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

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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
- \( \sim 300,000 \text{ km/sec} \) in a vacuum, slower in fiber
- \( SF \geq \sim 15 \text{ msec} \) → 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:
- 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 $\rightarrow$ 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

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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?
**Unreliability of IP**

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  - 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

\[\text{Bandwidth} \times \text{Delay} = \text{Bandwidth-delay} \]

- For full utilization want \( \# \text{bytes in flight} \geq \text{bandwidth} \times \text{delay} \)
  (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 `SOMEBODY` 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/receive`
- 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**

```bash
socket – make socket
bind – assign address
listen – listen for clients
```

**Server**

```bash
socket – make socket
bind* – assign address
listen – listen for clients
```

`*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/receive` syscalls, like `sendto/recvfrom` w/o last 2 args

Uses of connected UDP sockets

- Kernel demultiplexes 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_data not used
  - m_flags is bitwise or of various bits
    - E.g., if cluster, or if pkt header used

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 *m, 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 – takes mbuf chain of data to be 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]
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
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  - Crash recovery
  - 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, readdir, …
  - 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?

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:
    sattr3 obj_attributes;
  case GUARDED:
  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;
    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?
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 write call

```c
struct writeargs {
    fhandle file;
    switch (stat status) {
        unsigned beginoffset; case NFS_OK:
        unsigned offset; case fattr attributes;
        unsigned totalcount; default:
        nfdata data; void;
    }
} attrstat NFSPROC_WRITE(writeargs) = 8;
```

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

NFSv3 Write arguments

```c
struct write3args {
    enum stable_how {
        nfs_fh3 file;
        uint64 offset;
        uint32 count;
        stable_how stable;
        opaque data<>
    }
} wcc_data file_wcc;
uint64 size;
uint32 count;
stable_how committed;
writeverf3 verf;
};

WCC_DATA file_wcc;
uint64 size;
uint32 count;
stable_how committed;
writeverf3 verf;
```

- 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

```c
struct write3resok {
    struct wcc_attr {
        struct wcc_data file_wcc;
        uint32 count;
        stable_how committed;
        writeverf3 verf;
    };
    Case NFS3_OK:
    wcc3resok resok;
    default:
    wcc_data resfail;
};
```

- Several fields added to achieve these goals

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)
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/flashes 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 statting a file