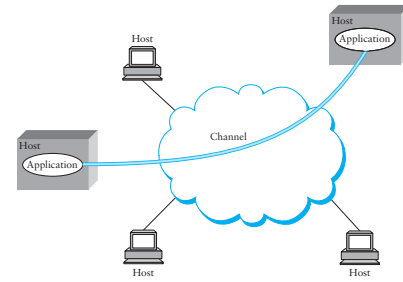


## Outline

- 1 Networking overview
- 2 Systems issues
- 3 Implementing networking in the kernel
- 4 Network file systems

1 / 47

## Computer networking



- Goal: two applications on different computers exchange data
- Requires inter-process (not just inter-node) communication

2 / 47

## The 7-Layer and 4-Layer Models

	OSI	TCP/IP
7	Application	Applications (FTP, SMTP, HTTP, etc.)
6	Presentation	
5	Session	
4	Transport	TCP (host-to-host)
3	Network	IP
2	Data link	Network access (usually Ethernet)
1	Physical	

3 / 47

## Link Layer: Ethernet

- Originally designed for shared medium (coax), now generally not shared medium (switched)
- Vendors give each device a unique 48-bit MAC address
  - Specifies which card should receive a packet
- Ethernet switches can scale to switch local area networks (thousands of hosts), but not much larger

- Packet format:
 

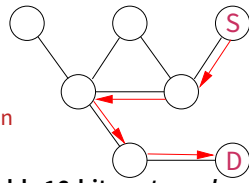
Preamble	Dest addr	Src addr	Type	Body	CRC
----------	-----------	----------	------	------	-----

  - Preamble helps device recognize start of packet
  - CRC allows receiving card to ignore corrupted packets
  - Body up to 1,500 bytes for same destination
  - All fields besides preamble/CRC must be set by sender's OS (NIC cards tell the OS what the card's MAC address is, Special addresses used for broadcast/multicast)

4 / 47

## Network Layer: Internet Protocol (IP)

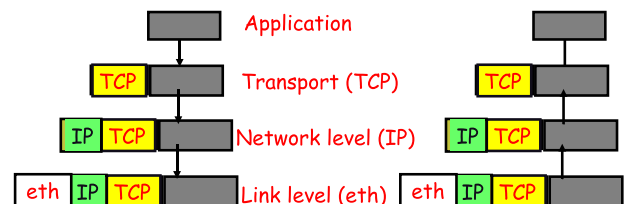
- IP used to connect multiple networks
  - Runs over a variety of physical networks—Ethernet, DSL, 5G
- Every host has a unique 4-byte IP address (16-bytes for IPv6)
  - (Or at least thinks it has, when there is address shortage)
- Packets are **routed** based on destination IP address
  - Address space is structured to make routing practical at global scale
  - E.g., 171.66.\*.\* goes to Stanford
  - So packets need IP addresses in addition to MAC addresses
- Inside IP: UDP or TCP transport layer adds 16-bit port number
  - UDP – unreliable datagram protocol, exposes lost/reordered/delayed (but typically not corrupted) packets
  - TCP – transmission control protocol  $\approx$  reliable pipe



5 / 47

## Principle: Encapsulation

- Stick packets inside packets
- How you realize packet switching and layering in a system
  - E.g., an Ethernet packet may encapsulate an IP packet
  - An IP router forwards a packet from one Ethernet to another, creating a new Ethernet packet containing the same IP packet
  - In principle, an inner layer should not depend on outer layers (not always true)



6 / 47

## Outline

- 1 Networking overview
- 2 Systems issues
- 3 Implementing networking in the kernel
- 4 Network file systems

7 / 47

## Unreliability of IP

- **Network does not deliver packets reliably**
  - May drop, reorder, delay, corrupt, duplicate packets
- **OS must implement reliable TCP on top of IP**
- **Straw man: Wait for ack for each packet**
  - Send a packet, wait for acknowledgment, send next packet
  - If no ack, timeout and try again
- **Problems?**

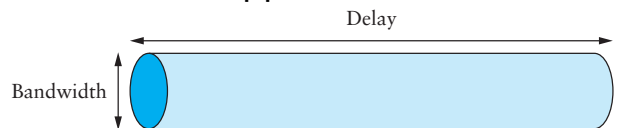
8 / 47

## Unreliability of IP

- **Network does not deliver packets reliably**
  - May drop, reorder, delay, corrupt, duplicate packets
- **OS must implement reliable TCP on top of IP**
- **Straw man: Wait for ack for each packet**
  - Send a packet, wait for acknowledgment, send next packet
  - If no ack, timeout and try again
- **Problems:**
  - Low performance over high-delay network (bandwidth is one packet per round-trip time)
  - Possible congestive collapse of network (if everyone keeps retransmitting when network overloaded)

8 / 47

## Performance: Bandwidth-delay

- **Network delay over WAN will never improve much**
  - **But throughput (bits/sec) is constantly improving**
  - **Can view network as a pipe**
- 
- For full utilization want # bytes in flight  $\geq$  bandwidth  $\times$  delay (But don't want to overload the network, either)
  - **What if protocol doesn't involve bulk transfer?**
    - E.g., ping-pong protocol will have poor throughput
  - **Another implication: Concurrency & response time critical for good network utilization**

9 / 47

## A little bit about TCP

- **Want to save network from congestion collapse**
  - Packet loss usually means congestion, so back off exponentially
- **Want multiple outstanding packets at a time**
  - Get transmit rate up to  $n$ -packet window per round-trip
- **Must figure out appropriate value of  $n$  for network**
  - Slowly increase transmission by one packet per acked window
  - When a packet is lost, cut window size in half
- **Connection set up and teardown complicated**
  - Sender never knows when last packet might be lost
  - Must keep state around for a while (2MSL, e.g., 4 min) after close
- **Lots more hacks required for good performance, robustness**
  - Initially ramp  $n$  up faster (but too fast caused collapse in 1986 [Jacobson], so TCP had to be changed)
  - Fast retransmit when single packet lost

10 / 47

## Lots of OS issues for TCP

- **Have to track unacknowledged data**
  - Keep a copy around until recipient acknowledges it
  - Keep timer around to retransmit if no ack
  - Receiver must keep out of order segments & reassemble
- **When to wake process receiving data?**
  - E.g., sender calls `write (fd, message, 8000)`;
  - First TCP segment arrives, but is only 512 bytes
  - Could wake recipient, but useless w/o full message
  - TCP sets "PUSH" bit at end of 8000 byte write data
- **When to send short segment, vs. wait for more data**
  - Usually send only one unacked short segment
  - But bad for some apps, so provide `NODELAY` option
- **Must ack received segments very quickly**
  - Otherwise, effectively increases RTT, decreasing bandwidth

11 / 47

## Outline

- 1 Networking overview
- 2 Systems issues
- 3 Implementing networking in the kernel
- 4 Network file systems

12 / 47

## Sockets

- Sockets  $\approx$  bi-directional pipes
- Name endpoints by IP address and 16-bit *port number*
- A *connection* is thus named by 5 components
  - Protocol (TCP), local IP, local port, remote IP, remote port
  - Note TCP requires connected sockets, while UDP does not
- Kernel stores connection state in a *protocol control block structure (PCB)*
  - Keep all PCB's in a hash table
  - When packet arrives (if destination IP address belongs to host), use 5-tuple to find PCB and determine what to do with packet

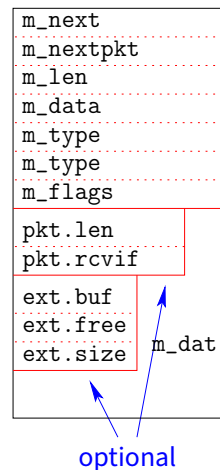
13 / 47

## Socket implementation

- Need to implement layering efficiently
  - Add UDP header to data, Add IP header to UDP packet, ...
  - De-encapsulate Ethernet packet so IP code doesn't get confused by Ethernet header
- Don't store packets in contiguous memory
  - Moving data to make room for new header would be slow
- BSD solution: mbufs [Leffler]  
(Note [Leffler] calls `m_nextpkt` by old name `m_act`)
  - Small, fixed-size (256 byte) structures
  - Makes allocation/deallocation easy (no fragmentation)
- BSD Mbufs working example for this lecture
  - Linux uses `sk_buffs`, which are similar idea

14 / 47

## mbuf details



- Packets made up of multiple mbufs
  - Chained together by `m_next`
  - Such linked mbufs called *chains*
- Chains linked with `m_nextpkt`
  - Linked chains known as *queues*
  - E.g., device output queue
- Total mbuf size 256 B  $\Rightarrow$   $\sim$ 230 data bytes (depends on size of pointers)
  - First in chain has `pkt` header
- Cluster mbufs have more data
  - `ext` header points to data
  - Up to 2 KB not collocated with mbuf
  - `m_dat` not used
- `m_flags` is bitwise or of various bits
  - E.g., if cluster, or if `pkt` header used

15 / 47

## Adding/deleting data with mbufs

- `m_data` always points to start of data
  - Can be `m_dat`, or `ext.buf` for cluster mbuf
  - Or can point into middle of that area
- To strip off a packet header (e.g., TCP/IP)
  - Increment `m_data`, decrement `m_len`
- To strip off end of packet
  - Decrement `m_len`
- Can add data to mbuf if buffer not full
- Otherwise, add data to chain
  - Chain new mbuf at head/tail of existing chain

16 / 47

## mbuf utility functions

- `mbuf *m_copym(mbuf *m, int off, int len, int wait);`
  - Creates a copy of a subset of an mbuf chain
  - Doesn't copy clusters, just increments reference count
  - `wait` says what to do if no memory (`wait` or return `NULL`)
- `void m_adj(struct mbuf *mp, int len);`
  - Trim `|len|` bytes from head or (if negative) tail of chain
- `mbuf *m_pullup(struct mbuf *n, int len);`
  - Put first `len` bytes of chain contiguously into first mbuf
- Example: Ethernet packet containing IP datagram
  - Trim Ethernet header using `m_adj`
  - Call `m_pullup (n, sizeof (ip_hdr));`
  - Access IP header as regular C data structure

17 / 47

## Socket implementation

- Each socket fd has associated socket structure with:
  - Send and receive buffers
  - Queues of incoming connections (on listen socket)
  - A *protocol control block* (PCB)
  - A *protocol handle* (`struct protosw *`)
- PCB contains protocol-specific info. E.g., for TCP:
  - 5-tuple of protocol (TCP), source/destination IP address and port
  - Information about received packets & position in stream
  - Information about unacknowledged sent packets
  - Information about timeouts
  - Information about connection state (setup/teardown)

18 / 47

## protosw structure

- Goal: abstract away differences between protocols
  - In C++, might use virtual functions on a generic socket struct
  - Here just put function pointers in `protosw` structure
- Also includes a few data fields
  - *domain, type, protocol* – to match `socket` syscall args, so know which `protosw` to select
  - *flags* – to specify important properties of protocol
- Some protocol flags:
  - `ATOMIC` – exchange atomic messages only (like UDP, not TCP)
  - `ADDR` – address given with messages (like unconnected UDP)
  - `CONNREQUIRED` – requires connection (like TCP)
  - `WANTRCVD` – notify socket of consumed data (e.g., so TCP can wake up a sending process blocked by flow control)

19 / 47

## protosw functions

- `pr_slowtimo` – called every 1/2 sec for timeout processing
- `pr_drain` – called when system low on space
- `pr_input` – returns mbuf chain of data read from socket
- `pr_output` – takes mbuf chain of data written to socket
- `pr_usrreq` – multi-purpose user-request hook
  - Used for bind/listen/accept/connect/disconnect operations
  - Used for out-of-band data

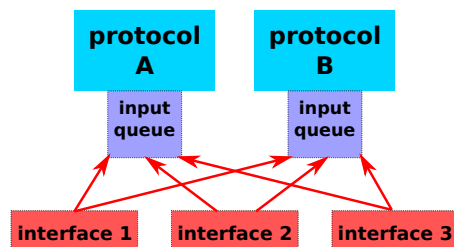
20 / 47

## Network interface cards

- Each NIC driver provides an `ifnet` data structure
  - Like `protosw`, tries to abstract away the details
- Data fields:
  - Interface name (e.g., “eth0”)
  - Address list (e.g., Ethernet address, broadcast address, ...)
  - Maximum packet size
  - Send queue
- Function pointers
  - `if_output` – prepend header and enqueue packet
  - `if_start` – start transmitting queued packets
  - Also `ioctl`, timeout, initialize, reset

21 / 47

## Input handling



- NIC driver figures out protocol of incoming packet
- Enqueues packet for appropriate protocol handler
  - If queue full, drop packet (can create livelock [Mogul])
- Posts “soft interrupt” for protocol-layer processing
  - Runs at lower priority than hardware (NIC) interrupt ... but higher priority than process-context kernel code

22 / 47

## Routing

- An OS must route all transmitted packets
  - Machine may have multiple NICs plus “loopback” interface
  - Which interface should a packet be sent to, and what MAC address should packet have?
- Routing is based purely on the destination address
  - Even if host has multiple NICs w. different IP addresses
  - (Linux *rules* let you select among routing tables by source IP)
- OS maintains routing table
  - Maps IP address & prefix-length → next hop
- Use radix tree for efficient lookup
  - Branch at each node in tree based on single bit of target
  - When you reach leaf, that is your next hop
- Most OSes provide packet forwarding
  - Received packets for non-local address routed out another interface

23 / 47

## Outline

- 1 Networking overview
- 2 Systems issues
- 3 Implementing networking in the kernel
- 4 **Network file systems**

24 / 47

## Network file systems

- **What's a network file system?**
  - Looks like a file system (e.g., FFS) to applications
  - But data potentially stored on another machine
  - Reads and writes must go over the network
  - Also called distributed file systems
- **Advantages of network file systems**
  - Easy to share if files available on multiple machines
  - Often easier to administer servers than clients
  - Access way more data than fits on your local disk
  - Network + remote buffer cache faster than local disk
- **Disadvantages**
  - Network + remote disk slower than local disk
  - Network or server may fail even when client OK
  - Complexity, security issues

25 / 47

## NFS version 2 [Sandberg]

- **Background: ND (networked disk)**
  - Creates disk-like device even on diskless workstations
  - Can create a regular (e.g., FFS) file system on it
  - But no sharing—Why?
- **ND idea still used today by Linux NBD**
  - Useful for network booting/diskless machines, not file sharing
- **Some Goals of NFS**
  - Access same FS from multiple machines simultaneously
  - Maintain Unix semantics
  - Crash recovery
  - Competitive performance with ND
- **NFS version 2 protocol specified in [RFC 1094]**

26 / 47

## NFS version 2 [Sandberg]

- **Background: ND (networked disk)**
  - Creates disk-like device even on diskless workstations
  - Can create a regular (e.g., FFS) file system on it
  - But no sharing—Why?
  - FFS assumes disk doesn't change under it
- **ND idea still used today by Linux NBD**
  - Useful for network booting/diskless machines, not file sharing
- **Some Goals of NFS**
  - Access same FS from multiple machines simultaneously
  - Maintain Unix semantics
  - Crash recovery
  - Competitive performance with ND
- **NFS version 2 protocol specified in [RFC 1094]**

26 / 47

## NFS implementation

- **Virtualized the file system with *vnodes***
  - Ersatz virtual functions/interface/trait (like `protosw`)
- **Vnode structure represents an open (or openable) file**
- **Bunch of generic “vnode operations”:**
  - lookup, create, open, close, getattr, setattr, read, write, fsync, remove, link, rename, mkdir, rmdir, symlink, readdir, readlink, ...
  - Called through function pointers, so most system calls don't care what type of file system a file resides on
- **NFS vnode operations perform *Remote Procedure Calls (RPC)***
  - Client sends request to server over network, awaits response
  - Each system call may require a series of RPCs
  - **System mostly determined by RPC [RFC 1831] Protocol**
  - Uses XDR protocol specification language [RFC 1832]

27 / 47

## Stateless operation

- **Designed for “stateless operation”**
  - Motivated by need to recover from server crashes
- **Requests are self-contained**
- **Requests are idempotent**
  - Unreliable UDP transport
  - Client retransmits requests until it gets a reply
  - Writes must be stable before server returns
- **Can this really work?**

28 / 47

## Stateless operation

- **Designed for “stateless operation”**
  - Motivated by need to recover from server crashes
- **Requests are self-contained**
- **Requests are <sup>mostly</sup> idempotent**
  - Unreliable UDP transport
  - Client retransmits requests until it gets a reply
  - Writes must be stable before server returns
- **Can this really work?**
  - Of course, FS not stateless – it stores files
  - E.g., *mkdir* can't be idempotent – second time dir exists
  - But many operations, e.g., *read*, *write* are idempotent
  - Importantly, server doesn't track open files, so reboot doesn't invalidate any file descriptors on clients

28 / 47

## NFS version 3

- **Same general architecture as NFS 2**
- **Specified in RFC 1813 (subset of Open Group spec)**
  - XDR defines C structures that can be sent over network; includes tagged unions (to know which union field active)
  - Protocol defined as a set of Remote Procedure Calls (RPCs)
- **New access RPC**
  - Supports clients and servers with different uids/gids
- **Better support for caching**
  - Unstable writes while data still cached at client
  - More information for cache consistency
- **Better support for exclusive file creation**

29 / 47

## NFSv3 File handles

```
struct nfs_fh3 {
    /* XDR notation for variable-length array
     * with 0-64 opaque bytes: */
    opaque data<64>;
};
```

- **Server assigns an opaque file handle to each file**
  - Client obtains first file handle out-of-band (mount protocol)
  - File handle hard to guess – security enforced at mount time
  - Subsequent file handles obtained through lookups
- **File handle internally specifies file system & file**
  - Device number, i-number, *generation number*, ...
  - Generation number changes when inode recycled
- **Handle generally *doesn't* contain filename**
  - Clients may keep accessing an open file after it's renamed

30 / 47

## File attributes

```
struct fattr3 {
    ftype3 type;
    uint32 mode;
    uint32 nlink;
    uint32 uid;
    uint32 gid;
    uint64 size;
    uint64 used;
    specdata3 rdev;
    uint64 fsid;
    uint64 fileid;
    nfstime3 atime;
    nfstime3 mtime;
    nfstime3 ctime;
};
```

- **Most operations can optionally return `fattr3`**
- **Attributes used for cache-consistency**

31 / 47

## Lookup

```
struct diropargs3 {
    nfs_fh3 dir;
    filename3 name;
};

struct lookup3resok {
    nfs_fh3 object;
    post_op_attr obj_attributes;
    post_op_attr dir_attributes;
};
```

```
union lookup3res switch (nfsstat3 status) {
case NFS3_OK:
    lookup3resok resok;
default:
    post_op_attr resfail;
};
```

- **Maps (directory handle, filename) → handle**
  - Client walks hierarchy one file at a time
  - No symlinks expanded or file system boundaries crossed
  - Client must expand symlinks

32 / 47

## Create

```
struct create3args {
    diropargs3 where;
    createhow3 how;
};

union createhow3 switch (createmode3 mode) {
case UNCHECKED:
case GUARDED:
    sattr3 obj_attributes;
case EXCLUSIVE:
    createverf3 verf;
};
```

- **UNCHECKED – succeed if file exists**
- **GUARDED – fail if file exists**
- **EXCLUSIVE – persistent record of create**

33 / 47

## Read

```
struct read3args {
    nfs_fh3 file;
    uint64 offset;
    uint32 count;
};

struct read3resok {
    post_op_attr file_attributes;
    uint32 count;
    bool eof;
    opaque data<>;
};

union read3res switch (nfsstat3 status) {
    case NFS3_OK:
        read3resok resok;
    default:
        post_op_attr resfail;
};
```

- Offset explicitly specified (not implicit in handle)
- Client can cache result

34 / 47

## Data caching

- Client can cache blocks of data read and written
- Consistency based on times in `fattnr3`
  - **mtime**: Time of last modification to file
  - **ctime**: Time of last change to inode (Changed by explicitly setting mtime, increasing size of file, changing permissions, etc.)
- Algorithm: If mtime or ctime changed by another client, flush cached file blocks

35 / 47

## Write discussion

- When is it okay to lose data after a crash?
  - Local file system?

36 / 47

## Write discussion

- When is it okay to lose data after a crash?
  - Local file system?  
If no calls to `fsync`, OK to lose 30 seconds of work after crash
  - Network file system?

36 / 47

## Write discussion

- When is it okay to lose data after a crash?
  - Local file system?  
If no calls to `fsync`, OK to lose 30 seconds of work after crash
  - Network file system?  
What if server crashes but not client?  
Application not killed, so shouldn't lose previous writes
- NFSv2 addresses problem by having server write data to disk before replying to a write RPC
  - Caused performance problems
- Could NFS2 clients just perform write-behind?
  - Implementation issues – used blocking kernel threads on write
  - Semantics – how to guarantee consistency after server crash
  - Solution: small # of pending write RPCs, but write through on close; if server crashes, client keeps re-writing until acked

36 / 47

## NFSv2 write call

```
struct writeargs {
    fhandle file;
    /* ... */
    unsigned offset;
    /* ... */
    nfsdata data;
};

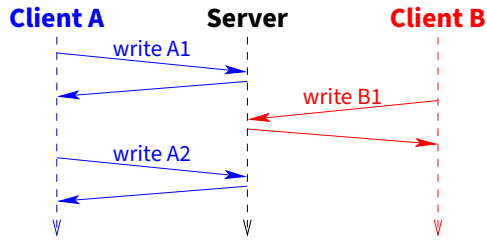
union attrstat switch (stat status) {
    case NFS_OK:
        fattnr attributes;
    default:
        void;
};

attrstat NFSPROC_WRITE(writeargs) = 8;
```

- On successful write, returns new file attributes
- Can NFSv2 keep cached copy of file after writing it?

37 / 47

## Write race condition



- Suppose client overwrites 2-block file
  - Client A knows attributes of file after writes A1 & A2
  - But client B could overwrite block 1 between the A1 & A2
  - No way for client A to know this hasn't happened
  - Must flush cache before next file read (or at least open)

38 / 47

## NFSv3 Write arguments

```
struct write3args {
    nfs_fh3 file;
    uint64 offset;
    uint32 count;
    stable_how stable;
    opaque data<>;
};

enum stable_how {
    UNSTABLE = 0,
    DATA_SYNC = 1,
    FILE_SYNC = 2
};
```

- Two goals for NFSv3 write:
  - Don't force clients to flush cache after writes
  - Don't equate *cache* consistency with *crash* consistency  
I.e., don't wait for disk just so another client can see data

39 / 47

## Write results

```
struct write3resok {
    wcc_data file_wcc;
    uint32 count;
    stable_how committed;
    writeverf3 verf;
};

union write3res
    switch (nfsstat3 status) {
case NFS3_OK:
    write3resok resok;
default:
    wcc_data resfail;
};
```

```
struct wcc_attr {
    uint64 size;
    nfstime3 mtime;
    nfstime3 ctime;
};

struct wcc_data {
    wcc_attr *before;
    post_op_attr after;
};
```

- Several fields added to achieve these goals

40 / 47

## Data caching after a write

- Write will change mtime/ctime of a file
  - "after" will contain new times
  - With NFSv2, would require cache to be flushed
- With NFSv3, "before" contains previous values
  - If before matches cached values, no other client has changed file
  - Okay to update attributes without flushing data cache

41 / 47

## Write stability

- Server write must be at least as stable as requested
- If server returns write UNSTABLE
  - Means permissions okay, enough free disk space, ...
  - But data not on disk and might disappear (after crash)
- If DATA\_SYNC, data on disk, maybe not attributes
- If FILE\_SYNC, operation complete and stable

42 / 47

## Commit operation

- Client cannot discard any UNSTABLE write
  - If server crashes, data will be lost
- COMMIT RPC commits a range of a file to disk
  - Invoked by client when client cleaning buffer cache
  - Invoked by client when user closes/flushes a file
- How does client know if server crashed?
  - Write and commit return writeverf3
  - Value changes after each server crash (can be boot time)
  - Client must resend all writes if verf value changes

43 / 47

## Attribute caching

- **Close-to-open consistency**
  - Annoying if writes not visible after a file close (Edit file, compile on another machine, get old version)
  - Nowadays, all NFS opens fetch attributes from server
- **Still, lots of other need for attributes (e.g., `ls -al`)**
- **Attributes cached between 5 and 60 seconds**
  - Files recently changed more likely to change again
  - Do weighted cache expiration based on age of file
- **Drawbacks:**
  - Must pay for round-trip to server on every file open
  - Can get stale info when `stat`ting a file

44 / 47

## NFS version 4 [RFC 3530]

- **Much more complicated than version 3**
  - NFS2: 27 page spec, NFS3: 126 pages, NFS4: 275 pages, NFS4.1: 617 pages
- **Designed to run over higher-latency networks**
  - Support for multi-component lookups to save RTTs
  - Support for batching multiple operations in one RPC
  - Support for leases (in two slides) and stateful (open, close) operation
- **Designed to be more generic and less Unix-specific**
  - E.g., support for extended file attributes, etc.
- **Lots of security stuff**
- **NFS 4.1 [RFC5661] has better support for NAS**
  - Store file data and metadata in different places

45 / 47

## Callbacks

- **NFSv2 and v3 poll server for cache consistency**
  - Client requests attributes (via ACCESS) when file opened
  - Attributes validate or invalidate cached copy of file
- **Alternative: Server calls back to clients caching file (AFS)**
  - Invalidate immediately, rather than when cache needed
  - Requires server to maintain list of all clients caching info
- **Advantages**
  - Tight consistency, 0 RTT opens of cached files
- **Disadvantages**
  - Server must maintain a lot of state
  - Updates potentially slow
    - Must persistently record who is caching things on server
    - Must wait for  $n$  clients to acknowledge invalidations
  - When a client goes down, other clients will block

46 / 47

## Leases

- **Hybrid mix of polling and callbacks**
  - Server agrees to notify client of changes for a limited period of time – the lease term
  - After the lease expires, client must poll for freshness
- **Avoids paying for a server round trip in many cases**
- **Server doesn't need to keep long-term track of callbacks**
  - E.g., lease time can be shorter than crash-reboot—no need to keep callbacks persistently
- **If client crashes, resume normal operation after lease expiration**

47 / 47