TECHNION

Azrieli Continuing Education and External Studies Division

Module 5.7.2 : Network Programming

Socket API?

- Q. What would you expect when learning a new Unix command (*e.g., ls*) ?
  a) Source code
  b) Program options

=> Implementation detail

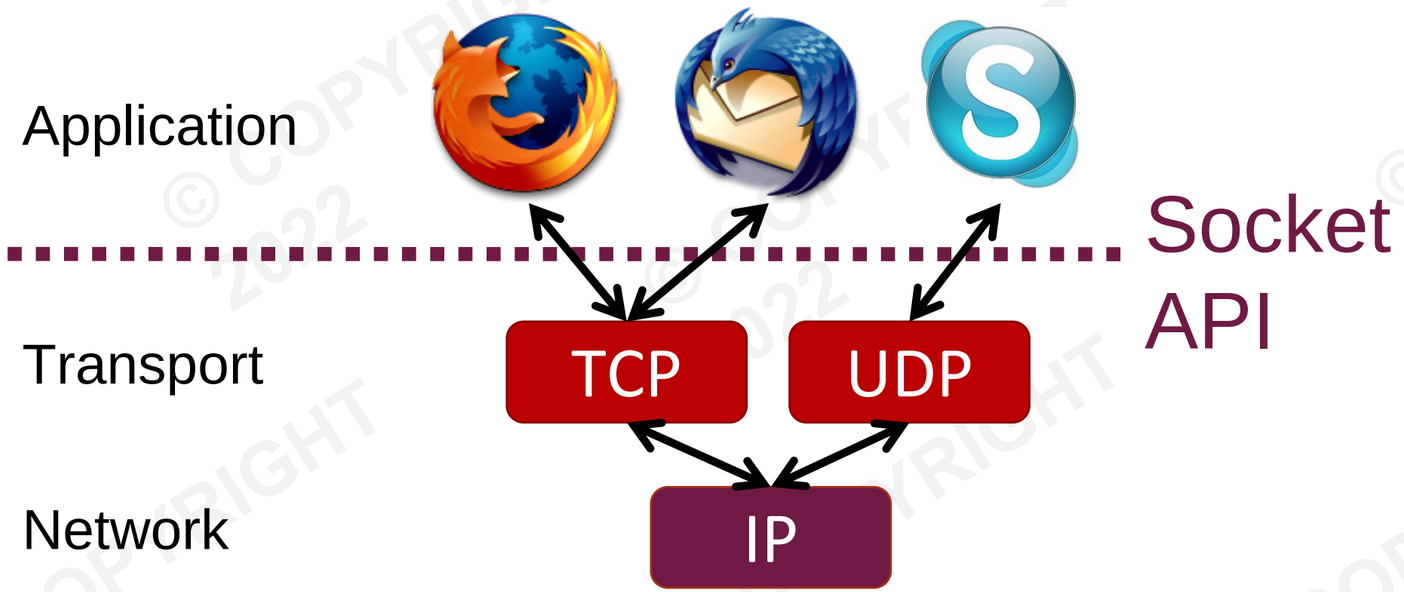
=> Interface

- *Application Programming Interface (API)*
  - Interface to a particular “service”
  - Abstracts away from implementation detail
  - Set of functions, data structures, and constants.

- Socket API
  - Network programming interface

Socket API

- Socket API
  - Network programming interface



BSD Socket API

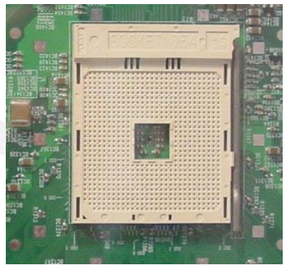
- Developed at UC Berkeley (1980's)
- Most popular network API
- Ported to various OSes, various languages
  - Windows Winsock, BSD, OS X, Linux, Solaris, …
  - Socket modules in Java, Python, Perl, …
- Similar to Unix file I/O API
  - In the form of *file descriptor* (type of handler).
  - Can share the same "read()/write()/close()" system calls.

Outline

- Socket API motivation, background
- Types of sockets (TCP vs. UDP)
- Elementary API functions
- I/O multiplexing
- Project 1 – tiny World of Warcraft
- Appendix (not covered in the lecture)

Sockets

- Various sockets… Any similarity?


- Endpoint of a connection
  - Identified by IP address and Port number

- Primitive to implement high-level networking interfaces
  - e.g., Remote procedure call (RPC)

Types of Sockets

Stream Socket (aka TCP)

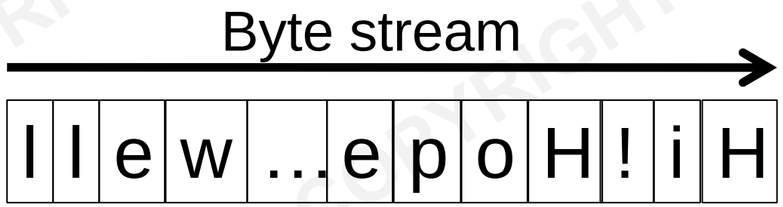
- Connection-oriented
  - Requires connection, establishment, and termination
- Reliable delivery
  - Orderly delivery
  - Retransmission
  - No duplicates
- High variance in latency
  - Cost of the service
- File-like interface (streaming)
- E.g., HTTP, SSH, FTP, …

Datagram socket (aka UDP)

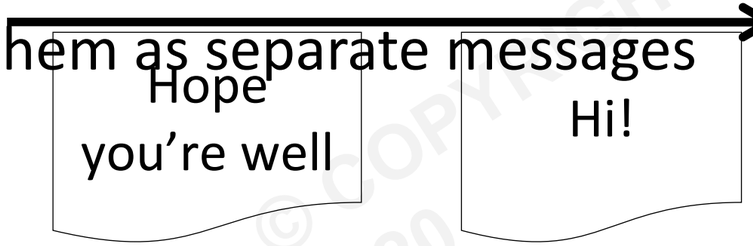
- Connection-less
- “Best-effort” delivery
  - Possible out-of-order delivery
  - No retransmission
  - Possible duplicates
- Low variance in latency
  - Cost of the service
- Packet-like interface
  - Requires packetizing
- E.g., DNS, VoIP, VOD, AOD, …

Types of Sockets (cont'd)

- When sending "Hi!" and "Hope you're well"
- TCP treats them as a single byte stream



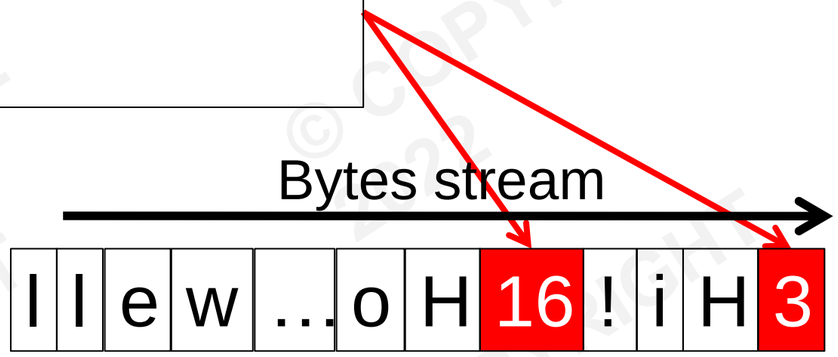
- UDP treats them as separate messages



Types of Sockets (cont'd)

- Thus, TCP requires application-level message boundary.
  - By carrying length in application-level header
  - E.g.

```
struct my_app_hdr {
        int length
}
```

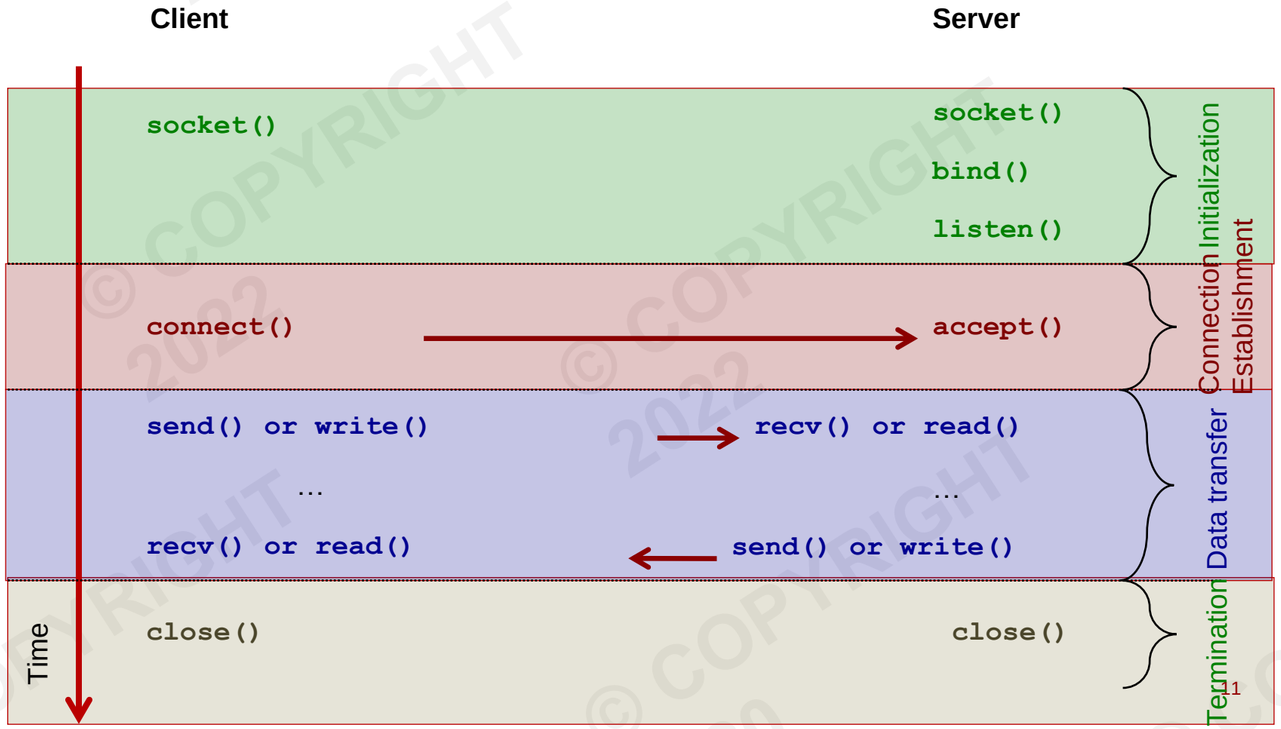


Outline of the Sockets

- Socket API motivation, background
- Types of sockets (TCP vs. UDP)
- Elementary API functions
- I/O multiplexing
- Project 1 – tiny World of Warcraft

Scenario #1 – TCP client-server

- Sequence of actions



Initialization: server + client, `socket()`

```
int sock = socket(AF_INET, SOCK_STREAM, 0);
if (sock < 0) {
  perror("socket() failed");
  abort();
}
```

- **`socket()`: returns a socket descriptor**
- **`AF_INET`: IPv4 address family.** (also OK with PF_INET)
  - C.f. IPv6 => AF_INET6
- **`SOCK_STREAM`: streaming socket type**
  - C.f. SOCK_DGRAM
- **`perror()`**: prints out an error message

Error Code in Unix Programming

```
extern int  errno;    // by #include <errno.h>
```

- Many Unix system calls and library functions set "`errno`" on errors.

- Macros for error codes ('E' + error name)
  - `EINTR, EWOULDBLOCK, EINVAL, …`
  - "`man` *func_name*" shows possible error code for the function name.

- Functions to convert error code into human-readable messages.
  - `void perror(const char *my_str)`
    - Always looks for **`errno`**
    - Prints "my str: error code string"

  - `const char *strerror(int err_code)`
    - You must provide an error code.
    - returns a string for the `err_code`.

Initialization: server, `bind()`

- The server needs to bind a particular port number.

```
struct sockaddr_in sin;

memset(&sin, 0, sizeof(sin));

sin.sin_family = AF_INET;

sin.sin_addr.s_addr = INADDR_ANY;

sin.sin_port = htons(server_port);



if (bind(sock, (struct sockaddr *) &sin, sizeof(sin)) < 0) {

    perror("bind failed");

    abort();

}
```

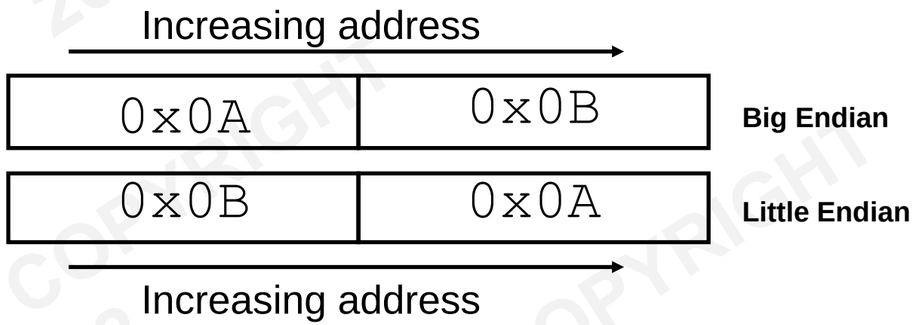
- **`bind()`**: binds a socket with a particular port number.
  - Kernel remembers which process has bound with which port(s).
  - Only one process can bind a particular port number at a time.

- **struct sockaddr_in**: Ipv4 socket address structure. (c.f., struct sockaddr_in6)

- **INADDR_ANY**: If server has multiple IP addresses, binds any address.

Endians

- Q) You have a 16-bit number: 0x0A0B. How is it stored in memory?



- Host byte order is not uniform
  - Some machines are Big endian, others are Little endian

- Communicating between machines with different host byte orders is problematic
  - Transferred $256 (0x0100), but received $1 (0x0001)

Endians (cont'd)

- Network byte order: Big endian
  - To avoid the endian problem
- We must use the network byte order when sending 16bit, 32bit and 64bit numbers.
- Utility functions for easy conversion:

```
uint16_t htons(uint16_t host16bitvalue);

uint32_t htonl(uint32_t host32bitvalue);

uint16_t ntohs(uint16_t net16bitvalue);

uint32_t ntohl(uint32_t net32bitvalue);
```

- Hint: **h**, **n**, **s**, and **l** stand for host byte order, network byte order, short(16bit), and long(32bit), respectively.

Initialization: server, `bind()`

- Server needs to bind a particular port number.

```
struct sockaddr_in sin;

memset(&sin, 0, sizeof(sin));

sin.sin_family = AF_INET;

sin.sin_addr.s_addr = INADDR_ANY;

sin.sin_port = htons(server_port);
```

```
if (bind(sock, (struct sockaddr *) &sin, sizeof(sin)) < 0) {
    perror("bind failed");
    abort();
}
```

- `bind()`: binds a socket with a particular port number.
  - Kernel remembers which process has bound which port(s).
  - Only one process can bind a particular port number at a time.

- `struct sockaddr_in`: Ipv4 socket address structure. (c.f., struct sockaddr_in6)

Reusing the same port

- After TCP connection closes, waits for 2MSL, which is twice maximum segment lifetime (from 1 to 4 mins, implementation dependent). Why?
- Segment refers to maximum size of packet
- Port number cannot be reused before 2MSL
- But server port numbers are fixed => Must be reused
- Solution: Put this code before `bind()`

```
int optval = 1;

if (setsockopt(sock, SOL_SOCKET, SO_REUSEADDR, &optval, sizeof(optval)) < 0) {

    perror("reuse failed");

    abort();

}
```

- **setsockopt()**: changes socket, protocol options.
  - e.g., buffer size, timeout value, ...

Initialization: server, `listen()`

- Socket is active, by default
- We need to make it passive to get connections.

```
if (listen(sock, back_log) < 0) {
 perror("listen failed");
 abort();
}
```

- **`listen()`**: converts an active socket to passive

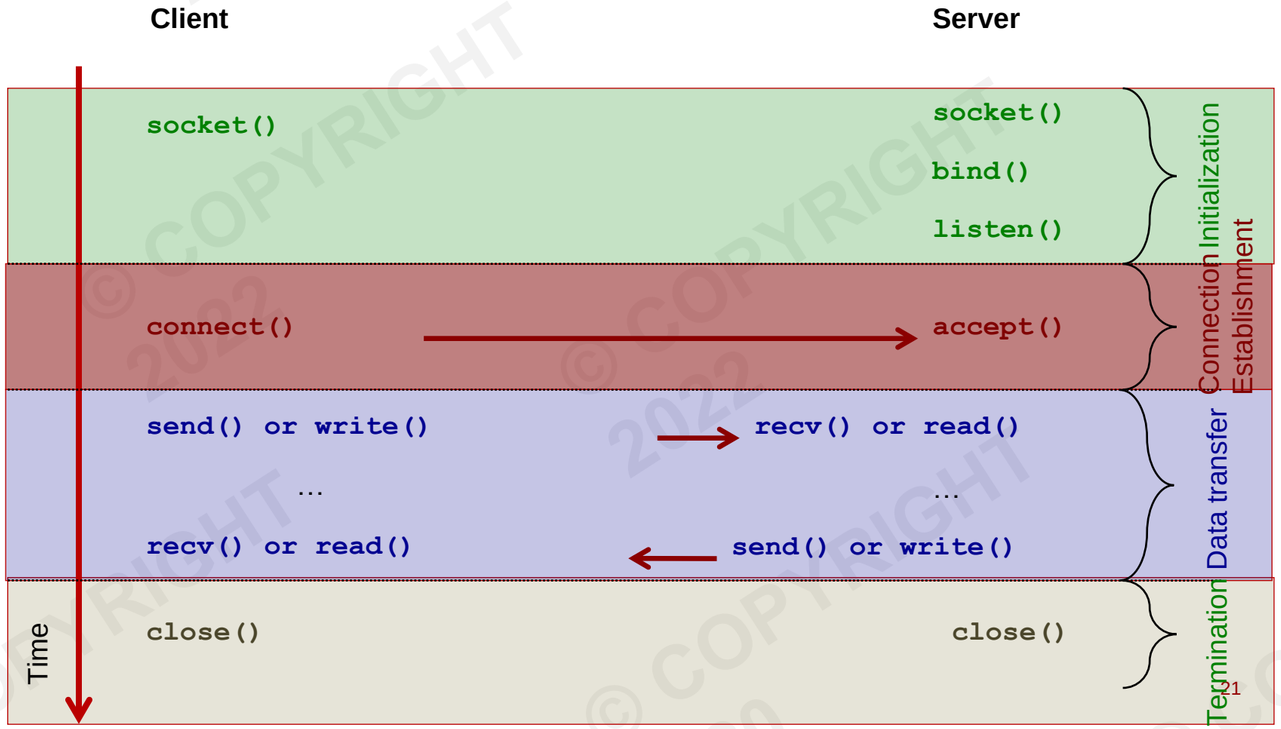
- **`back_log`**: connection-waiting queue size. (e.g., 32)
  - Busy server may need a large value (e.g., 1024, …)

Initialization Summary

- Client
  - `socket()`
- Server
  - `socket()`
  - `setsockopt(sock, SOL_SOCKET, SO_REUSEADDR)`
  - `bind()`
  - `listen()`
- Pitfalls
  - The order of the functions matter
  - Do not forget to use “`htons()`” to handle the port number

Scenario #1 – TCP Client-Server

- Sequence of actions.



Connection Establishment (client)

```
struct sockaddr_in sin;

memset(&sin, 0 ,sizeof(sin));



sin.sin_family                  = AF_INET;

sin.sin_addr.s_addr = inet_addr("128.32.132.214");

sin.sin_port = htons(80);



if (connect(sock, (struct sockaddr *) &sin, sizeof(sin)) < 0) {

        perror("connection failed");

        abort();

}
```

- `Connect()`: waits until connection establishes/fails.

- `inet_addr()`: converts an IP address string into a 32bit address number (network byte order).

Host Name, IP address, Port number

- Host Name
  - Human-readable name (e.g., www.eecs.berkeley.edu)
  - Variable length
  - Could have multiple IP addresses

- IP Version 4 Address
  - Usually represented as dotted numbers for human readability
    - E.g., 128.32.132.214
  - 32 bits in network byte order
    - E.g., 1.2.3.4 => 0x04030201

- Port Number
  - Identifies a service (or application) on a host
    - E.g., TCP Port 80 => web service, UDP Port 53 => name service (DNS)
  - 16 bit unsigned number (0~65535)

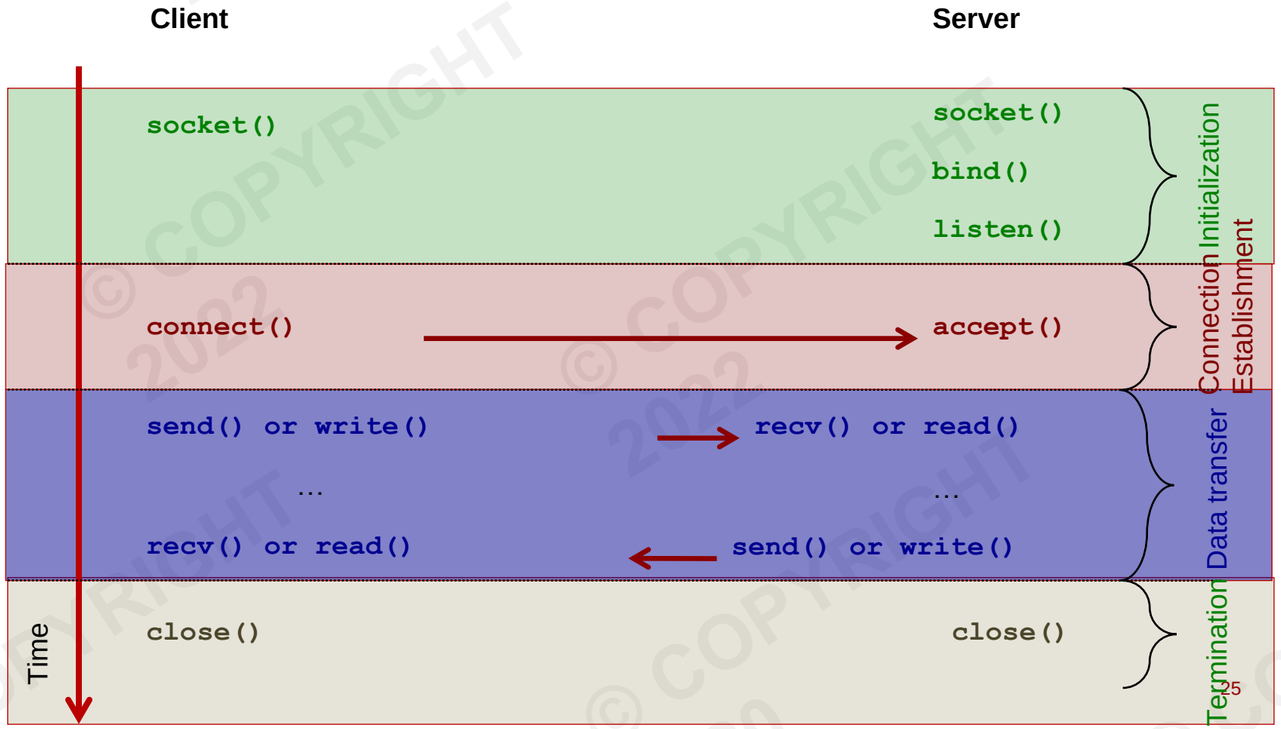
Connection Establishment (server)

```
struct sockaddr_in client_sin;

int addr_len = sizeof(client_sin);

int client_sock = accept(listening_sock,

                         (struct sockaddr *) &client_sin,

                         &addr_len);

if (client_sock < 0) {

      perror("accept failed");

      abort();

}
```

- **`accept()`**: returns a new socket descriptor for a client connection in the connection-waiting queue.
  - This socket descriptor communicates with the client
  - The passive socket (listening_sock) is not to communicate with a client
- **`client_sin`**: contains client IP address and port number
  - Q) Are they in Big endian or Litten endian?

Scenario #1 – TCP client-server

- Sequence of actions



Sending Data: server+client, `send()`

```
char *data_addr = "hello, world";

int data_len = 12;



int sent_bytes = send(sock, data_addr, data_len, 0);

if (sent_bytes < 0) {

     perror("send failed");

}
```

- **`send()`**: sends data, returns the number of sent bytes
  - Also OK with "`write()`", "`writev()`"
- **`data_addr`**: address of data to send.
- **`data_len`**: size of the data.

- With blocking sockets (default), "send()" blocks until it sends all the data.
- With non-blocking sockets, **sent_bytes** may not equal to **data_len**
  - If kernel does not have enough space, then it accepts only partial data.
  - You must retry for the unsent data.

Receiving Data: server+client, `recv()`

```
char buffer[4096];

int expected_data_len = sizeof(buffer);



int read_bytes = recv(sock, buffer, expected_data_len, 0);

if (read_bytes == 0) {                  // connection is closed

      …

} else if (read_bytes < 0) { // error

     perror("recv failed");

} else {            // Recived. But no guarantee read_bytes == expected_data_len

     …

}
```

- **`recv()`**: reads bytes from the socket and returns the number of read bytes.
  - Also OK with "**`read()`**" and "**`readv()`**"

- **`read_bytes`** may not equal to **`expected_data_len`**
  - If no data is available, then it blocks.
  - If only partial data is available, then read_bytes < expected_data_len

Termination: server+client, close()

```
// after use the socket

close(sock);
```

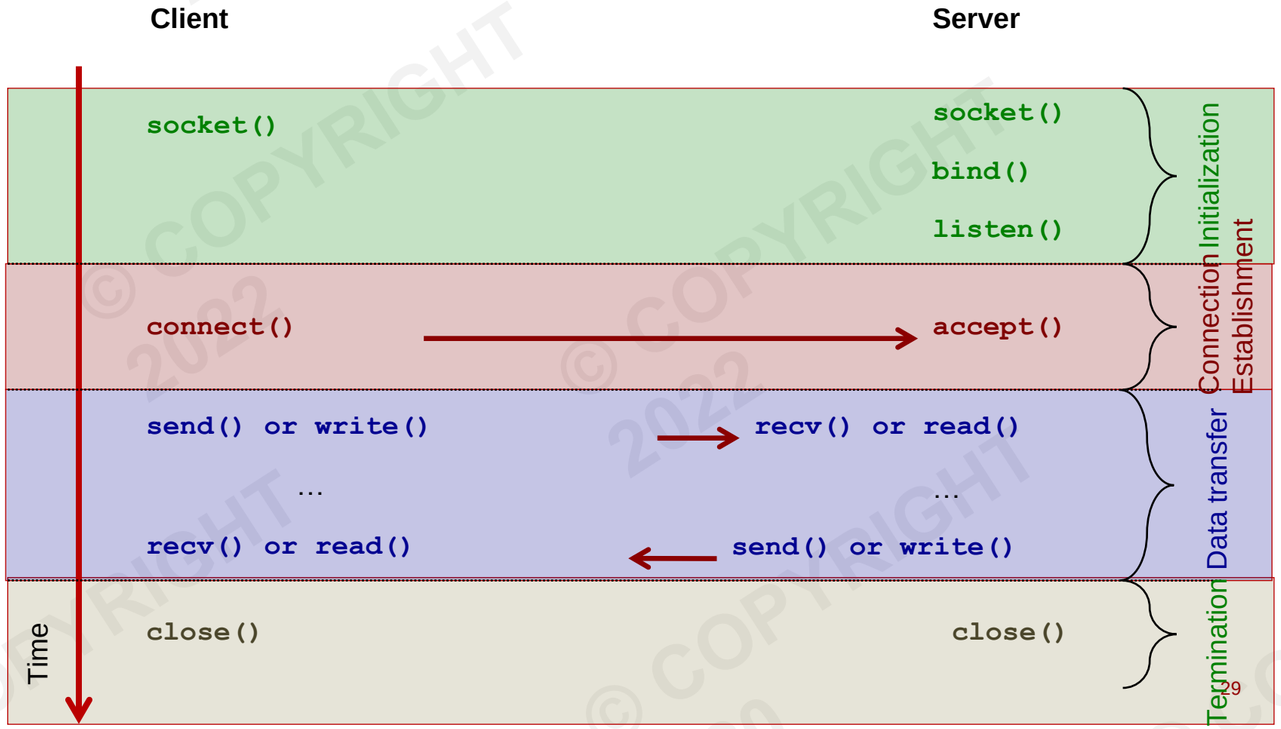
- **`close()`**: closes the socket descriptor.

- We cannot open files/sockets more than 1024*
  - We must release the resource after use.

* Super user can overcome this constraint, but regular user cannot.

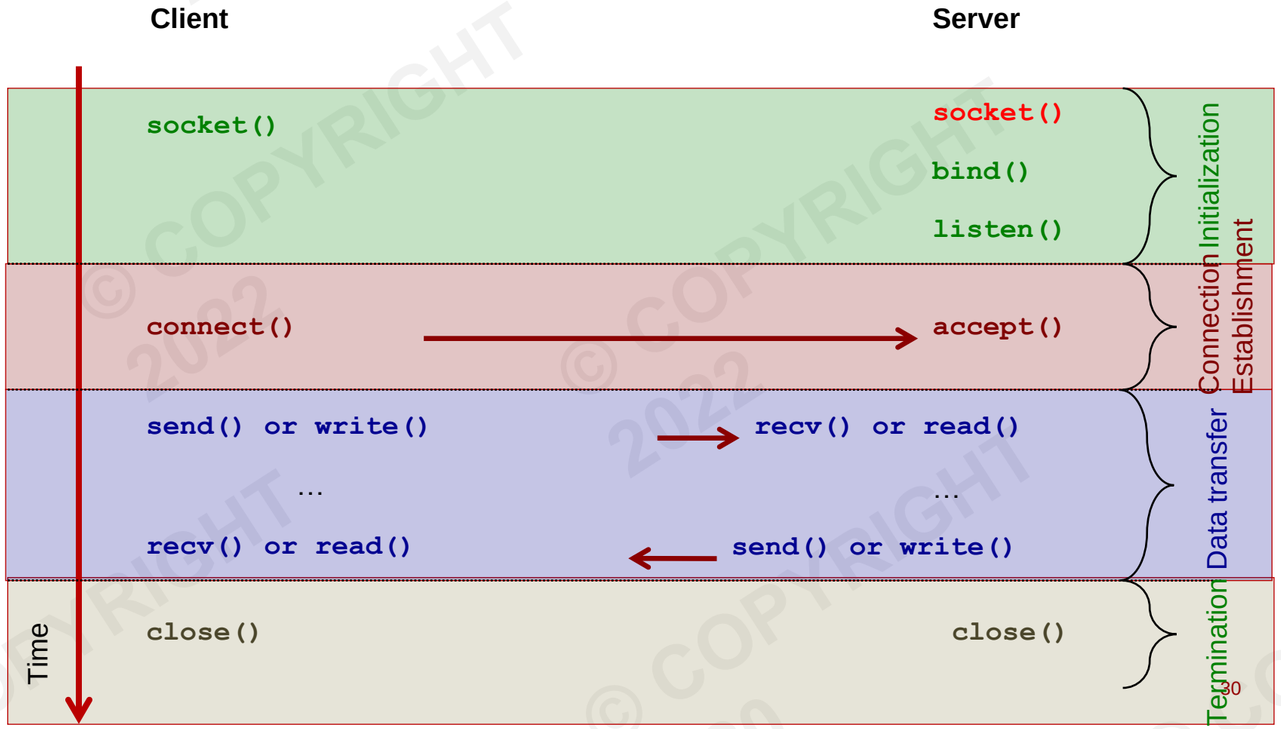
Scenario #2 – UDP client-server

- Q) What must be changed?



Scenario #2 – UDP client-server

- A) We need a different initialization



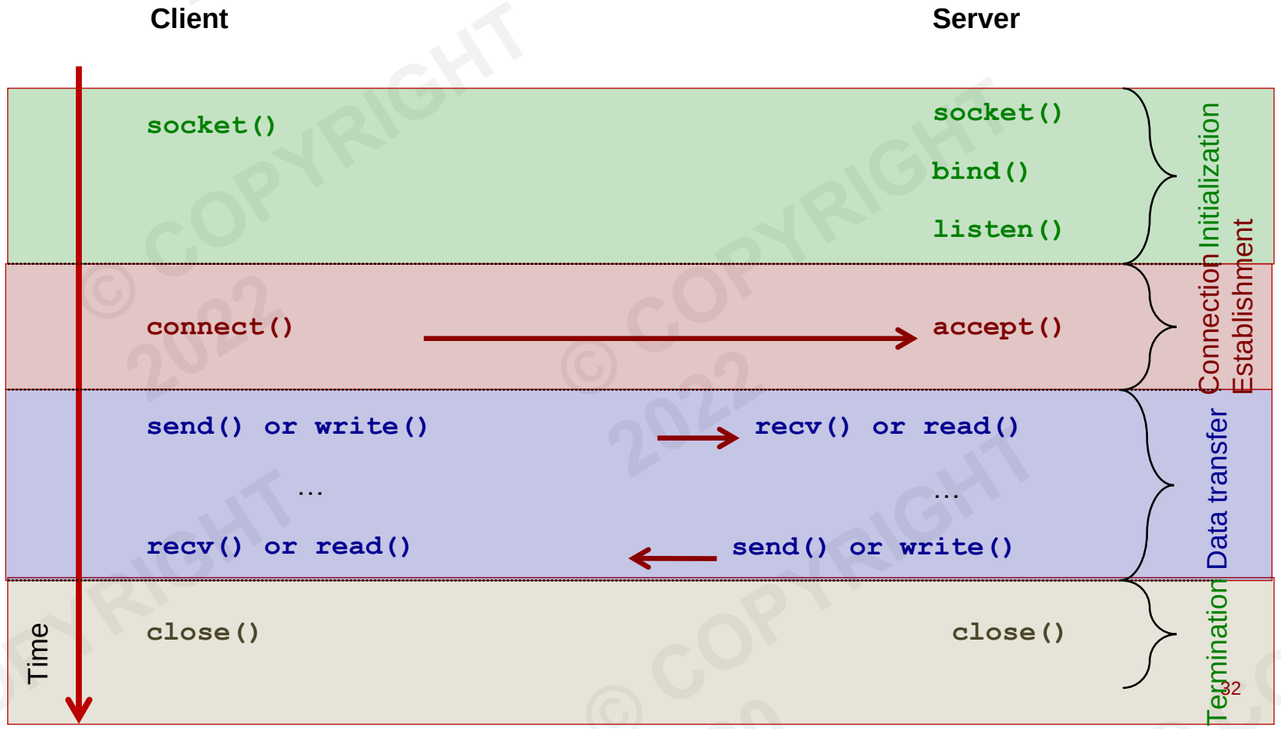
Initialization: UDP

```
int sock = socket(AF_INET, SOCK_DGRAM, 0);
if (sock < 0) {
  perror("socket failed");
  abort();
}
```

- UDP uses SOCK_DGRAM instead of SOCK_STREAM

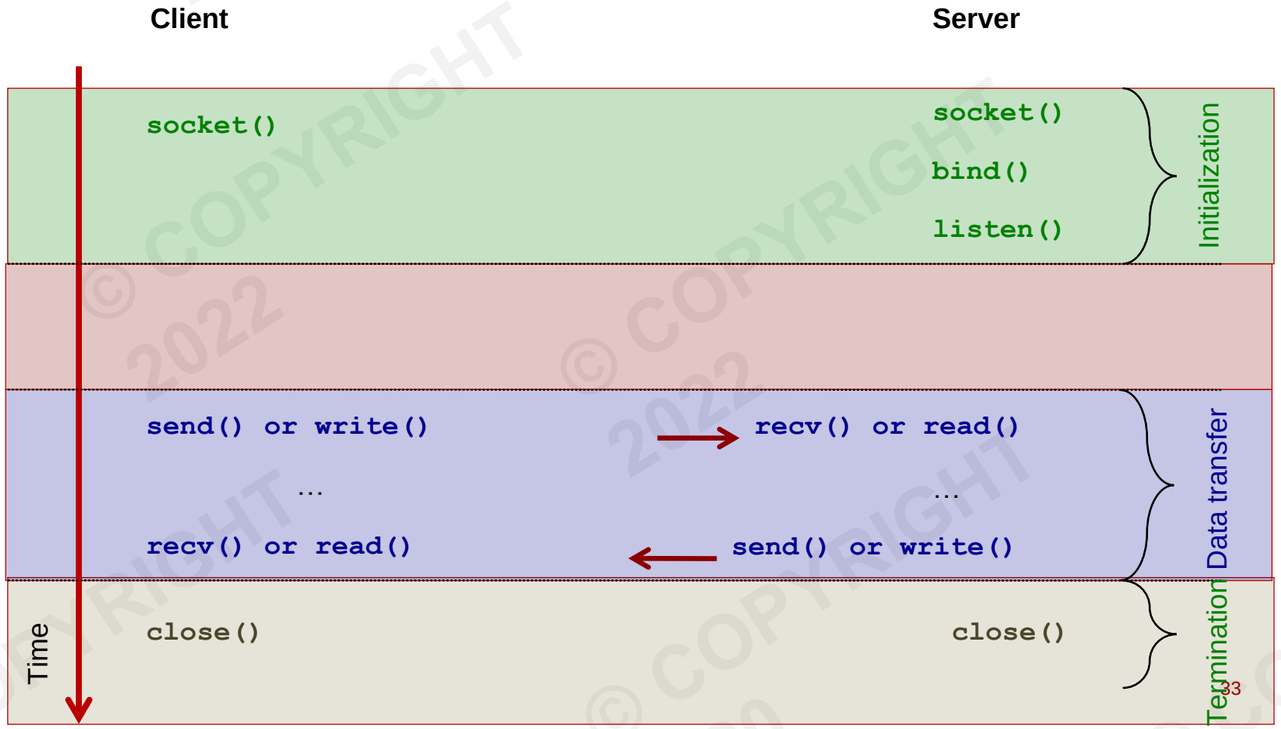
Scenario #2 – UDP client-server

- Q) What else must be changed?



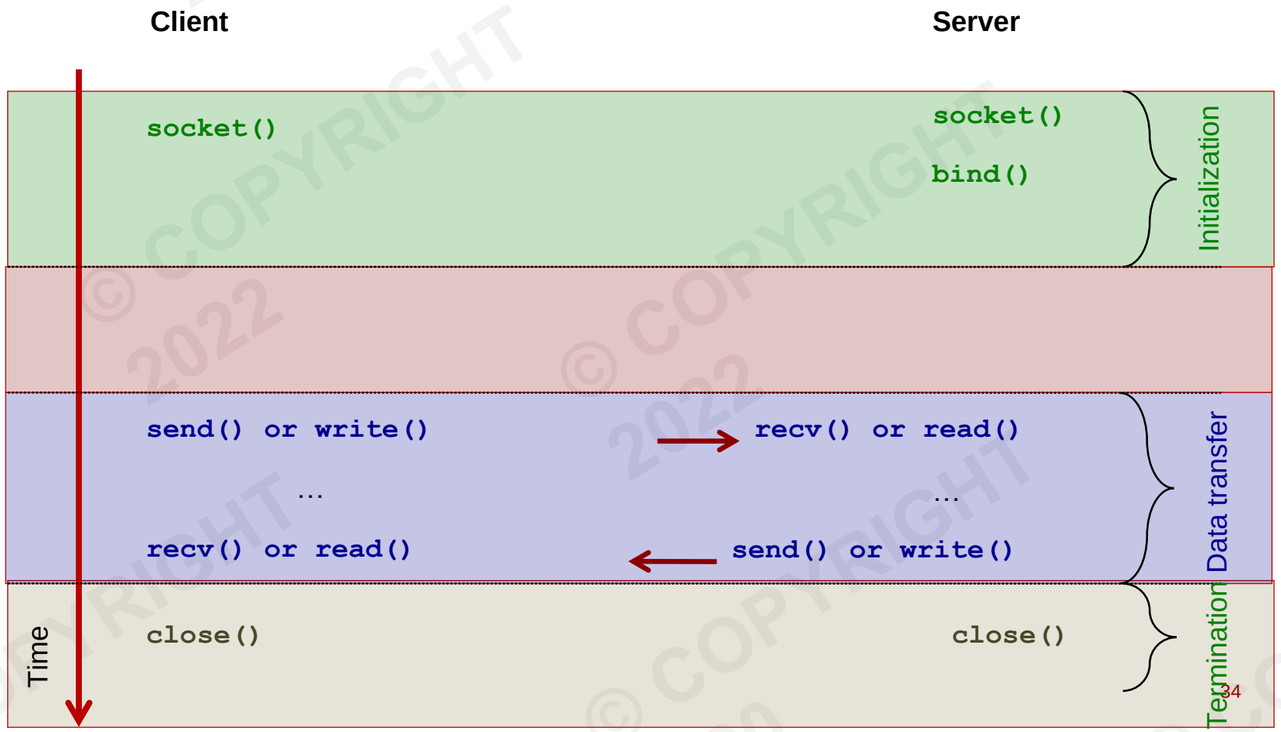
Scenario #2 – UDP client-server

- A) UDP is **connection-less**. We remove all connection related steps.



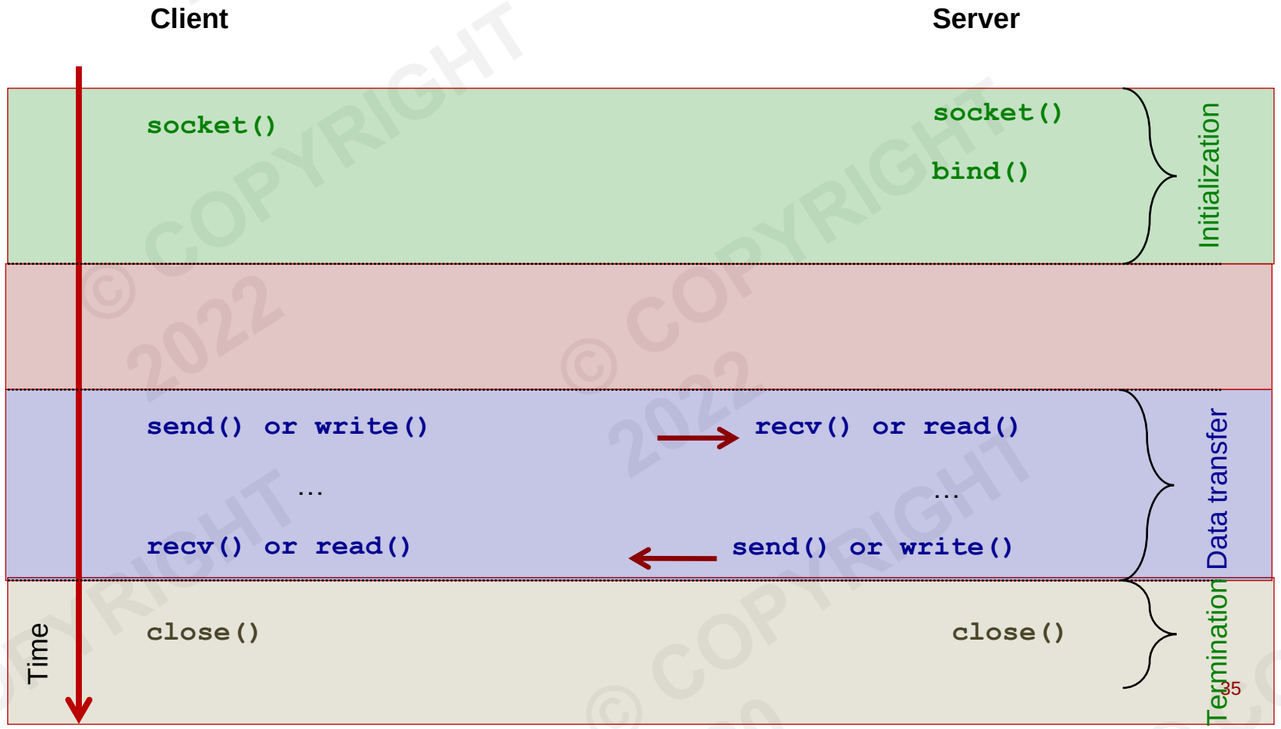
Scenario #2 – UDP client-server

- A) `listen()` is also related to connection. Remove it.



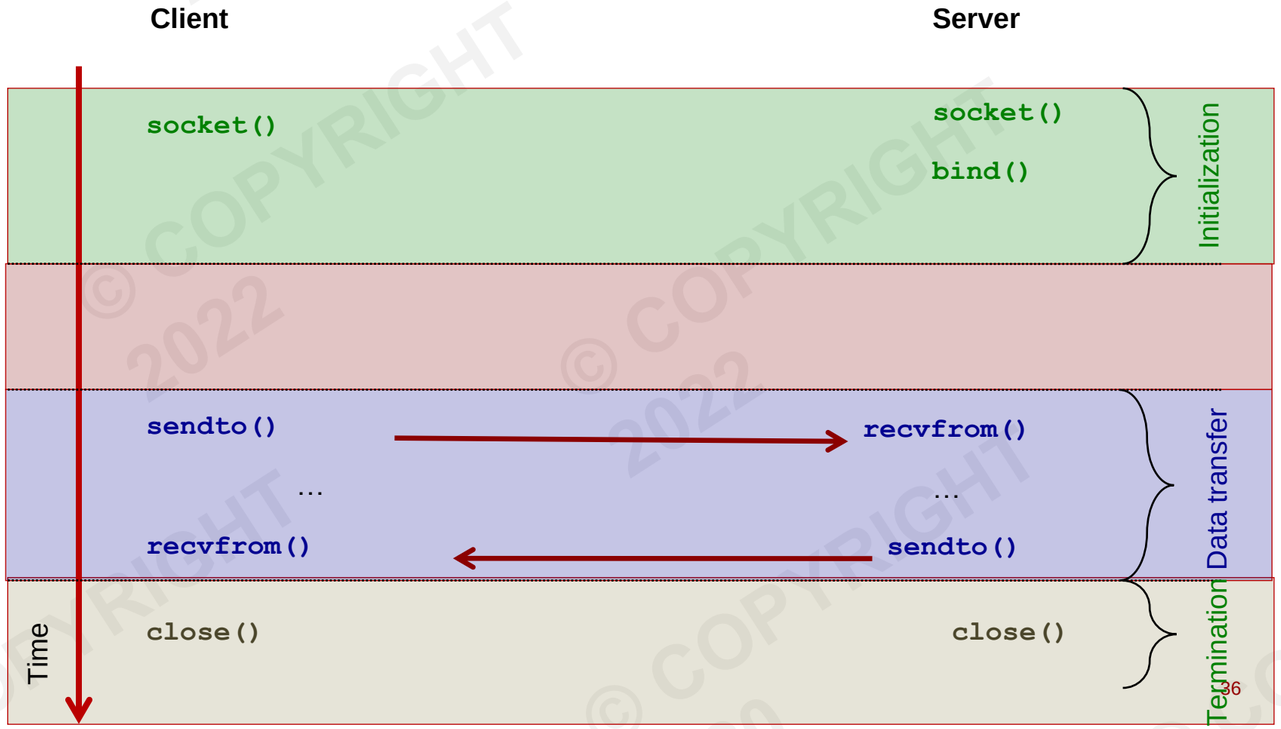
Scenario #2 – UDP client-server

- Q) Now it's unclear where to send packets and from where I can receive them! Can we solve this?



Scenario #2 – UDP client-server

- A) Give <address,port> information when sending a packet. That is, use **`sendto()`** and **`recvfrom()`** instead of `send()` and `recv()`.



Send Data Over UDP: `sendto()`

```
struct sockaddr_in sin;

memset(&sin, 0, sizeof(sin));



sin.sin_family = AF_INET;

sin.sin_addr.s_addr = inet_addr("128.32.132.214");

sin.sin_port = htons(1234);



sent_bytes = sendto(sock, data, data_len, 0,

                                                    (struct sockaddr *) &sin, sizeof(sin));

if (sent_bytes < 0) {

     perror("sendto failed");

     abort();

}
```

- **`sendto()`**: sends a packet to a specific destination address and port
  - c.f., in TCP, we do this destination setting when calling "`connect()`".
- As opposed to TCP, UDP packetizes data. So, "`sendto()`" sends all data or nothing.

Receive Data Over UDP: `recvfrom()`

```
struct sockaddr_in sin;

int sin_len;

char buffer[4096];



int read_bytes = recvfrom(sock, buffer, sizeof(buffer), 0,
                          (struct sockaddr *) &sin, &sin_len);



if (read_bytes < 0) {

     perror("recvfrom failed");

     abort();

}
```

- **`recvfrom()`**: reads bytes from the socket and sets the source information.

- Reading 0 bytes does not mean "connection closed", unlike TCP.
  - Recall UDP does not have a notion of "connection".

API functions Summary

TCP

- Initialization
  - socket(AF_INET, SOCK_STREAM, 0)
  - setsockopt(sock, SOL_SOCKET, SO_REUSEADDR, …)
  - bind()
  - listen()
- Conneciton
  - connect()
  - accept()
- Data transfer
  - send()
  - recv()
- Termination
  - close()

UDP

- Initialization
  - socket(AF_INET, SOCK_DGRAM, 0)
  - setsockopt(sock, SOL_SOCKET, SO_REUSEADDR, …)
  - bind()
- No connection
- Data transfer
  - sendto()
  - recvfrom()
- Termination
  - close()

Outline

- Socket API motivation, background
- Types of sockets (TCP vs. UDP)
- Elementary API functions
- I/O multiplexing
- Project 1 – tiny World of Warcraft

How To Handle Multiple Inputs

- Data sources
  - Standard input (e.g., keyboard)
  - Multiple sockets
- Problem: asynchronous data arrival
  - Program does not know when it will arrive.
- If no data available, "`recv()`" blocks.
- If blocked from one source, cannot handle other sources.
  - Suppose a web server cannot handle multiple connections
- Solutions
  - Polling using non-blocking socket ➔ Inefficient
  - I/O multiplexing using select() ➔ Simple
  - Multithreading ➔ More complex. Not covered today

Polling Using Non-Blocking Socket

- This approach wastes CPU cycles

```
int opt = fcntl(sock, F_GETFL);
if (opt < 0) {
        perror("fcntl failed");
        abort();
}
if (fcntl(sock, F_SETFL, opt | O_NONBLOCK) < 0) {
        perror("fcntl failed");
        abort();
}
while (1) {
        int read_bytes = recv(sock, buffer, sizeof(buffer), 0);
        if (read_bytes < 0) {
                if (errno == EWOULDBLOCK) {
                        // OK. Simply no data
                } else {
                        perror("recv failed");
                        abort();
                }
}
```

Gets the socket's option

Updates the socket's option with non-blocking option

When no data, we see EWOULDBLOCK error code.

I/O Multiplexing Using `select()`

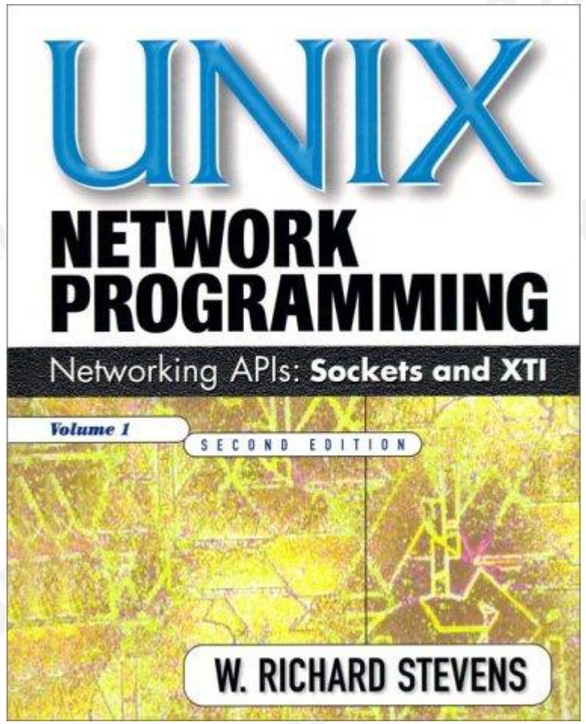
```
fd_set read_set;

struct timeval timeout


FD_ZERO(&read_set);

FD_SET(sock1, &read_set);

FD_SET(sock2, &read_set);

timeout.tv_sec = 0;

timeout.tv_usec = 5000;


if (select(MAX(sock1, sock2) + 1, &read_set, NULL,
                                                  NULL, &timeout) < 0)

        perror("select failed");

        abort();

}


if (FD_ISSET(sock1, &read_set)) {

        // sock1 has data

}

if (FD_ISSET(sock2, &read_set)) {

        // sock2 has data
```

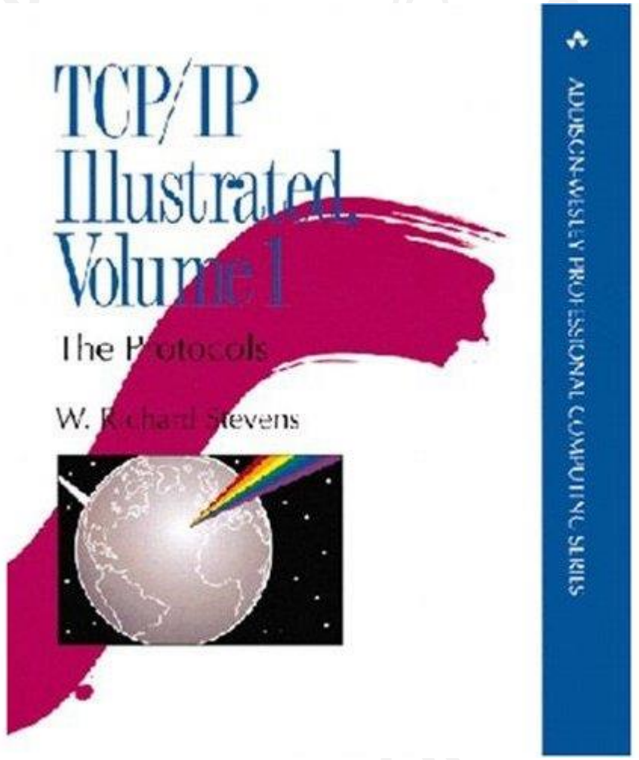
Initializes arguments for select()

Pass NULL instead of &timeout if you want to wait indefinitely

Checks I/O events.

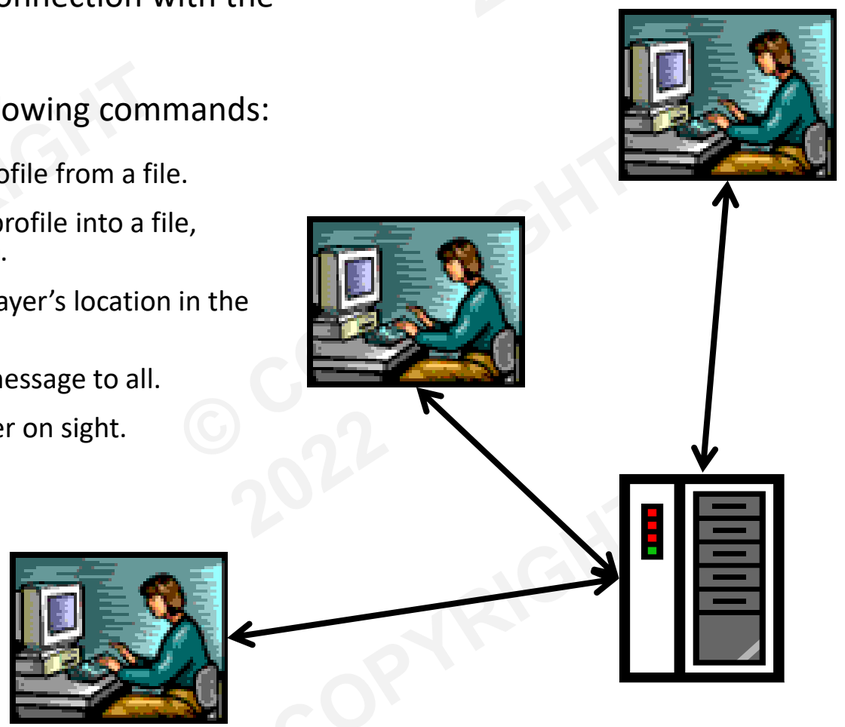
Bibles – both by W. Richard Stevens





Project 1 – *tiny* World of Warcraft

- Game client forms TCP connection with the game server.
- It should support the following commands:
  - Login: loads player profile from a file.
  - Logout: saves player profile into a file, closes the connection.
  - Move: updates the player's location in the game.
  - Speak: sends a chat message to all.
  - Attack: attacks a player on sight.



Project 1 – *tiny* World of Warcraft

- Divided into 2 parts:
  - Part 1: Develop a game client
    - Message formats and commands will be given.
    - Can test your client on provided reference server.
  - Part 2: Develop a game server
    - It should work with your client

Appendix – Programming Tips

- Will not be covered during the lecture.
- Please refer to the following tips if you're interested…

Tip #1

- How to check the host byte order of my machine?

```
union {
  uint16_t number;
  uint8_t  bytes[2];
} test;

test.number = 0x0A0B;

printf("%02x%02x\n", test.bytes[0],
       test.bytes[1]);
```

Tip #2

- How to get the IP address from host name.
  - Use **gethostbyname()**

```
struct sockaddr_in sin;
struct hostent *host;
host = gethostbyname("www.berkeley.edu");
sin.sin_addr.s_addr
  = *(unsigned *) host->h_addr_list[0];
```

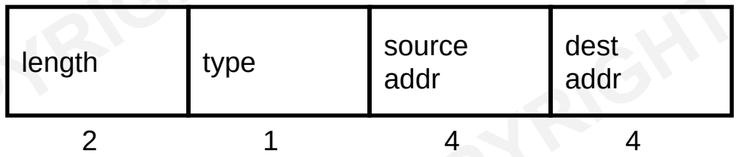
Tip #3

- By default, Unix terminates the process with **SIGPIPE** if you write to a TCP socket which has been closed by the other side. You can disable it by:

```
signal(SIGPIPE, SIG_IGN);
```

Tip #4 - Structure Packing

- We have the following application-level packet header format (the numbers denote field size in bytes)



- So, we define the header as struct like this:

```
struct my_pkt_hdr {
      unsigned short length;
      unsigned char type;
      unsigned int source_addr;
      unsigned int dest_addr;
};
```

- Q) What is the result of sizeof(struct my_pkt_hdr)?

Tip #4 - Structure Packing (cont'd)

- Compiler will try to be 4-byte aligned (on 32bit machines).
- To avoid the previous case, we must pack struct.

Windows programming style

```
#pragma pack(push, 1)
struct my_pkt_hdr {
        unsigned short length;
        unsigned char type;
        unsigned int source_addr;
        unsigned int dest_addr;
};
#pragma pack(pop)
```

OR

GCC style

```
struct my_pkt_hdr {
        unsigned short length;
        unsigned char type;
        unsigned int source_addr;
        unsigned int dest_addr;
} __attribute__((packed));
```

Using `man` Pages

- Best source to study system calls and library functions.
  - Tells which header files should be included.
  - Describes how each function works.
  - Tells what the return value means and what error number can happen.
  - E.g., `man connect`