Administrivia

• Project 3 due Thursday
  - As usual, due at 4:15pm
  - Extension to midnight if you come to class
  - For longer extensions, please email cs140-staff

• Project 4 goes out at end of week

• This Friday will have section on project 4
Lab 1 grades

- Mean: 149
Lab 2 grades

- Mean: 162
Networks

• What is a network?
  - A system of lines/channels that interconnect
  - E.g., railroad, highway, plumbing, communication, telephone, computer

• What is a computer network?
  - A form of communication network—moves information
  - Nodes are general-purpose computers

• Computer networks are particularly interesting
  - You can program the nodes
  - Very easy to innovate and develop new uses of network
  - Contrast: Telephone network—can’t program most phones, need FCC approval for new devices, etc.
Physical connectivity

• Computers send bits over physical \textit{links}
  - E.g., Coax, twisted pair, fiber, radio, …
  - Bits may be encoded as multiple lower-level “chips”

• Two categories of physical links
  - \textit{Point-to-point} networks (e.g., fiber, twisted pair):
  - \textit{Shared transmission medium} networks (e.g., coax, radio):
    - Any message can be seen by all nodes
    - Allows broadcast/multicast, but introduces contention

• One implication: speed of light matters!
  - \(~300,000 \text{ km/sec}\) in a vacuum, slower in fiber
  - SF \(\geq ~15 \text{ msec}\) \(\rightarrow\) NYC
    - Moore’s law does not apply!
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 $\# \text{ bytes in flight} \geq \text{bandwidth} \times \text{delay}$
  (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 is critical for good network utilization
Indirect connectivity

- Rarely have direct physical connection to destination
- Instead, communications usually “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

- **Circuit switched networks** provide virtual links
  - E.g., old telephone network when numbers dialed

- **Packet switched networks**
  - Pack a bunch of bytes together intended for same destination
  - Slap a *header* on packet describing where it should go
  - Most networks today are packet switched
Example: Ethernet

- Originally designed for shared medium (coax)
  - Medium Access Control (MAC) protocol governs access to coax
  - E.g., don’t transmit when someone else is
  - If you collide, used randomized backoff and try again

- Vendors give each device a unique 48-bit MAC address
  - Specifies which node should receive a packet

- Packet format:
  - Preamble helps device recognize start of packet
  - CRC allows 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)
Why Ethernet is insufficient

- **Ethernet Limits**
  - 2,500m diameter
  - 100 nodes

- **Can bridge multiple Ethernets**
  - First time you see destination address, send packet to all segments
  - Then learn where devices are, and avoid forwarding useless packets

- **A switch is like a bridge with** \( n > 2 \) **ports**
  - Widely used within organizations
  - But could never scale to the size of the Internet

- **Moreover, need to communicate across networks**
  - E.g., laptop w. DSL or wireless contacting server w. Ethernet
Internet Protocol (IP)

• IP used to connect multiple networks
  - Runs over a variety of physical networks
  - Most computers today speak IP

• Every host has a unique 4-byte IP address
  - (Or at least thinks it has, when address shortages)
  - E.g., www.ietf.org → 132.151.6.21

• 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
Layering

- Stick packets inside packets
  - 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. E.g., IP packets should be independent of Ethernet
    [Annoyingly, TCP (next) has a checksum that violates this]

![Layering Diagram]
ARP

- When forwarding an IP packet from Ethernet $A$ to Ethernet $B$, what MAC address should you use?
  - If destination host physically connected, use its MAC address
  - Otherwise, use MAC address of next router (given IP address)

- Must map IP addresses into physical addresses

- ARP – *address resolution protocol*
  - Broadcast request for MAC address of IP address
  - Everybody learns the requesting node’s MAC address (since broadcast request has requester’s MAC and IP addresses)
  - Target machine responds with its MAC address

- OS keeps ARP cache w. IP$\rightarrow$MAC addr. mappings
  - Periodically discard entries that have not been refreshed
  - E.g., run “arp -a” on Unix to see contents of ARP cache
## ARP Ethernet packet format

<table>
<thead>
<tr>
<th></th>
<th>Hardware type = 1</th>
<th>ProtocolType = 0x0800</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLen = 48</td>
<td>SourceHardwareAddr (bytes 0–3)</td>
<td>Operation</td>
</tr>
<tr>
<td>PLen = 32</td>
<td>SourceHardwareAddr (bytes 4–5)</td>
<td>SourceProtocolAddr (bytes 0–1)</td>
</tr>
<tr>
<td></td>
<td>SourceProtocolAddr (bytes 2–3)</td>
<td>TargetHardwareAddr (bytes 0–1)</td>
</tr>
<tr>
<td></td>
<td>TargetHardwareAddr (bytes 2–5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TargetProtocolAddr (bytes 0–3)</td>
<td></td>
</tr>
</tbody>
</table>

[Hardware address = MAC address]
Inter-process communication

- Want abstraction of inter-process (not just inter-node) communication
- Solution: Encapsulate other protocols within IP
Failure

- Many more failure modes on net than w. local IPC
- Several types of error can affect packet delivery
  - Bit errors (e.g., electrical interference, cosmic rays)
  - Packet loss (packets dropped when queues fill on overload)
  - Link and node failure
- In addition, properly delivered frames can be delayed, reordered, even duplicated
- How much should OS expose to application
  - Some failures cannot be masked (e.g., server dead)
  - Others can be (e.g., retransmit lost packet)
  - But masking errors may be wrong for some applications (e.g., old audio packet no longer interesting if too late to play)
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
Uses of TCP

• Most applications use TCP
  - Easier interface to program to (reliability)
  - Automatically avoids congestion (don’t need to worry about taking down network)

• Servers typically listen on well-known ports
  - SSH: 22
  - Email: 25
  - Finger: 79
  - Web / HTTP: 80

• Example: Interacting with www.stanford.edu
  - Browser resolves IP address of www.stanford.edu (171.67.216.15)
  - Browser connects to TCP port 80 on 171.67.216.15
  - Over TCP connection, browser requests and gets home page
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:
  - 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)
A little bit about TCP

- **Want to save network from congestive 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 tear down 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
OS interface to TCP/IP

- What interface should OS provide to TCP/IP?
- **Inspired by pipes** (int pipe (int fds[2]);)
  - Allow Inter-process communication on one machine
  - Writes to fds[1] will be read on fds[0]
  - Can give each file descriptor to a different process (w. fork)

- **Idea: Provide similar abstraction across machines**
  - Write data on one machine, read it on the other
  - Allows processes to communicate over the network

- **Complications across machines**
  - How do you set up the file descriptors between processes?
  - How do you deal with failure?
  - How do you get good performance?
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
  - 32-bit IP address specifies machine
  - 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**

<table>
<thead>
<tr>
<th>Client</th>
<th>Server</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>socket – make socket</td>
</tr>
<tr>
<td></td>
<td>bind – assign address</td>
</tr>
<tr>
<td></td>
<td>listen – listen for clients</td>
</tr>
<tr>
<td></td>
<td>socket – make socket</td>
</tr>
<tr>
<td></td>
<td>bind* – assign address</td>
</tr>
<tr>
<td></td>
<td>connect – connect to listening socket</td>
</tr>
<tr>
<td></td>
<td>accept – accept connection</td>
</tr>
</tbody>
</table>

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

```c
struct sockaddr_in {
    short sin_family;    /* = AF_INET */
    u_short sin_port;    /* = htons (PORT) */
    struct in_addr sin_addr;
    char sin_zero[8];
} sin;

int s = socket (AF_INET, SOCK_STREAM, 0);
bzero (&sin, sizeof (sin));
sin.sin_family = AF_INET;
sin.sin_port = htons (13);    /* daytime port */
sin.sin_addr.s_addr = htonl (IP_ADDRESS);
connect (s, (sockaddr *) &sin, sizeof (sin));
```
Server interface

struct sockaddr_in sin;
int s = socket (AF_INET, SOCK_STREAM, 0);
bzero (&sin, sizeof (sin));
sin.sin_family = AF_INET;
sin.sin_port = htons (9999);
sin.sin_addr.s_addr = htonl (INADDR_ANY);
bind (s, (struct sockaddr *) &sin, sizeof (sin));
listen (s, 5);

for (;;) {
    socklen_t len = sizeof (sin);
    int cfd = accept (s, (struct sockaddr *) &sin, &len);
    /* cfd is new connection; you never read/write s */
    do_something_with (cfd);
    close (cfd);
}
Using UDP

- **Call socket** with SO_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
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)

• Mbufs working example for this lecture
  - Linux uses sk_buffs, which are similar idea
### mbuf details

- **Pkts made up of multiple mbufs**
  - Chained together by `m_next`  
  - Such linked mbufs called *chains*

- **Chains linked w. `m_nextpkt`**
  - Linked chains known as *queues*
  - E.g., device output queue

- **Most mbufs have 108 data bytes**
  - First in chain has `pkt` header

- **Cluster mbufs have more data**
  - `ext` header points to data
  - Up to 2 KB not collocated w. `mbuf`
  - `m_dat` not used

- **`m_flags` or of various bits**
  - E.g., if cluster, or if `pkt` header used
Adding/deleting data w. 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 w. `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 w. 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 w. messages (like unconnected UDP)
  - `CONNREQUIRED` – requires connection (like TCP)
  - `WANTRCV` – 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
  - Various other control operations
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, enqueue packet
  - `if_start` – start transmitting queued packets
  - Also `ioctl`, `timeout`, `initialize`, `reset`
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 some packet filters can 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 if