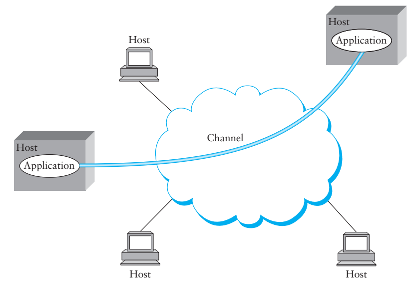
## Outline

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



## Computer networking




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

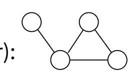


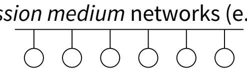
## The 7-Layer and 4-Layer Models

| | 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 | |



## Physical Layer

- **Computers send bits over physical *links***
  - E.g., Coax, twisted pair, fiber, radio, ...
  - Bits may be encoded as multiple lower-level "chips"
- **Two categories of physical links**
  - *Point-to-point* networks (e.g., fiber, twisted pair): 
  - *Shared transmission medium* networks (e.g., coax, radio):

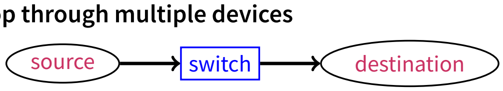
    - Any message can be seen by all nodes
    - Allows broadcast/multicast, but introduces contention
- **One important constraint: speed of light**
  - $\sim 300,000\ \mathrm{km/sec}$ in a vacum, slower in fiber

    SF $\xrightarrow{\geq \sim 15\ \mathrm{msec}}$ NYC    Moore's law does not apply!



## Link Layer, Indirect Connectivity

- **When no direct physical connection to destination**
- **Hop through multiple devices**

  - Allows links and devices to be shared for multiple purposes
  - Must determine which bits are part of which messages intended for which destinations
- ***Packet switched* networks**
  - Pack a bunch of bytes together intended for same destination
  - Slap a *header* on packet describing where it should go



## Link Layer: Ethernet

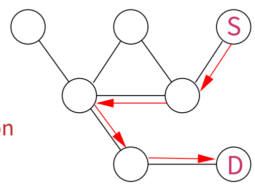
- **Originally designed for shared medium (coax), now generally not shared medium (switched)**
- **Vendors give each device a unique 48-bit *MAC address***
  - Specifies which card should receive a packet
- **Ethernet switches can scale to switch local area networks (thousands of hosts), but not much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

| 64 | 48 | 48 | 16 | | 32 |
|---|---|---|---|---|---|
| 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 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
  - Hence can connect Ethernet, DSL, mobile networks, etc.
  - Most computers today speak IP
- **Every host has a unique 4-byte IP address (16-bytes for IPv6)**
  - (Or at least thinks it has, when there is address shortage)
  - E.g., www.ietf.org → 104.20.0.85
- **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






## UDP and TCP

- **UDP and TCP most popular protocols on IP**
  - Both use 16-bit *port* number as well as 32-bit IP address
  - Applications *bind* a port & receive traffic to that port
- **UDP – unreliable datagram protocol**
  - Exposes packet-switched nature of Internet
  - Sent packets may be dropped, reordered, even duplicated (but generally not corrupted)
- **TCP – transmission control protocol**
  - Provides illusion of a reliable "pipe" between two processes on two different machines
  - Masks lost & reordered packets so apps don't have to worry
  - Handles congestion & flow control



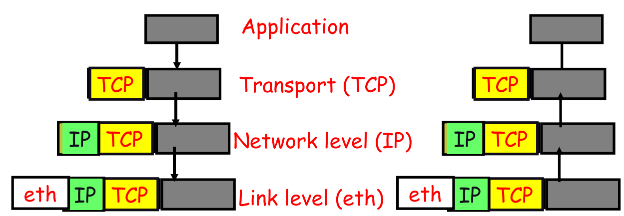
## Principles: Packet Switching & Layering

- **Packet switching**
  - A *packet* is a self contained unit of data which contains information necessary for it to reach its destination
  - Independently, for each arriving packet, compute its outgoing link
  - Makes forwarding simple (depends only on packet)
- **Layering**
  - Break system functionality into a hierarchy of layers
  - Each layer uses only the service of the layer below it
  - Layers communicate sequentially with the layers above or below



## 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 packets, reorder packets, delay packets
  - May even corrupt packets, or duplicate them
- **How to implement reliable TCP on top of IP network?**
  - Note: This is entirely the job of the OS at the end nodes
- **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?**

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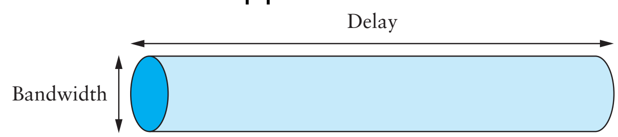
- **Straw man: Wait for ack for each packet**
  - Send a packet, wait for acknowledgment, send next packet
  - If no ack, timeout and try again
- **Problems:**
  - Low performance over high-delay network (bandwidth is one packet per round-trip time)
  - Possible congestive collapse of network (if everyone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

- **Abstraction for communication between machines**
- **Datagram sockets: Unreliable message delivery**
  - With IP, gives you UDP
  - Send atomic messages, which may be reordered or lost
  - Special system calls to read/write: `send`/`recv`
- **Stream sockets: Bi-directional pipes**
  - With IP, gives you TCP
  - Bytes written on one end read on the other
  - Reads may not return full amount requested—must re-read

## Socket naming

- **TCP & UDP name communication endpoints by**
  - E.g., 32-bit IPv4 address specifies machine (128 bits for IPv6)
  - 16-bit TCP/UDP port number demultiplexes within host
- **A *connection* is thus named by 5 components**
  - Protocol (TCP), local IP, local port, remote IP, remote port
  - TCP requires connected sockets, but not UDP
- **OS keeps connection state in protocol control block (PCB) structure**
  - 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



## System calls for using TCP

| **Client** | **Server** |
|---|---|
| | `socket` – make socket |
| | `bind` – assign address |
| | `listen` – listen for clients |
| `socket` – make socket | |
| `bind`* – assign address | |
| `connect` – connect to listening socket | |
| | `accept` – accept connection |

*This call to `bind` is optional; `connect` can choose address & port.



## Using UDP

- **Call `socket` with `SOCK_DGRAM`, `bind` as before**
- **New system calls for sending individual packets**
  - `int sendto(int s, const void *msg, int len, int flags, const struct sockaddr *to, socklen_t tolen);`
  - `int recvfrom(int s, void *buf, int len, int flags, struct sockaddr *from, socklen_t *fromlen);`
  - Must send/get peer address with each packet
- **Can use UDP in connected mode**
  - `connect` assigns remote address
  - `send`/`recv` syscalls, like `sendto`/`recvfrom` w/o last 2 args



## Uses of connected UDP sockets

- **Kernel demultplexes packets based on port**
  - Allows different processes getting packets from different peers
  - For security, ports $<$ 1024 usually can't be bound
  - But can safely inherit UDP port below that connected to one particular peer
- **Feedback based on ICMP messages**
  - Say no process has bound UDP port you sent packet to...
  - With `sendto`, you might think network dropping packets
  - Server sends port unreachable message, but only detect it when using connected sockets



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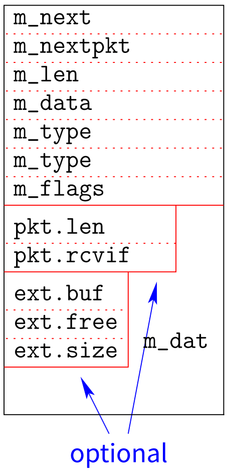
## Socket implementation

- **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 ⇒ ∼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:**
  - Pointer to IP TCB with 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**
  - *type, domain, 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

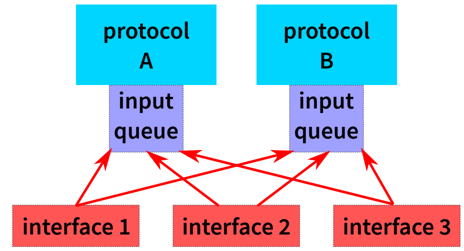
- `pr_slowtimo` – **called every 1/2 sec for timeout processing**
- `pr_drain` – **called when system low on space**
- `pr_input` – **returns mbuf chain of data read from socket**
- `pr_output` – **takes mbuf chain of data written to socket**
- `pr_usrreq` – **multi-purpose user-request hook**
  - Used 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 OSes have features to redirect based on 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



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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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  - But no sharing—Why?
  - FFS assumes disk doesn't change under it
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  - Competitive performance with ND
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## 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

- **Designed for "stateless operation"**
  - Motivated by need to recover from server crashes
- **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 {              specdata3 rdev;
  ftype3 type;               uint64 fsid;
  uint32 mode;               uint64 fileid;
  uint32 nlink;              nfstime3 atime;
  uint32 uid;                nfstime3 mtime;
  uint32 gid;                nfstime3 ctime;
  uint64 size;             };
  uint64 used;
```

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



## Lookup

```
struct diropargs3 {       struct lookup3resok {
  nfs_fh3 dir;              nfs_fh3 object;
  filename3 name;           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 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 {   struct read3resok {
  nfs_fh3 file;        post_op_attr file_attributes;
  uint64 offset;       uint32 count;
  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?**
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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 beginoffset;
  unsigned offset;
  unsigned totalcount;
  nfsdata data;
};
```

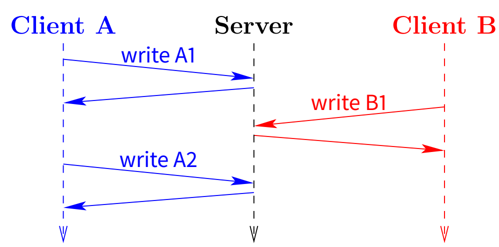
```
union attrstat
    switch (stat status) {
case NFS_OK:
  fattr attributes;
default:
  void;
};
```

```
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