CSC2/452 Computer Organization
Networking

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URCS

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Outline

Outline

Administrivia

- Assignment #4 is out
  - Due date: Tuesday, Nov 26, 7PM
- Assignment #5 (last!) will be out Dec 2
  - Due on Dec 11

Outline

Communication between computers

- Getting different computers to work together requires networking
- Many different ways of physically building a network
  - Physical: Copper, Optical fibre, Wireless, etc.
  - Technologies: Ethernet, InfiniBand, GSM, CDMA, 802.11 etc.
- Lots of physical (and logical) components
  - Nodes, bridges, routers, etc.
- Ultimately, though, software needs to use the network
  - The focus of today's class
  - See the textbook for details on network organization
  - Or take CSC2/457

Streams and Packets

- Stream-oriented communication
  - Data is sent in some order and must be received in that same order
  - Usually because data bytes are ordered (e.g. contents of a file)
  - Communication must be reliable, data bytes must not be lost and errors must be detected
  - Usually long-lived
- Packet-oriented communication
  - Data is sent as “packets”, independent pieces of data
  - Packets are not ordered, can be delivered out-of-order
  - Packets may be lost, corrupted or duplicated
  - Communication usually does not last longer than a single packet

Circuit-switching vs Packet switching

- Switching: determining the path taken by data
- Circuit-switching
  - Establish a circuit from source to destination once at beginning of connection
  - Data takes the path established by the circuit
  - Beloved of telephone companies
  - e.g. ISDN, ATM (not the machines dispensing money)
- Packet-switching
  - No fixed path from source to destination
  - Packets choose their own path, on a hop-by-hop basis
  - Foundation of the Internet
  - e.g. Internet Protocol

Stream-oriented communication using packets?

- ARPA chose packet-switching for the initial design of the Internet because it was highly resilient
  - Imagine the network as a graph, with computers as nodes and communication links as edges
  - Packet-switching can get the data across even when many links and nodes fail
  - Usually by choosing a path around these failures
- But, packets can:
  - be reordered
  - can be corrupted
  - can get lost
- How to build an abstraction of stream-oriented communication over a packet-switched network?

Outline

Internet Protocol

- The building block of the Internet
  - two major versions: IPv4 and IPv6
- IP is designed to connect networks (hence *inter*net(working))
  - Typically, machines on a single network can talk directly to each other
  - IP specifies how to route packets across networks
- All nodes in the network have an address
  - IPv4: 32-bit addresses
  - IPv6: 128-bit addresses
- IP usually runs over a local network protocol
  - Usually, Ethernet for wired networks

Ethernet: A local network protocol

- Designed at Xerox PARC by Bob Metcalfe
- Originally designed for a shared broadcast medium
  - All computers share the same communication medium
  - Two (or more) computers cannot talk at the same time
  - Key question: how to allow computers to share this medium?

How Ethernet solves the shared medium problem

- Computers check if a communication is in progress
- If not, they start communicating
- If two computers started communicating at the same time, they'll interfere with each other
  - Called a *collision*
  - These collisions can be detected
- Both computers will stop and try again after waiting a *random* interval of time
  - This interval of time will increase exponentially on each unsuccessful attempt
  - Called *random (or exponential) backoff*
- Alternatives to Ethernet: Token Ring

How IP works

```
$ route -n
Kernel IP routing table
Destination     Gateway         Genmask         Flags Metric Ref    Use Iface
0.0.0.0         192.168.1.1     0.0.0.0         UG    600    0        0 wlan0
192.168.1.0     0.0.0.0         255.255.255.0   U     600    0        0 wlan0
```

- Each node contains a routing table (you can use the command `route`) to print it out
- The routing table contains information on how to route packets
- In the example above
  - addresses 192.168.1.0 to 192.168.1.255 are local and packets should be sent directly via interface wlan0
  - all other addresses should be sent to the gateway at 192.168.1.1 which will forward them
- These are IPv4 addresses, consisting of four 8-bit numbers separated by periods.

Local IP transmission

- If 192.168.1.5 wants to send packets to 192.168.1.1, it can send them directly
- However, this requires knowing the MAC address of 192.168.1.1
  - Media Access Control, i.e. the "Ethernet" address
- Usually, this is done by broadcasting a query to all local nodes: "who is 192.168.1.1?"
  - This is called the address resolution protocol (or ARP)
  - The result is cached to avoid frequent broadcasts
- Once a MAC address is obtained, Ethernet can be used to directly send the packet

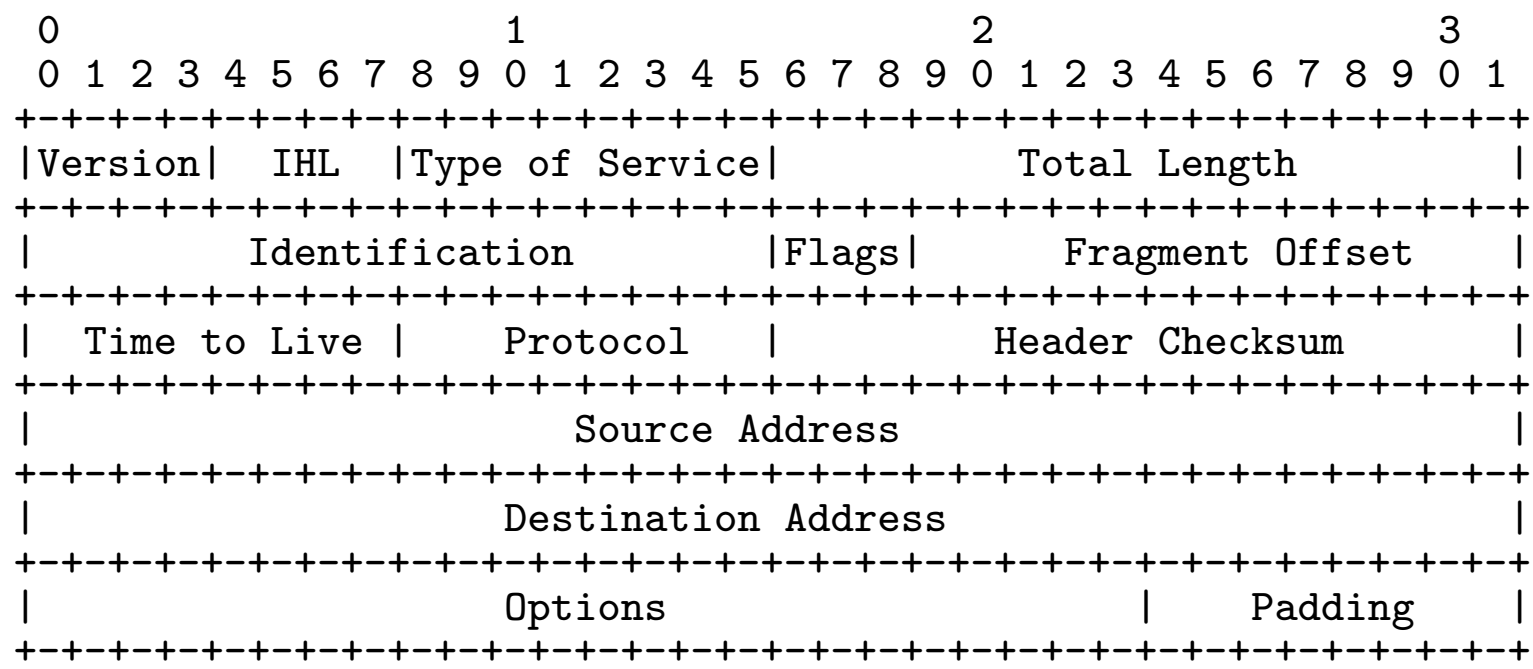
Non-local IP transmission

- If 192.168.1.5 wants to send packets to 8.8.8.8, it cannot send them directly
- For non-local addresses, packets are sent to the gateway
  - The gateway is on the local network
- The gateway is connected to at least two networks
  - If the packet is intended for one of its two networks, it can do local delivery
  - Otherwise, it forwards the packet to the next gateway
- The forwarding step can be made faster using "routers"
  - Gateways that discover and remember the fastest path to a network

IP Data transmission algorithm

- If address is local
  - find MAC address using ARP (if not known)
  - send packet directly using link-layer protocol (i.e. Ethernet)
- If address is non-local
  - send packet to gateway

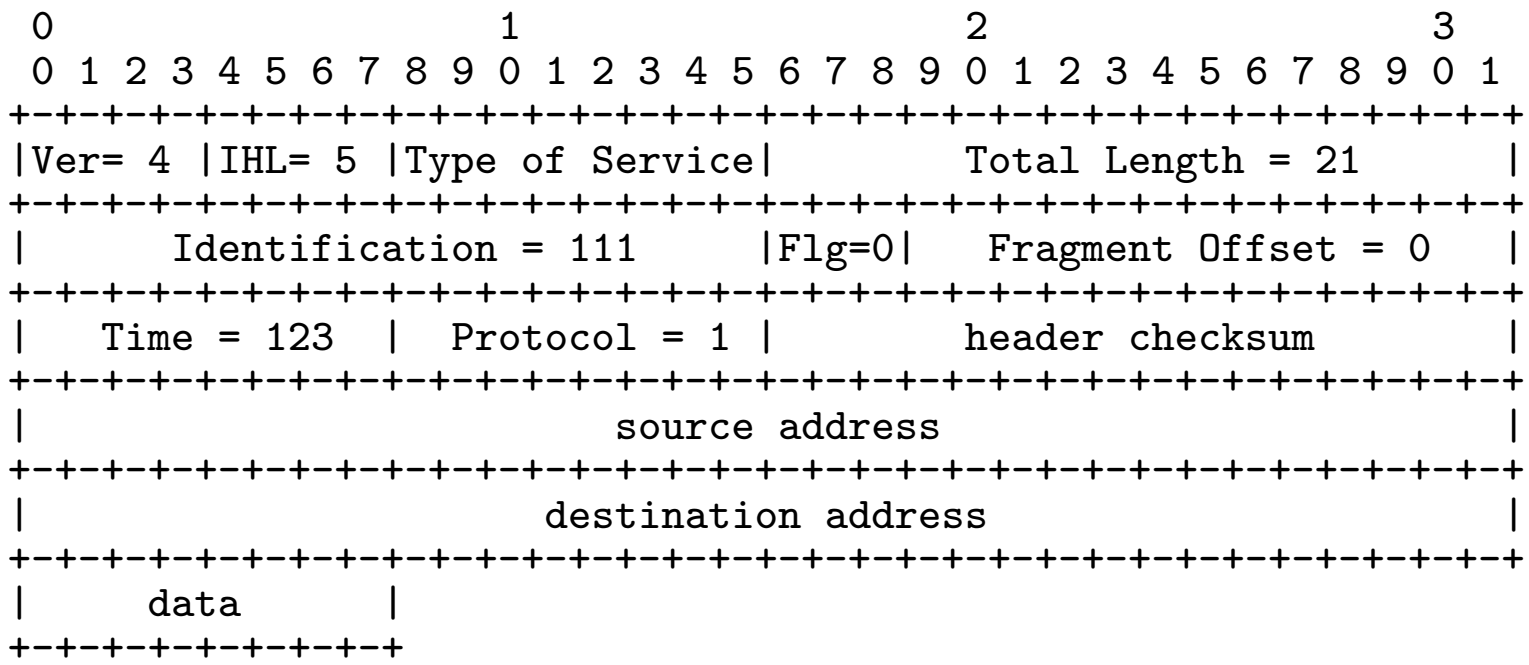
IP Packets



- TTL: field is decremented by one by each gateway/router
  - Packet discarded when the field reaches 0
- Protocol: identifies next-level protocol
  - Ethernet at bottom, followed by IP, followed by ...

(from historical standard RFC 791)

Example IP Packet (or 'Datagram')

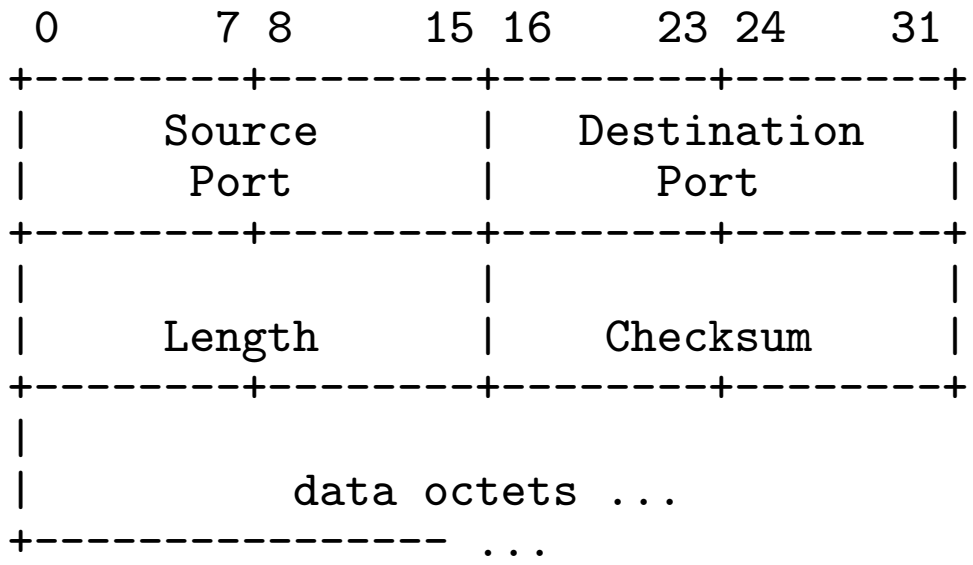


- Protocol 1 is Internet Control Message Protocol (ICMP)
  - The protocol used for sending `pings`
  - Or network error messages ("Destination unreachable")
  - BTW, this is not a valid ICMP packet, just an example

TCP and UDP

- Like ICMP, these are next level protocols built on top of IP
- User Datagram Protocol or UDP
  - Provides user-level (think application-level) packet communication
  - Recall, IP is for node-to-node communication
- Transmission Control Protocol or TCP
  - Provides a reliable, stream-oriented communication on top of IP
  - Also user/application-level

UDP



- UDP extends IP addresses with the notion of a *port*
  - A port is a 16-bit unsigned number (0 to 65535)
- An application "listens" on a well-known port
  - e.g. 8.8.8.8:53, where 53 is the port on node 8.8.8.8
  - data addressed to a port is forwarded to the application
- UDP packets are encapsulated in IP
  - I.e. a UDP packet is the "data" portion of an IP packet
  - Protocol is set to 17

TCP

- TCP must:
  - provided stream-like data transfer
  - deliver data in order
  - detect data corruption
  - handle lost packets
- Usually implemented over IP, so TCP/IP

General outline of TCP

- TCP provides stream-like data transfer
  - By using the notion of a *connection* before transferring data
  - Each connection is identified by an address:port pair, one for both sides of a connection
  - e.g. 192.168.1.2:5810 to 8.8.8.8:80
- Delivers data in order
  - Adds sequence numbers which aid ordering
- Detect data corruption
  - Adds checksums
- Handles lost packets
  - Sequence numbers identify lost or late packets
  - Packets are retransmitted after a timeout
  - Also identifies duplicate packets
- Many other details
  - Setting up connections
  - Congestion control

Well-known ports

- TCP requires a connection to be established
  - Need to know addresses of both nodes
  - Need source port and destination port
- Many destination ports are well-known
  - 80 is for a web server using HTTP
  - 443 is for a web server using HTTPS
  - 21 is for file transfer protocol
  - 22 is for secure shell
  - 25 is for SMTP (i.e. sending email)
- Your OS usually assigns a random port to the source side of the connection

Programmer's Perspective

- Does your application need reliable, ordered communication?
  - Use TCP
- Is it transactional and can handle missing/corrupted packets?
  - Use UDP
- Note sometimes protocols mandate use of TCP or UDP
  - Domain name service (DNS) uses UDP (but also supports TCP)
  - HTTP/1 and HTTP/2 only use TCP

Outline

Sockets

- Original terminology from ARPANET
  - Usage today very different from that definition
- A socket is one end of a connection (i.e. one address:port pair)
- Programming interface for networking applications
  - Developed and popularized by BSD Unix
- Nearly the same interface in any operating system
  - And across programming languages
  - the Plan9 OS is a notable exception

Creating sockets

```
#include <sys/types.h>
#include <sys/socket.h>

int socket(int domain, int type, int protocol);
```

- `domain` is `AF_INET` for IPv4
  - also used `AF_UNIX` for Inter-process Communication
- `type` is `SOCK_STREAM` or `SOCK_DGRAM`
  - Roughly correspond to TCP and UDP respectively
- `protocol` is usually 0
- `socket` returns a file descriptor
  - Use `read` and `write` for TCP
  - Use `send` and `recv` for UDP (can also be used for TCP)

Specifying destination

```
int connect(int sockfd, const struct sockaddr *addr,
            socklen_t addrlen);
```

- For TCP, `connect` will try to open a connection to `addr`
- For UDP, `connect` will send any future packets to `addr`
  - It will also only accept packets sent by `addr`
- These must be numeric addresses, not names
  - I.e. 172.217.7.14 not `google.com`

Aside: Resolving names to addresses

```
#include <sys/types.h>
#include <sys/socket.h>
#include <netdb.h>

int getaddrinfo(const char *node, const char *service,
                const struct addrinfo *hints,
                struct addrinfo **res);
```

- Names are "converted" into addresses using a *resolver*
  - Known as name resolution
  - Needs to look up a database of names to addresses
- Nearly always use the Domain Name Server (DNS) protocol
  - But can also use other alternatives like UPnP
- `getaddrinfo` takes a name (`node`) and a `service` ("http") and returns an address
  - `service` can be NULL
  - Don't use `gethostbyname` which is obsolete

Sending data

```
ssize_t send(int sockfd, const void *buf, size_t len, int flags);
```

- Sends data to a destination
  - Must have been specified using a previous `connect` call

Receiving data

```
ssize_t recv(int sockfd, void *buf, size_t len, int flags);
```

- Receives data from a socket
  - This must be a connected socket
- `recv` will block until data is received

Blocking vs Nonblocking I/O

- Many functions that perform I/O block by default
  - `read`, `recv`, `scanf`
- Although this simplifies programming, programs may want to check if data is available or not
- Programs can use `fcntl` to set a socket to *non-blocking* mode
- In this case, if the operation would normally block, it will instead return `EWOULDBLOCK`
  - Or `EAGAIN`
- Allows you to overlap I/O with computation
  - Very useful prior to threading

Asynchronous I/O

- Instead of checking if an I/O operation has completed, you can use asynchronous I/O
- OS will notify your program that I/O is complete
- All operations in asynchronous I/O are non-blocking by default
- See manual page for `aio` for more information
  - Or see Overlapped I/O in Windows

Overview of Client-side Interface

- Create a `socket`
- `connect` it
- `send` or `recv` data from it
- `close` it

Outline

Server-side sockets: `bind`

```
int bind(int sockfd, const struct sockaddr *addr,
         socklen_t addrlen);
```

- `sockfd` is obtained from `socket`
- `addr` is *local* address to accept requests on
  - Usually set to 0.0.0.0 for IPv4 to accept requests on all of the node's IP addresses

Listen

```
int listen(int sockfd, int backlog);
```

- `sockfd` is a socket for which `bind` has been called
- `backlog` specifies queue depth – connections made after this has been exceeded may be refused

Accept

```
int accept(int sockfd, struct sockaddr *addr, socklen_t *addrlen);
```

- Waits until a connection is made (unless the socket is non-blocking) to `sockfd`
  - which must be a socket on which `listen` has been called
- Returns the address of the other side of the connection in `addr`
- Returns the file descriptor for an accepted socket, i.e. the connection
  - This is used to send and receive data
  - The original socket continues to listen for more connections

Outline

Echo Server: Creating and Binding a socket

```
l = socket(AF_INET, SOCK_STREAM, 0);
if(l == -1) {
  perror("socket");
  exit(1);
}

struct sockaddr_in addr;

memset(&addr, 0, sizeof(addr));
addr.sin_family = AF_INET;
addr.sin_port = htons(5000);  /* convert to network byte order */
addr.sin_addr.s_addr = INADDR_ANY;

if(bind(l, (struct sockaddr *) &addr, sizeof(addr)) == -1) {
  perror("bind");
  exit(1);
}
```

Echo Server: Listening

```
if(listen(l, 1) == -1) {
  perror("listen");
  exit(1);
}
```

Echo Server: Accept Loop

```
struct sockaddr_in sender;
socklen_t addrlen = sizeof(sender);
int s, r;

char buf[256];

while((s = accept(l, (struct sockaddr *) &sender, &addrlen)) != -1) {
  r = recv(s, buf, 255, 0);
  if(r == -1) {
    perror("recv");

    close(s);
  } else {
    buf[r] = '\0';

    printf("received '%s'\n", buf);

    if(send(s, buf, r, 0) == -1) {
      perror("send");
    }

    close(s);
  }
}
```

Echo Client: Creating a socket

```
l = socket(AF_INET, SOCK_STREAM, 0);
if(l == -1) {
  perror("socket");
  exit(1);
}
```

Echo Server: Connecting

```
struct sockaddr_in addr;

memset(&addr, 0, sizeof(addr));
addr.sin_family = AF_INET;
addr.sin_port = htons(5000);
addr.sin_addr.s_addr = htonl(0x7f000001); // 127.0.0.1

if(connect(l, (struct sockaddr *) &addr, sizeof(addr)) == -1) {
  perror("connect");
  exit(1);
}
printf("connected\n");
```

Echo Server: Send/Recv

```
char buf[256];
int r;

r = scanf("%255s", buf);
if(r != 1) {
  perror("scanf");
  exit(1);
}

if(send(l, buf, strlen(buf)+1, 0) == -1) {
  perror("send");
  exit(1);
}

r = recv(l, buf, 255, 0);
if(r == -1) {
  perror("recv");
  exit(1);
} else {
  buf[r] = '\0';
  printf("got '%s'\n", buf);
}
```

Problems with the Echo Server

- The echo server handles one connection at a time
- It is serial
- What if a client connects but does not send a message?
  - What happens to clients who connected after that client?

References

- Chapter 11 of the textbook
  - And Chapter 12.2 which talks about I/O multiplexing (one solution to one client at a time)
- Read the manual pages for `socket` and pages related to it
  - Or read the GNU libc manual for sockets