CS162
Operating Systems and Systems Programming
Lecture 23

Network Communication Abstractions / Distributed Programming

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Review: Reliable Message Delivery: the Problem

- All physical networks can garble and/or drop packets
  - Physical media: packet not transmitted/received
    - » If transmit close to maximum rate, get more throughput – even if some packets get lost
    - » If transmit at lowest voltage such that error correction just starts correcting errors, get best power/bit
  - Congestion: no place to put incoming packet
    - » Point-to-point network: insufficient queue at switch/router
    - » Broadcast link: two host try to use same link
    - » In any network: insufficient buffer space at destination
    - » Rate mismatch: what if sender send faster than receiver can process?
- Reliable Message Delivery on top of Unreliable Packets
  - Need some way to make sure that packets actually make it to receiver
    - » Every packet received at least once
    - » Every packet received at most once
  - Can combine with ordering: every packet received by process at destination exactly once and in order

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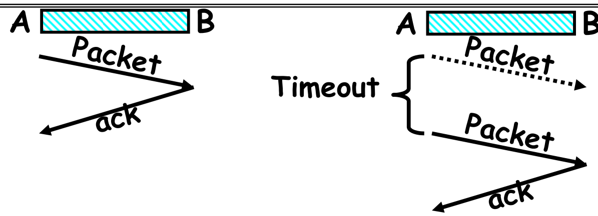
Goals for Today

- Finish Discussion of TCP/IP
- Messages
  - Send/receive
  - One vs. two-way communication
- Distributed Decision Making
  - Two-phase commit/Byzantine Commit
- Remote Procedure Call
- Distributed File Systems (Part I)

Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne. Many slides generated from my lecture notes by Kubiatowicz.

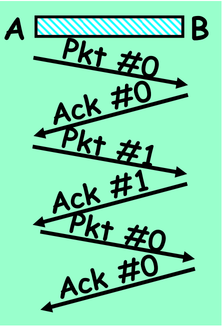
Using Acknowledgements



- How to ensure transmission of packets?
  - Detect garbling at receiver via checksum, discard if bad
  - Receiver acknowledges (by sending "ack") when packet received properly at destination
  - Timeout at sender: if no ack, retransmit
- Some questions:
  - If the sender doesn't get an ack, does that mean the receiver didn't get the original message?
    - » No
  - What if ack gets dropped? Or if message gets delayed?
    - » Sender doesn't get ack, retransmits. Receiver gets message twice, acks each.

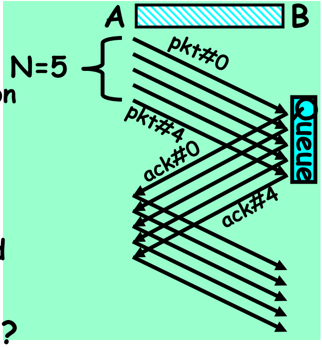
How to deal with message duplication

- Solution: put sequence number in message to identify re-transmitted packets
  - Receiver checks for duplicate #'s; Discard if detected
- Requirements:
  - Sender keeps copy of unack'ed messages
    - » Easy: only need to buffer messages
  - Receiver tracks possible duplicate messages
    - » Hard: when ok to forget about received message?
- **Alternating-bit protocol:**
  - Send one message at a time; don't send next message until ack received
  - Sender keeps last message; receiver tracks sequence # of last message received
- Pros: simple, small overhead
- Con: Poor performance
  - Wire can hold multiple messages; want to fill up at (wire latency × throughput)
- Con: doesn't work if network can delay or duplicate messages arbitrarily

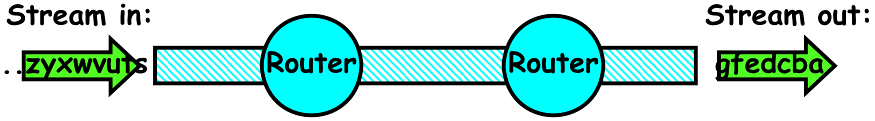


Better messaging: Window-based acknowledgements

- **Windowing protocol (not quite TCP):**
  - Send up to N packets without ack
    - » Allows pipelining of packets
    - » Window size (N) < queue at destination
  - Each packet has sequence number
    - » Receiver acknowledges each packet
    - » Ack says "received all packets up to sequence number X"/send more
- Acks serve dual purpose:
  - Reliability: Confirming packet received
  - Ordering: Packets can be reordered at destination
- What if packet gets garbled/dropped?
  - Sender will timeout waiting for ack packet
    - » Resend missing packets⇒ Receiver gets packets out of order!
  - Should receiver discard packets that arrive out of order?
    - » Simple, but poor performance
  - Alternative: Keep copy until sender fills in missing pieces?
    - » Reduces # of retransmits, but more complex
- What if ack gets garbled/dropped?
  - Timeout and resend just the un-acknowledged packets

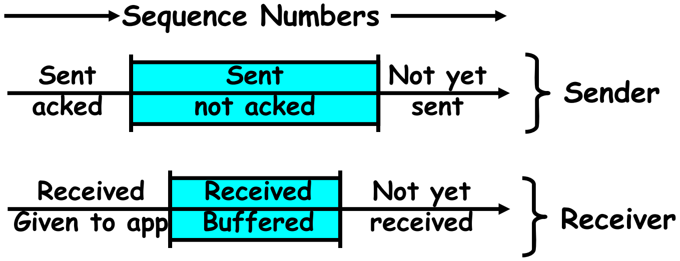


Transmission Control Protocol (TCP)



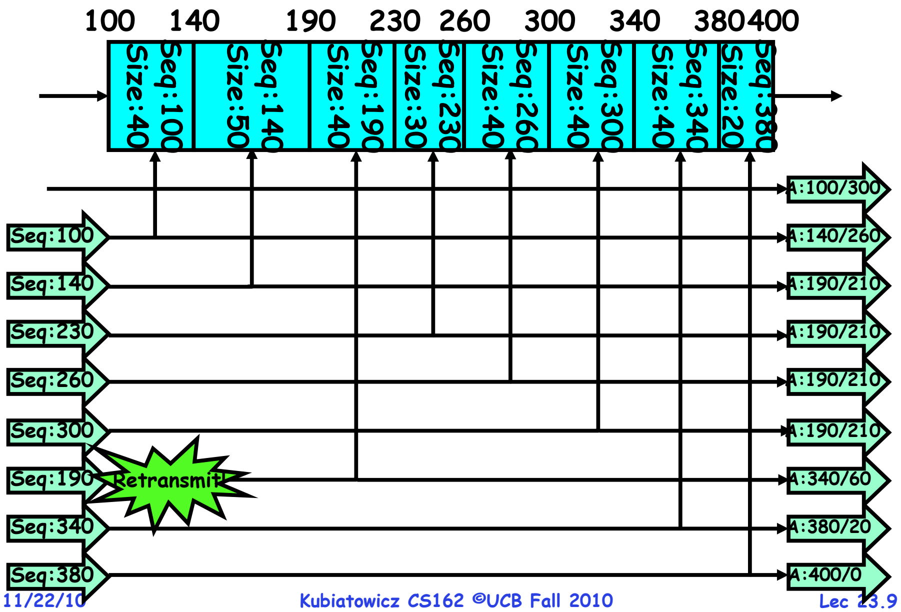
- Transmission Control Protocol (TCP)
  - TCP (IP Protocol 6) layered on top of IP
  - Reliable byte stream between two processes on different machines over Internet (read, write, flush)
- TCP Details
  - Fragments byte stream into packets, hands packets to IP
    - » IP may also fragment by itself
  - Uses window-based acknowledgement protocol (to minimize state at sender and receiver)
    - » "Window" reflects storage at receiver – sender shouldn't overrun receiver's buffer space
    - » Also, window should reflect speed/capacity of network – sender shouldn't overload network
  - Automatically retransmits lost packets
  - Adjusts rate of transmission to avoid congestion
    - » A "good citizen"

TCP Windows and Sequence Numbers



- Sender has three regions:
  - Sequence regions
    - » sent and ack'ed
    - » Sent and not ack'ed
    - » not yet sent
  - Window (colored region) adjusted by sender
- Receiver has three regions:
  - Sequence regions
    - » received and ack'ed (given to application)
    - » received and buffered
    - » not yet received (or discarded because out of order)

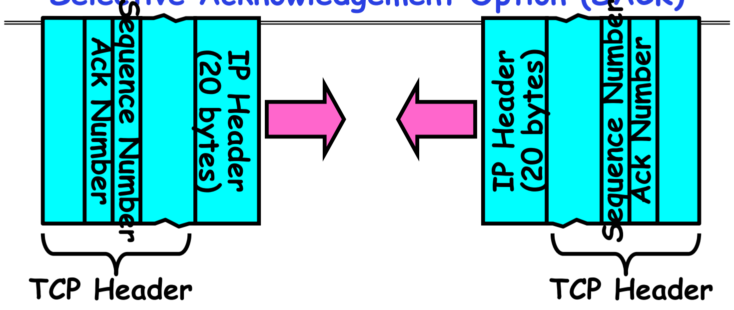
Window-Based Acknowledgements (TCP)



Administrivia

- Project 4 design document:
  - Extension to Wednesday night
- Final Exam
  - Thursday 12/16, 8:00AM-11:00AM, 10 Evans
  - All material from the course
    - » With slightly more focus on second half, but you are still responsible for all the material
  - Two sheets of notes, both sides
  - Will need dumb calculator (No phones, devices with net)
- There *is* a lecture on Wednesday
  - Including this one, we are down to 4 lectures…!
- Optional Final Lecture: Monday 12/6
  - Send me topics you might want to hear about
  - Won't be responsible for topics on Final
  - Starting to get interesting suggestions!
  - Examples:
    - » Realtime OS, Secure Hardware, Quantum Computing
    - » Dragons… Etc.

Selective Acknowledgement Option (SACK)



- Vanilla TCP Acknowledgement
  - Every message encodes Sequence number and Ack
  - Can include data for forward stream and/or ack for reverse stream
- Selective Acknowledgement
  - Acknowledgement information includes not just one number, but rather ranges of received packets
  - Must be specially negotiated at beginning of TCP setup
    - » Not widely in use (although in Windows since Windows 98)

Congestion Avoidance

- Congestion
  - How long should timeout be for re-sending messages?
    - » Too long→wastes time if message lost
    - » Too short→retransmit even though ack will arrive shortly
  - Stability problem: more congestion ⇒ ack is delayed ⇒ unnecessary timeout ⇒ more traffic ⇒ more congestion
    - » Closely related to window size at sender: too big means putting too much data into network
- How does the sender's window size get chosen?
  - Must be less than receiver's advertised buffer size
  - Try to match the rate of sending packets with the rate that the slowest link can accommodate
  - Sender uses an adaptive algorithm to decide size of N
    - » Goal: fill network between sender and receiver
    - » Basic technique: slowly increase size of window until acknowledgements start being delayed/lost
- TCP solution: "slow start" (start sending slowly)
  - If no timeout, slowly increase window size (throughput) by 1 for each ack received
  - Timeout ⇒ congestion, so cut window size in half
  - "*Additive Increase, Multiplicative Decrease*"

Sequence-Number Initialization

- How do you choose an initial sequence number?
  - When machine boots, ok to start with sequence #0?
    - » No: could send two messages with same sequence #!
    - » Receiver might end up discarding valid packets, or duplicate ack from original transmission might hide lost packet
  - Also, if it is possible to predict sequence numbers, might be possible for attacker to hijack TCP connection
- Some ways of choosing an initial sequence number:
  - Time to live: each packet has a deadline.
    - » If not delivered in X seconds, then is dropped
    - » Thus, can re-use sequence numbers if wait for all packets in flight to be delivered or to expire
  - Epoch #: uniquely identifies *which* set of sequence numbers are currently being used
    - » Epoch # stored on disk, Put in every message
    - » Epoch # incremented on crash and/or when run out of sequence #
  - Pseudo-random increment to previous sequence number
    - » Used by several protocol implementations

Use of TCP: Sockets

- **Socket:** an abstraction of a network I/O queue
  - Embodies one side of a communication channel
    - » Same interface regardless of location of other end
    - » Could be local machine (called “UNIX socket”) or remote machine (called “network socket”)
  - First introduced in 4.2 BSD UNIX: big innovation at time
    - » Now most operating systems provide some notion of socket
- Using Sockets for Client-Server (C/C++ interface):
  - On server: set up “server-socket”
    - » Create socket, Bind to protocol (TCP), local address, port
    - » Call listen(): tells server socket to accept incoming requests
    - » Perform multiple accept() calls on socket to accept incoming connection request
    - » Each successful accept() returns a new socket for a new connection; can pass this off to handler thread
  - On client:
    - » Create socket, Bind to protocol (TCP), remote address, port
    - » Perform connect() on socket to make connection
    - » If connect() successful, have socket connected to server

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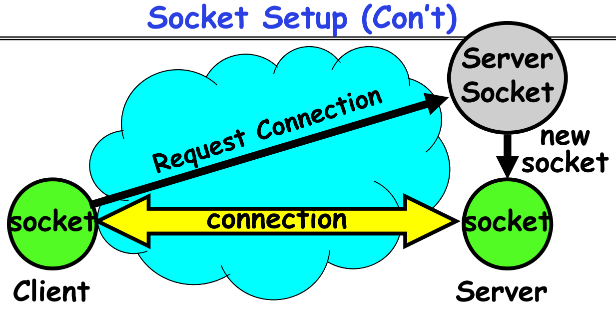
Socket Setup (Con’t)



- Things to remember:
  - Connection involves 5 values:
    [Client Addr, Client Port, Server Addr, Server Port, Protocol]
  - Often, Client Port “randomly” assigned
    - » Done by OS during client socket setup
  - Server Port often “well known”
    - » 80 (web), 443 (secure web), 25 (sendmail), etc
    - » Well-known ports from 0—1023
- Note that the uniqueness of the tuple is really about two Addr/Port pairs and a protocol

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Socket Example (Java)

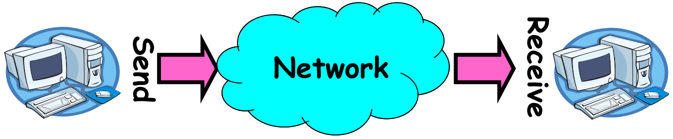
```
server:
     //Makes socket, binds addr/port, calls listen()
     ServerSocket sock = new ServerSocket(6013);
     while(true) {
       Socket client = sock.accept();
       PrintWriter pout = new
         PrintWriter(client.getOutputStream(),true);

       pout.println(“Here is data sent to client!”);
         …
       client.close();
     }

client:
     // Makes socket, binds addr/port, calls connect()
     Socket sock = new Socket(“169.229.60.38”,6013);
     BufferedReader bin =
       new BufferedReader(
         new InputStreamReader(sock.getInputStream));
     String line;
     while ((line = bin.readLine())!=null)
       System.out.println(line);
     sock.close();
```

Distributed Applications

- How do you actually program a distributed application?
  - Need to synchronize multiple threads, running on different machines
    - » No shared memory, so cannot use test&set



  - One Abstraction: send/receive messages
    - » Already atomic: no receiver gets portion of a message and two receivers cannot get same message
- Interface:
  - Mailbox (mbox): temporary holding area for messages
    - » Includes both destination location and queue
  - `Send(message,mbox)`
    - » Send message to remote mailbox identified by mbox
  - `Receive(buffer,mbox)`
    - » Wait until mbox has message, copy into buffer, and return
    - » If threads sleeping on this mbox, wake up one of them

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Using Messages: Send/Receive behavior

- When should `send(message,mbox)` return?
  - When receiver gets message? (i.e. ack received)
  - When message is safely buffered on destination?
  - Right away, if message is buffered on source node?
- Actually two questions here:
  - When can the sender be sure that receiver actually received the message?
  - When can sender reuse the memory containing message?
- Mailbox provides 1-way communication from T1→T2
  - T1→buffer→T2
  - Very similar to producer/consumer
    - » Send = V, Receive = P
    - » However, can't tell if sender/receiver is local or not!

Messaging for Producer-Consumer Style

- Using send/receive for producer-consumer style:

```
Producer:
   int msg1[1000];
   while(1) {
      prepare message;
      send(msg1,mbox);
   }
```

Send Message

```
Consumer:
   int buffer[1000];
   while(1) {
      receive(buffer,mbox);
      process message;
   }
```

Receive Message

- No need for producer/consumer to keep track of space in mailbox: handled by send/receive
  - One of the roles of the window in TCP: window is size of buffer on far end
  - Restricts sender to forward only what will fit in buffer

Messaging for Request/Response communication

- What about two-way communication?
  - Request/Response
    - » Read a file stored on a remote machine
    - » Request a web page from a remote web server
  - Also called: client-server
    - » Client ≡ requester, Server ≡ responder
    - » Server provides "service" (file storage) to the client
- Example: File service

```
Client: (requesting the file)
   char response[1000];

   send("read rutabaga", server_mbox);
   receive(response, client_mbox);
```

Request File

Get Response

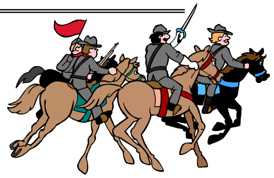
```
Server: (responding with the file)
   char command[1000], answer[1000];

   receive(command, server_mbox);
   decode command;
   read file into answer;
   send(answer, client_mbox);
```

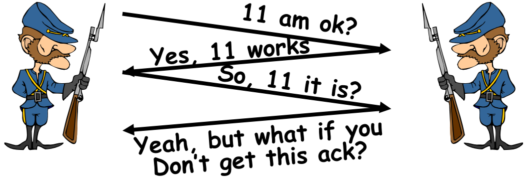
Receive Request

Send Response

General's Paradox



- 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
- 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 machines agree to do something, or not do it, atomically
- Two-Phase Commit protocol does this
  - Use a persistent, stable log on each machine to 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 can be used to complete this process such that all machines either commit or don't commit

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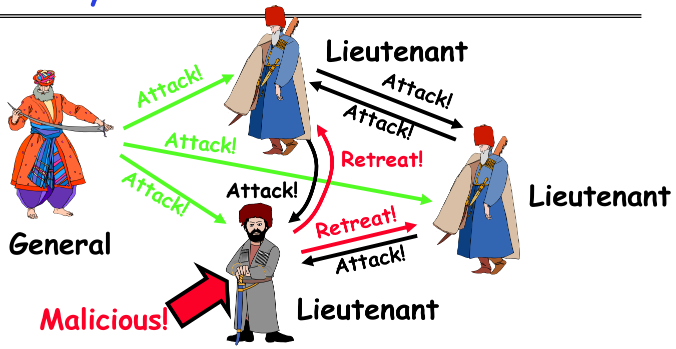
Two phase commit example

- Simple Example: A≡WellsFargo Bank, B≡Bank of America
  - Phase 1: Prepare Phase
    - » A writes "Begin transaction" to log
      A→B: OK to transfer funds to me?
    - » Not enough funds:
      B→A: transaction aborted; A writes "Abort" to log
    - » Enough funds:
      B: Write new account balance & promise to commit to log
      B→A: OK, I can commit
  - Phase 2: A can decide for both whether they will commit
    - » A: write new account balance to log
    - » Write "Commit" to log
    - » Send message to B that commit occurred; wait for ack
    - » Write "Got Commit" to log
- What if B crashes at beginning?
  - Wakes up, does nothing; A will timeout, abort and retry
- What if A crashes at beginning of phase 2?
  - Wakes up, sees that there is a transaction in progress; sends "Abort" to B
- What if B crashes at beginning of phase 2?
  - B comes back up, looks at log; when A sends it "Commit" message, it will say, "oh, ok, commit"

Distributed Decision Making Discussion

- 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
- 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
- Alternative: There are alternatives such as "Three Phase Commit" which don't have this blocking problem
- What happens if one or more of the nodes is malicious?
  - Malicious: attempting to compromise the decision making

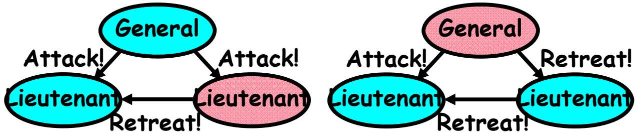
Byzantine General's Problem



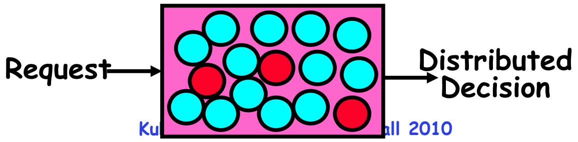
- Byazantine General's Problem (n players):
  - One General
  - n-1 Lieutenants
  - Some number of these (f) can be insane or malicious
- The commanding general must send an order to his n-1 lieutenants such that:
  - IC1: All loyal lieutenants obey the same order
  - IC2: If the commanding general is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



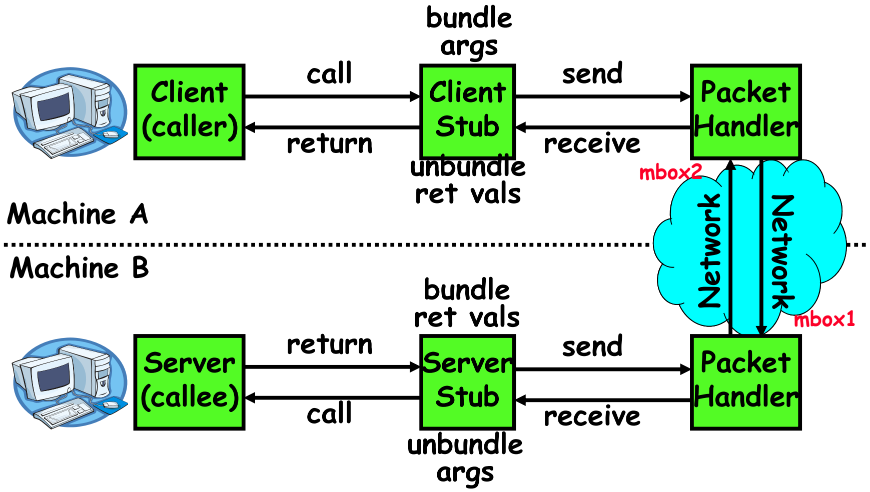
  - With f faults, need n > 3f to solve problem
- Various algorithms exist to solve problem
  - Original algorithm has #messages exponential in n
  - Newer algorithms have message complexity $O(n^2)$
    - » One from MIT, for instance (Castro and Liskov, 1999)
- Use of BFT (Byzantine Fault Tolerance) algorithm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



Remote Procedure Call

- 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
- Better 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");`
- 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

- 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
- Cross-platform issues:
  - What if client/server machines are different architectures or in different languages?
    - » Convert everything to/from some canonical form
    - » Tag every item with an indication of how it is encoded (avoids unnecessary conversions).

RPC Details (continued)

- 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
- 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 distributed 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
- 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

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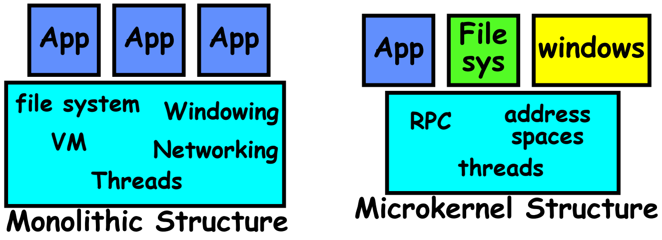
Cross-Domain Communication/Location Transparency

- How do address spaces communicate with one another?
  - Shared Memory with Semaphores, monitors, etc…
  - File System
  - Pipes (1-way communication)
  - "Remote" procedure call (2-way communication)
- RPC's can be used to communicate between address spaces on different machines or the same machine
  - Services can be run wherever it's most appropriate
  - Access to local and remote services looks the same
- Examples of modern RPC systems:
  - CORBA (Common Object Request Broker Architecture)
  - DCOM (Distributed COM)
  - RMI (Java Remote Method Invocation)

Microkernel operating systems

- Example: split kernel into application-level servers.
  - File system looks remote, even though on same machine



App App App

file system Windowing

VM Networking

Threads

Monolithic Structure

App File sys windows

RPC address spaces

threads

Microkernel Structure

- Why split the OS into separate domains?
  - Fault isolation: bugs are more isolated (build a firewall)
  - Enforces modularity: allows incremental upgrades of pieces of software (client or server)
  - Location transparent: service can be local or remote
    - » For example in the X windowing system: Each X client can be on a separate machine from X server; Neither has to run on the machine with the frame buffer.

Conclusion

- TCP: Reliable byte stream between two processes on different machines over Internet (read, write, flush)
  - Uses window-based acknowledgement protocol
  - Congestion-avoidance dynamically adapts sender window to account for congestion in network
- Two-phase commit: distributed decision making
  - First, make sure everyone guarantees that 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 and unpacking of arguments without user programming (in stub)