CS162
Operating Systems and Systems Programming
Lecture 22

TCP Flow Control, Distributed Decision Making, RPC

April 17th, 2017
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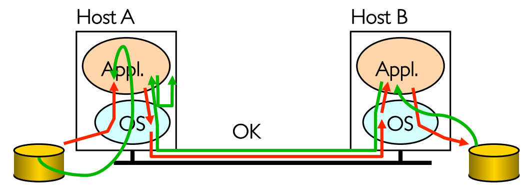
http://cs162.eecs.Berkeley.edu

Example: Reliable File Transfer



- Solution 1: make each step reliable, and then concatenate them
- Solution 2: end-to-end **check** and try again if necessary

Discussion

- Solution 1 is incomplete
  – What happens if memory is corrupted?
  – Receiver has to do the check anyway!
- Solution 2 is complete
  – Full functionality can be entirely implemented at application layer with no need for reliability from lower layers
- *Is there any need to implement reliability at lower layers?*
  – Well, it could be more efficient

End-to-End Principle

Implementing this functionality in the network:

- Doesn't reduce host implementation complexity
- Does increase network complexity
- Probably imposes delay and overhead on all applications, even if they don't need functionality
- However, implementing in network can enhance performance in some cases
  – E.g., very losy link

Conservative Interpretation of E2E

- Don't implement a function at the lower levels of the system unless it can be completely implemented at this level
- Unless you can relieve the burden from hosts, don't bother

Moderate Interpretation

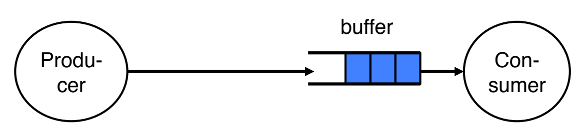
- Think twice before implementing functionality in the network
- If hosts can implement functionality correctly, implement it in a lower layer only as a performance enhancement
- But do so only if it does not impose burden on applications that do not require that functionality
- This is the interpretation we are using

Goals of Today's Lecture

- TCP flow control
- Two-Phase Commit
- RPCs

Flow Control

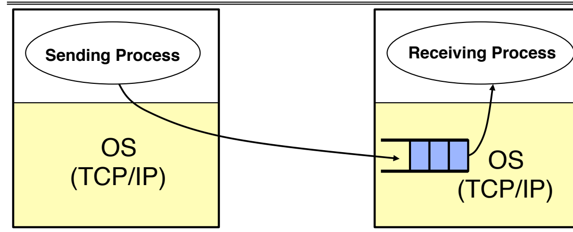
- Recall: Flow control ensures a fast sender does not overwhelm a slow receiver
- Example: Producer-consumer with bounded buffer (Lecture 5)
  - A buffer between producer and consumer
  - Producer puts items into buffer as long as buffer **not full**
  - Consumer consumes items from buffer



TCP Flow Control

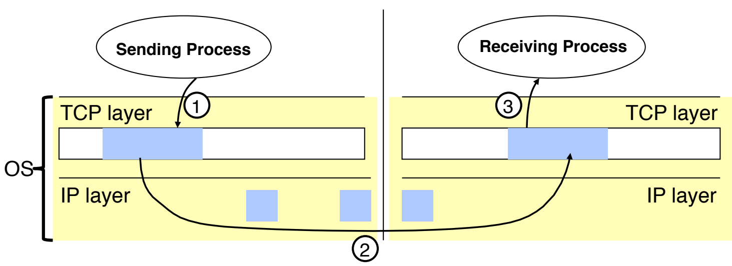
- TCP: sliding window protocol at byte (not packet) level
  - Go-back-N: TCP Tahoe, Reno, New Reno
  - Selective Repeat (SR): TCP Sack
- Receiver tells sender how many more bytes it can receive without overflowing its buffer (i.e., AdvertisedWindow)
- The ack(nowledgement) contains sequence number N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

TCP Flow Control



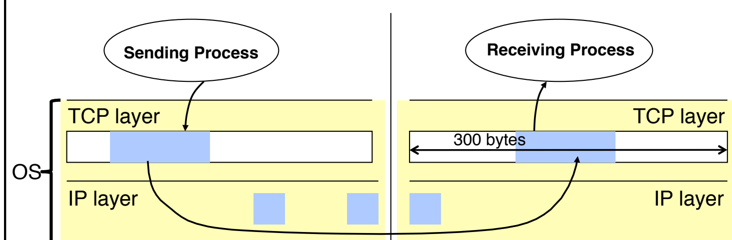
- TCP/IP implemented by OS (Kernel)
  - Cannot do context switching on sending/receiving every packet
    - » At 1Gbps, it takes 12 usec to send an 1500 bytes, and 0.8usec to send an 100 byte packet
- Need buffers to match …
  - sending app with sending TCP
  - receiving TCP with receiving app

TCP Flow Control



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

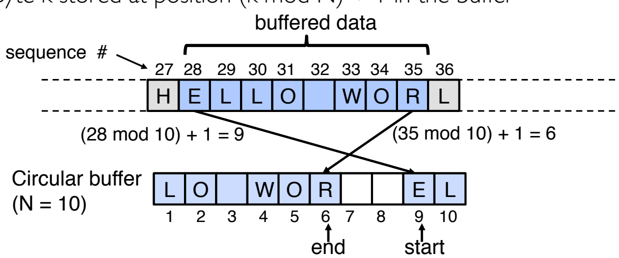
TCP Flow Control



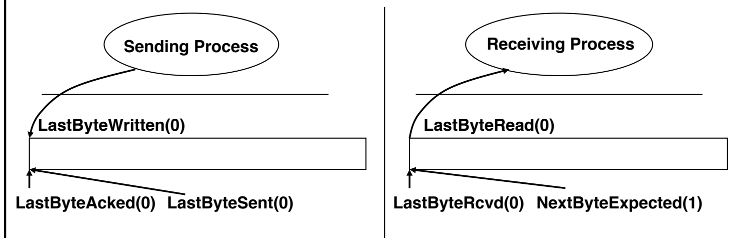
- Example assumptions:
  - Maximum IP packet size = 100 bytes
  - Size of the receiving buffer (MaxRcvBuf) = 300 bytes
- Recall, ack indicates the next expected byte in-sequence, not the last received byte
- Use circular buffers

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

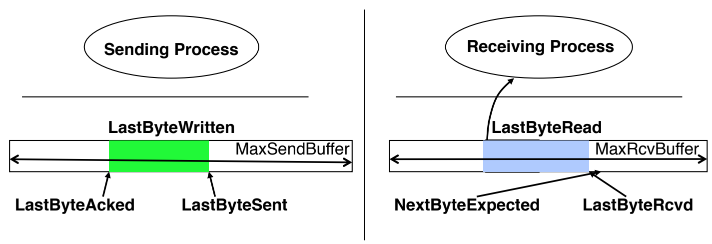


TCP Flow Control



- 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



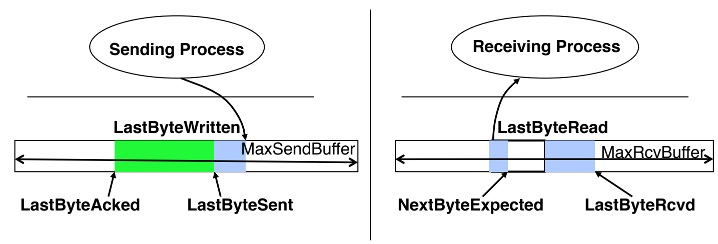
- AdvertisedWindow: number of bytes TCP receiver can receive

AdvertisedWindow = MaxRcvBuffer – (LastByteRcvd – LastByteRead)

- SenderWindow: number of bytes TCP sender can send

SenderWindow = AdvertisedWindow – (LastByteSent – LastByteAcked)

TCP Flow Control



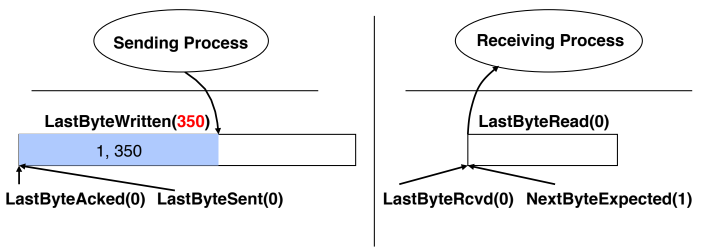
- Still true if receiver missed data….

AdvertisedWindow = MaxRcvBuffer – (LastByteRcvd – LastByteRead)

- WriteWindow: number of bytes sending process can write

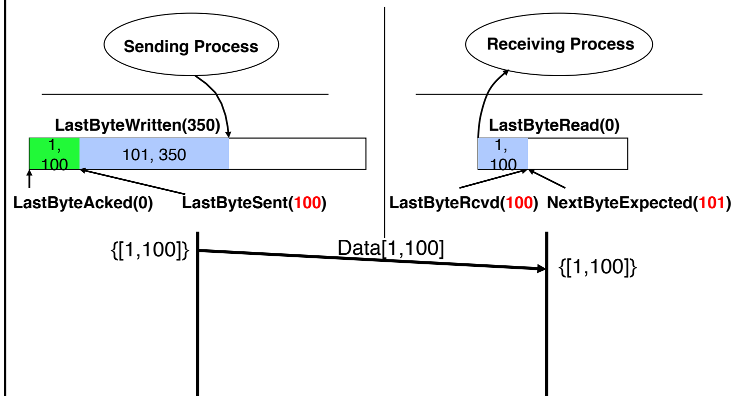
WriteWindow = MaxSendBuffer – (LastByteWritten – LastByteAcked)

TCP Flow Control



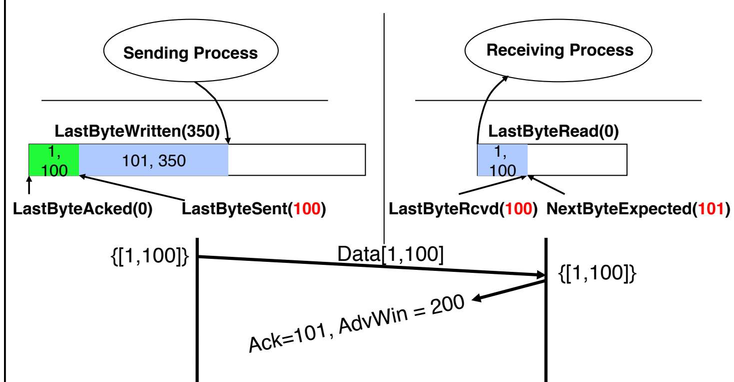
- Sending app sends 350 bytes
- Recall:
  - We assume IP only accepts packets no larger than 100 bytes
  - MaxRcvBuf = 300 bytes, so initial Advertised Window = 300 byets

TCP Flow Control



Sender sends first packet (i.e., first 100 bytes) and receiver gets the packet

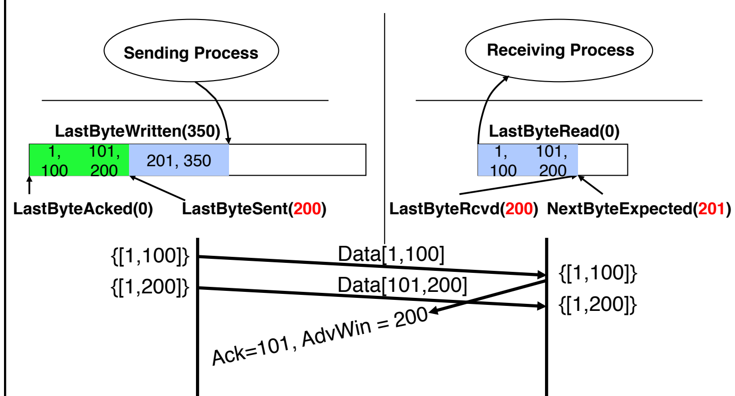
TCP Flow Control



Receiver sends ack for 1st packet

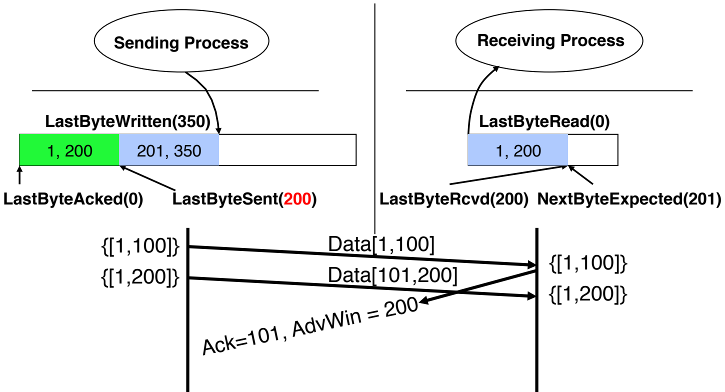
AdvWin = MaxRcvBuffer – (LastByteRcvd – LastByteRead)
= 300 – (100 – 0) = 200

TCP Flow Control



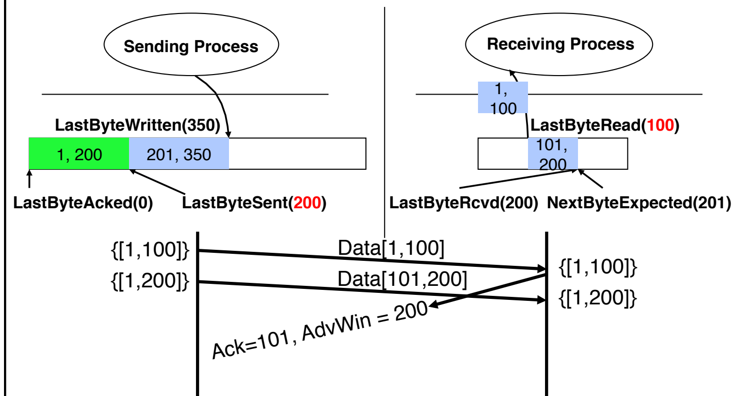
Sender sends 2nd packet (i.e., next 100 bytes) and receiver gets the packet

TCP Flow Control



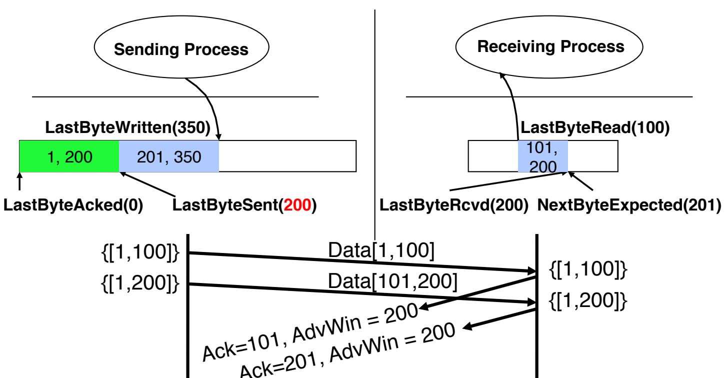
Sender sends 2nd packet (i.e., next 100 bytes) and receiver gets the packet

TCP Flow Control



Receiving TCP delivers first 100 bytes to recienving process

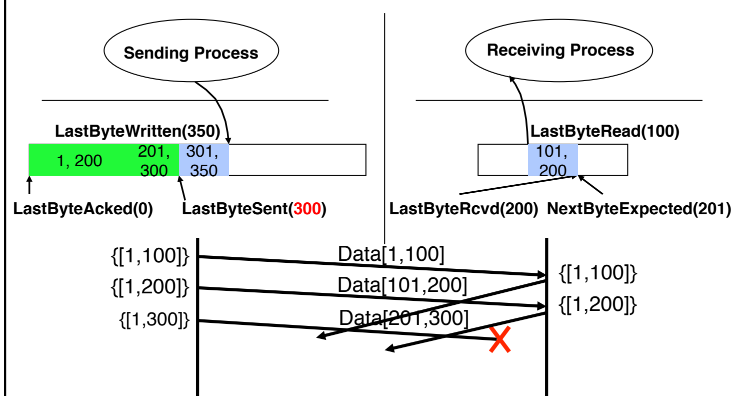
TCP Flow Control



Receiver sends ack for 2nd packet

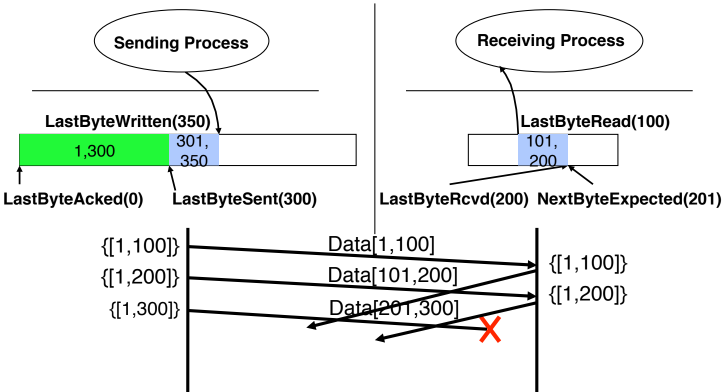
AdvWin = MaxRcvBuffer – (LastByteRcvd – LastByteRead)
= 300 – (200 – 100) = 200

TCP Flow Control



Sender sends 3rd packet (i.e., next 100 bytes) and the packet is lost

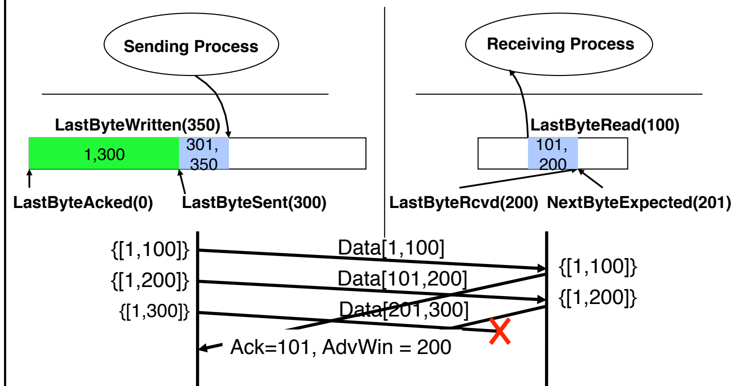
TCP Flow Control



Sender stops sending as window full

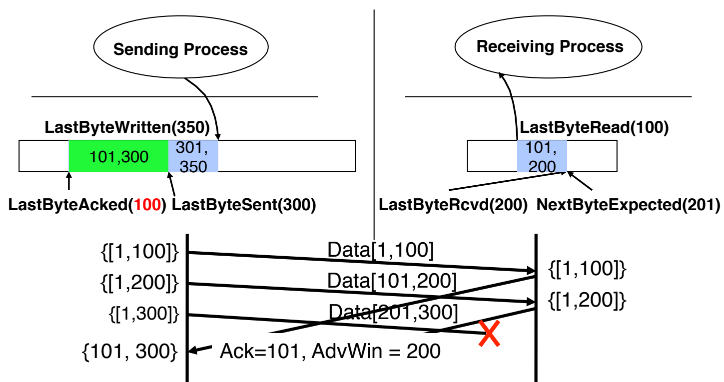
SndWin = AdvWin – (LastByteSent – LastByteAcked)
= 300 – (300 – 0) = 0

TCP Flow Control



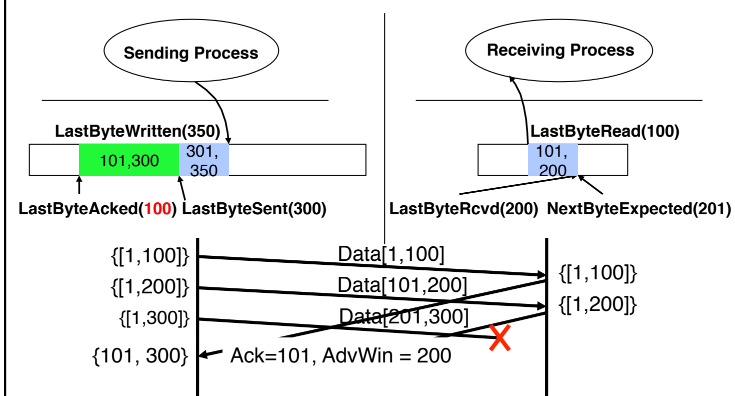
- Sender gets ack for 1st packet
- AdvWin = 200

TCP Flow Control



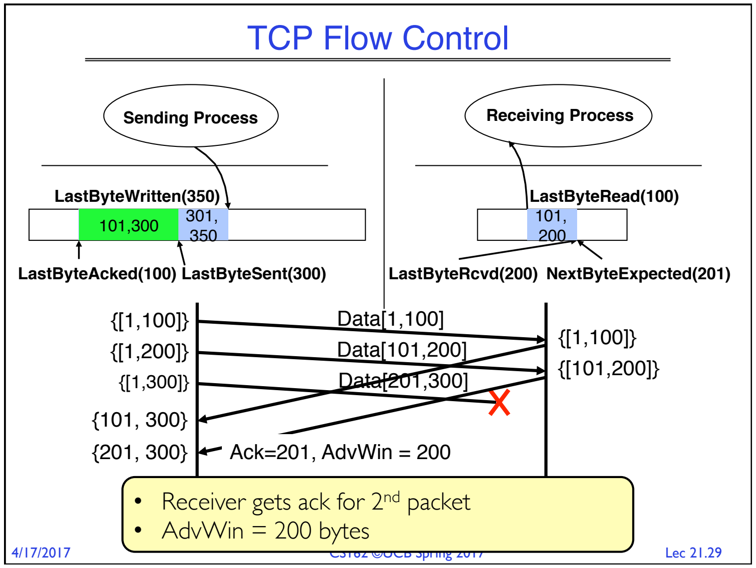
- Ack for 1st packet (ack indicates next byte expected by receiver)
- Receiver no longer needs first 100 bytes

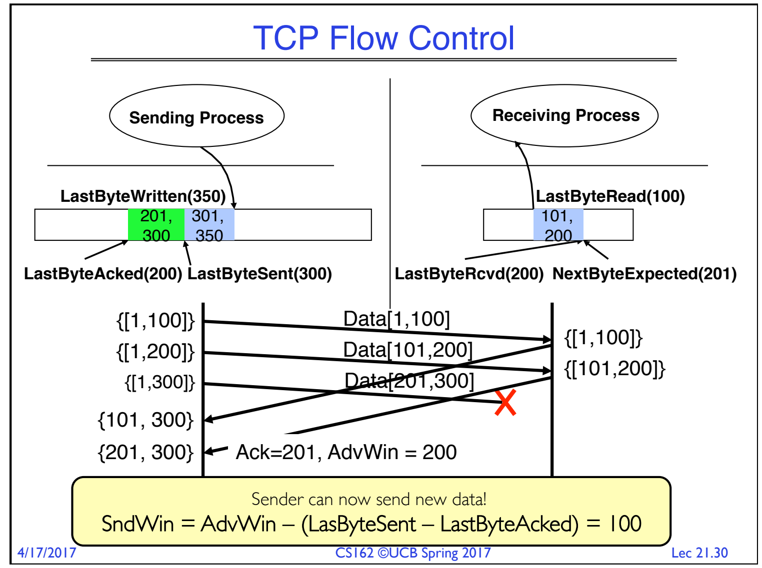
TCP Flow Control

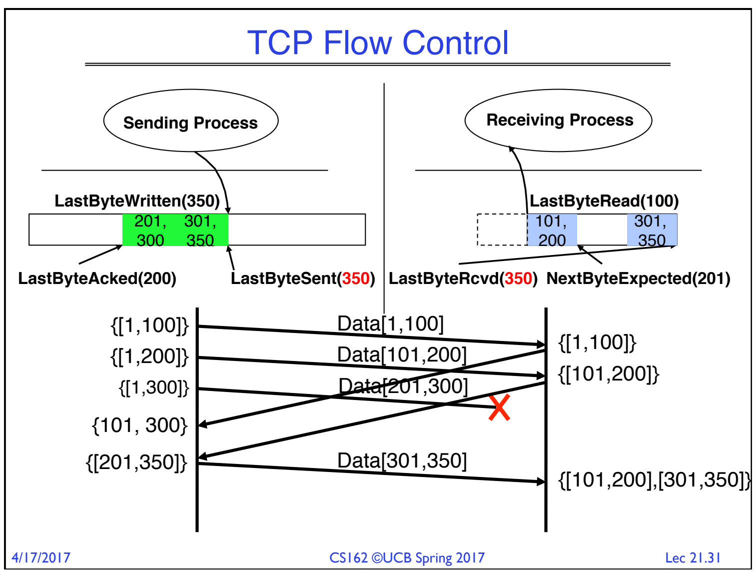


Sender still cannot send as window full

SndWin = AdvWin – (LastByteSent – LastByteAcked)
= 200 – (300 – 100) = 0


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
101,300
301, 350
LastByteAcked(100) LastByteSent(300)
LastByteRead(100)
101, 200
LastByteRcvd(200) NextByteExpected(201)
{[1,100]}
{[1,200]}
{[1,300]}
{101, 300}
{201, 300}
Data[1,100]
Data[101,200]
Data[201,300]
Ack=201, AdvWin = 200
{[1,100]}
{[101,200]}
Receiver gets ack for 2nd packet
AdvWin = 200 bytes
4/17/2017
Lec 21.29


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
201, 300
301, 350
LastByteAcked(200) LastByteSent(300)
LastByteRead(100)
101, 200
LastByteRcvd(200) NextByteExpected(201)
{[1,100]}
{[1,200]}
{[1,300]}
{101, 300}
{201, 300}
Data[1,100]
Data[101,200]
Data[201,300]
Ack=201, AdvWin = 200
{[1,100]}
{[101,200]}
Sender can now send new data!
SndWin = AdvWin – (LasByteSent – LastByteAcked) = 100
4/17/2017
CS162 ©UCB Spring 2017
Lec 21.30


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
201, 300
301, 350
LastByteAcked(200)
LastByteSent(350)
LastByteRead(100)
101, 200
301, 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]}
4/17/2017
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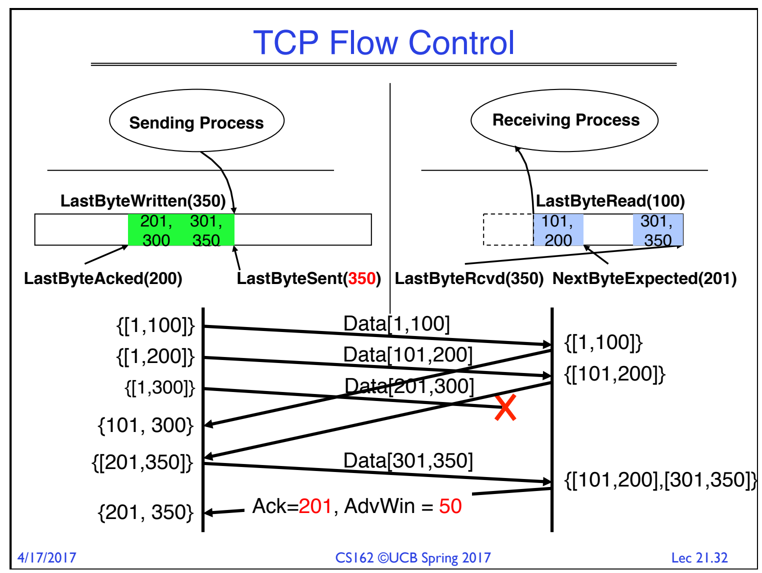
Lec 21.31


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
201, 300
301, 350
LastByteAcked(200)
LastByteSent(350)
LastByteRead(100)
101, 200
301, 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]}
4/17/2017
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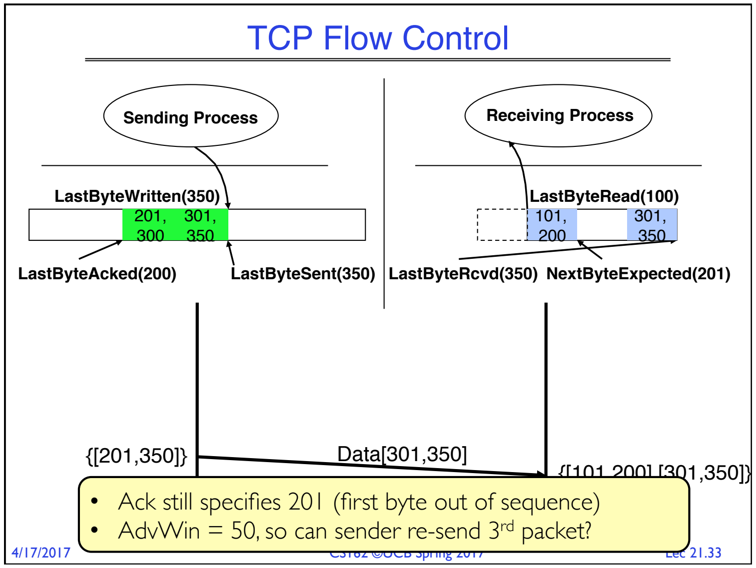
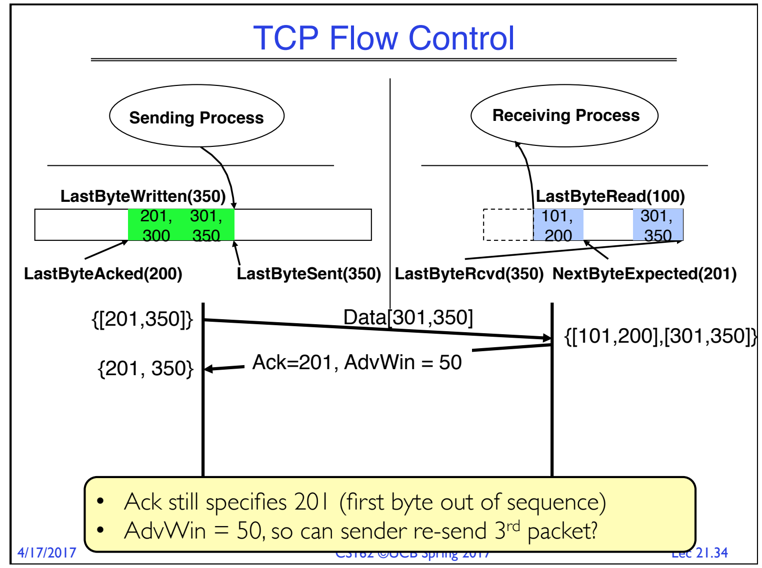
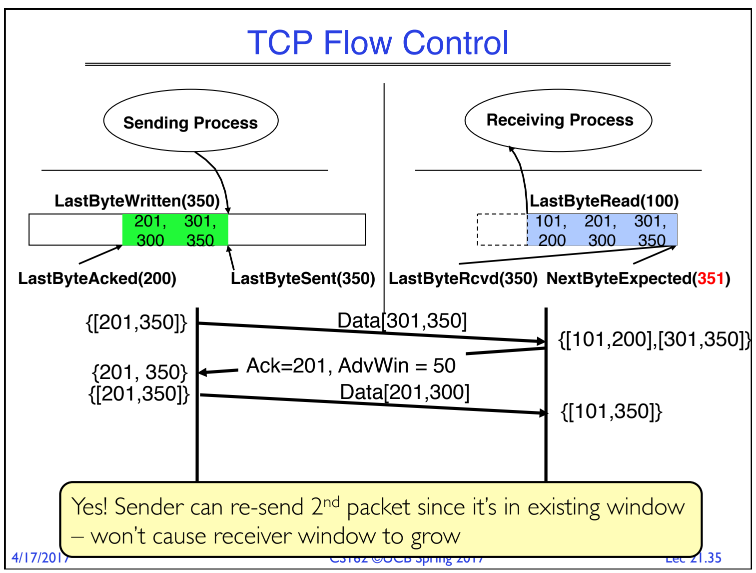
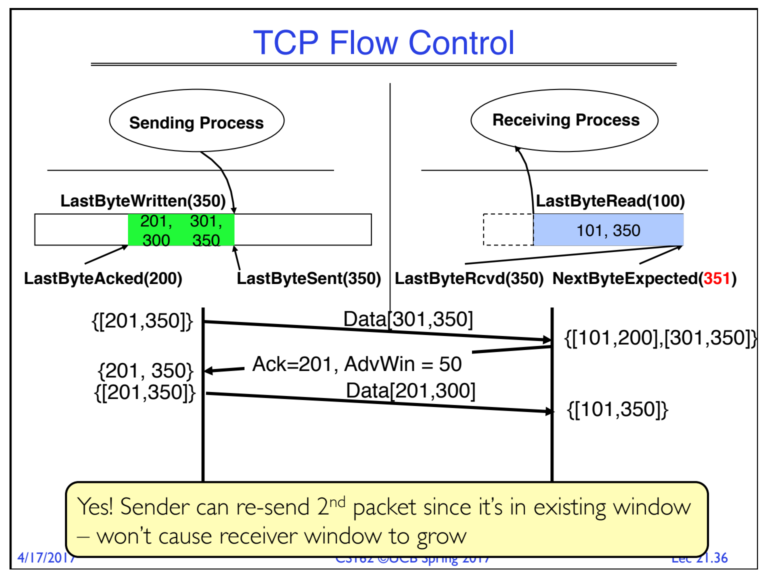
Lec 21.32

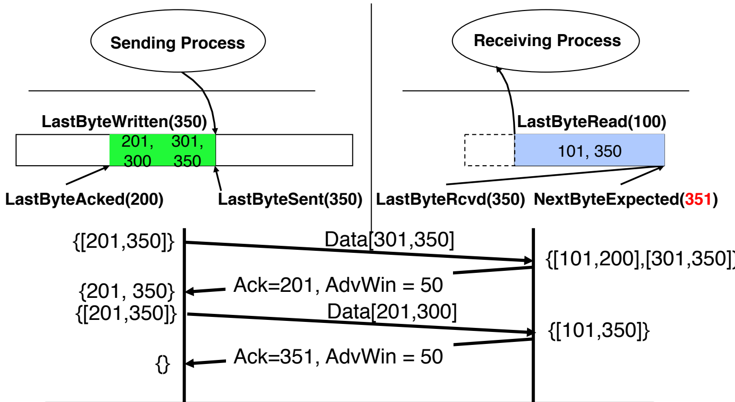

TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
201, 300
301, 350
LastByteAcked(200)
LastByteSent(350)
LastByteRead(100)
101, 200
301, 350
LastByteRcvd(350)
NextByteExpected(201)
{[201,350]}
Data[301,350]
Ack still specifies 201 (first byte out of sequence)
AdvWin = 50, so can sender re-send 3rd packet?
4/17/2017
Lec 21.33


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
201, 300
301, 350
LastByteAcked(200)
LastByteSent(350)
LastByteRead(100)
101, 200
301, 350
LastByteRcvd(350)
NextByteExpected(201)
{[201,350]}
Data[301,350]
{[101,200],[301,350]}
{201, 350}
Ack=201, AdvWin = 50
Ack still specifies 201 (first byte out of sequence)
AdvWin = 50, so can sender re-send 3rd packet?
4/17/2017
Lec 21.34


TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
201, 300
301, 350
LastByteAcked(200)
LastByteSent(350)
LastByteRead(100)
101, 200
201, 300
301, 350
LastByteRcvd(350)
NextByteExpected(351)
{[201,350]}
Data[301,350]
{[101,200],[301,350]}
{201, 350}
Ack=201, AdvWin = 50
{[201,350]}
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
Lec 21.35

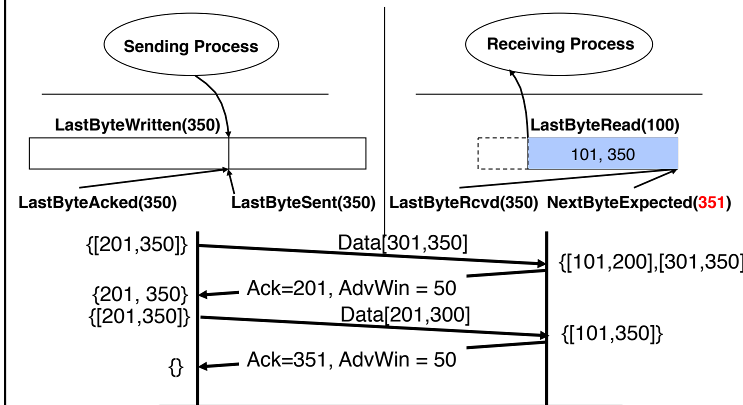

TCP Flow Control
Sending Process
Receiving Process
LastByteWritten(350)
201, 300
301, 350
LastByteAcked(200)
LastByteSent(350)
LastByteRead(100)
101, 350
LastByteRcvd(350)
NextByteExpected(351)
{[201,350]}
Data[301,350]
{[101,200],[301,350]}
{201, 350}
Ack=201, AdvWin = 50
{[201,350]}
Data[201,300]
{[101,350]}
Yes! Sender can re-send 2nd packet since it's in existing window – won't cause receiver window to grow
Lec 21.36

TCP Flow Control



- Sender gets 3rd packet and sends Ack for 351
- AdvWin = 50

TCP Flow Control



Sender DONE with sending all bytes!

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 cs168)
- In practice there is another set of buffers in the protocol stack, at the link layer (i.e., Network Interface Card)

Administrivia

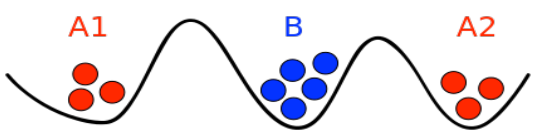
- Midterm 3 coming up on **Mon 4/24 6:30-8PM**
  - All topics up to and including Lecture 15
    - » Focus will be on Lectures 16 – 23 and associated readings, and Projects 3
    - » But expect 20-30% questions from materials from Lectures 1-15
  - VLSB 2040 and VLSB 2060
  - Closed book
  - 2 pages hand-written notes both sides

Goals of Today's Lecture

- TCP flow control
- Two-Phase Commit
- RPCs

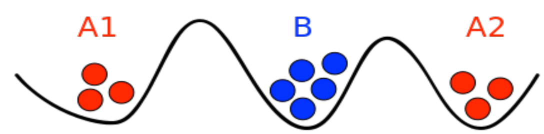
BREAK

General's Paradox

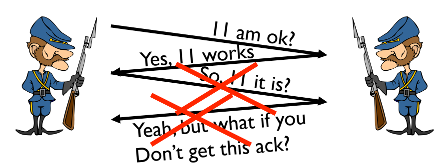


- Constraints of problem:
  - Two generals, on separate mountains
  - Can only communicate via messengers
  - Messengers can be captured
- Problem: need to coordinate attack
  - If they attack at different times, they all die
  - If they attack at same time, they win
- Named after Custer, who died at Little Big Horn because he arrived a couple of days too early

General's Paradox



- Can messages over an unreliable network be used to guarantee two entities do something simultaneously?
  - Remarkably, "no", even if all messages get through



  - No way to be sure last message gets through!

Two-Phase Commit

- Since we can't solve the General's Paradox (i.e. simultaneous action), let's solve a related problem
- Distributed transaction: Two or more machines agree to do something, or not do it, atomically
- Two-Phase Commit protocol: Developed by Turing award winner Jim Gray (first Berkeley CS PhD, 1969)

Two-Phase Commit Protocol

- Persistent stable log on each machine: keep track of whether commit has happened
  - If a machine crashes, when it wakes up it first checks its log to recover state of world at time of crash
- Prepare Phase:
  - The global coordinator requests that all participants will promise to commit or rollback the transaction
  - Participants record promise in log, then acknowledge
  - If anyone votes to abort, coordinator writes `"Abort"` in its log and tells everyone to abort; each records `"Abort"` in log
- Commit Phase:
  - After all participants respond that they are prepared, then the coordinator writes `"Commit"` to its log
  - Then asks all nodes to commit; they respond with ACK
  - After receive ACKs, coordinator writes `"Got Commit"` to log
- Log used to guarantee that all machines either commit or don't

2PC Algorithm

- One coordinator
- N workers (replicas)
- High level algorithm description:
  - Coordinator asks all workers if they can commit
  - If all workers reply "VOTE-COMMIT", then coordinator broadcasts "GLOBAL-COMMIT"

    Otherwise coordinator broadcasts "GLOBAL-ABORT"
  - Workers obey the GLOBAL messages
- Use a persistent, stable log on each machine to keep track of what you are doing
  - If a machine crashes, when it wakes up it first checks its log to recover state of world at time of crash

Detailed Algorithm

Coordinator Algorithm

Coordinator sends **VOTE-REQ** to all workers

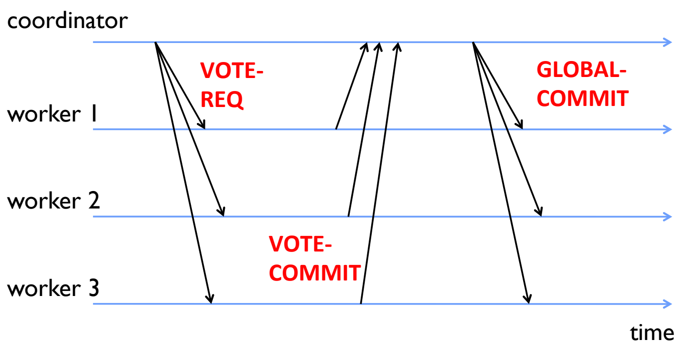
- If receive **VOTE-COMMIT** from all N workers, send **GLOBAL-COMMIT** to all workers
- If doesn't receive **VOTE-COMMIT** from all N workers, send **GLOBAL-ABORT** to all workers

Worker Algorithm

- Wait for **VOTE-REQ** from coordinator
- If ready, send **VOTE-COMMIT** to coordinator
- If not ready, send **VOTE-ABORT** to coordinator
  - And immediately abort

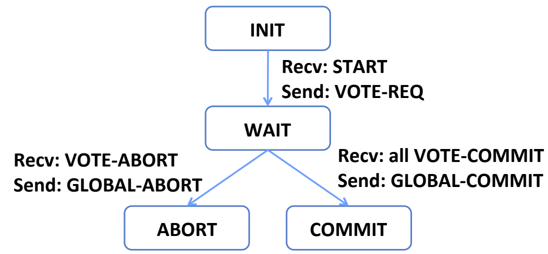
- If receive **GLOBAL-COMMIT** then commit
- If receive **GLOBAL-ABORT** then abort

Failure Free Example Execution

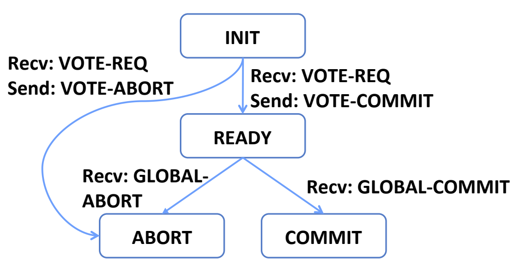


State Machine of Coordinator

- Coordinator implements simple state machine:

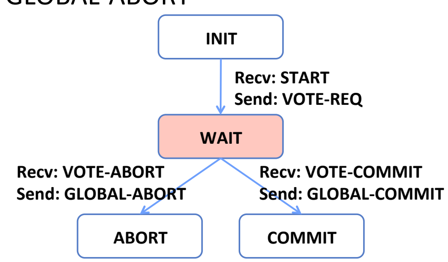


State Machine of Workers

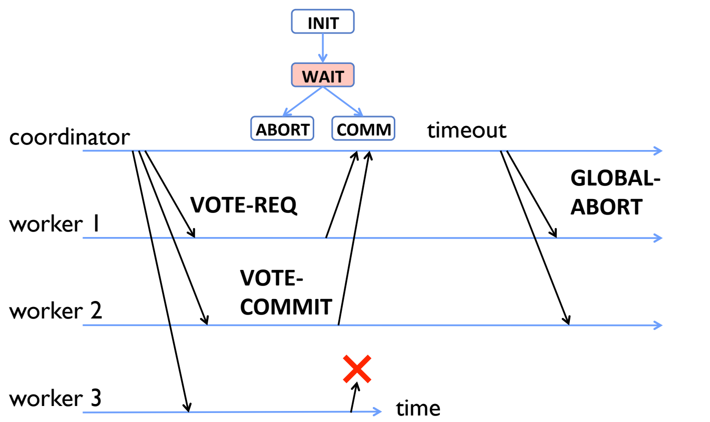


Dealing with Worker Failures

- Failure only affects states in which the coordinator is waiting for messages
- Coordinator only waits for votes in "WAIT" state
- In WAIT, if doesn't receive N votes, it times out and sends GLOBAL-ABORT

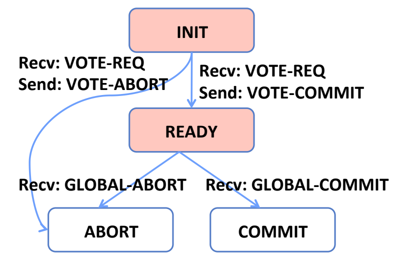


Example of Worker Failure

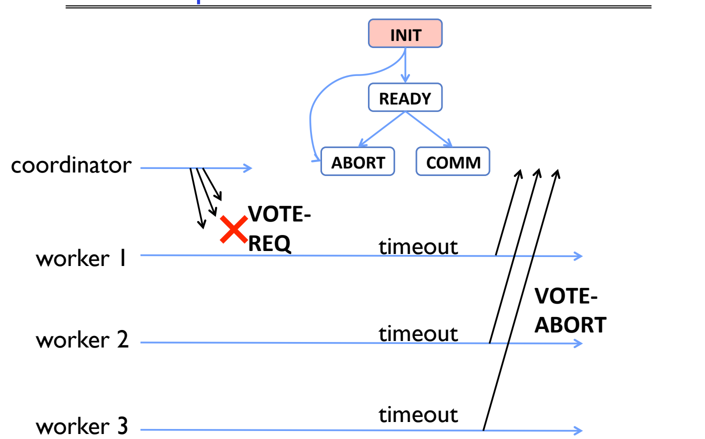


Dealing with Coordinator Failure

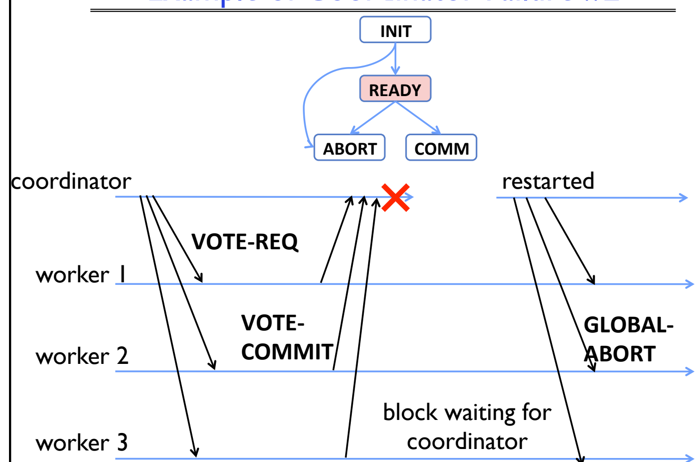
- Worker waits for VOTE-REQ in INIT
  – Worker can time out and abort (coordinator handles it)
- Worker waits for GLOBAL-* message in READY
  – If coordinator fails, workers must **BLOCK** waiting for coordinator to recover and send GLOBAL_* message



Example of Coordinator Failure #1



Example of Coordinator Failure #2

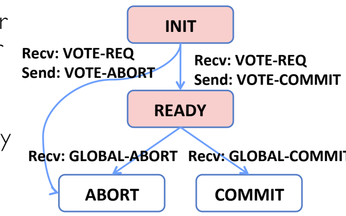


Durability

- All nodes use stable storage to store current state
  - stable storage is non-volatile storage (e.g. backed by disk) that guarantees atomic writes.
- Upon recovery, it can restore state and resume:
  - Coordinator aborts in INIT, WAIT, or ABORT
  - Coordinator commits in COMMIT
  - Worker aborts in INIT, ABORT
  - Worker commits in COMMIT
  - Worker asks Coordinator in READY

Blocking for Coordinator to Recover

- A worker waiting for global decision can ask fellow workers about their state
  - If another worker is in **ABORT** or **COMMIT** state then coordinator must have sent **GLOBAL-***
    - » Thus, worker can safely abort or commit, respectively



  - If another worker is still in **INIT** state then both workers can decide to abort
  - If all workers are in ready, need to **BLOCK** (don't know if coordinator wanted to abort or commit)

Distributed Decision Making Discussion (1/2)

- Why is distributed decision making desirable?
  - Fault Tolerance!
  - A group of machines can come to a decision even if one or more of them fail during the process
    - » Simple failure mode called "failstop" (different modes later)
  - After decision made, result recorded in multiple places

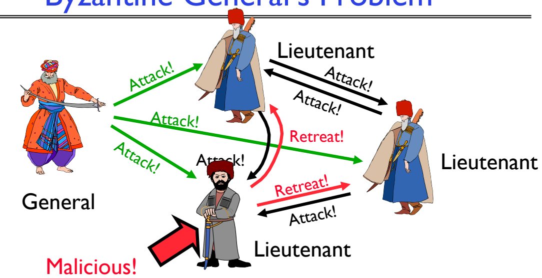
Distributed Decision Making Discussion (2/2)

- Undesirable feature of Two-Phase Commit: Blocking
  - One machine can be stalled until another site recovers:
    - » Site B writes `"prepared to commit"` record to its log, sends a `"yes"` vote to the coordinator (site A) and crashes
    - » Site A crashes
    - » Site B wakes up, check its log, and realizes that it has voted `"yes"` on the update. It sends a message to site A asking what happened. At this point, B cannot decide to abort, because update may have committed
    - » B is blocked until A comes back
  - A blocked site holds resources (locks on updated items, pages pinned in memory, etc) until learns fate of update

PAXOS

- PAXOS: An alternative used by Google and others that does not have this blocking problem
  - Develop by Leslie Lamport (Turing Award Winner)
- What happens if one or more of the nodes is malicious?
  - Malicious: attempting to compromise the decision making

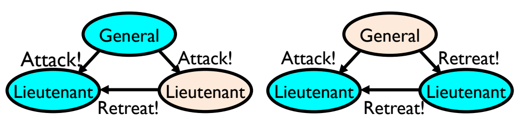
Byzantine General's Problem



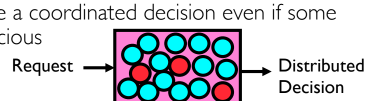
- Byazantine General's Problem (n players):
  - One General and n-1 Lieutenants
  - Some number of these (*f*) can be insane or malicious
- The commanding general must send an order to his n-1 lieutenants such that the following Integrity Constraints apply:
  - IC1: All loyal lieutenants obey the same order
  - IC2: If the commanding general is loyal, then all loyal lieutenants obey the order he sends

Byzantine General's Problem (con't)

- Impossibility Results:
  - Cannot solve Byzantine General's Problem with $n=3$ because one malicious player can mess up things



  - With f faults, need $n > 3f$ to solve problem
- Various algorithms exist to solve problem
  - Original algorithm has #messages exponential in n
  - Newer algorithms have message complexity $O(n^2)$
    - » One from MIT, for instance (Castro and Liskov, 1999)
- Use of BFT (Byzantine Fault Tolerance) algorithm
  - Allow multiple machines to make a coordinated decision even if some subset of them ($< n/3$) are malicious



Goals of Today's Lecture

- TCP flow control
- Two-Phase Commit
- RPCs

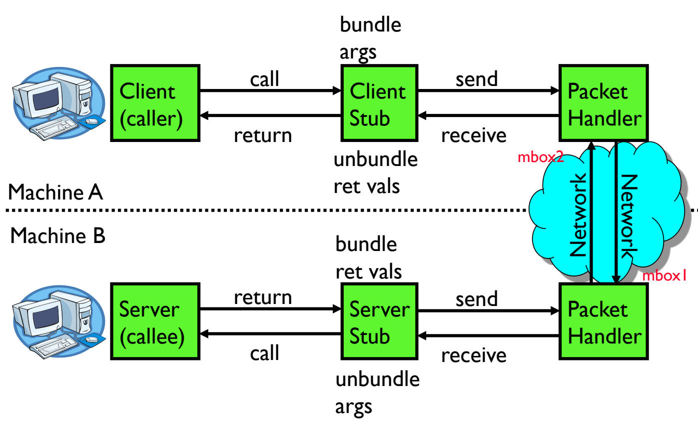
Remote Procedure Call (RPC)

- Raw messaging is a bit too low-level for programming
  - Must wrap up information into message at source
  - Must decide what to do with message at destination
  - May need to sit and wait for multiple messages to arrive
- Another option: Remote Procedure Call (RPC)
  - Calls a procedure on a remote machine
  - Client calls:
    `remoteFileSystem→Read("rutabaga");`
  - Translated automatically into call on server:
    `fileSys→Read("rutabaga");`

RPC Implementation

- Request-response message passing (under covers!)
- "Stub" provides glue on client/server
  - Client stub is responsible for "marshalling" arguments and "unmarshalling" the return values
  - Server-side stub is responsible for "unmarshalling" arguments and "marshalling" the return values.
- Marshalling involves (depending on system)
  - Converting values to a canonical form, serializing objects, copying arguments passed by reference, etc.

RPC Information Flow



RPC Details (1/3)

- Equivalence with regular procedure call
  - Parameters ⇔ Request Message
  - Result ⇔ Reply message
  - Name of Procedure: Passed in request message
  - Return Address: mbox2 (client return mail box)
- Stub generator: Compiler that generates stubs
  - Input: interface definitions in an "interface definition language (IDL)"
    - » Contains, among other things, types of arguments/return
  - Output: stub code in the appropriate source language
    - » Code for client to pack message, send it off, wait for result, unpack result and return to caller
    - » Code for server to unpack message, call procedure, pack results, send them off

RPC Details (2/3)

- Cross-platform issues:
  - What if client/server machines are different architectures/ languages?
    - » Convert everything to/from some canonical form
    - » Tag every item with an indication of how it is encoded (avoids unnecessary conversions)
- How does client know which mbox to send to?
  - Need to translate name of remote service into network endpoint (Remote machine, port, possibly other info)
  - Binding: the process of converting a user-visible name into a network endpoint
    - » This is another word for "naming" at network level
    - » Static: fixed at compile time
    - » Dynamic: performed at runtime

RPC Details (3/3)

- Dynamic Binding
  - Most RPC systems use dynamic binding via name service
    - » Name service provides dynamic translation of service → mbox
  - Why dynamic binding?
    - » Access control: check who is permitted to access service
    - » Fail-over: If server fails, use a different one
- What if there are multiple servers?
  - Could give flexibility at binding time
    - » Choose unloaded server for each new client
  - Could provide same mbox (router level redirect)
    - » Choose unloaded server for each new request
    - » Only works if no state carried from one call to next
- What if multiple clients?
  - Pass pointer to client-specific return mbox in request

Problems with RPC: Non-Atomic Failures

- Different failure modes in dist. system than on a single machine
- Consider many different types of failures
  - User-level bug causes address space to crash
  - Machine failure, kernel bug causes all processes on same machine to fail
  - Some machine is compromised by malicious party
- Before RPC: whole system would crash/die
- After RPC: One machine crashes/compromised while others keep working
- Can easily result in inconsistent view of the world
  - Did my cached data get written back or not?
  - Did server do what I requested or not?
- Answer? Distributed transactions/Byzantine Commit

Problems with RPC: Performance

- Cost of Procedure call « same-machine RPC « network RPC
- Means programmers must be aware that RPC is not free
  - Caching can help, but may make failure handling complex

Summary

- Two-phase commit: distributed decision making
  - First, make sure everyone guarantees they will commit if asked (prepare)
  - Next, ask everyone to commit
- Byzantine General's Problem: distributed decision making with malicious failures
  - One general, n-1 lieutenants: some number of them may be malicious (often "f" of them)
  - All non-malicious lieutenants must come to same decision
  - If general not malicious, lieutenants must follow general
  - Only solvable if $n \geq 3f+1$
- Remote Procedure Call (RPC): Call procedure on remote machine
  - Provides same interface as procedure
  - Automatic packing/unpacking of args without user programming