Remote Procedure Call (RPC) and Transparency

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Transparency in Distributed Systems

- Programmers accustomed to writing code for a single box
- Transparency: retain “feel” of writing for one box, when writing code that runs distributedly
- Goals:
  - Preserve original, unmodified client code
  - Preserve original, unmodified server code
  - RPC should glue together client and server without changing behavior of either
  - Programmer shouldn’t have to think about network

Transparency in Distributed Systems

How achievable is true transparency?
We will use NFS as a case study.
But first, an introduction to RPC itself.

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Remote Procedure Call: Central Idea

- Within a single program, running on a single box, well-known notion of procedure call (aka function call):
  - Caller pushes arguments onto stack
  - Jumps to address of callee function
  - Callee reads arguments from stack
  - Callee executes, puts return value in register
  - Callee returns to next instruction in caller
- RPC aim: let distributed programming look no different from local procedure calls

RPC Abstraction

- Library makes an API available to locally running applications
- Let servers export their local APIs to be accessible over the network, as well
- On client, procedure call generates request over network to server
- On server, called procedure executes, result returned in response to client

RPC Implementation Details

- Data types may be different sizes on different machines (e.g., 32-bit vs. 64-bit integers)
- Little-endian vs. big-endian machines
  - Big-endian: 0x11223344 is 0x11, 0x22, 0x33, 0x44
  - Little-endian is 0x44, 0x33, 0x22, 0x11
- Need mechanism to pass procedure parameters and return values in machine-independent fashion
- Solution: Interface Description Language (IDL)

Interface Description Languages

- Compile interface description, produces:
  - Types in native language (e.g., Java, C, C++)
  - Code to marshal native data types into machine-neutral byte streams for network (and vice-versa)
  - Stub routines on client to forward local procedure calls as requests to server
- For Sun RPC, IDL is XDR (eXternal Data Representation)

Example: Sun RPC and XDR

- Define API for procedure calls between client and server in XDR file, e.g., **`proto.x`**
- Compile: **`rpcgen proto.x,`** producing
  - **`proto.h`**: RPC procedure prototypes, argument and return value data structure definitions
  - **`proto_clnt.c`**: per-procedure client stub code to send RPC request to remote server
  - **`proto_svc.c`**: server stub code to dispatch RPC request to specified procedure
  - **`proto_xdr.c`**: argument and result marshaling/ unmarshaling routines, host-network/network-host byte order conversions

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Let's consider a simple example…

  - **`proto_svc.c`**: server stub code to dispatch RPC request to specified procedure
  - **`proto_xdr.c`**: argument and result marshaling/ unmarshaling routines, host-network/network-host byte order conversions

Sun RPC and XDR: Programming Caveats

- Server routine return values must always be pointers (e.g., `int *`, not `int`)
  - should declare return value `static` in server routine
- Arguments to server-side procedures are **pointers** to temporary storage
  - to store arguments beyond procedure end, must copy data, not merely pointers
  - in these cases, typically allocate memory for copy of argument using `malloc()`
- If new to C, useful background in Mark Handley's "C for Java programmers" tutorial:
  - https://moodle.ucl.ac.uk/mod/resource/view.php?id=430247
  - § 2.9 – 2.13 describe memory allocation

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- Arguments to server-side procedures are **pointers** to temporary storage
  - to store arguments beyond procedure end, must copy

Now, back to our NFS case study…

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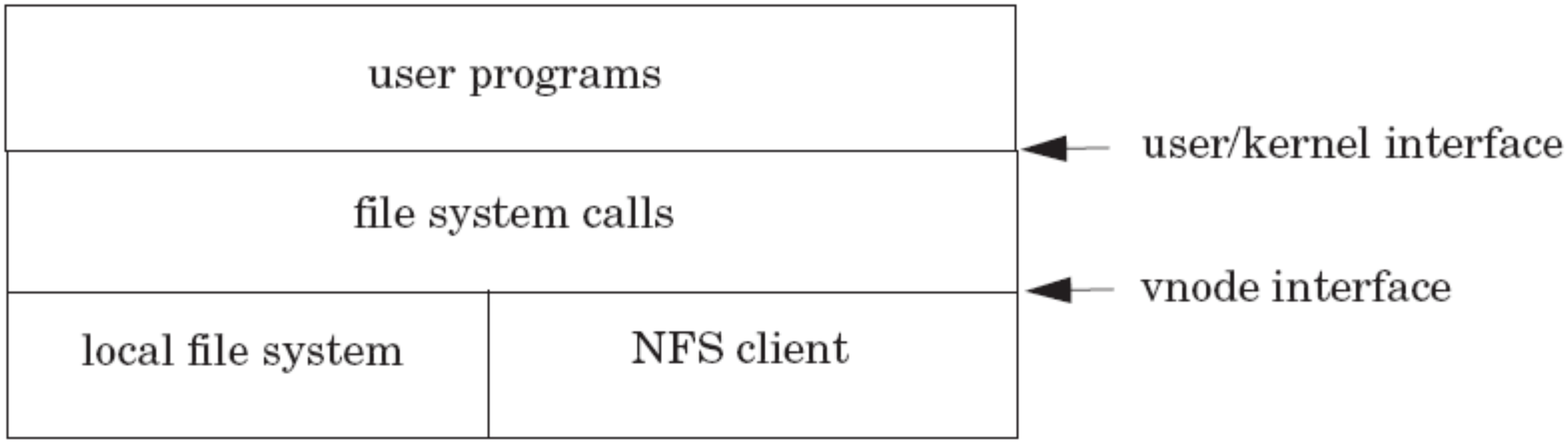
“Non-Distributed” NFS

- Applications
- Syscalls
- Kernel filesystem implementation
- Local disk

- RPC must “split up” the above
- Where does NFS make the split?

NFS Structure on Client



- NFS splits client at vnode interface, below syscall implementation
- Client-side NFS code essentially stubs for system calls:
  - Package up arguments, send them to server

NFS and Syntactic Transparency

- Does NFS preserve the syntax of the client function call API (as seen by applications)?
  - Yes!
  - Arguments and return values of system calls not changed in form or meaning

NFS and Server-Side Transparency

- Does NFS require changes to pre-existing filesystem code on server?
  - Some, but not much.
  - NFS adds in-kernel threads (to block on I/O, much like user-level processes do)
  - Server filesystem implementation changes:
    - File handles over wire, not file descriptors
    - Generation numbers added to on-disk i-nodes
    - User IDs carried as arguments, rather than implicit in process owner
    - Support for synchronous updates (e.g., for WRITE)

NFS and File System Semantics

- You don’t get transparency merely by preserving the same API
- System calls must mean the same thing!
- If they don’t, pre-existing code may compile and run, but yield incorrect results!
- Does NFS preserve the UNIX filesystem’s semantics?
- **No! Let us count the ways…**

NFS's New Semantics: Server Failure

- On one box, open() only fails if file doesn't exist
- Now open() and all other syscalls can fail if server has died!
  - Apps must know how to retry or fail gracefully
- **Or** open() could hang forever—never the case before!
  - Apps must know how to set own timeouts if don't want to hang
- This is **not** a quirk of NFS—it's fundamental!

NFS's New Semantics: close() Might Fail

- Suppose server out of disk space
- But client WRITEs asynchronously, only on close(), for performance
- Client waits in close() for WRITEs to finish
- close() never returns error for local fs!
  - Apps must check not only write(), but also close(), for disk full!
- Reason: NFS batches WRITEs
  - If WRITEs were synchronous, close() couldn't fill disk, but performance would be awful

NFS's New Semantics: Errors Returned for Successful Operations

- Suppose you call rename("a", "b") on file in NFS-mounted fs
- Suppose server completes RENAME, crashes before replying
- NFS client resends RENAME
- "a" doesn't exist; error returned!
- **Never happens on local fs…**
- Side effect of statelessness of NFS server:
  - Server could remember all ops it's completed, but that's hard
  - Must keep that state consistent and persistent across crashes (i.e., on disk)!
  - Update the state first, or perform the operation first?

NFS's New Semantics: Deletion of Open Files

- Client A open()s file for reading
- Client B deletes it while A has it open
- Local UNIX fs: A's subsequent reads work
- NFS: A's subsequent reads fail
- Side effect of statelessness of NFS server:
  - Could have fixed this—server could track open()s
  - AFS tracks state required to solve this problem

Semantics vs. Performance

- Insight: **preserving semantics produces poor performance**
- e.g., for write() to local fs, UNIX can delay actual write to disk
  - Gather writes to multiple adjacent blocks, and so write them with one disk seek
  - If box crashes, you lose **both** the running app and its dirty buffers in memory
- Can we delay WRITEs in this way on NFS server?

NFS Server and WRITE Semantics

- Suppose WRITE RPC stores client data in buffer in memory, returns success to client
- Now server crashes and reboots
  - App doesn't crash—in fact, doesn't notice!
  - And **written data mysteriously disappear!**
- Solution: NFS server does synchronous WRITEs
  - Doesn't reply to WRITE RPC until data on disk
  - If write() returns on client, even if server crashes, data safe on disk
  - Per previous lecture: 3 seeks, 45 ms, 22 WRITES/s, 180 KB/s max throughput!
  - < 10% of max disk throughput
- NFS v3 and AFS fix this problem (more complex)

Semantics vs. Performance (2)

- Insight: **improving performance changes consistency semantics!**
- Suppose clients cache disk blocks when they read them
- But writes always go through to server
- Not enough to get consistency!
  - Write editor buffer on one box, make on other
  - Do make/compiler see changes?
- Ask server "has file changed?" at every read()?
  - Almost as slow as just reading from server…

NFS: Semantics vs. Performance

- NFS’ solution: close-to-open consistency
  - Ask server “has file changed?” at each open()
  - Don’t ask on each read() after open()
  - If B changes file while A has it open, A doesn’t see changes
- OK for emacs/make, but not always what you want:
  - `make > make.log` (on server)
  - `tail -f make.log` (on my desktop)
- Side effect of statelessness of NFS server
  - Server could track who has cached blocks on reads
  - Send “invalidate” messages to clients on changes

Security Radically Different

- Local system: UNIX enforces read/write protections per-user
  - Can't read my files without my password
- How does NFS server authenticate user?
- Easy to send requests to NFS server, and to forge NFS replies to client
- Does it help for server to look at source IP address?
- **So why aren't NFS servers ridiculously vulnerable?**
  - Hard to guess correct file handles!

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Fixable: SFS, AFS, some NFS versions use cryptography to authenticate client

Very hard to reconcile with statelessness!

NFS Still Very Useful

- People fix programs to handle new semantics
  - Must mean NFS useful enough to motivate them to do so!
- People install firewalls for security
- NFS still gives many advantages of transparent client/server

Multi-Module Distributed Systems

- NFS in fact rather simple:
  - One server, one data type (file handle)
- What if symmetric interaction, many data types?
- Say you build system with three modules in one address space:
  - Web front end, customer DB, order DB
- Represent user connections with object:

```
class connection {
   int fd; int state; char *buf; }
```

- Easy to pass object references among three modules (e.g., pointer to current connection)

Multi-Module Distributed Systems

- NFS in fact rather simple:
  - One server, one data type (file handle)
- What if symmetric interaction, many data types?

What if we split system into three separate servers?

  - Web front end, customer DB, order DB
- Represent user connections with object:

```
class connection {
  int fd; int state; char *buf; }
```

- Easy to pass object references among three modules (e.g., pointer to current connection)

Multi-Module Systems: Challenges

- How do you pass `class connection` between servers?
  - Could RPC stub just send object's elements?
- What if processing flow for connection goes: order DB -> customer DB -> front end to send reply?
- Front end only knows **contents** of passed connection object; underlying connection may have changed!
- Wanted to pass object references, not object contents
- NFS solution: file handles
  - No support from RPC to help with this!

RPC: Failure Happens

- New failure modes not seen in simple, same-host procedure calls:
  - Remote server failure
  - Communication (network) failure
- RPCs can return “failure” instead of results
- Possible failure outcomes:
  - Procedure didn’t execute
  - Procedure executed once
  - Procedure executed multiple times
  - Procedure partially executed
- Generally, “at most once” semantics preferred

Achieving At-Most-Once Semantics

- Risk: Request message lost
  - Client must retransmit requests when no reply received
- Risk: Reply message lost
  - Client may retransmit previously executed request
  - OK when operations idempotent; some aren’t, though (e.g., “charge customer”)
  - Server can keep “replay cache” to reply to repeated requests without re-executing them

Summary: RPC Non-Transparency

- Partial failure, network failure
- Latency
- Efficiency/semantics tradeoff
- Security—rarely transparent!
- Pointers: write-sharing, portable object references
- Concurrency (if multiple clients)
- Solutions:
  - Expose "remoteness" of RPC to application, or
  - Work harder to achieve transparent RPC

Conclusions

- Of RPC's goals, automatic marshaling most successful
- Mimicking procedure call interface in practice not so useful
- Attempt at full transparency mostly a failure!
  - (You can try hard: consider Java RMI)
- Next time: implicit communication through distributed shared memory!