Week 7 Lecture 1 and 2

NWEN 241
Systems Programming

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Announcements

- **Exercise 3 is out, due on 1 May 2024 23:59)**
  - Visit https://ecs.wgtn.ac.nz/Courses/NWEN241_2024T1/Exercises for the handout

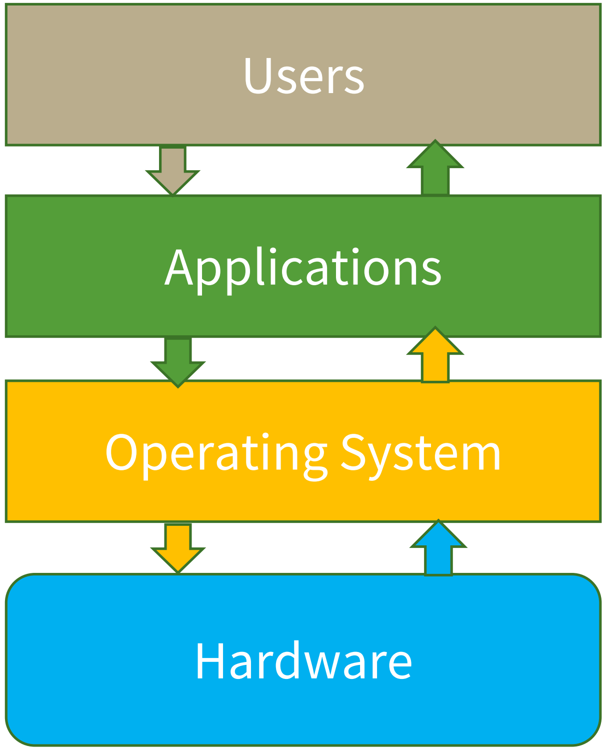
- **Assignment 3 is out, due on 13 May 2024 23:59**
  - Visit https://ecs.wgtn.ac.nz/Courses/NWEN241_2024T1/Assignments for the handout

Content

- System calls (Introduction here, details next week)

- Interprocess communication

System calls - What and Why?



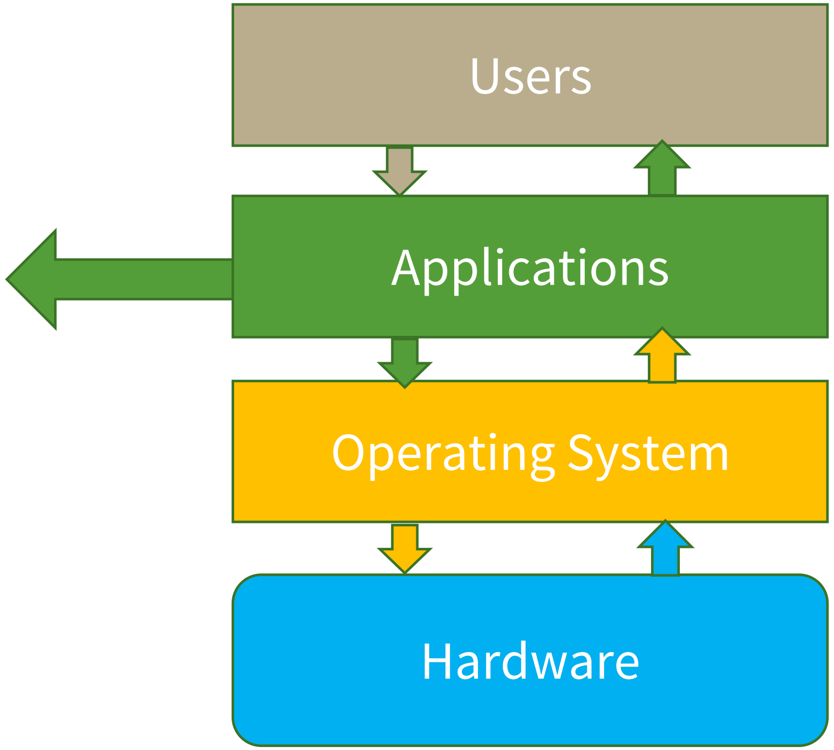
Conceptual View of a Computer System

System calls - What and Why?

- Typically needs access to **system resources**.

- System resources can be:
  a) **physical** – e.g. input devices, screen displays.
  OR
  b) **Virtual** – e.g. files, network connections, threads.

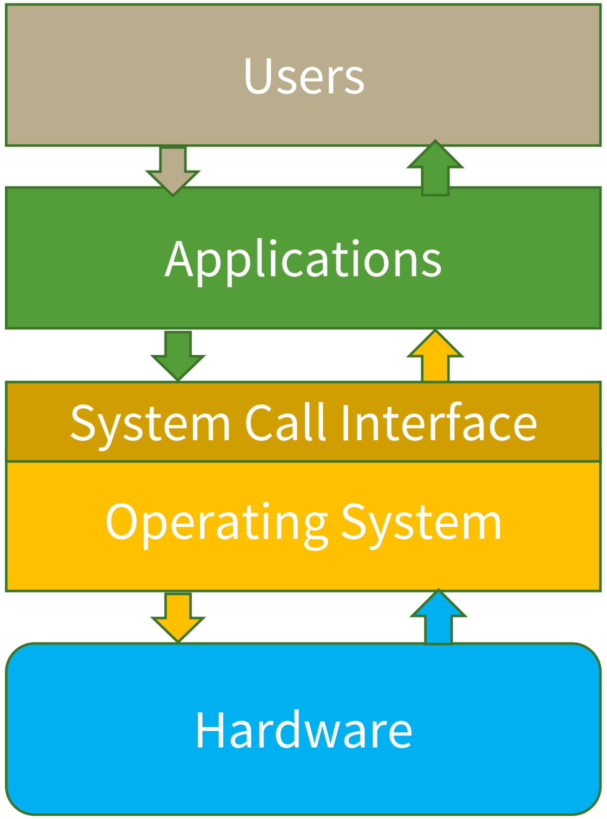
- Applications need O.S. to enable them access these resources.



Conceptual View of a Computer System

System calls - What and Why?

- Operating Systems **do not allow application software to access system resources directly** due to security and reliability issues.
- A program can **request** the services of system resources from OS through **system calls**.
- **System calls** are **function invocations made from application into the OS** in order to request some service or resource from the operating system.
- Application developers often do not have direct access to system calls but can access them through a **system call API**, which in turn invokes the system call.



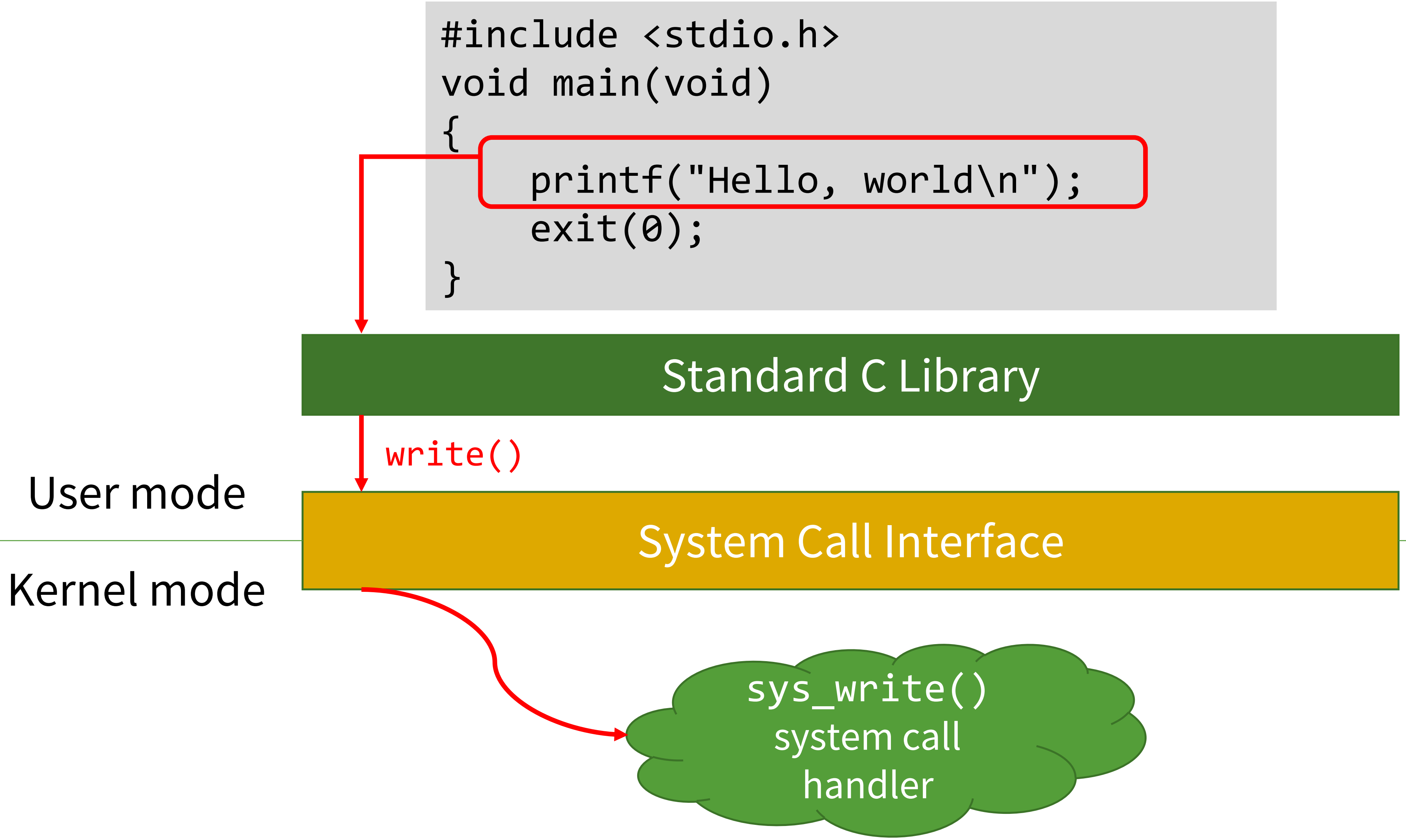
An example of a system call usage

- Consider the following example:

```
#include<stdio.h>

int main()
{
  printf("Hello World");
  return 0;
}
```

C Library function **printf "asks" the operating system to print for the calling program** by using the system call API routines

System call invocation – *Example*



```
#include <stdio.h>
void main(void)
{
    printf("Hello, world\n");
    exit(0);
}
```

Standard C Library

`write()`

User mode

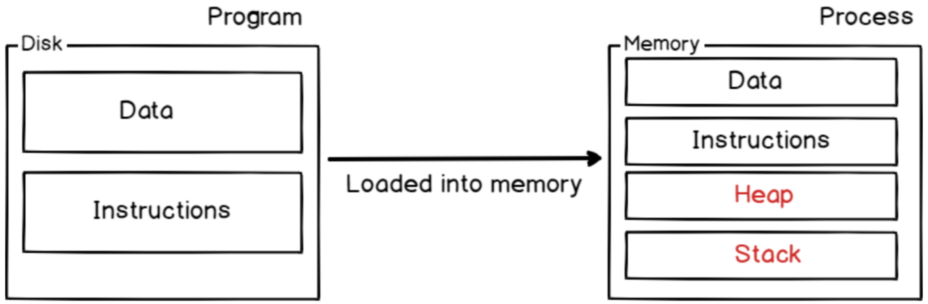
System Call Interface

Kernel mode

`sys_write()`
system call
handler

Interprocess Communication

What is a process ?



- Program and process are related terms.

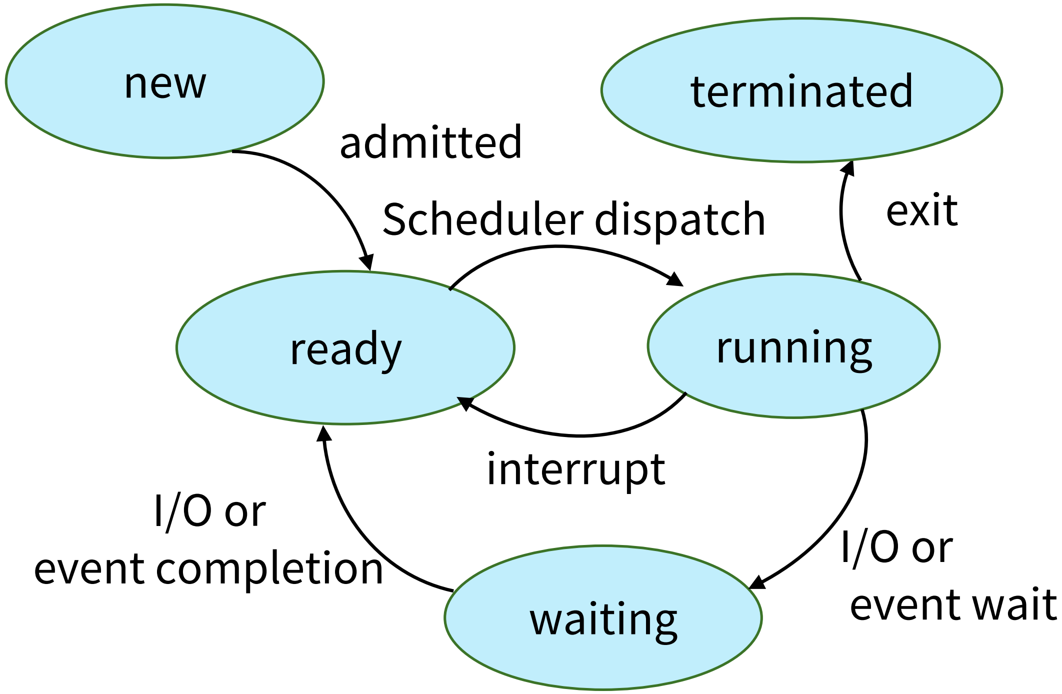
Program is a set of instructions to carry out a specified task	**Process** is a program in execution

Passive entity	Active entity
Program is a stored in disk and does not require any other resource.	**Process** requires system resources such as CPU, memory, I/O etc.
Life span - Longer	Life span – limited
Each time a program is run a new process is created.	

Process lifecycle

As a process executes, it changes **state**

- **new**: The process is being created
- **ready**: The process is waiting to be assigned to a processor
- **running**: Instructions are being executed
- **waiting**: The process is waiting for some event to occur
- **terminated**: The process has finished execution



Process management system calls

The following system calls are used for basic process management.

- `fork()`
- `exec()`

Defined in `unistd.h`

- `wait()`

Defined in `sys/wait.h`

- `exit()`

Defined in `stdlib.h`

Process - Independent Vs Cooperating

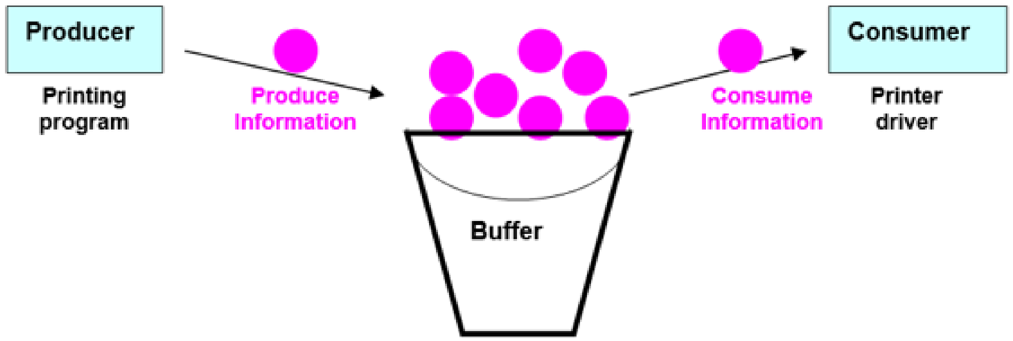
- **Independent** processes: processes that don’t interact with other processes

- **Cooperating** processes: process can affect or be affected by other processes.

- In order to co-operate processes need to **communicate**
  - **Inter Process Communication**

Cooperating Processes

- Reasons for cooperating processes:
    - Information sharing
    - Computation speedup
    - Modularity
    - Convenience

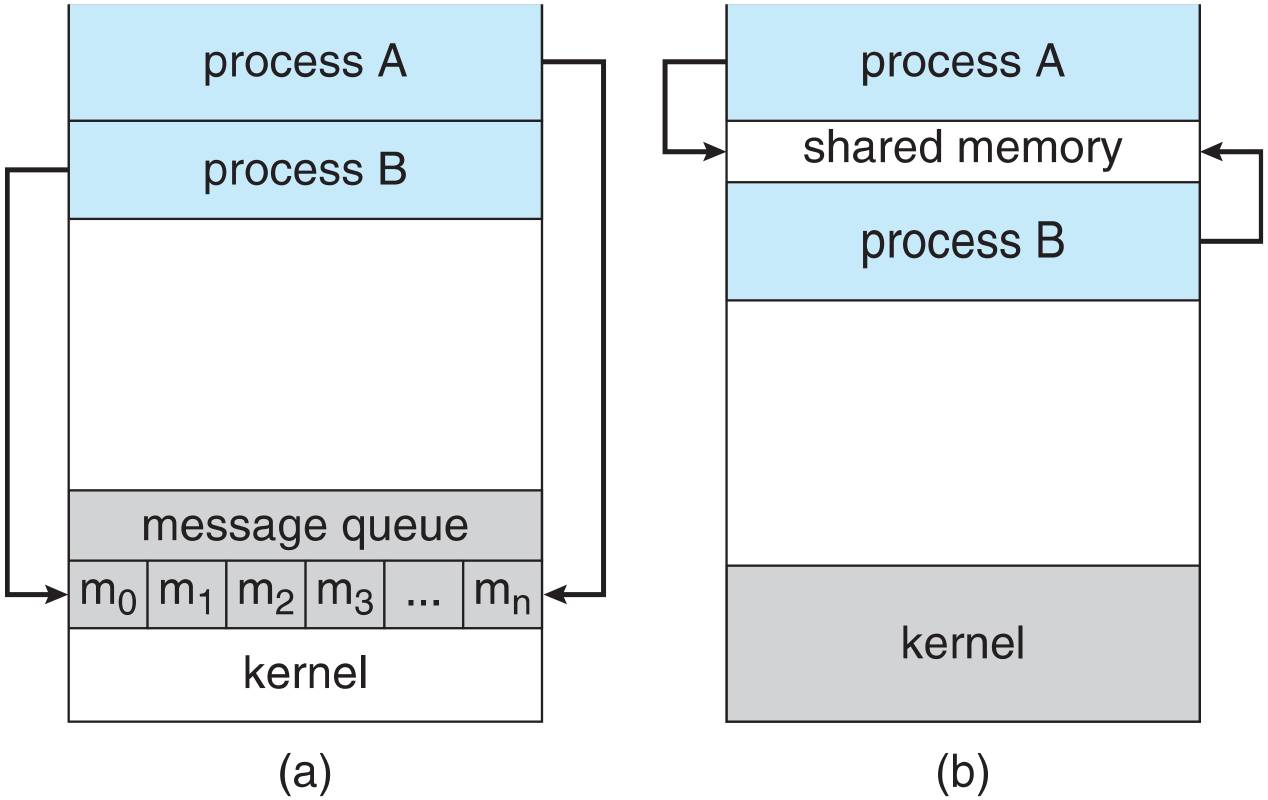


- Cooperating processes can reside on **same machine** or in **different machines (on a network)**.

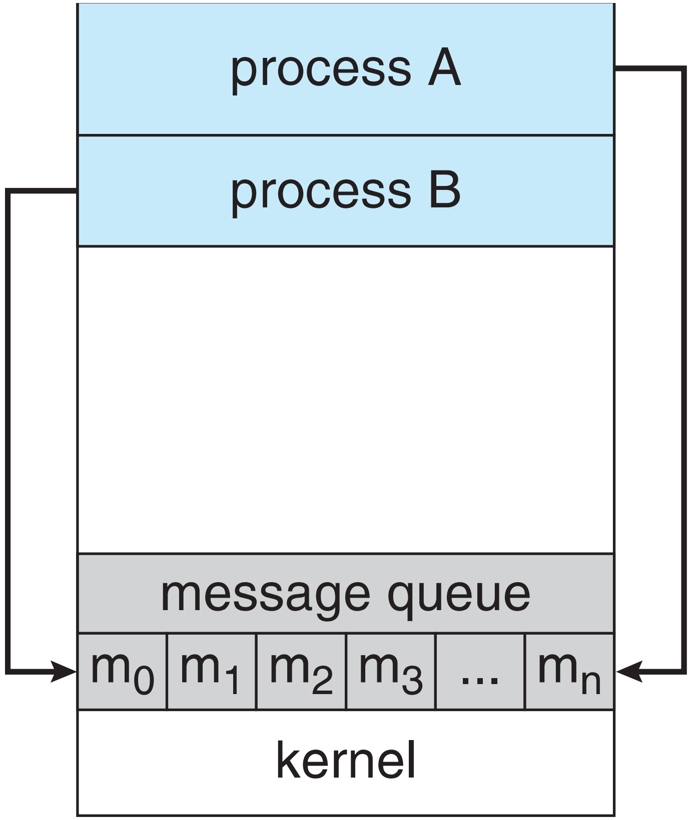
Interprocess communication

- Cooperating processes need **interprocess communication** (**IPC**)

- Two primary models of IPC
  - **Message passing**
  - **Shared memory**



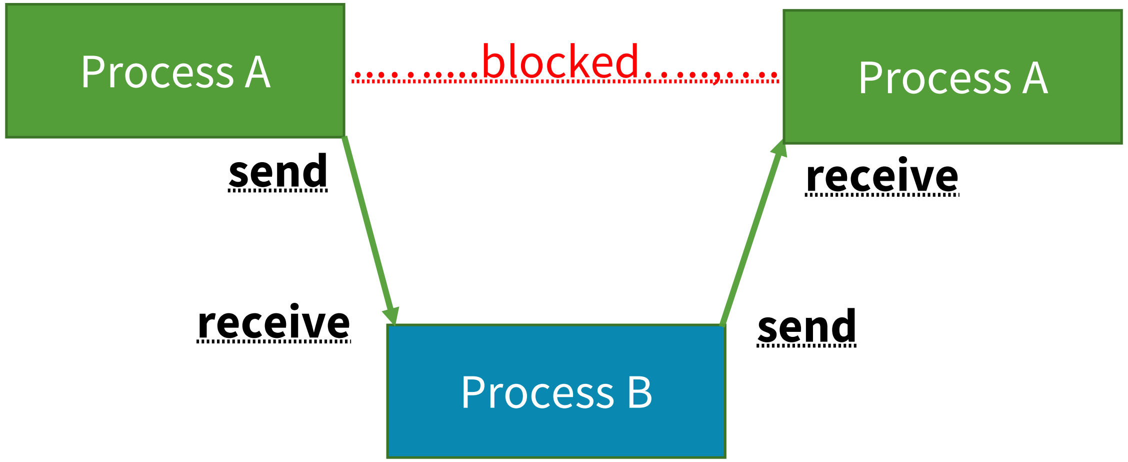
Message passing



- Processes communicate with each other without resorting to shared variables
- IPC facility provides two primitive operations:
  - `send(`***message***`)`
  - `receive(`***message***`)`
- If *A* and *B* wish to communicate, they need to:
  - establish a ***communication link*** between them
  - exchange messages via send/receive

Design options - Synchronization

Blocking (Synchronous)



Process A

blocked

Process A

send

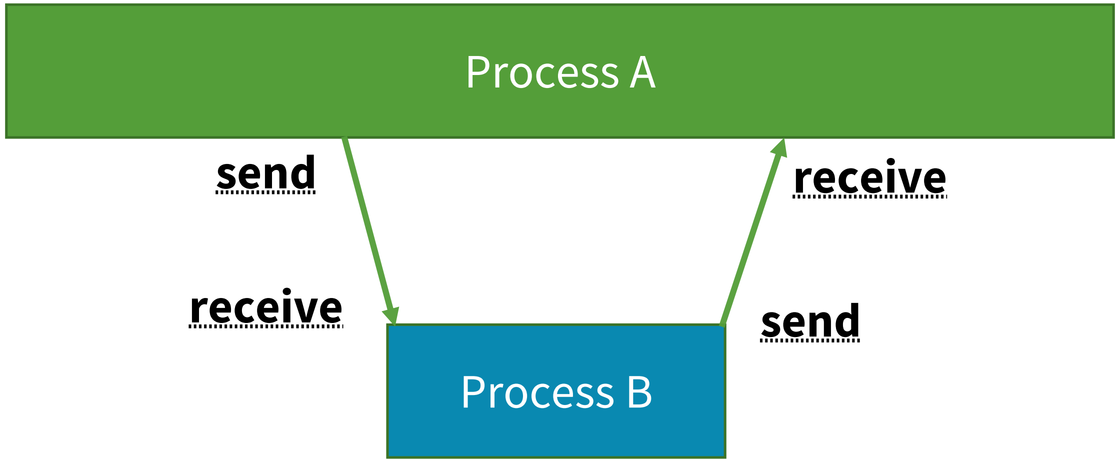
receive

receive

send

Process B

Non-blocking (Asynchronous)



Process A

send

receive

receive

send

Process B

Design options - Synchronization

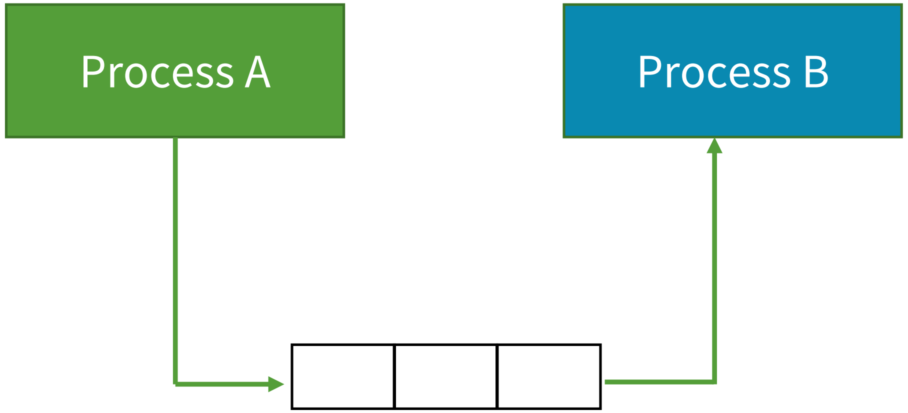
	Blocking	Non - Blocking
Send	Has the sender block until the message is received	Has the sender send the message and continue
Receive	Has the receiver block until a message is available	Has the receiver shown its willing to receive message and continue

Different combinations possible

Design options - Buffering

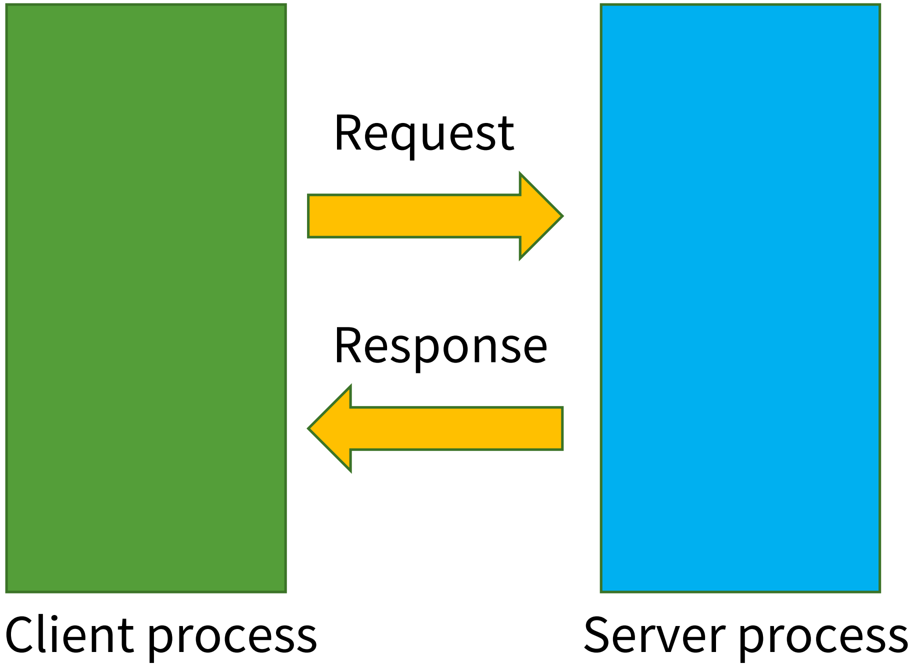
- **Queue** of messages attached to the link

- Implemented in one of three ways:
  - **Zero capacity** – 0 messages
    Sender must wait for receiver
  - **Bounded capacity** – finite length of *n* messages
    Sender must wait if link full
  - **Unbounded capacity** – infinite length
    Sender never waits



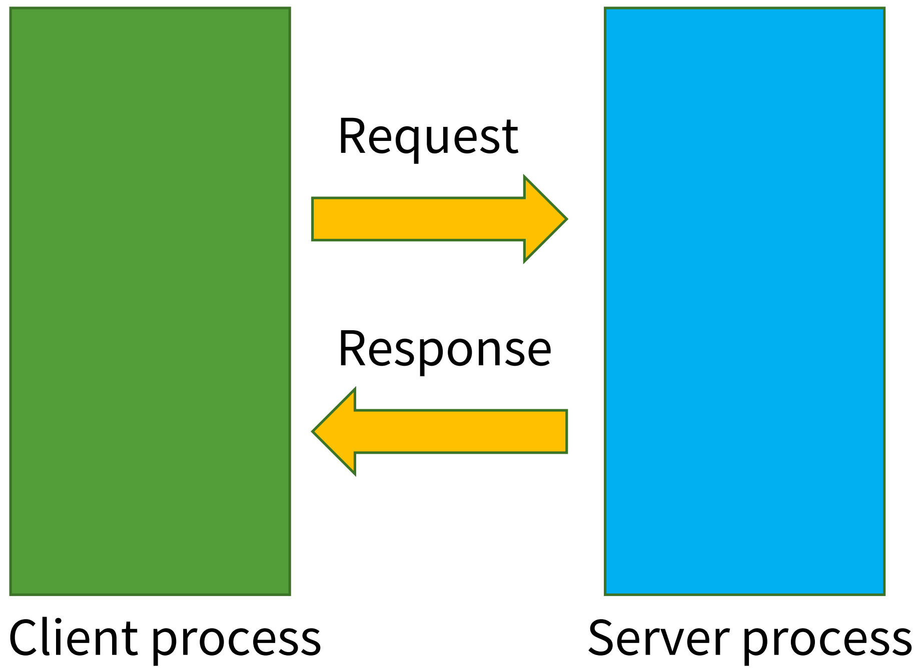
Client-server model

- Most common IPC paradigm
- Based on the producer-consumer model of process cooperation
- Client makes the request for some resource or service to the server process
- Server process handles the request and sends the response (result) back to the client



Client-server model

- **Client process** needs to know the existence and the address of the server
- However, the **Server** does not need to know the existence or address of the client prior to the connection
- **Once a connection** is established, both sides can send and receive information

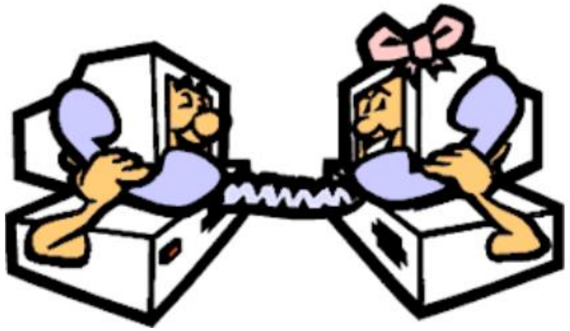


Client-server communication

- Remote Procedure Calls
- Pipes
- **Sockets**

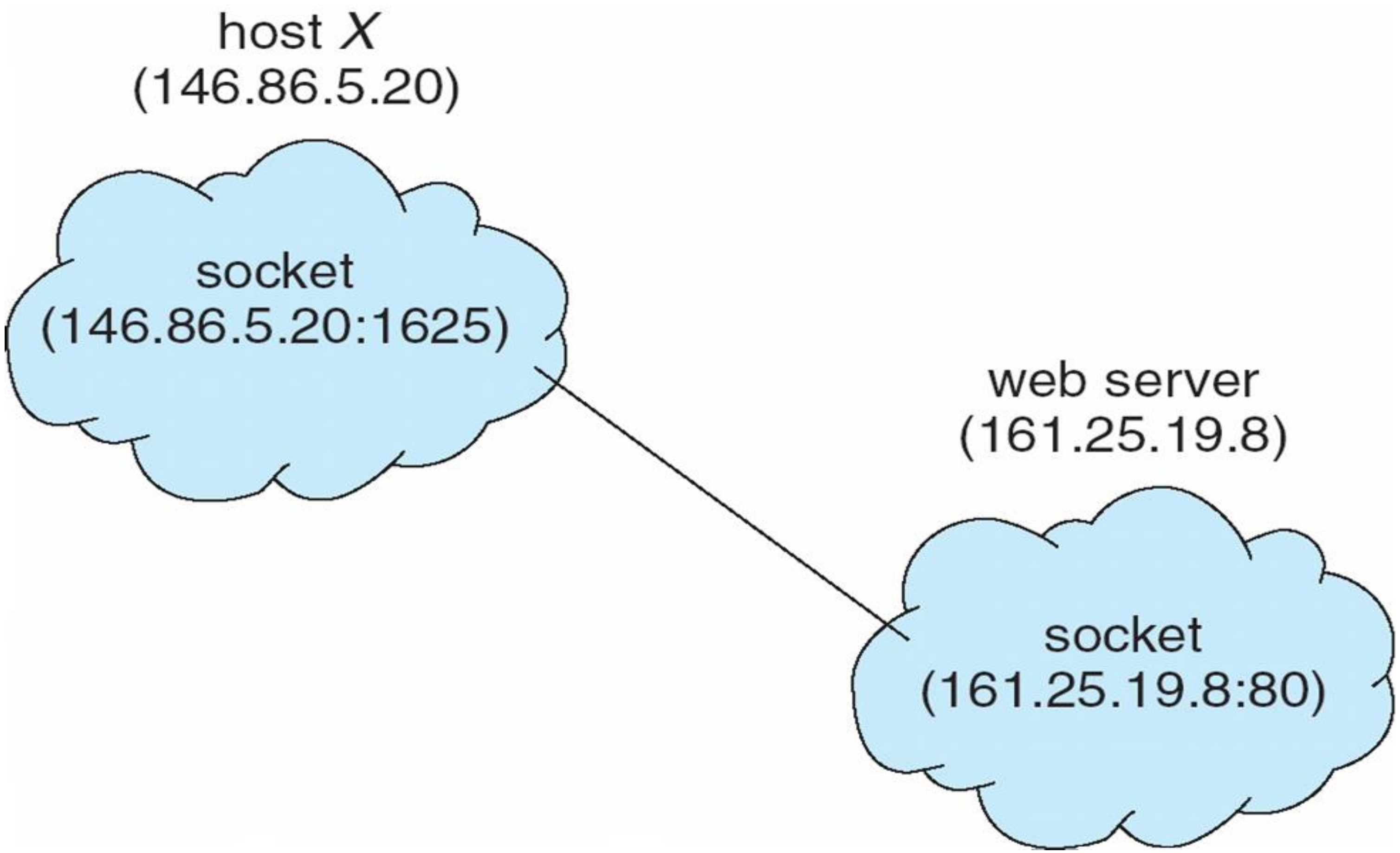
What is socket?

- What do we need to know to allow two processes on a network to communicate?
  - **Identity of the communicating machines**
    - **IP Address**
  - **Identity of the communicating processes on these machines**
    - **Port**



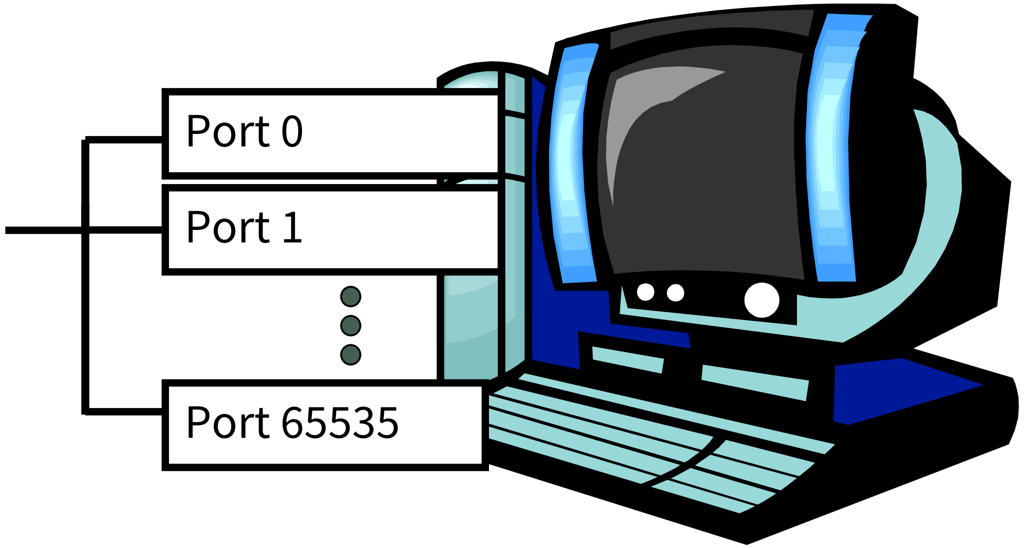
- Concatenation of **IP address** and **port** defines a **socket**
  - A **socket** is defined as an endpoint for communication
  - Example: The socket **161.25.19.8:1625** refers to port **1625** on host **161.25.19.8**

Socket communication



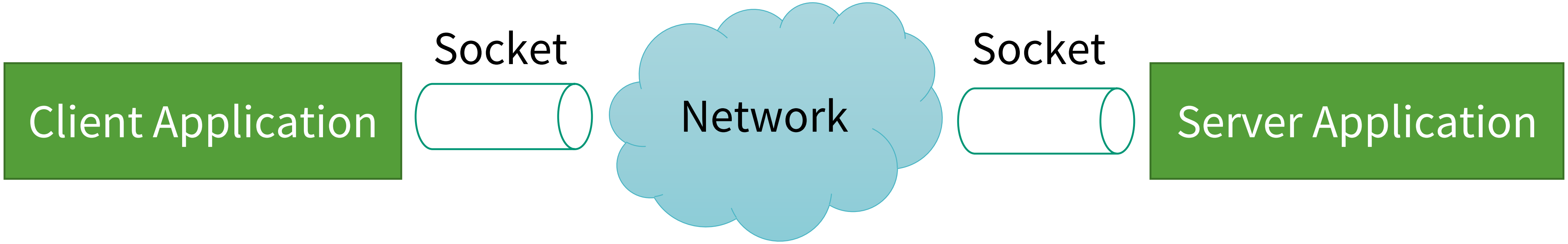
Port numbers

- Each host has **65,536** ports
- Use of ports 0-1023 requires privileges
- Some ports are reserved for specific apps
  - 20, 21: FTP
  - 23: Telnet
  - 80: HTTP
  - see RFC 1700



Sockets as programming interface

- An interface between application and network
  - The application creates a socket
  - The socket type dictates the style of communication
  - TCP (Transmission Control Protocol) vs UDP (User Datagram protocol)
    - reliable vs. best effort
    - connection-oriented vs. connectionless



Socket types

- `SOCK_STREAM`
  - a.k.a. **TCP**
  - reliable delivery
  - in-order guaranteed
  - connection-oriented
  - bidirectional

- `SOCK_DGRAM`
  - a.k.a. **UDP**
  - unreliable delivery
  - no order guarantees
  - no notion of “connection” – app indicates destination for each packet
  - can send or receive

We will focus on SOCK_STREAM or TCP socket type

TCP Vs UDP

Feature	TCP	UDP
Connection status	Requires an established connection to transmit data (connection should be closed once transmission is complete)	Connectionless protocol with no requirements for opening, maintaining, or terminating a connection
Guaranteed delivery	Can guarantee delivery of data to the destination router	Cannot guarantee delivery of data to the destination
Retransmission of data	Retransmission of lost packets is possible	No retransmission of lost packets
Method of transfer	Data is read as a byte stream; messages are transmitted to segment boundaries	UDP packets with defined boundaries; sent individually and checked for integrity on arrival
Speed	Slower than UDP (due to overheads involved for maintaining accuracy)	Faster than TCP
Optimal use	Where accuracy is more important than speed. Used by HTTPS, FTP, etc.	Where speed is more important than accuracy Video conferencing, streaming, DNS, VoIP, etc.

Note: TCP establishes a virtual connection – packets may or may not follow the same path (depends if the Network layer protocol are connection oriented.) . IP – is connection-less

System calls

- `socket()`
- `bind()`
- `listen()`
- `accept()`
- `connect()`
- `send() / sendto()`
- `recv() / recvfrom()`

Include

`sys/types.h`
`sys/socket.h`

TCP Server overview

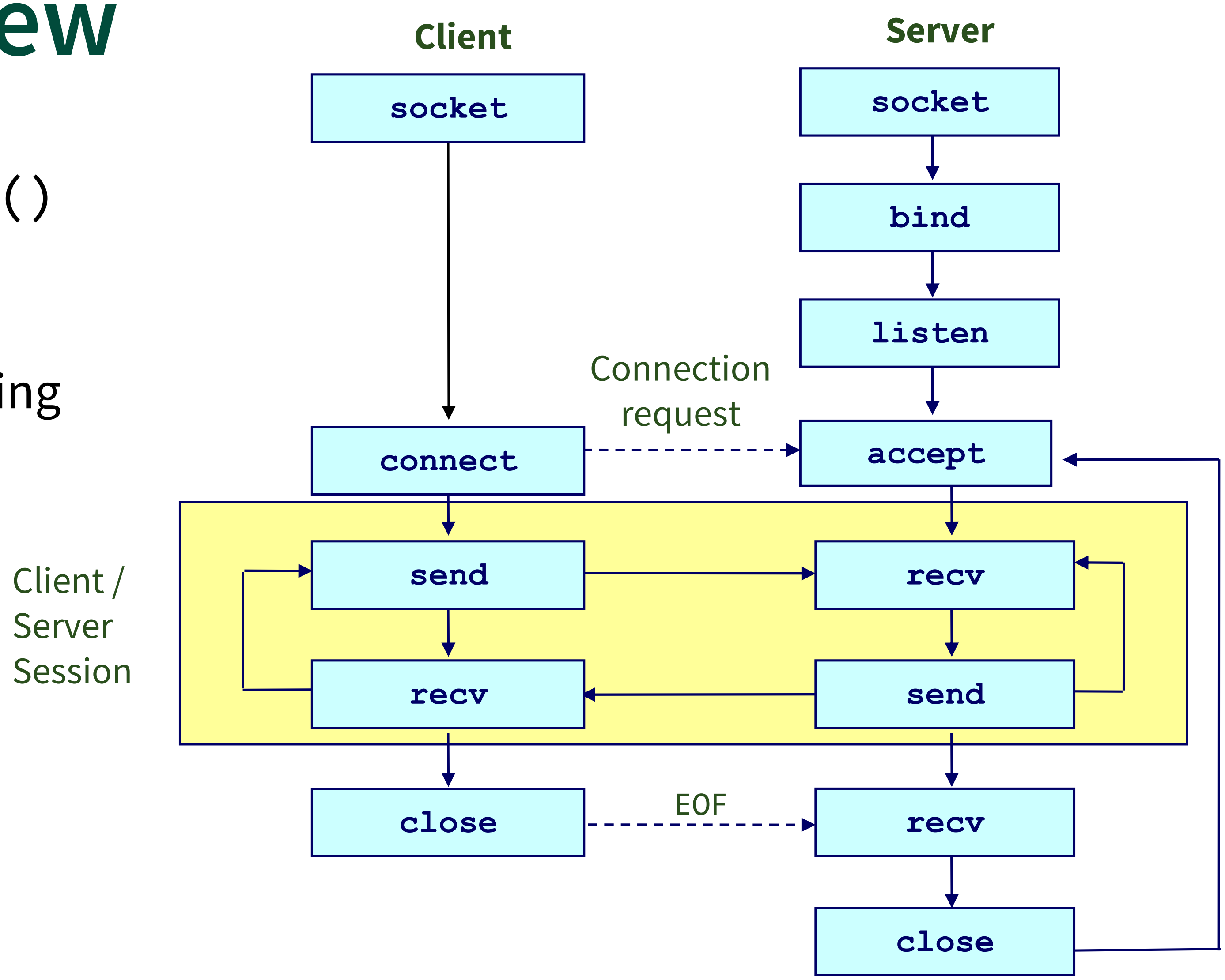
1) Create a socket with the `socket()` system call

2) Bind the socket to an address using the `bind()` system call

3) Listen for connections with the `listen()` system call

4) Accept a connection with the `accept()` system call

5) Send and receive data

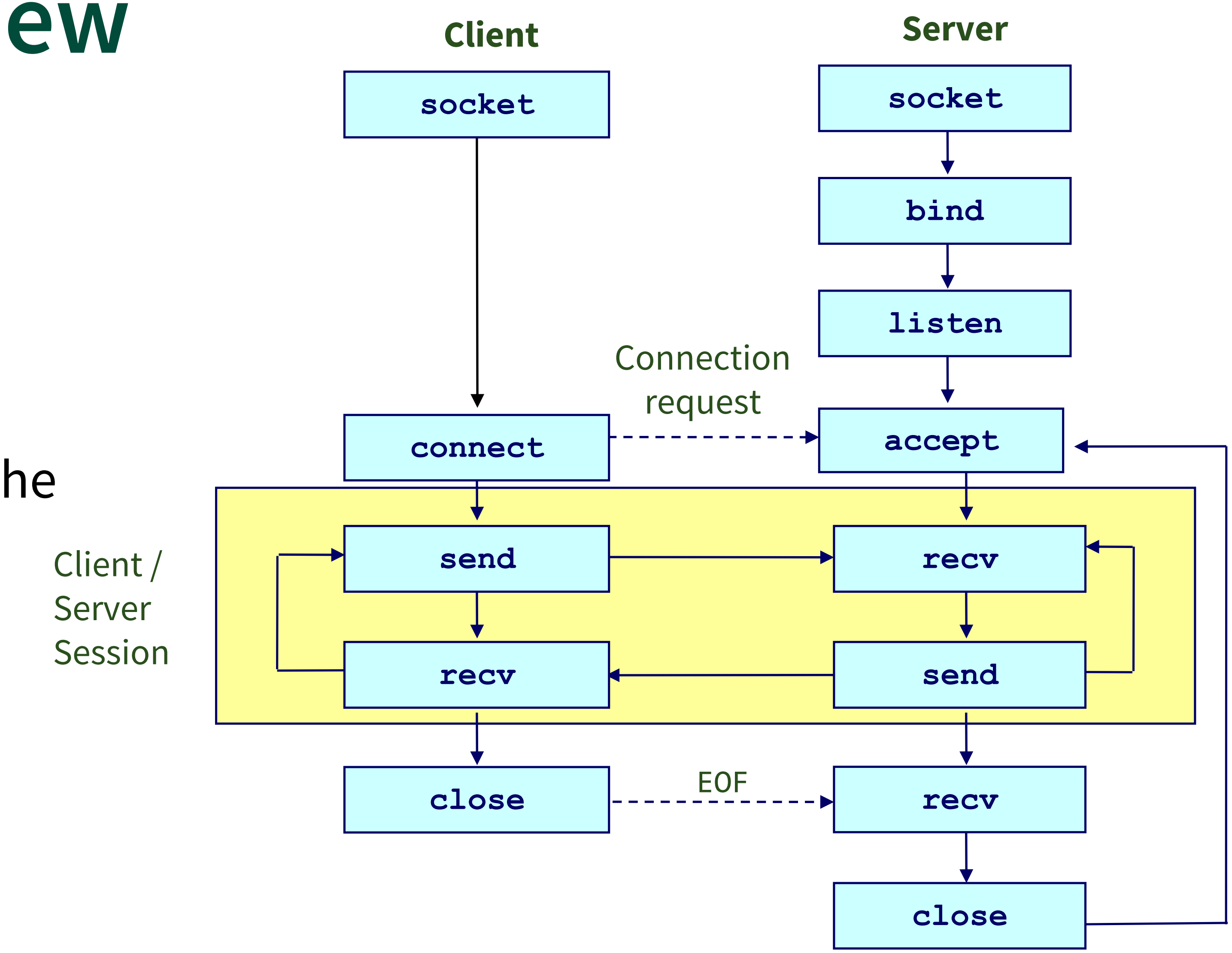


TCP Client overview

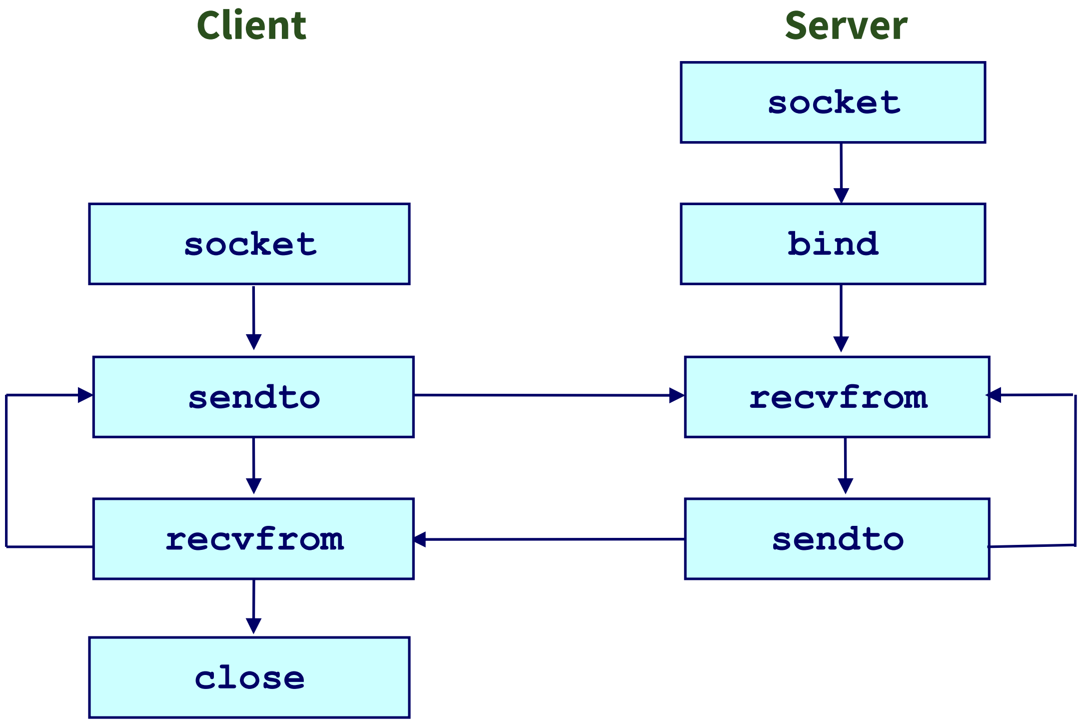
1) Create a socket with the `socket()` system call

2) Connect the socket to the address of the server using the `connect()` system call

3) Send and receive data



Client-server communication overview - UDP



Client

Server

`socket`

`bind`

`recvfrom`

`sendto`

`socket`

`sendto`

`recvfrom`

`close`

Server: step 1

- Create a socket with the `socket()` system call

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

  - *`domain`* – communication domain (protocol family) such as `AF_INET` (IPv4) or `AF_INET6` (IPv6)
  - *`type`* – communication semantics such as `SOCK_STREAM` (TCP) or `SOCK_DGRAM` (UDP)
  - *`protocol`* specifies the protocol. Normally only a single protocol exists to support a particular socket type within a given protocol family, in which case protocol can be specified as 0.

  - Creates an endpoint of communication.
  - If successful, returns **socket file descriptor**, otherwise, returns -1

Server: step 1 example

- Create TCP socket

```
int fd = socket(AF_INET, SOCK_STREAM, 0);
if (fd == -1) {
    printf("Error creating socket");
    exit(0);
}
```

- Create UDP socket

```
int fd = socket(AF_INET, SOCK_DGRAM, 0);
if (fd == -1) {
    printf("Error creating socket");
    exit(0);
}
```

Server: step 2

- Bind the socket to an address using the `bind()` system call

Generic descriptor for any kind of socket

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

  - *`sockfd`* is the socket file descriptor (returned by `socket()`)
  - *`addr`* is a pointer to the structure *`struct sockaddr`* `(generic data type for address)` which contains the host IP address and port number to bind to
  - *`addrlen`* is the length of what addr points to

  - Binding means associating and reserving a port number for use by the socket
  - If successful, returns 0, otherwise, returns -1

`struct sockaddr`

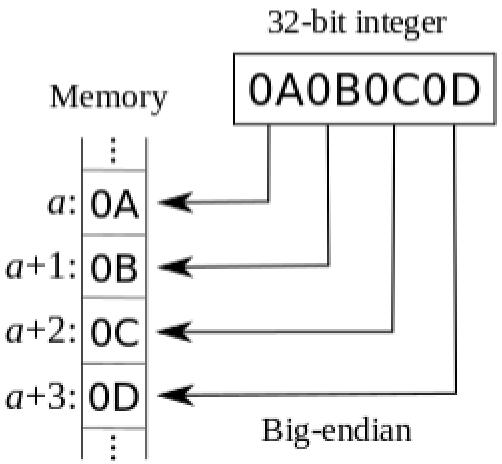
Struct specific to IPV4 protocol based communication

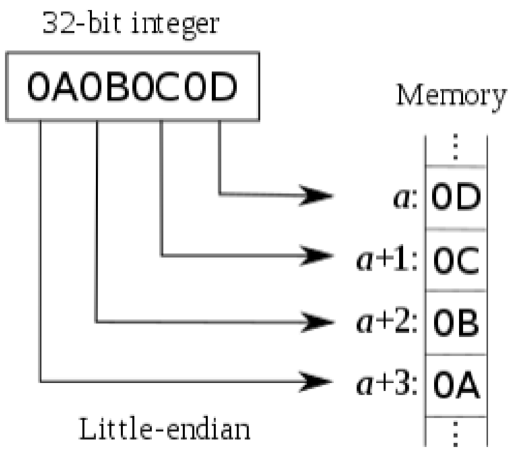
- `struct sockaddr_in` in IPv4 `(included the <netinet/in.h> header)`

```
struct sockaddr_in {
    short sin_family;          // AF_INET
    unsigned short sin_port;   // port number
    struct in_addr sin_addr;   // Internet address in
                               //network byte order


};

struct in_addr {
    unsigned long s_addr;     // IPv4 address in network
                             //byte order
};
```

Host and network byte order

- Little-endian and big-endian issue?





A big-endian system stores the most significant byte of a word at the smallest memory address and the least significant byte at the largest.

A little-endian system, in contrast, stores the least-significant byte at the smallest address.

Host and network byte order

- Byte ordering also matters in network communication
  - Host and network may differ in byte ordering
  - Host byte order may be little-endian or big-endian
  - Network byte order is always big-endian

- Functions for converting between host and network byte order without having to first know what method is used for the host byte order::

```
uint32_t htonl(uint32_t hostlong);
uint16_t htons(uint16_t hostshort);
uint32_t ntohl(uint32_t netlong);
uint16_t ntohs(uint16_t netshort);
```

Server: step 2 example

```
struct sockaddr_in {
    short sin_family;
    unsigned short sin_port;
    struct in_addr sin_addr;
};

struct in_addr {
    unsigned long s_addr;
};
```

```
int fd = socket(AF_INET, SOCK_STREAM, 0);
…

struct sockaddr_in addr;
addr.sin_family = AF_INET;
addr.sin_port = htons(1234);  // port 1234
addr.sin_addr.s_addr = INADDR_ANY; // any address

if (bind(fd, (struct sockaddr *)&addr, sizeof(addr))<0) {
    printf("Error binding socket");
    exit(0);
}
```

Server: step 3

- Listen for connections with the `listen()` system call

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

  - *`sockfd`* is the socket file descriptor (returned by `socket()`)
  - *`backlog`* is the maximum number of pending connections to allow for this socket
    - `SOMAXCONN` is defined as the number of maximum pending connections allowed by the operating system

  - If successful, returns 0, otherwise, returns -1

Server: step 3 example

```
int fd = socket(AF_INET, SOCK_STREAM, 0);
…

if(listen(fd, SOMAXCONN) < 0) {
    printf("Error listening for connections");
    exit(0);
}
```

Server: step 4

- Accept a connection with the `accept()` system call

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

  - *`sockfd`* is the socket file descriptor (returned by `socket()`)
  - *`addr`* is a pointer to the structure `struct sockaddr` which will contain the details of the peer socket (client)
  - *`addrlen`* is a pointer to the length of what addr points to

  - If successful, returns non-negative **socket file descriptor**, otherwise, returns -1

Server: step 4 example

```
int fd = socket(AF_INET, SOCK_STREAM, 0);
…
struct sockaddr_in client_addr;
int addrlen = sizeof(client_addr);

int client_fd = accept(fd, (struct sockaddr *)&client_addr,
                       (socklen_t*)&addrlen);
if(client_fd < 0) {
    printf("Error accepting connection");
    exit(0);
}
```

Server: step 5

- **Send** and receive data

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

  - *`sockfd`* is the socket file descriptor (returned by accept())
  - *`buf`* is a pointer to buffer to be sent
  - *`len`* is the length of buffer to be sent
  - *`flags`* is bitwise OR of zero or more options

- Used in connection-oriented sockets (TCP)
- If successful, returns number of characters sent, otherwise, returns -1
- `send(sockfd, buf, len, 0);` is equivalent to `write(sockfd, buf, len);`

Server: step 5

- **Send** and receive data

```
ssize_t sendto(int sockfd, const void *buf, size_t len, int flags,
               const struct sockaddr *dest_addr, socklen_t addrlen);
```

  - *`sockfd`* is the socket file descriptor (returned by socket())
  - *`buf`* is a pointer to buffer to be sent
  - *`len`* is the length of buffer to be sent
  - *`flags`* is bitwise OR of zero or more options
  - *`dest_addr`* is a pointer to the structure `struct sockaddr` which will contain the details of the peer socket
  - *`addrlen`* is a pointer to the length of what `dest_addr` points to
- Used in non-connection-oriented sockets (UDP)
- If successful, returns number of characters sent, otherwise, returns -1

Server: step 5 example using `send()`

```
int fd = socket(AF_INET, SOCK_STREAM, 0);
…
int client_fd = accept(fd, (struct sockaddr *)& client_addr,
                       (socklen_t*)&addrlen);
…

char msg[] = "hello, world";
ssize_t r = send(client_fd, msg, strlen(msg), 0);
if(r < 0) {
    printf("Error sending message");
    close(client_fd);
    exit(0);
}
```

Server: step 5

- Send and **receive** data

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

  - *`sockfd`* is the socket file descriptor (returned by accept())
  - *`buf`* is a pointer to buffer to be received
  - *`len`* is the length of buffer to be received
  - *`flags`* is bitwise OR of zero or more options

- Used in connection-oriented sockets (TCP)
- If successful, returns number of characters received, otherwise, returns -1
- If peer socket is shutdown/closed, will return 0
- `recv(sockfd, buf, len, 0);` is equivalent to `read(sockfd, buf, len);`

Server: step 5

- Send and **receive** data

```
ssize_t recvfrom(int sockfd, void *buf, size_t len, int flags,
                 struct sockaddr *src_addr, socklen_t *addrlen);
```

  - *`sockfd`* is the socket file descriptor (returned by socket())
  - *`buf`* is a pointer to buffer to be received
  - *`len`* is the length of buffer to be received
  - *`flags`* is bitwise OR of zero or more options
  - *`src_addr`* is a pointer to the structure `struct sockaddr` which will contain the details of the peer socket
  - *`addrlen`* is a pointer to the length of what src_addr points to
- Used in non-connection-oriented sockets (UDP)
- If successful, returns number of characters received, otherwise, returns -1
- If peer socket is shutdown/closed, will return 0

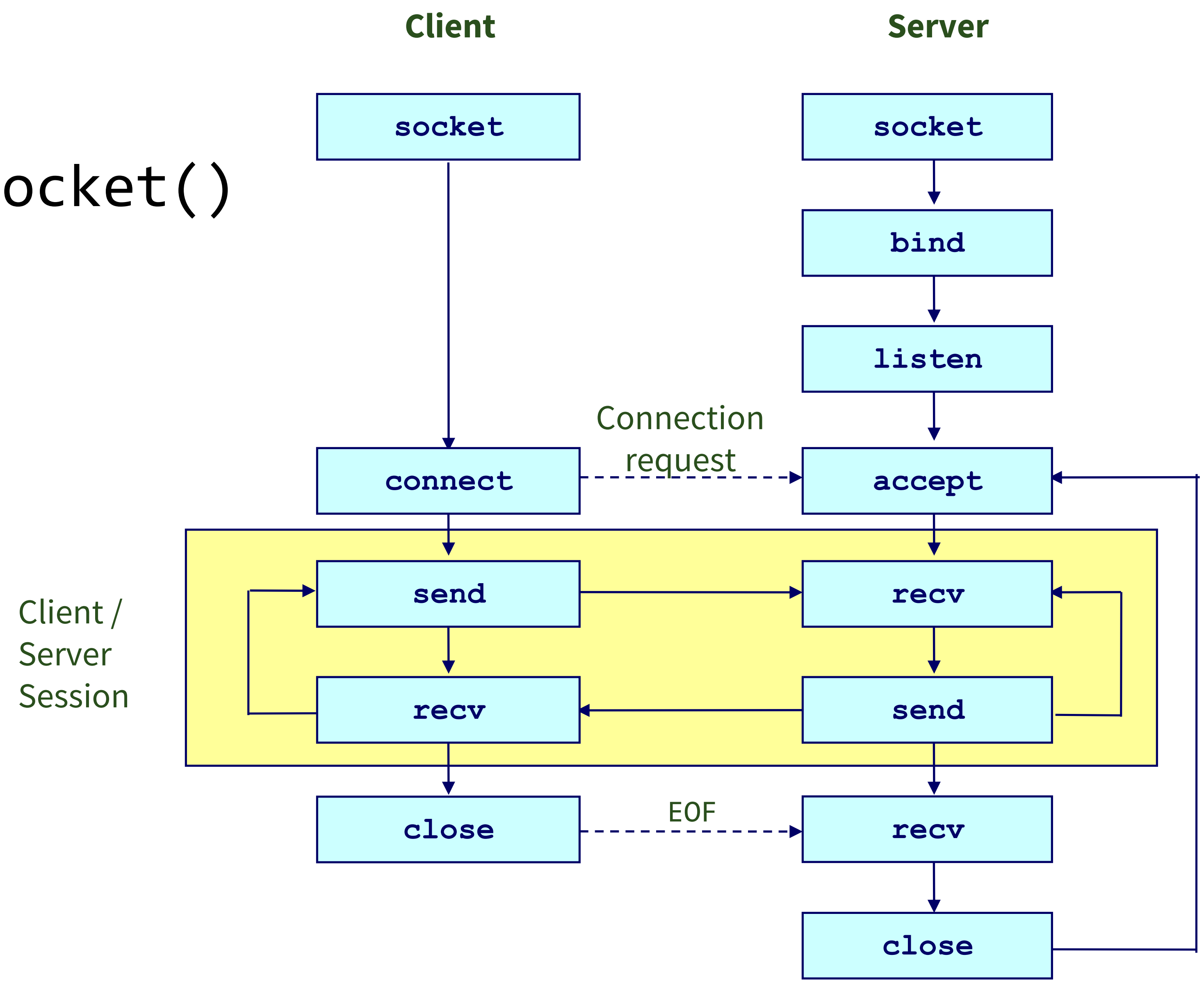
Server: step 5 example using `recv()`

```
int fd = socket(AF_INET, SOCK_STREAM, 0);
…
int client_fd = accept(fd, (struct sockaddr *)& client_addr,
                       (socklen_t*)&addrlen);
…

char incoming[100];
ssize_t r = recv(client_fd, incoming, 100, 0);
if(r <= 0) {
    printf("Error receiving message");
    close(client_fd);
    exit(0);
}
// Do something with receiving message
printf("Received message: %s", incoming);
```

Client: step 1

- Create a socket with the `socket()` system call

- Same as server step 1



Client: step 2

- Connect the socket to the address of the server using the `connect()` system call
  - This step is only required for connection-oriented sockets (TCP)

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

  - *`sockfd`* is the socket file descriptor (returned by socket())
  - *`addr`* is a pointer to the structure `struct sockaddr` which will contain the details of the server socket
  - *`addrlen`* is a pointer to the length of what addr points to

  - If successful, returns 0, otherwise, returns -1

Client: step 3

- Send and receive data

- Same as server step 5

Closing a socket

- Socket must be closed after its use

```
int shutdown(int sockfd, int how);
```

```
int close(int sockfd);
```

  - *`sockfd`* is the socket file descriptor (returned by socket())
  - *`how`* can either be SHUT_RD (further receptions disallowed), SHUT_WR (further transmissions disallowed), or SHUT_RDWR (further receptions and transmissions disallowed)
  - Shutdown blocks communication without destroying the socket, close blocks the communication and destroys the socket.
  - If successful, returns 0, otherwise, returns -1

Next Lecture

- Process Management System calls