NFS/RDMA Linux Client

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Outline

- NFS/RDMA Protocol(s)
- Implementation on Linux
- Results
- Next steps

What is NFS/RDMA

- A binding of NFS v2, v3, v4 atop RDMA transport such as Infiniband, iWARP
- A significant performance optimization
- An enabler for NAS in the high-end

Benefits of RDMA

- Reduced Client Overhead
- Data copy avoidance (zero-copy)
- Userspace I/O (OS Bypass)
- Reduced latency
- Increased throughput, ops/sec

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Followon NFS/RDMA Benefits

- Protocol enhancements and extensions
  - Databases, cluster computing, etc
- Scalable cluster/distributed filesystem
- As we raise the “NAS bar”, the protocol should express richer semantics

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What has been proposed

- IETF NFSv4 Working Group
- From the bottom up:
  - RPC/RDMA
  - NFS RDMA binding
  - NFSv4 Transport enhancements
    - Sessions
    - Exactly-once semantics

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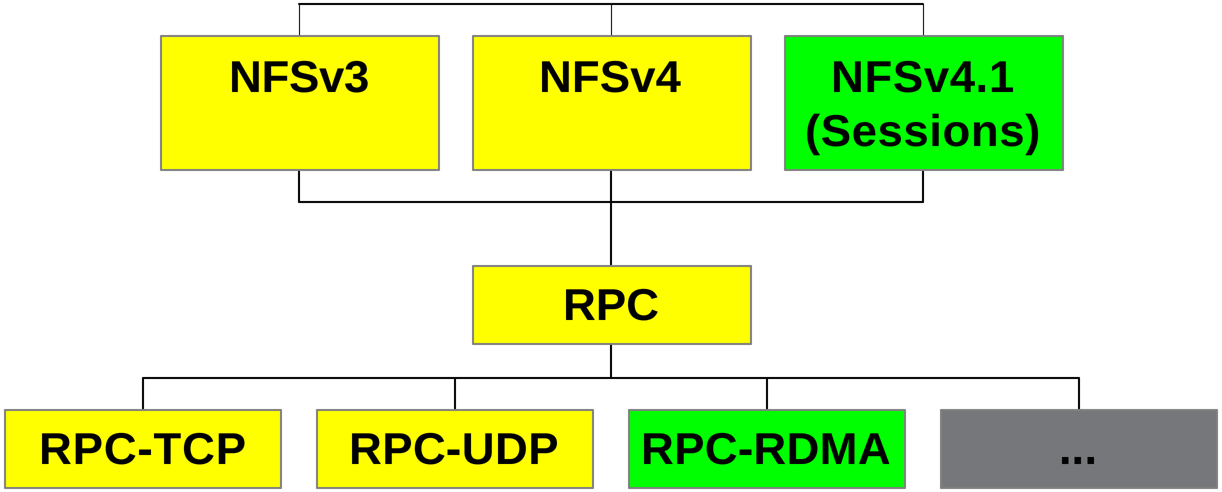
NFS-RDMA Protocol Stack



RPC/RDMA

- Core RDMA transport binding for RPC in general
- Provides
  - Encoding, etc
  - Inline and Direct (RDMA chunk) transfer
  - Credits
- http://www.ietf.org/internet-drafts/draft-callaghan-rpcrdma-00.txt

NFS Direct

- NFS binding for RPC/RDMA
- Provides
  - Inline and Direct (RDMA) NFS RPC definitions
  - “What gets chunked”
- http://www.ietf.org/internet-drafts/draft-callaghan-nfsdirect-00.txt

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NFSv4 RDMA and Sessions

- Transport Enhancement for NFSv4
- Provides
  - Session concept
  - Exactly-once semantics
  - General for TCP and RDMA
- http://www.ietf.org/internet-drafts/draft-talpey-nfsv4-rdma-sess-01.txt

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NFS RDMA Problem Statement

- IETF Problem Statement for NFS over RDMA
- Provides
  - Rationale
  - Outlines requirements
  - IETF-chartered first step
- http://www.ietf.org/internet-drafts/draft-ietf-nfsv4-nfs-rdma-problem-statement-00.txt

NFS RDMA Requirements

- IETF Requirements doc for NFS over RDMA
- Provides
  - Detailed requirements
  - Input to RDDP group
  - IETF-chartered first step
- http://www.ietf.org/internet-drafts/draft-callaghan-nfsrdmareq-00.txt

The Documents Together:

- Form the basis for a complete NFS over RDMA solution
- All NFS versions, and general RPC
- Do not fundamentally propose new NFS features (but enable a few)

Applying to NFSv3

- Immediate performance benefit
- Straightforward integration with existing implementation
- High market acceptance
- “NFS on Steroids”
- Side protocols (NLM) problematic

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Applying to NFSv4+

- Performance
- Enhanced correctness
  - “The goodness of NFSv4”
  - Exactly-once semantics (“EOS”)
  - No side protocols / side connections
- Sessions
  - Trunking
  - Failover
  - Efficient resource management
  - (Other benefits from EOS)
  - For both TCP and RDMA

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Roadmap

- Early win: NFSv3 on IB
- Prepare the Transport: NFSv4 Sessions
- Enable the applications by extending the protocol
- Employ (*and foster*) iWARP
- NFSv4/RDMA as cluster FS

Client Implementation Goals

- Support NFS/RDMA
- Support other transports:
  - TOE
  - IPv6
  - “Bypass” (pNFS)
- Integrate with Linux

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Existing Linux RPC support

- Single module – sunrpc.o
- Only IPPROTO_{TCP,UDP}
- Only kernel sockets API
- Much specific knowledge roto-tilled:
  - Stream/dgram (framing needed)
  - Connection oriented (reconnect needed)
  - Reliable (retransmit needed)
- Endpoint is 1-1 per xprt (mount)

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Solution: RPC Transport Switch

- Abstraction for transport type
- One each for
  - TCP
  - UDP
  - RDMA
  - More to come

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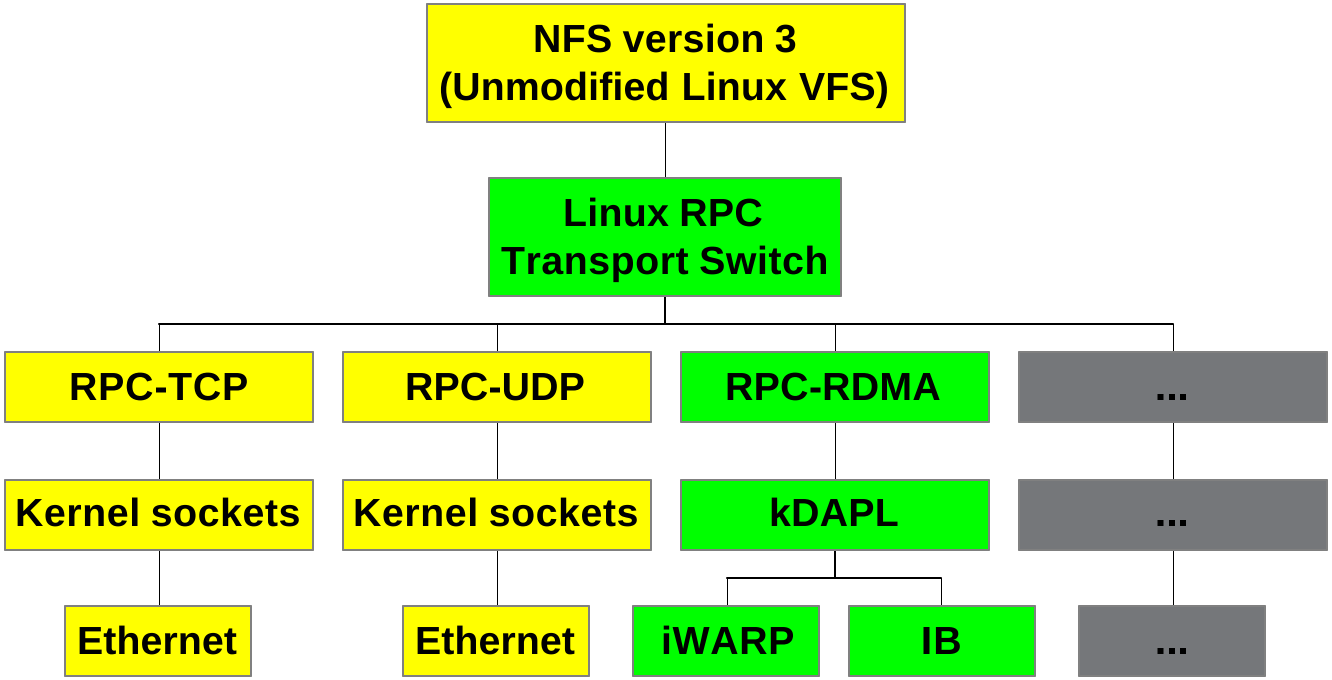
NFS-RDMA
Client Software Stack



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Transport Switch Vector

New pointer in the "struct rpc_xprt":

```
/* abstract functions provided by a transport */
struct rpc_xprt_procs {
	void *	(*allocate)(struct rpc_xprt *, struct rpc_task *, unsigned int);
	int	(*sendmsg)(struct rpc_xprt *, struct rpc_rqst *);
	void	(*free)(struct rpc_xprt *, struct rpc_task *, void *);
	void	(*reconnect)(struct rpc_task *);
	int	(*create)(struct rpc_xprt *, struct xprt_create_data *);
	int	(*destroy)(struct rpc_xprt *);
	void	(*close)(struct rpc_xprt *);
};
```

Socket Transport Creation

```
#define RPC_MAX_TRANSPORTS 16
#define RPC_XPRT_TCP  0         /* sock_create_data */
#define RPC_XPRT_UDP  1         /* sock_create_data */
#define RPC_XPRT_RDMA 2         /* rdma_create_data */

struct sock_create_data {
        struct sockaddr_in      srvaddr;
        struct rpc_timeout *    timeo;
};
```

RDMA Transport Creation

```
struct rdma_create_data {
        /* Generic fields */
        struct sockaddr_in      srvaddr;
        struct rpc_timeout *    timeo;

        /* Server RDMA address and port */
        struct sockaddr         addr;
        u64                     port;

        /* Per-mount tuning */
        int             max_requests;   /* max credits/requests in flight */
        int             rsize;          /* server r/w sizes (mount opts) */
        int             wsize;

        /* Per-server configuration - must be <= remote settings */
        int             max_inline_send;        /* Inline data max */
        int             max_inline_recv;        /* Inline data max */
        int             padding;                /* Inline write pad */
};
```

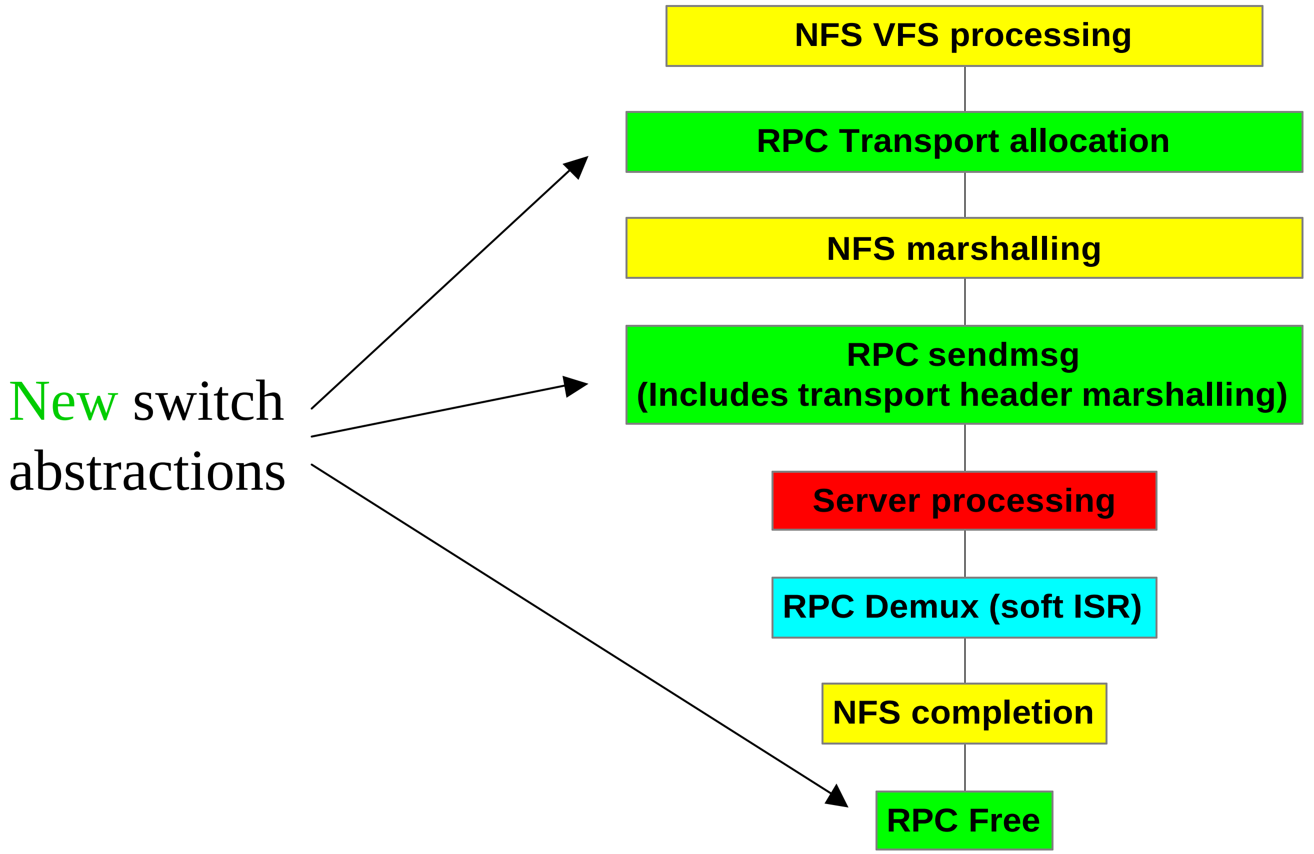
Transport Switch Registry

```
/*
 * rpc_transport represents a transport for use by RPC.
 * This is provided by each transport.
 */
struct rpc_transport {
	char			name[8];
	int			transport_number;
	struct rpc_xprt_procs	procs;
};
int xprt_register(struct rpc_transport *);
int xprt_unregister(struct rpc_transport *);
/* Alternative for xprt_create_proto that is transport-switch aware. */
struct rpc_xprt *xprt_create_transport(struct xprt_create_data *);
```

Transport Hooks

- Each transport registers with switch
- NFS mount (and others) specify transport type and per-transport create data
- Transport gets control via xprt_procs
- Can unregister/unload

Lifecycle of an RPC



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Memory Representation

- Leverage Linux implementation heavily
- Use allocation hook to set up preregistered request/reply buffers (headers)
- Use iovec (<= 2.4.19) or pagelist (>= 2.4.20) to map any data

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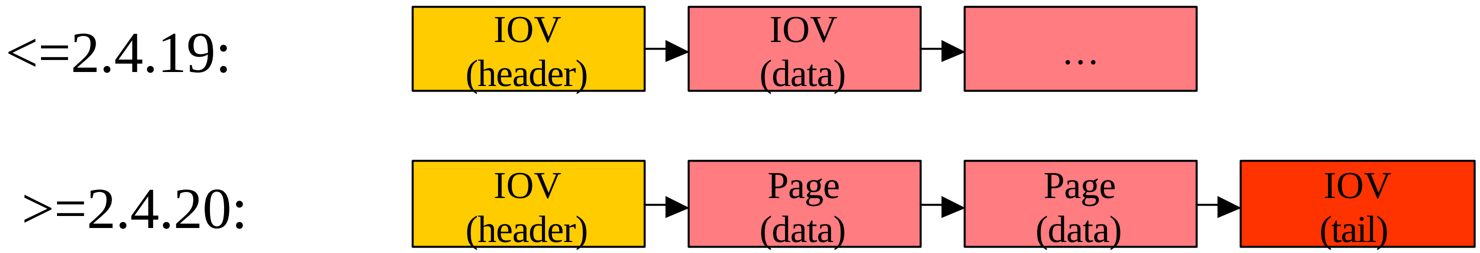
Memory Representation



- Header segment always copied to inline
  - All metadata ops, small reads/writes “pulled up”
- Data segments translated directly to rpcrdma “chunks”
- No need for NFS layer to become involved

Transfer models

- Follow the RPC/RDMA protocol
- Full inline (no chunking)
- Direct read, write (via write/read chunks, respectively)
- "Overflow transfer" via reply chunks or position-0 requests
- Write padding supported

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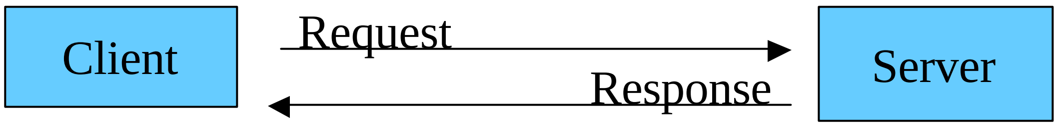
Inline I/O Operations

- "Small ops": metadata and inline Read and Write
  - Just like regular RPC



  - Pre-allocated buffers, pre-registered with the transport
  - Configurable message size limit
  - Low transport latency, simple model
  - Header padding for write data alignment

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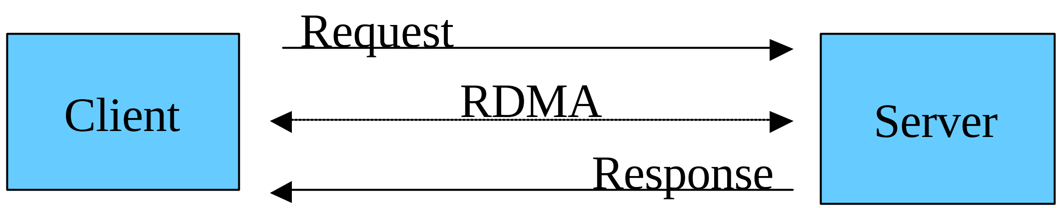
Direct I/O Operations

- Direct Read and Write
  - 3-part transfer



  - Server initiates RDMA operation
  - Buffer placed per request
  - Used for large messages
  - Zero-copy, low CPU cost

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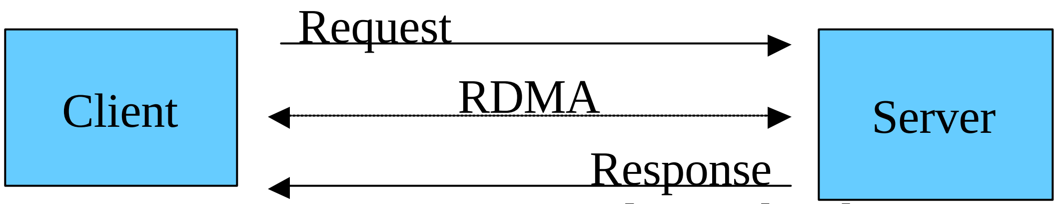
Overflow Direct Operations

- Large metadata transfers
  - 3-part transfer



  - Client expresses entire request or reply as chunk
  - Server performs RDMA operation
  - Used when request or response size > max
    - e.g. rename, readlink, readdir
  - Provides correctness for corner cases
    - Not on read/write path

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Buffer Cache

- Operation to Linux buffer cache fully supported
- RDMA to/from cache, bcopy to/from user
- Improved overhead from sockets case
  - Protocol offload, copy avoidance
- Convenient because buffer cache is in kernel address space

Direct I/O

- User directio fully supported in appropriate kernels (>= 2.4.19)
- User pages passed as pagelist by NFS
- Pages are registered for RDMA
- Zero-copy, zero-touch
- When physical addressing in use, no kmap/kunmap is required (no TLB inval)

Client Implementation

- Patch for sunrpc (transport switch)
- RPC/RDMA module
  – 3000 lines of code, 2 headers, 3 C files
- kDAPL "null" provider
- IB kDAPL providers under way

Client Implementation

- Available as open source
  - BSD-style license
  - www.sourceforge.net/projects/nfs-rdma
- Supported Linuxes:
  - RedHat 7.3 (2.4.18)
  - SuSE 8 Enterprise (2.4.19)
  - RHEL 3.0 (2.4.21)
  - 2.6 support under way

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kDAPL

- Kernel Direct Access Programming Library
- Transport API for RDMA
  - Implemented as part of each driver, with global registry
- Supports iWARP, Infiniband, VIA
- Open reference implementation
- www.datcollaborative.org
- www.sourceforge.net/projects/dapl

Performance

1. Streaming throughput
2. Transactional throughput
3. Seat-of-pants

- Tests run on Dell 2650
  - SuSE Linux Enterprise Server 8 (~2.4.19)
  - 4x Infiniband connection (10Gb)
  - 2.4GHz dual Xeon
  - Hyperthreading disabled
  - NetApp 960 Filer(s)

Streaming Throughput

- 4K synchronous random reads from server cache
  – i.e. single thread, no caching, no readahead.
- Achieves ~350MBytes/sec
  – This includes one data copy from kernel->user!
- Uses only 20% of client CPU
- RDMA, low latency, protocol offload all contribute

Transactional Throughput

- OLTP benchmark (4-way CPU)
- Compared to 1Gb NFS/TCP, 2Gb Fibre Channel
  - These runs are *not* bandwidth limited
- NFS runs encounter 1 data copy (database !O_DIRECT)

	OLTP ops	System time	Limit
NFS/TCP	17K	21%	Idle time
Fibre	21K	20%	Host CPU
RDMA	20K	26%	Host CPU (data copy)

Seat-of-pants

- Build the Linux kernel
- NFS runs encounter significant creat/open/close attribute traffic – expect much better w/v4

	Build time
Local disk	3:05
NFS/TCP	6:10
RDMA	4:10

Next Steps

- Transport switch
  - Clean up, generalize
  - Integrate with 2.6.x
  - Expose transport creation args via mount

Next Steps

- Linux Infiniband support
- For base kernel, also in distributions
  - Infiniband vendors
- With kDAPL support

Next Steps

- NFSv4/RDMA/Sessions
- UMich CITI
- http://www.citi.umich.edu/projects/rdma/

Next Steps

- NFS/RDMA Linux Server
- (TBD)

Next Steps

- Other applications of transport switch
  - TOE
    - Non kernel-sockets TOE API may add efficiency
  - IPv6
    - Better express addressing, transport differences
  - pNFS (parallel NFS)
    - Fibre Channel / iSCSI "bypass"
  - Multiple TCP endpoints
    - Simple trunked/failover mountpoints

Next Steps

- iWARP support
- Emerging technology in 2004

Backup – NFSv4/Sessions

The Proposal

- Add a session to NFSv4
- Enable operation on single connection
  - Firewall-friendly
- Enable multiple connections for trunking, multipathing
- Enable RDMA accounting (credits, etc)
- *Provide Exactly-Once semantics*
- Transport-independent

5 new ops

- SESSION_CREATE
- SESSION_BIND
- SESSION_DESTROY
- OPERATION_CONTROL
- CB_CREDITRECALL

Channels versus Connections

- Channel: a connection bound to a specific purpose:
  - Operations (1 or more connections)
  - Callbacks (typically 1 connection)
- Multiple connections per client, multiple channels per connection
  - Many-to-many relationship
- All operations require a streamid/channelid
  - Encoded into COMPOUND

Session Connection Model

- Client connects to server
- First time only:
  - New session via SESSION_CREATE
- Initialize channel:
  - Bind “channel” via SESSION_BIND
  - May bind operations, callback to same connection
  - May connect additional times
    - Trunking, multipathing, failover, etc.
- CCM fits perfectly here
- If connection lost, may reconnect to existing session
- When done:
  - Destroy session context via SESSION_DESTROY

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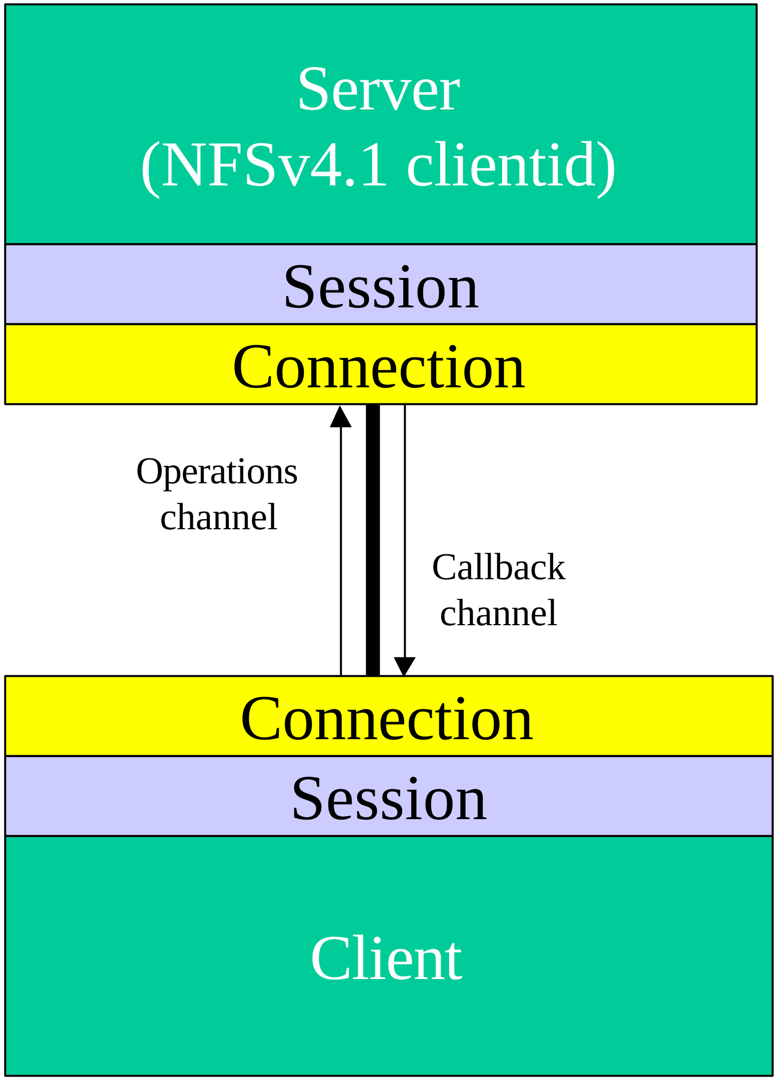
Example Session – single connection



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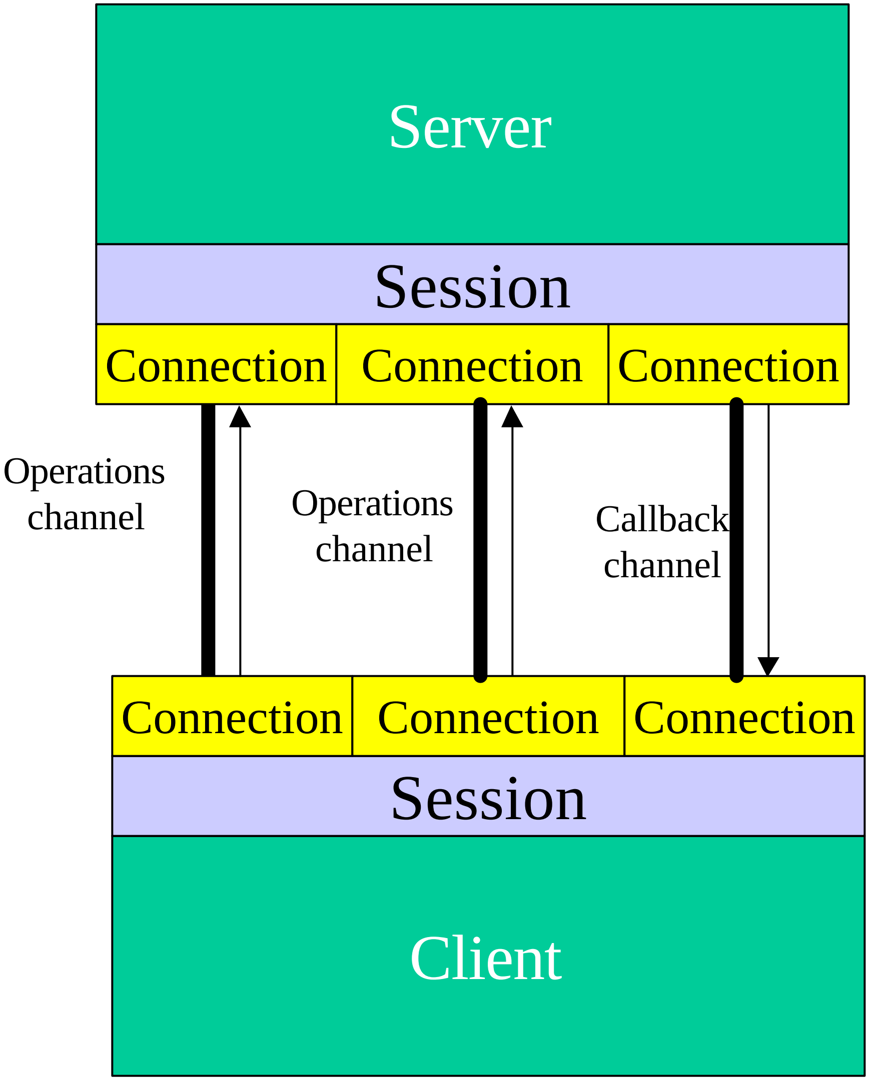
Example Session – multiple connections



Example Session – single connection

- Resource-friendly
- Firewall-friendly
- No performance impact
- Isn't this the way callbacks should have been spec'ed?

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Exactly-Once Semantics

- Highly desirable, but never achievable
- Need flow control (N) , operation sizing (M) in order to support RDMA
- Flow control provides an “ack window”
  - Use this to retire response cache entries
- N * M = response cache size
- Session provides accounting and storage
- Done!

Streamid

- A per-operation identifier in the range 0..N-1 of server's current flow control
  - In effect, an index into an array of legal in-progress ops
- Highly efficient processing – no lookup
- Used in conjunction with RPC transaction id to maintain duplicate request cache

Chaining

- Problem: COMPOUND restricted in length at session negotiation
- Chaining provides strict sequencing of requests
  - "compound for compounds"
- Start, middle, end flags (and none)
- Maintains current and saved filehandles like COMPOUND

Connection model and negotiation

- Simplest form – no session at all
- Session binding enables use of RDMA
  - Per-channel (connection) RDMA mode
  - Mix TCP and RDMA channels per-client!
- TCP mode if either RDMA mode is off
- Dynamic enabling of RDMA at session binding
  - After RDMA mode, sizes, credits, etc exchanged
- Statically enabled RDMA (e.g. Infiniband) also supported
  - Requires preposted buffer

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V4 Protocol integration

- Piggyback on existing COMPOUND
- New OPERATION_CONTROL first in each session COMPOUND request and reply
- Conveys channelid, streamid, and chaining

Tag	Minor (==1)	numops	Operation_Control	Operations…

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V4 efficiencies

- No need for sequenceid
  - Field will stay, but ignored under a session
- No need for clientid per-op
  - Clientid may be provided as zero
- Each request within session renews leases
- OPEN_CONFIRM not needed
- CCM is enabled