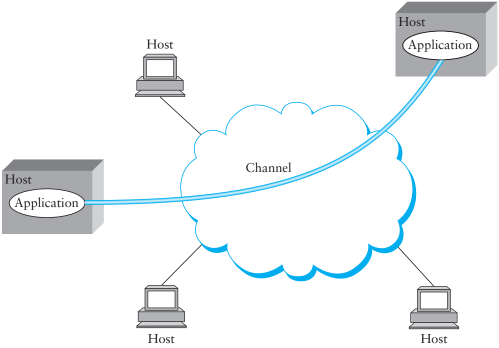
Outline

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

Computer networking



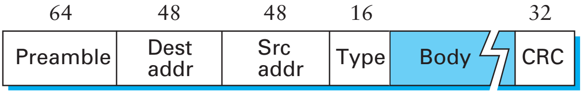
- **Goal: two applications on different computers exchange data**
- **Requires inter-process (not just inter-node) communication**

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	

Link Layer: Ethernet

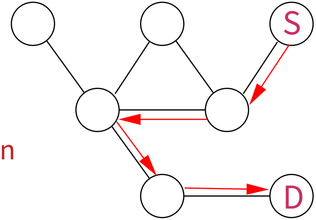
- **Originally designed for shared medium (coax), now generally not shared medium (switched)**
- **Vendors give each device a unique 48-bit *MAC address***
  - Specifies which card should receive a packet
- **Ethernet switches can scale to switch local area networks (thousands of hosts), but not much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



  - Preamble helps device recognize start of packet
  - CRC allows receiving card to ignore corrupted packets
  - Body up to 1,500 bytes for same destination
  - All other fields 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)

Network Layer: Internet Protocol (IP)

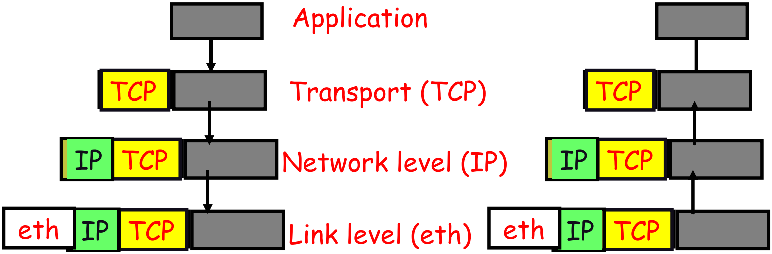
- **IP used to connect multiple networks**
  - Runs over a variety of physical networks—Ethernet, DSL, 5G
- **Every host has a unique 4-byte IP address (16-bytes for IPv6)**
  - (Or at least thinks it has, when there is address shortage)
- **Packets are *routed* based on destination IP address**
  - 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

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)



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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?**

Unreliability of IP

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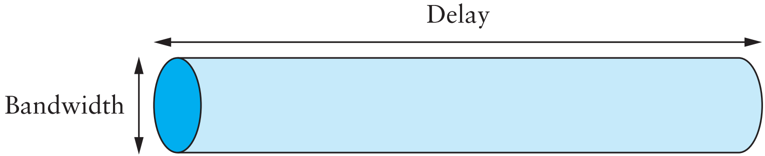
- **Straw man: Wait for ack for each packet**
  - Send a packet, wait for acknowledgment, send next packet
  - If no ack, timeout and try again
- **Problems:**
  - Low performance over high-delay network
    (bandwidth is one packet per round-trip time)
  - Possible congestive collapse of network
    (if everyone keeps retransmitting when network overloaded)

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**

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**
  - 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

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

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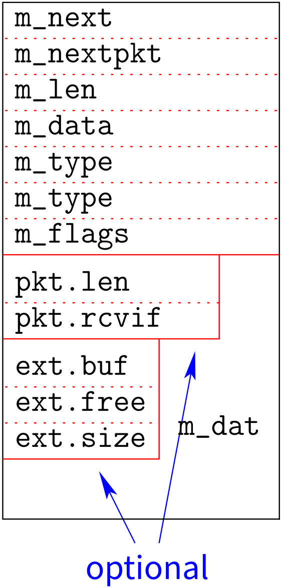
Sockets

- **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

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

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

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

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

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)

`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)

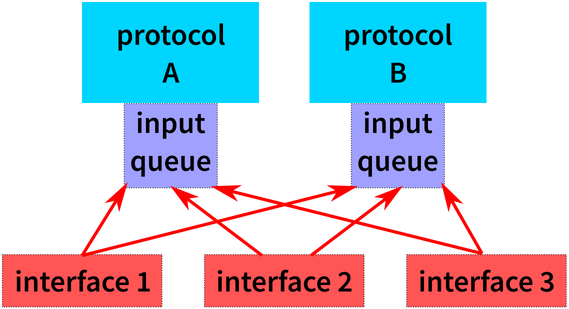
protosw functions

- 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

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

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

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
  - (Though linux lets you select a routing table by source IP)
- **OS maintains routing table**
  - Maps IP address & prefix-length $\rightarrow$ 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

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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

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]**

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  - 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
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  - Maintain Unix semantics
  - Crash recovery
  - Competitive performance with ND
- **NFS version 2 protocol specified in [RFC 1094]**

NFS implementation

- **Virtualized the file system with *vnodes***
  - Basically poor man's C++ (like `protosw` struct)
- **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]

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?**

Stateless operation

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- **Requests are self-contained**
- **Requests are** *mostly* **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

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**

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

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**

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** $\langle$directory handle, filename$\rangle \rightarrow$ handle
  - Client walks hierarchy one file at a time
  - No symlinks expanded or file system boundaries crossed
  - Client must expand symlinks

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**

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**

Data caching

- **Client can cache blocks of data read and written**
- **Consistency based on times in** `fattr3`
  - 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**

Write discussion

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

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  - *Local file system?*
    If no calls to *fsync*, OK to lose 30 seconds of work after crash
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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

NFSv2 write call

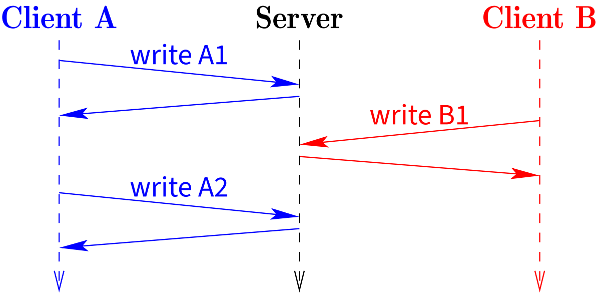
```
struct writeargs {
  fhandle file;
  /* ... */
  unsigned offset;
  /* ... */
  nfsdata data;
};
```

```
union attrstat
    switch (stat status) {
case NFS_OK:
  fattr 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?**

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)

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

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**

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

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**

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

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

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

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**
  - 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

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**