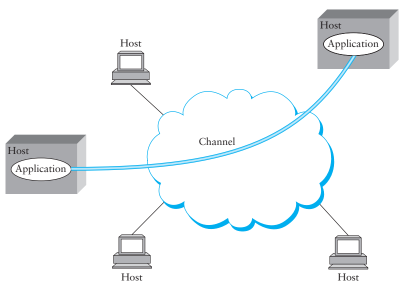
Outline

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

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.

Inter-process communication



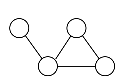
- **Want abstraction of inter-process (not just inter-node) communication**
- **Goal: two different applications, running on different computers, can exchange data as if they had a pipe between them.**

The 7-Layer and 4-Layer Models

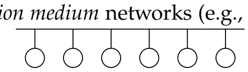
	OSI	TCP/IP
7	Application	Applications (FTP, SMTP, HTTP, etc.)
6	Presentation	
5	Session	
4	Transport	TCP (host-to-host)
3	Network	IP
2	Data link	Network access (usually Ethernet)
1	Physical	

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):

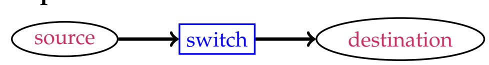


    - ▹ Any message can be seen by all nodes
    - ▹ Allows broadcast/multicast, but introduces contention
- **One implication: speed of light matters!**
  - $\sim 300,000$ km/sec in a vacum, slower in fiber

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

Link Layer, Indirect Connectivity

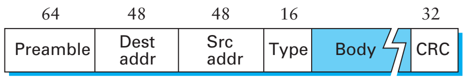
- **Rarely have direct physical connection to destination**
- **Instead, communications usually "hop" through multiple devices**



  - Allows links and devices to be shared for multiple purposes
  - Must determine which bits are part of which messages intended for which destinations
- ***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

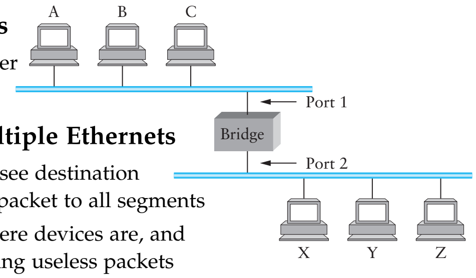
- **Originally designed for shared medium (coax), now generally not shared medium (switched)**
- **Vendors give each device a unique 48-bit *MAC address***
  - Specifies which card should receive a packet
- **Ethernet switches can scale to switch local area networks (thousands of hosts), but not much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



  - Preamble helps device recognize start of packet
  - CRC allows 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

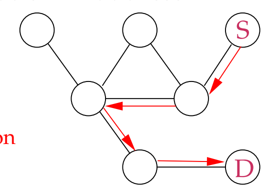
- **Ethernet Limits**
  - 2,500m diameter
  - 100 nodes
- **Can *bridge* multiple Ethernets**
  - First time you see destination address, send packet to all segments
  - Then learn where devices are, and avoid forwarding useless packets



- **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

Network Layer: 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 there is address shortage)
  - 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



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

Principle: Packet Switching

- **A packet is a self contained unit of data which contains information necessary for it to reach its destination**
- **Packet switching: independently for each arriving packet, compute its outgoing link. If the link is free, send it. Otherwise, queue it for later (or drop).**
  - Makes forwarding very simple
  - Allows simple sharing of links

Principle: Layering

- **Break system functionality into a set of components**
- **Each component ("layer") provides a well-defined service**
- **Each layer uses only the service of the layer below it**
- **Layers communicate sequentially with the layers above or below**

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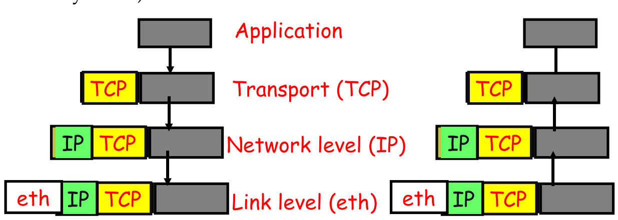
Principle: Encapsulation

- **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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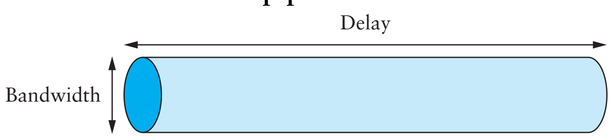
- **Problems:**
  - Low performance over high-delay network (bandwidth is one packet per round-trip time)
  - Possible congestive collapse of network (if everyone keeps retransmitting when network overloaded)

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**

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)

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 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

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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

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.

Client interface

```
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 `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

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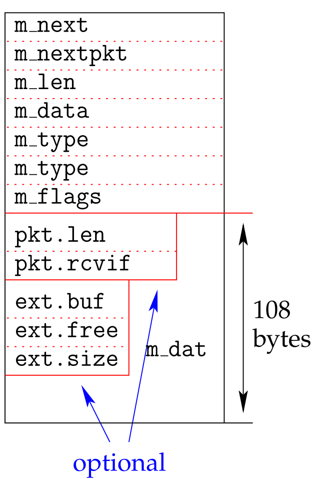
Socket implementation

- **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



- **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 ≈230 data bytes (depends on pointers)**
  - 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)

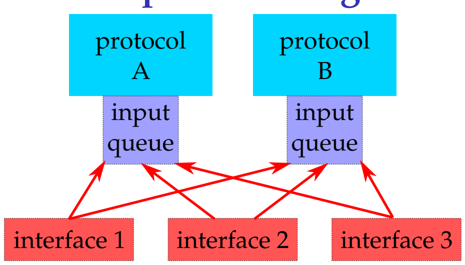
`protosw` structure

- **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)
  - WANTRCVD – notify socket of consumed data (e.g., so TCP can wake up a sending process blocked by flow control)

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

Input handling



- **NIC driver determines packet protocol**
- **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 if