tear-down) connection

Open Connection: 3-Way Handshaking

- Goal: agree on a set of parameters, i.e., the start sequence number for each side
  - Starting sequence number: sequence of first byte in stream
  - Starting sequence numbers are random

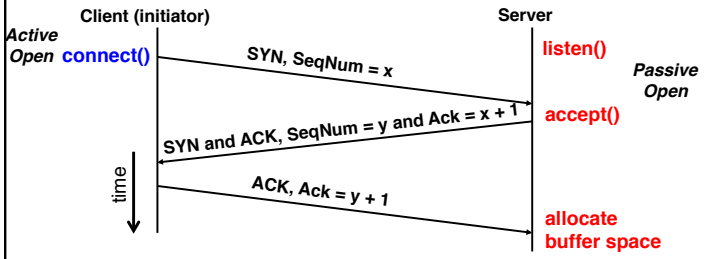
Open Connection: 3-Way Handshaking

- Server waits for new connection calling listen()
- Sender call connect() passing socket which contains server's IP address and port number
  - OS sends a special packet (SYN) containing a proposal for first sequence number, x



Open Connection: 3-Way Handshaking

- If it has enough resources, server calls accept() to accept connection, and sends back a SYN ACK packet containing
  - client's sequence number incremented by one, (x + 1)
    - » Why is this needed?
  - A sequence number proposal, y, for first byte server will send

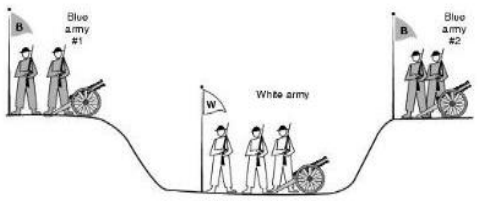


3-Way Handshaking (cont'd)

- Three-way handshake adds 1 RTT delay
- Why?
  - Congestion control: SYN (40 byte) acts as cheap probe
  - Protects against delayed packets from other connection (would confuse receiver)

Close Connection (Two Generals Problem)

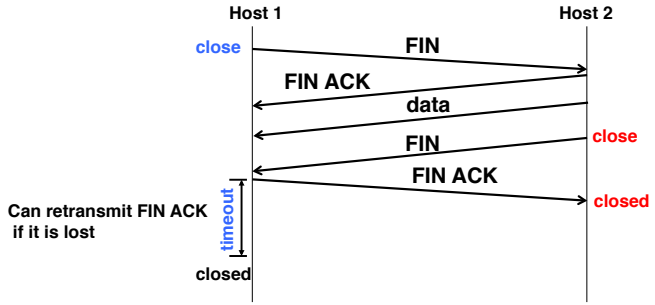
- Goal: both sides agree to close the connection
- Two-army problem:
  - "Two blue armies need to simultaneously attack the white army to win; otherwise they will be defeated. The blue army can communicate only across the area controlled by the white army which can intercept the messengers."



- What is the solution?

Close Connection

- 4-ways tear down connection



Reliable Transfer

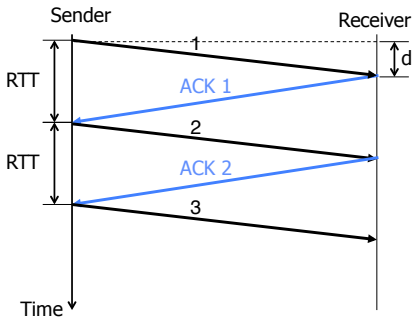
- Retransmit missing packets
  - Numbering of packets and ACKs
- Do this efficiently
  - Keep transmitting whenever possible
  - Detect missing packets and retransmit quickly
- Two schemes
  - Stop & Wait
  - Sliding Window (Go-back-n and Selective Repeat)

Detecting Packet Loss?

- Timeouts
  - Sender timeouts on not receiving ACK
- Missing ACKs
  - Sender ACKs each packet
  - Receiver detects a missing packet when seeing a gap in the sequence of ACKs
  - Need to be careful! Packets and acks might be reordered
- NACK: Negative ACK
  - Receiver sends a NACK specifying a packet it is missing

Stop & Wait w/o Errors

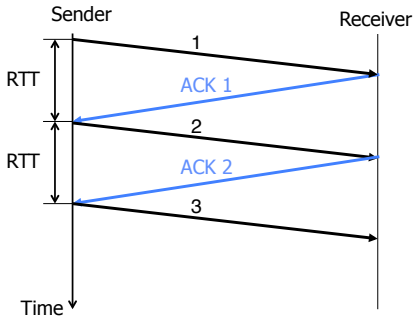
- Send; wait for ack; repeat
- RTT: Round Trip Time (RTT): time it takes a packet to travel from sender to receiver and back
  - One-way latency (d): one way delay from sender and receiver



RTT = 2*d (if latency is symmetric)

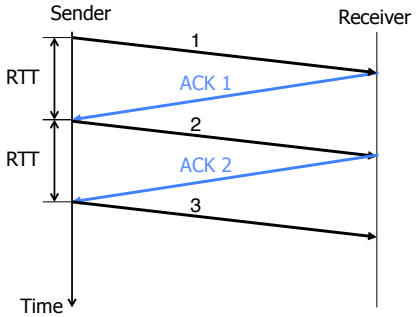
Stop & Wait w/o Errors

- How many packets can you send?
- 1 packet / RTT
- Throughput: number of bits delivered to receiver per sec



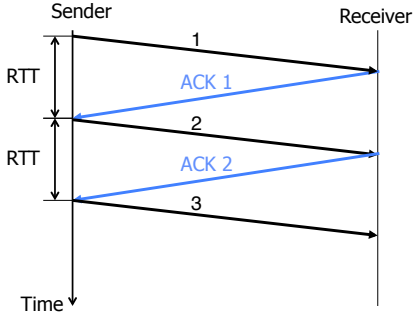
Stop & Wait w/o Errors

- Say, RTT = 100ms
- 1 packet = 1500 bytes
- Throughput = 1500*8bits/0.1s = 120 Kbps



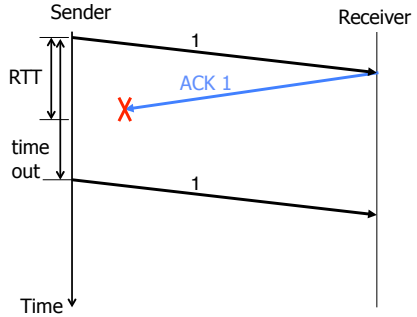
Stop & Wait w/o Errors

- Can be highly inefficient for high capacity links
- Throughput doesn't depend on the network capacity → even if capacity is 1Gbps, we can only send 120 Kbps!



Stop & Wait with Errors

- If a loss wait for a retransmission timeout and retransmit
- Ho do you pick the timeout?

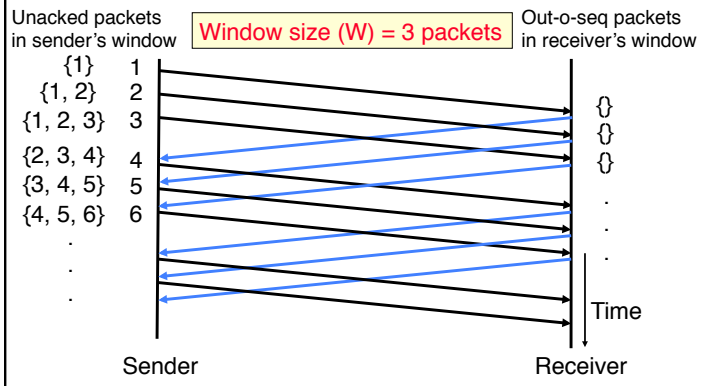


Sliding Window

- *window* = set of adjacent sequence numbers
- The size of the set is the *window size*
- Assume window size is n
- Let A be the last ack'd packet of sender without gap; then window of sender = {A+1, A+2, …, A+n}
- Sender can send packets in its window
- Let B be the last received packet without gap by receiver, then window of receiver = {B+1,…, B+n}
- Receiver can accept out of sequence, if in window

Sliding Window w/o Errors

- Throughput = W*packet_size/RTT



Example: Sliding Window w/o Errors

- Assume
  - Link capacity, C = 1Gbps
  - Latency between end-hosts, RTT = 80ms
  - packet_length = 1000 bytes
- What is the window size W to match link's capacity, C?

- Solution

  We want Throughput = C

  Throughput = W*packet_size/RTT

  C = W*packet_size/RTT

  W = C*RTT/packet_size = 10^9bps*80*10^{-3}s/(8000b) = 10^4 packets

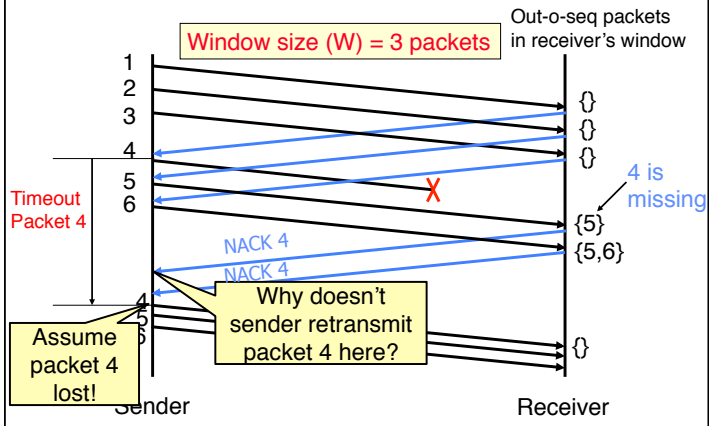
Window size ~ Bandwidth (Capacity), delay (RTT/2)

Sliding Window with Errors

- Two approaches
  - Go-Back-n (GBN)
  - Selective Repeat (SR)
- In the absence of errors they behave identically

- Go-Back-n (GBN)
  - Transmit up to *n* unacknowledged packets
  - If timeout for ACK(*k*), retransmit *k*, *k+1*, …
  - Typically uses NACKs instead of ACKs
    - » Recall, NACK specifies first in-sequence packet missed by receiver

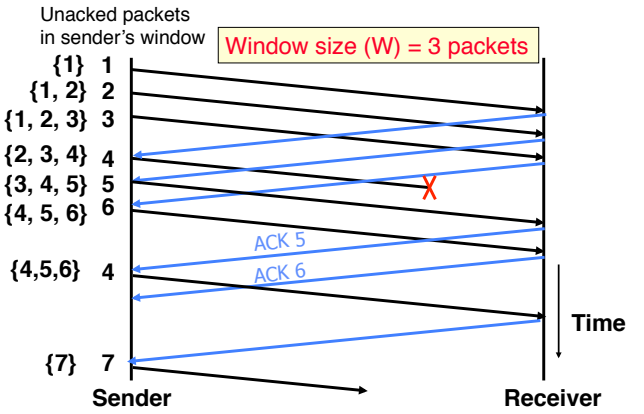
GBN Example with Errors



Selective Repeat (SR)

- Sender: transmit up to *n* unacknowledged packets;
- Assume packet *k* is lost
- Receiver: indicate packet *k* is missing (use ACKs)
- Sender: retransmit packet *k*

SR Example with Errors



Summary

- TCP: Reliable Byte Stream
  - Open connection (3-way handshaking)
  - Close connection: no perfect solution; no way for two parties to agree in the presence of arbitrary message losses (Two General problem)
- Reliable transmission
  - S&W not efficient for links with large capacity (bandwidth) delay product
  - Sliding window more efficient but more complex

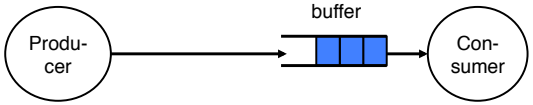
Announcements

- I'll no longer be away this Wednesday, so I'll be teaching the lecture
- Project 3 initial design due: Thursday, Nov 1

5min Break

Flow Control

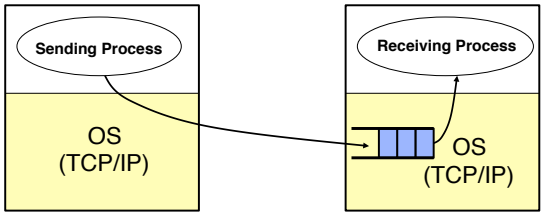
- Recall: Flow control ensures a fast sender does not overwhelm a slow receiver
- Example: Producer-consumer with bounded buffer (Lecture 5)
  - A buffer between producer and consumer
  - Producer puts items into buffer as long as buffer **not full**
  - Consumer consumes items from buffer



TCP Flow Control

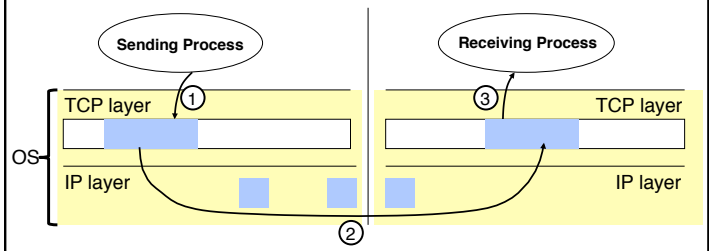
- TCP: sliding window protocol at byte (not packet) level
  - Go-back-N: TCP Tahoe, Reno, New Reno
  - Selective Repeat (SR): TCP Sack
- Receiver tells sender how many more bytes it can receive without overflowing its buffer (i.e., AdvertisedWindow)
- The ACK contains sequence number N of next byte the receiver expects, i.e., receiver has received all bytes in sequence up to and including N-1

TCP Flow Control



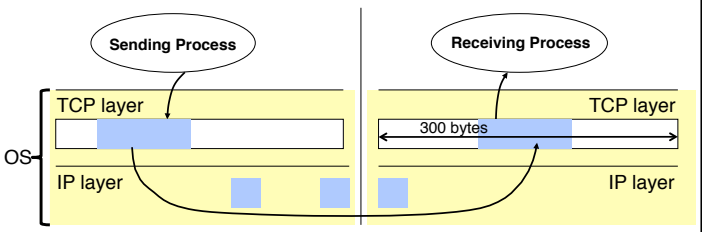
- TCP/IP implemented by OS (Kernel)
  - Cannot do context switching on sending/receiving every packet
    - » At 1Gbps, it takes 12 usec to send an 1500 bytes, and 0.8usec to send an 100 byte packet
- Need buffers to match …
  - sending app with sending TCP
  - receiving TCP with receiving app

TCP Flow Control



- Three pairs of producer-consumer's
  - ① sending process → sending TCP
  - ② Sending TCP → receiving TCP
  - ③ receiving TCP → receiving process

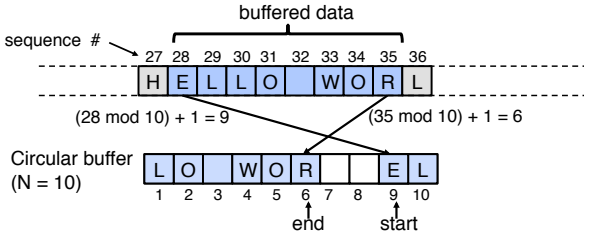
TCP Flow Control



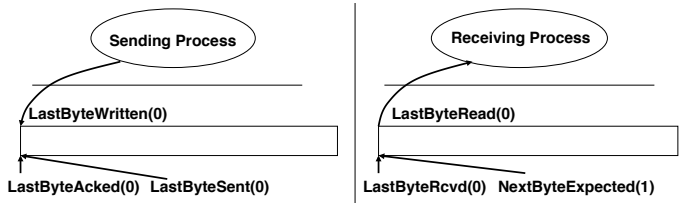
- Example assumptions:
  - Maximum IP packet size = 100 bytes
  - Size of the receiving buffer (MaxRcvBuf) = 300 bytes
- Recall, ack indicates the next expected byte in-sequence, not the last received byte
- Use circular buffers

Circular Buffer

- Assume
  - A buffer of size N
  - A stream of bytes, where bytes have increasing sequence numbers
    - » Think of stream as an unbounded array of bytes and of sequence number as indexes in this array
- Buffer stores at most N consecutive bytes from the stream
- Byte k stored at position (k mod N) + 1 in the buffer

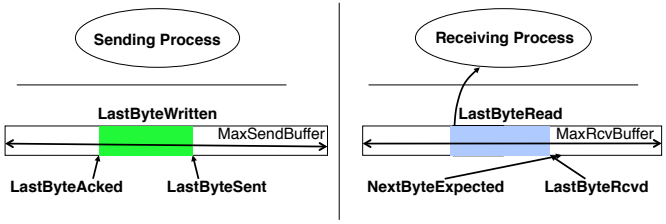


TCP Flow Control



- LastByteWritten: last byte written by sending process
- LastByteSent: last byte sent by sender to receiver
- LastByteAcked: last ack received by sender from receiver
- LastByteRcvd: last byte received by receiver from sender
- NextByteExpected: last in-sequence byte expected by receiver
- LastByteRead: last byte read by the receiving process

TCP Flow Control



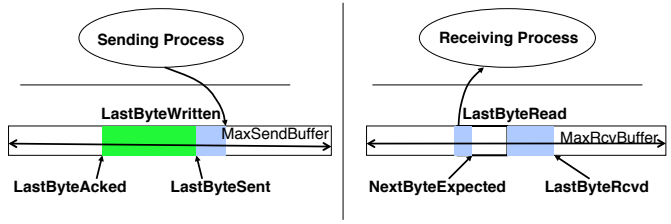
- AdvertisedWindow: number of bytes TCP receiver can receive

AdvertisedWindow = MaxRcvBuffer – (LastByteRcvd – LastByteRead)

- SenderWindow: number of bytes TCP sender can send

SenderWindow = AdvertisedWindow – (LastByteSent – LastByteAcked)

TCP Flow Control



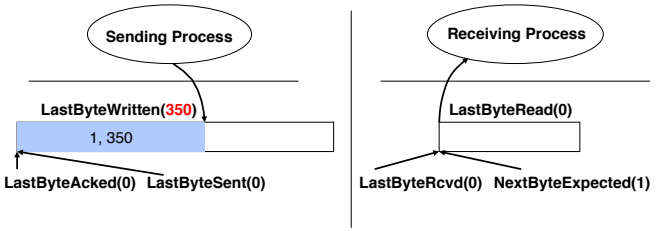
- Still true if receiver missed data….

AdvertisedWindow = MaxRcvBuffer – (LastByteRcvd – LastByteRead)

- WriteWindow: number of bytes sending process can write

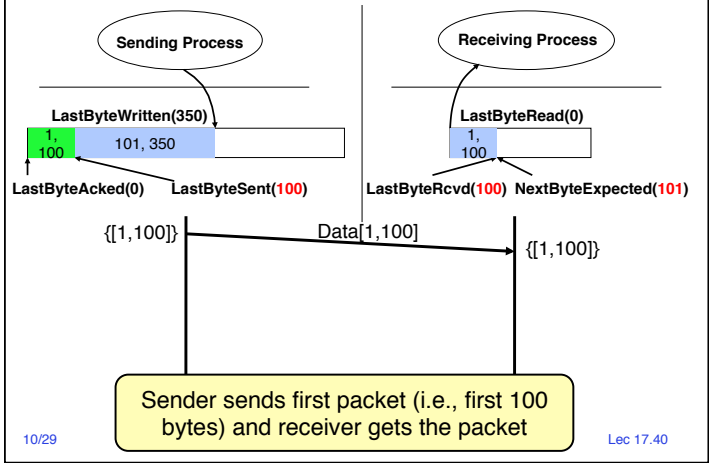
WriteWindow = MaxSendBuffer – (LastByteWritten – LastByteAcked)

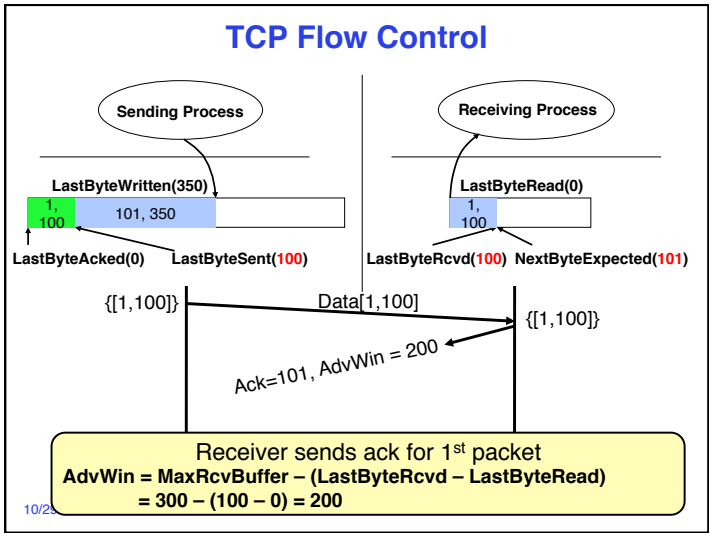
TCP Flow Control

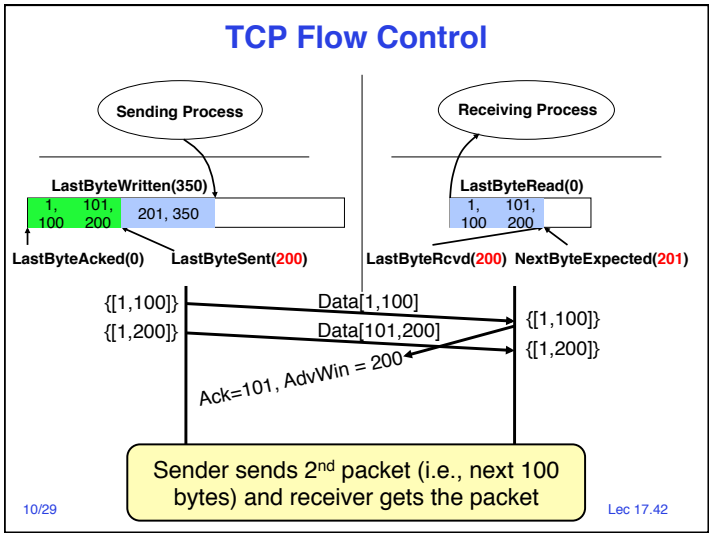


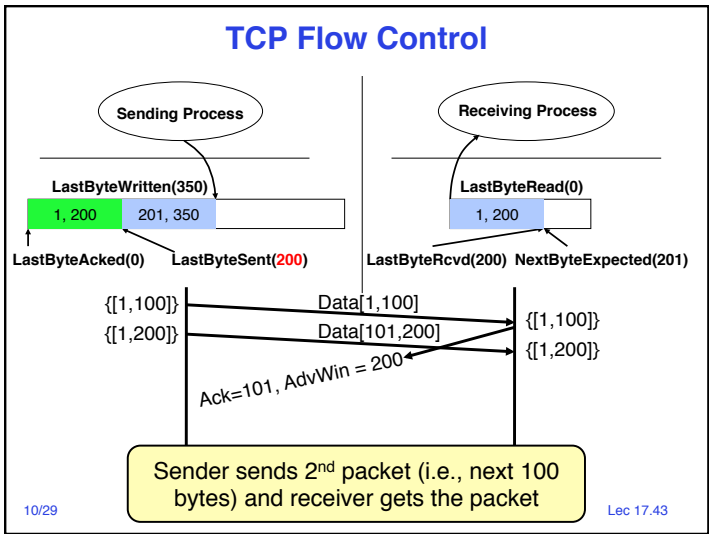
- Sending app sends 350 bytes
- Recall:
  - We assume IP only accepts packets no larger than 100 bytes
  - MaxRcvBuf = 300 bytes, so initial Advertised Window = 300 byets

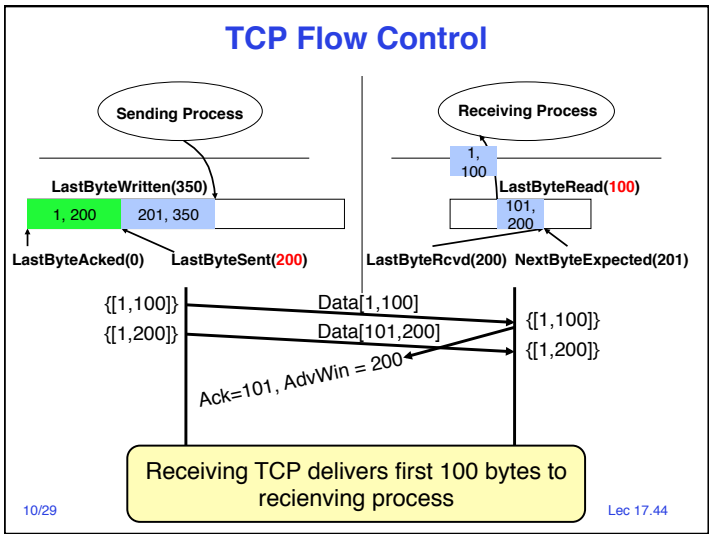
TCP Flow Control

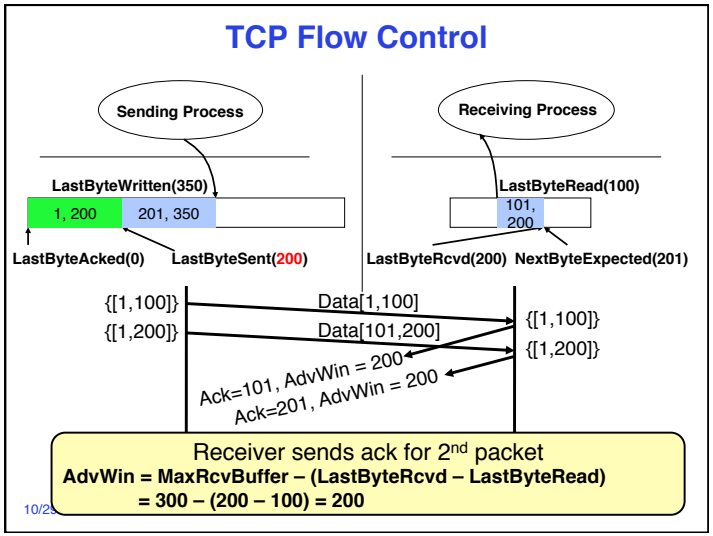


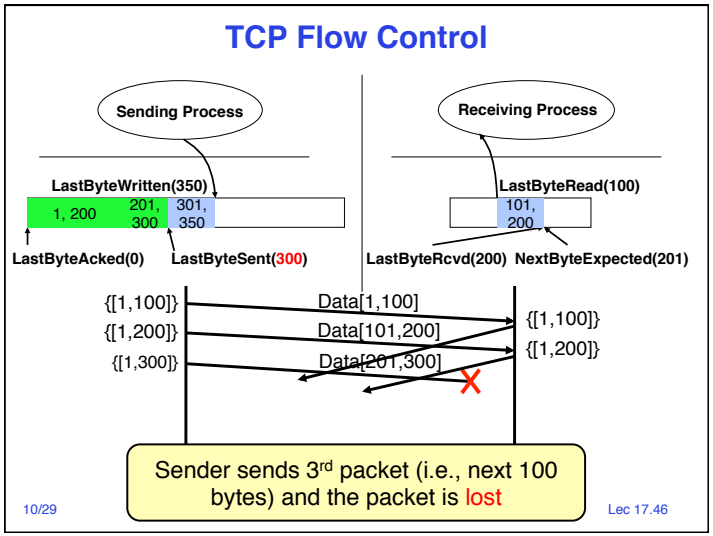

TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
1, 100
101, 350
LastByteRead(0)
1, 100
LastByteAcked(0)
LastByteSent(100)
LastByteRcvd(100)
NextByteExpected(101)
{[1,100]}
Data[1,100]
{[1,100]}
Ack=101, AdvWin = 200
Receiver sends ack for 1st packet
AdvWin = MaxRcvBuffer – (LastByteRcvd – LastByteRead)
= 300 – (100 – 0) = 200
10/29

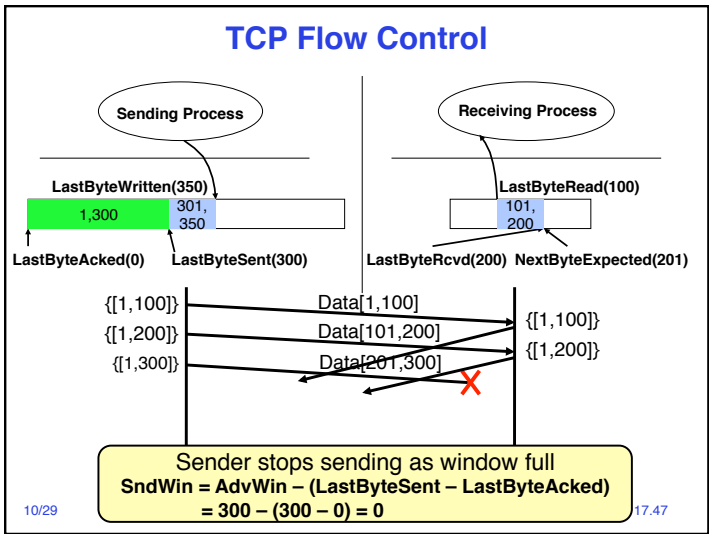

TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
1, 100
101, 200
201, 350
LastByteRead(0)
1, 100
101, 200
LastByteAcked(0)
LastByteSent(200)
LastByteRcvd(200)
NextByteExpected(201)
{[1,100]}
{[1,200]}
Data[1,100]
Data[101,200]
{[1,100]}
{[1,200]}
Ack=101, AdvWin = 200
Sender sends 2nd packet (i.e., next 100 bytes) and receiver gets the packet
10/29
Lec 17.42

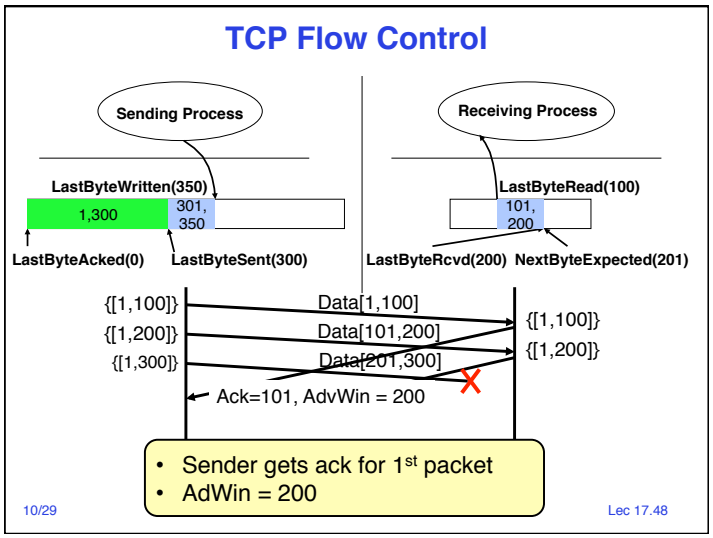

TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
1, 200
201, 350
LastByteRead(0)
1, 200
LastByteAcked(0)
LastByteSent(200)
LastByteRcvd(200)
NextByteExpected(201)
{[1,100]}
{[1,200]}
Data[1,100]
Data[101,200]
{[1,100]}
{[1,200]}
Ack=101, AdvWin = 200
Sender sends 2nd packet (i.e., next 100 bytes) and receiver gets the packet
10/29
Lec 17.43


TCP Flow Control
Sending Process
Receiving Process
1, 100
LastByteWritten(350)
1, 200
201, 350
LastByteRead(100)
101, 200
LastByteAcked(0)
LastByteSent(200)
LastByteRcvd(200)
NextByteExpected(201)
{[1,100]}
{[1,200]}
Data[1,100]
Data[101,200]
{[1,100]}
{[1,200]}
Ack=101, AdvWin = 200
Receiving TCP delivers first 100 bytes to recienving process
10/29
Lec 17.44

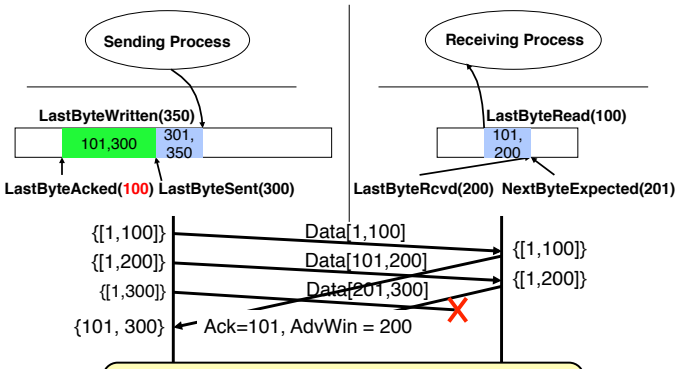

TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
1, 200
201, 350
LastByteRead(100)
101, 200
LastByteAcked(0)
LastByteSent(200)
LastByteRcvd(200)
NextByteExpected(201)
{[1,100]}
{[1,200]}
Data[1,100]
Data[101,200]
{[1,100]}
{[1,200]}
Ack=101, AdvWin = 200
Ack=201, AdvWin = 200
Receiver sends ack for 2nd packet
AdvWin = MaxRcvBuffer – (LastByteRcvd – LastByteRead)
= 300 – (200 – 100) = 200
10/29


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
1, 200
201, 300
301, 350
LastByteRead(100)
101, 200
LastByteAcked(0)
LastByteSent(300)
LastByteRcvd(200)
NextByteExpected(201)
{[1,100]}
{[1,200]}
{[1,300]}
Data[1,100]
Data[101,200]
Data[201,300]
{[1,100]}
{[1,200]}
Sender sends 3rd packet (i.e., next 100 bytes) and the packet is lost
10/29
Lec 17.46


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
1,300
301, 350
LastByteRead(100)
101, 200
LastByteAcked(0)
LastByteSent(300)
LastByteRcvd(200)
NextByteExpected(201)
{[1,100]}
{[1,200]}
{[1,300]}
Data[1,100]
Data[101,200]
Data[201,300]
{[1,100]}
{[1,200]}
Sender stops sending as window full
SndWin = AdvWin – (LastByteSent – LastByteAcked)
= 300 – (300 – 0) = 0
10/29
17.47

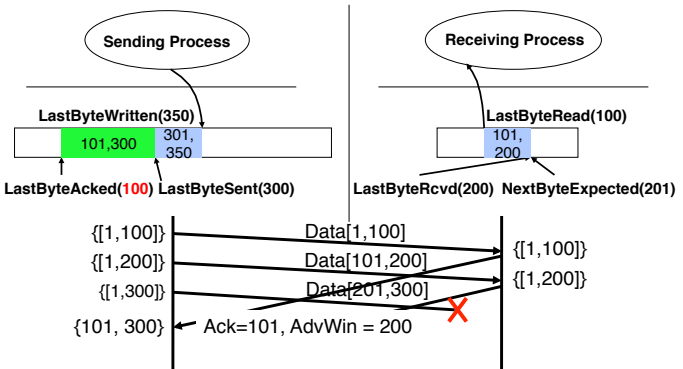

TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
1,300
301, 350
LastByteRead(100)
101, 200
LastByteAcked(0)
LastByteSent(300)
LastByteRcvd(200)
NextByteExpected(201)
{[1,100]}
{[1,200]}
{[1,300]}
Data[1,100]
Data[101,200]
Data[201,300]
{[1,100]}
{[1,200]}
Ack=101, AdvWin = 200
• Sender gets ack for 1st packet
• AdWin = 200
10/29
Lec 17.48

TCP Flow Control



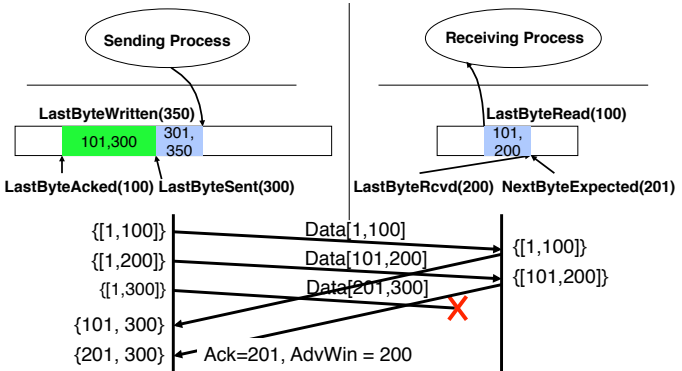
- Ack for 1st packet (ack indicates next byte expected by receiver)
- Receiver no longer needs first 100 bytes

TCP Flow Control



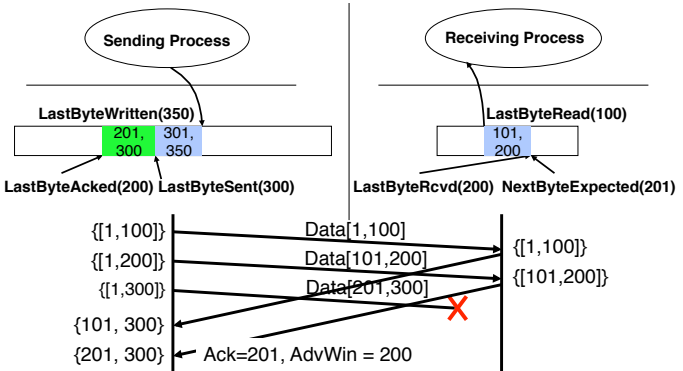
Sender still cannot send as window full
SndWin = AdvWin – (LastByteSent – LastByteAcked)
= 200 – (300 – 100) = 0

TCP Flow Control

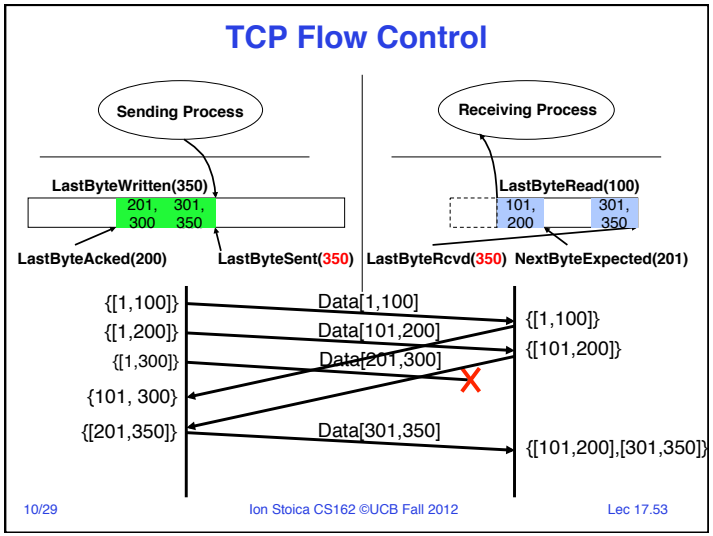


- Receiver gets ack for 2nd packet
- AdvWin = 200 bytes

TCP Flow Control



Sender can now send new data!
SndWin = AdvWin – (LasByteSent – LastByteAcked) = 100


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
201, 300
301, 350
LastByteRead(100)
101, 200
301, 350
LastByteAcked(200)
LastByteSent(350)
LastByteRcvd(350)
NextByteExpected(201)
{[1,100]}
{[1,200]}
{[1,300]}
{101, 300}
{[201,350]}
Data[1,100]
Data[101,200]
Data[201,300]
Data[301,350]
{[1,100]}
{[101,200]}
{[101,200],[301,350]}
10/29
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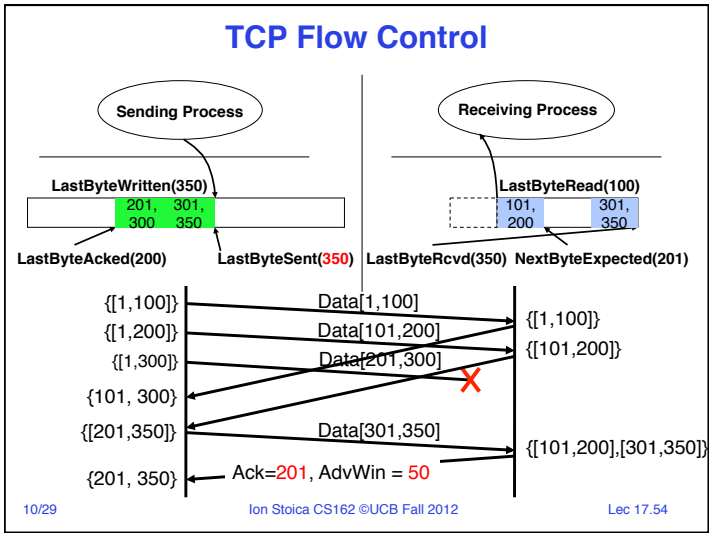
Lec 17.53


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
201, 300
301, 350
LastByteRead(100)
101, 200
301, 350
LastByteAcked(200)
LastByteSent(350)
LastByteRcvd(350)
NextByteExpected(201)
{[1,100]}
{[1,200]}
{[1,300]}
{101, 300}
{[201,350]}
{201, 350}
Data[1,100]
Data[101,200]
Data[201,300]
Data[301,350]
Ack=201, AdvWin = 50
{[1,100]}
{[101,200]}
{[101,200],[301,350]}
10/29
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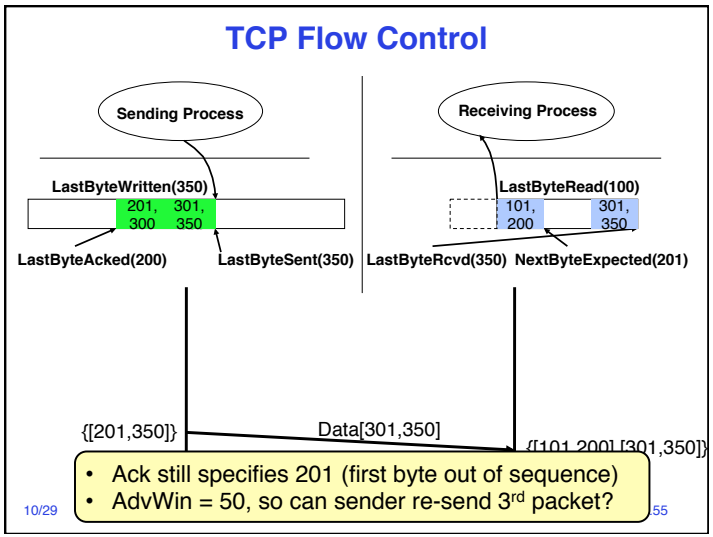
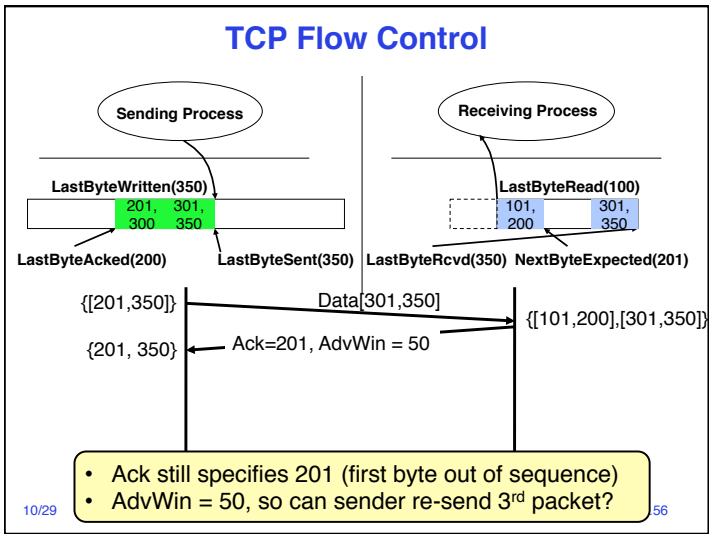
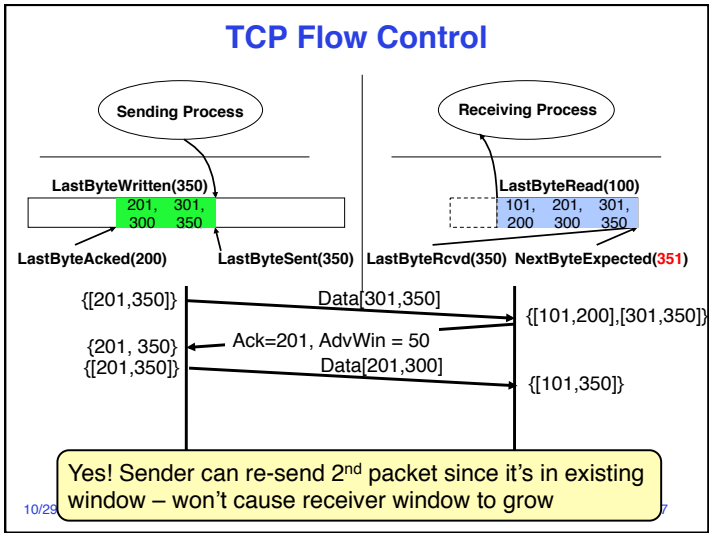
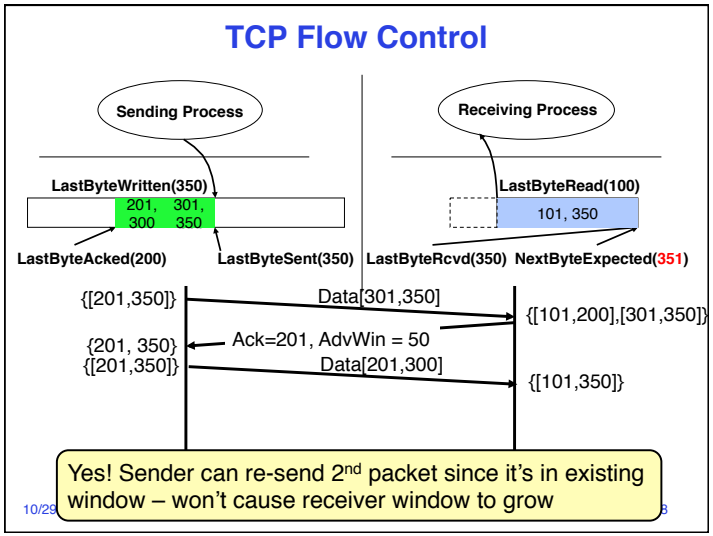
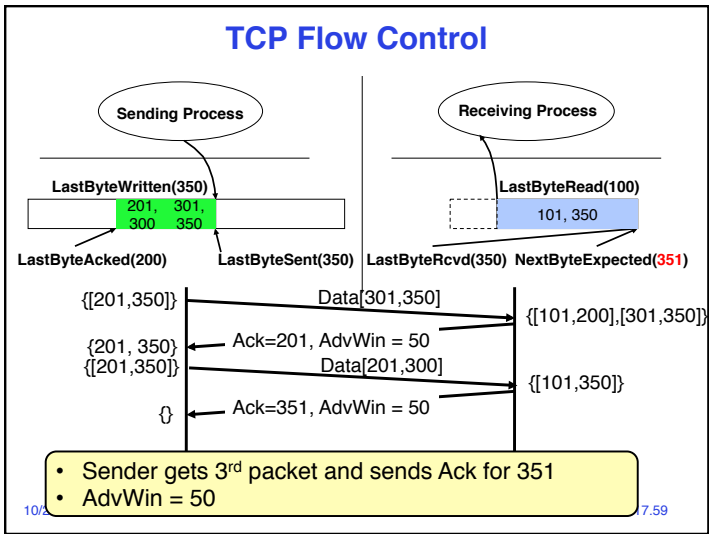
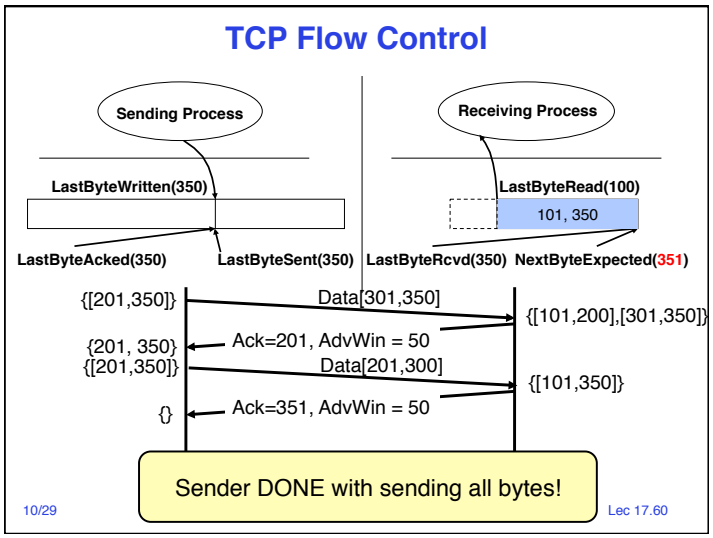

TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
201, 300
301, 350
LastByteRead(100)
101, 200
301, 350
LastByteAcked(200)
LastByteSent(350)
LastByteRcvd(350)
NextByteExpected(201)
{[201,350]}
Data[301,350]
• Ack still specifies 201 (first byte out of sequence)
• AdvWin = 50, so can sender re-send 3rd packet?
10/29
55


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
201, 300
301, 350
LastByteRead(100)
101, 200
301, 350
LastByteAcked(200)
LastByteSent(350)
LastByteRcvd(350)
NextByteExpected(201)
{[201,350]}
{201, 350}
Data[301,350]
Ack=201, AdvWin = 50
{[101,200],[301,350]}
• Ack still specifies 201 (first byte out of sequence)
• AdvWin = 50, so can sender re-send 3rd packet?
10/29
56


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
201, 300, 301, 350
LastByteRead(100)
101, 200, 201, 300, 301, 350
LastByteAcked(200)
LastByteSent(350)
LastByteRcvd(350)
NextByteExpected(351)
{[201,350]}
Data[301,350]
{[101,200],[301,350]}
{201, 350}
{[201,350]}
Ack=201, AdvWin = 50
Data[201,300]
{[101,350]}
Yes! Sender can re-send 2nd packet since it's in existing window – won't cause receiver window to grow


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
201, 300, 301, 350
LastByteRead(100)
101, 350
LastByteAcked(200)
LastByteSent(350)
LastByteRcvd(350)
NextByteExpected(351)
{[201,350]}
Data[301,350]
{[101,200],[301,350]}
{201, 350}
{[201,350]}
Ack=201, AdvWin = 50
Data[201,300]
{[101,350]}
Yes! Sender can re-send 2nd packet since it's in existing window – won't cause receiver window to grow


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
201, 300, 301, 350
LastByteRead(100)
101, 350
LastByteAcked(200)
LastByteSent(350)
LastByteRcvd(350)
NextByteExpected(351)
{[201,350]}
Data[301,350]
{[101,200],[301,350]}
{201, 350}
{[201,350]}
Ack=201, AdvWin = 50
Data[201,300]
{[101,350]}
{}
Ack=351, AdvWin = 50
• Sender gets 3rd packet and sends Ack for 351
• AdvWin = 50


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
LastByteRead(100)
101, 350
LastByteAcked(350)
LastByteSent(350)
LastByteRcvd(350)
NextByteExpected(351)
{[201,350]}
Data[301,350]
{[101,200],[301,350]}
{201, 350}
{[201,350]}
Ack=201, AdvWin = 50
Data[201,300]
{[101,350]}
{}
Ack=351, AdvWin = 50
Sender DONE with sending all bytes!
10/29
Lec 17.60

Discussion

- Why not have a huge buffer at the receiver (memory is cheap!)?
- Sending window (SndWnd) also depends on network congestion
  - **Congestion control**: ensure that a fast receiver doesn't overwhelm a router in the network (discussed in detail in ee122)
- In practice there is another set of buffers in the protocol stack, at the **link layer** (i.e., Network Interface Card)

Summary: Reliability & Flow Control

- Flow control: three pairs of producer consumers
  - Sending process → sending TCP
  - Sending TCP → receiving TCP
  - Receiving TCP → receiving process
- Reliable transmission
  - S&W not efficient for links with large capacity (bandwidth) delay product
  - Sliding window far more efficient
- TCP: Reliable Byte Stream
  - Open connection (3-way handshaking)
  - Close connection: no perfect solution; no way for two parties to agree in the presence of arbitrary message losses (Two General problem)

Summary: Networking (Internet Layering)