Introduction to Sockets Programming in C using TCP/IP

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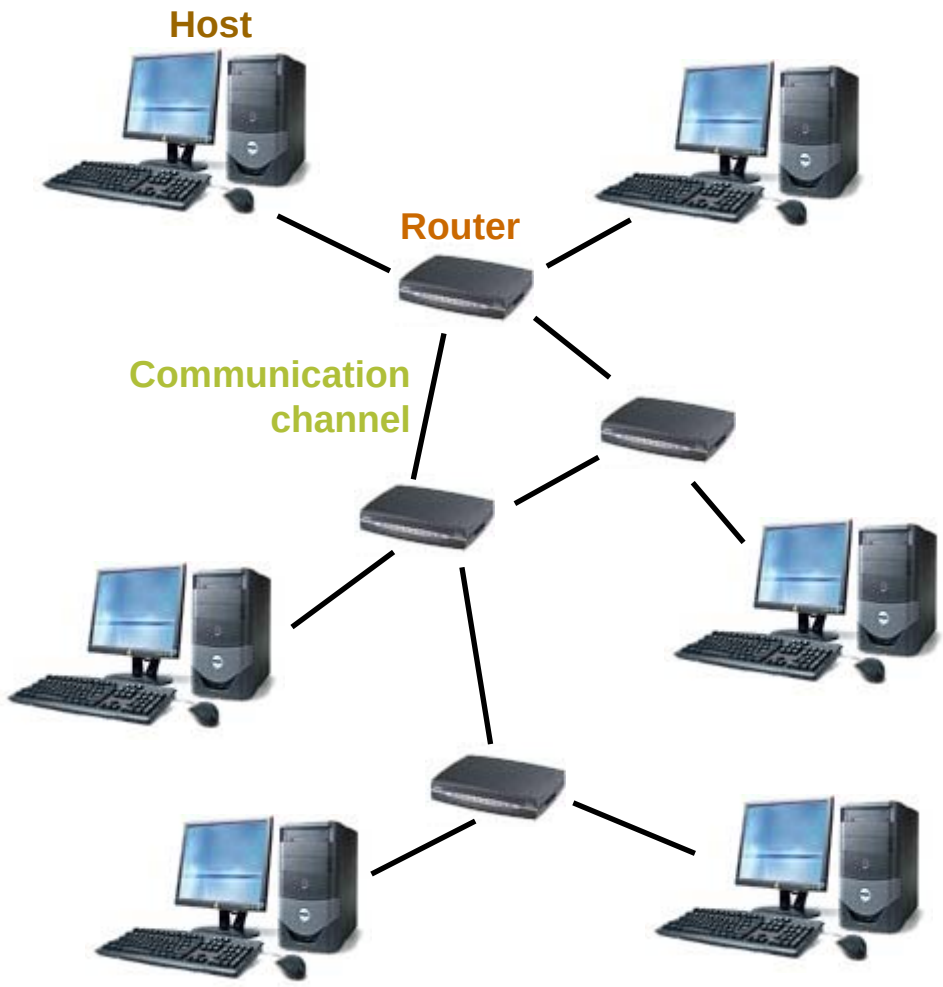
Introduction

- Computer Network
  - hosts, routers, communication channels
- Hosts run applications
- Routers forward information
- Packets: sequence of bytes
  - contain control information
  - e.g. destination host
- Protocol is an agreement
  - meaning of packets
  - structure and size of packets

  e.g. Hypertext Transfer Protocol (HTTP)



Protocol Families - TCP/IP

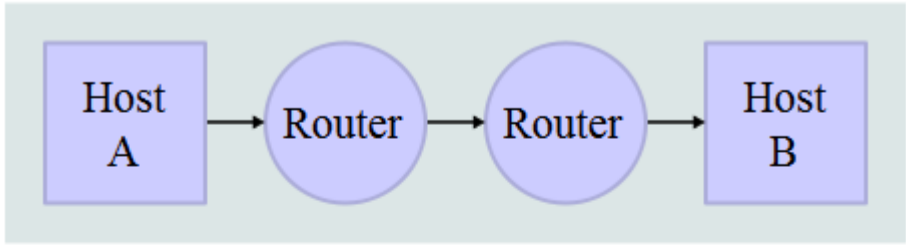
- Several protocols for different problems

☞ **Protocol Suites** or **Protocol Families:** TCP/IP

- TCP/IP provides **end-to-end** connectivity specifying how data should be
  - formatted,
  - addressed,
  - transmitted,
  - routed, and
  - received at the destination
- can be used in the internet and in stand-alone private networks
- it is organized into **layers**

TCP/IP

Network Topology *



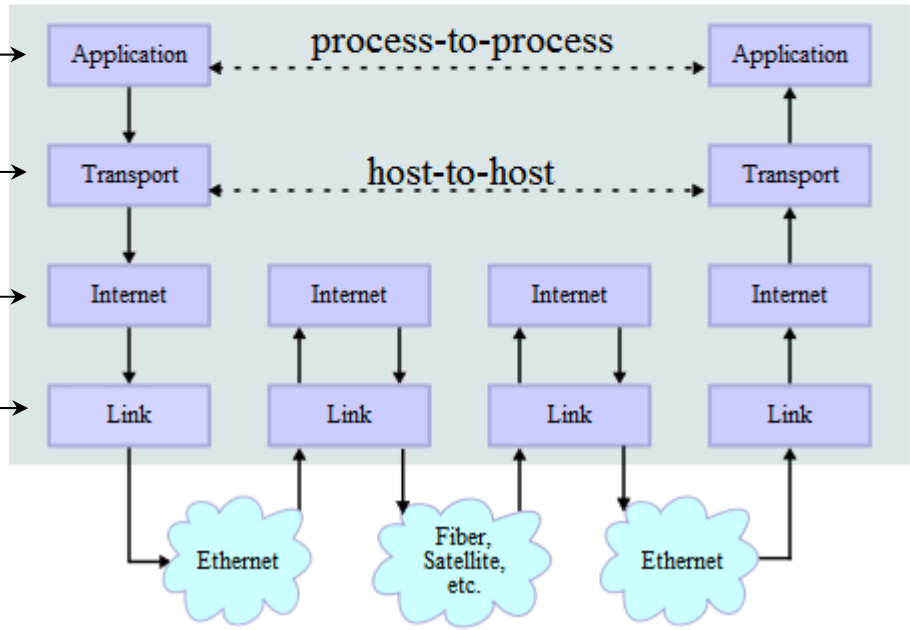
Data Flow

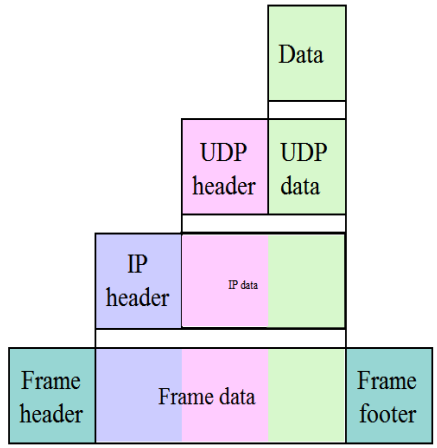
FTP, SMTP, …

Transport Layer
TCP or UDP

Network Layer
IP

Communication
Channels



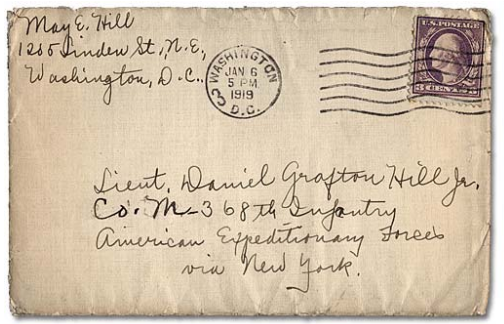


* image is taken from "http://en.wikipedia.org/wiki/TCP/IP_model"

Internet Protocol (IP)

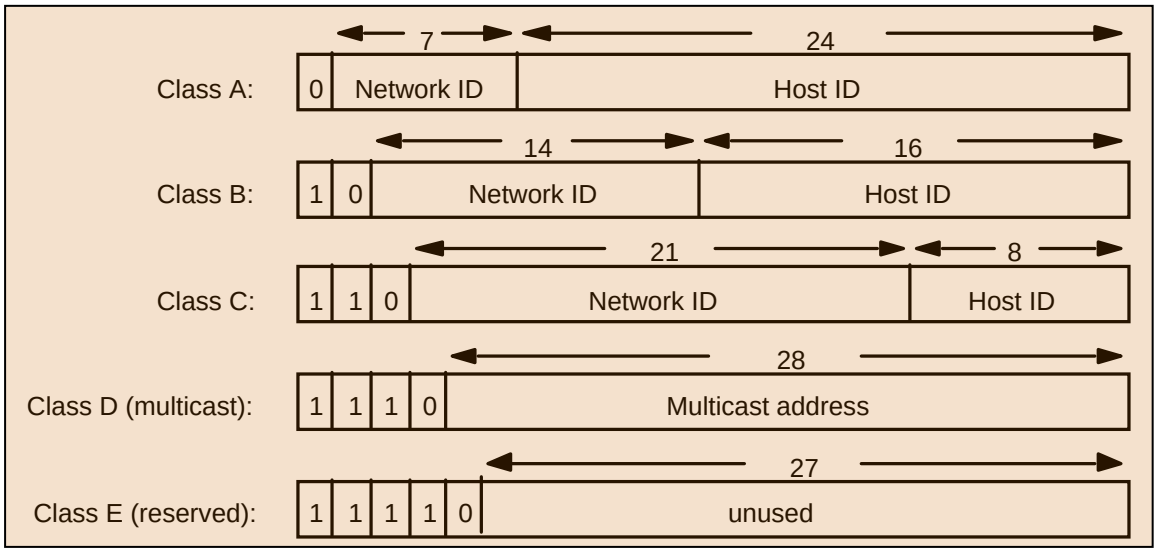
- provides a **datagram** service
  - packets are handled and delivered independently
- **best-effort** protocol
  - may loose, reorder or duplicate packets

- each packet must contain an **IP address** of its destination



Addresses - IPv4

- The **32** bits of an IPv4 address are broken into **4 octets**, or 8 bit fields (0-255 value in decimal notation).
- For networks of different size,
  - the first one (for large networks) to three (for small networks) octets can be used to identify the **network**, while
  - the rest of the octets can be used to identify the **node** on the network.



Range of addresses

1.0.0.0 to
127.255.255.255

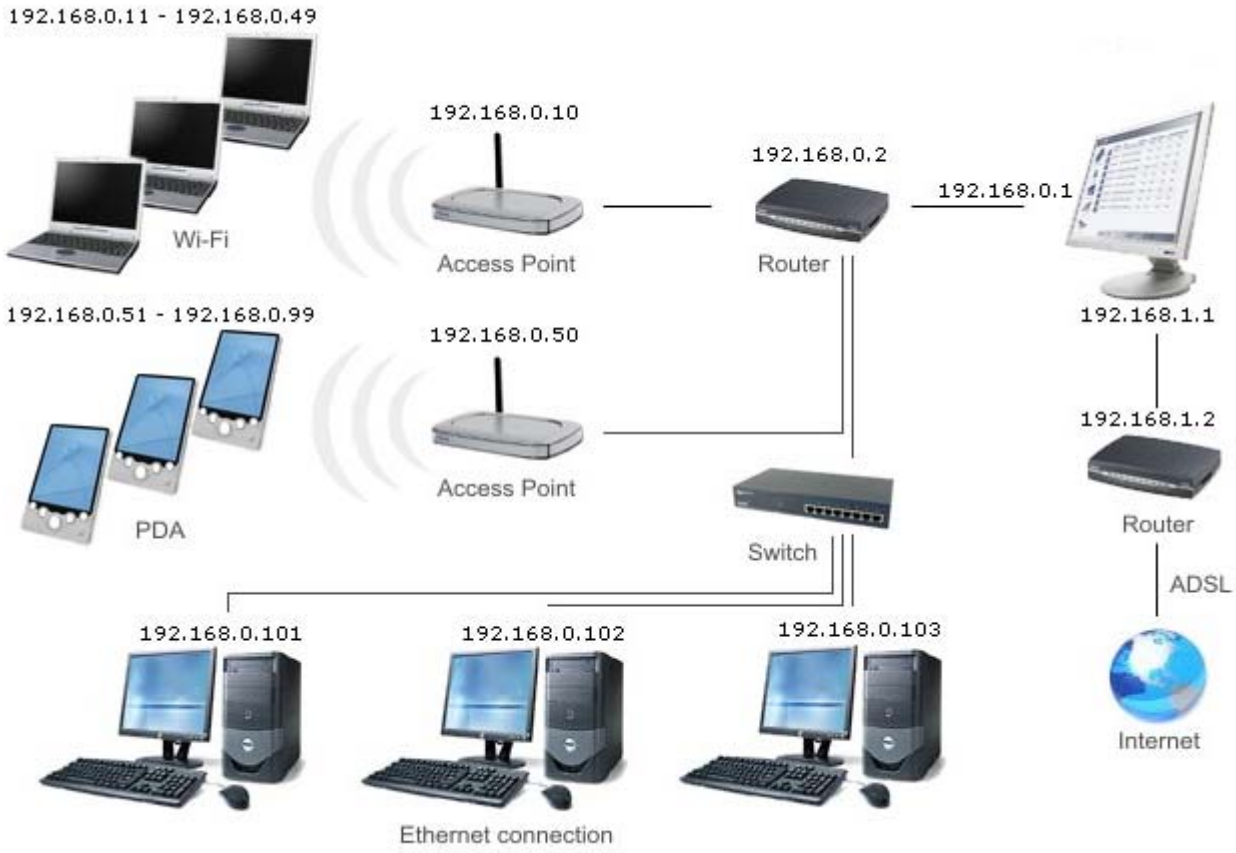
128.0.0.0 to
191.255.255.255

192.0.0.0 to
223.255.255.255

224.0.0.0 to
239.255.255.255

240.0.0.0 to
255.255.255.255

Local Area Network Addresses - IPv4



TCP vs UDP

- Both use **port numbers**
  - application-specific construct serving as a communication endpoint
  - 16-bit unsigned integer, thus ranging from 0 to 65535
  - ☞ to provide **end-to-end** transport
- UDP: User Datagram Protocol
  - no acknowledgements
  - no retransmissions
  - out of order, duplicates possible
  - connectionless, i.e., app indicates destination for each packet
- TCP: Transmission Control Protocol
  - reliable **byte-stream channel** (in order, all arrive, no duplicates)
    - similar to file I/O
  - flow control
  - connection-oriented
  - bidirectional

TCP vs UDP

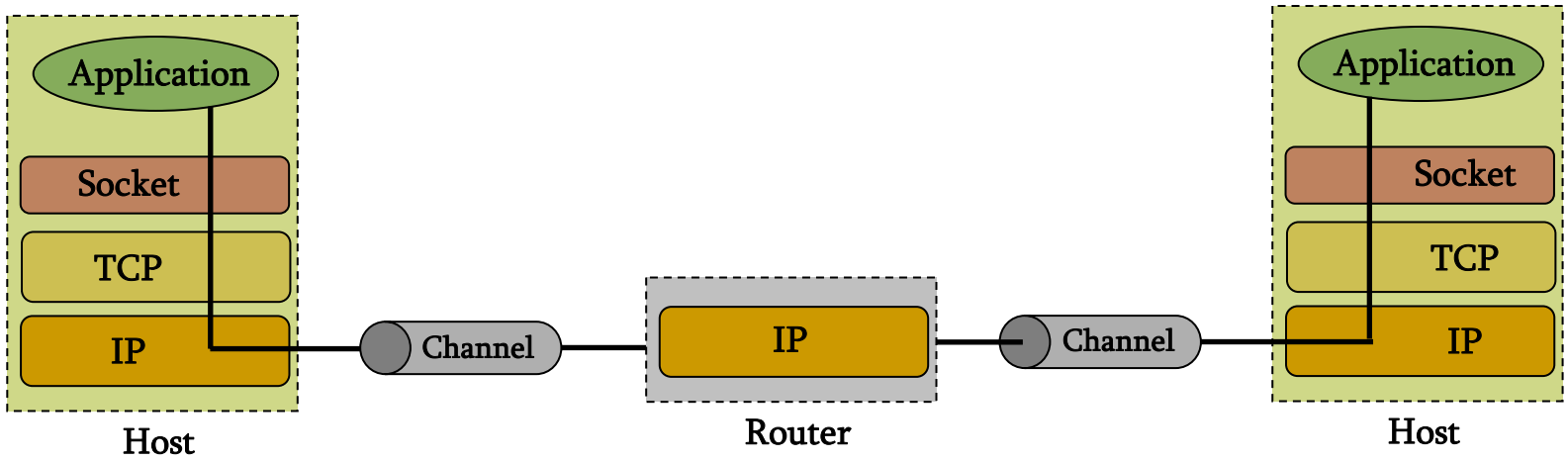
- TCP is used for services with a large data capacity, and a persistent connection
- UDP is more commonly used for quick lookups, and single use query-reply actions.

- Some common examples of TCP and UDP with their default ports:

DNS lookup	UDP	53
FTP	TCP	21
HTTP	TCP	80
POP3	TCP	110
Telnet	TCP	23

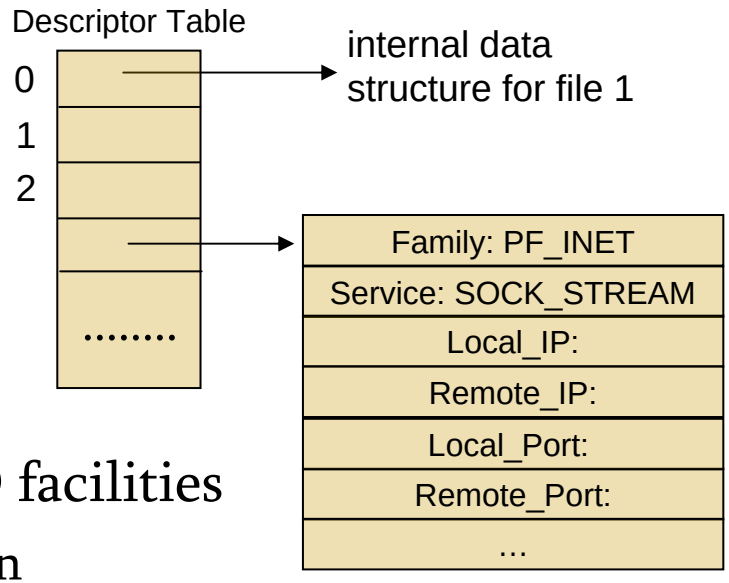
Berkley Sockets

- Universally known as **Sockets**
- It is an abstraction through which an application may send and receive data
- Provide **generic access** to interprocess communication services
  - e.g. IPX/SPX, Appletalk, TCP/IP
- Standard API for networking

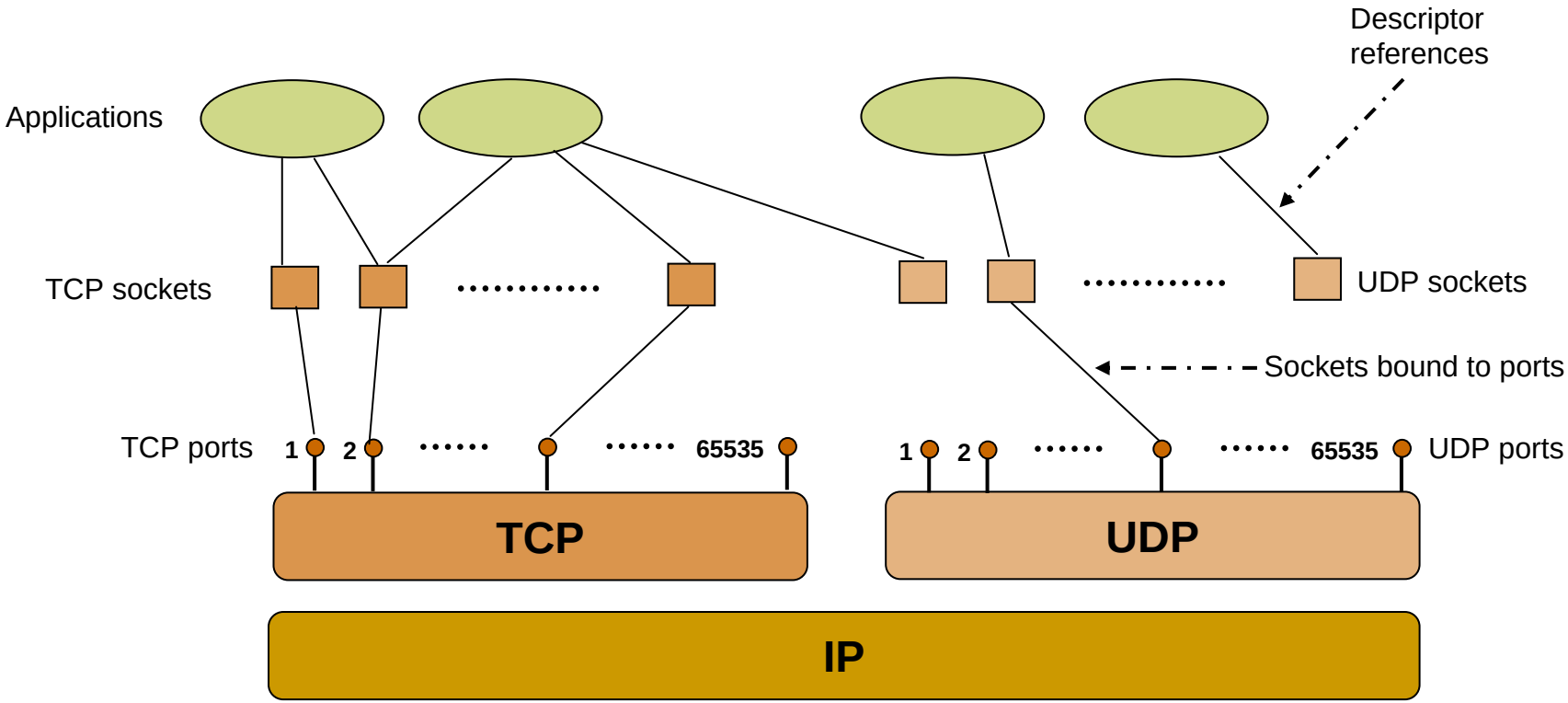


Sockets

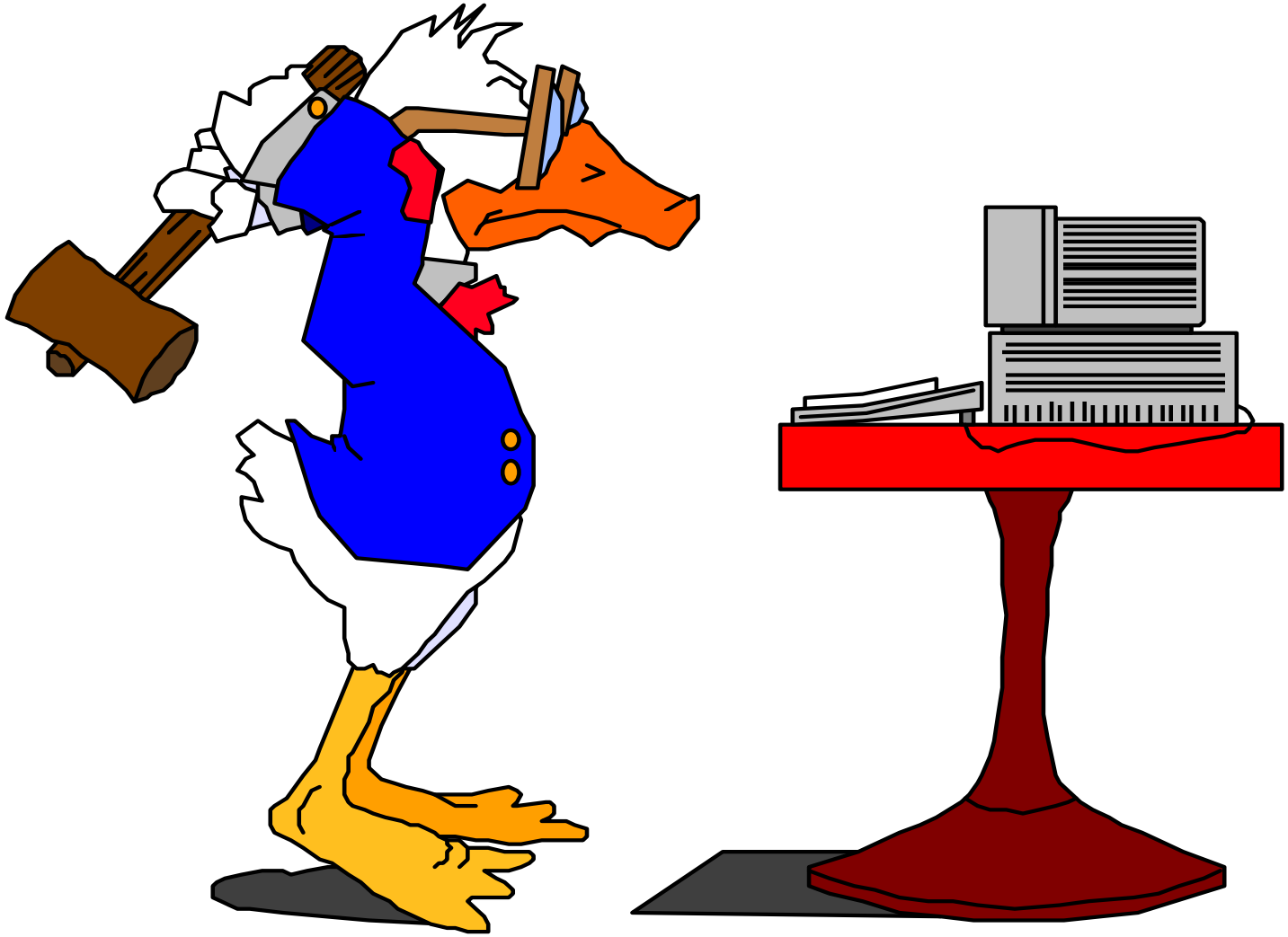
- Uniquely identified by
  - an internet address
  - an end-to-end protocol (e.g. TCP or UDP)
  - a port number
- Two types of (TCP/IP) sockets
  - Stream sockets (e.g. uses TCP)
    - provide reliable byte-stream service
  - Datagram sockets (e.g. uses UDP)
    - provide best-effort datagram service
    - messages up to 65.500 bytes
- Socket extend the convectional UNIX I/O facilities
  - file descriptors for network communication
  - extended the read and write system calls



Sockets


Descriptor references
Applications
TCP sockets
UDP sockets
Sockets bound to ports
TCP ports
1
2
65535
1
2
65535
UDP ports
TCP
UDP
IP

Socket Programming



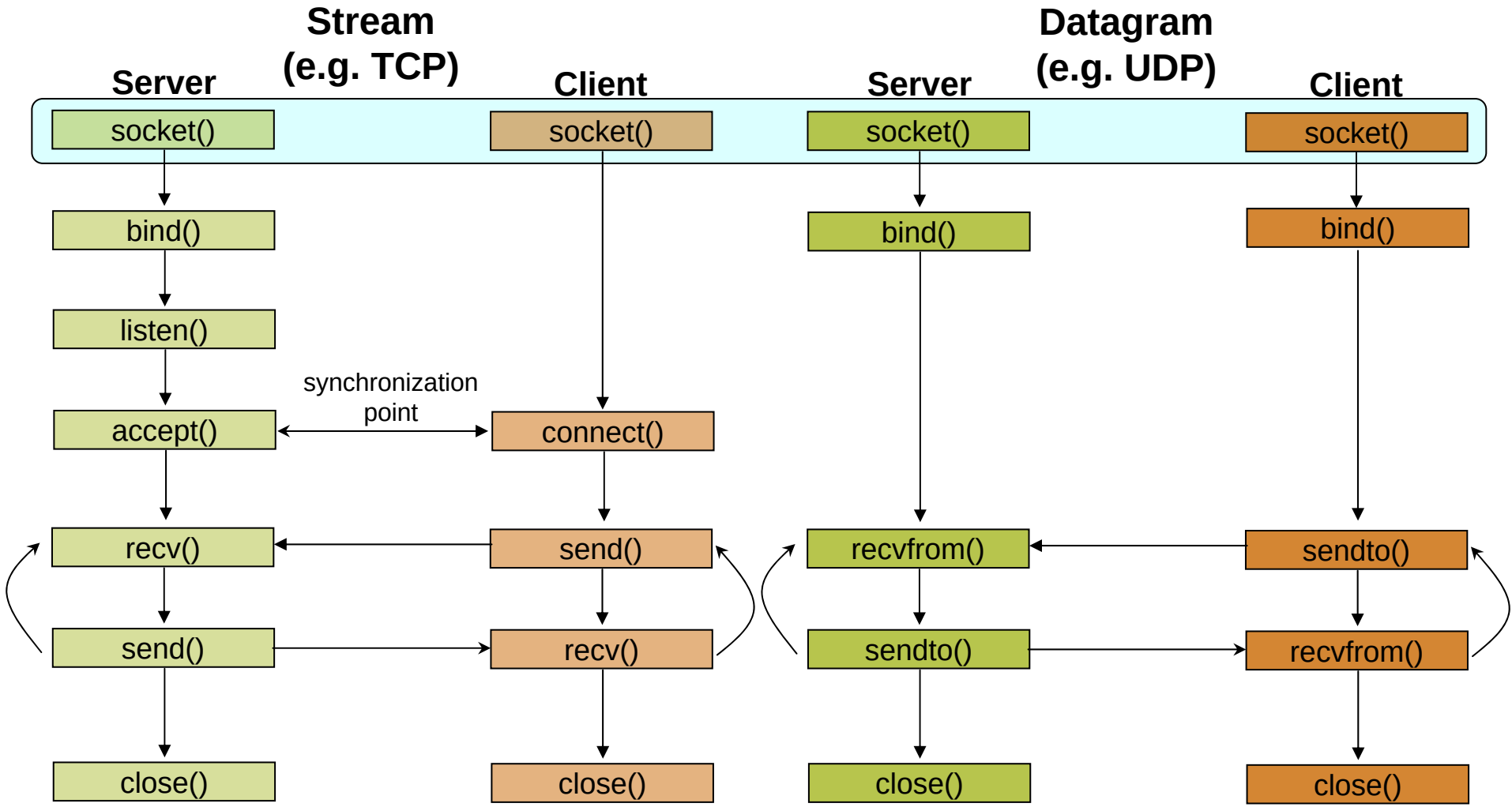
Client-Server communication

- Server
  - passively waits for and responds to clients
  - passive socket
- Client
  - initiates the communication
  - must know the address and the port of the server
  - active socket

Sockets - Procedures

Primitive	Meaning
Socket	Create a new communication endpoint
Bind	Attach a local address to a socket
Listen	Announce willingness to accept connections
Accept	Block caller until a connection request arrives
Connect	Actively attempt to establish a connection
Send	Send some data over the connection
Receive	Receive some data over the connection
Close	Release the connection

Client - Server Communication - Unix

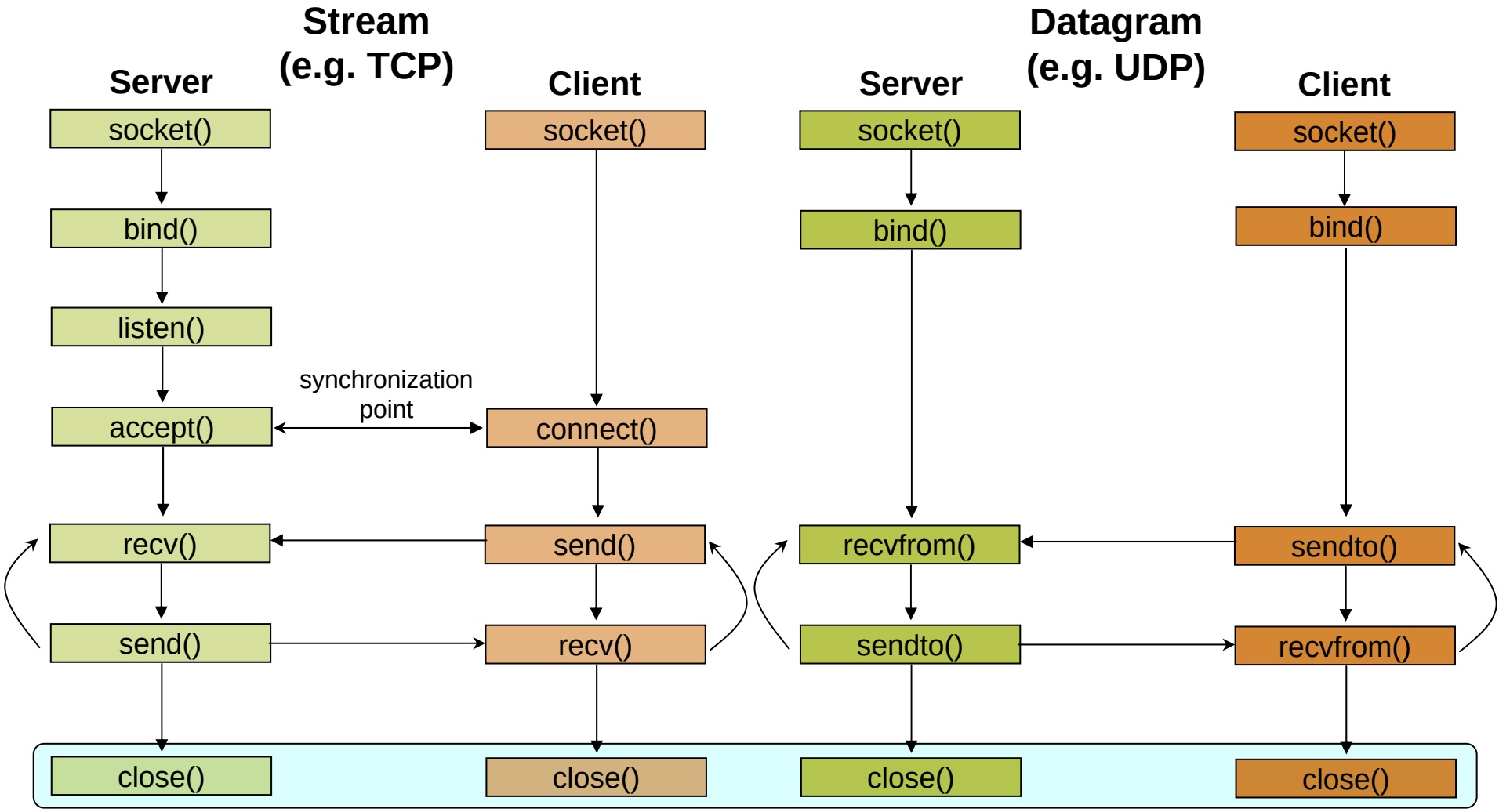


Socket creation in C: `socket()`

- `int sockid = socket(family, type, protocol);`
  - sockid: socket descriptor, an integer (like a file-handle)
  - family: integer, communication domain, e.g.,
    - PF_INET, IPv4 protocols, Internet addresses (typically used)
    - PF_UNIX, Local communication, File addresses
  - type: communication type
    - SOCK_STREAM - reliable, 2-way, connection-based service
    - SOCK_DGRAM - unreliable, connectionless, messages of maximum length
  - protocol: specifies protocol
    - IPPROTO_TCP IPPROTO_UDP
    - usually set to 0 (i.e., use default protocol)
  - upon failure returns -1

☞ NOTE: socket call does not specify where data will be coming from, nor where it will be going to – it just creates the interface!

Client - Server Communication - Unix



Socket close in C: `close()`

- When finished using a socket, the socket should be closed

- `status = close(sockid);`
  - sockid: the file descriptor (socket being closed)
  - status: 0 if successful, -1 if error

- Closing a socket
  - closes a connection (for stream socket)
  - frees up the port used by the socket

Specifying Addresses

- Socket API defines a **generic** data type for addresses:

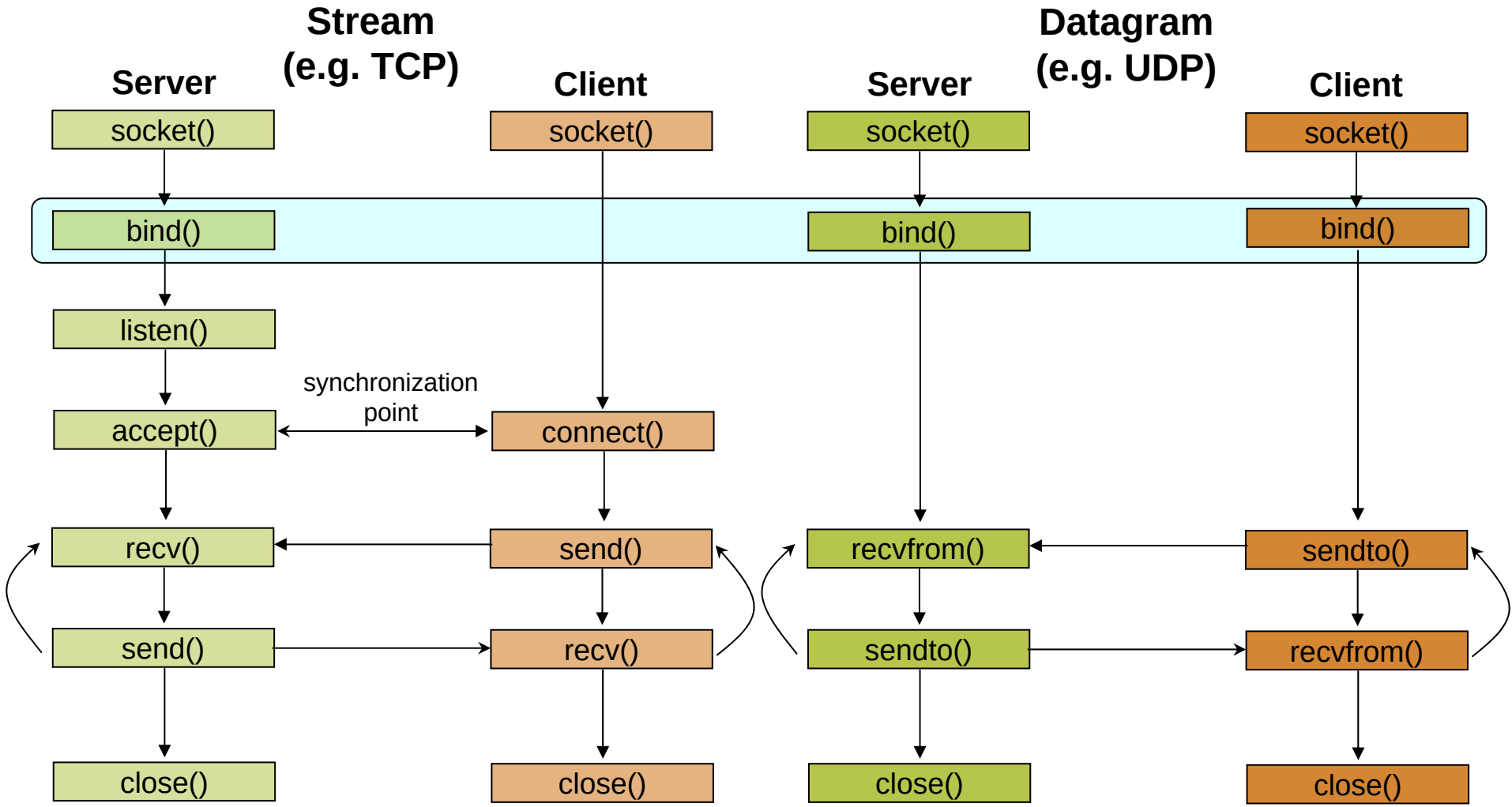
```
struct sockaddr {
   unsigned short sa_family;  /* Address family (e.g. AF_INET) */
   char sa_data[14];          /* Family-specific address information */
}
```

- Particular form of the sockaddr used for **TCP/IP** addresses:

```
struct in_addr {
   unsigned long s_addr;          /* Internet address (32 bits) */
}
struct sockaddr_in {
   unsigned short sin_family;     /* Internet protocol (AF_INET) */
   unsigned short sin_port;       /* Address port (16 bits) */
   struct in_addr sin_addr;     /* Internet address (32 bits) */
   char sin_zero[8];              /* Not used */
}
```

☞ **Important**: sockaddr_in can be casted to a sockaddr

Client - Server Communication - Unix



Assign address to socket: `bind()`

- associates and reserves a port for use by the socket

- `int status = bind(sockid, &addrport, size);`
  - sockid: integer, socket descriptor
  - addrport: struct sockaddr, the (IP) address and port of the machine
    - for TCP/IP server, internet address is usually set to INADDR_ANY, i.e., chooses any incoming interface
  - size: the size (in bytes) of the addrport structure
  - status: upon failure -1 is returned

bind()- Example with TCP

```
int sockid;
struct sockaddr_in addrport;
sockid = socket(PF_INET, SOCK_STREAM, 0);

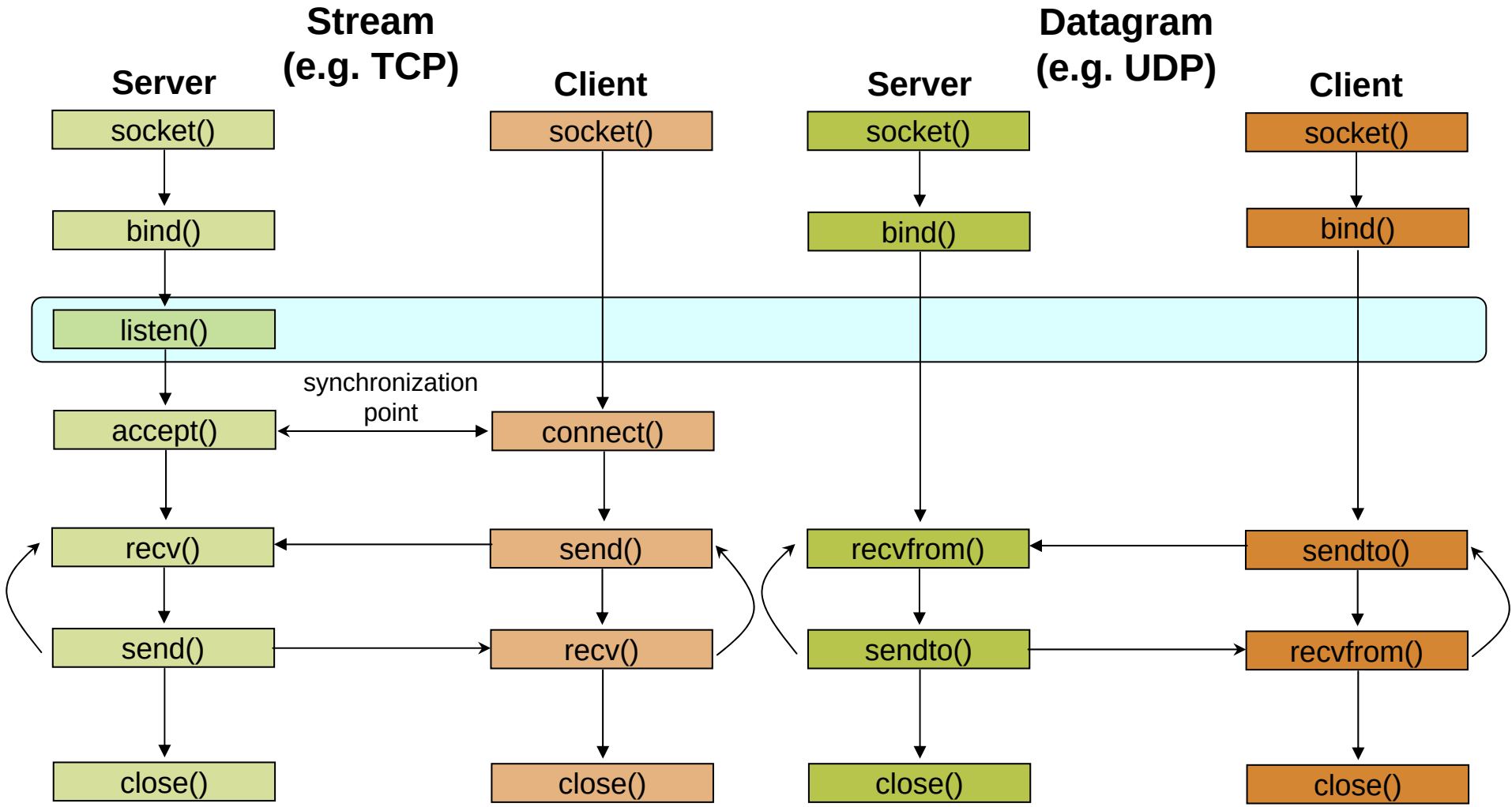
addrport.sin_family = AF_INET;
addrport.sin_port = htons(5100);
addrport.sin_addr.s_addr = htonl(INADDR_ANY);
if(bind(sockid, (struct sockaddr *) &addrport, sizeof(addrport))!= -1) {
   …}
```

Skipping the `bind()`

- bind can be skipped for both types of sockets

- Datagram socket:
  - if only sending, no need to bind. The OS finds a port each time the socket sends a packet
  - if receiving, need to bind
- Stream socket:
  - destination determined during connection setup
  - don't need to know port sending from (during connection setup, receiving end is informed of port)

Client - Server Communication - Unix



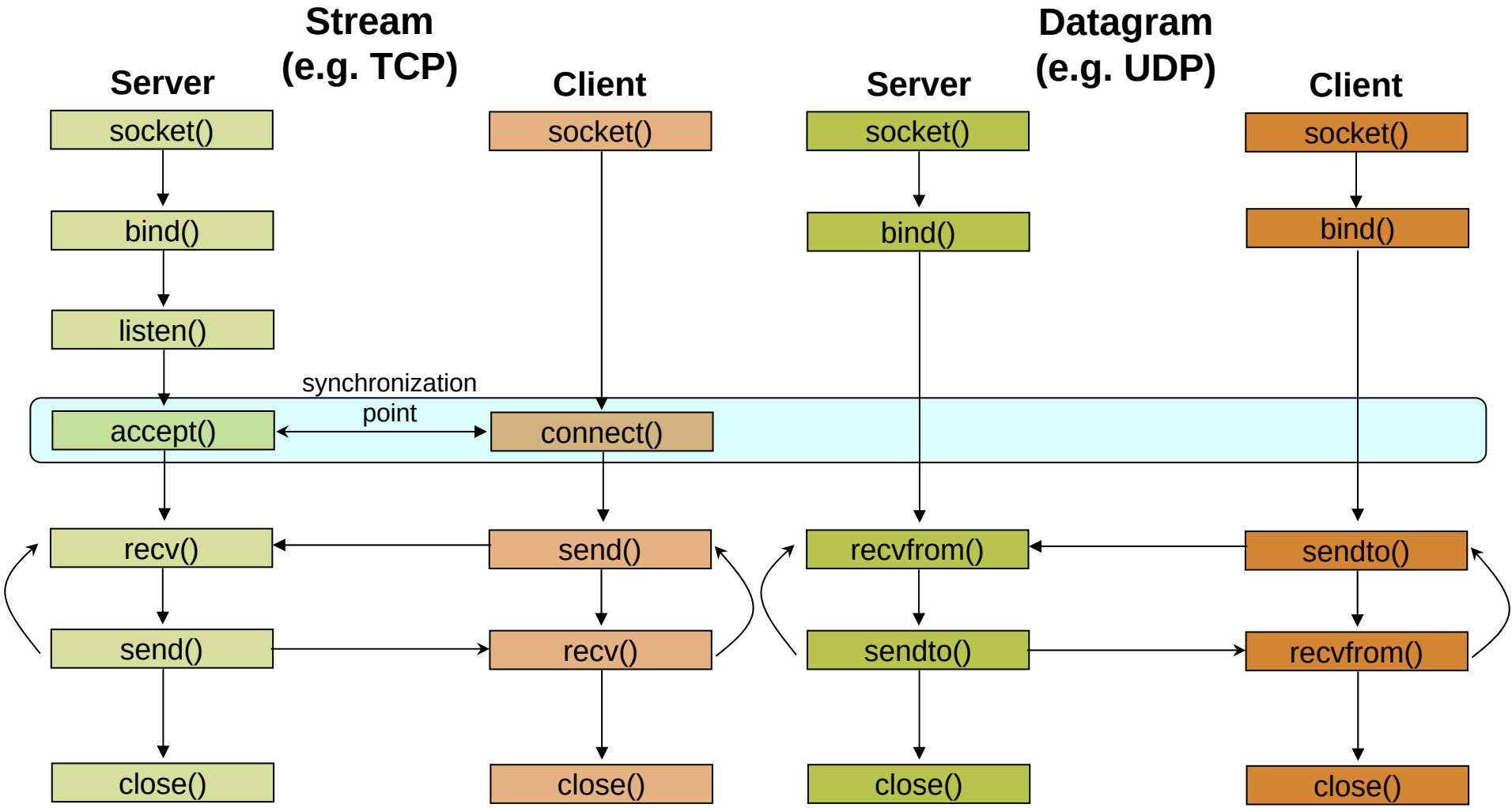
Assign address to socket: `bind()`

- Instructs TCP protocol implementation to listen for connections

- `int status = listen(sockid, queueLimit);`
  - sockid: integer, socket descriptor
  - queuelen: integer, # of active participants that can "wait" for a connection
  - status: 0 if listening, -1 if error
- `listen()` is **non-blocking**: returns immediately

- The listening socket (sockid)
  - is never used for sending and receiving
  - is used by the server only as a way to get new sockets

Client - Server Communication - Unix



Establish Connection: `connect()`

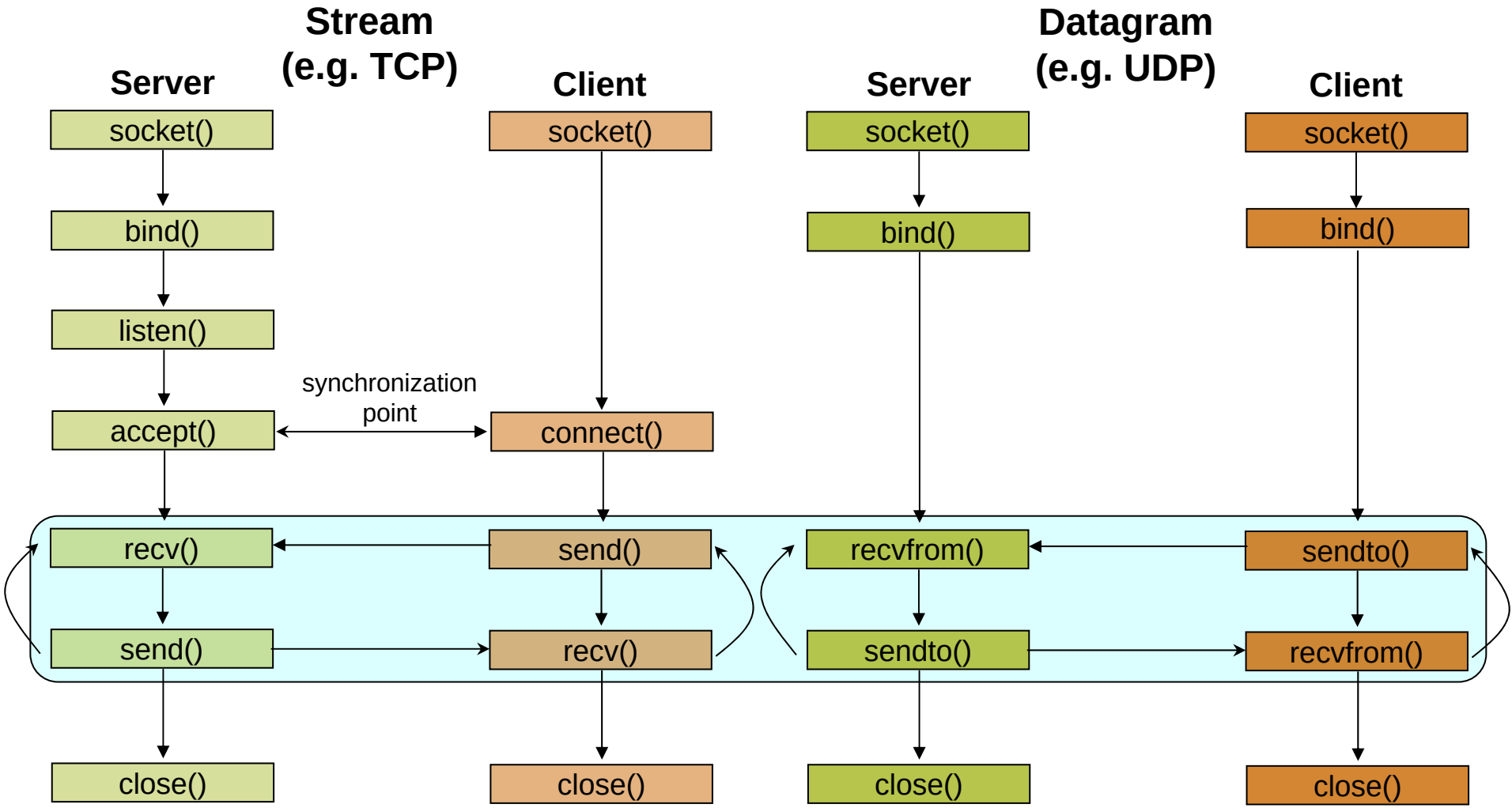
- The client establishes a connection with the server by calling `connect()`

- ```
  int status = connect(sockid, &foreignAddr, addrlen);
  ```
  - sockid: integer, socket to be used in connection
  - foreignAddr: struct sockaddr: address of the passive participant
  - addrlen: integer, sizeof(name)
  - status: 0 if successful connect, -1 otherwise
- `connect()` is **blocking**
  ```

Incoming Connection: `accept()`

- The server gets a socket for an incoming client connection by calling `accept()`
- `int s = accept(sockid, &clientAddr, &addrLen);`
  - s: integer, the new socket (used for data-transfer)
  - sockid: integer, the orig. socket (being listened on)
  - clientAddr: struct sockaddr, address of the active participant
    - filled in upon return
  - addrLen: sizeof(clientAddr): value/result parameter
    - must be set appropriately before call
    - adjusted upon return
- `accept()`
  - is **blocking**: waits for connection before returning
  - dequeues the next connection on the queue for socket (sockid)

Client - Server Communication - Unix



Exchanging data with stream socket

- `int count = send(sockid, msg, msgLen, flags);`
  - msg: const void[], message to be transmitted
  - msgLen: integer, length of message (in bytes) to transmit
  - flags: integer, special options, usually just 0
  - count: # bytes transmitted (-1 if error)
- `int count = recv(sockid, recvBuf, bufLen, flags);`
  - recvBuf: void[], stores received bytes
  - bufLen: # bytes received
  - flags: integer, special options, usually just 0
  - count: # bytes received (-1 if error)
- Calls are **blocking**
  - returns only after data is sent / received

Exchanging data with datagram socket

- `int count = sendto(sockid, msg, msgLen, flags, &foreignAddr, addrlen);`
  - msg, msgLen, flags, count: same with `send()`
  - foreignAddr: struct sockaddr, address of the destination
  - addrLen: sizeof(foreignAddr)

- `int count = recvfrom(sockid, recvBuf, bufLen, flags, &clientAddr, addrlen);`
  - recvBuf, bufLen, flags, count: same with `recv()`
  - clientAddr: struct sockaddr, address of the client
  - addrLen: sizeof(clientAddr)

- Calls are **blocking**
  - returns only after data is sent / received

Example - Echo

- A client communicates with an “echo” server
- The server simply echoes whatever it receives back to the client

Example - Echo using stream socket

The server starts by getting ready to receive client connections...

Client

1. Create a TCP socket
2. Establish connection
3. Communicate
4. Close the connection

Server

1. Create a TCP socket
2. Assign a port to socket
3. Set socket to listen
4. Repeatedly:
   a. Accept new connection
   b. Communicate
   c. Close the connection

Example - Echo using stream socket

```
/* Create socket for incoming connections */
if ((servSock = socket(PF_INET, SOCK_STREAM, IPPROTO_TCP)) < 0)
     DieWithError("socket() failed");
```

Client

1. Create a TCP socket
2. Establish connection
3. Communicate
4. Close the connection

Server

1. **Create a TCP socket**
2. Assign a port to socket
3. Set socket to listen
4. Repeatedly:
   a. Accept new connection
   b. Communicate
   c. Close the connection

Example - Echo using stream socket

```
echoServAddr.sin_family = AF_INET;                  /* Internet address family */
echoServAddr.sin_addr.s_addr = htonl(INADDR_ANY);   /* Any incoming interface */
echoServAddr.sin_port = htons(echoServPort);        /* Local port */

if (bind(servSock, (struct sockaddr *) &echoServAddr, sizeof(echoServAddr)) < 0)
    DieWithError("bind() failed");
```

Client

1. Create a TCP socket
2. Establish connection
3. Communicate
4. Close the connection

Server

1. Create a TCP socket
2. **Assign a port to socket**
3. Set socket to listen
4. Repeatedly:
   a. Accept new connection
   b. Communicate
   c. Close the connection

Example - Echo using stream socket

```
/* Mark the socket so it will listen for incoming connections */
if (listen(servSock, MAXPENDING) < 0)
        DieWithError("listen() failed");
```

Client

1. Create a TCP socket
2. Establish connection
3. Communicate
4. Close the connection

Server

1. Create a TCP socket
2. Assign a port to socket
3. **Set socket to listen**
4. Repeatedly:
   a. Accept new connection
   b. Communicate
   c. Close the connection

Example - Echo using stream socket

```
for (;;) /* Run forever */
{
  clntLen = sizeof(echoClntAddr);

  if ((clientSock=accept(servSock,(struct sockaddr *)&echoClntAddr,&clntLen))<0)
      DieWithError("accept() failed");
  ...
```

Client

1. Create a TCP socket
2. Establish connection
3. Communicate
4. Close the connection

Server

1. Create a TCP socket
2. Assign a port to socket
3. Set socket to listen
4. Repeatedly:
   a. **Accept new connection**
   b. Communicate
   c. Close the connection

Example - Echo using stream socket

Server is now blocked waiting for connection from a client

...

A client decides to talk to the server

Client

1. Create a TCP socket
2. Establish connection
3. Communicate
4. Close the connection

Server

1. Create a TCP socket
2. Assign a port to socket
3. Set socket to listen
4. Repeatedly:
   a. **Accept new connection**
   b. Communicate
   c. Close the connection

Example - Echo using stream socket

```
/* Create a reliable, stream socket using TCP */
if ((clientSock = socket(PF_INET, SOCK_STREAM, IPPROTO_TCP)) < 0)
     DieWithError("socket() failed");
```

Client

1. **Create a TCP socket**
2. Establish connection
3. Communicate
4. Close the connection

Server

1. Create a TCP socket
2. Assign a port to socket
3. Set socket to listen
4. Repeatedly:
   a. **Accept new connection**
   b. Communicate
   c. Close the connection

Example - Echo using stream socket

```
echoServAddr.sin_family = AF_INET;                    /* Internet address family */
echoServAddr.sin_addr.s_addr = inet_addr(echoservIP); /* Server IP address*/
echoServAddr.sin_port = htons(echoServPort);          /* Server port */

if (connect(clientSock, (struct sockaddr *) &echoServAddr,
                        sizeof(echoServAddr)) < 0)
    DieWithError("connect() failed");
```

Client

1. Create a TCP socket
2. **Establish connection**
3. Communicate
4. Close the connection

Server

1. Create a TCP socket
2. Assign a port to socket
3. Set socket to listen
4. Repeatedly:
   a. **Accept new connection**
   b. Communicate
   c. Close the connection

Example - Echo using stream socket

Server's accept procedure in now unblocked and returns client's socket

```
for (;;) /* Run forever */
{
  clntLen = sizeof(echoClntAddr);

  if ((clientSock=accept(servSock,(struct sockaddr *)&echoClntAddr,&clntLen))<0)
     DieWithError("accept() failed");
  ...
```

Client

1. Create a TCP socket
2. **Establish connection**
3. Communicate
4. Close the connection

Server

1. Create a TCP socket
2. Assign a port to socket
3. Set socket to listen
4. Repeatedly:
   a. **Accept new connection**
   b. Communicate
   c. Close the connection

Example - Echo using stream socket

```
echoStringLen = strlen(echoString);     /* Determine input length */

/* Send the string to the server */
if (send(clientSock, echoString, echoStringLen, 0) != echoStringLen)
     DieWithError("send() sent a different number of bytes than expected");
```

Client

1. Create a TCP socket
2. Establish connection
3. **Communicate**
4. Close the connection

Server

1. Create a TCP socket
2. Assign a port to socket
3. Set socket to listen
4. Repeatedly:
   a. **Accept new connection**
   b. Communicate
   c. Close the connection

Example - Echo using stream socket

```
/* Receive message from client */
if ((recvMsgSize = recv(clntSocket, echoBuffer, RCVBUFSIZE, 0)) < 0)
    DieWithError("recv() failed");
/* Send received string and receive again until end of transmission */
while (recvMsgSize > 0) { /* zero indicates end of transmission */
   if (send(clientSocket, echobuffer, recvMsgSize, 0) != recvMsgSize)
      DieWithError("send() failed");
   if ((recvMsgSize = recv(clientSocket, echoBuffer, RECVBUFSIZE, 0)) < 0)
      DieWithError("recv() failed");
}
```

Client

1. Create a TCP socket
2. Establish connection
3. **Communicate**
4. Close the connection

Server

1. Create a TCP socket
2. Assign a port to socket
3. Set socket to listen
4. Repeatedly:
   a. Accept new connection
   b. **Communicate**
   c. Close the connection

Example - Echo using stream socket

Similarly, the client receives the data from the server

Client

1. Create a TCP socket
2. Establish connection
3. **Communicate**
4. Close the connection

Server

1. Create a TCP socket
2. Assign a port to socket
3. Set socket to listen
4. Repeatedly:
   a. Accept new connection
   b. **Communicate**
   c. Close the connection

Example - Echo using stream socket

```
close(clientSock);
```

Client

1. Create a TCP socket
2. Establish connection
3. Communicate
4. **Close the connection**

```
close(clientSock);
```

Server

1. Create a TCP socket
2. Assign a port to socket
3. Set socket to listen
4. Repeatedly:
   a. Accept new connection
   b. Communicate
   c. **Close the connection**

Example - Echo using stream socket

Server is now blocked waiting for connection from a client ...

Client

1. Create a TCP socket
2. Establish connection
3. Communicate
4. Close the connection

Server

1. Create a TCP socket
2. Assign a port to socket
3. Set socket to listen
4. Repeatedly:
   a. **Accept new connection**
   b. Communicate
   c. Close the connection

Example - Echo using datagram socket

```
/* Create socket for sending/receiving datagrams */
if ((servSock = socket(PF_INET, SOCK_DGRAM, IPPROTO_UDP)) < 0)
     DieWithError("socket() failed");
```

```
/* Create a datagram/UDP socket */
if ((clientSock = socket(PF_INET, SOCK_DGRAM, IPPROTO_UDP)) < 0)
     DieWithError("socket() failed");
```

Client

1. **Create a UDP socket**
2. Assign a port to socket
3. Communicate
4. Close the socket

Server

1. **Create a UDP socket**
2. Assign a port to socket
3. Repeatedly
   - Communicate

Example - Echo using datagram socket

```
echoServAddr.sin_family = AF_INET;                  /* Internet address family */
echoServAddr.sin_addr.s_addr = htonl(INADDR_ANY);   /* Any incoming interface */
echoServAddr.sin_port = htons(echoServPort);        /* Local port */

if (bind(servSock, (struct sockaddr *) &echoServAddr, sizeof(echoServAddr)) < 0)
    DieWithError("bind() failed");
```

```
echoClientAddr.sin_family = AF_INET;                  /* Internet address family */
echoClientAddr.sin_addr.s_addr = htonl(INADDR_ANY);   /* Any incoming interface */
echoClientAddr.sin_port = htons(echoClientPort);      /* Local port */

if(bind(clientSock,(struct sockaddr *)&echoClientAddr,sizeof(echoClientAddr))<0)
    DieWithError("connect() failed");
```

Client

1. Create a UDP socket
2. **Assign a port to socket**
3. Communicate
4. Close the socket

Server

1. Create a UDP socket
2. **Assign a port to socket**
3. Repeatedly
   - Communicate

Example - Echo using datagram socket

```
echoServAddr.sin_family = AF_INET;                    /* Internet address family */
echoServAddr.sin_addr.s_addr = inet_addr(echoservIP); /* Server IP address*/
echoServAddr.sin_port = htons(echoServPort);          /* Server port */

echoStringLen = strlen(echoString);     /* Determine input length */

/* Send the string to the server */
if (sendto( clientSock, echoString, echoStringLen, 0,
            (struct sockaddr *) &echoServAddr, sizeof(echoServAddr))
          != echoStringLen)
     DieWithError("send() sent a different number of bytes than expected");
```

Client

1. Create a UDP socket
2. Assign a port to socket
3. **Communicate**
4. Close the socket

Server

1. Create a UDP socket
2. **Assign a port to socket**
3. Repeatedly
   - Communicate

Example - Echo using datagram socket

```
for (;;) /* Run forever */
{
   clientAddrLen = sizeof(echoClientAddr)   /* Set the size of the in-out parameter */
   /*Block until receive message from client*/
    if ((recvMsgSize = recvfrom(servSock, echoBuffer, ECHOMAX, 0),
         (struct sockaddr *) &echoClientAddr, sizeof(echoClientAddr))) < 0)
         DieWithError("recvfrom() failed");

   if (sendto(servSock, echobuffer, recvMsgSize, 0,
              (struct sockaddr *) &echoClientAddr, sizeof(echoClientAddr))
           != recvMsgSize)
         DieWithError("send() failed");
}
```

Client

1. Create a UDP socket
2. Assign a port to socket
3. **Communicate**
4. Close the socket

Server

1. Create a UDP socket
2. Assign a port to socket
3. Repeatedly
   - **Communicate**

Example - Echo using datagram socket

Similarly, the client receives the data from the server

Client

1. Create a UDP socket
2. Assign a port to socket
3. **Communicate**
4. Close the socket

Server

1. Create a UDP socket
2. Assign a port to socket
3. Repeatedly
   - **Communicate**

Example - Echo using datagram socket

```
close(clientSock);
```

Client

1. Create a UDP socket
2. Assign a port to socket
3. Communicate
4. **Close the socket**

Server

1. Create a UDP socket
2. Assign a port to socket
3. **Repeatedly**
   - Communicate

Client - Server Communication - Unix