

Life, Liberty, and the Pursuit of... **Sockets!**

15-441: Computer Networks

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Getting Help

Google Group

Check regularly and post your questions here. Others likely have the same questions!

<https://groups.google.com/forum/#!forum/cmu-15-441-fall-2013>

Course Staff

Don't email individually unless your question is specific to particular instructors/TAs.

staff-441@cs.cmu.edu

Many thanks to

Wolfgang Richter
Athula Balachandran

for some fantastic materials

for the original Fall 2011 materials, see
<https://github.com/theonewolf/15-441-Recitation-Sessions>

Recitation Slides in 2 Places

Course Website — PDF

<http://www.cs.cmu.edu/~prs/15-441-F13/>

GitHub — PDF + Extras

`git clone git@github.com:dtaylor/15-441-Recitation-Sessions.git`

Extras



echo_client.c
echo_server.c

Who took 15-213?

And made an HTTP proxy?

Project 1: HTTP déjà vu

- Blast from the past 15-213
- This time a real HTTP server with:
 - **SSL**
 - `select()` IO for concurrent connections
 - **HTTP 1.1**
 - **CGI**
- Big project, **start early!**

What's in a socket?

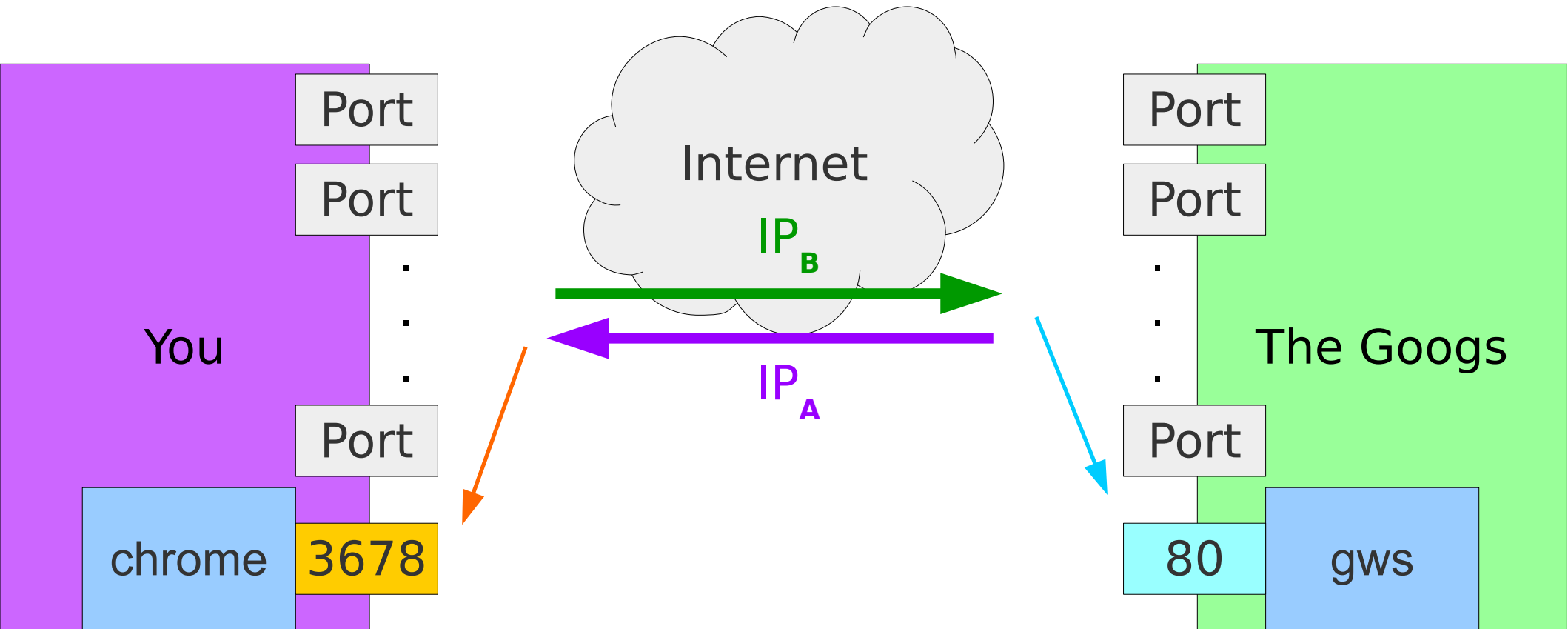
- I want computer A to talk to computer B?
- But how:
 - **Request-Reply**: Synchronous, RPC
 - **Publish-Subscribe**: Asynchronous, Broadcast
 - **Push-Pull**: Worker queue, Round Robin
- Source (IP/TCP) <ip,port>
- Destination (IP/TCP) <ip,port>

What's “in” a socket?

I want a program on computer A to talk to a program on computer B

Source <ip,port> + Destination <ip,port>

IP? Port!?



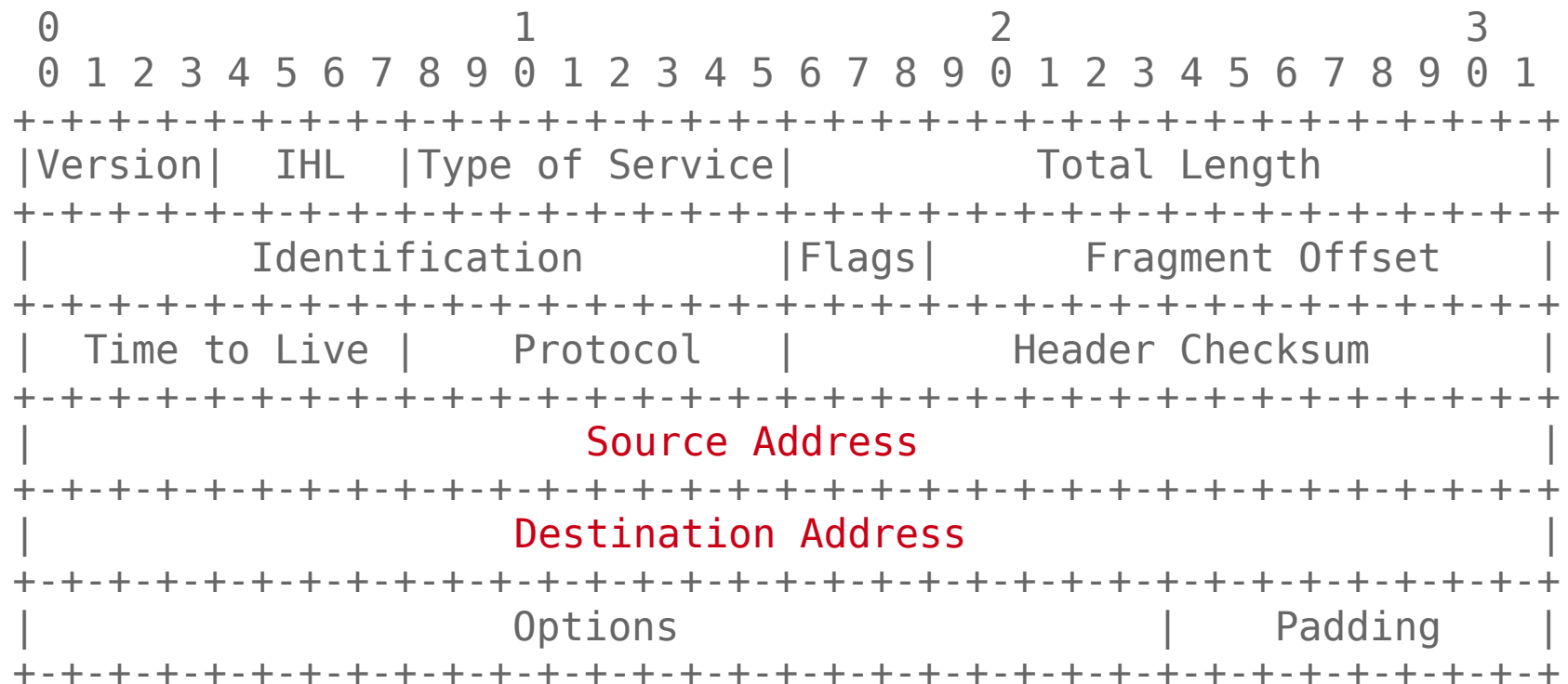
Source $\langle \text{ip}, \text{port} \rangle$ + Destination $\langle \text{ip}, \text{port} \rangle$

Identifies the
Machine

Identifies a Socket
(multiple apps want to network!)

IPv4 Details: RFC791

<http://www.ietf.org/rfc/rfc791.txt>

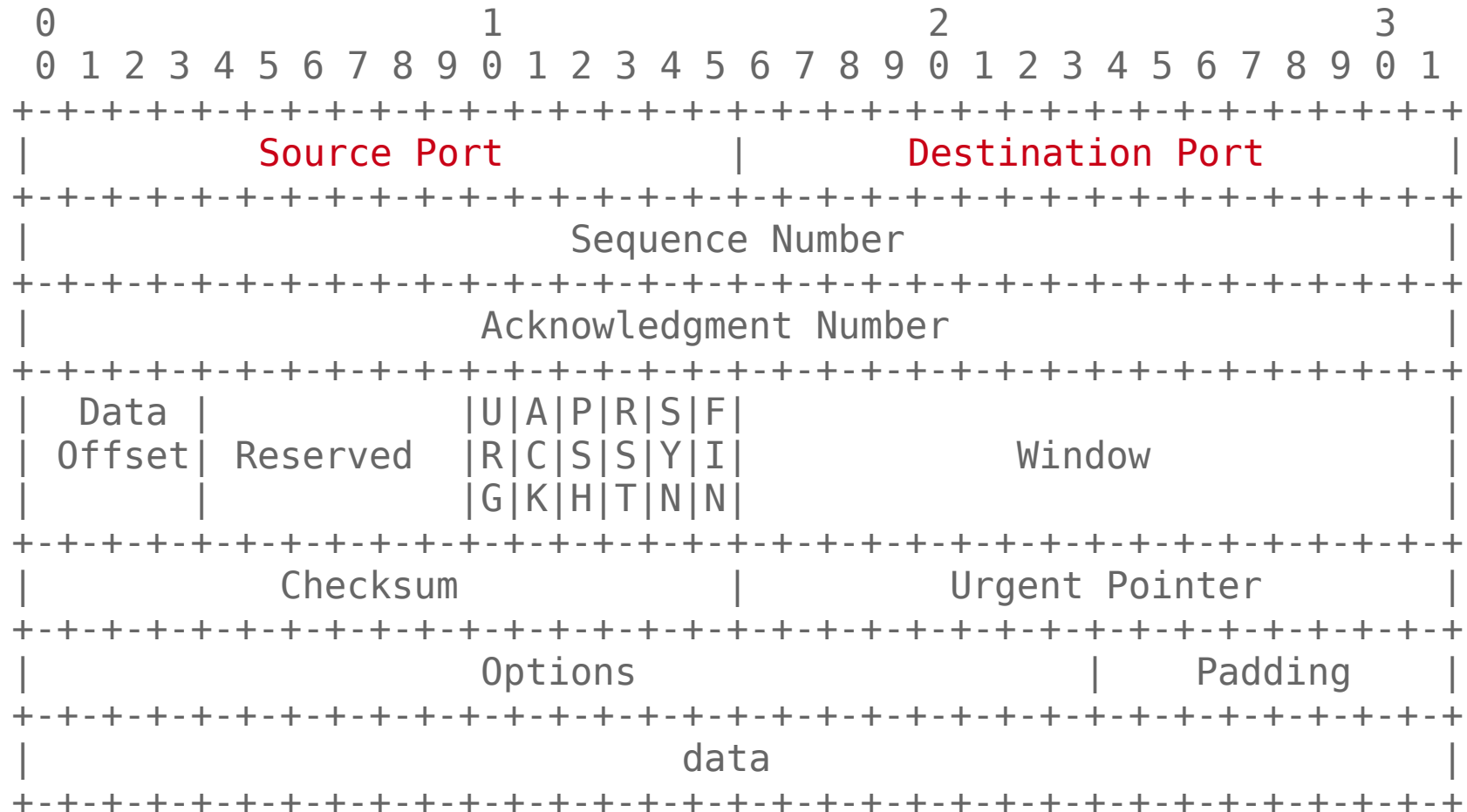


Example Internet Datagram Header

Figure 4.

TCP Details: RFC793 + Others

<http://www.ietf.org/rfc/rfc793.txt>



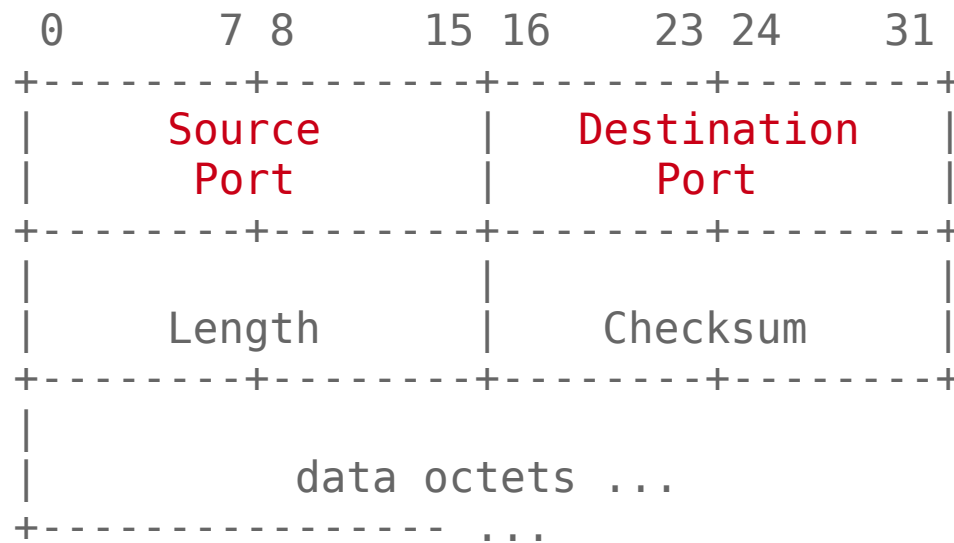
TCP Header Format

Note that one tick mark represents one bit position.

Figure 3.

UDP Details: RFC768

<http://www.ietf.org/rfc/rfc768.txt>



User Datagram Header Format

The Network Stack

Linux Stack

Application

Chrome

User Space

Application Layer

Application Layer

HTTP

Kernel Space

System Call

Transport Layer

TCP

Protocol Agnostic

Network Layer

IP

Network Protocols

Link Layer

Ethernet Driver

Device Agnostic

Hardware Layer

Ethernet

Device Drivers

Physical Hardware

IP Addresses

- 32 bit—4,294,967,296 possible addresses
- Assigned by IANA
(Internet Assigned Numbers Authority)

Port Numbers

- 16 bit—65,536 possible ports [0,65535]
- [0,1023] are well-known ports (reserved)
 - 80 — Hypertext Transport Protocol (HTTP)
 - 22 — Secure Shell (SSH)
 - 25 — Simple Mail Transfer Protocol (SMTP)
- [1024,49151] are registered ports (IANA)
 - 2967 — Symantec AntiVirus
 - 3074 — XBOX Live
- [49152,65535] are ephemeral ports (temp)

How to: Server

- Create a socket via `socket()`
- Bind to an endpoint via `bind()`
- Listen for connections via `listen()`
- Accept connections via `accept()`
- Read from socket via `recv()`
- Write to socket via `send()`

socket()

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

```
int socket(int socket_family, int socket_type, int protocol);
```

Generally set `socket_family` to `PF_INET` → IPv4

`socket_type` to `SOCK_STREAM` → TCP

`protocol` to `0` → Yes, TCP

socket() Code Example

```
#include <stdio.h>
#include <stdlib.h>
#include <sys/socket.h>

int main(int argc, char* argv[])
{
    int sock = socket(PF_INET, SOCK_STREAM, 0);
    return EXIT_SUCCESS;
}
```

socket_family

Family	Meaning
PF_UNIX, PF_LOCAL	Local communication
PF_INET	IPv4
PF_INET6	IPv6
PF_IPX	IPX - Novell
PF_NETLINK	Kernel user interface device
PF_X25	ITU-T X.25
PF_AX25	Amateur radio AX.25
PF_ATMPVC	Raw ATM PVCs
PF_APPLETALK	Appletalk
PF_PACKET	Low level packet interface

socket_type

Type	Meaning
SOCK_STREAM	Sequenced, reliable TCP
SOCK_DGRAM	Connectionless UDP
SOCK_SEQPACKET	SOCK_STREAM w/ fixed length
SOCK_RAW	Raw network protocol access
SOCK_RDM	Reliable datagram no order
SOCK_PACKET	Deprecated

socket () Error States

Type	Meaning
EACCESS	Permission denied
EAFNOSUPPORT	Address family unsupported
EINVAL	Unknown protocol
EMFILE	Process file table overflow
ENFILE	Total open files limit reached
ENOBUFS or ENOMEM	System out of memory
EPROTONOSUPPORT	Specified protocol not supported

bind()

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

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

After creating a socket as described, then create a `sockaddr` struct.

bind() Code Example

```
#include <stdio.h>
#include <stdlib.h>
#include <sys/socket.h>
#include <netinet/in.h>

int main(int argc, char* argv[])
{
    int sock = socket(PF_INET, SOCK_STREAM, 0);
    struct sockaddr_in addr;
    addr.sin_family = AF_INET;
    addr.sin_port = htons(1025);
    addr.sin_addr.s_addr = INADDR_ANY;
    int err = bind(sock, (struct sockaddr *)
                  &addr, sizeof(addr));
    return EXIT_SUCCESS;
}
```


sin_family

Address Family	Meaning
AF_INET	IPv4
AF_INET6	IPv6
AF_UNIX	Local communication
AF_APPLETALK	Appletalk addressing
AF_PACKET	Packet addressing
AF_X25	ITU-T X.25 addressing
AF_NETLINK	Between kernel and user

sin_port

- Set to port you want to **connect/listen**

Conversion Function	Explanation
uint16_t htons(uint16_t)	Host to network short
uint32_t htonl(uint32_t)	Host to network long
uint16_t ntohs(uint16_t)	Network to host short
uint32_t htonl(uint32_t)	Network to host long

bind() Error States

Type	Meaning
EADDRINUSE	Address in use already
EBADF	Invalid socket
EINVAL	Socket already bound
ENOTSOCK	File descriptor, not socket

listen()

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

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

After `bind()`ing, you can `listen()` for connections.

listen() Code Example

```
#include <stdio.h>
#include <stdlib.h>
#include <sys/socket.h>
#include <netinet/in.h>

int main(int argc, char* argv[])
{
    int sock = socket(PF_INET, SOCK_STREAM, 0);
    struct sockaddr_in addr;
    addr.sin_family = AF_INET;
    addr.sin_port = htons(1025);
    addr.sin_addr.s_addr = INADDR_ANY;
    int err = bind(sock, (struct sockaddr *)
                  &addr, sizeof(addr));
    int err2 = listen(sock, 5);
    return EXIT_SUCCESS;
}
```

backlog

- Queue length for incoming sockets
- Fully established already

listen() Error States

Type	Meaning
EADDRINUSE	Port already listened to
EBADF	Not a valid descriptor
ENOTSOCK	Not a socket passed in
EOPNOTSUPP	Can't listen() on this socket

accept ()

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

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

After `listen()`ing, you can `accept()` connections.

Pass in the socket from before, and **pointers to data structures defined by you**.

These **represent connected client state** for future use.

accept() Code Example

```
#include <stdio.h>
#include <stdlib.h>
#include <sys/socket.h>
#include <netinet/in.h>

int main(int argc, char* argv[])
{
    int sock = socket(PF_INET, SOCK_STREAM, 0);
    struct sockaddr_in addr, caddr;
    addr.sin_family = AF_INET;
    addr.sin_port = htons(1025);
    addr.sin_addr.s_addr = INADDR_ANY;
    int err = bind(sock, (struct sockaddr *)&addr, sizeof(addr));
    int err2 = listen(sock, 5);
    socklen_t len = sizeof(caddr);
    int client = accept(sock, (struct sockaddr *)&caddr, &len);
    return EXIT_SUCCESS;
}
```

accept () Error States 1

Type	Meaning
EAGAIN or EWOULDBLOCK	No connections, non-blocking
EBADF	Not a valid descriptor
ECONNABORTED	Connection was aborted
EINTER	Interrupted before connection
EINVAL	Socket not listening
EMFILE	Per-process open file limit reached
ENFILE	System open file limit reached

accept () Error States 2

Type	Meaning
ENOTSOCK	Descriptor of file, not socket
EOPNOTSUPP	Socket is not SOCK_STREAM
EFAULT	Can not write to addr
ENOBUFS, ENOMEM	Out of memory
EPROTO	Protocol error
EPERM	Firewall rules forbid connection

recv()

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

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

After accept()ing, you can recv() data.

For now set flags to 0

recv() Code Example

```
#include <stdio.h>
#include <stdlib.h>
#include <sys/socket.h>
#include <netinet/in.h>

int main(int argc, char* argv[])
{
    char buf[256];
    int sock = socket(PF_INET, SOCK_STREAM, 0);
    struct sockaddr_in addr, caddr;
    addr.sin_family = AF_INET;
    addr.sin_port = htons(1025);
    addr.sin_addr.s_addr = INADDR_ANY;
    int err = bind(sock, (struct sockaddr *)
                  &addr, sizeof(addr));
    int err2 = listen(sock, 5);
    socklen_t len = sizeof(caddr);
    int client = accept(sock, (struct sockaddr *)
                      &caddr, &len);
    ssize_t read = recv(client, buf, 256, 0);
    return EXIT_SUCCESS;
}
```

flags

Flag	Meaning
MSG_DONTWAIT	Non-blocking check for data
MSG_ERRQUEUE	Receive errors from socket
MSG_OOB	Out-of-band data request
MSG_PEEK	Return data without removing
MSG_TRUNC	Return real packet length
MSG_WAITALL	Block until full request satisfied

recv () Error States 1

Type	Meaning
EAGAIN	Would block but not supposed
EBADF	Not a valid descriptor
ECONNREFUSED	Remote host refused conn
EFAULT	Receive buffer pointer bad
EINTER	Receive interrupted by interrupt
EINVAL	Invalid argument passed
ENOMEM	Out of Memory
ENOTCONN	Socket not connected yet
ENOTSOCK	Socket argument isn't a socket

send()

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

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

After accept()ing, you can send() data.

For now set flags to 0

send() Code Example

```
#include <stdio.h>
#include <stdlib.h>
#include <sys/socket.h>
#include <netinet/in.h>

int main(int argc, char* argv[])
{
    char buf[256];
    int sock = socket(PF_INET, SOCK_STREAM, 0);
    struct sockaddr_in addr, caddr;
    addr.sin_family = AF_INET;
    addr.sin_port = htons(1025);
    addr.sin_addr.s_addr = INADDR_ANY;
    int err = bind(sock, (struct sockaddr *)
                    &addr, sizeof(addr));
    int err2 = listen(sock, 5);
    socklen_t len = sizeof(caddr);
    int client = accept(sock, (struct sockaddr *)
                       &caddr, &len);
    ssize_t sent = send(client, buf, 256, 0);
    return EXIT_SUCCESS;
}
```

flags

Flag	Meaning
MSG_CONFIRM	Link layer forward progress
MSG_DONTROUTE	Don't use a gateway
MSG_DONTWAIT	Non-blocking send
MSG_EOR	Terminate record
MSG_MORE	Caller has more data to send
MSG_NOSIGNAL	No SIGPIPE on error
MSG_OOB	Send out-of-band data

send () Error States 1

Type	Meaning
EACCESS	Write permission denied
EAGAIN or EWOULDBLOCK	Block not supposed to
EBADF	Invalid descriptor specified
ECONNRESET	Connection reset by peer
EDESTADDRREQ	Not connecting, no peer set
EFAULT	Invalid user address specified
EINTER	Signal interrupt
EINVAL	Invalid argument
EISCONN	Connected already

send () Error States 2

Type	Meaning
EMSGSIZE	Atomic send, too big message
ENOBUFS	Output queue physically full
ENOMEM	Out of memory
ENOTCONN	Socket not connected
ENOTSOCK	Argument is not a socket
EOPNOTSUPP	Some flags are incorrect
EPIPE	Local end shutdown

How to: Client

- Create a socket via `socket()`
- Connect to an endpoint via `connect()`
- Read from socket via `recv()`
- Write to socket via `send()`

connect()

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

```
int connect(int socket, const struct sockaddr *serv_addr, socklen_t protocol);
```

Use socket as before, get **serv_addr** from `getaddrinfo()`.

Free with `freeaddrinfo()`.

connect() Code Example

```
#include <netdb.h>
#include <stdlib.h>
#include <string.h>
#include <sys/socket.h>

int main(int argc, char* argv[])
{
    struct addrinfo addr, *caddr;
    memset(&addr, 0, sizeof(addr));
    addr.ai_family = AF_UNSPEC;
    addr.ai_socktype = SOCK_STREAM;
    getaddrinfo("www.google.com", "80", &addr, &caddr);
    int sock = socket(caddr->ai_family, caddr->ai_socktype,
                     caddr->ai_protocol);
    connect(sock, caddr->ai_addr, caddr->ai_addrlen);
    return EXIT_SUCCESS;
}
```

ai_family

Family	Meaning
AF_UNSPEC	Any protocol family
AF_INET	IPv4
AF_INET6	IPv6

connect () Error States 1

Type	Meaning
EACCESS	Permission denied
EACCESS, EPERM	Connect broadcast without flag
EADDRINUSE	Local address already in use
EAFNOSUPPORT	Incorrect address family
EAGAIN	No more free local ports
EALREADY	Non-blocking, previous incomplete connection
EBADF	File descriptor not valid

connect () Error States 2

Type	Meaning
ECONNREFUSED	No remote listening socket
EFAULT	Socket address structure outside user address space
EINPROGRESS	Non-blocking, cannot immediately connect
EINTER	Interrupt by caught signal
EISCONN	Socket already connected
ENETUNREACH	Unreachable network
ENOTSOCK	File descriptor not a socket

Socket Programming Gotchas

- **Endianness Matters: Network Byte Order**
 - `htons()` - host to network short
 - `ntohs()` - network to host short
- **Cleanup state—avoid memory leaks**
 - `freeaddrinfo()`
 - Check correctness with `valgrind`
- **Error Handling**
 - Tedious, but worth it (and required!)
- **Timeouts**
 - Implement for robust networking behavior

Socket Programming Gotchas

- **Never expect to `recv()` what you `send()`**
 - Assume partial receipt of data possible
 - Use buffers intelligently to mitigate this
 - Send byte counts first, read until finished
- **Prepare your code for random failures**
 - We introduce random faults when grading
 - Test too—`ctrl+c` server and client randomly
- **Cleanup Allocated Memory**
 - `close()` sockets, etc.

Concurrency

- Threads
 - Server gives each client its own thread
 - Not in this class!
- `select()`
 - Watch a **set of sockets** (in main thread)
 - Use `select()` to find sockets ready for I/O
 - Server-side only—clients are agnostic

select()

```
#include <sys/select.h>

int select(int nfds, fd_set *readfds, fd_set *writefds,
           fd_set *exceptfds, struct timeval *timeout);

void FD_CLR(int fd, fd_set *set);
int  FD_ISSET(int fd, fd_set *set);
void FD_SET(int fd, fd_set *set);
void FD_ZERO(fd_set *set);
```

After accept()ing, you timeout poll using select().
Manipulate set of descriptors with FD_*, then select().

Error Checking

- Read documentation first
- Sometimes you need to:

```
#include <errno.h>
```

```
...
```

```
switch (errno)  
{
```

```
...
```

```
}
```

System Call Documentation:

POSIX – Portable Operating System Interface for Unix
IEEE 1003.1-2008, The Open Group

“POSIX.1-2008 defines a standard operating system interface and environment, including a command interpreter (or “shell”), and common utility programs to support applications portability at the source code level.”

<http://pubs.opengroup.org/onlinepubs/9699919799/>

Also, more correct, **your system's man pages!**

Another excellent resource:

Beej's Guide to Network Programming

<http://beej.us/guide/bgnet/>

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