CSCI-1680
Layering and Encapsulation

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Based partly on lecture notes by David Mazières, Phil Levis, Rodrigo Fonseca

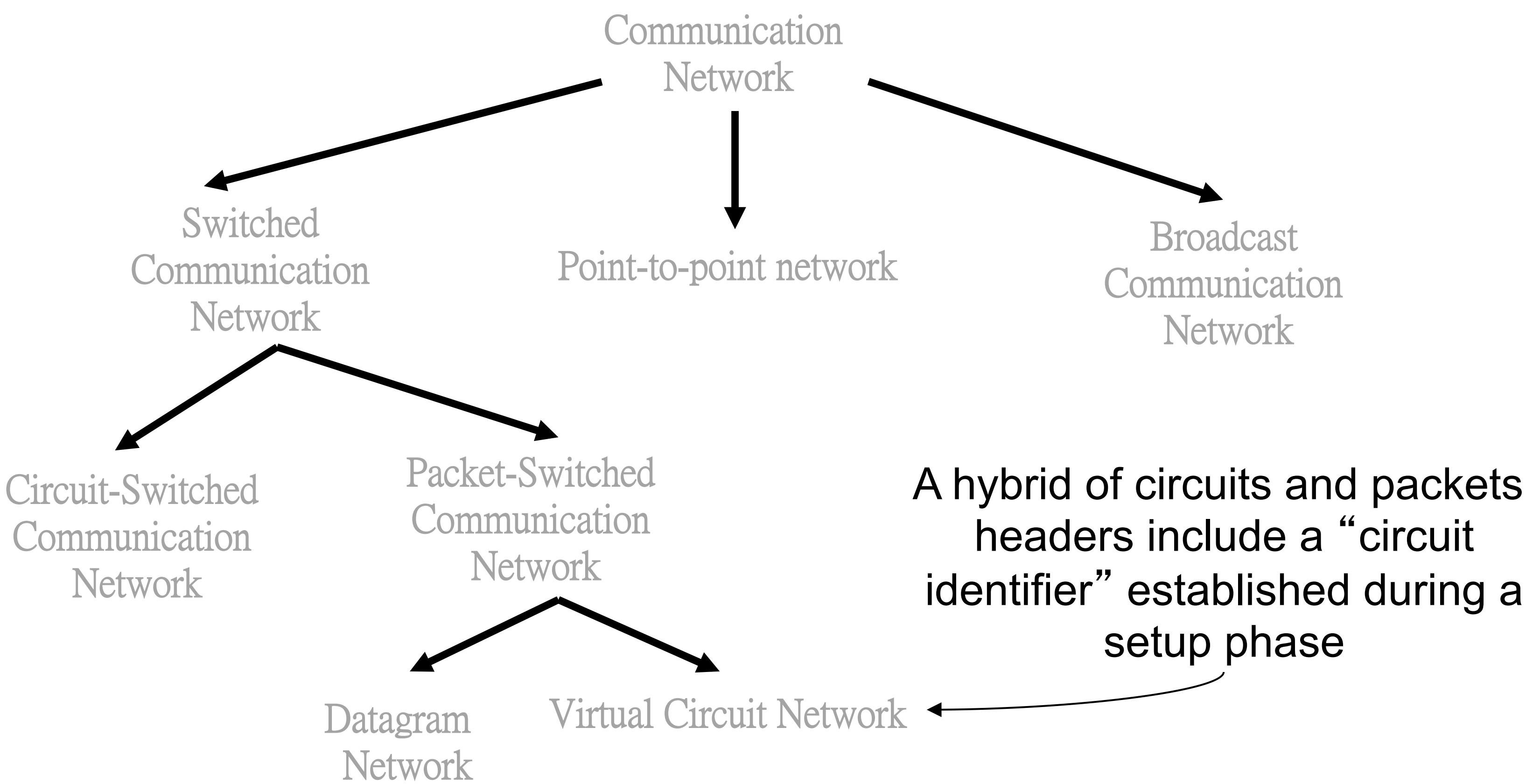
Administrivia

- **Homework 0:**
  - Sign and hand in Collaboration Policy
  - Sign up for Piazza
  - Send us your github account
- **Signup for Snowcast milestone**
  - Thursday from 8pm to 10pm (tentative)
  - See Piazza for details

Today

- **Review**
  - Switching, Multiplexing
- **Layering and Encapsulation**
- **Intro to IP, TCP, UDP**
- **Extra material: sockets primer**

A Taxonomy of networks



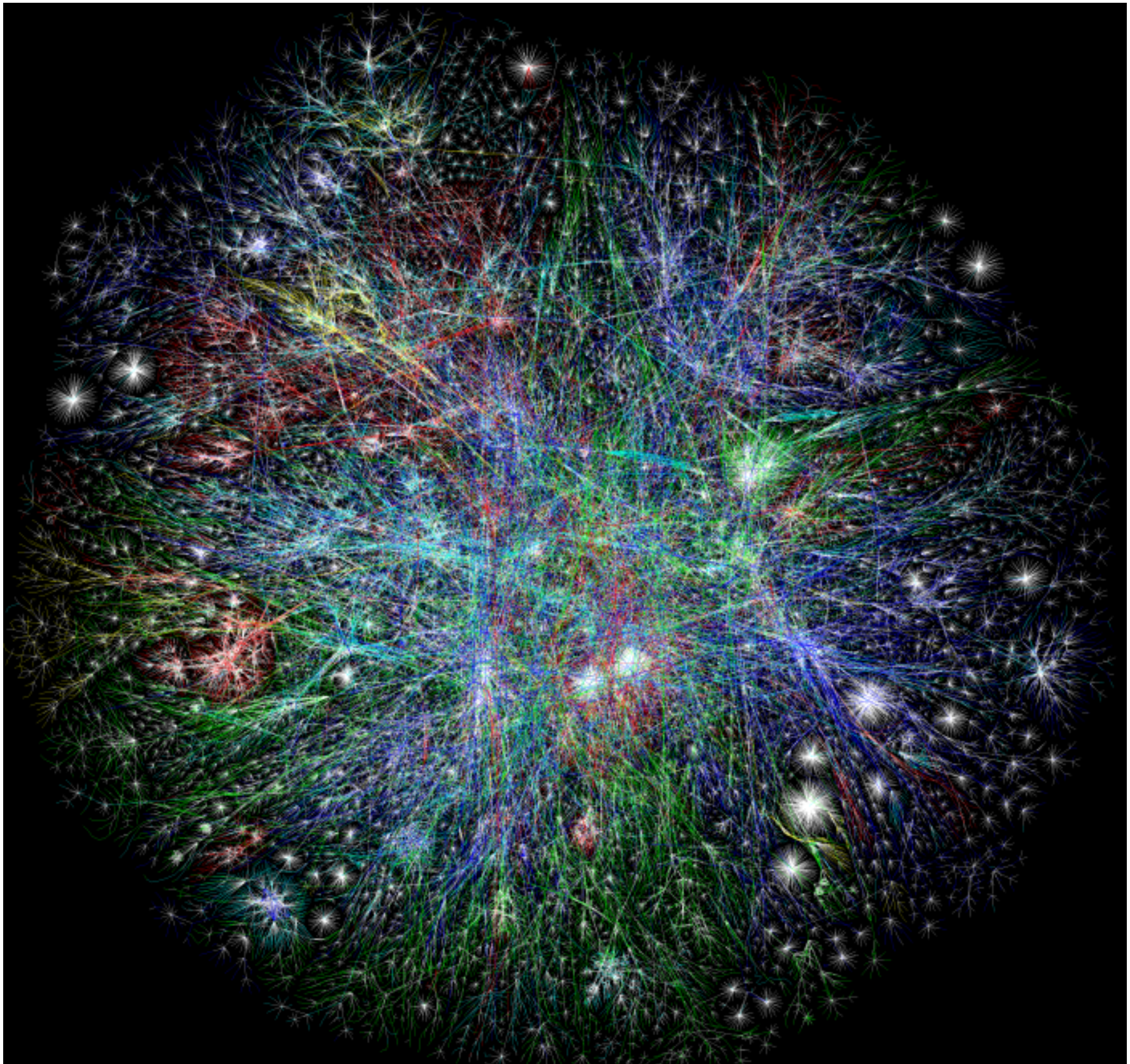
Circuit Switching

- **Guaranteed allocation**
  - Time division / Frequency division multiplexing
- **Low space overhead**
- **Easy to reason about**

- **Failures: must re-establish connection**
  - For any failures along path
- **Overload: all or nothing**
  - No graceful degradation
- **Waste: allocate for peak, waste for less than peak**
- **Set up time**

Packet Switching

- **Break information in small chunks: *packets***
- **Each packet forwarded independently**
  - Must add metadata to each packet
- **Allows statistical multiplexing**
  - High utilization
  - Very flexible
  - Fairness not automatic
  - Highly variable queueing delays
  - Different paths for each packet (why is this bad?)



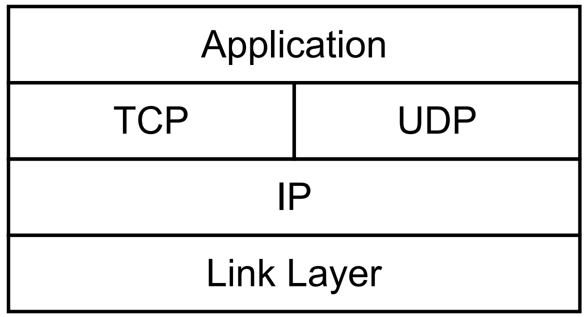
Traceroute map of the Internet, ~5 million edges, circa 2003. opte.org

Managing Complexity

- *Very* **large number of computers**
- **Incredible variety of technologies**
  - Each with very different constraints
- **No single administrative entity**
- **Evolving demands, protocols, applications**
  - Each with very different requirements!

- **How do we make sense of all this?**

Layering



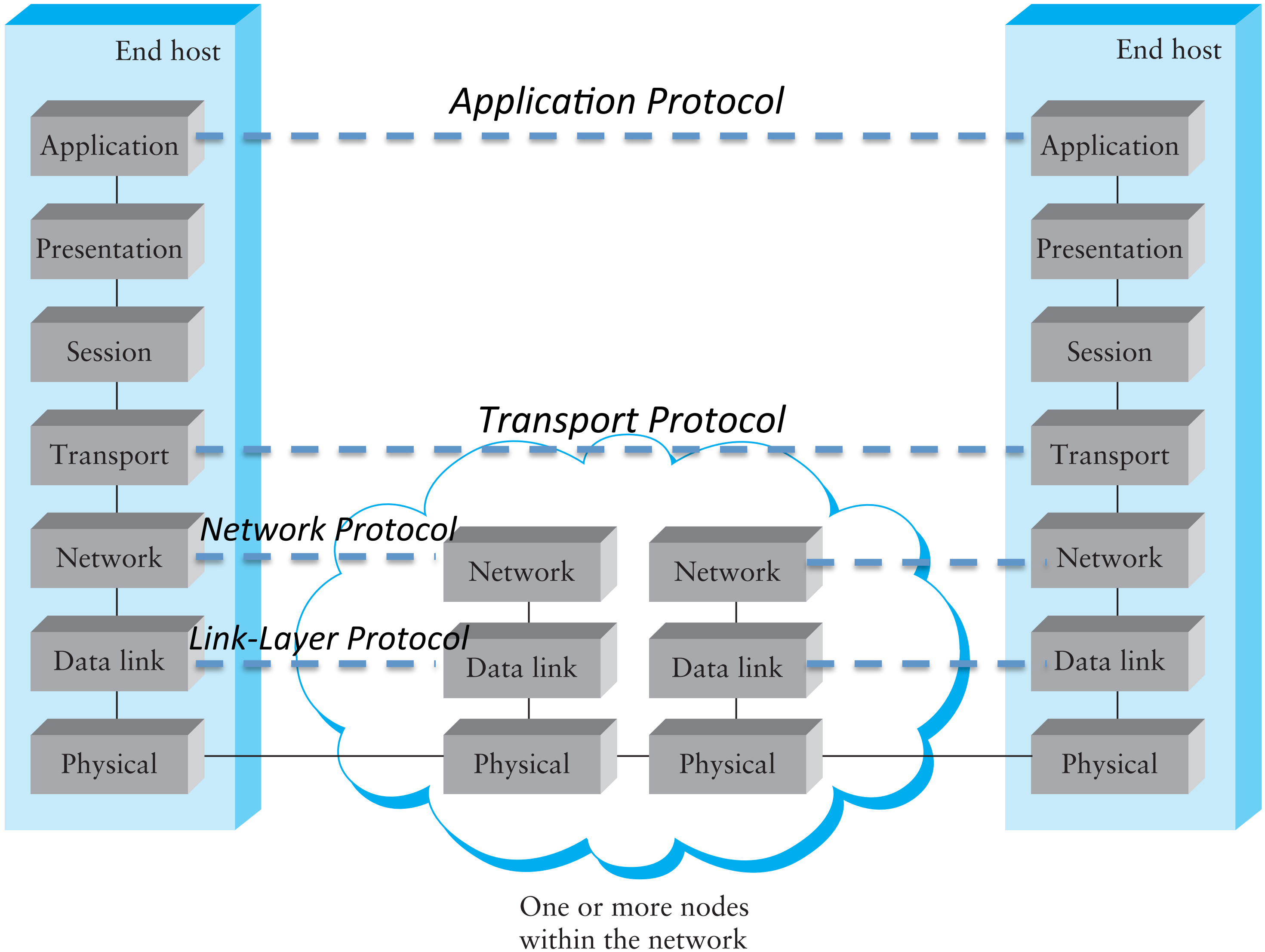
- **Separation of concerns**
  - Break problem into separate parts
  - Solve each one independently
  - Tie together through common interfaces: abstraction
  - Encapsulate data from the layer above inside data from the layer below
  - Allow independent evolution

Analogy to Delivering a Letter

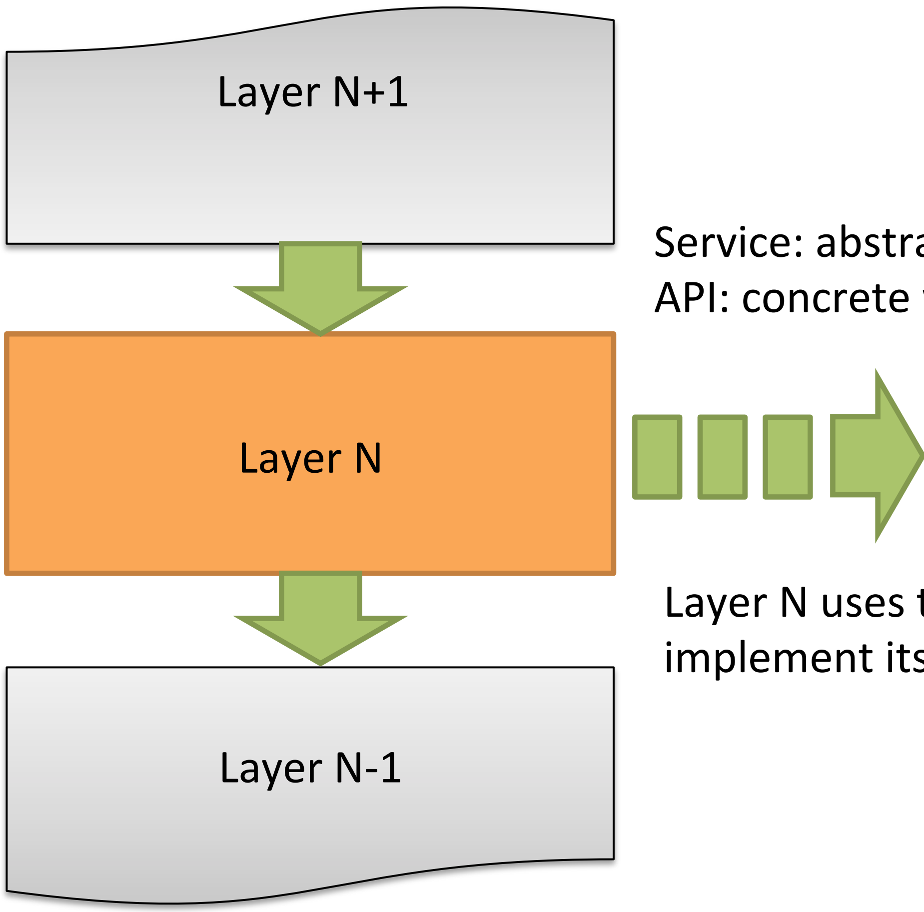
Layers

- **Application – what the users sees, *e.g.*, HTTP**
- **Presentation – crypto, conversion between representations**
- **Session – can tie together multiple streams (*e.g.*, audio & video)**
- **Transport – demultiplexes, provides reliability, flow and congestion control**
- **Network – sends *packets*, using *routing***
- **Data Link – sends *frames*, handles media access**
- **Physical – sends individual bits**

OSI Reference Model



Layers, Services, Protocols



Service: abstraction provided to layer above
API: concrete way of using the service

Protocol: rules for communication within same layer

Layer N uses the services provided by N-1 to implement its protocol and provide its own services

Layers, Services, Protocols

Application	Service: user-facing application. Application-defined messages
Transport	Service: multiplexing applications Reliable byte stream to other node (TCP), Unreliable datagram (UDP)
Network	Service: move packets to any other node in the network IP: Unreliable, best-effort service model
Link	Service: move frames to other node across link. May add reliability, medium access control
Physical	Service: move bits to other node across link

Protocols

- **What do you need to communicate?**
  - Definition of message formats
  - Definition of the semantics of messages
  - Definition of valid sequences of messages
    - Including valid timings
- **Also, who do you talk to? …**

Addressing

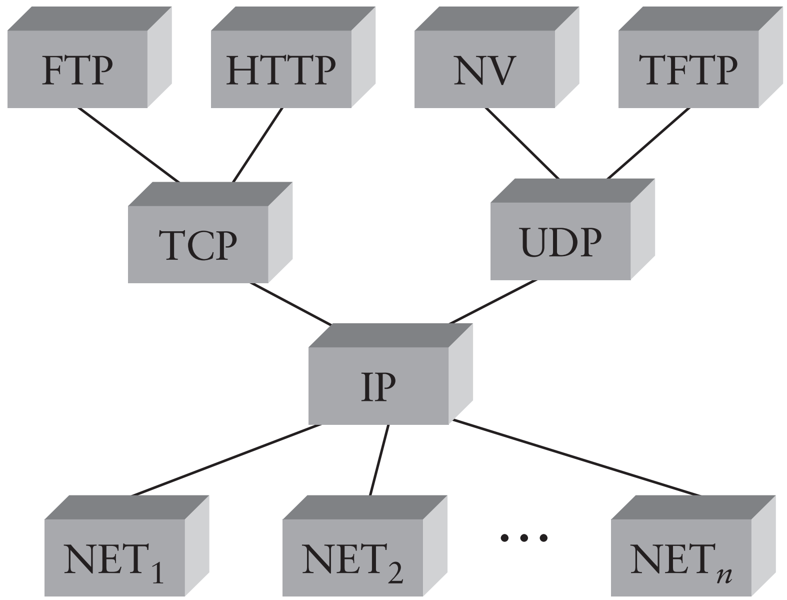
- **Each node typically has a unique* name**
  - When that name also tells you how to get to the node, it is called an *address*
- **Each layer can have its own naming/addressing**
- ***Routing* is the process of finding a path to the destination**
  - In packet switched networks, each packet must have a destination address
  - For circuit switched, use address to set up circuit
- **Special addresses can exist for broadcast/ multicast/anycast**

** within the relevant scope*

Challenge

- **Decide on how to factor the problem**
  – What services at which layer?
  – What to leave out?
  – More on this later (End-to-end principle)
- **For example:**
  – IP offers pretty crappy service, even on top of reliable links… why?
  – TCP: offers reliable, in-order, no-duplicates service. Why would you want UDP?

IP as the Narrow Waist

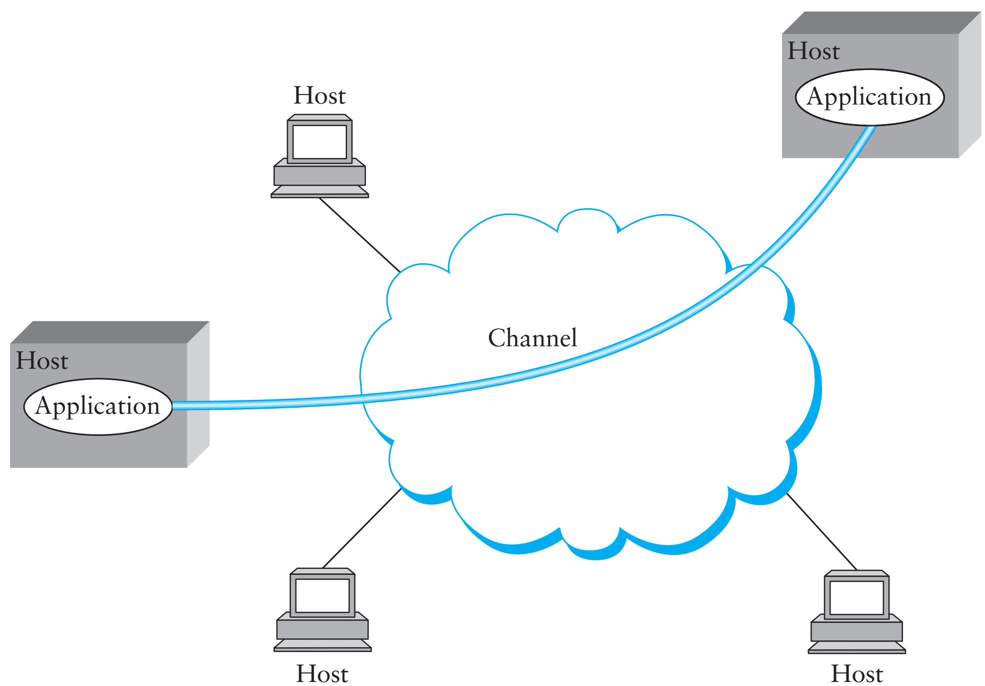


- **Many applications protocols on top of UDP & TCP**
- **IP works over many types of networks**
- **This is the "Hourglass" architecture of the Internet.**
  - If every network supports IP, applications run over many different networks (*e.g.*, cellular network)

Network Layer: Internet Protocol (IP)

- **Used by most computer networks today**
  - Runs *over* a variety of physical networks, can connect Ethernet, wireless, modem lines, etc.
- **Every host has a unique 4-byte IP address (IPv4)**
  - *E.g.*, www.cs.brown.edu →128.148.32.110
  - The *network* knows how to route a packet to any address
- **Need more to build something like the Web**
  - Need naming (DNS)
  - Interface for browser and server software (sockets)
  - Need demultiplexing within a host: which packets are for web browser, Skype, or the mail program? (ports)

Inter-process Communication



- **Talking from host to host is great, but we want abstraction of inter-process communication**
- **Solution: *encapsulate* another protocol within IP**

Transport: UDP and TCP

- **UDP and TCP most popular protocols on IP**
  - Both use 16-bit *port* number & 32-bit IP address
  - Applications *bind* a port & receive traffic on that port
- **UDP – User (unreliable) Datagram Protocol**
  - Exposes packet-switched nature of Internet
  - Adds multiplexing on top of IP
  - Sent packets may be dropped, reordered, even duplicated (but there is corruption protection)
- **TCP – Transmission Control Protocol**
  - Provides illusion of reliable 'pipe' or 'stream' between two processes anywhere on the network
  - Handles congestion and flow control

Uses of TCP

- **Most applications use TCP**
  - Easier to program (reliability is convenient)
  - Automatically avoids congestion (don't need to worry about overloading the network)
- **Servers typically listen on "well-known" ports:**
  - SSH: 22
  - SMTP (email): 25
  - Finger: 79
  - HTTP (web): 80

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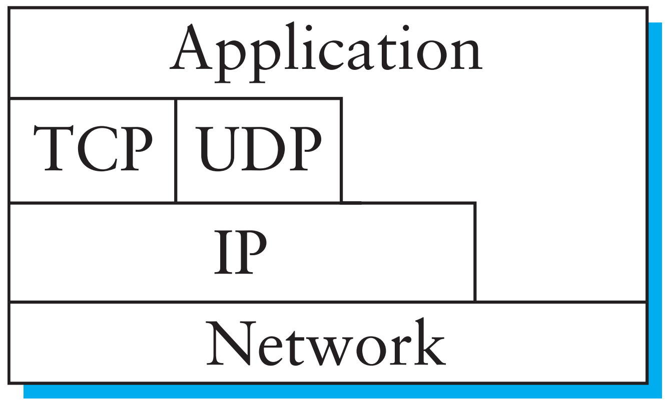
Internet Layering



- **Strict layering not *required***
  - TCP/UDP "cheat" to detect certain errors in IP-level information like address
  - Overall, allows evolution, experimentation

Using TCP/IP

- **How can applications use the network?**
- ***Sockets* API.**
  – Originally from BSD, widely implemented (*BSD, Linux, Mac OS X, Windows, …)
  – Higher-level APIs build on them
- **After basic setup, use much like files**

Sockets: Communication Between Machines

- **Network sockets are file descriptors too**
- **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 another
  - read() may not return full amount requested. Check return value and read() again! (But returning zero bytes = eof)

System calls for using TCP

Client

Server

`socket` – **make socket**

`bind` – **assign address, port**

`listen` – **listen for clients**

`socket` – **make socket**

`bind*` – **assign address**

`connect` – **connect to listening socket**

`accept` – **accept connection**

- **client bind is optional, connect can choose address & port.**

Socket Naming

- **Recall how TCP & UDP name communication endpoints**
  - IP address (128.148.32.110) specifies host (netif)
  - 16-bit port number demultiplexes within host
  - Well-known services listen on standard ports (*e.g.* ssh: 22, http: 80, mail: 25, see /etc/services for list)
  - Clients connect from arbitrary ports to well known ports
- **A connection is named by 5 components**
  - Protocol, local IP, local port, remote IP, remote port
  - TCP requires connected sockets, but not UDP

Dealing with Address Types

- **All values in network byte order (Big Endian)**
  - `htonl()`, `htons()`: host to network, 32 and 16 bits
  - `ntohl()`, `ntohs()`: network to host, 32 and 16 bits
  - Always convert! On some machines, it's a no-op.
- **All address types begin with family**
  - `sa_family` in `sockaddr` tells you actual type
- **Not all addresses are the same size**
  - e.g., `struct sockaddr_in6` is typically 28 bytes, yet generic `struct sockaddr` is only 16 bytes
  - Most calls also take the socketaddr length
  - New `sockaddr_storage` is "big enough"

Client Skeleton (IPv4)

```
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));
while ((n = read (s, buf, sizeof (buf))) > 0)
  write (1, buf, n);
```

Server Skeleton (IPv4)

```
int s = socket (AF_INET, SOCK_STREAM, 0);
struct sockaddr_in sin;
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 calls for sending/receiving individual packets**
  - `sendto(int s, const void *msg, int len, int flags, const struct sockaddr *to, socklen t tolen);`
  - `recvfrom(int s, void *buf, int len, int flags, struct sockaddr *from, socklen t *fromlen);`
  - Must send/get peer address with each packet
- **Example:** `udpecho.c`
- **Can use UDP in connected mode (Why?)**
  - connect assigns remote address
  - `send`/`recv` syscalls, like `sendto`/`recvfrom` w/o last two arguments

Uses of UDP Connected Sockets

- **Kernel demultiplexes packets based on port**
  – Can have different processes getting UDP packets from different peers
- **Feedback based on ICMP messages (future lecture)**
  – Say no process has bound UDP port you sent packet to
  – Server sends port unreachable message, but you will only receive it when using connected socket

Serving Multiple Clients

- **A server may block when talking to a client**
  - Read or write of a socket connected to a slow client can block
  - Server may be busy with CPU
  - Server might be blocked waiting for disk I/O
- **Concurrency through multiple processes**
  - Accept, fork, close in parent; child services request
- **Advantages of one process per client**
  - Don't block on slow clients
  - May use multiple cores
  - Can keep disk queues full for disk-heavy workloads

Threads

- **One process per client has disadvantages:**
  - High overhead – fork + exit ~100μsec
  - Hard to share state across clients
  - Maximum number of processes limited
- **Can use threads for concurrency**
  - Data races and deadlocks make programming tricky
  - Must allocate one stack per request
  - Many have heavy thread-switch overhead

Rough equivalents to `fork()`, `waitpid()`, `exit()`, `kill()`, plus locking primitives.

Non-blocking I/O

- **fcntl sets O_NONBLOCK flag on descriptor**

```
int n;
if ((n = fcntl(s, F_GETFL)) >= 0)
  fcntl(s, F_SETFL, n|O_NONBLOCK);
```

- **Non-blocking semantics of system calls:**
  – read immediately returns -1 with errno EAGAIN if no data
  – write may not write all data, or may return EAGAIN
  – connect may fail with EINPROGRESS (or may succeed, or may fail with a real error like ECONNREFUSED)
  – accept may fail with EAGAIN or EWOULDBLOCK if no connections present to be accepted

Use select() to know when to act.

```
struct timeval {
  long    tv_sec;         /* seconds */
  long    tv_usec;        /* and microseconds */
};

int select (int nfds, fd_set *readfds, fd_set *writefds,
            fd_set *exceptfds, struct timeval *timeout);
FD_SET(fd, &fdset);
FD_CLR(fd, &fdset);
FD_ISSET(fd, &fdset);
FD_ZERO(&fdset);
```

- **Entire program runs in an *event loop***
- ***poll() is similar, epoll() is "better" in some ways.***

Event-driven servers

- **Quite different from processes/threads**
  - Race conditions, deadlocks rare
  - Often more efficient
- **But…**
  - Unusual programming model.
  - Sometimes difficult to avoid blocking. (You must know your libraries are also asynchronous.)
  - Scaling to more CPUs is more complex.

Coming Up

- Next class: Physical Layer
- Same day: Snowcast milestones