INF1060:
Introduction to Operating Systems and Data Communication

# Data Communication:

# Introduction to Berkeley Sockets

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(adapted from lectures by Pål Halvorsen, Carsten Griwodz &
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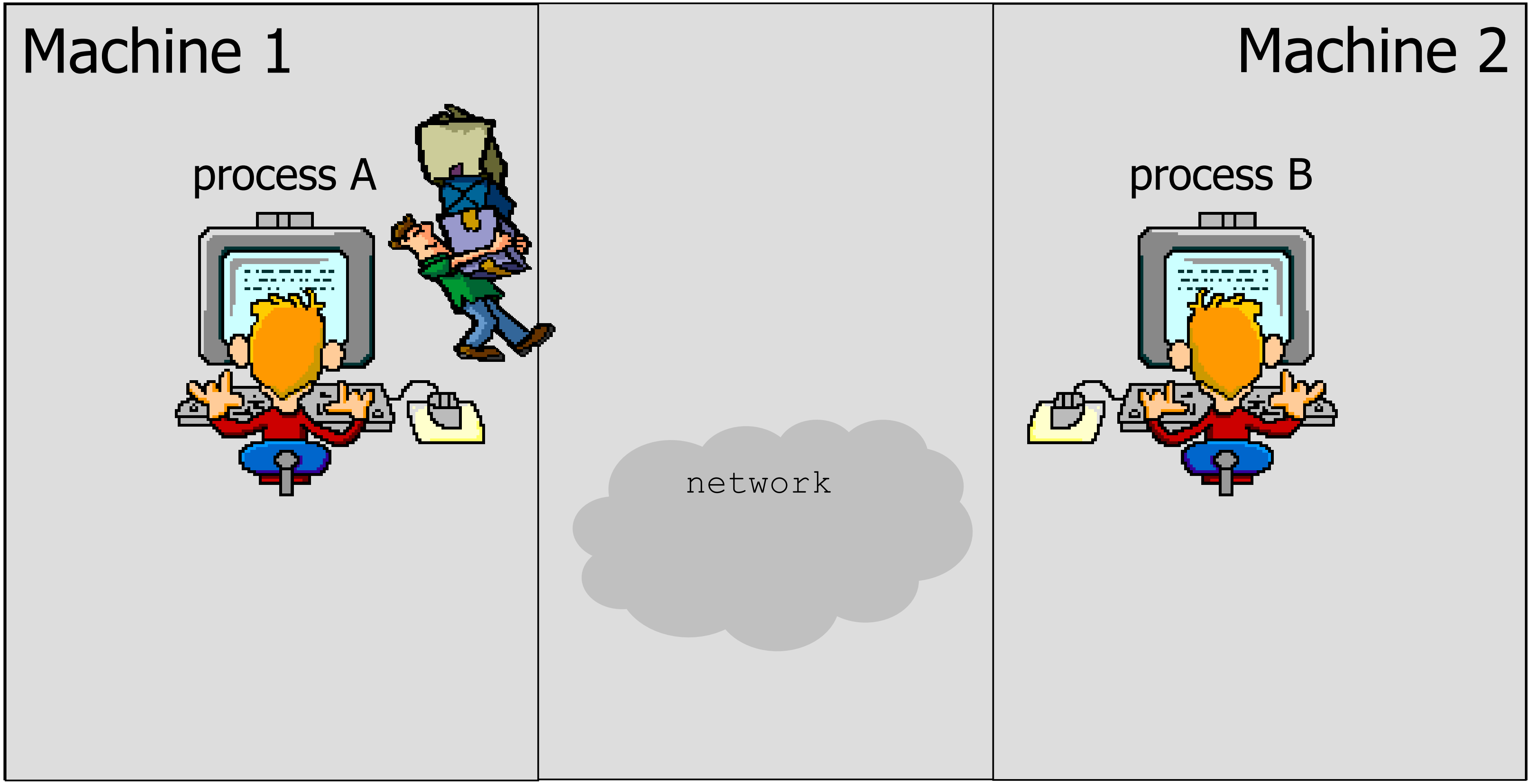
# Big Picture



Machine 1

process A

network

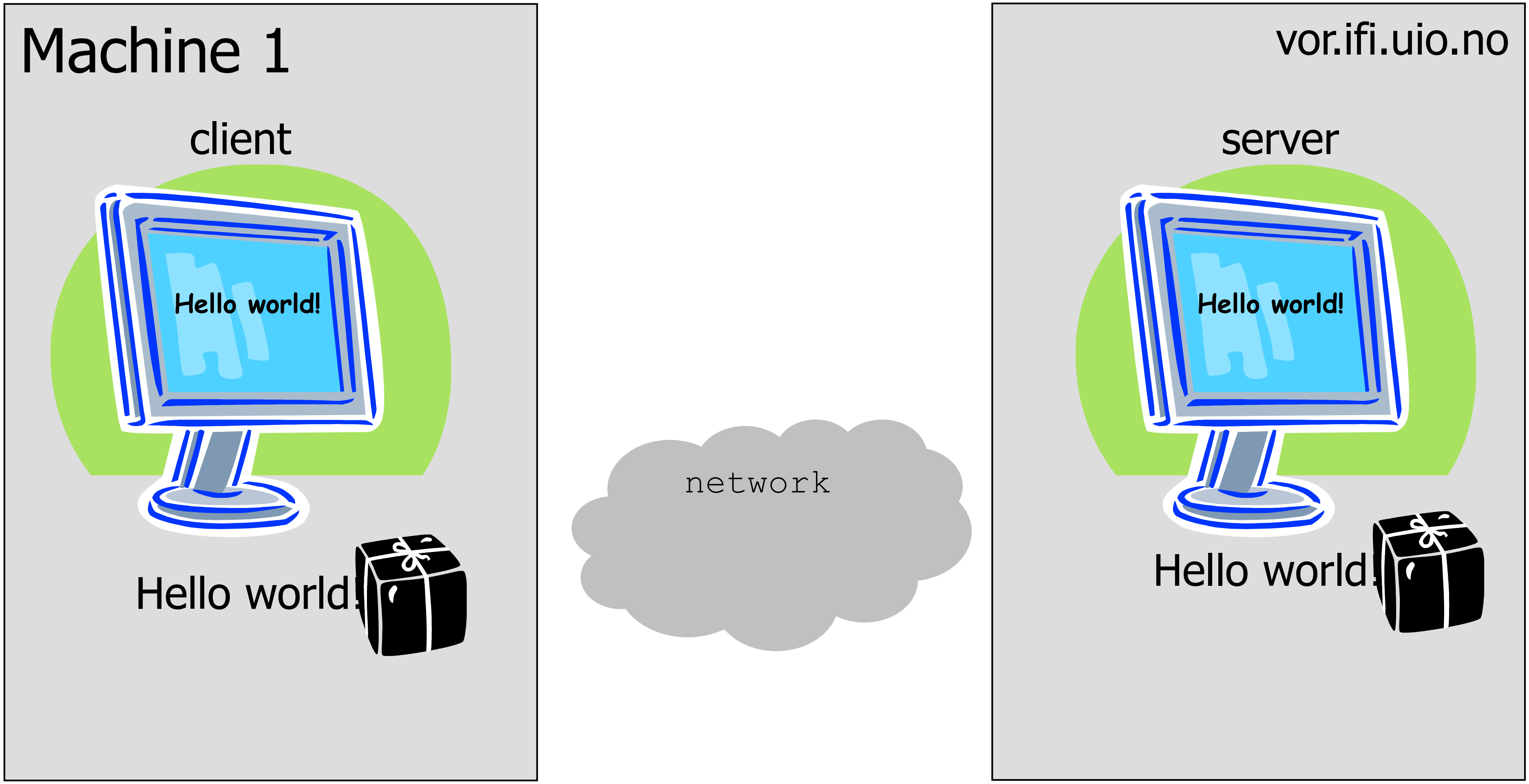
Machine 2

process B

# Goal

- Introduce socket API
- We will write two programs
  - A “client” and a “server”
- Each will run on one machine
  - For instance “vor.ifi.uio.no” (129.240.65.59) (maybe outdated IP)
- They will work as follows (see next slide)
  - The client sends the text “Hello world!” to the server
  - The server writes the received text on the screen
  - The server sends the received text back to the client and quits
  - The client writes the received text onto the screen and quits

# What we want



Machine 1

client

Hello world!

Hello world!

network

vor.ifi.uio.no

server

Hello world!

Hello world!

# What we want

## Client

```
int main()
{
  char buf[13];







  /* Send data */
  write(sd, “Hello world!”, 12);

  /* Read data from the socket */
  read(sd, buf, 12);

  /* Add a string termination sign,
     and write to the screen. */
  buf[12] = ‘\0’;
  printf(“%s\n”, buf);


}
```

## Server

```
int main()
{
  char buf[13];









  /* read data from the sd and
     write it to the screen */
  read(sd, buf, 12);
  buf[12] = ‘\0’;
  printf(“%s\n”, buf );

  /* send data back over the connection */
  write(sd, buf, 12);


}
```

# Read & Write

- Same functions used for files etc.

- The call **`read`**`(sd, buffer, n);`
  - Reads *up to* `n` characters
  - From socket `sd`
  - Stores them in the character array `buffer`

- The call **`write`**`(sd, buffer, n);`
  - Writes *up to* `n` characters
  - From character array `buffer`
  - To the socket `sd`

# Alternatives to Read & Write

- The call `recv(sd, buffer, n, flags);`
  - Flags, normally just `0`, but e.g., `MSG_DONTWAIT`, `MSG_MORE`, …
    - Used to control the behavior of the function
    - Several flags can be specified at once with bitwise or operaions
    - `MSG_DONTWAIT | MSG_MORE`
- The call `send(sd, buffer, n, flags);`
  - Flags, same as above
- Several similar functions like …`to/from`, …`msg`

# Creation of a connection

- One side **must** be the active one
  - Take the initiative in creating the connection
  - This side is called the ***client***
- The other side **must** be passive
  - It is prepared for accepting connections
  - Waits for someone else to take initiative
  - This side is called the ***server***
- From now: server is a **process,** not a machine

# Special for the server side

- In case of **TCP**
  - One socket on the server side is dedicated to waiting for a connection
  - For each client that takes the initiative, a separate socket on the server side is created
  - This is useful for all servers that must be able to serve several clients concurrently (web servers, mail servers, …)

# To do – in the code

## Client

```
<Necessary includes>

int main()
{
   char buf[13];
   <Declare some more data structures>
   <Create a socket called “sd”>
   <Identify the server that you want to contact>
   <Connect to the server>

   /* Send data */
   write(sd, “Hello world!”, 12);

   /* Read data from the socket */
   read(sd, buf, 12);

   /* Add a string termination sign,
      and write to the screen. */
   buf[12] = ‘\0’;
   printf(“%s\n”, buf);

   <Closing code>
}
```

## Server

```
<Necessary includes>

int main()
{
   char buf[13];
   <Declare some more data structures>
   <Create a socket called “request-sd”>
   <Define how the client can connect>
   <Wait for a connection, and create a new socket “sd”
     for that connection>


   /* read data from the sd and
      write it to the screen */
   read(sd, buf, 12);
   buf[12] = ‘\0’;
   printf(“%s\n”, buf );

   /* send data back over the connection */
   write(sd, buf, 12);

   <Closing code>
}
```

# To do-list

- Client:
  - Declare some data structures
  - Create a socket
  - Identify the server
  - Connect to the server

- Server:
  - Declare some data structures
  - Create a socket
  - Define how the client can connect
  - Wait for a connection
  - Handle the connection

# <Create a socket>

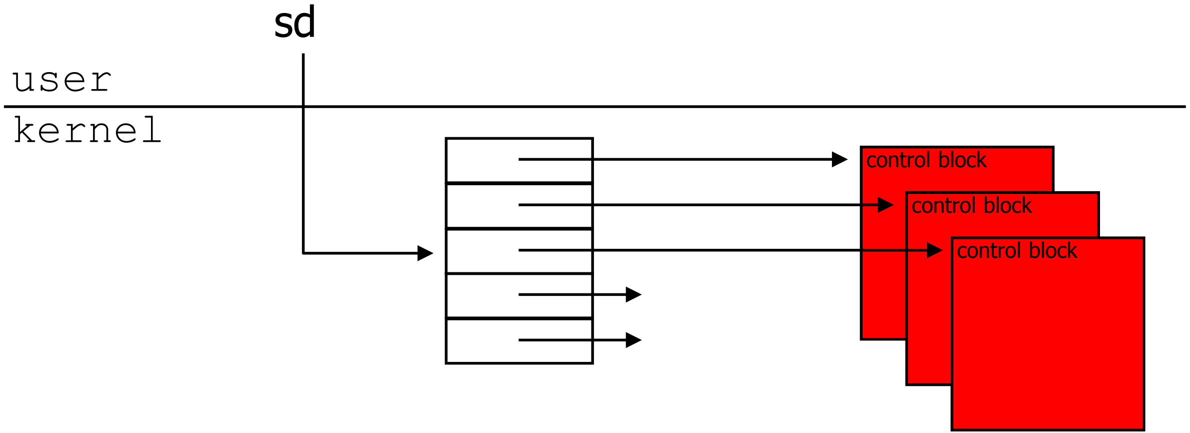
Client

```
/* declarations */
int sd;

/* creation of the socket */
sd = socket(PF_INET,
            SOCK_STREAM,
            IPPROTO_TCP);
```

Server

```
/* declarations */
int request_sd;

/* creation of the socket */
request_sd = socket(PF_INET,
                    SOCK_STREAM,
                    IPPROTO_TCP);
```

- Call to the function **socket()** creates a transport control block (hidden in kernel), and returns a reference to it (integer used as index)



# More about the `socket` call

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

- `PF_INET`, `SOCK_STREAM` and `IPPROTO_TCP` are constants that are defined in the included files
- The use of the constants that we use here (as above) creates a *TCP socket*
- Many other possibilities exist
  - Domain: `PF_UNIX, PF_INET, PF_INET6, …`
  - Type: `SOCK_STREAM, SOCK_DGRAM, …`
  - Protocol: `IPPROTO_TCP, IPPROTO_UDP, …`
- `protocol` can be NULL, OS choses apropriate proocol (use with care!)

# How to identify clients to accept, and servers to contact?

- Machine??
  - by its IP address (e.g., 129.240.65.59)
- Application/service/program??
  - by (IP address and) port number
  - standard applications have own, “well-known” port numbers
    - SSH: 22
    - Mail: 25
    - Web: 80
    - Look in `/etc/services` for more

# Address structure

- `struct` **`sockaddr_in`** `:`
  - `sin_family` address family used (defined through a macro)
  - `sin_port` 16-bit transport protocol port number
  - `sin_addr` 32-bit IP address defined as a new structure `in_addr` having one `s_addr` element only
  - `sin_zero` padding (to have an equal size as a `sockaddr` struct)
- Defines IP address and port number in a way the Berkeley socket API needs it
- `man 7 ip`

# Address structure - handout

- Fill address type (“family”), address and port number into the structure
  - `serveraddr.sin_family = AF_INET;`
  - `serveraddr.sin_addr.s_addr = INADDR_ANY;` (@ server)
  - `inet_pton( AF_INET, “129.240.65.59”, &serveraddr.sin_addr );` (@ client)
  - `serveraddr.sin_port = htons( 2009 );`
  - `AF_INET`
    - a constant indicating that Internet protocols will be used
  - `INADDR_ANY`
    - a constant meaning any (Internet) address
    - in this context: any own Internet address

# Address structure

## Client

```
/* declaration */
struct sockaddr_in serveraddr;

/* clear the structure */
memset(&serveraddr, 0,
      sizeof(struct sockaddr_in));

/* This will be an address of the
 * Internet family */
serveraddr.sin_family = AF_INET;

/* Add the server address - vor */
inet_pton(AF_INET,
          “129.240.65.59”,
          &serveraddr.sin_addr);

/* Add the port number */
serveraddr.sin_port = htons(2009);
```

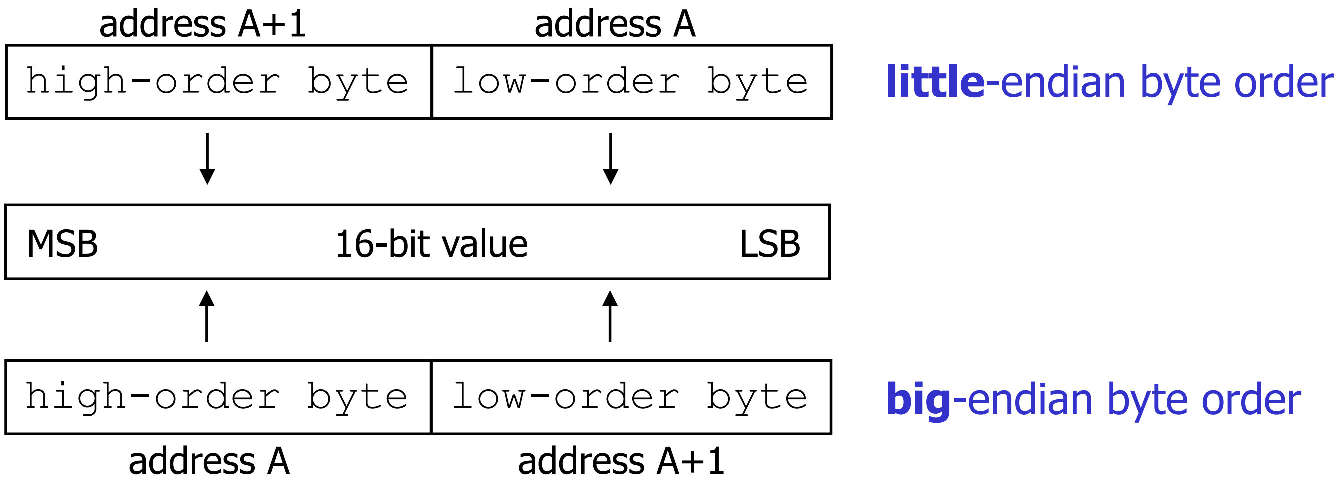
## Server

```
/* declaration */
struct sockaddr_in serveraddr;

/* clear the structure */
memset(&serveraddr, 0,
      sizeof(struct sockaddr_in));

/* This will be an address of the
 * Internet family */
serveraddr.sin_family = AF_INET;

/* Allow all own addresses to receive */
serveraddr.sin_addr.s_addr = INADDR_ANY;

/* Add the port number */
serveraddr.sin_port = htons(2009);
```

# Byte Order

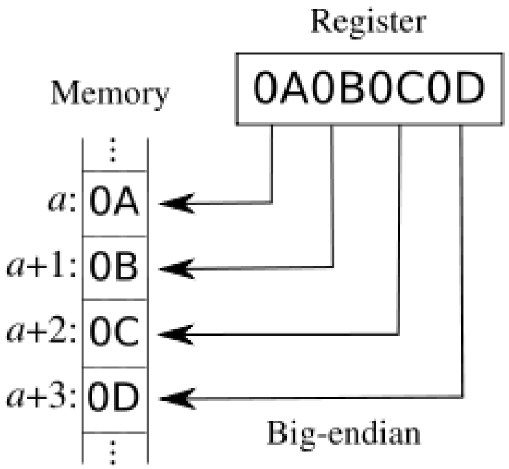
- Different machines may have different representation of multi-byte values

- Consider a 16-bit integer: made up of 2 bytes



# Byte Order: Storing 32-bit 0x0A0B0C0D

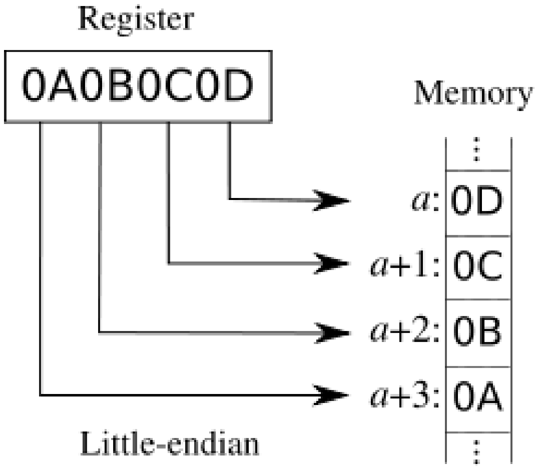
- Assuming 8-bit (one byte) atomic elements…
- **…big endian:**
  - the most significant byte (MSB), 0x0A, is stored on the *lowest* memory address
  - the least significant byte (LSB), 0x0D, is stored on the **highest** memory address



increasing memory addresses →

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| … | 0x0A | 0x0B | 0x0C | 0x0D | … |

- **… little endian:**
  - 0x0A is stored on the **highest** memory address
  - 0x0D is stored on the *lowest* memory address



increasing memory addresses →

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| … | 0x0D | 0x0C | 0x0B | 0x0A | … |

# Byte Order: IP address example

- IPv4 host address: represents a 32-bit address
  - written on paper (”dotted decimal notation”): `129.240.71.213`
  - binary in bits: `10000001 11110000 01000111 10001011`
  - hexadecimal in bytes: `0x81 0xf0 0x47 0x8b`

- Big-endian (”normal” left to right):
  - one 4 byte `int` on PowerPC, POWER, Sparc, …: 0x81f0478b

Problem!

- Little-endian:
  - one 4 byte `int` on x86, StrongARM, XScale, …: 0x8b47f081

- **Network byte order**: 0x81f0478b

# Byte Order: Translation

- Byte order translation makes communication over several platforms possible

- `htons() / htonl()`
  - host-to-network short / long
  - translate a 16 / 32-bit integer value to network format

- `ntohs() / ntohl()`
  - network-to-host short/long
  - translate a 16 / 32-bit integer value to host format

- Little-endian (x86 etc.): `ntohl(0x81f0478b) == 0x8b47f081`

- Big-endian (PowerPC etc.): `ntohl(0x81f0478b) == 0x81f0478b`

# Presentation and Numeric Address Formats

- The network…
  - …does not interpret the "dotted decimal notation" *presentation* format
  - …needs a *numeric* binary format in network byte order
- `inet_pton()`
  - translate the text string to a numeric binary format needed by the address structure
- `inet_ntop()`
  - translate the (numeric binary) network address structure to a text string

`inet_pton()` is new for IPv6.

Oldest:

```
serveraddr.sin_addr.s_addr =
          inet_addr(“129.240.65.59”);
```

Newer:

```
inet_aton(“129.240.65.59”,
          &serveraddr.sin_addr);
```

# How far have we gotten now?

## Client

```
<Necessary includes>

int main()
{
  char buf[13];
✓ <Declare some more data structures>
✓ <Create a socket called “sd”>
✓ <Identify the server that you want to contact>
✗ <Connect to the server>

  /* Send data */
  write(sd, “Hello world!”, 12);

  /* Read data from the socket */
  read(sd, buf, 12);

  /* Add a string termination sign,
     and write to the screen. */
  buf[12] = ‘\0’;
  printf(“%s\n”, buf);

✗ <Closing code>
}
```

## Server

```
<Necessary includes>

int main()
{
  char buf[13];
✓ <Declare some more data structures>
✓ <Create a socket called “request-sd”>
✓ <Define how the client can connect>
✗ <Wait for a connection, and create a new socket “sd”
   for that connection>


  /* read data from the sd and
     write it to the screen */
  read(sd, buf, 12);
  buf[12] = ‘\0’;
  printf(“%s\n”, buf );

  /* send data back over the connection */
  write(sd, buf, 12);

✗ <Closing code>
}
```

# Bind and Listen

- `bind( int sfd, struct sockaddr *a, socklen_t al )`
  - A machine can have several addresses (several network cards, loopback, …)
  - Tells the socket on the server side which local protocol (i.e., *IP address* and *port number)* to listen to

- `listen( int sfd, int backlog )`
  - Prepares the server for listening to connect requests, and initializes a queue for connect requests
  - The second parameter (often `SOMAXCONN`) defines how long the queue(s) should be

# Connect and Accept

- `connect( int sfd, struct sockaddr *serv_a, socklen_t al )`
  - connects client socket to a server that is specified in the address structure
  - a three-way handshake is initiated for TCP
  - possible errors
    - ETIMEDOUT – no response (after several tries) and timer expired
    - ECONNREFUSED – server not running or not allowed to connect
    - EHOSTUNREACH – HOST not reachable
    - ENETUNREACH – NET not reachable
- `sd = accept( int sfd, struct sockaddr *a, socklen_t *al )`
  - take the first connect request from the connect request queue
  - wait for the connect request to arrive if the queue is empty
  - returns a ***new socket*** that the server can use to communicate with the client
  - `a` (`clientaddr`) contains information about the client
  - `al` must be initialized, so accept knows size of `a`

# Binding, Listening, Accepting and Connecting

## Client

```
/* Connect */
connect(sd,
        (struct sockaddr*)&serveraddr,
        sizeof(struct sockaddr_in));
```

## Server

```
/* Bind the address to the socket */
bind(request_sd,
     (struct sockaddr*)&serveraddr,
     sizeof(struct sockaddr_in);


/* Activate listening on the socket */
listen(request_sd, SOMAXCONN);


/* Create client addr struct*/
  clientaddrlen =
          sizeof(struct sockaddr_in);

/* Wait for connection */
sd = accept(request_sd,
          (struct sockaddr*)&clientaddr,
          &clientaddrlen);
```

# Closing of Sockets

Client

```
/* Close the socket */
close(sd);
```

Server

```
/* Close both sockets */
close(sd);
close(request_sd);
```

- Note that the semantics of close depends
  - On the kind of protocol
  - Some possible extra settings
  - (similar for file descriptors used to operate on disk…)
- All data that has not been read yet may be thrown away

# Complete Client

## Client

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

int main()
{
  /* Declarations */
  struct sockaddr_in serveraddr;
  int sd;
  char buf[13];

  /* Create socket */
  sd = socket(PF_INET,
                SOCK_STREAM,
                IPPROTO_TCP);

  /* Clear address structure */
  memset(&serveraddr, 0,
        sizeof(struct sockaddr_in));

  /* Add address family */
  serveraddr.sin_family = AF_INET;
```

## Client ctd.

```
  /* Add IP address of vor.ifi.uio.no */
  inet_pton(AF_INET, “129.240.65.59”,
            &serveraddr.sin_addr);
  /* Add the port number */
  serveraddr.sin_port = htons(2009);

  /* Connect */
  connect(sd,
          (struct sockaddr*)&serveraddr,
          sizeof(struct sockaddr_in));

  /* Send data */
  write(sd, “Hello world!”, 12 );

  /* Read data */
  read(sd, buf, 12 );

  /* add string end sign, write to screen*/
  buf[12] = ‘\0’;
  printf(“%s\n”, buf);

  /* Close socket */
  close(sd);
}
```

# Complete Server

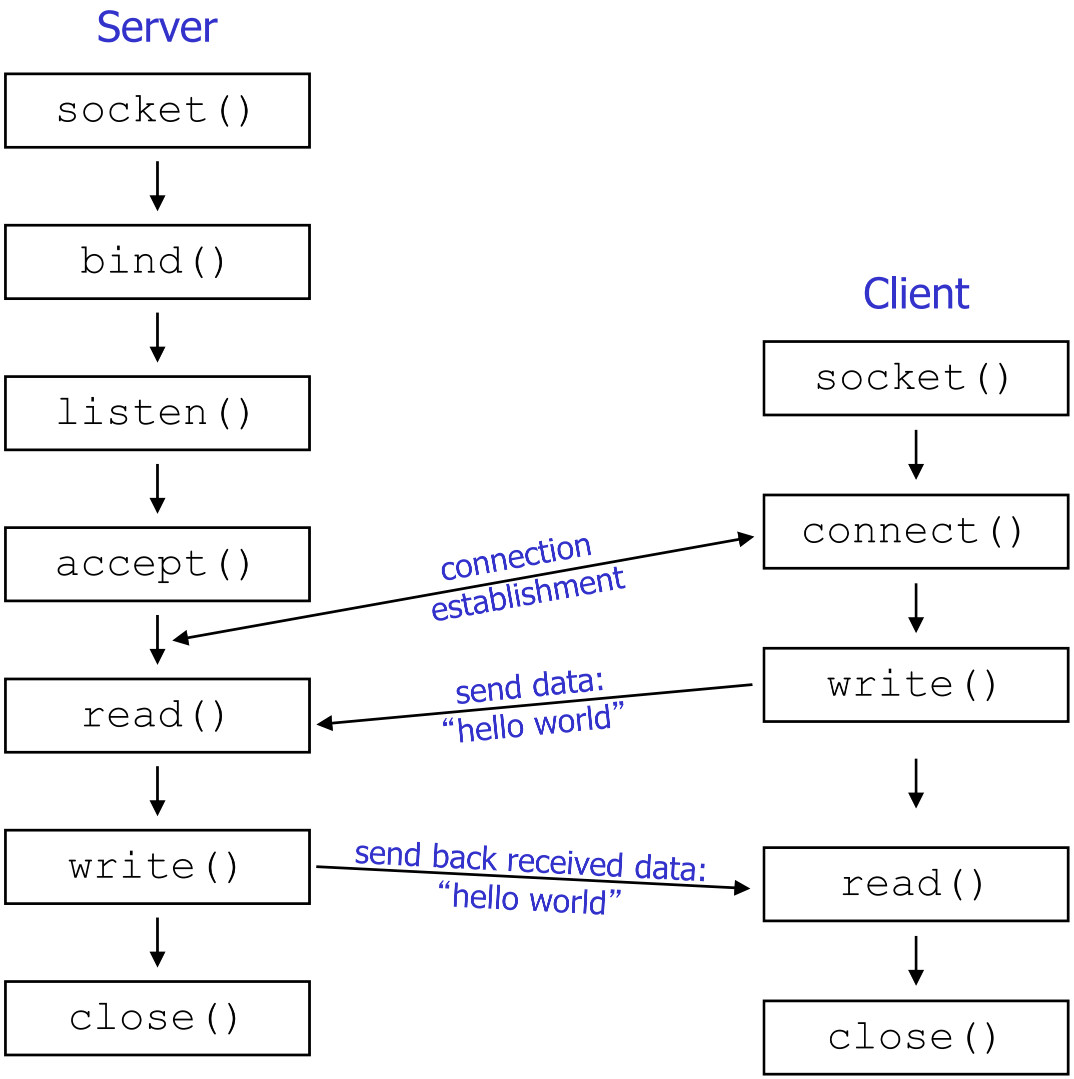
## Server

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

int main()
{
  /* Declarations */
  struct sockaddr_in serveraddr;
  struct sockaddr_in clientaddr;
  int clientaddrlen;
  int request_sd, sd;
  char buf[13];

  /* Create socket */
  request_sd = socket(PF_INET,
                      SOCK_STREAM,
                      IPPROTO_TCP);

  /* Fill in the address structure */
  memset(&serveraddr, 0,
         sizeof(struct sockaddr_in));
  serveraddr.sin_family = AF_INET;
  serveraddr.sin_addr.s_addr = INADDR_ANY;
  serveraddr.sin_port = htons(2009);
```

## Server ctd.

```
   /* Bind address to socket */
   bind(request_sd,
        (struct sockaddr*)&serveraddr,
        sizeof(struct sockaddr_in));

   /* Activate connect request queue */
   listen(request_sd, SOMAXCONN);

   /* Receive connection */
   clientaddrlen =
       sizeof(struct sockaddr_in);
   sd = accept(request_sd,
            (struct sockaddr*)&clientaddr,
            &clientaddrlen);

   /* Read data from socket and write it */
   read(sd, buf, 12);
   buf[12] = ‘\0’;
   printf(“%s\n”, buf);

   /* Send data back over connection */
   write(sd, buf, 12);

   /*Close sockets */
   close(sd); close(request_sd);
}
```

# Summary of
# Socket Functions for our Elementary TCP Client-Server



# Get the code yourself

- Similar examples can be found on the INF1060 Github page
- Also other examples!!

# Complete Server – improvements?

## Server

```
...

int main()
{
  /* Declarations */
  ...


  /* Create socket */
  request_sd = socket(...);

  /* Fill in the address structure */
  ...

  /* Bind address to socket */
  bind(...);

  /* Activate connect request queue */
  listen(...);
```

## Server ctd.

```

  /* Receive connection */
  sd = accept(...);

  /* Process  the request*/
  ...

  /*Close sockets */
  close(sd);









  close(request_sd);
}
```

Iterative servers?

# Iterative Servers

## Server

```
...

int main()
{
  /* Declarations */
  ...


  /* Create socket */
  request_sd = socket(...);

  /* Fill in the address structure */
  ...

  /* Bind address to socket */
  bind(...);

  /* Activate connect request queue */
  listen(...);
```

## Server ctd.

```
  for (;;) {
    /* Receive connection */
    sd = accept(...);

    /* Process  the request*/
    ...







    /*Close sockets */
    close(sd);
  }

  close(request_sd);
}
```

Concurrent servers?

# Concurrent Iterative Servers

## Server

```
...

int main()
{
  /* Declarations */
  ...
  pid_t pid;

  /* Create socket */
  request_sd = socket(...);

  /* Fill in the address structure */
  ...

  /* Bind address to socket */
  bind(...);

  /* Activate connect request queue */
  listen(...);
```

## Server ctd.

```
  for (;;) {
    /* Receive connection */
    sd = accept(...);

    if ((pid = fork()) == 0) {
       close(request_sd);
      /* Process  the request*/
      ...

      /*Close sockets */
      close(sd);
      exit(0);
    }

    /*Close sockets */
    close(sd);
  }

  close(request_sd);
}
```

# Select

- Problems with these examples:
  - iterative: cannot serve more than one socket at once
  - concurrent: overhead (a process per socket)

- Solution: functions that tell you when a socket becomes available (`select, poll`)

- `int select(int nfds, fd_set *restrict readfds, fd_set *restrict writefds,fd_set *restrict errorfds, struct timeval *restrict timeout)`
  - check whether fd's (sockets) from the `nfds` set are available for reading (`readfds`), writing (`writefds`), or have exceptional conditions pending (`errorfds`)
  - Null argument: don't check. Timeout = time limit for check (`Null` = block).
  - result is given by changing `readfds` / `writefds` / `errorfds`

# Select usage and macros

- Select usage
  - Declare and initialize fd_set; add relevant sockets to fd_set; give select a copy of fd_set for every operation of interest (read/write/exceptional); loop through copies to take action

- Preparing fd_set is done with some macros
  - `FD_CLR(fd, &fdset)`
    - removes the socket descriptor `fd` from the socket descriptor set `fdset`
  - `FD_ISSET(fd, &fdset)`
    - returns nonzero if socket descriptor `fd` is a member of `fdset`; else 0
  - `FD_SET(fd, &fdset)`
    - adds socket descriptor `fd` to `fdset`
  - `FD_ZERO(&fdset)`
    - initializes `fdset` to 0, representing the empty set
  - `FD_SETSIZE` - max. number of FDs; use this as the first parameter for select

# Complete Select-based Server

Test with e.g. two clients!

## Server

```
#include <netinet/in.h>
#include <sys/socket.h>
#include <netdb.h>
#include <stdio.h>
#include <string.h>
#include <time.h>

int main()
{
  /* Declarations */
  struct sockaddr_in serveraddr;
  struct sockaddr_in clientaddr;
  int clientaddrlen, i, rc;
  int request_sd, sd[2], numsocks, maxsocks;
  char buf[13];
  fd_set fds, readfds;
  struct timeval timeout;

  numsocks = 0; maxsocks = 2;
  timeout.tv_sec = 20;
  timeout.tv_usec = 0;

  /* Create socket */
  request_sd = socket(PF_INET,
                        SOCK_STREAM,
                        IPPROTO_TCP);
```

## Server ctd.

```
/* Fill in the address structure */
memset(&serveraddr, 0,
      sizeof(struct sockaddr_in));
serveraddr.sin_family = AF_INET;
serveraddr.sin_addr.s_addr = INADDR_ANY;
serveraddr.sin_port = htons(2009);

/* Bind address to socket */
bind(request_sd,
     (struct sockaddr*)&serveraddr,
     sizeof(struct sockaddr_in));

/* Activate connect request queue */
listen(request_sd, SOMAXCONN);

/* Initialize fd set */
FD_ZERO(&fds);
FD_SET(request_sd, &fds);
```

# Complete Select-based Server ctd.

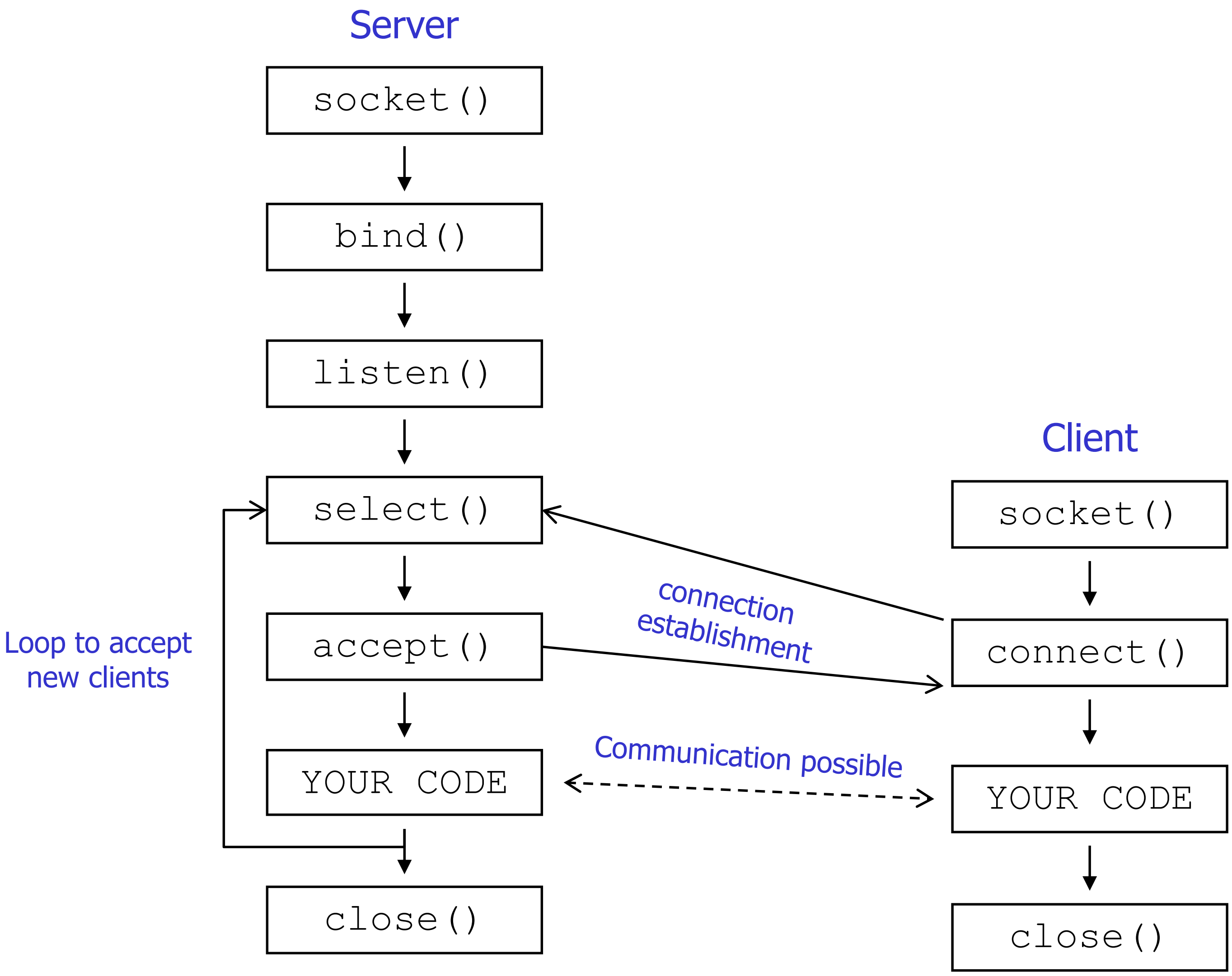
## Server ctd.

```
  for (;;) {

    readfds=fds;
    rc=select(FD_SETSIZE, &readfds, NULL,
                    NULL, &timeout);

    /* Something went wrong */
    if (rc<0)
      return -1;

    /* Nothing happened,select continued */
    if (rc==0) {
      printf("Timeout!\n");

      for(i=0; i<numsocks; i++) {
        /* Send a response */
        write(sd[i], "Server ACK!",11);
        /* Close sockets */
        close(sd[i]);
        FD_CLR(sd[i], &fds);

      }
      return 0;

    }
```

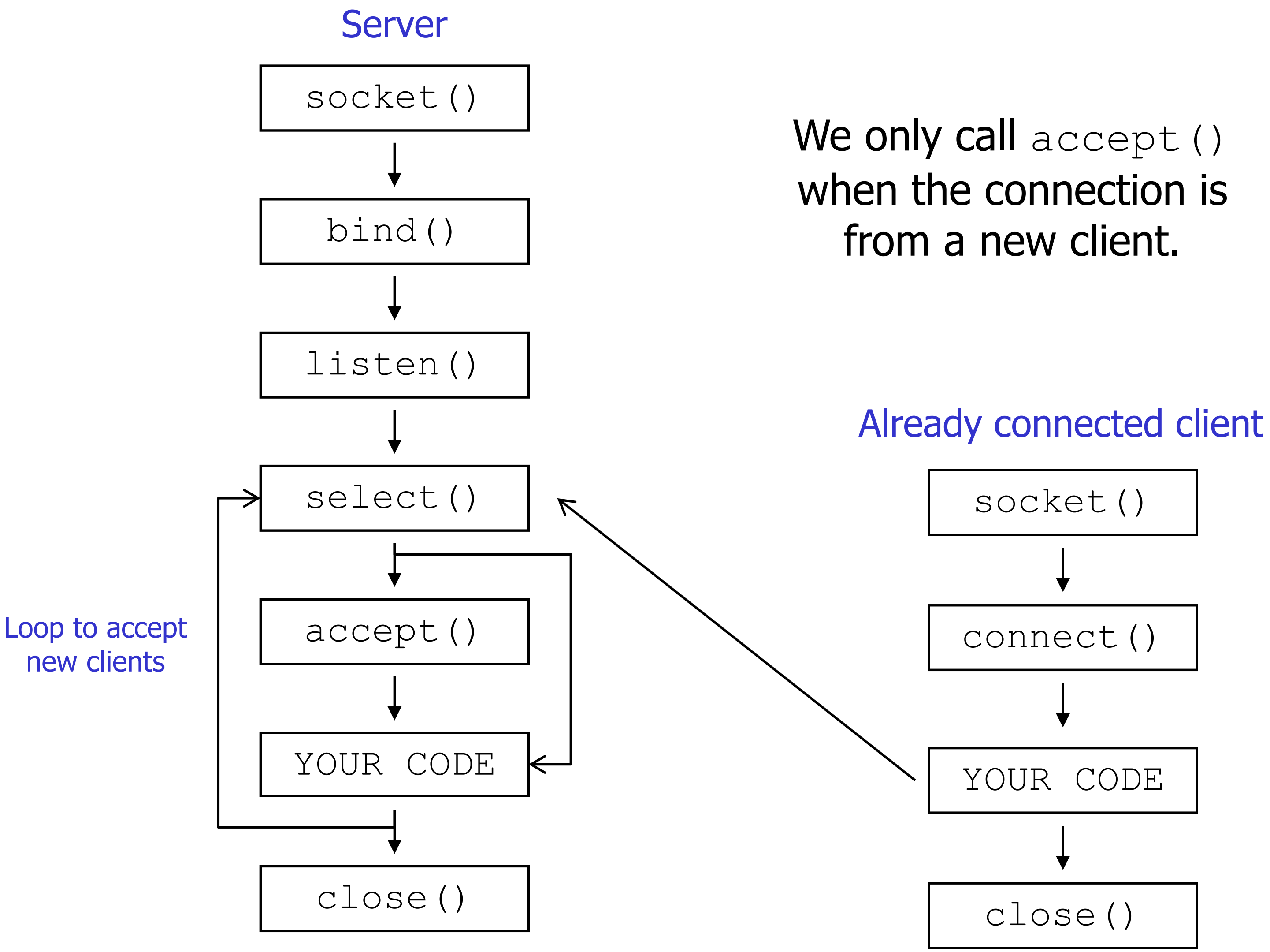
## Server ctd.

```
    for (i = 0; i < FD_SETSIZE; i++)
      if(FD_ISSET (i, &readfds)) {

        if(i == request_sock) {
          /* new connection request */
          if(numsocks < maxsocks) {
            sd[numsocks] = accept(request_sock,
              (struct sockaddr *)&clientaddr,
              (socklen_t *)&clientaddrlen);
            FD_SET(sd[numsocks], &fds);
            numsocks++;
          } else {
            printf(”Ran out of socket space.\n");
            return -1;
          }
        } else {
          /* data arrived on an existing socket */
          read(i, buf,12);
          buf[12] = '\0';
          printf("From socket %d: %s\n",i,buf);
        }
      }
  }
  close(request_sock);
}
```

# Outline for select based iterative server



# Outline for select based iterative server



We only call `accept()` when the connection is from a new client.

# Summary

- We have implemented a short program where two processes communicate over a network

- Next: the magic of how data is sent…

# Literature

- "Berkeley UNIX System Calls and Interprocess Communication", Lawrence Besaw, University of Wisconsin
- Many books:
  - Kurose/Ross, "Computer Networking: A Top-Down Approach Featuring the Internet", 2nd ed., Addison-Wesley
  - Andrew Tanenbaum, "Computer Networks", 4th ed., Prentice Hall
  - W. Richard Stevens, "Unix Network Programming – Networking APIs: Sockets and XTI", volume 1, 2nd ed., Prentice Hall