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Internet Programming

Programming with Sockets

Brief Introduction to Networks

Introduction

- There is one way computers can communicate
  - By sending network messages to each other
  - All kinds of communication are built from messages

- There is one way programs can send/receive network messages
  - Through sockets
  - All other communication paradigms are built from sockets

Two Different Kinds of Networks

- **Circuit switching**
  - One electrical circuit assigned per communication
  - Example: the (analog) phone network
  - Guaranteed **constant quality** of service
  - **Waste of resources** (periods of silence), fault tolerance

- **Packet switching**
  - Messages are split into **packets**, which are transmitted independently
    - Packets can take different routes
    - Network infrastructures are shared among users
  - Example: the Internet, and most computer networks
  - **Good resource usage**, **fault tolerance**
  - **Variable QOS**, packets may be delivered in the wrong order

Internet Protocol

- Most computer networks use the Internet Protocol
  - Even if they are not connected to the Internet

- The base protocol: IP (Internet Protocol)
  - Send packets of limited size
    - Up to 65,536 bytes
    - But if the MTU (Maximum Transmission Unit) of some link on the path is lower, the packet will be fragmented (IPv4) or dropped (IPv6)
    - Minimum allowed MTU is 576 bytes; in practice nowadays higher
  - Each packet is sent to an IP address
    - Example: 130.37.193.13
  - IP offers no guarantee:
    - Packets may get **lost**
    - Packets may be **delivered twice**
    - Packets may be **delivered in wrong order**
    - Packets may be **corrupted during transfer**

- Usually, programs do not use IP directly
  - All other Internet Protocols are built over IP

UDP: User Datagram Protocol

- UDP is very similar to IP
  - Send/receive packets
  - No guarantee
- In UDP, packets are called **datagrams**
  - Each datagram is sent to an **IP address** and a **port number**
  - Example: 130.37.193.13 port=1234
- Ports allow to distinguish between several programs running simultaneously on the same machine
  - Program A uses port 1234
  - Program B uses port 1235
  - When a datagram is received, the OS knows which program it should be delivered to.

TCP: Transmission Control Protocol

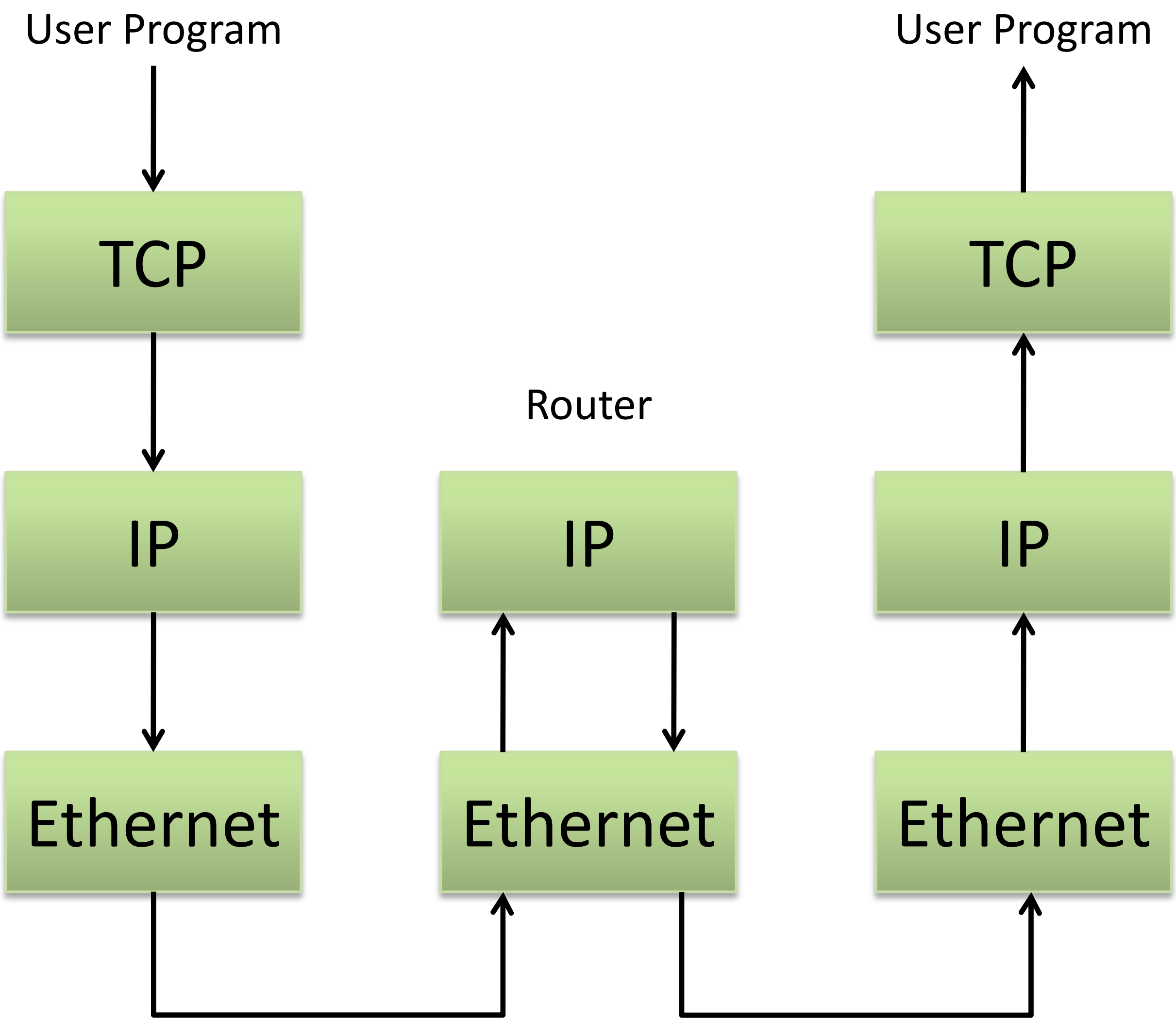
- TCP establishes connections between pairs of machines
  - To communicate with a remote host, we must first connect to it
- TCP provides the illusion of a reliable data flow to the users
  - Flows are split into packets, but the users don't see them
  - Provides **flow control** and **congestion control**
    - QUESTION: What is the difference?!?
- TCP guarantees that the data sent will not be lost, unordered or corrupted
  - The sender gives numbers to packets so that the receiver can reorder them
  - The receiver acknowledges received packets so that the sender can retransmit lost packets
- Communication is bidirectional
  - The same connection can be used to send data in both directions
  - E.g., a request and its response

A Very Simplified View

- Establish connections
- Split data streams into packets
- ACK received packets
- Retransmit lost packets
- Reorder packets

- Find how to reach a given host
- If on the same network → easy
- Otherwise → send to a router

- Transform packets into electrical signals
- Make sure signals do not interfere with each other



IP Addressing and Name Resolution

IP Address Conversion

- IP Addresses
  - 32-bit integers: **2183468070** (good for computers!)
  - Dotted strings: **130.37.20.38** (good for humans!)
  - DNS name: **www.cs.vu.nl** (even better for humans!)

- You can convert between **integer** and **dotted string**:

```
#include <arpa/inet.h>
int inet_aton(const char *dotted, struct in_addr *in); /* Dotted to
                                                           Network */
char *inet_ntoa(struct in_addr network); /* Network to Dotted */
                                         /* number to alphanumeric */
```

  - **in_addr_t**: unsigned 32-bit integer
  - **struct in_addr**: structure containing an **in_addr_t**:

```
struct in_addr {
  in_addr_t s_addr;
};
```

    - there are historic reasons why this is done that way…

Big/Little-endian, Network Ordering

- Computers represent numbers in different orderings:
  - Is significant byte first or last?
    - Big-endian: 0x12345678 → 0x12 0x34 0x56 0x78
      - examples: PowerPC, Sparc, UltraSparc
    - Little-endian: 0x12345678 → 0x78 0x56 0x34 0x12
      - examples: Alpha, i386, AMD64

- Network byte ordering
  - A standard representation (defined as Big-Endian)

- To convert numbers: host <---> network ordering

```
#include <netinet/in.h>
uint16_t htons(uint16_t value);   /* Host to Network, 16 bits */
uint32_t htonl(uint32_t value);   /* Host to Network, 32 bits */
uint16_t ntohs(uint16_t value);   /* Network to Host, 16 bits */
uint32_t ntohl(uint32_t value);   /* Network to Host, 32 bits */
```

sockaddr_in: Unix Network Addresses

- Unix represents network addresses with a **struct sockaddr**
  - This structure is generic for all kinds of networks
  - For Internet addresses, we use **sockaddr_in**

```
struct sockaddr_in {
  sa_family_t    sin_family; /* set to AF_INET */
  in_port_t      sin_port;   /* Port number */
  struct in_addr sin_addr;   /* Contains the IP address */
};

struct in_addr {
  in_addr_t      s_addr;     /* IP address in network ordering */
};
```

- **sin_family**: indicates which type of address. Always set to AF_INET.
- **sin_port**: port number, in network byte order
- **sin_addr.s_addr**: IP address, in network byte order. To represent an unspecified IP address, set it to `htonl(INADDR_ANY)`.
  - QUESTION: When is this useful?

Domain Names

- Internet Protocols are all based on IP addresses
  - But IP addresses are hard for humans to remember
  - Our web server: **http://130.37.20.20**
  - Better: **http://www.cs.vu.nl**
- Using Domain Names
  - Domain names cannot be used directly by network protocols
  - Network protocols only use IP addresses
  - But you can convert domain names into IP addresses thanks to DNS
- Domain Name Service (DNS): handles Domain Name resolution
  - Hundreds of thousands of servers around the world that cooperate to resolve addresses
  - To learn more on how this works, go to the Distributed Systems course!

Converting Domain Names to IP

- Conversion is done by `gethostbyname()`

```
#include <netdb.h>
struct hostent *gethostbyname(const char *name);
```

- ...where `struct hostent` is as follows

```
struct hostent {
  char    *h_name;        /* official name of host */
  char    **h_aliases;    /* alias list */
  int     h_addrtype;     /* host address type */
  int     h_length;       /* length of address */
  char    **h_addr_list;  /* list of addresses */
};
```

  - **h_addr_list**: A null-terminated array of network addresses for the host

gethostbyname()

- Example:

```
#include <netdb.h>

int print_resolv(const char *name) {
  struct hostent *resolv;
  struct in_addr *addr;

  resolv = gethostbyname(name);
  if (resolv==NULL) {
    printf("Address not found for %s\n", name);
    return -1;
  }
  else {
    addr = (struct in_addr*) resolv->h_addr_list[0];
    printf("The IP address of %s is %s\n", name, inet_ntoa(*addr));
    return 0;
  }
}
```

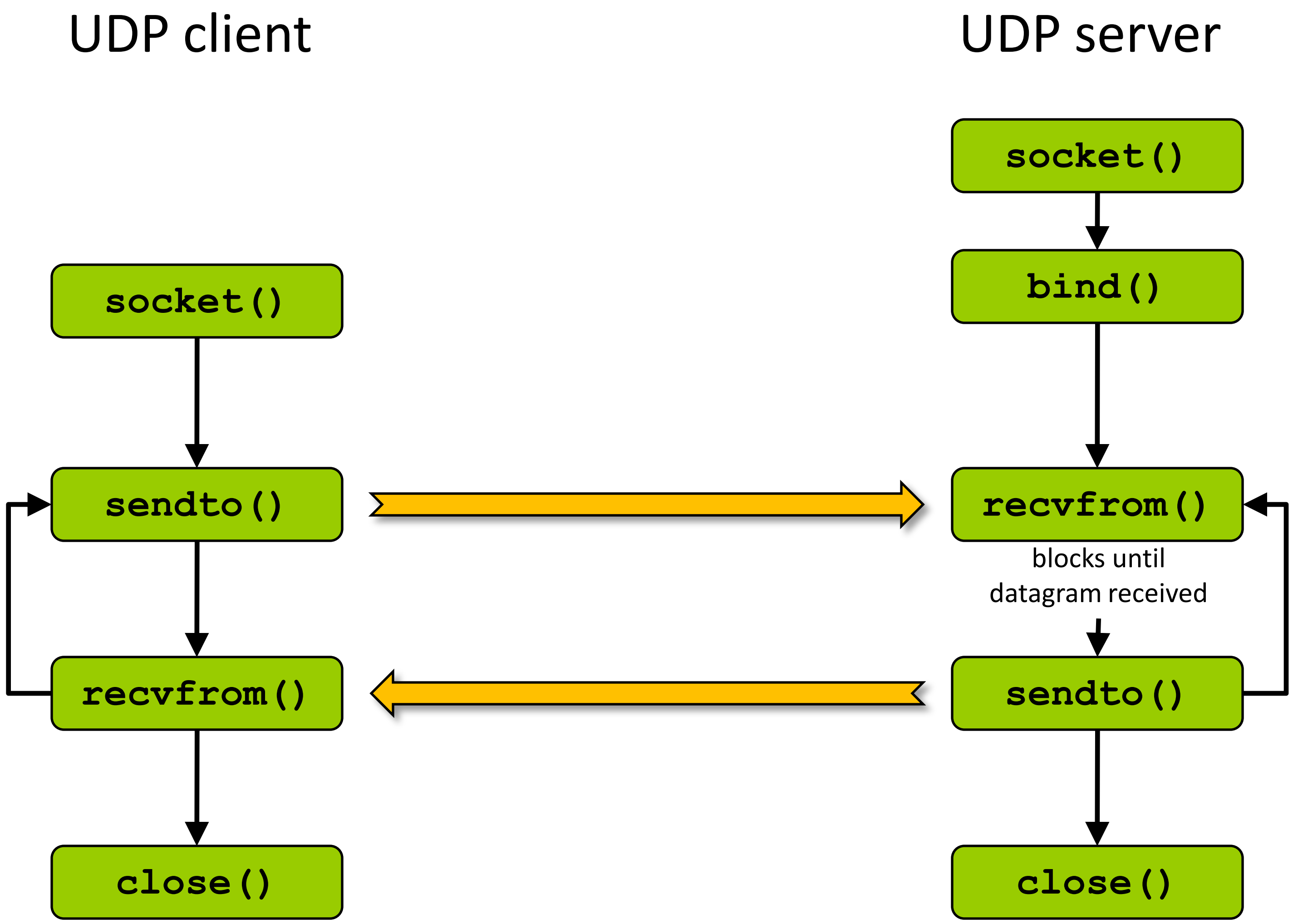
UDP Sockets

UDP

- Defined in RFC 768

- Popular UDP-based protocols
  - **DNS** – Domain Name System
  - **NFS** – Network File System
  - **SNMP** – Simple Network Management Protocol
  - **DHCP** – Dynamic Host Configuration Protocol
  - **RIP** – Routing Information Protocol

UDP Socket Functions



Creating a Socket

- socket() creates a new socket (for either UDP or TCP)

```
#include <sys/types.h>
#include <sys/socket.h>
int socket(int domain, int type, int protocol);
```

- To create an Internet socket, use:
  - **domain** = AF_INET
  - **type** = SOCK_DGRAM for UDP, SOCK_STREAM for TCP
  - **protocol** = 0
  - **Return value**: socket descriptor, or -1 for error

bind(): Assign an Address to a Socket

- bind() is used to specify the address of the socket
  - IP addr + port number

```
#include <sys/types.h>
#include <sys/socket.h>
#include <netinet/in.h>
int bind(int sockfd, struct sockaddr *my_addr, socklen_t addrlen);
```

  - **sockfd**: the socket descriptor
  - **my_addr**: a pointer to struct sockaddr_in (containing the address)
  - **addrlen**: the size of struct sockaddr_in
  - **Return value**: 0 for success, -1 for error

- If you don't specify them, the system gives them a value:
  - IP address → the IP address of the running host (this is usually correct)
  - Port number → any number (of an unused port)

- **QUESTION:** When do you need to specify a port number, and when can you omit it?

Example use of socket() and bind()

- To create a UDP socket on port 1234:

```
int fd, err;
struct sockaddr_in addr;

fd = socket(AF_INET,SOCK_DGRAM,0);
if (fd<0) { ... }

addr.sin_family      = AF_INET;
addr.sin_port        = htons(1234);
addr.sin_addr.s_addr = htonl(INADDR_ANY);

err = bind(fd, (struct sockaddr *) &addr, sizeof(struct sockaddr_in));
if (err<0) { ... }
```

- For historic reasons, you are obliged to explicitly cast your struct sockaddr_in * into a struct sockaddr *

- **QUESTION:** Is INADDR_ANY equivalent to 127.0.0.1?

Sending and Receiving Datagrams

- sendto() and recvfrom() are very similar:

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

int sendto(
  int sockfd,
  const void *buf,
  size_t len,
  int flags,
  const struct sockaddr *to,
  socklen_t tolen
);
```

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

int recvfrom(
  int sockfd,
  void *buf,
  size_t len,
  int flags,
  struct sockaddr *from,
  socklen_t *fromlen
);
```

sockfd	socket descriptor	
***buf**	buffer of message to send/receive	
len	buffer length	
flags	0	0
***to / *from**	destination address	source address (value-return)
tolen / *fromlen	sizeof(struct sockaddr)	sizeof(…) (value-return)
Return value	Number of bytes sent/received, or -1 for error	

Use of sendto() and recvfrom()

- Example:

```
(the socket is already created)

char msg[64];
int err;
struct sockaddr_in dest;

strcpy(msg,"hello, world!");

dest.sin_family      = AF_INET;
dest.sin_port        = htons(1234);
dest.sin_addr.s_addr =
            inet_addr("130.37.193.13");

err = sendto(fd,
      msg,
      strlen(msg)+1,
      0,
      (struct sockaddr*) &dest,
      sizeof(struct sockaddr_in));

if (err<0) { ... }
```

```
(the socket is created and bound to a
well-known port)

char msg[64];
int len, flen;
struct sockaddr_in from;

flen = sizeof(struct sockaddr_in);
len = recvfrom(fd,
      msg,
      sizeof(msg),
      0,
      (struct sockaddr*) &from,
      &flen);
if (len<0) { ... }

printf("Received %d bytes from host %s
port %d: %s", len,
       inet_ntoa(from.sin_addr),
       ntohs(from.sin_port),
       msg);
```

Closing a socket

- Sockets must be closed when they are no longer in use:

```
#include <unistd.h>
int close(int sockfd);
```

  - **sockfd**: the socket descriptor
  - **Return value**: 0 for success, -1 for error

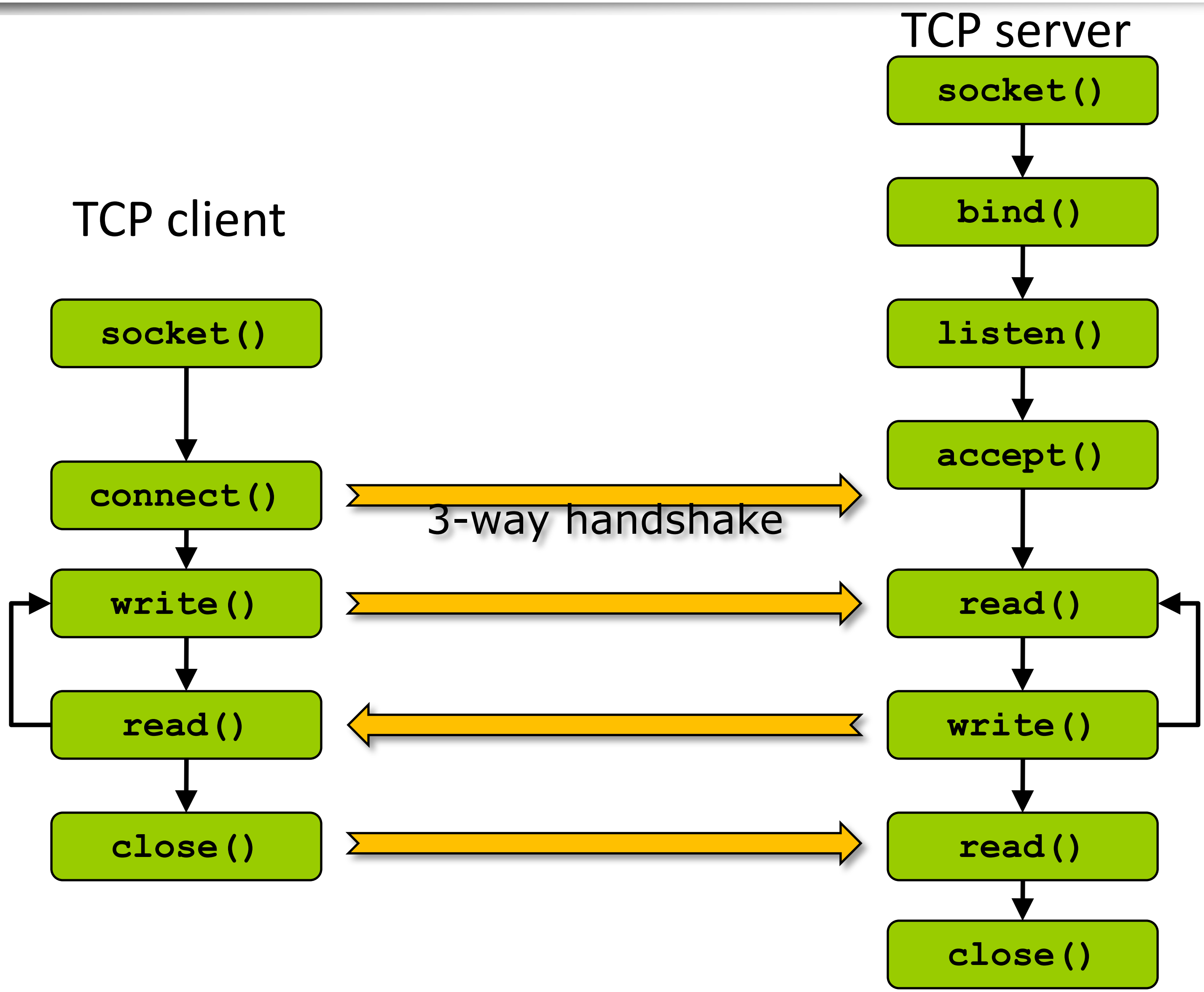
TCP Sockets

TCP

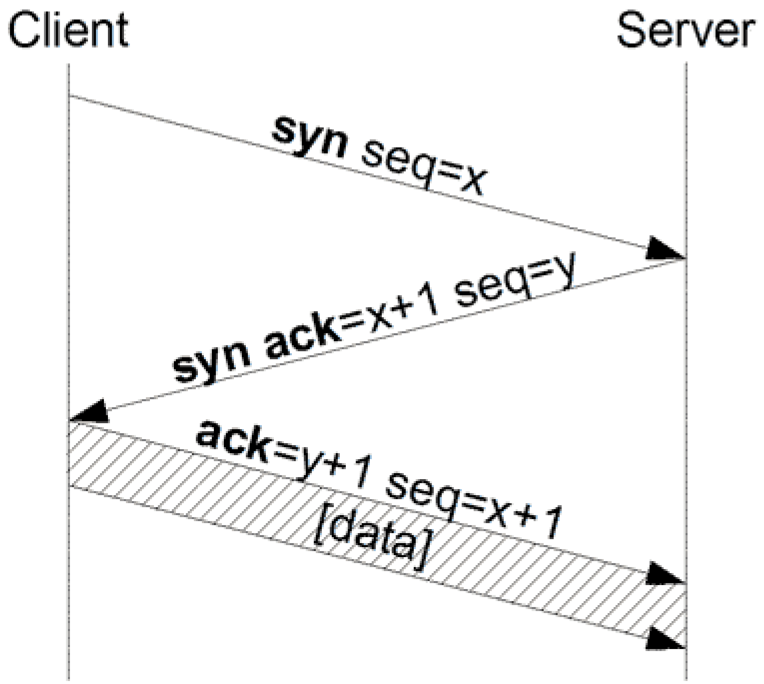
- Defined in RFC 793

- Popular TCP-based protocols
  - TELNET
  - FTP – File Transfer Protocol
  - SMTP – Simple Mail Transfer Protocol
  - HTTP – Hyper Text Transfer Protocol
  - SSH – Secure Shell

TCP Socket Functions



The TCP three-way handshake



Creating a Socket

- Some functions are the same as in UDP

- socket(): creates a socket

```
sockfd = socket(AF_INET, SOCK_STREAM, 0);
```

- bind(): to specify the address of a socket
  - Only useful for server sockets
  - Exactly like UDP sockets

listen(): Setting a Server Socket

- By default, TCP sockets are created as client sockets
  - A client socket cannot receive incoming connections

- Server sockets need to maintain more state
  - TCP establishes connections thanks to the three-way handshake:
    - The client sends a connection request
    - The server answers
    - The client acknowledges the server’s answer
  - Server sockets must allocate resources for handling connections

- To convert a client socket to a server socket, use listen()
  - And indicate how many not-yet-accepted connections can be supported in parallel
  - If this number is exceeded, the server will refuse connections

listen()

- The interface is simple

```
#include <sys/socket.h>
int listen(int sockfd, int backlog);
```

  - **sockfd**: the socket descriptor
  - **backlog**: the size of the buffer (often set to 5)
  - **Return value**: 0 for success, -1 for error

- **Note**
  - backlog is **not** **a limit on the number of connections** established in parallel!
  - It only limits the number of **pending connections** (i.e., connections before having been accepted)

Initiating a TCP connection

- Clients initiate connections to servers thanks to **connect()**:

```
#include <sys/types.h>
#include <sys/socket.h>
int connect(int sockfd,
            const struct sockaddr *serv_addr,
            socklen_t addrlen);
```

  - **sockfd**: the socket descriptor
  - **serv_addr**: a pointer to a struct sockaddr_in containing the address where to connect to
    - Obviously you must specify the destination IP address and port number
  - **addrlen**: sizeof(struct sockaddr_in)
  - **Return value**: 0 for success, -1 for error

- connect() binds the client's socket to a random unused port

- **QUESTION:** When can it fail?

Possible Connection Errors

- Destination Unreachable
  - The SYN message receives an ICMP error from some intermediate router
  - The client keeps trying for some time
  - After some time, it returns an EHOSTUNREACH error to the process
- Server reached, but no process bound to that port
  - The SYN message receives a RST (Reset) reply from the server’s TCP
  - The client’s TCP returns an ECONNREFUSED error to the process instantly
- Server reached, but listen backlog exhausted
  - Like the previous case
- No response → timeout
  - The SYN message receives no response
  - The client’s TCP sends SYN message again (after 6sec, 24sec)
  - After some time, an ETIMEDOUT error is returned to the client process

Waiting for an Incoming Connection

- **accept()** blocks the process until an incoming connection is received
  - When a connection is received, accept() creates a new socket dedicated to this connection
    - The new socket is used to communicate with the client
    - The original socket is immediately ready to wait for other connections

- accept():

```
#include <sys/types.h>
#include <sys/socket.h>
int accept(int sockfd, struct sockaddr *addr, socklen_t *addrlen);
```

  - **sockfd**: the socket descriptor
  - **addr**: a pointer to a sockaddr_in structure where the address of the client will be copied
  - **addrlen**: a pointer to an integer containing the size of addr
  - **Return value**: the descriptor of the newly created socket, or -1 for error

Example use of accept()

```
int sock, newsock, res;
sockaddr_in client_addr;
socklen_t addrlen;

(the socket sock is created and bound)

res = listen(sock,5);
if (res < 0) { ... }

addrlen = sizeof(struct sockaddr_in);

newsock = accept(sock, (struct sockaddr *) &client_addr, &addrlen);

if (newsock < 0) { ... }
else
{
  printf("Connection from %s!\n", inet_ntoa(client_addr.sin_addr));
}
```

Writing data to a socket

- write works the same for sending data to a TCP socket or writing to a file

```
#include <unistd.h>
ssize_t write(int sockfd, const void *buf, size_t count);
```

  - **sockfd**: socket descriptor
  - **buf**: buffer to be sent
  - **count**: size of buffer
  - **Return value**: number of bytes sent, or -1 for error

- Attention: When writing to a socket, write may send **fewer bytes** than requested
  - Due to limits in internal kernel buffer space

- Always check the return value of write, and resend the non-transmitted data

writen()

- A wrapper function (from Stevens book, page 78)

```
ssize_t writen(int fd, const void *vptr, size_t n)
{
  size_t nleft;
  ssize_t nwritten;
  const char *ptr;

  ptr = vptr;
  nleft = n;
  while (nleft > 0) {
    if ( ((nwritten = write(fd, ptr, nleft)) <= 0 ) {
      if (errno == EINTR)
        nwritten = 0;  /* and call write() again */
      else
        return -1;   /* error */
    }
    nleft -= nwritten;
    ptr += nwritten;
  }
  return n;
}
```

Reading data from a socket

- read() blocks the process until receiving data from the socket

```
#include <unistd.h>
ssize_t read(int sockfd, void *buf, size_t count);
```

  - **sockfd**: socket descriptor
  - **buf**: buffer where to write the data read
  - **count**: size of buffer
  - **Return value**: number of bytes read, or -1 for error

- Attention: When reading from a socket, read() may read **fewer bytes** than requested
  - It delivers the data that have been received
  - This does not mean that the stream of data is finished, there may be more to come
  - The end-of-file (EOF) is notified to the read by read() returning 0

Closing a TCP socket

- To stop sending data to a socket, use close():

```
#include <unistd.h>
int close(int sockfd);
```

- Anyone can call this, either the client or the server

- This sends an EOF message to the other party
  - When receiving an EOF, read returns 0 bytes
  - Subsequent reads and writes will return errors

Asymmetric Disconnection

- Sometimes you may want to tell the other party that you are finished, but let it finish before closing the connection

```
#include <sys/socket.h>
int shutdown(int sockfd, int how);
```

  - **how**: SHUT_WR for stopping writing, SHUT_RD for stopping reading

- When one party has closed the connection, the other can still write data (and then close the connection as well)

To initiate a disconnection	To receive a disconnection
❑ shutdown(fd, SHUT_WR) ❑ Keep on reading the last data ❑ Until receiving an EOF ❑ close() the socket	❑ read() keeps receiving data ❑ read() receives EOF ❑ Keep on writing the last data ❑ close() the socket

Socket Options

Socket Options

- Various attributes that are used to determine the behavior of sockets.
- Setting options tells the OS/Protocol Stack the behavior we want.
- Support for generic options (apply to all sockets) and protocol specific options.

Option types

- Many socket options are **boolean flags** indicating whether some feature is enabled (1) or disabled (0).
- Other options are associated with more complex types including **int**, **timeval**, **in_addr**, **sockaddr**, etc.
- Some options are read-only (we can’t set the value)

Getting and Setting option values

- Use getsockopt() and setsockopt():

```
#include <sys/socket.h>
int getsockopt(int sockfd, int level, int optname,
                      void *optval, socklen_t *optlen);
int setsockopt(int sockfd, int level, int optname,
                      const void *optval, socklen_t optlen);
```

  - **sockfd**: the socket descriptor
  - **level**: SOL_SOCKET (for socket options)
  - **optname**: the option name (a #define)
  - **optval**: a buffer containing the option value
  - **optlen**: the length of optval

General Options

- Protocol independent options
- Handled by the generic socket system code
- Some general options are supported only by specific types of sockets (SOCK_DGRAM, SOCK_STREAM)

Some Generic Options

- SO_BROADCAST
- SO_DONTROUTE
- SO_ERROR
- SO_KEEPALIVE
- SO_LINGER
- SO_RCVBUF,SO_SNDBUF
- SO_REUSEADDR

SO_BROADCAST

- Boolean option: enables/disables sending of broadcast messages
- Underlying Data Link layer must support broadcasting!
- Applies only to SOCK_DGRAM sockets
- Prevents applications from sending broadcasts by mistake
  - OS looks for this flag when broadcast address is specified
  - e.g., ping –b 130.37.193.255

SO_DONTROUTE

- Boolean option: enables bypassing of normal routing
  - If destination is directly attached to an interface, OK.
  - Otherwise, ENETUNREACH is returned
- Used by routing daemons (*routed*, *gated*, etc.)
  - Bypasses the routing table
  - The routing table could be incorrect

SO_ERROR

- Integer value option
  - The value is an error indicator value (similar to errno)
  - Read only!

- Reading (by calling getsockopt()) clears any pending error
  - so, you can only read it once

SO_KEEPALIVE

- Boolean option
  - enabled means that TCP sockets should send a probe to peer if no data flow for a "long time"
  - Allows a process to determine whether peer process/host has crashed

- **QUESTION:** Consider what would happen to an open telnet or ssh connection without keepalive

- Typically used by servers
  - some sort of garbage collection of terminated clients

SO_LINGER

- Value is of type:

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

struct linger {
  int l_onoff;    /* 0 = off */
  int l_linger;   /* time in seconds */
};
```

- Controls whether and how long a call to **close()** waits for pending ACKs
  - l_onoff = 0 → default behavior: close() returns immediately, and the system tries to deliver any pending packets from the send buffer
  - l_onoff = 1 → close() returns when:
    - either all pending packets have been sent and acknowledged by the remote TCP stack
    - or l_linger seconds have elapsed

- Only for connection-oriented sockets (e.g., TCP)

SO_LINGER

- Without SO_LINGER, the node closing a connection has no way of knowing that the other peer received all sent data

- With SO_LINGER, it can know that all sent data reached the other peer's TCP stack

- **QUESTION:** Isn't this what shutdown(fd, SHUT_WR) does?
  - Not exactly!
  - shutdown(fd, SHUT_WR) closes your own write channel, but you can still read
  - Reading till you receive EOF (read() returns 0 bytes) means that the other peer did a close()
  - Therefore, shutdown() assures you that the other peer has read all your data, while SO_LINGER assures you that your data reached the other peer's TCP stack, but you don't know if it was read!

SO_RCVBUF, SO_SNDBUF

- Integer values options
  - Change the receive and send buffer sizes.
- Can be used with STREAM and DGRAM sockets.
- With TCP, this option affects the window size used for flow control
  - Must be established before the connection is made

SO_REUSEADDR

- Boolean option
  - Enables binding to an address (port) that is already in use.
- Used by servers that are transient
  - Allows binding a passive socket to a port currently in use (with active sockets) by other processes.
- Can be used to establish separate servers for the same service on different interfaces (or different IP addresses on the same interface)
  - Virtual Web Servers can work this way
- Very useful in your assignments!

I/O Multiplexing

I/O Multiplexing

- We saw so far how a process can handle a single connection
  - **accept()** and **read()** block until something is received on a given socket

- How can a program handle multiple sockets?
  - Use multiple processes
  - Use non-blocking I/O
    - It works for read() but not for accept()

- select() monitors multiple file descriptors
  - It blocks the process until any one of them is ready for reading or writing

- poll() is similar to select()
  - With additional information about streams

select() [1/3]

- select() monitors several file descriptors simultaneously

```
#include <sys/select.h>
int select(int n,
           fd_set *readfds,
           fd_set *writefds,
           fd_set *exceptfds,
           struct timeval *timeout);
```

  - **n**: the highest numbered file descriptor, plus 1
  - **readfds**: a list of file descriptors to monitor for reading
  - **writefds**: a list of file descriptors to monitor for writing
  - **exceptfds**: a list of file descriptors to monitor for exceptions
  - **timeout**: a duration after which select() returns anyway.
    - Set `timeout.tv_sec = timeout.tv_usec = 0` for zero timeout (return immediately)
    - Set `timeout = NULL` for no timeout
  - **Return value**: the number of (i.e., how many) descriptors ready for I/O, or 0 in case of timeout, or -1 for error

select() [2/3]

- fd_set is a bitset representing a list of file descriptors
  - Do not manipulate fd_set directly, always use special macros:

```
FD_ZERO (fd_set *set);             /* clears all bits */
FD_SET  (int fd, fd_set *set);     /* turns  on  bit 'fd' */
FD_CLR  (int fd, fd_set *set);     /* turns  off bit 'fd' */
FD_ISSET(int fd, fd_set *set);     /* checks if  bit 'fd' is set */
```

- select() modifies the contents of readfds, writefds, and exceptfds

- After select()
  - file descriptors that are ready for use are turned on (in their set)
  - non-ready descriptors are turned off

- To wait for a socket to be ready to accept(), put it in the read set

select() [3/3]

- Example use:

```
int nb, fd1=5, fd2=8;
char buf[1024];
fd_set read_set;

while (1) {
  FD_ZERO(&read_set);
  FD_SET(fd1, &read_set);
  FD_SET(fd2, &read_set);

  nb = select(20, &read_set, NULL, NULL, NULL);
  if (nb<=0) { ... }
  if (FD_ISSET(fd1, &read_set)) {
    bzero(buf,1024);
    nb = read(fd1, buf, 1024);
    if (nb<0) { ... }
    if (nb==0) printf("Received EOF on fd1!\n");
    else printf("Received data on fd1: %s\n", buf);
  }
  if (FD_ISSET(fd2, &read_set)) { ... }
}
```

Server Structures

Server Structures

- Often, a server accepts connections to **one** (TCP) socket
  - But it wants to process several requests in parallel
  - Better use of server's resources
  - Incoming requests can start being executed immediately after reception (not having to wait for previous client)

- Depending on its nature, a server can receive between 0 and dozens of thousands requests per second

- Several server structures can be used:
  - Iterative (i.e., not concurrent)
  - One Process Per Client
  - Preforking
  - select() loop
  - Many other variants…

Iterative Servers

- An iterative server treats one request after the other

```
int fd, newfd;
while (1) {
  newfd = accept(fd, ...);
  treat_request(newfd);
  close(newfd);
}
```

- Simple
- Potentially low resource utilization
  - If treat_request() does not utilize all the CPU, resources are being wasted
- Potentially long queue of incoming connections waiting for accept()
  - Increased service latency
  - If the queue increases, the server may start rejecting new connections

One Process Per Client [1/2]

- A new child process is created to handle each connection
  - Also known as “One Child Per Client”

```
void sig_chld(int) {
  while (waitpid(0, NULL, WNOHANG) > 0) {}
  signal(SIGCHLD,sig_chld);
}

int main() {
  int fd, newfd, pid;
  // socket(), bind(), and listen() have been omitted

  signal(SIGCHLD, sig_chld);
  while (1) {
    newfd = accept(fd, ...);
    if (newfd < 0) continue;
    pid = fork();
    if (pid==0) { treat_request(newfd); exit(0); }
    else        { close(newfd); }
  }
}
```

One Process Per Client [2/2]

- This is the most common type of concurrent server
  - Several requests are treated simultaneously
  - Incoming requests are accepted and treated immediately
- QUESTION: What are the downsides?
  - It may not be suitable for highly loaded servers
    - Ok for ~1K connections per day, but for ~1M?
  - fork() takes a lot of time!
- MORE QUESTIONS!
  - Why is the **signal()** call necessary?
  - What happens if treat_request() needs to modify a global variable? How can you obtain the desired effect?
    - e.g., to update request statistics

Preforking

- The server first creates a pool of processes dedicated to treating requests
- Each client is delegated to a child process
- No **`fork()`** is done per connecting client
- Performance gain!

Preforking: Each child calls accept()

- Typical example

```
#define NB_PROC 10

void recv_requests(int fd) { /* An iterative server */
  int newfd;
  while (1) {
    newfd = accept(fd,...);
    treat_request(newfd);
    close(newfd);
  }
}

int main() {
  int fd=socket(AF_INET, SOCK_STREAM, 0);
  // bind() and listen() have been omitted

  for (int i=0; i<NB_PROC; i++)      /* Create NB_PROC children */
    if (fork()==0)
      recv_requests(fd);
}
```

Preforking: Each child calls accept()

- Multiple accepts on a single socket descriptor
  - In System V types of Unix (Solaris, HP-UX, etc.), not possible!
  - However, allowed in BSD-based Unix systems
- Where it is allowed, accept() internally defines a condition variable
  - Condition: “Block until a client opens a connection”
  - Predicate: “Is a client available in the queue so I can accept it?”
- QUESTION: Can you guess some problem?
  - When a client appears, all processes waiting on that condition variable are woken up
  - Only one is allowed to run at a time, so the first one accepts the client
  - When other processes get the mutex, they first check if the predicate is still valid, and block again since the client is already accepted
  - For large process pools → performance penalty per connecting client

Preforking: Mutex on accept()

- A solution is to protect access to accept() by a single mutex shared by all processes:

```
void recv_requests(int fd) { /* An iterative server */
  int f;
  while (1)
  {
    /* --- ACQUIRE MUTEX --- */
    newfd=accept(fd,...);
    /* --- RELEASE MUTEX --- */

    treat_request(newfd);
    close(f);
  }
}
```

- For systems NOT supporting concurrent accepts on a single socket:
  - Solves the problem
- For the rest systems:
  - Improves performance

Preforking: accept() on parent

- Another alternative:
  - accept on the parent
  - pass socket descriptor to a free child

- Difficulties?
  - Keeping track of which children are free or loaded
  - Communicating to the children
    - Keeping open pipes
    - Using shared memory, semaphores, condition variables
    - Requires **descriptor passing** (out of the scope of this course)

- Advantages?
  - Parent has control over which processes to delegate clients to
  - Can achieve more efficient memory usage by using the same processes

One Thread Per Client

- Very similar to One Process Per Client
  - Attention to pay with race conditions, due to shared memory!

- Starting a thread per client is faster than preforking a pool of processes!

Prethreading

- Very similar to preforking
- Even faster than One Thread Per Client (which is already faster than Preforking)
- Locking access to **`accept()`** by a mutex, further improves performance

Forking vs. Threading

- If threading is faster than forking, why not always use threading?
  - The system might not support threads
  - The application might be easier to design as separate processes
  - In certain cases, **One Process Per Client** can be faster than **One Thread Per Client**
  - **QUESTION:** When?! ☺
  - **ANSWER:** When the code treating a client needs to execute another program. Then, forking a unithreaded process and then doing an exec would be faster than creating a new thread, then forking a multithreaded process and finally doing the exec

Select Loop

- A single process (and single thread) manages multiple connections thanks to **select()**
  - This is quite **difficult** to do correctly
  - You must split request treatment into a set of non-blocking stages
  - You must maintain a list of data structures containing the current state of each concurrent request
    - Which stage it is in
    - All internal data it needs

- Implementing a select loop server is left to the students as exercise ☺

- For example, the *Squid Web* cache is implemented as a select loop

inetd

- For servers with **low load**, it is recommended to use
  - One Process Per Client
  - …or even Iterative

- For servers with **extremely low load** (e.g., one invocation per day or week)
  - **inetd**
  - No need to run the server at all, while not needed
  - Define the service's protocol (TCP/UDP), port, and executable in /etc/services
  - inetd listens on that port
  - Upon reception of a client, it forks and execs the executable