Course topics

- **Networking background**
- **Local storage**
  - File systems, database consistency, crash recovery
- **Distributed file systems**
  - Scalability, security, availability, consistency
- **Storage Architectures**
  - Virtualizing storage, RAID, Storage-area networks
- **Other storage systems**
  - Untrusted storage, OO databases, peer-to-peer systems

Class overview

- **Readings & class discussion**
- **Solo labs:**
  - Asynchronous programming: multifinger
  - Network programming: TCP proxy
  - Encrypting file system
  - File server
- **Final project (in groups)**
- **Midterm and final quizes**

System calls

- **Problem: How to access resources other than CPU**
  - Disk, network, terminal, other processes
  - CPU prohibits instructions that would access devices
  - Only privileged OS "kernel" can access devices
- **Applications request I/O operations from kernel**
- **Kernel supplies well-defined *system call* interface**
  - Applications set up syscall arguments and *trap* to kernel
  - Kernel performs operation and returns result
- **Higher-level functions built on syscall interface**
  - `printf`, `scanf`, `gets`, etc. all user-level code

I/O through the file system

- **Applications "open" files/devices by name**
  - I/O happens through open files
- `int open(char *path, int flags, ...);`
  - `flags`: `O_RDONLY`, `O_WRONLY`, `O_RDWR`
  - `O_CREAT`: create the file if non-existent
  - `O_EXCL`: (w. `O_CREAT`) create if file exists already
  - `O_TRUNC`: Truncate the file
  - `O_APPEND`: Start writing from end of file
  - `mode`: final argument with `O_CREAT`
- **Returns file descriptor—used for all I/O to file**

Error returns

- **What if** `open` **fails? Returns -1 (invalid fd)**
- **Most system calls return -1 on failure**
  - Specific kind of error in global int `errno`
- `#include <sys/errno.h>` **for possible values**
  - 2 = `ENOENT` "No such file or directory"
  - 13 = `EACCES` "Permission Denied"
- `perror`, `strerror` **print human-readable messages**
  - `perror ("initfile");`
  - `printf ("initfile: %s\n", strerror (errno));`
    → "`initfile: No such file or directory`"

Operations on file descriptors

- `int read (int fd, void *buf, int nbytes);`
  - Returns number of bytes read
  - Returns 0 bytes at end of file, or -1 on error
- `int write (int fd, void *buf, int nbytes);`
  - Returns number of bytes read, -1 on error
- `off_t lseek (int fd, off_t pos, int whence);`
  - `whence`: 0 – start, 1 – current, 2 – end
    - Returns previous file offset, or -1 on error
- `int close (int fd);`
- `int fsync (int fd);`
  - Guarantee that file contents is stably on disk

Other system calls on pathnames

- `int chdir (const char *dir);`
  - Change working directory (what `cd` command does)
- `int mkdir (const char *dir);`
- `int rmdir (const char *dir);`
  - Make and remove direcories
- `int unlink (const char *path);`
  - Delete pathname specified by path
- `int link (const char *p1, const char *p1);`
  - Creates `p2`; `p1` & `p2` identical directory entries
- `int symlink (const char *p1, const char *p2);`
  - Creates `p2`; `p2` is an *alias* for name `p1`

The rename system call

- `int symlink (const char *p1, const char *p2);`
  - Changes name `p2` to reference file `p1`
  - Removes file name `p1`
- **Guarantees that `p2` will exist despite any crashes**
  - `p2` may still be old file
  - `p1` and `p2` may both be new file
  - but `p2` will always be old or new file
- `fsync`/`rename` **idiom used extensively**
  - E.g., emacs: Writes file `.#file#`
  - Calls `fsync` on file descriptor
  - `rename (".#file#", "file");`

File descriptor numbers

- **File descriptors are inherited by processes**
  - When one process spawns another, same fds by default
- **Descriptors 0, 1, and 2 have special meaning**
  - 0 – "standard input" (`stdin` in ANSI C)
  - 1 – "standard output" (`stdout, printf` in ANSI C)
  - 2 – "standard error" (`stderr, perror` in ANSI C)
  - Normally all three attached to terminal

Manipulating file descriptors

- `int dup2 (int oldfd, int newfd);`
  - Closes `newfd`, if it was a valid descriptor
  - Makes `newfd` an exact copy of `oldfd`
  - Two file descriptors will share same offset (`lseek` on one will affect both)
- `int fcntl (int fd, F_SETFD, int val)`
  - Sets *close on exec* flag if `val` = 1, clears if `val` = 0
  - Makes file descriptor non-inheritable by spawned programs

Pipes

- `int pipe (int fds[2]);`
  - Returns two file descriptors in `fds[0]` and `fds[1]`
  - Writes to `fds[1]` will be read on `fds[0]`
  - When last copy of `fds[1]` closed, `fds[0]` will return EOF
  - Returns 0 on success, -1 on error
- **Operations on pipes**
  - `read/write/close` – as with files
  - When `fds[1]` closed, `read(fds[0])` returns 0 bytes
  - When `fds[0]` closed, `write(fds[1])`:
    - Kills process with `SIGPIPE`, or if blocked
    - Fails with EPIPE

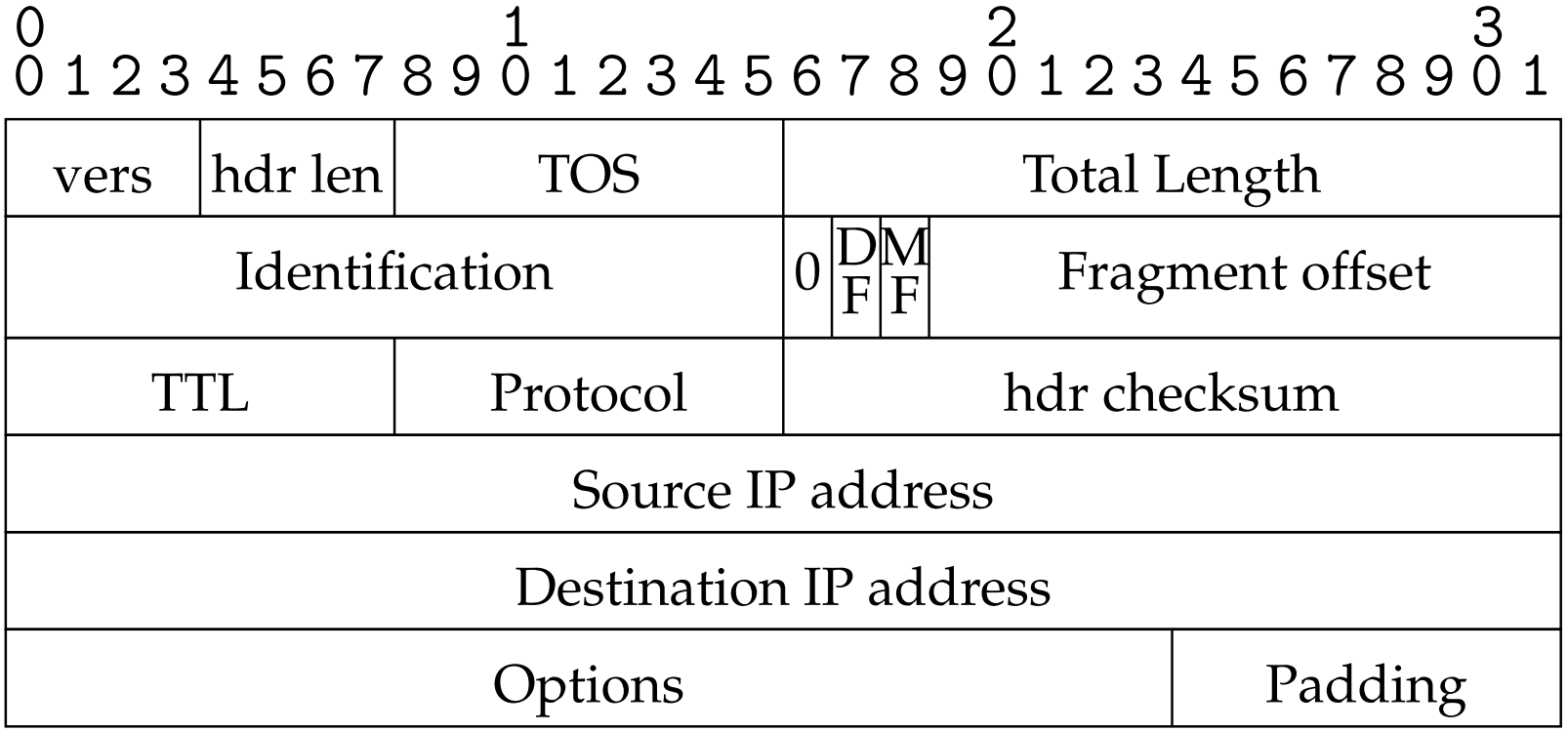
Sockets: Communication between machines

- **Datagram sockets: Unreliable message delivery**
  - On Internet: User Datagram Protocol (UDP)
  - Send atomic messages, which may be reordered or lost
  - Special system calls to read/write: `send/recv`
- **Stream sockets: Bi-directional pipes**
  - On Internet: Transmission Control Protocol (TCP)
  - Bytes written on one end read on the other
  - Reads may not return full amount requested—must re-read

Socket naming

- **Every Internet host has a unique 32-bit *IP address***
  - Often written in "dotted-quad" notation: 204.168.181.201
  - DNS protocol maps names (www.nyu.edu) to IP addresses
  - Network routes packets based on IP address
- **16-bit *port number* demultiplexes TCP traffic**
  - Well-known services "listen" on standard ports: finger—79, HTTP—80, mail—25, ssh—22
  - Clients connect from arbitrary ports to well known ports
  - A connection consists of five components: Protocol (TCP), local IP, local port, remote IP, remote port
- **All Internet traffic routed as small packets**
  - Each packet contains address information in header

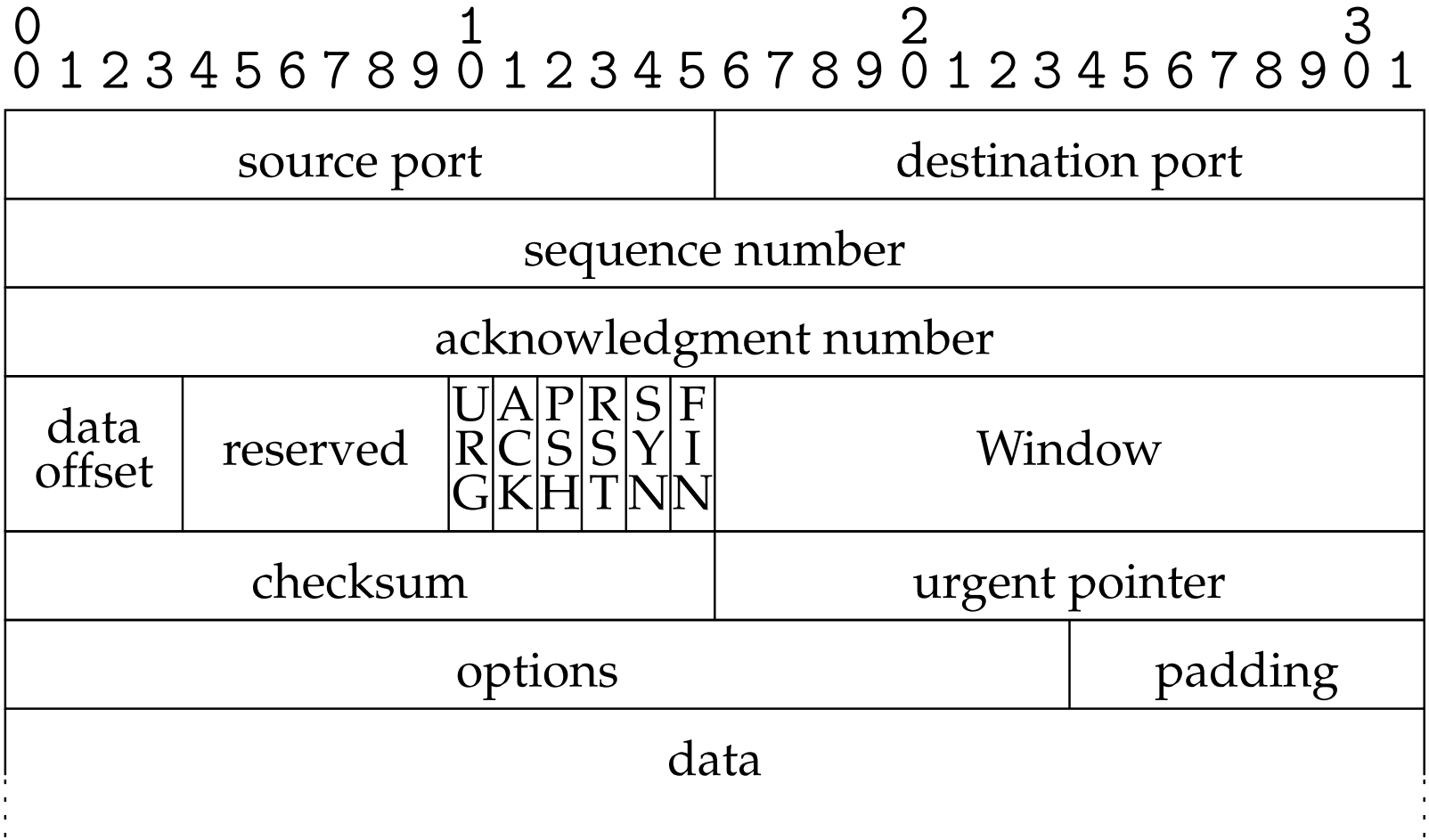
IP header


0 1 2 3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
vers
hdr len
TOS
Total Length
Identification
0
DF
MF
Fragment offset
TTL
Protocol
hdr checksum
Source IP address
Destination IP address
Options
Padding

IP header details

- **Routing is based on destination address**
- **TTL (time to live) decremented at each hop (avoids loops)**
- **Fragmentation used for large packets**
  - Fragmented in network if links crossed with smaller MTU
  - MF bit means more fragments for this IP packet
  - DF bit says "don't fragment" (returns error to sender)
- **Almost always want to avoid fragmentation**
  - When fragment is lost, whole packet must be retransmitted
- **Following IP header is "payload" data**
  - Typically beginning with TCP or UDP header

TCP header


0 1 2 3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
source port
destination port
sequence number
acknowledgment number
data offset
reserved
URG
ACK
PSH
RST
SYN
FIN
Window
checksum
urgent pointer
options
padding
data

TCP fields

- Ports
- Seq no. – segment position in byte stream
- Ack no. – seq no. sender expects to receive next
- Data offset – # of 4-byte header & option words
- Window – willing to receive (flow control)
- Checksum
- Urgent pointer

TCP Flags

- **URG – urgent data present**
- **ACK – ack no. valid (all but first segment)**
- **PSH – push data up to application immediately**
- **RST – reset connection**
- **SYN – "synchronize" establishes connection**
- **FIN – close connection**

A TCP Connection (no data)

```
orchard.48150 > essex.discard:
        S 1871560457:1871560457(0) win 16384
essex.discard > orchard.48150:
        S 3249357518:3249357518(0) ack 1871560458 win 17376
orchard.48150 > essex.discard: . ack 1 win 17376
orchard.48150 > essex.discard: F 1:1(0) ack 1 win 17376
essex.discard > orchard.48150: . ack 2 win 17376
essex.discard > orchard.48150: F 1:1(0) ack 2 win 17376
orchard.48150 > essex.discard: . ack 2 win 17375
```

Connection establishment

- **Three-way handshake:**
  - $C \rightarrow S$: SYN, seq S_C
  - $S \rightarrow C$: SYN, seq S_S, ack $S_C + 1$
  - $C \rightarrow S$: ack $S_S + 1$
- **If no program listening: server sends RST**
- **If server backlog exceeded: ignore SYN**
- **If no SYN-ACK received: retry, timeout**

Connection termination

- **FIN bit says no more data to send**
  - Caused by close or shutdown on sending end
  - Both sides must send FIN to close a connection
- **Typical close:**
  - $A \rightarrow B$: FIN, seq S_A, ack S_B
  - $B \rightarrow A$: ack $S_A + 1$
  - $B \rightarrow A$: FIN, seq S_B, ack $S_A + 1$
  - $A \rightarrow B$: ack $S_B + 1$
- **Can also have simultaneous close**
- **After last message, can A and B forget about closed socket?**

TIME_WAIT

- **Problems with closed socket**
  - What if final ack is lost in the network?
  - What if the same port pair is immediately reused for a new connection? (Old packets might still be floating around.)
- **Solution: "active" closer goes into TIME_WAIT**
  - Active close is sending FIN before receiving one
  - After receiving ACK and FIN, keep socket around for 2MSL (twice the "maximum segment lifetime")
- **Can pose problems with servers**
  - OS has too many sockets in TIME_WAIT, slows things down
  - Hack: Can send RST and delete socket, set SO_LINGER socket option to time 0 (useful for benchmark programs)

Sending data

- **Data sent in MSS-sized segments**
  - Chosen to avoid fragmentation (e.g., 1460 on ethernet LAN)
  - Write of 8K might use 6 segments—PSH set on last one
  - PSH avoids unnecessary context switches on receiver
- **Sender's OS can delay sends to get full segments**
  - Nagle algorithm: Only one unacknowledged short segment
  - TCP_NODELAY option avoids this behavior
- **Segments may arrive out of order**
  - Sequence number used to reassemble in order
- **Window achieves flow control**
  - If window 0 and sender's buffer full, write will block or return EAGAIN

A TCP connection (3 byte echo)

```
orchard.38497 > essex.echo:
        S 1968414760:1968414760(0) win 16384
essex.echo > orchard.38497:
        S 3349542637:3349542637(0) ack 1968414761 win 17376
orchard.38497 > essex.echo: . ack 1 win 17376
orchard.38497 > essex.echo: P 1:4(3) ack 1 win 17376
essex.echo > orchard.38497: . ack 4 win 17376
essex.echo > orchard.38497: P 1:4(3) ack 4 win 17376
orchard.38497 > essex.echo: . ack 4 win 17376
orchard.38497 > essex.echo: F 4:4(0) ack 4 win 17376
essex.echo > orchard.38497: . ack 5 win 17376
essex.echo > orchard.38497: F 4:4(0) ack 5 win 17376
orchard.38497 > essex.echo: . ack 5 win 17375
```

Delayed ACKs

- **Goal: Piggy-back ACKs on data**
  - Echo server just echoes, why send separate ack first?
  - Delay ACKs for 200 msec in case application sends data
  - If more data received, immediately ACK second segment
  - Note: Never delay duplicate ACKs (if segment out of order)
- **Warning: Can interact badly with Nagle**
  - "My login has 200 msec delays"
  - Set TCP_NODELAY
  - In `libasync` library, call `tcp_nodelay (fd);`

Retransmission

- **TCP dynamically estimates round trip time**
- **If segment goes unacknowledged, must retransmit**
- **Use exponential backoff (in case loss from congestion)**
  - Optimization in case of single lost packet—just halve sending rate
- **After $\sim$10 minutes, give up and reset connection**

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

Example client

```
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);
```

Example server

```
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, (sockaddr *) &sin, sizeof (sin));
listen (s, 5);

for (;;) {
  socklen_t len = sizeof (sin);
  int cfd = accept (s, (sockaddr *) &sin, &len);
  /* do something with cfd */
  close (cfd);
}
```

Concurrent connections

- **Servers must handle multiple clients concurrently**
  - Read or write of a socket connected to slow client can block
  - Overlap network latency with CPU, transmission, disk I/O
  - Keep disk queues full when server accesses disk
- **Can use one process per client: accept, fork, close**
  - High overhead, cannot share state between clients
- **Can use threads for concurrency**
  - Data races and deadlock make programming tricky
  - Must allocate one stack per request
- **Use non-blocking read/write calls**
  - Unusual programming model

Non-blocking I/O

- `fcntl` **sets** `O_NONBLOCK` **flag on descriptor**
  - In `libasync`, can call `make_async (fd);`
- **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 real error like `ECONNREFUSED`)
  - `accept` may fail with `EAGAIN` if no pending connections

How do you know when to read/write?

```
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);
```

Asynchronous programming model

- **Many non-blocking file descriptors in one process**
  - Wait for pending I/O events on file many descriptors
  - Each event triggers some *callback* function
- **Lab:** `libasync` **– supports event-driven model**
  - Register callbacks on file descriptors
  - Call `amain()` – main select loop
  - Add/delete callbacks from within callbacks

`callback.h`

- **Problem: Need state from one callback to next**
- `wrap` **bundles a function with its arguments**

```
callback<void, int>::ref errwrite = wrap (write, 2);
(*errwrite) ("hello", 5);  // writes "hello" to stderr
```

- `void fdcb(int fd, selop op, cb_t cb);`
  registers callbacks on file descriptor `fd`
  - `op` is `selread` or `selwrite`
  - `cb` is void callback (no arguments), or `NULL` to clear

libasync example server

```
void doaccept (int lfd) {
  sockaddr_in sin;
  bzero (&sin, sizeof (sin));
  socklen_t sinlen = sizeof (sin);
  int cfd = accept (lfd, (sockaddr *) &sin, &sinlen);
  if (cfd >= 0) { /* ... */ }
}
int main (int argc, char **argv) {
  // ...
  int lfd = inetsocket (SOCK_STREAM, your_port, INADDR_ANY);
  if (lfd < 0) fatal << "socket: " << strerror (errno) << "\n";
  if (listen (lfd, 5) < 0) fatal ("listen: %m\n");
  fdcb (lfd, selread, wrap (doaccept, lfd));
  amain ();
}
```

Remote procedure call

- **Abstract away network in distributed programs**
  - Idea: Distributed programming looks like function call
  - Reality: Can't abstract away everything (e.g., failure)
- **Next class: Sun RPC**
  - XDR defines structures that can be transmitted on the wire
  - RPC is simple layer that sends arg. structs and gets returns