CS162
Operating Systems and Systems Programming
Lecture 24

Networking and TCP/IP (Con't), RPC, Distributed File Systems

November 23rd, 2020

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Recall: Distributed Consensus Making

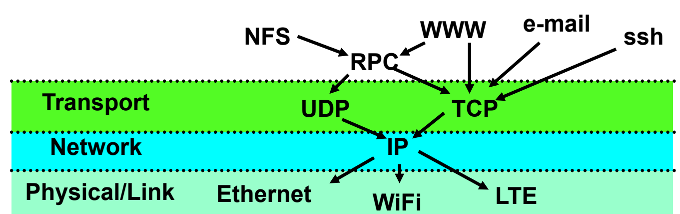
- Consensus problem
  – All nodes propose a value
  – Some nodes might crash and stop responding
  – Eventually, all remaining nodes decide on the same value from set of proposed values
- Distributed Decision Making
  – Choose between "true" and "false"
  – Or Choose between "commit" and "abort"
- Equally important (but often forgotten!): make it durable!
  – How do we make sure that decisions cannot be forgotten?
    » This is the "D" of "ACID" in a regular database
  – In a global-scale system?
    » What about erasure coding or massive replication?
    » Like BlockChain applications!

Recall: 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

Recall: Network Protocols

- Networking protocols: many levels
  – Physical level: mechanical and electrical network (e.g., how are 0 and 1 represented)
  – Link level: packet formats/error control (for instance, the CSMA/CD protocol)
  – Network level: network routing, addressing
  – Transport Level: reliable message delivery
- Protocols on today's Internet:



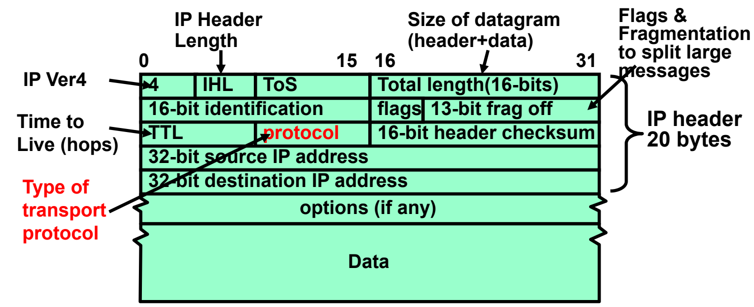
Network Layering

- Layering: building complex services from simpler ones
  - Each layer provides services needed by higher layers by utilizing services provided by lower layers
- The physical/link layer is pretty limited
  - Packets are of limited size (called the "Maximum Transfer Unit or MTU: often 200-1500 bytes in size)
  - Routing is limited to within a physical link (wire) or perhaps through a switch
- Our goal in the following is to show how to construct a secure, ordered, message service routed to anywhere:

Physical Reality: Packets	Abstraction: Messages
Limited Size (MTU)	Arbitrary Size
Unordered (sometimes)	Ordered
Unreliable	Reliable
Machine-to-machine	Process-to-process
Only on local area net	Routed anywhere
Asynchronous	Synchronous
Insecure	Secure

Recall: IPv4 Packet Format

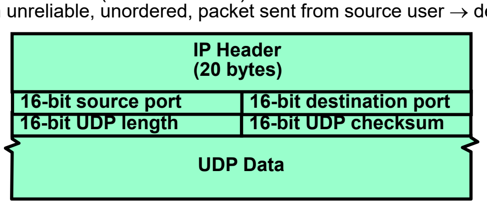
- IP Packet Format:



- IP Datagram: an unreliable, unordered, packet sent from source to destination
  - Function of network – deliver datagrams!

Building a messaging service on IP

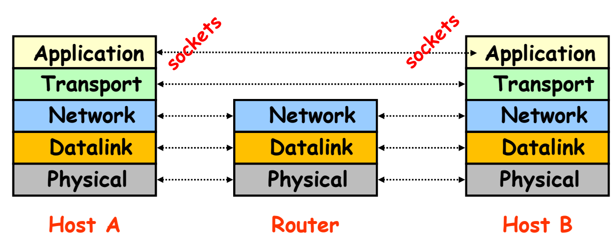
- Process to process communication
  - Basic routing gets packets from machine→machine
  - What we really want is routing from process→process
    » Add "ports", which are 16-bit identifiers
    » A communication channel (connection) defined by 5 items: [source addr, source port, dest addr, dest port, protocol]
- For example: The Unreliable Datagram Protocol (UDP)
  - Layered on top of basic IP (IP Protocol 17)
    » Datagram: an unreliable, unordered, packet sent from source user → dest user (Call it UDP/IP)



  - Important aspect: low overhead!
    » Often used for high-bandwidth video streams
    » Many uses of UDP considered "anti-social" – none of the "well-behaved" aspects of (say) TCP/IP

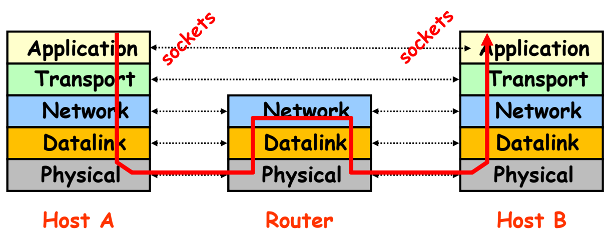
Internet Architecture: Five Layers

- Lower three layers implemented everywhere
- Top two layers implemented only at hosts

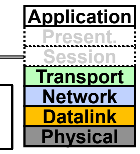


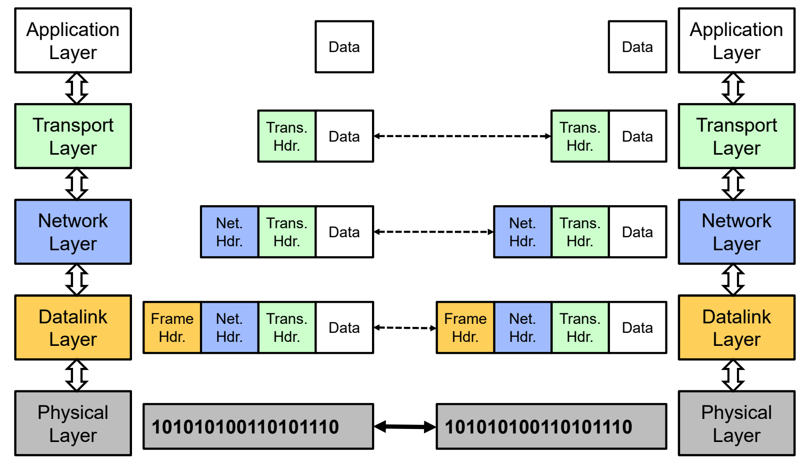
Internet Architecture: Five Layers

- Communication goes down to physical network
- Then from network peer to peer
- Then up to relevant layer

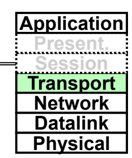


Layering Analogy: Packets in Envelopes



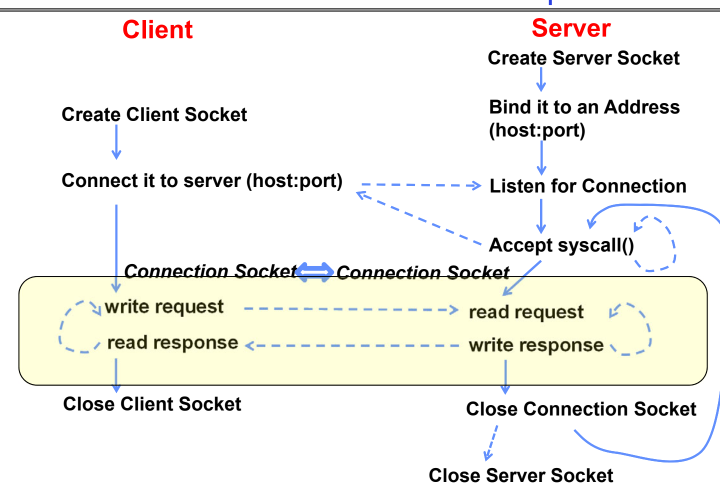


Internet Transport Protocols



- Datagram service (**UDP**): IP Protocol 17
  – No-frills extension of “best-effort” IP
  – Multiplexing/Demultiplexing among processes
- Reliable, in-order delivery (**TCP**): IP Protocol6
  – Connection set-up & tear-down
  – Discarding corrupted packets (segments)
  – Retransmission of lost packets (segments)
  – Flow control
  – Congestion control
- Other examples:
  – DCCP (33), Datagram Congestion Control Protocol
  – RDP (26), Reliable Data Protocol
  – SCTP (132), Stream Control Transmission Protocol

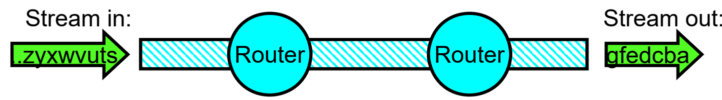
Recall: Sockets in concept



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

Transmission Control Protocol (TCP)

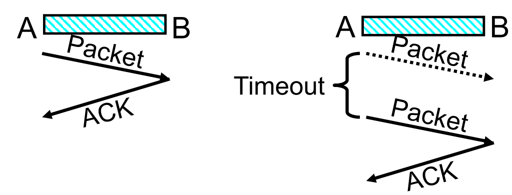


- Transmission Control Protocol (TCP)
  - TCP (IP Protocol 6) layered on top of IP
  - Reliable byte stream between two processes on different machines over Internet (read, write, flush)
- TCP Details
  - Fragments byte stream into packets, hands packets to IP
    - » IP may also fragment by itself
  - 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”

Problem: Dropped Packets

- All physical networks can garble or drop packets
  - Physical hardware problems (bad wire, bad signal)
- Therefore, IP can garble or drop packets
  - It doesn't repair this itself (end-to-end principle!)
- Building reliable message delivery
  - Confirm that packets aren't garbled
  - Confirm that packets arrive **exactly once**

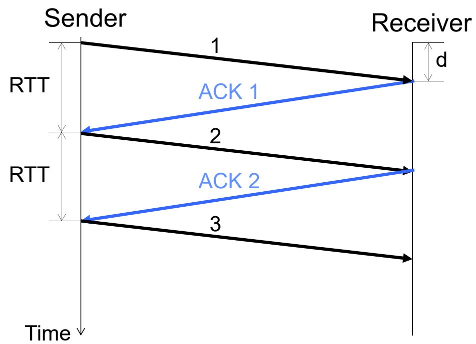
Using Acknowledgements



- 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, ACK each

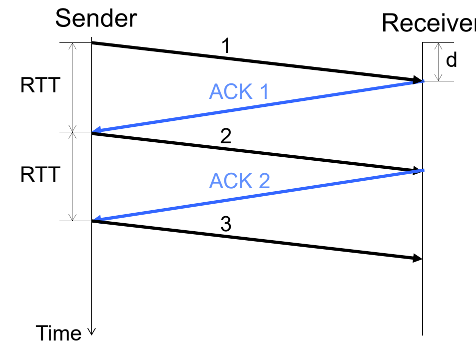
Stop-and-Wait (No Packet Loss)

- Send; wait for ACK; repeat
- 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
- For symmetric latency,
  $RTT = 2d$



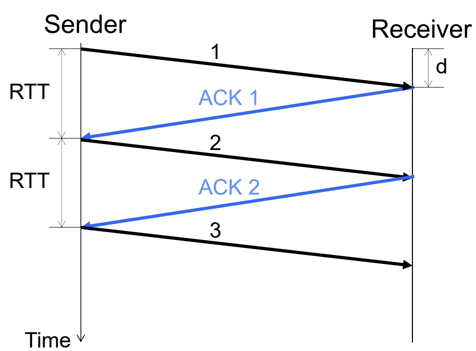
Stop-and-Wait (No Packet Loss)

- How fast can you send data?
- Little's Law applied to the network:
  $n = B \cdot \text{RTT}$
- For Stop-and-Wait, $n = 1$ packet
- So bandwidth is 1 packet per RTT
  - Depends only on latency, not network capacity (!)



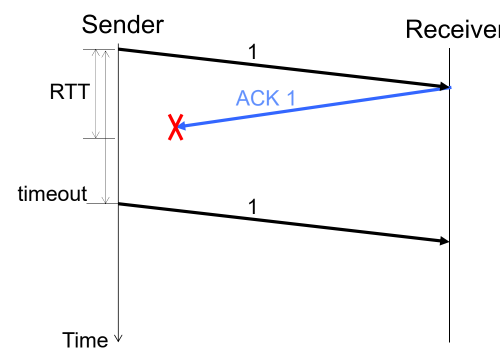
Stop-and-Wait (No Packet Loss)

- So bandwidth is 1 packet per RTT
  - Depends only on latency, not network capacity (!)
- Suppose RTT = 100 ms and 1 packet is 1500 bytes
- Throughput = $\frac{1500 \cdot 8}{0.1}$ = 120 Kbps
- Very inefficient if we have a 100 Mbps link!



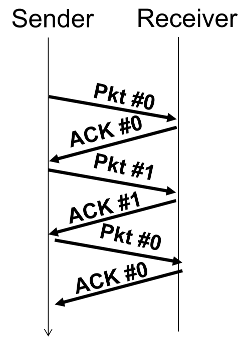
Stop-and-Wait with Packet Loss

- Loss recovery relies on timeouts
- How to choose a good timeout?
  - Too short – lots of duplication
  - Too long – packet loss is really disruptive!
- How to deal with duplication?
  - Retransmission certainly opens up the possibility for



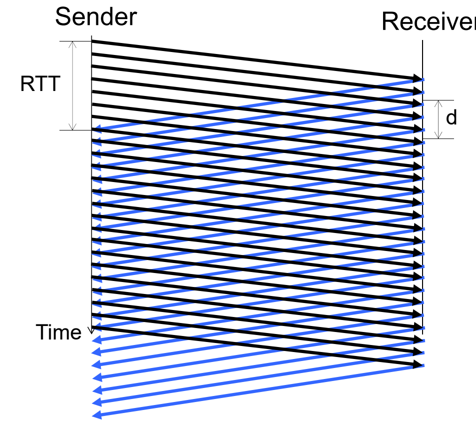
How to Deal with Message Duplication?

- Solution: put sequence number in message to identify re-transmitted packets
  – Receiver checks for duplicate number's; Discard if detected
- Requirements:
  – Sender keeps copy of unACK'd 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 number of last message received
- Pros: simple, small overhead
- Con: doesn't work if network can delay or duplicate messages arbitrarily



Advantages of Moving Away From Stop-and-Wait

- Larger space of acknowledgements
  – Pipelining: don't wait for ACK before sending next packet
- ACKs serve dual purpose:
  – Reliability: Confirming packet received
  – Ordering: Packets can be reordered at destination
- How much data is in flight now?
  – Bytes in-flight: W_{send} = RTT × B
  – Here B is in "bytes/second"
  – $W_{send} \equiv$ Sender's "Window Size"
  – Packets in flight = (W_{send} / packet size)
- How long does the sender have to keep the packets around?
- How long does the receiver have to keep the packets' data?
- What if sender is sending packets faster than the receiver can process the data?



Administrivia

- Midterm 3: Thursday 12/3: 5-7PM as before
  – Material up to Lecture 25
  – Cameras and Zoom screen sharing again as with Midterm 2
  – Review session TBA
- Lecture 26 will be a fun lecture
  – Let me know if there are topics you would like to discuss!

Recall: CS 162 Collaboration Policy

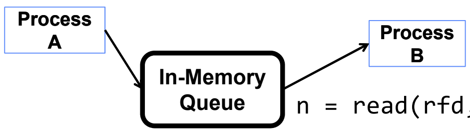
Explaining a concept to someone in another group
Discussing algorithms/testing strategies with other groups
Discussing debugging approaches with other groups
Searching online for generic algorithms (e.g., hash table)

Sharing code or test cases with another group
Copying OR reading another group's code or test cases
Copying OR reading online code or test cases from prior years
Helping someone in another group to debug their code

- We compare all project submissions against prior year submissions and online solutions and will take actions (described on the course overview page) against offenders
- Don't put a friend in a bad position by asking for help that they shouldn't give!

Recall: Communication Between Processes

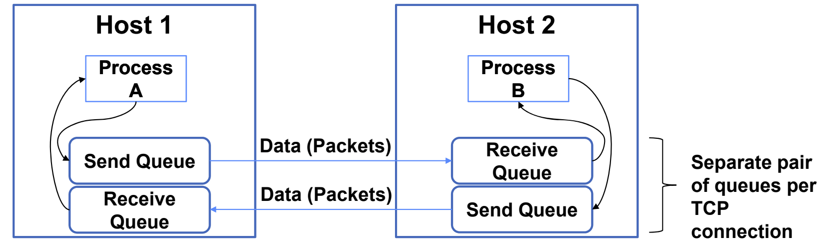
```
write(wfd, wbuf, wlen);
```




```
n = read(rfd,rbuf, rmax);
```

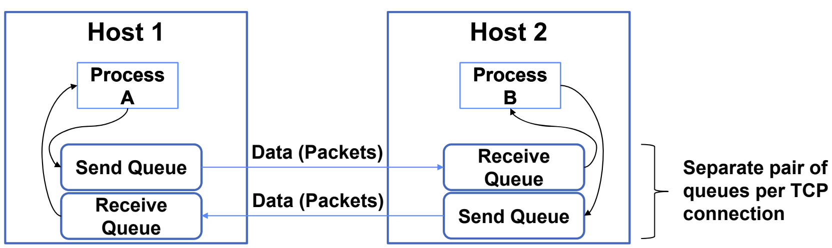
- Data written by A is held in memory until B reads it
- Queue has a fixed capacity
  – Writing to the queue blocks if the queue if full
  – Reading from the queue blocks if the queue is empty
- POSIX provides this abstraction in the form of ***pipes***

Buffering in a TCP Connection



- A single TCP connection needs ***four*** in-memory queues:
  – Send buffer: add data on write syscall, remove data when ACK received
  – Receive buffer: add data when packets received, remove data on read syscall

Window Size: Space in Receive Queue



- A host's *window size* for a TCP connection is how much remaining space it has in its receive queue
- A host advertises its window size in *every* TCP packet it sends!
- **Sender never sends more than receiver's advertised window size**

Sliding Window Protocol

- TCP sender knows receiver's window size, and aims never to exceed it
- But packets that it previously send may arrive, filling the window size!

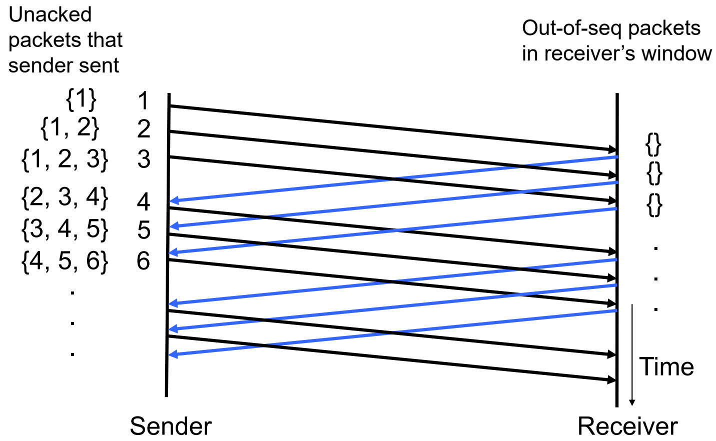
Rule: TCP sender ensures that:

Number of Sent but UnACKed Bytes < Receiver's Advertised Window Size

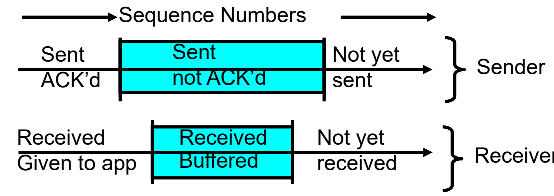
- Can send new packets as long as sent-but-unacked packets haven't already filled the advertised window size

Sliding Window (No Packet Loss)

- Example:Window size (w) = 3 packets
- Window size to fill link is given by:
  $w = B_{pkt} \cdot \text{RTT}$
- $B_{pkt} \equiv Packets/sec$
- Little's Law once again!
- For TCP, window is in *bytes*, not *packets*

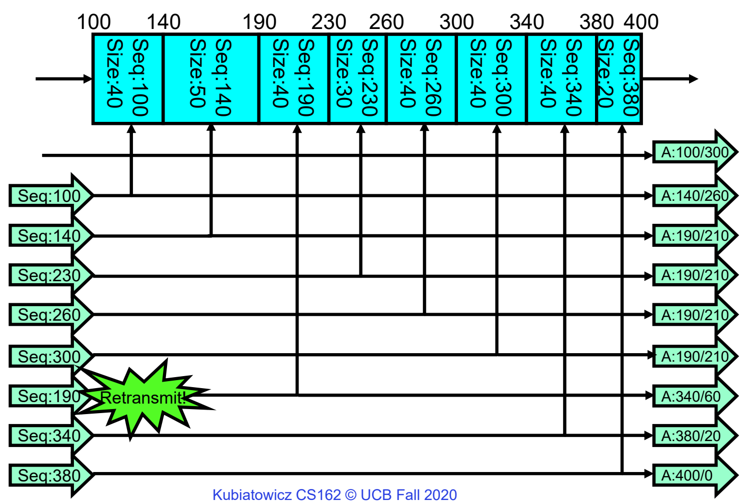


TCP Windows and Sequence Numbers: PER BYTE!



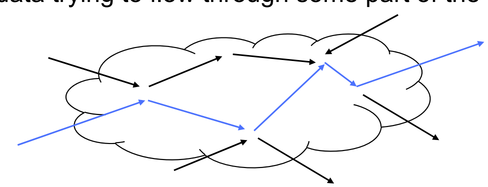
- Sender has three regions:
  - Sequence regions
    - » sent and ACK'd
    - » sent and not ACK'd
    - » not yet sent
  - Window (colored region) adjusted by sender
- Receiver has three regions:
  - Sequence regions
    - » received and ACK'd (given to application)
    - » received and buffered
  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

Window-Based Acknowledgements (TCP)



Congestion

- Too much data trying to flow through some part of the network

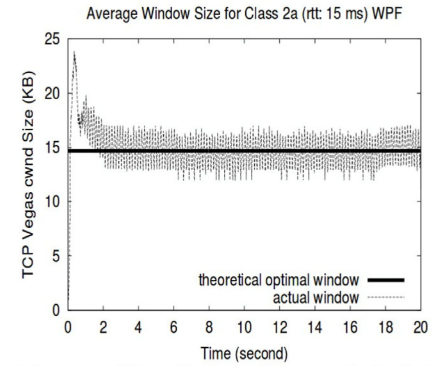


- IP's solution: Drop packets
- What happens to TCP connection?
  - Lots of retransmission – wasted work and wasted bandwidth (when bandwidth is scarce)

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*"

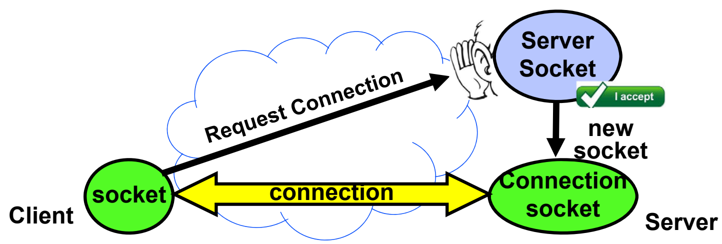
Congestion Management



From Low, Peterson, and Wang, "Understanding vegas: Duality Model", J. ACM, March 2002.

- TCP artificially restricts the window size if it sees packet loss
- Careful control loop to make sure:
  1. We don't send too fast and overwhelm the network
  2. We utilize most of the bandwidth the network has available
  - In general, these are conflicting goals!

Recall: Connection Setup over TCP/IP

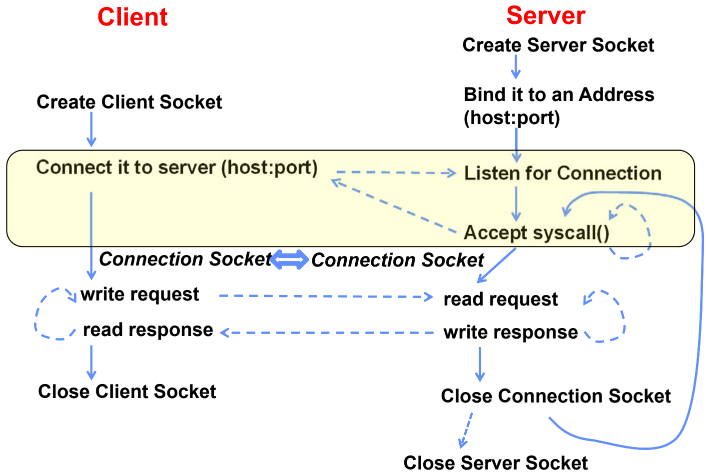


- 5-Tuple identifies each connection:
  1. Source IP Address
  2. Destination IP Address
  3. Source Port Number
  4. Destination Port Number
  5. Protocol (always TCP here)
- Often, Client Port "randomly" assigned
  - Done by OS during client socket setup
- Server Port often "well known"
  - 80 (web), 443 (secure web), 25 (sendmail), etc
  - Well-known ports from 0—1023

Establishing TCP Service

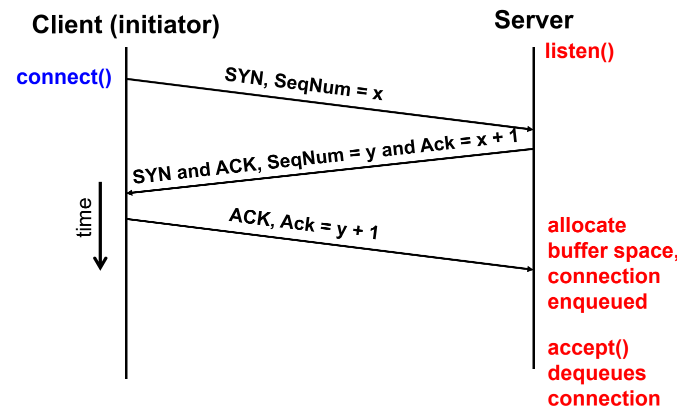
1. Open connection: 3-way handshaking
2. Reliable byte stream transfer from (IPa, TCP_Port1) to (IPb, TCP_Port2)
   - Indication if connection fails: Reset
3. Close (tear-down) connection

Sockets in concept

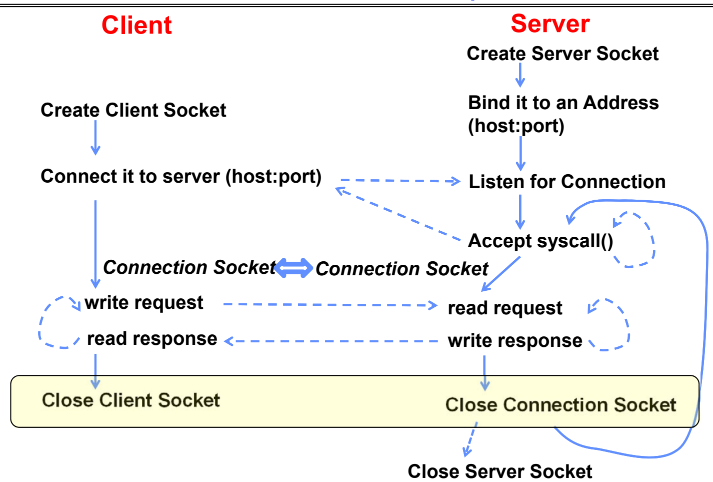


Open Connection: 3-Way Handshake

- Server calls listen() to wait for a new connection
- Client calls connect() providing server's IP address and port number
- Each side sends SYN packet proposing an initial sequence number (one for each sender) and ACKs the other

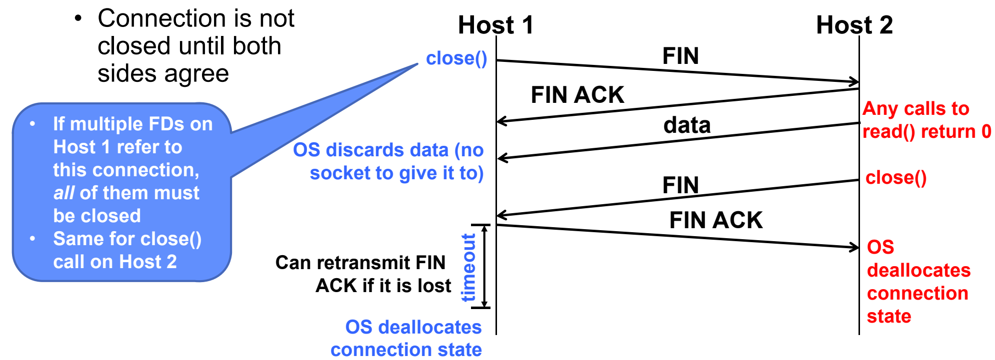


Sockets in concept



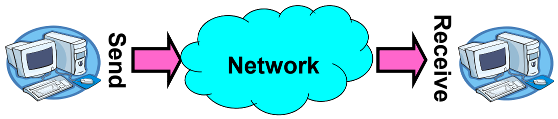
Close Connection: 4-Way Teardown

- Connection is not closed until both sides agree



Recall: Distributed Applications Build With Messages

- 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

Question: Data Representation

- An object in memory has a machine-specific binary representation
  - Threads within a single process have the same view of what's in memory
  - Easy to compute offsets into fields, follow pointers, etc.
- In the absence of shared memory, externalizing an object requires us to turn it into a sequential sequence of bytes
  - **Serialization/Marshalling**: Express an object as a sequence of bytes
  - **Deserialization/Unmarshalling**: Reconstructing the original object from its marshalled form at destination

Simple Data Types

`uint32_t x;`

- Suppose I want to write a x to a file
- First, open the file: `FILE* f = fopen(“foo.txt”, “w”);`
- Then, I have two choices:
  1. `fprintf(f, “%lu”, x);`
  2. `fwrite(&x, sizeof(uint32_t), 1, f);`
     - » Or equivalently, `write(fd, &x, sizeof(uint32_t));` (perhaps with a loop to be safe)
- Neither one is “wrong” but sender and receiver should be consistent!

Machine Representation

- Consider using the machine representation:
  - `fwrite(&x, sizeof(uint32_t), 1, f);`
- How do we know if the recipient represents x in the same way?
  - For pipes, is this a problem?
  - What about for sockets?

Endianness

Processor	Endianness
Motorola 68000	Big Endian
PowerPC (PPC)	Big Endian
Sun Sparc	Big Endian
IBM S/390	Big Endian
Intel x86 (32 bit)	Little Endian
Intel x86_64 (64 bit)	Little Endian
Dec VAX	Little Endian
Alpha	Bi (Big/Little) Endian
ARM	Bi (Big/Little) Endian
IA-64 (64 bit)	Bi (Big/Little) Endian
MIPS	Bi (Big/Little) Endian

- For a byte-address machine, which end of a machine-recognized object (e.g., int) does its byte-address refer to?
- Big Endian: address is the most-significant bits
- Little Endian: address is the least-significant bits

```
int main(int argc, char *argv[])
{
  int val = 0x12345678;
  int i;
  printf("val = %x\n", val);
  for (i = 0; i < sizeof(val); i++) {
    printf("val[%d] = %x\n", i, ((uint8_t *) &val)[i]);
  }
}
```

```
(base) CullerMac19:code09 culler$ ./endian
val = 12345678
val[0] = 78
val[1] = 56
val[2] = 34
val[3] = 12
```


What Endian is the Internet?

NAME

arpa/inet.h - definitions for internet operations

SYNOPSIS

```
#include <arpa/inet.h>
```

DESCRIPTION

The **in_port_t** and **in_addr_t** types shall be defined as described in *<netinet/in.h>*.

The **in_addr** structure shall be defined as described in *<netinet/in.h>*.

The INET_ADDRSTRLEN [IP6] and INET6_ADDRSTRLEN macros shall be defined as described in *<netinet/in.h>*.

The following shall either be declared as functions, defined as macros, or both. If functions are declared, function prototypes

```
uint32_t htonl(uint32_t);
uint16_t htons(uint16_t);
uint32_t ntohl(uint32_t);
uint16_t ntohs(uint16_t);
```

The **uint32_t** and **uint16_t** types shall be defined as described in *<inttypes.h>*.

The following shall be declared as functions and may also be defined as macros. Function prototypes shall be provided.

```
in_addr_t    inet_addr(const char *);
char        *inet_ntoa(struct in_addr);
const char  *inet_ntop(int, const void *restrict, char *restrict,
                 socklen_t);
int          inet_pton(int, const char *restrict, void *restrict);
```

Inclusion of the *<arpa/inet.h>* header may also make visible all symbols from *<netinet/in.h>* and *<inttypes.h>*.

- **Big Endian**
  - **Network byte order**
  - **Vs. "host byte order"**

Dealing with Endianness

- Decide on an "on-wire" endianness
- Convert from native endianness to "on-wire" endianness before sending out data **(serialization/marshalling)**
  - `uint32_t htonl(uint32_t)` and `uint16_t htons(uint16_t)` convert from native endianness to network endianness (big endian)
- Convert from "on-wire" endianness to native endianness when receiving data **(deserialization/unmarshalling)**
  - `uint32_t ntohl(uint32_t)` and `uint16_t ntohs(uint16_t)` convert from network endianness to native endianness (big endian)

What About Richer Objects?

```
typedef struct word_count
{
  char *word;
  int count;
  struct word_count *next;
}
word_count_t;
```

- Consider `word_count_t` of Homework 0 and 1 …
- Each element contains:
  - An `int`
  - A *pointer* to a string (of some length)
  - A *pointer* to the next element
- `fprintf_words` writes these as a sequence of lines (character strings with `\n`) to a file stream
- What if you wanted to write the whole list as a binary object (and read it back as one)?
  - How do you represent the string?
  - Does it make any sense to write the pointer?

Data Serialization Formats

- JSON and XML are commonly used in web applications
- Lots of ad-hoc formats


```
{
  "glossary": {
    "title": "example glossary",
    "GlossDiv": {
      "title": "S",
      "GlossList": {
        "GlossEntry": {
          "ID": "SGML",
          "SortAs": "SGML",
          "GlossTerm": "Standard Generalized Markup Language",
          "Acronym": "SGML",
          "Abbrev": "ISO 8879:1986",
          "GlossDef": {
            "para": "A meta-markup language, used to create markup languages such as DocBook.",
            "GlossSeeAlso": ["GML", "XML"]
          },
          "GlossSee": "markup"
        }
      }
    }
  }
}
```

```
<!DOCTYPE glossary PUBLIC "-//OASIS//DTD DocBook V3.1//EN">
 <glossary><title>example glossary</title>
  <GlossDiv><title>S</title>
   <GlossList>
    <GlossEntry ID="SGML" SortAs="SGML">
     <GlossTerm>Standard Generalized Markup Language</GlossTerm>
     <Acronym>SGML</Acronym>
     <Abbrev>ISO 8879:1986</Abbrev>
     <GlossDef>
      <para>A meta-markup language, used to create markup
languages such as DocBook.</para>
      <GlossSeeAlso OtherTerm="GML">
      <GlossSeeAlso OtherTerm="XML">
     </GlossDef>
     <GlossSee OtherTerm="markup">
    </GlossEntry>
   </GlossList>
  </GlossDiv>
 </glossary>
```

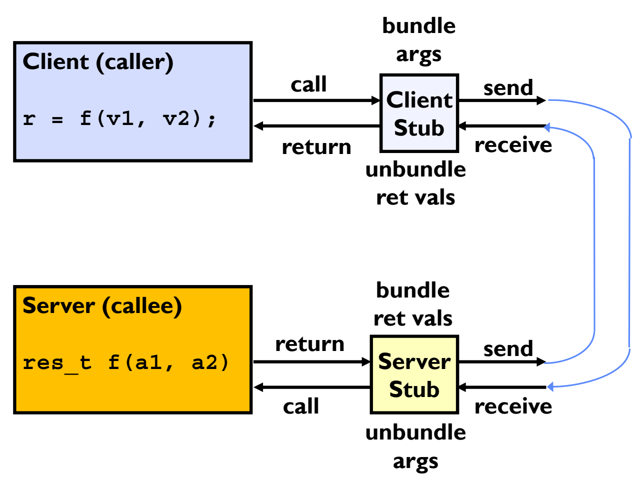

Data Serialization Formats

Name	Creator-maintainer	Based on	Standardized?	Specification	Binary?	Human-readable?	Supports references?	Schema-IDL?	Standard APIs	Supports Zero-copy operations
Apache Avro	Apache Software Foundation	N/A	No	Apache Avro™ 1.8.1 Specification	Yes	No	N/A	Yes (built-in)	N/A	N/A
Apache Parquet	Apache Software Foundation	N/A	No	Apache Parquet[1]	Yes	No	No	N/A	Java, Python	No
ASN.1	ISO, IEC, ITU-T	N/A	Yes	ISO/IEC 8824; X.680 series of ITU-T Recommendations	Yes (BER, DER, PER, OER, or custom via ECN)	Yes (XER, JER, GSER, or custom via ECN)	Partial	Yes (built-in)	N/A	Yes (OER)
Bencode	Bram Cohen (creator) BitTorrent, Inc. (maintainer)	N/A	De facto standard via BitTorrent Enhancement Proposal (BEP)	Part of BitTorrent protocol specification	Partially (numbers and delimiters are ASCII)	No	No	No	No	N/A
Binn	Bernardo Ramos	N/A	No	Binn Specification	Yes	No	No	No	No	Yes
BSON	MongoDB	JSON	No	BSON Specification	Yes	No	No	No	No	N/A
CBOR	Carsten Bormann, P. Hoffman	JSON (loosely)	Yes	RFC 7049	Yes	No	Yes through tagging	Yes (CDDL)	No	Yes
Comma-separated values (CSV)	RFC author: Yakov Shafranovich	N/A	Partial (myriad informal variants used)	RFC 4180 (among others)	No	Yes	No	No	No	No
Common Data Representation (CDR)	Object Management Group	N/A	Yes	General Inter-ORB Protocol	Yes	No	Yes	Yes	ADA, C, C++, Java, Cobol, Lisp, Python, Ruby, Smalltalk	N/A
D-Bus Message Protocol	freedesktop.org	N/A	Yes	D-Bus Specification	Yes	No	No	Partial (Signature strings)	Yes (see D-Bus)	N/A
Efficient XML Interchange (EXI)	W3C	XML, Efficient XML	Yes	Efficient XML Interchange (EXI) Format 1.0	Yes	Yes (XML)	Yes (XPointer, XPath)	Yes (XML Schema)	Yes (DOM, SAX, StAX, XQuery, XPath)	N/A
FlatBuffers	Google	N/A	No	flatbuffers github page Specification	Yes	Yes (Apache Arrow)	Partial (internal to the buffer)	Yes [2]	C++, Java, C#, Go, Python, Rust, JavaScript, PHP, C, Dart, Lua, TypeScript	Yes
Fast Infoset	ISO, IEC, ITU-T	XML	Yes	ITU-T X.891 and ISO/IEC 24824-1:2007	Yes	No	Yes (XPointer, XPath)	Yes (XML schema)	Yes (DOM, SAX, XQuery, XPath)	N/A
FHIR	Health_Level_7	REST basics	Yes	Fast Healthcare Interoperability Resources	Yes	Yes	Yes	Yes	Hapi for FHIR[1] JSON, XML, Turtle	No
Ion	Amazon	JSON	No	The Amazon Ion Specification	Yes	Yes	No	No	No	N/A
Java serialization	Oracle Corporation	N/A	Yes	Java Object Serialization	Yes	No	Yes	No	Yes	N/A
JSON	Douglas Crockford	JavaScript syntax	Yes	STD 90/RFC 8259 (ancillary: RFC 6901, RFC 6902), ECMA-404, ISO/IEC 21778:2017	No, but see BSON, Smile, UBJSON	Yes	Yes (JSON Pointer (RFC 6901); alternately: JSONPath, JPath, JSPON, json:select()), JSON-LD	Partial (JSON Schema Proposal, ASN.1 with JER, Kwalify, Rx, Itemscript Schema), JSON-LD	Partial (Clarinet, JSONQuery, JSONPath), JSON-LD	No
MessagePack	Sadayuki Furuhashi	JSON (loosely)	No	MessagePack format specification	Yes	No	No	No	No	Yes
Netstrings	Dan Bernstein	N/A	No	netstrings.txt	Yes	Yes	No	No	No	Yes
OGDL	Rolf Veen	?	No	Specification	Yes (Binary Specification)	Yes	Yes (Path Specification)	Yes (Schema WD)		N/A
OPC-UA Binary	OPC Foundation	N/A	No	opcfoundation.org	Yes	No	Yes	No	No	N/A
OpenDDL	Eric Lengyel	C, PHP	No	OpenDDL.org	No	Yes	Yes	No	Yes (OpenDDL Library)	N/A
Pickle (Python)	Guido van Rossum	Python	De facto standard via Python Enhancement Proposals (PEPs)	[3] PEP 3154 -- Pickle protocol version 4	Yes	No	No	No	Yes ([4])	No
Property list	NeXT (creator) Apple (maintainer)	?	Partial	Public DTD for XML format	Yes (a)	Yes (b)	No	?	Cocoa, CoreFoundation, OpenStep, GnuStep	No
Protocol Buffers (protobuf)	Google	N/A	No	Developer Guide: Encoding	Yes	Partial (d)	No	Yes (built-in)	C++, C#, Java, Python, Javascript, Go	No

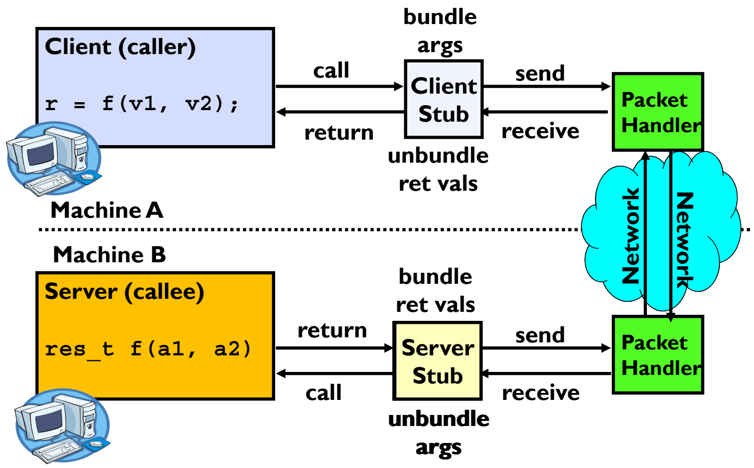
Remote Procedure Call (RPC)

- 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
  - And must deal with machine representation by hand
- Another option: Remote Procedure Call (RPC)
  - Calls a procedure on a remote machine
  - Idea: Make communication look like an ordinary function call
  - Automate all of the complexity of translating between representations
  - Client calls:
    `remoteFileSystem→Read("rutabaga");`
  - Translated automatically into call on server:
    `fileSys→Read("rutabaga");`

RPC Concept



RPC Information Flow



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 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 (destination queue) 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

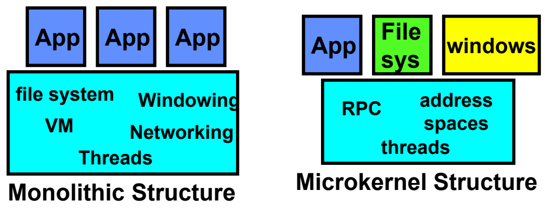
- RPC is *not* performance transparent:
  - Cost of Procedure call « same-machine RPC « network RPC
  - Overheads: Marshalling, Stubs, Kernel-Crossing, Communication
- Programmers must be aware that RPC is not free
  - Caching can help, but may make failure handling complex

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 or the same machine
  - Services can be run wherever it's most appropriate
  - Access to local and remote services looks the same
- Examples of RPC systems:
  - CORBA (Common Object Request Broker Architecture)
  - DCOM (Distributed COM)
  - RMI (Java Remote Method Invocation)

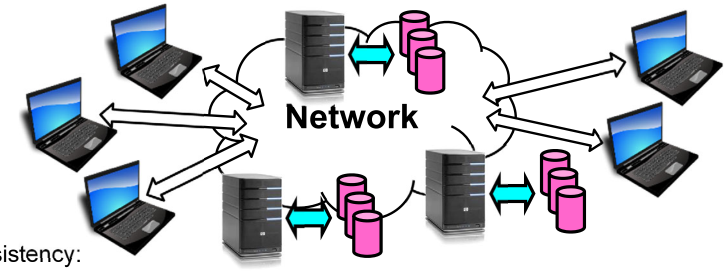
Microkernel operating systems

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



- 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.

Network-Attached Storage and the CAP Theorem



- Consistency:
  – Changes appear to everyone in the same serial order
- Availability:
  – Can get a result at any time
- Partition-Tolerance
  – System continues to work even when network becomes partitioned
- Consistency, Availability, Partition-Tolerance (CAP) Theorem: Cannot have all three at same time
  – Otherwise known as "Brewer's Theorem"

Summary

- 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
- Remote Procedure Call (RPC): Call procedure on remote machine or in remote domain
  – Provides same interface as procedure
  – Automatic packing and unpacking of arguments without user programming (in stub)
  – Adapts automatically to different hardware and software architectures at remote end
- Distributed File System:
  – Transparent access to files stored on a remote disk
  – Caching for performance