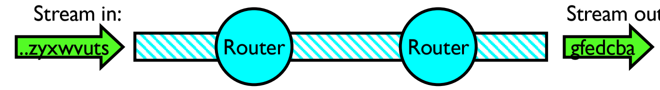
CS162
Operating Systems and Systems Programming
Lecture 25

RPC, NFS and AFS

April 26th, 2022

Prof. Anthony Joseph and John Kubiatowicz
http://cs162.eecs.Berkeley.edu

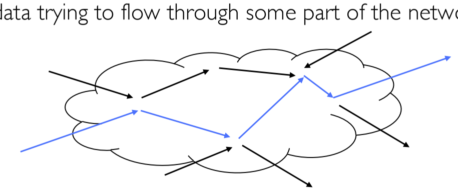
Recall: Transmission Control Protocol (TCP)



- 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"

Congestion

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

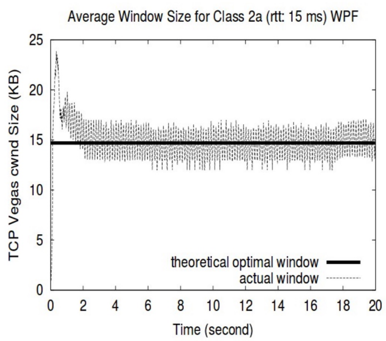


- IP's solution: Drop packets
- What happens to TCP connection?
  - Lots of retransmission – wasted work and wasted bandwidth (when bandwidth is scarce)

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*"

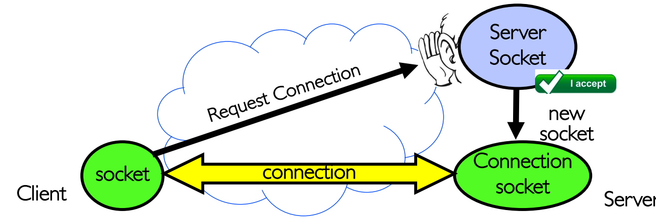
Congestion Management



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

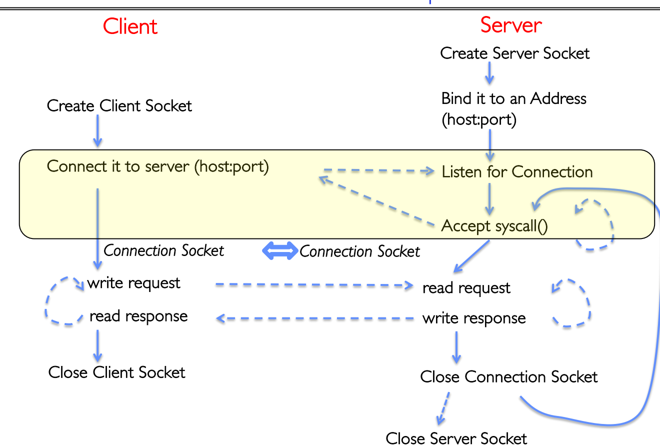


- 5-Tuple identifies each connection:
  1. Source IP Address
  2. Destination IP Address
  3. Source Port Number
  4. Destination Port Number
  5. Protocol (always TCP here)
- Often, Client Port "randomly" assigned
  - Done by OS during client socket setup
- Server Port often "well known"
  - 80 (web),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

Establishing TCP Service

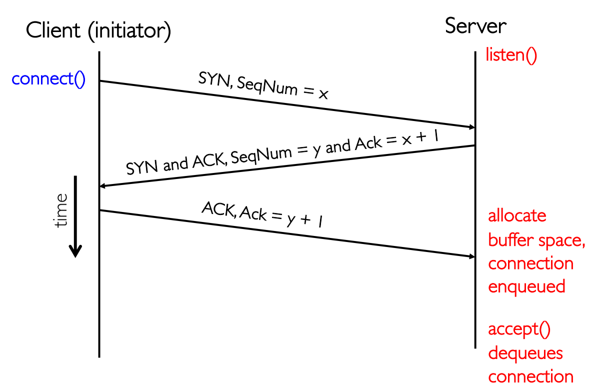
1. Open connection: 3-way handshaking
2. Reliable byte stream transfer from (IPa, TCP_Port1) to (IPb, TCP_Port2)
   - Indication if connection fails: Reset
3. Close (tear-down) connection

Sockets in concept

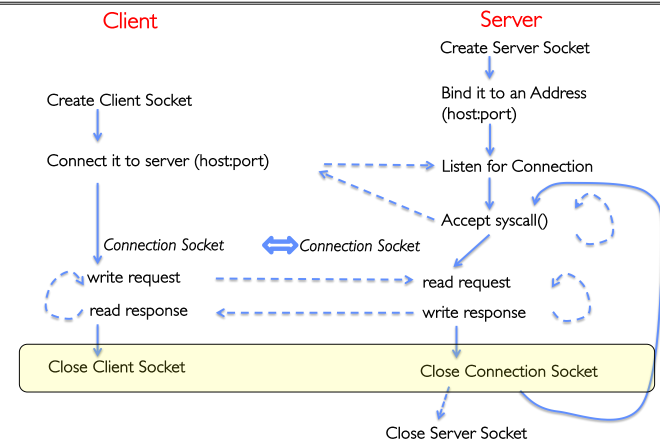


Open Connection: 3-Way Handshake

- 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

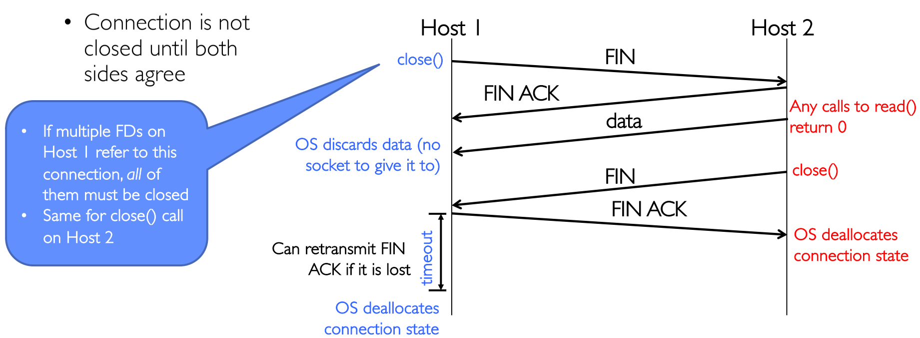


Sockets in concept



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

- 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

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

```
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?

- 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?

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


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>
```

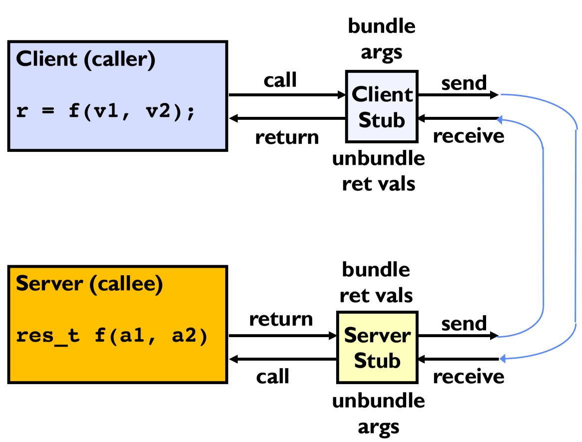
Data Serialization Formats

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[f]	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

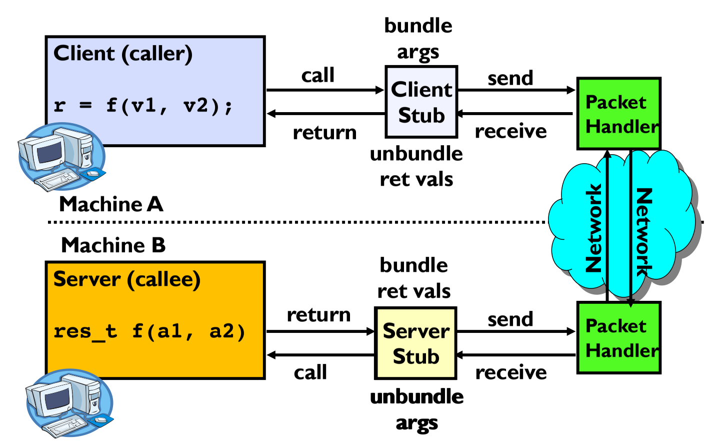
Remote Procedure Call (RPC)

- 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

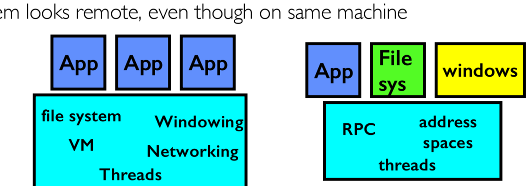
- RPC is *not* performance transparent:
  - Cost of Procedure call « same-machine RPC « network RPC
  - Overheads: Marshalling, Stubs, Kernel-Crossing, Communication
- Programmers must be aware that RPC is not free
  - Caching can help, but may make failure handling complex

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

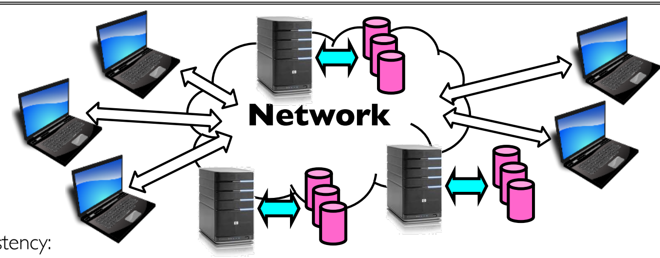
- Example: split kernel into application-level servers.
  - File system looks remote, even though on same machine



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.

Network-Attached Storage and the CAP Theorem

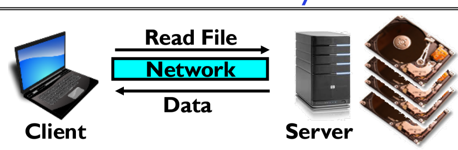


- Consistency:
  - Changes appear to everyone in the same serial order
- Availability:
  - Can get a result at any time
- Partition-Tolerance
  - System continues to work even when network becomes partitioned
- Consistency, Availability, Partition-Tolerance (CAP) Theorem: Cannot have all three at same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

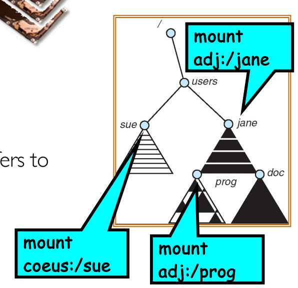
Administrivia

- Midterm 3: Thursday 4/28: 7-9PM
  - All course material
  - Review session Monday 4/25 1-3PM

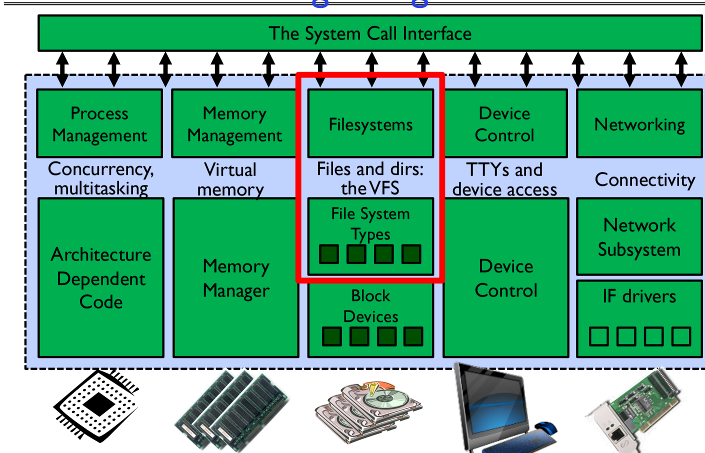
Distributed File Systems



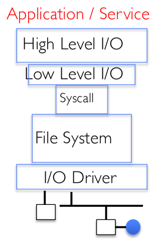
- Transparent access to files stored on a remote disk
- *Mount* remote files into your local file system
  - Directory in local file system refers to remote files
  - e.g., `/users/jane/prog/foo.c` on laptop actually refers to `/prog/foo.c` on `adj.cs.berkeley.edu`
- *Naming* Choices:
  - [Hostname,localname]: Filename includes server
    - » No location or migration transparency, except through DNS remapping
  - A global name space: Filename unique in "world"
    - » Can be served by any server



Enabling Design: VFS



Recall: Layers of I/O…



User App:

```
length = read(input_fd, buffer, BUFFER_SIZE);
```

User library:

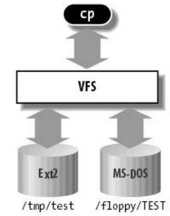
```
ssize_t read(int, void *, size_t) {
  marshal args into registers
  issue syscall
  register result of syscall to rtn value
};
```

```
Exception U→K, interrupt processing
void syscall_handler (struct intr_frame *f) {
   unmarshall call#, args from regs
   dispatch : handlers[call#](args)
   marshal results fo syscall ret
}
```

```
ssize_t vfs_read(struct file *file, char __user *buf,
                  size_t count, loff_t *pos) {
   User Process/File System relationship
   call device driver to do the work
}
```

Device Driver

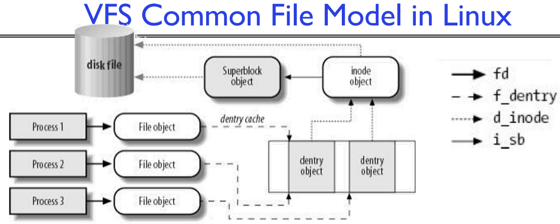
Virtual Filesystem Switch




```
inf = open("/floppy/TEST", O_RDONLY, 0);
outf = open("/tmp/test",
        O_WRONLY|O_CREAT|O_TRUNC, 0600);
do {
   i = read(inf, buf, 4096);
   write(outf, buf, i);
} while (i);
close(outf);
close(inf);
```

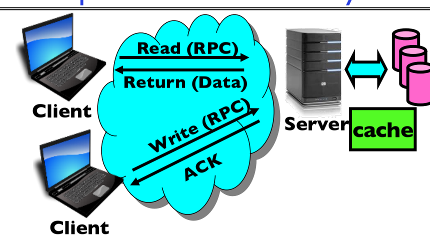
- VFS: Virtual abstraction similar to local file system
  - Provides virtual superblocks, inodes, files, etc
  - Compatible with a variety of local and remote file systems
    - » provides object-oriented way of implementing file systems
- VFS allows the same system call interface (the API) to be used for different types of file systems
  - The API is to the VFS interface, rather than any specific type of file system

VFS Common File Model in Linux



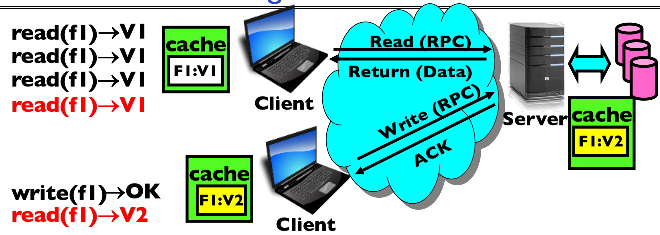
- Four primary object types for VFS:
  - superblock object: represents a specific mounted filesystem
  - inode object: represents a specific file
  - dentry object: represents a directory entry
  - file object: represents open file associated with process
- There is no specific directory object (VFS treats directories as files)
- May need to fit the model by faking it
  - Example: make it look like directories are files
  - Example: make it look like have inodes, superblocks, etc.

Simple Distributed File System



- Remote Disk: Reads and writes forwarded to server
  - Use Remote Procedure Calls (RPC) to translate file system calls into remote requests
  - No local caching, but can be cache at server-side
- Advantage: Server provides consistent view of file system to multiple clients
- Problems? Performance!
  - Going over network is slower than going to local memory
  - Lots of network traffic/not well pipelined
  - Server can be a bottleneck

Use of caching to reduce network load



- Idea: Use caching to reduce network load
  - In practice: use buffer cache at source and destination
- Advantage: if open/read/write/close can be done locally, don't need to do any network traffic…fast!
- Problems:
  - Failure:
    - » Client caches have data not committed at server
  - Cache consistency!
    - » Client caches not consistent with server/each other

Dealing with Failures

- What if server crashes? Can client wait until it comes back and just continue making requests?
  - Changes in server's cache but not in disk are lost
- What if there is shared state across RPC's?
  - Client opens file, then does a seek
  - Server crashes
  - What if client wants to do another read?
- Similar problem: What if client removes a file but server crashes before acknowledgement?

Stateless Protocol

- Stateless Protocol: A protocol in which all information required to service a request is included with the request
- Even better: Idempotent Operations – repeating an operation multiple times is same as executing it just once (e.g., storing to a mem addr.)
- Client: timeout expires without reply, just run the operation again (safe regardless of first attempt)
- Recall HTTP: Also a stateless protocol
  - Include cookies with request to simulate a session

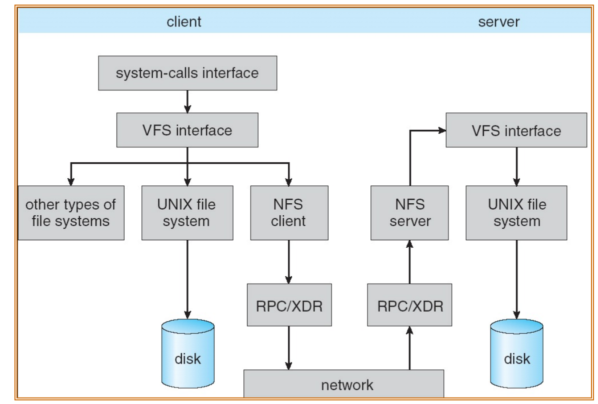
Case Study: Network File System (NFS)

- Three Layers for NFS system
  - UNIX file-system interface: open, read, write, close calls + file descriptors
  - VFS layer: distinguishes local from remote files
    - » Calls the NFS protocol procedures for remote requests
  - NFS service layer: bottom layer of the architecture
    - » Implements the NFS protocol
- NFS Protocol: RPC for file operations on server
  - XDR Serialization standard for data format independence
  - Reading/searching a directory
  - manipulating links and directories
  - accessing file attributes/reading and writing files
- Write-through caching: Modified data committed to server's disk before results are returned to the client
  - lose some of the advantages of caching
  - time to perform write() can be long
  - Need some mechanism for readers to eventually notice changes! (more on this later)

NFS Continued

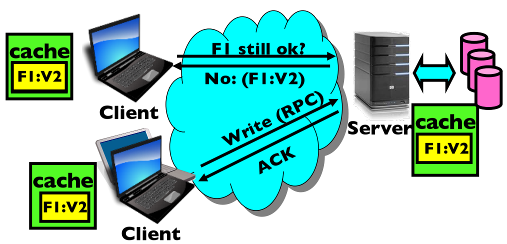
- NFS servers are stateless; each request provides all arguments require for execution
  - E.g. reads include information for entire operation, such as `ReadAt(inumber,position)`, not `Read(openfile)`
  - No need to perform network open() or close() on file – each operation stands on its own
- Idempotent: Performing requests multiple times has same effect as performing them exactly once
  - Example: Server crashes between disk I/O and message send, client resend read, server does operation again
  - Example: Read and write file blocks: just re-read or re-write file block – no other side effects
  - Example: What about "remove"? NFS does operation twice and second time returns an advisory error
- Failure Model: Transparent to client system
  - Is this a good idea? What if you are in the middle of reading a file and server crashes?
  - Options (NFS Provides both):
    - » Hang until server comes back up (next week?)
    - » Return an error. (Of course, most applications don't know they are talking over network)

NFS Architecture



NFS Cache consistency

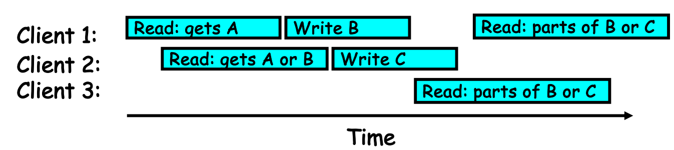
- NFS protocol: weak consistency
  - Client polls server periodically to check for changes
    - » Polls server if data hasn't been checked in last 3-30 seconds (exact timeout it tunable parameter).
    - » Thus, when file is changed on one client, server is notified, but other clients use old version of file until timeout.



  - What if multiple clients write to same file?
    - » In NFS, can get either version (or parts of both)
    - » Completely arbitrary!

Sequential Ordering Constraints

- What sort of cache coherence might we expect?
  - i.e. what if one CPU changes file, and before it's done, another CPU reads file?
- Example: Start with file contents = "A"



- What would we actually want?
  - Assume we want distributed system to behave exactly the same as if all processes are running on single system
    - » If read finishes before write starts, get old copy
    - » If read starts after write finishes, get new copy
    - » Otherwise, get either new or old copy
  - For NFS:
    - » If read starts more than 30 seconds after write, get new copy; otherwise, could get partial update

NFS Pros and Cons

- NFS Pros:
  - Simple, Highly portable
- NFS Cons:
  - Sometimes inconsistent!
  - Doesn't scale to large # clients
    - » Must keep checking to see if caches out of date
    - » Server becomes bottleneck due to polling traffic

Andrew File System

- Andrew File System (AFS, late 80's) → DCE DFS (commercial product)
- Callbacks: Server records who has copy of file
  - On changes, server immediately tells all with old copy
  - No polling bandwidth (continuous checking) needed
- Write through on close
  - Changes not propagated to server until close()
  - Session semantics: updates visible to other clients only after the file is closed
    - » As a result, do not get partial writes: all or nothing!
    - » Although, for processes on local machine, updates visible immediately to other programs who have file open
- In AFS, everyone who has file open sees old version
  - Don't get newer versions until reopen file

Andrew File System (con't)

- Data cached on local disk of client as well as memory
  - On open with a cache miss (file not on local disk):
    - » Get file from server, set up callback with server
  - On write followed by close:
    - » Send copy to server; tells all clients with copies to fetch new version from server on next open (using callbacks)
- What if server crashes? Lose all callback state!
  - Reconstruct callback information from client: go ask everyone "who has which files cached?"
- AFS Pro: Relative to NFS, less server load:
  - Disk as cache ⇒ more files can be cached locally
  - Callbacks ⇒ server not involved if file is read-only
- For both AFS and NFS: central server is bottleneck!
  - Performance: all writes→server, cache misses→server
  - Availability: Server is single point of failure
  - Cost: server machine's high cost relative to workstation

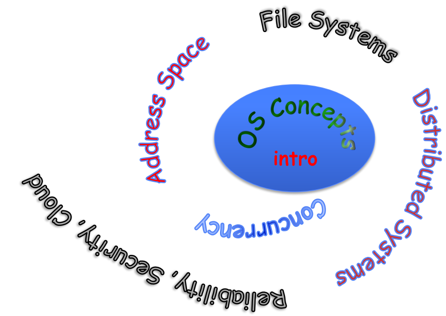
Summary (1/2)

- 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

Summary (2/2)

- Distributed File System:
  - Transparent access to files stored on a remote disk
  - Caching for performance
- VFS: Virtual File System layer (Or Virtual Filesystem Switch)
  - Provides mechanism which gives same system call interface for different types of file systems
- Cache Consistency: Keeping client caches consistent with one another
  - If multiple clients, some reading and some writing, how do stale cached copies get updated?
  - NFS: check periodically for changes
  - AFS: clients register callbacks to be notified by server of changes

Thank you!



- Thanks for all your great questions!
- Good Bye! You have all been great!