CS162
Operating Systems and Systems Programming
Lecture 23

Network Communication Abstractions / Remote Procedure Call

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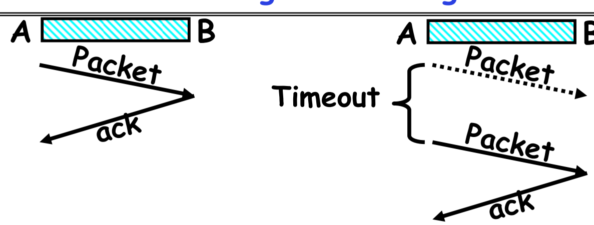
Review: Reliable Networking

- **Layering:** building complex services from simpler ones
- **Datagram:** an independent, self-contained network message whose arrival, arrival time, and content are not guaranteed
- Performance metrics
  - **Overhead:** CPU time to put packet on wire
  - **Throughput:** Maximum number of bytes per second
  - **Latency:** time until first bit of packet arrives at receiver
- **Arbitrary Sized messages:**
  - Fragment into multiple packets; reassemble at destination
- **Ordered messages:**
  - Use sequence numbers and reorder at destination
- **Reliable messages:**
  - Use Acknowledgements
  - Want a window larger than 1 in order to increase throughput

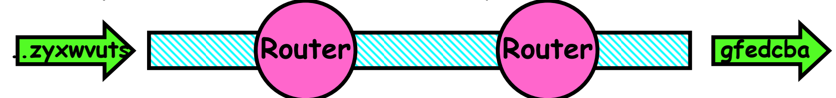
Review: Using Acknowledgements



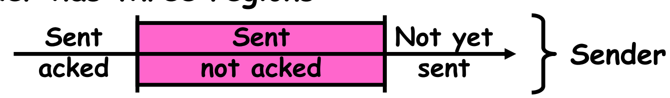
- How to ensure transmission of packets?
  - Detect garbling at receiver via checksum, discard if bad
  - Receiver acknowledges (by sending "ack") when packet received properly at destination
  - Timeout at sender: if no ack, retransmit
- Some questions:
  - If the sender doesn't get an ack, does that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

Review: TCP Windows and Sequence Numbers

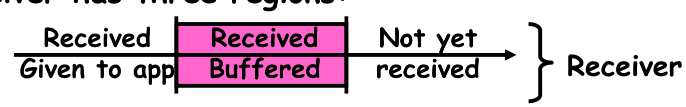
- TCP provides a stream abstraction:
  - Reliable byte stream between two processes on different machines over Internet (read, write, flush)
  - Input is an unbounded stream of bytes
  - Output is identical stream of bytes (same order)



- Sender has three regions:



  - Window (colored region) adjusted by sender
- Receiver has three regions:



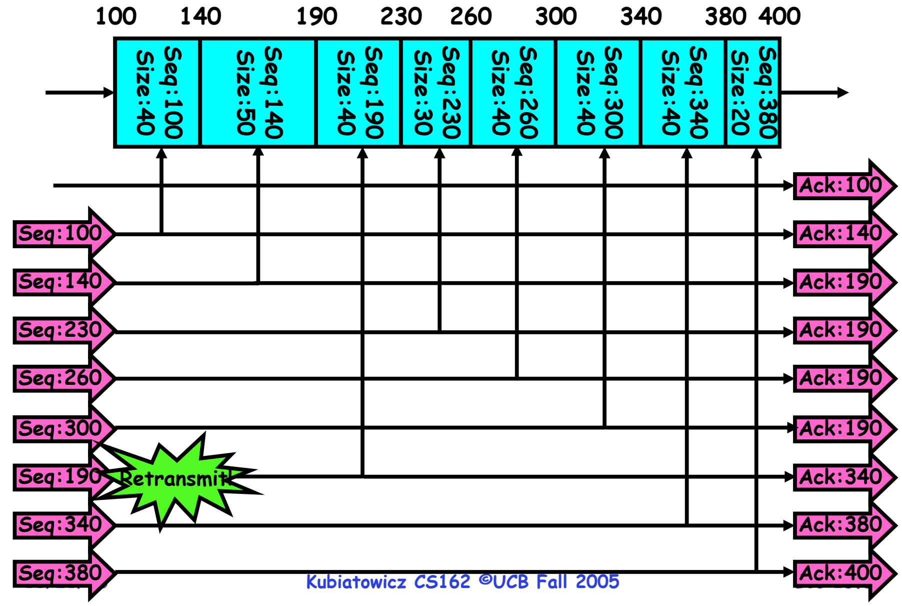
  - Maximum size of window advertised to sender at setup

Goals for Today

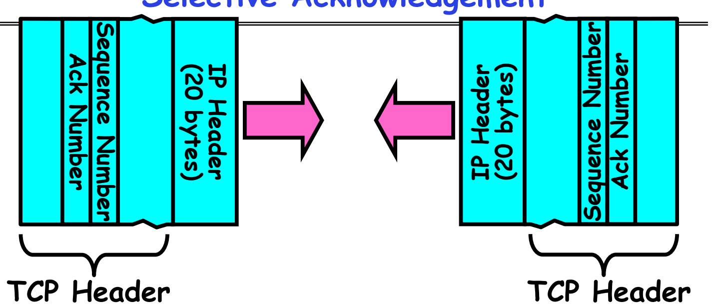
- Finish discussion of TCP
- Messages
  - Send/receive
  - One vs. two-way communication
- Distributed Decision Making
  - Two-phase commit/Byzantine Commit
- Remote Procedure Call

Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne

Window-Based Acknowledgements (TCP)



Selective Acknowledgement



- 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
- Specifically TCP solution: "slow start"
  - Start sending slowly
  - If no timeout, slowly increase window size (throughput)
  - Timeout ⇒ congestion, so cut window size in half

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 implementations at this time

Administrivia

- Cal Bears Rock!
  - 27 to 3 over Stanford
  - Quite a game: down at Stanford but more Cal fans than Stanford Fans
  - Also: Stanford fans don't seem to understand "the wave"
- My office hours
  - No office hours Thursday (Thanksgiving)
- Project 4 design document
  - Due Monday November 28th
- MIDTERM II: Wednesday November 30th or Monday December 5th?
  - 5:30-8:30pm, 10 Evans
  - All material from last midterm and up to previous class
  - Includes virtual memory
- Final Exam
  - December 17th, 12:30 – 3:30, 220 Hearst Gym
- Final Topics: Any suggestions?

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

Socket Example (Java)

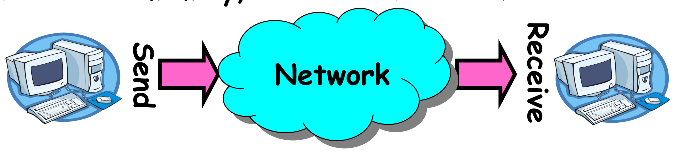
```
server:
      //Makes socket, binds addr/port, calls listen()
      ServerSocket sock = new ServerSocket(6013);
      while(true) {
        Socket client = sock.accept();
        PrintWriter pout = new
          PrintWriter(client.getOutputStream(),true);

        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",6018);
      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

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

Send Message (on `send(msg1,mbox);`)

Receive Message (on `receive(buffer,mbox);`)

- 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);

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

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

Request File (on `send("read rutabaga", server_mbox);`)

Get Response (on `receive(response, client_mbox);`)

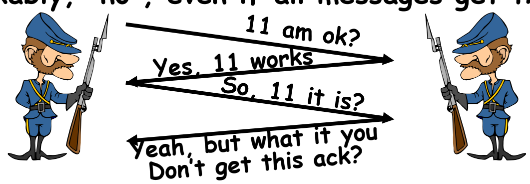
Receive Request (on `receive(command, server_mbox);`)

Send Response (on `send(answer, client_mbox);`)

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

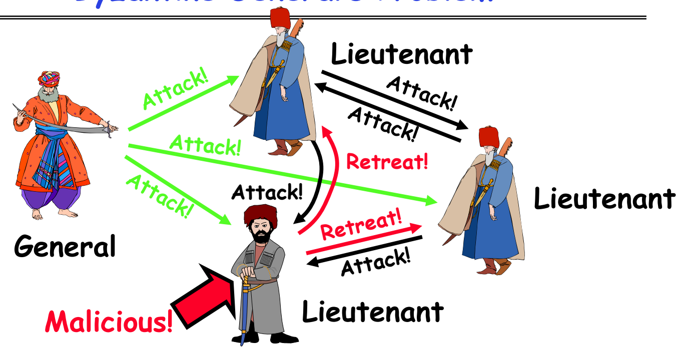
Two phase commit example

- Simple Example: A≡ATM machine, B≡The Bank
  - 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

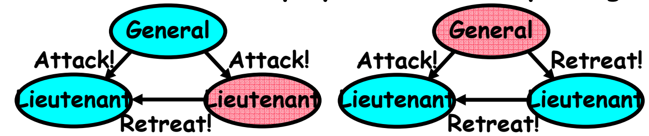
Byzantine General's Problem



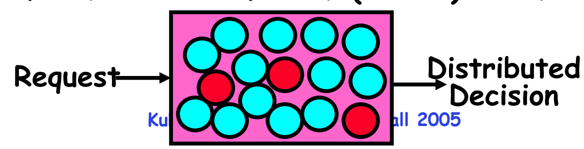
- Byazantine General's Problem (n players):
  - One General
  - n-1 Lieutenants
  - Some number of these (f) can be insane or malicious
- The commanding general must send an order to his n-1 lieutenants such that:
  - IC1: All loyal lieutenants obey the same order
  - IC2: If the commanding general is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



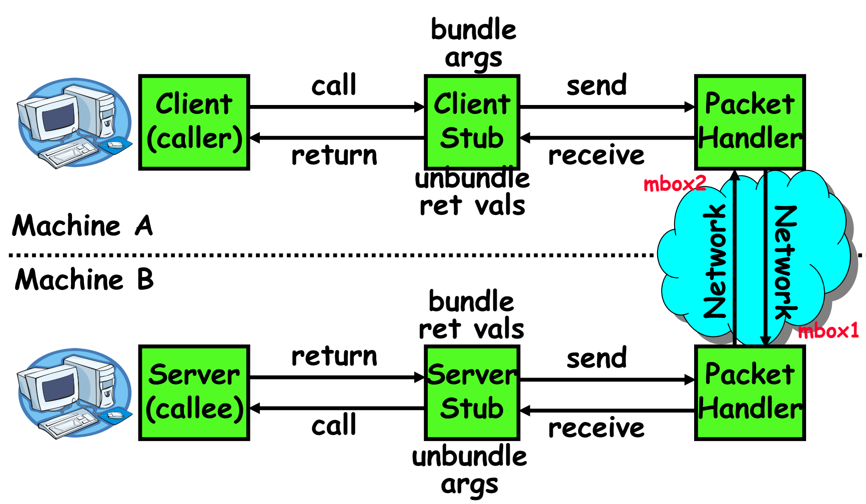
  - With f faults, need n > 3f to solve problem
- Various algorithms exist to solve problem
  - Original algorithm has #messages exponential in n
  - Newer algorithms have message complexity $O(n^2)$
    - » One from MIT, for instance (Castro and Liskov, 1999)
- Use of BFT (Byzantine Fault Tolerance) algorithm
  - 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 dynmaic 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

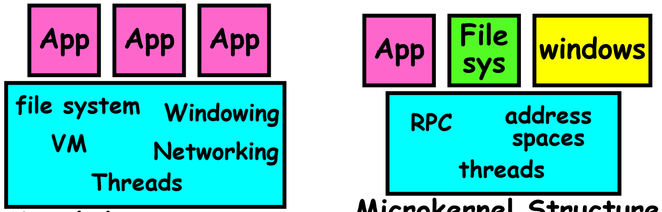
- Non-Atomic failures
  - Different failure modes in distributed system than on a single machine
  - Consider many different types of failures
    - » User-level bug causes address space to crash
    - » Machine failure, kernel bug causes all processes on same machine to fail
    - » Some machine is 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

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 on 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



Monolithic Structure   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)