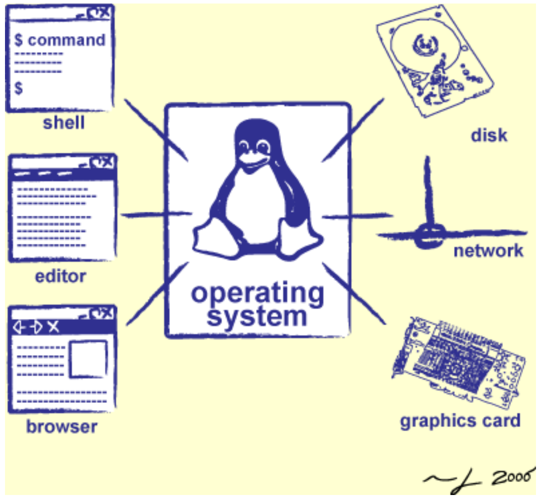
CS162
Operating Systems and Systems Programming
Lecture 5

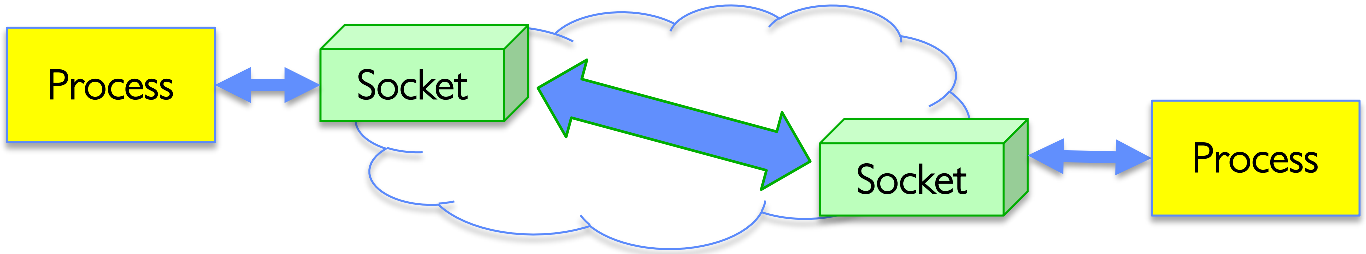
Abstractions 3: IPC, Pipes and Sockets
A quick programmer's viewpoint

Goals for Today: IPC and Sockets

- **Key Idea:** Communication between processes and across the world looks like File I/O
- Introduce Pipes and Sockets
- Introduce TCP/IP Connection setup for Webserver




```
write(wfd, wbuf, wlen);
```




```
n = read(rfd, rbuf, rmax);
```

Recall: Creating Processes with fork()

- `pid_t fork()` – copy the current process
  - State of original process duplicated in Parent and Child!
  - Address Space (Memory), File Descriptors, etc…

- Return value from **`fork()`**: pid (like an integer)
  - When > 0:
    - » Running in (original) Parent process
    - » return value is pid of new child
  - When = 0:
    - » Running in new Child process
  - When < 0:
    - » Error! Must handle somehow
    - » Running in original process

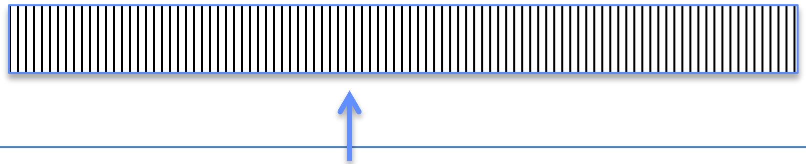
```
int status;
pid_t tcpid;
…
cpid = fork();
if (cpid > 0) {
  mypid = getpid();
  printf("[%d] parent of [%d]\n", mypid, cpid);
  tcpid = wait(&status);
  printf("[%d] bye %d(%d)\n",mypid,tcpid,status);
} else if (cpid == 0) {
  mypid = getpid();
  printf("[%d] child\n", mypid);
  exit(42);
}
…
```

Recall: Key Unix I/O Design Concepts

- Uniformity – Everything Is a File!
  - file operations, device I/O, and interprocess communication through open, read/write, close
  - Allows simple composition of programs
    - » find | grep | wc …
- Open before use
  - Provides opportunity for access control and arbitration
  - Sets up the underlying machinery, i.e., data structures
- Byte-oriented
  - Even if blocks are transferred, addressing is in bytes
- Kernel buffered reads
  - Streaming and block devices looks the same, read blocks yielding processor to other task
- Kernel buffered writes
  - Completion of out-going transfer decoupled from the application, allowing it to continue
- Explicit close

Recall: C High-Level File API – Streams

- Operates on "streams" – unformatted sequences of bytes (wither text or binary data), with a position:



```
#include <stdio.h>
FILE *fopen( const char *filename, const char *mode );
int fclose( FILE *fp );
```

- Open stream represented by pointer to a FILE data structure
  - Error reported by returning a NULL pointer
  - Pointer used in subsequent operations on the stream
  - Data buffered in user space

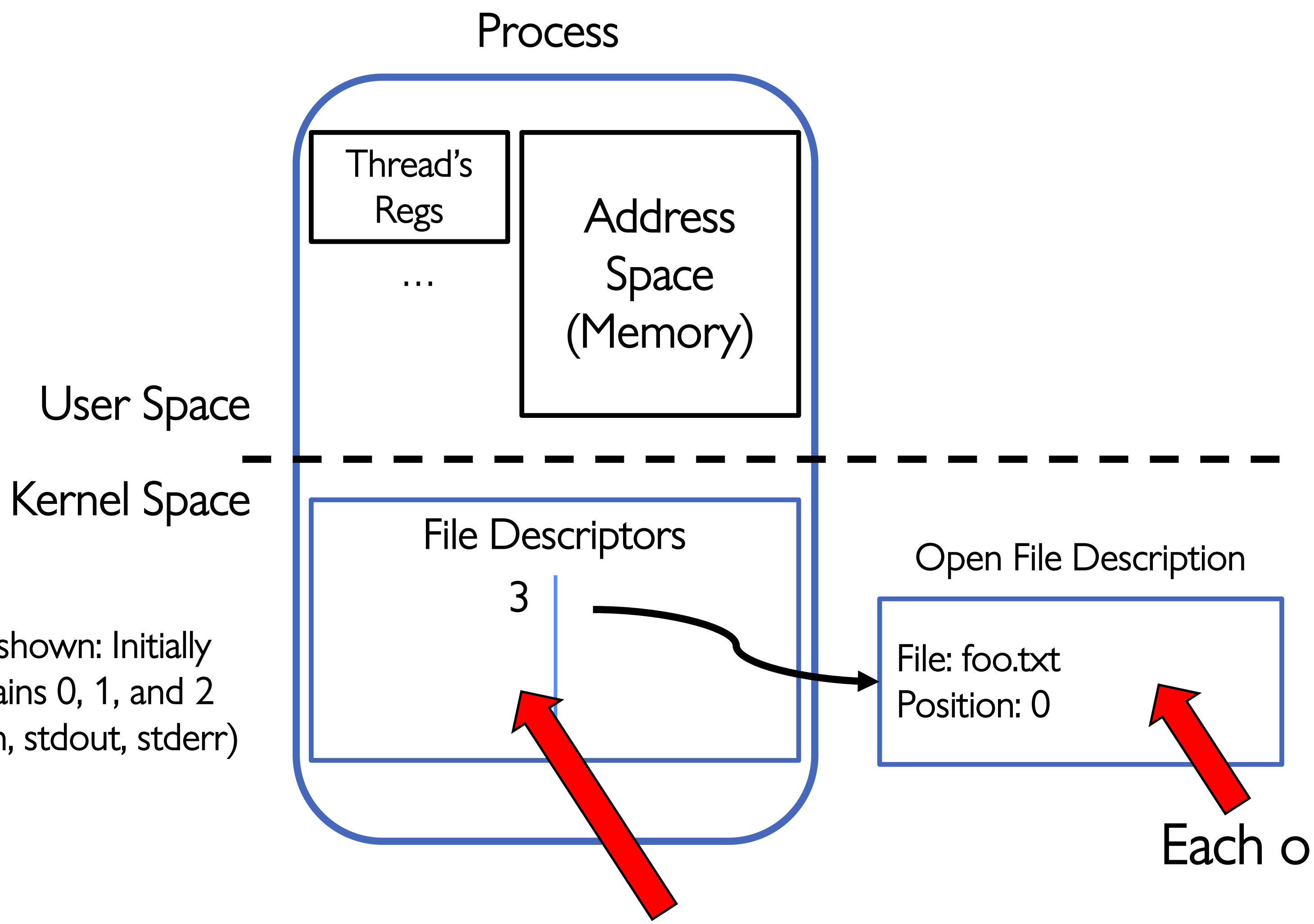
Recall: Low-Level File I/O: The RAW system-call interface

```
#include <fcntl.h>
#include <unistd.h>
#include <sys/types.h>

int open (const char *filename, int flags [, mode_t mode])
int creat (const char *filename, mode_t mode)
int close (int filedes)
```

- Integer return from `open()` is a *file descriptor*
  - *Error indicated by return < 0:* the global `errno` variable set with error
  - File Descriptor used in subsequent operations on the file
- Streams (opened with fopen()) have a file descriptor *inside of them!*
  - Retrievable with `fileno(FILE *stream)` ⇒ internal file descriptor

Recall: Representation of a Process (inside kernel!)



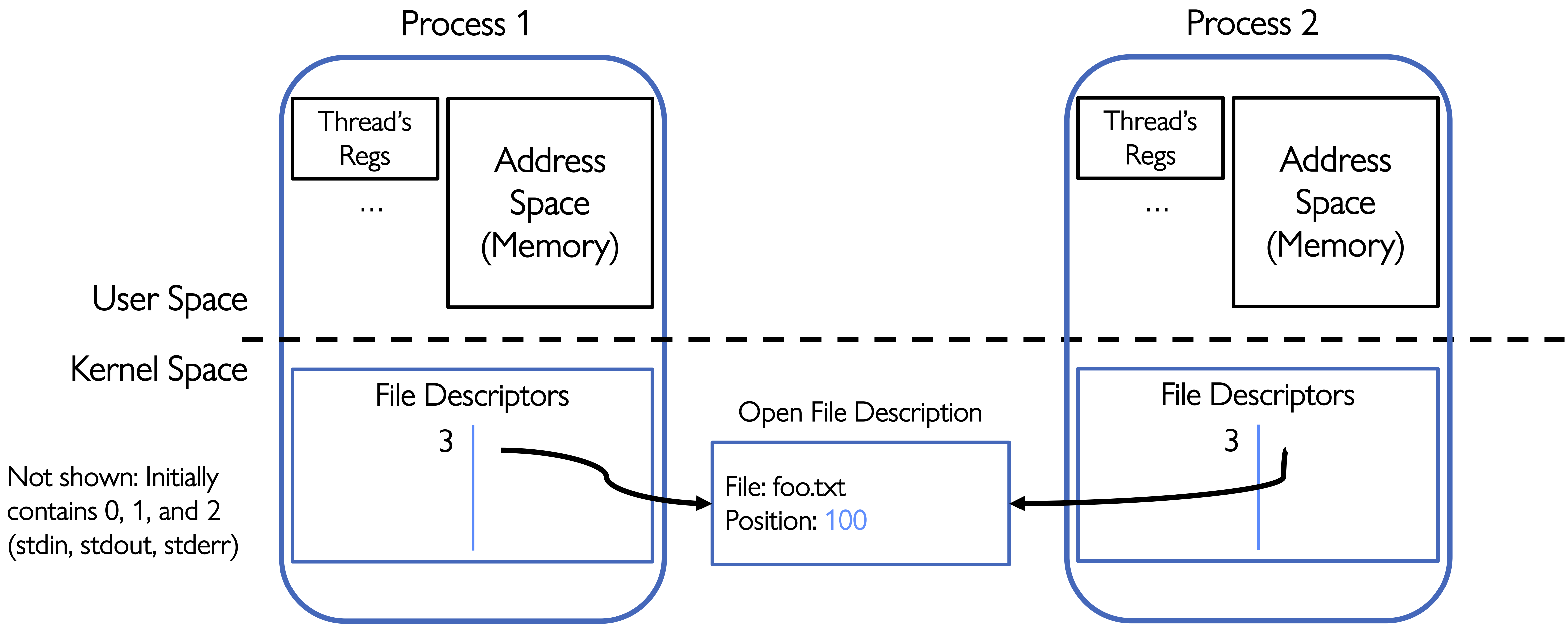
Suppose that we execute
open("foo.txt")
and that the result is 3

Not shown: Initially contains 0, 1, and 2 (stdin, stdout, stderr)

Each open file has file description

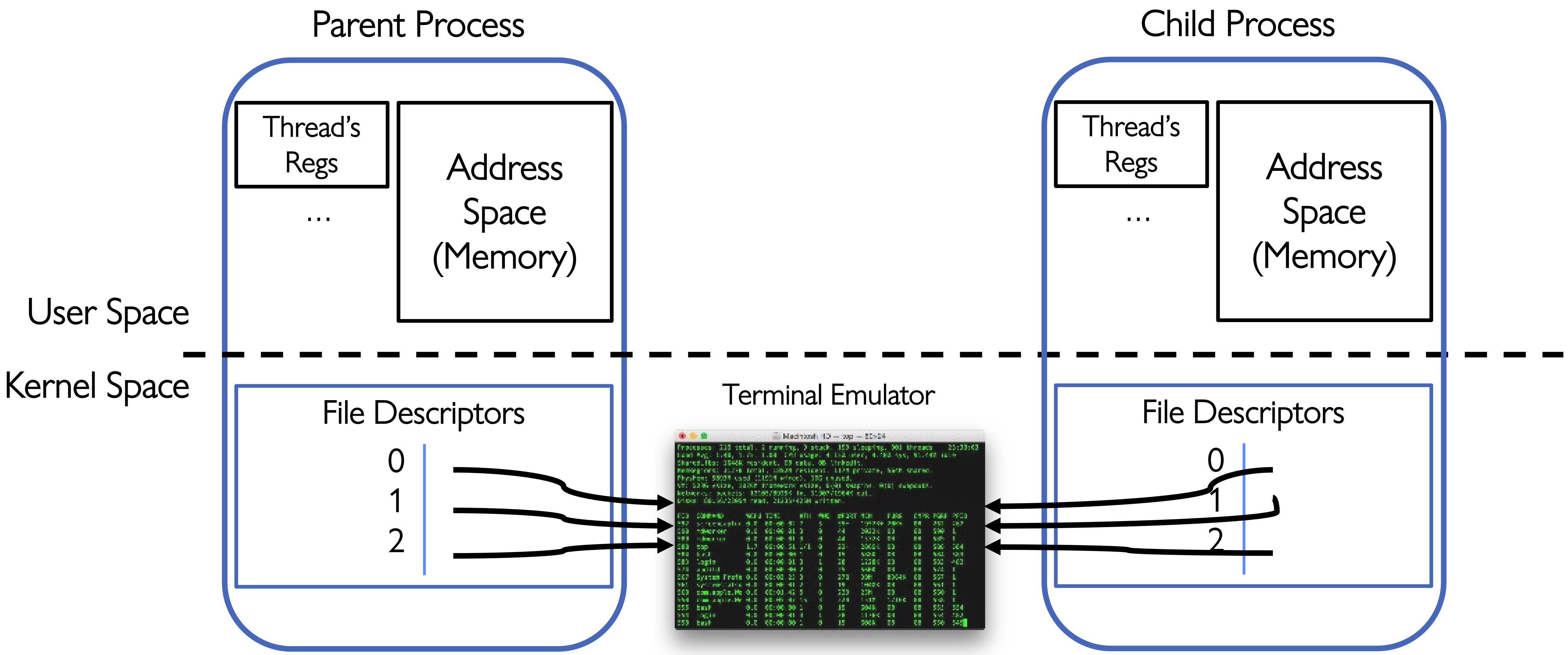
Descriptor Table provides redirection

Recall: What Happens on fork()?



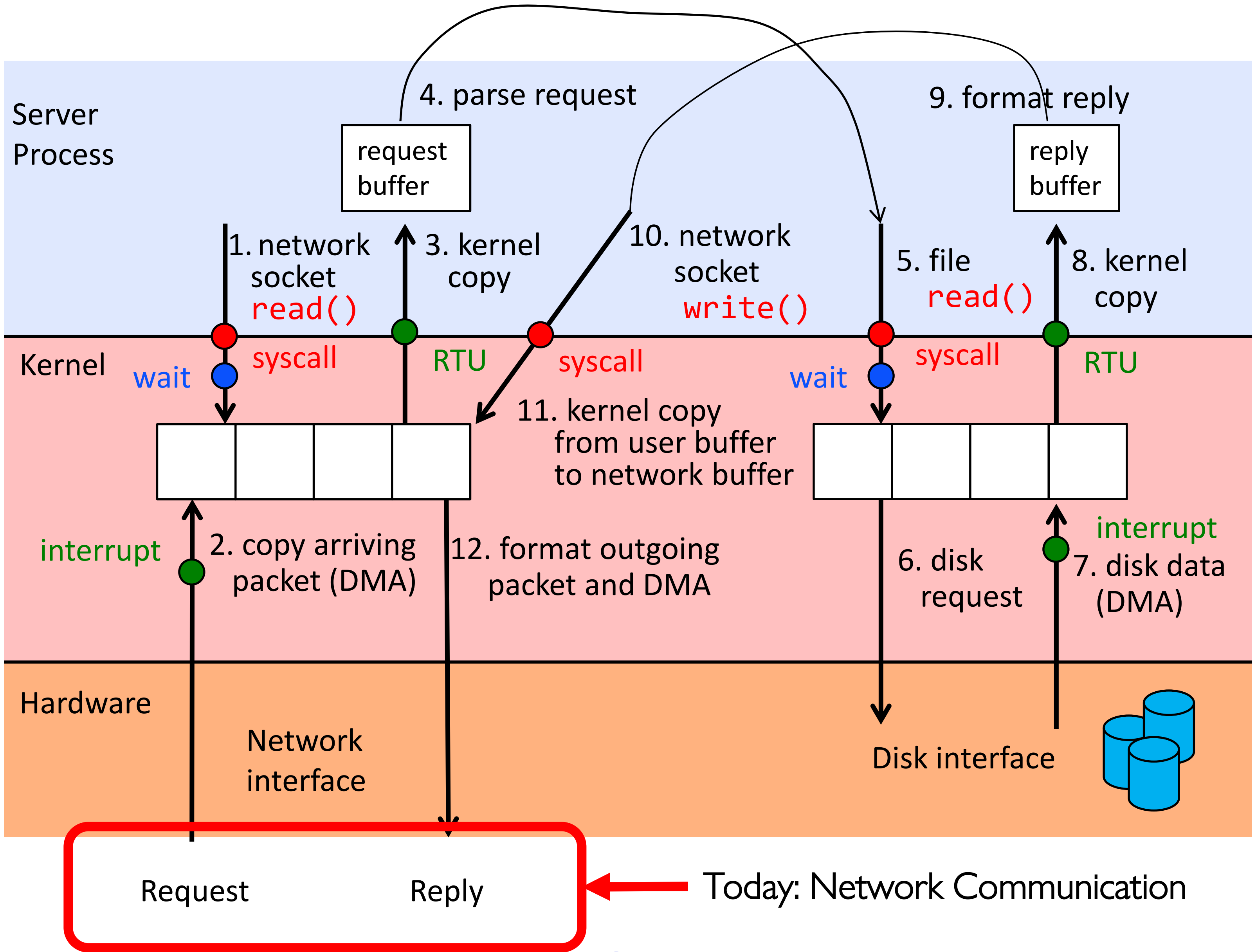
- After fork():
  - File Descriptors *copied*: child has same descriptor table as parent!
  - File Descriptions *shared*: child and parent can both manipulate/change open files

Recall standard file descriptors: 0, 1, 2



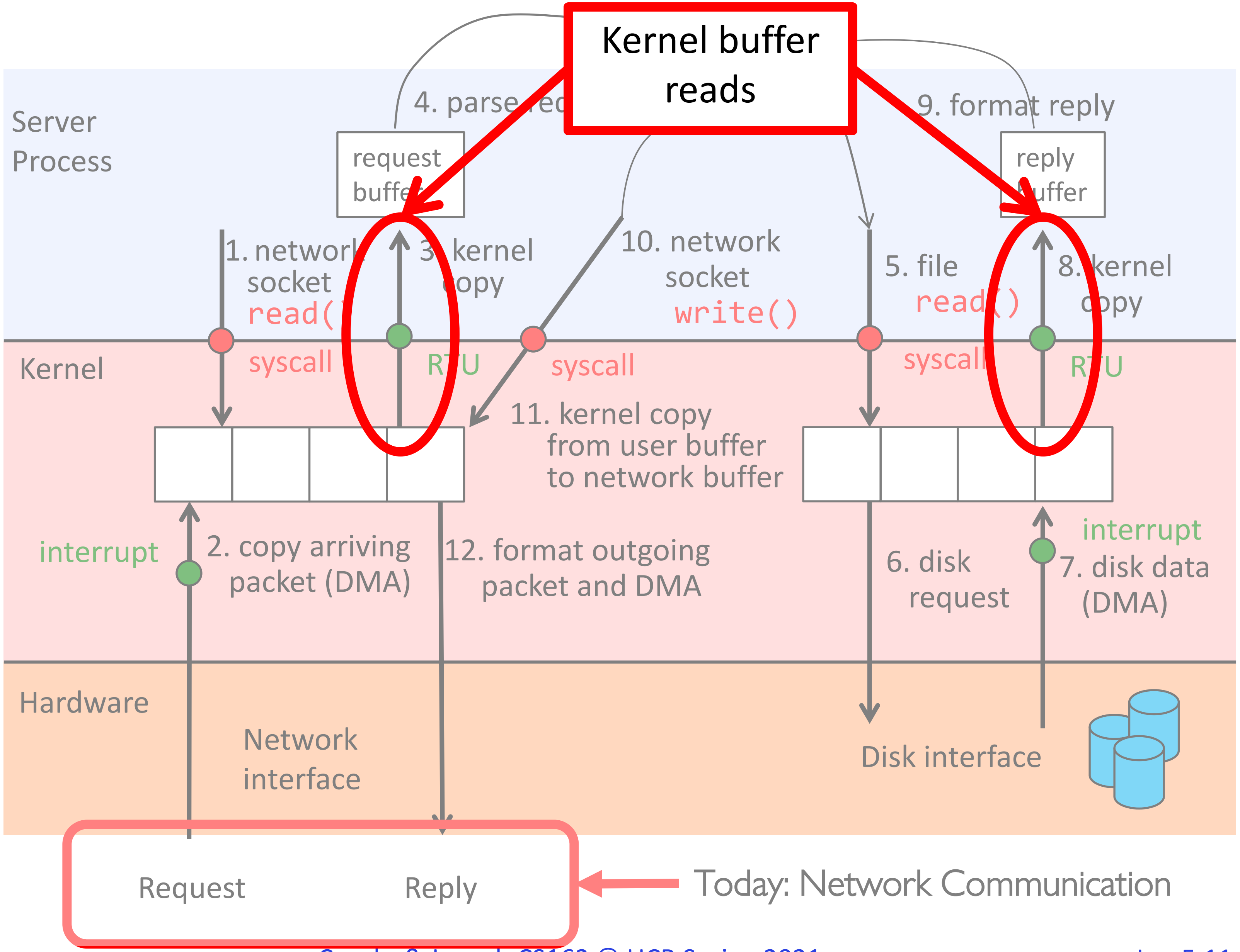
0: stdout (terminal output)
1: stderr (error output)
2: stdin (terminal input)

Putting it together: web server



Today: Network Communication

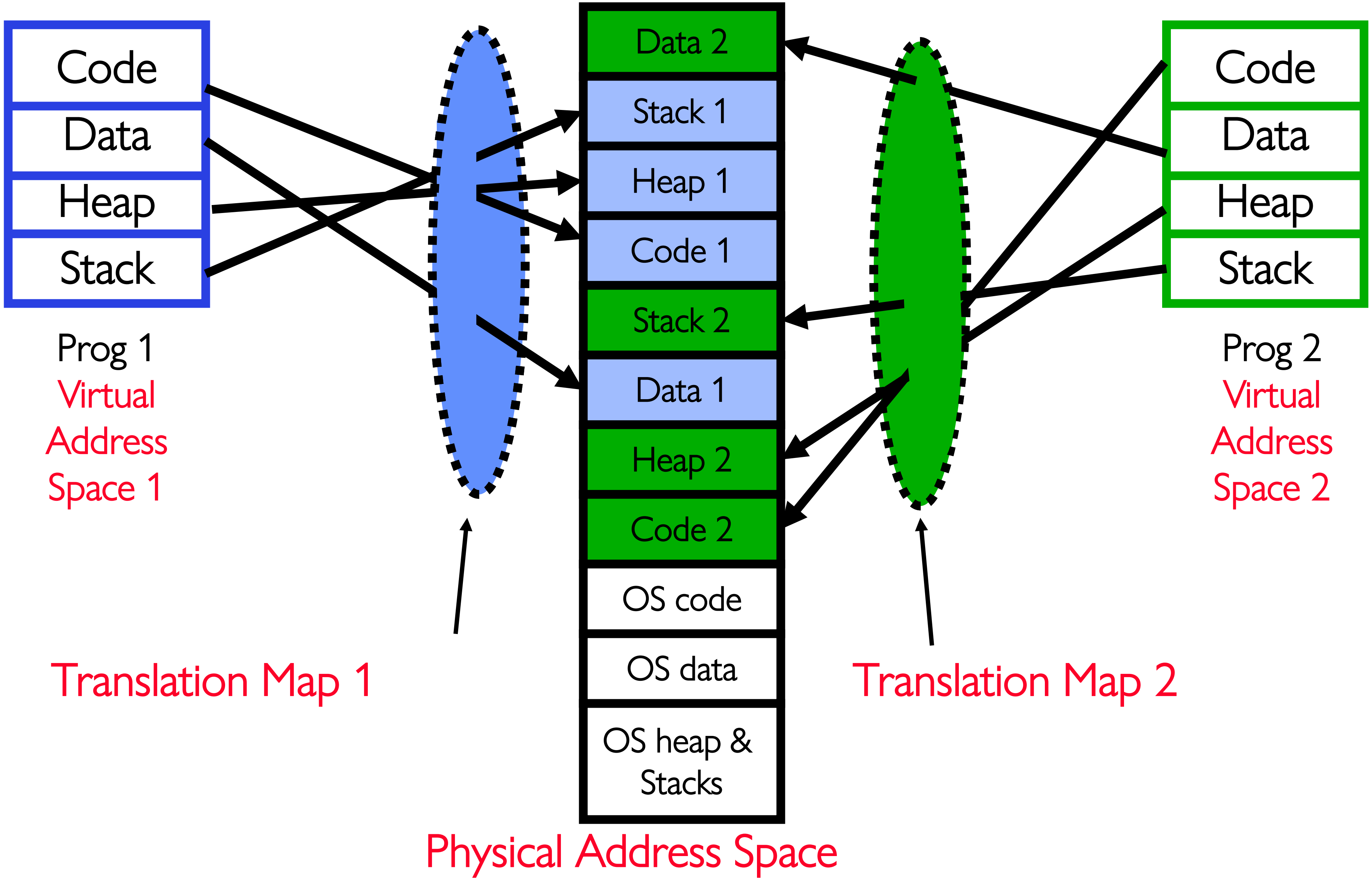
Putting it together: web server



Today: Communication Between Processes

- What if processes wish to communicate with one another?
  - Why? Shared Task, Cooperative Venture with Security Implications
- Process Abstraction Designed to Discourage Inter-Process Communication!
  - Prevent one process from interfering with/stealing information from another
- So, must do something special (and agreed upon by both processes)
  - Must "Punch Hole" in security
- This is called "Interprocess Communication" (or IPC)

Recall: Processes Protected from each other

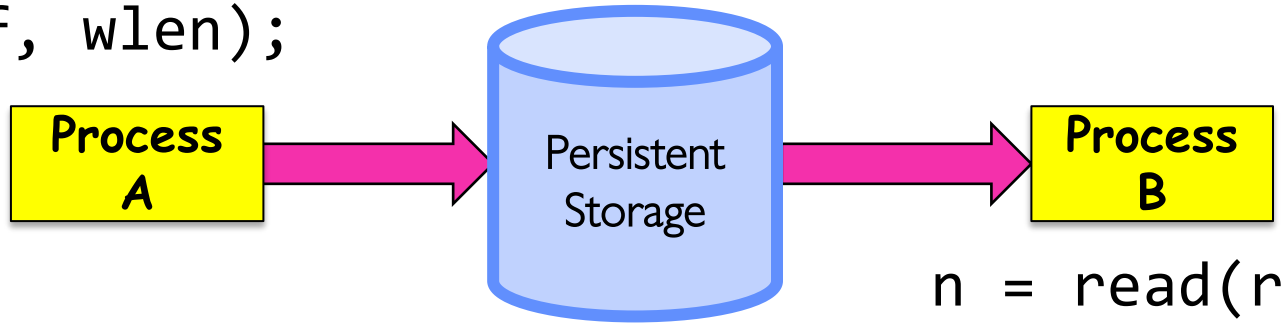


Communication Between Processes

- Producer (writer) and consumer (reader) may be distinct processes
  - Potentially separated in time
  - How to allow selective communication?

- Simple option: use a file!
  - We have already shown how parents and children share file descriptions:

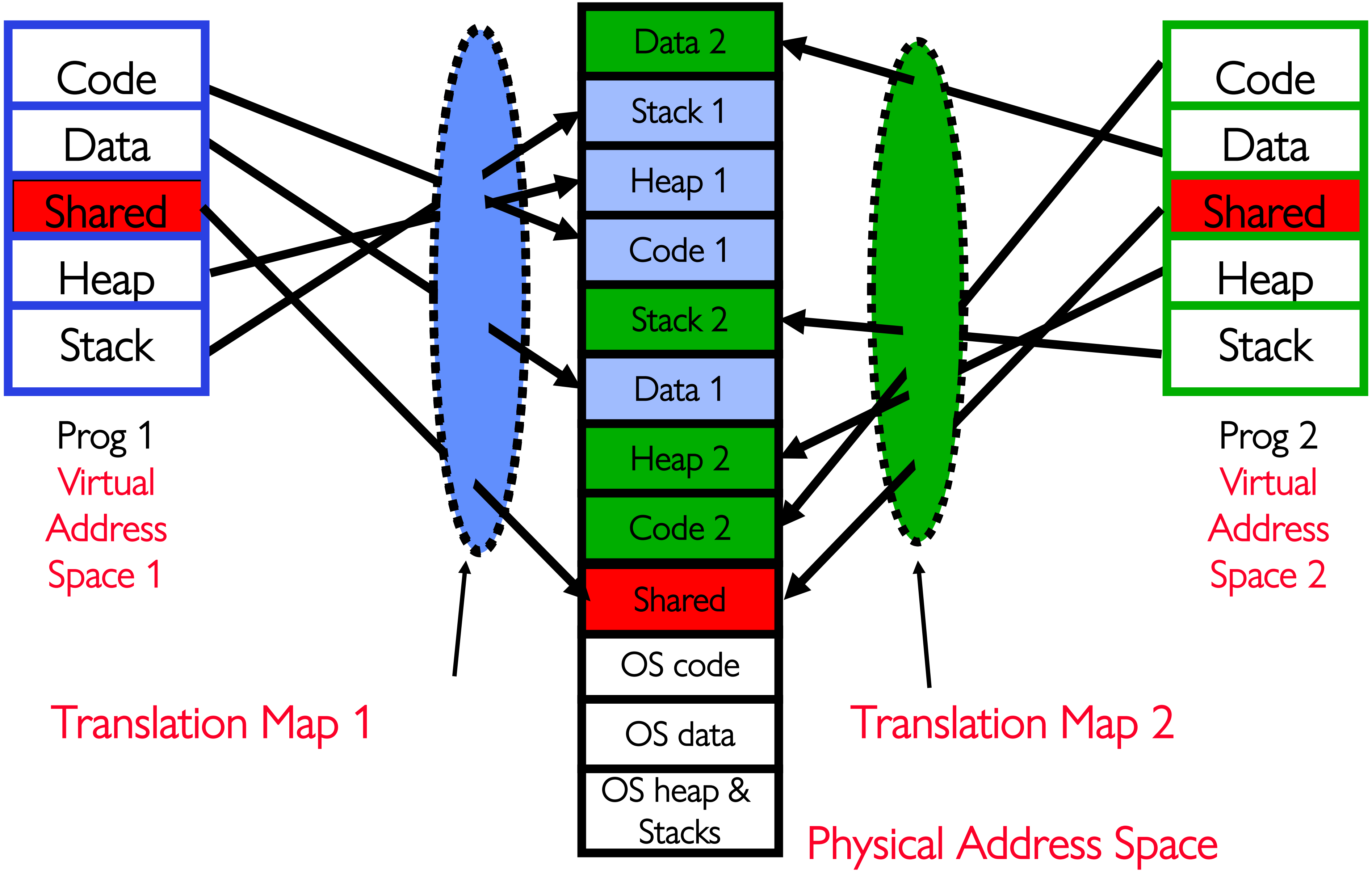
```
write(wfd, wbuf, wlen);
```




```
n = read(rfd, rbuf, rmax);
```

- Why might this be wasteful?
  - Very expensive if you only want transient communication (non-persistent)

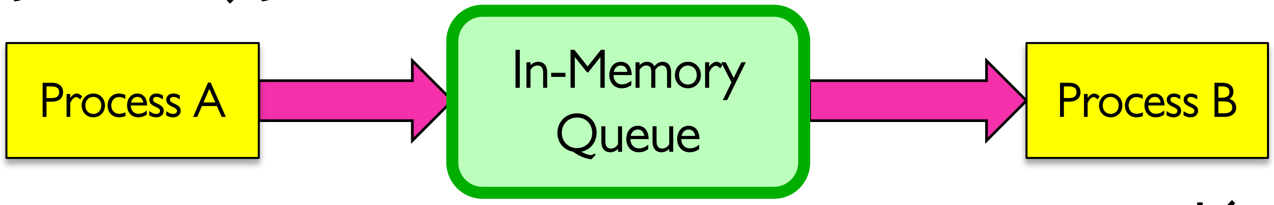
Shared Memory: Better Option?



Communication Between Processes (Another Option)

- Suppose we ask Kernel to help?
  - Consider an in-memory queue
  - Accessed via system calls (for security reasons):

```
write(wfd, wbuf, wlen);
```




```
n = read(rfd, rbuf, rmax);
```

- Data written by A is held in memory until B reads it
  - Same interface as we use for files!
  - Internally more efficient, since nothing goes to disk
- Some questions:
  - How to set up?
  - What if A generates data faster than B can consume it?
  - What if B consumes data faster than A can produce it?

One example of this pattern: POSIX/Unix PIPE

```
write(wfd, wbuf, wlen);
```


```
n = read(rfd, rbuf, rmax);
```

- Memory Buffer is finite:
  - If producer (A) tries to write when buffer full, it *blocks* (Put sleep until space)
  - If consumer (B) tries to read when buffer empty, it *blocks* (Put to sleep until data)

`int pipe(int fileds[2]);`

- Allocates two new file descriptors in the process
- Writes to `fileds[1]` read from `fileds[0]`
- Implemented as a fixed-size queue

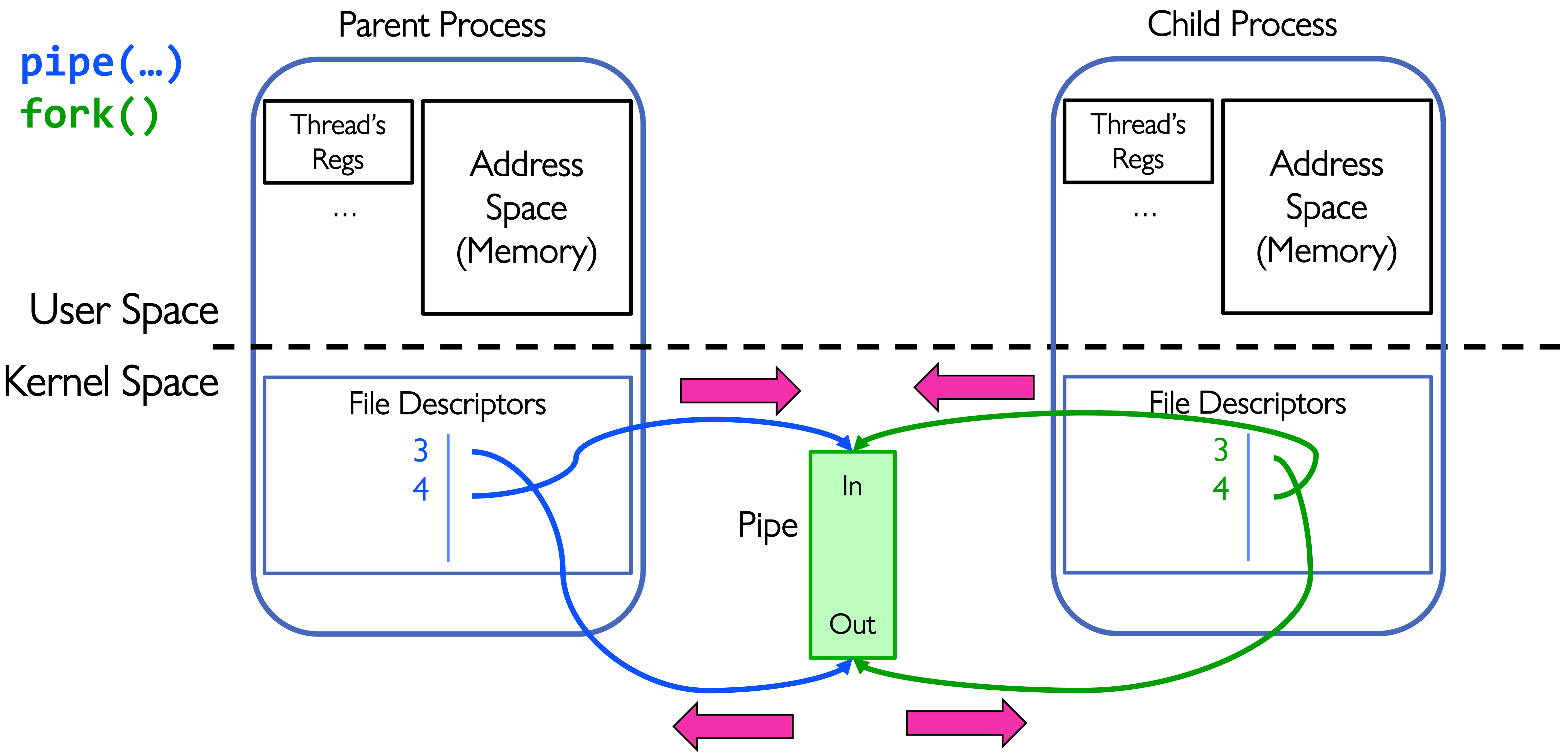
Single-Process Pipe Example

```
#include <unistd.h>
int main(int argc, char *argv[])
{
  char *msg = "Message in a pipe.\n";
  char buf[BUFSIZE];
  int pipe_fd[2];
  if (pipe(pipe_fd) == -1) {
    fprintf (stderr, "Pipe failed.\n"); return EXIT_FAILURE;
  }
  ssize_t writelen = write(pipe_fd[1], msg, strlen(msg)+1);
  printf("Sent: %s [%ld, %ld]\n", msg, strlen(msg)+1, writelen);

  ssize_t readlen  = read(pipe_fd[0], buf, BUFSIZE);
  printf("Rcvd: %s [%ld]\n", msg, readlen);

  close(pipe_fd[0]);
  close(pipe_fd[1]);
}
```

Pipes *Between* Processes



Inter-Process Communication (IPC): Parent ⇒ Child

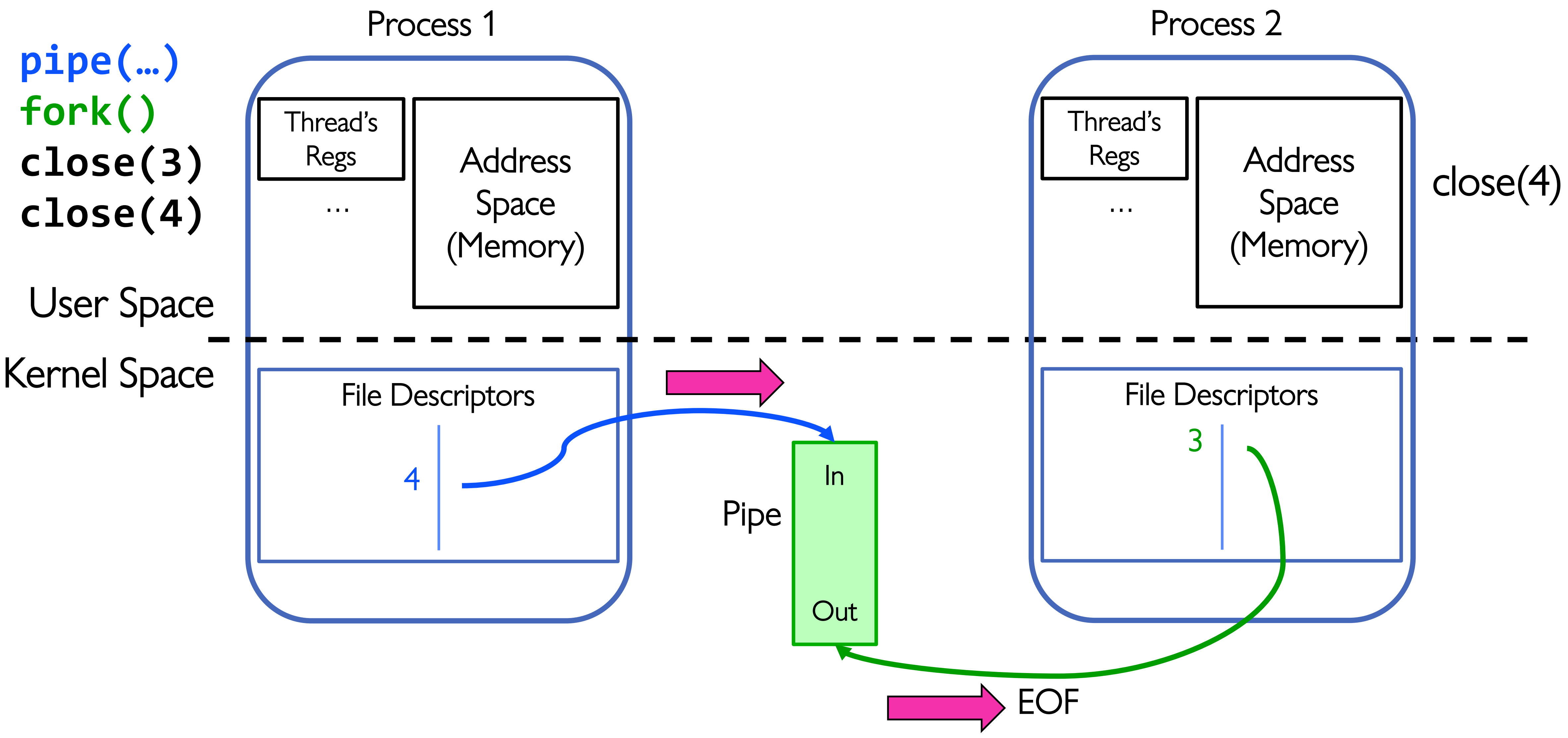
```
// continuing from earlier
pid_t pid = fork();
if (pid < 0) {
  fprintf (stderr, "Fork failed.\n");
  return EXIT_FAILURE;
}
if (pid > 0) {
  ssize_t writelen = write(pipe_fd[1], msg, msglen);
  printf("Parent: %s [%ld, %ld]\n", msg, msglen, writelen);
  close(pipe_fd[0]);
} else {
  ssize_t readlen  = read(pipe_fd[0], buf, BUFSIZE);
  printf("Child Rcvd: %s [%ld]\n", msg, readlen);
  close(pipe_fd[1]);
}
```

When do we get EOF on a pipe?

- After last "write" descriptor is closed, pipe is effectively closed:
  – Reads return only "EOF"
- After last "read" descriptor is closed, writes generate SIGPIPE signals:
  – If process ignores, then the write fails with an "EPIPE" error

EOF on a Pipe

```
pipe(…)
fork()
close(3)
close(4)
```



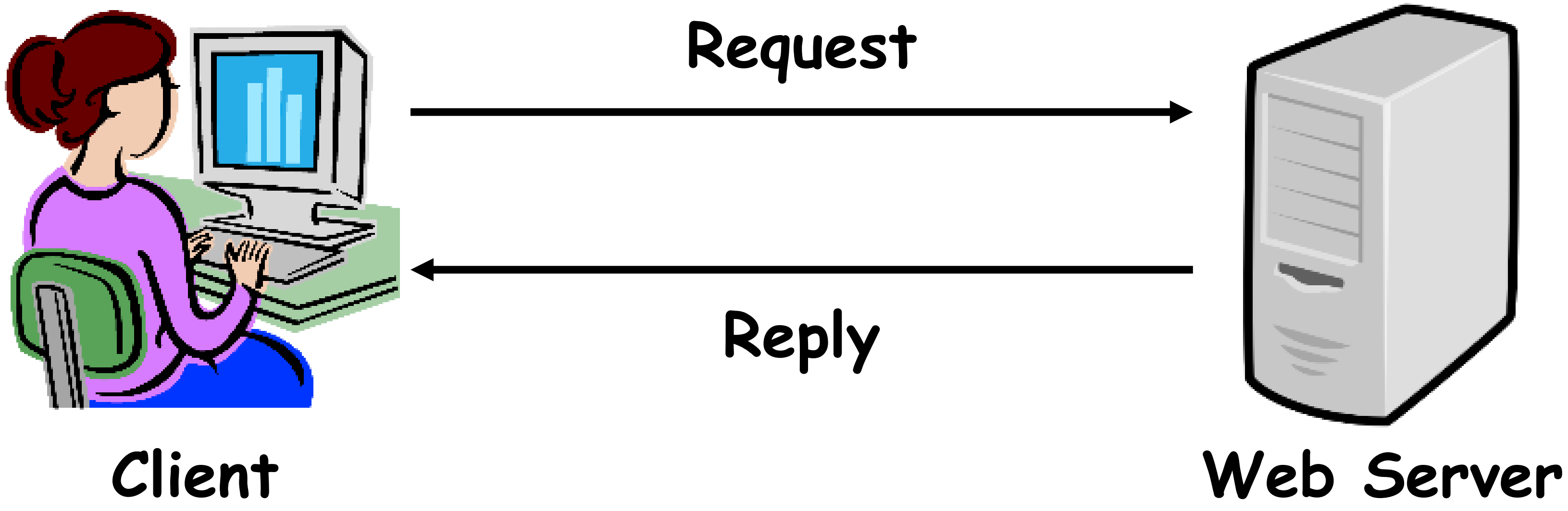
Once we have communication, we need a *protocol*

- A protocol is an agreement on how to communicate
- Includes
  - Syntax: how a communication is specified & structured
    - Format, order messages are sent and received
  - Semantics: what a communication means
    - Actions taken when transmitting, receiving, or when a timer expires
- Described formally by a state machine
  - Often represented as a message transaction diagram

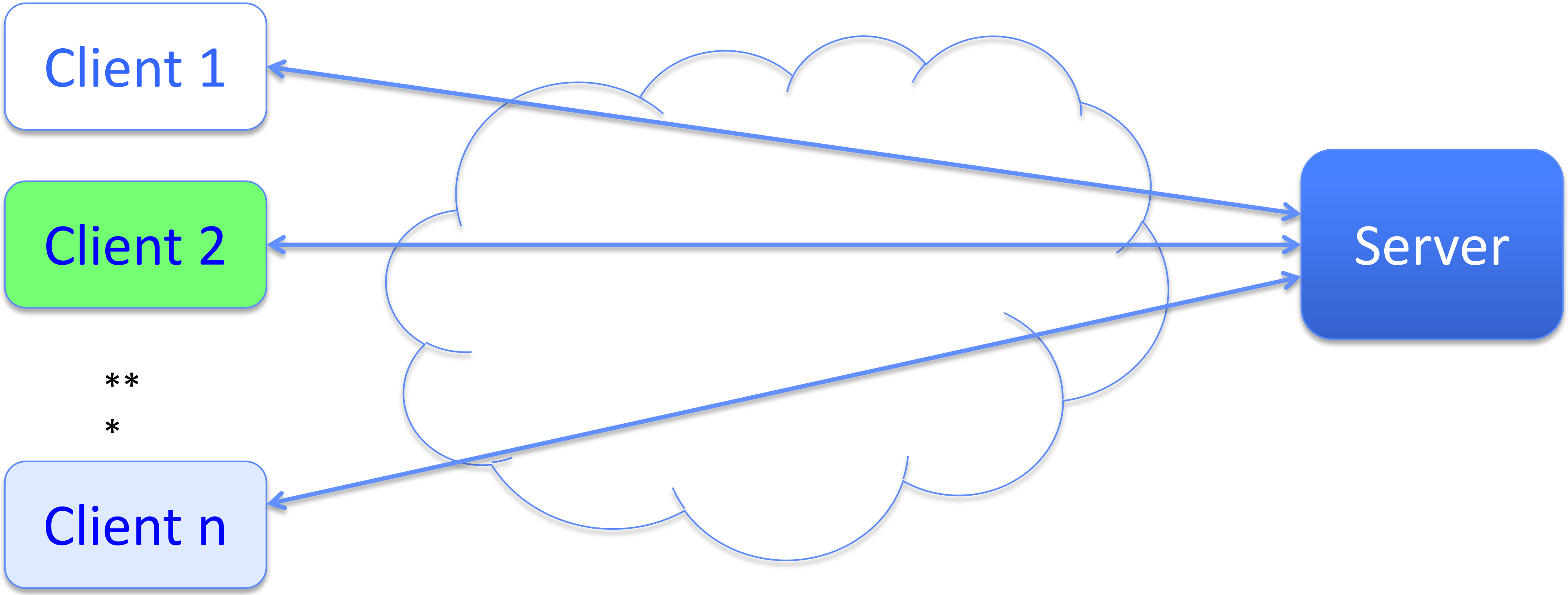
Examples of Protocols in Human Interaction

Crooks	**Joseph**
1. Telephone	
2. (Pick up / open up the phone)	
3. Listen for a dial tone / see that you have service	
4. Dial	
5. Should hear ringing …	
6.	Callee: “Hello?”
7. Caller: “Hi, it’s Natacha….” Caller: “Hey, do you think … blah blah blah …” pause	
8.	Callee: “Yeah, blah blah blah …” pause
9. Caller: Bye	
10.	Callee: Bye
11. Hang up	

Web Server



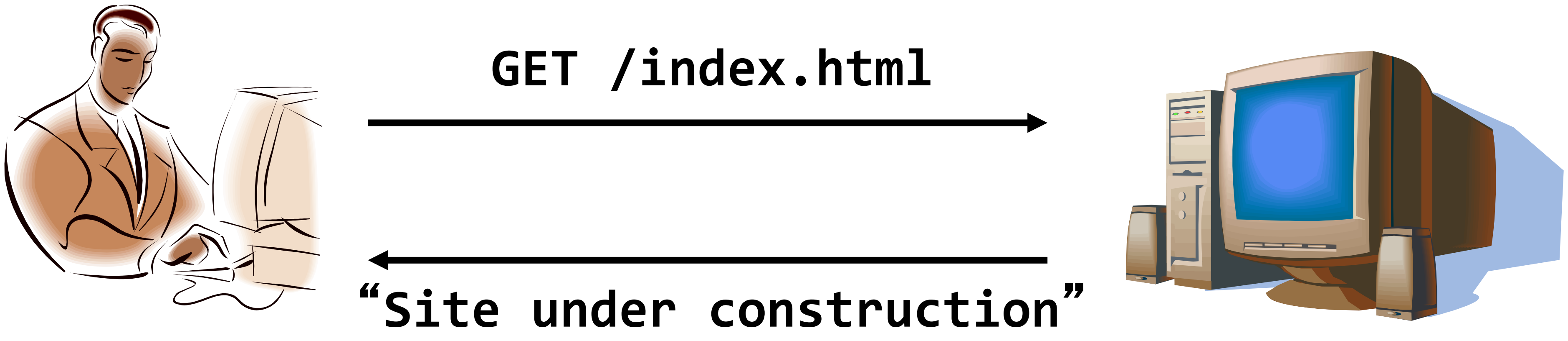
Client-Server Protocols: Cross-Network IPC



- Many clients accessing a common server
- File servers, www, FTP, databases

Client-Server Communication

- Client is "sometimes on"
  - Sends the server requests for services when interested
  - E.g., Web browser on laptop/phone
  - Doesn't communicate directly with other clients
  - Needs to know server's address
- Server is "always on"
  - Services requests from many clients
  - E.g., Web server for `www.cnn.com`
  - Doesn't initiate contact with clients
  - Needs a fixed, well-known address



What is a Network Connection?

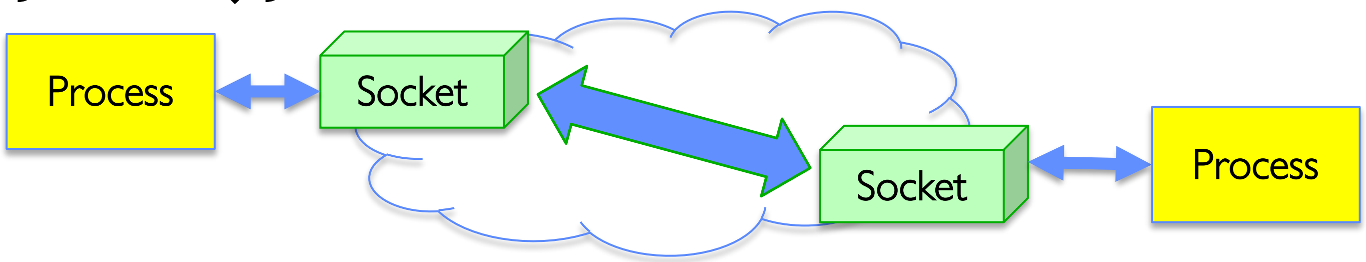
- Bidirectional *stream* of bytes between two processes on possibly different machines
  – For now, we are discussing "TCP Connections"

- Abstractly, a connection between two endpoints A and B consists of:
  – A queue (bounded buffer) for data sent from A to B
  – A queue (bounded buffer) for data sent from B to A

The Socket Abstraction: Endpoint for Communication

- **Key Idea:** Communication across the world looks like File I/O

```
write(wfd, wbuf, wlen);
```




```
n = read(rfd, rbuf, rmax);
```

- Sockets: Endpoint for Communication
  - Queues to temporarily hold results
- Connection: Two Sockets Connected Over the network
  - How to **open()**?

Sockets: More Details

- **Socket:** An abstraction for one endpoint of a network connection
  - Another mechanism for **inter-process communication**
  - Most operating systems (Linux, Mac OS X, Windows) provide this, even if they don't copy rest of UNIX I/O
  - Standardized by POSIX

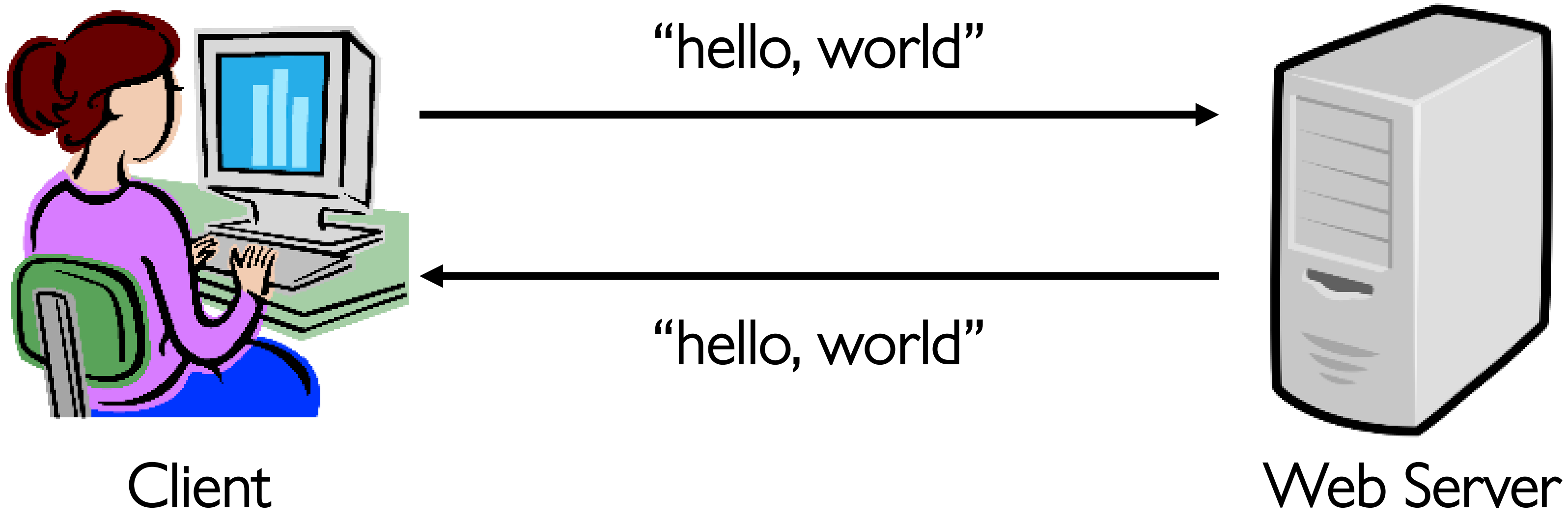
- Same abstraction for any kind of network
  - Local (within same machine)
  - The Internet (TCP/IP, UDP/IP)
  - Things "no one" uses anymore (OSI, Appletalk, IPX, …)

Sockets: More Details

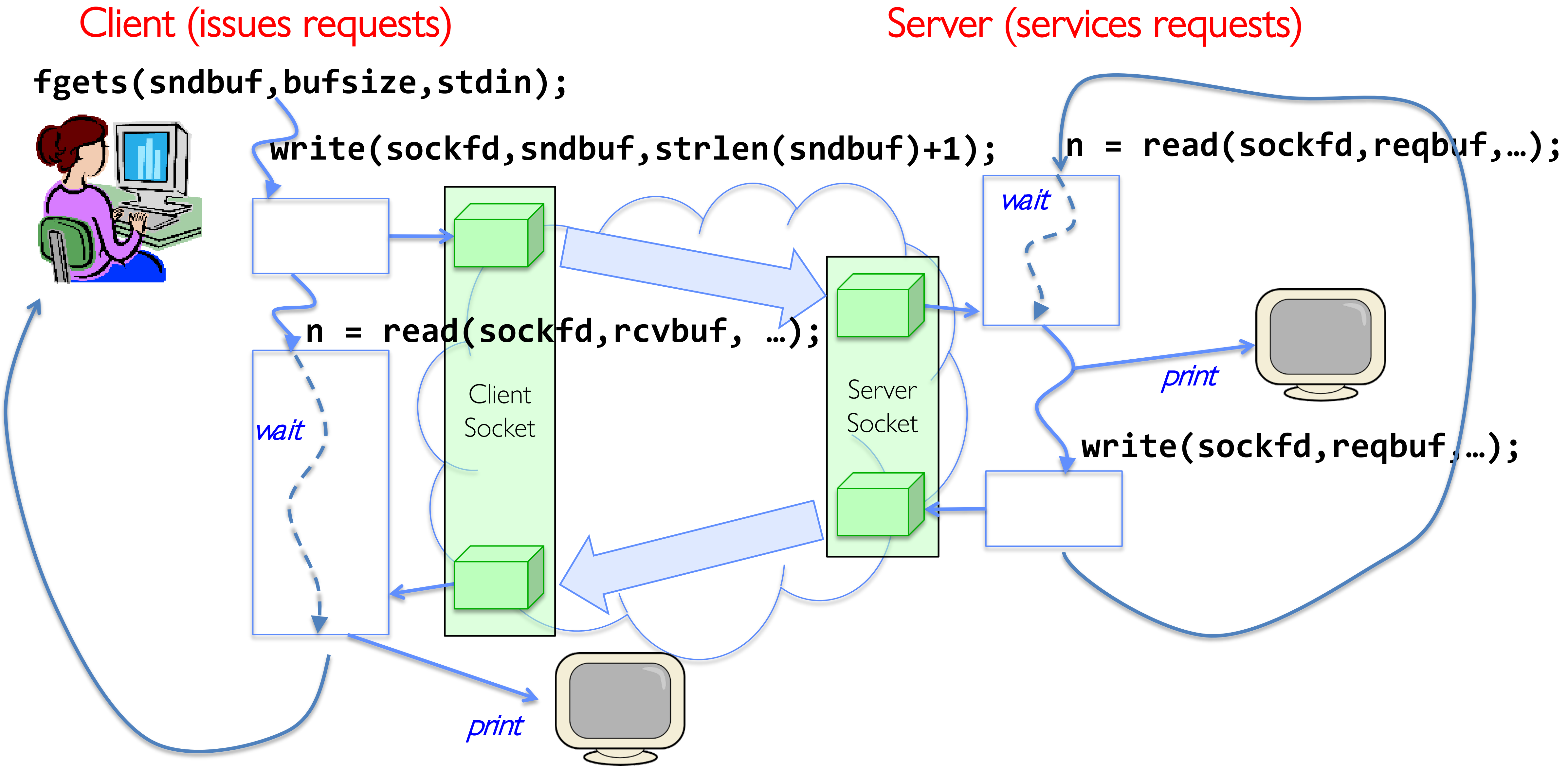
- Looks just like a file with a **file descriptor**
  - Corresponds to a network connection (*two* queues)
  - **`write`** adds to output queue (queue of data destined for other side)
  - **`read`** removes from its input queue (queue of data destined for this side)
  - Some operations do not work, e.g. **`lseek`**

- How can we use sockets to support real applications?
  - A bidirectional byte stream isn't useful on its own…
  - May need messaging facility to partition stream into chunks
  - May need RPC facility to translate one environment to another and provide the abstraction of a function call over the network

Simple Example: Echo Server



Simple Example: Echo Server



Echo client-server example

```
void client(int sockfd) {
  int n;
  char sndbuf[MAXIN]; char rcvbuf[MAXOUT];
  while (1) {
    fgets(sndbuf,MAXIN,stdin);                 /* prompt */
    write(sockfd, sndbuf, strlen(sndbuf)+1); /* send (including null terminator) */
    memset(rcvbuf,0,MAXOUT);                   /* clear */
    n=read(sockfd, rcvbuf, MAXOUT);            /* receive */
    write(STDOUT_FILENO, rcvbuf, n);           /* echo */
}
```

```
void server(int consockfd) {
  char reqbuf[MAXREQ];
  int n;
  while (1) {
    memset(reqbuf,0, MAXREQ);
    len = read(consockfd,reqbuf,MAXREQ); /* Recv */
    if (n <= 0) return;
    write(STDOUT_FILENO, reqbuf, n);
    write(consockfd, reqbuf, n); /* echo*/
  }
}
```

What Assumptions are we Making?

- Reliable
  - Write to a file => Read it back. Nothing is lost.
  - Write to a (TCP) socket => Read from the other side, same.
  - Like pipes
- In order (sequential stream)
  - Write X then write Y => read gets X then read gets Y
- When ready?
  - File read gets whatever is there at the time.
  - Assumes writing already took place
  - Blocks if nothing has arrived yet
  - Like pipes!

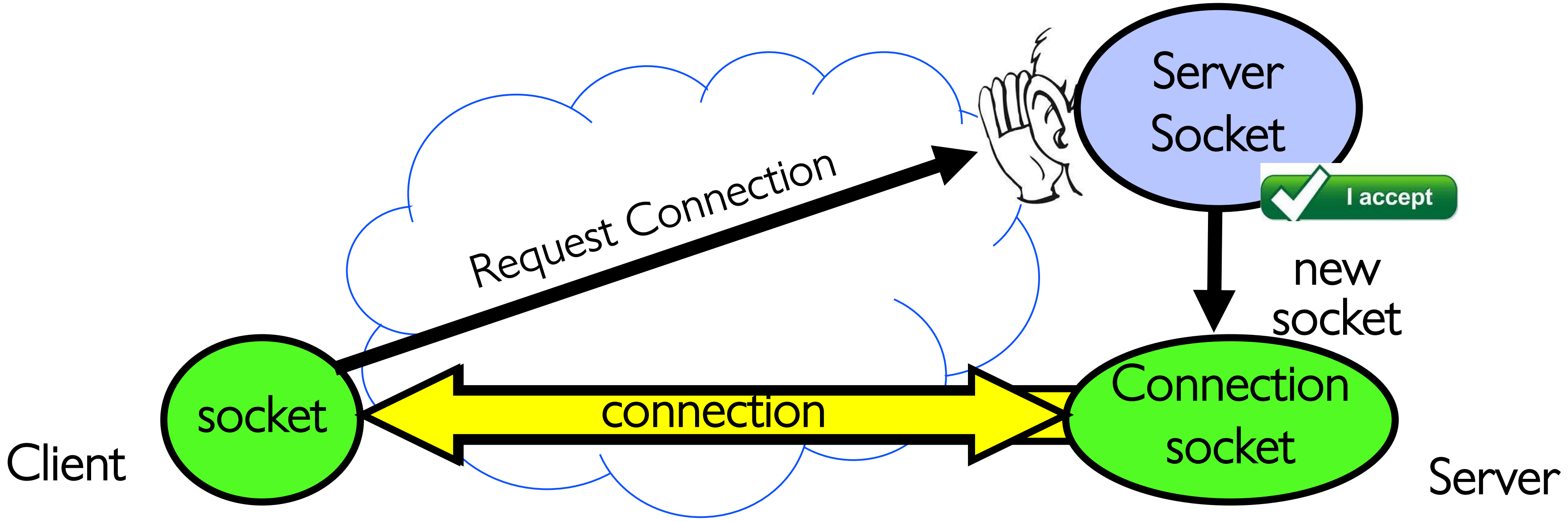
Socket Creation

- File systems provide a collection of permanent objects in a structured name space:
  - Processes open, read/write/close them
  - Files exist independently of processes
  - Easy to name what file to **`open()`**
- Pipes: one-way communication between processes on same (physical) machine
  - Single queue
  - Created transiently by a call to **`pipe()`**
  - Passed from parent to children (descriptors inherited from parent process)
- Sockets: two-way communication between processes on same or different machine
  - Two queues (one in each direction)
  - Processes can be on separate machines: no common ancestor
  - How do we *name* the objects we are **`open`**ing?
  - How do independent programs know that others wants to "talk" to them?

Namespaces for Communication over IP

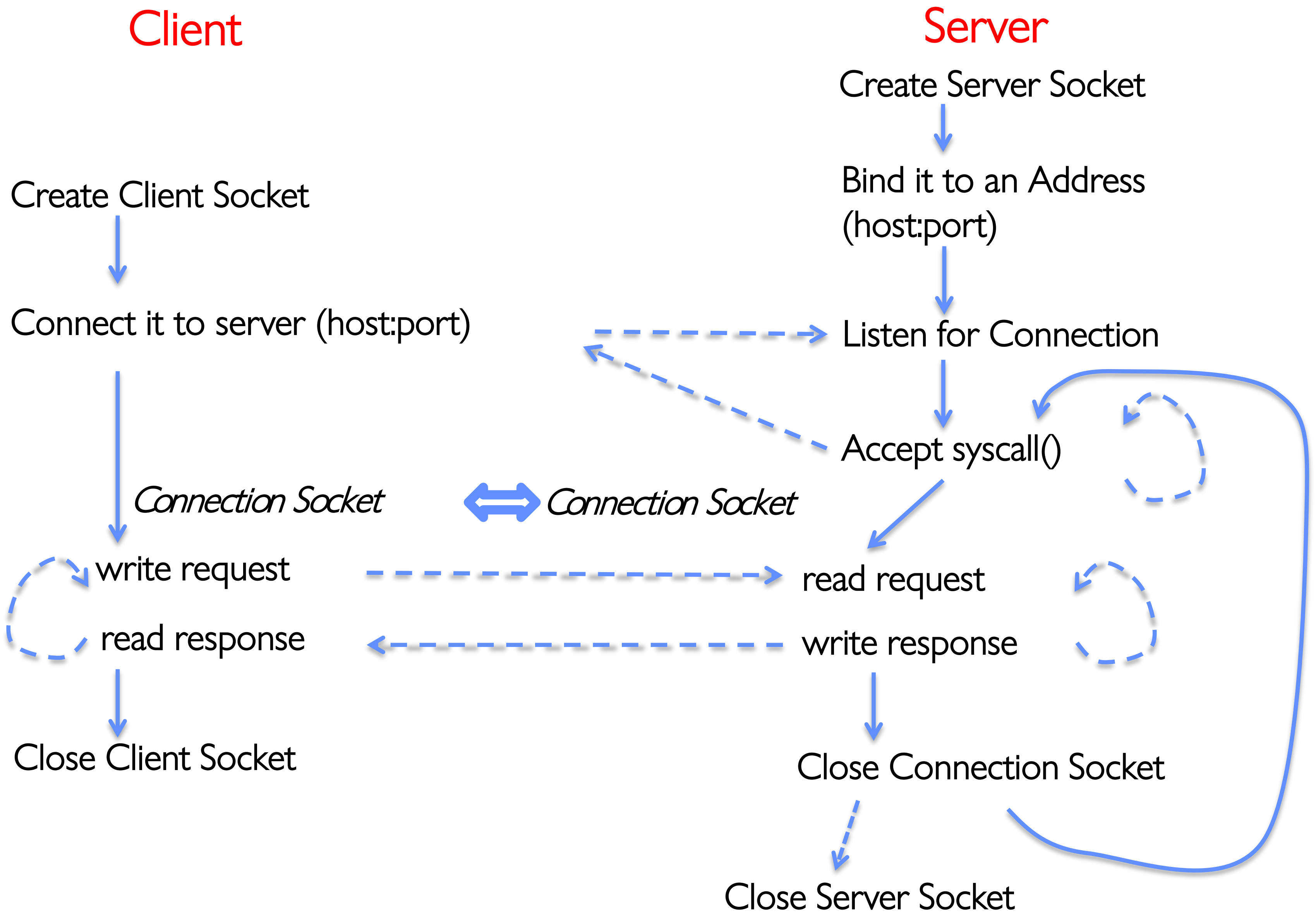
- Hostname
  - www.eecs.berkeley.edu
- IP address
  - 128.32.244.172 (IPv4, 32-bit Integer)
  - 2607:f140:0:81::f (IPv6, 128-bit Integer)
- Port Number
  - 0-1023 are "well known" or "system" ports
    - » Superuser privileges to bind to one
  - 1024 – 49151 are "registered" ports (registry)
    - » Assigned by IANA for specific services
  - 49152–65535 ($2^{15}+2^{14}$ to $2^{16}-1$) are "dynamic" or "private"
    - » Automatically allocated as "ephemeral ports"

Connection Setup over TCP/IP



- Special kind of socket: **server socket**
  - Has file descriptor
  - Can't read or write
- Two operations:
  1. **listen()**: Start allowing clients to connect
  2. **accept()**: Create a *new socket* for a *particular* client

Sockets in concept



Client Protocol

```
char *host_name, *port_name;

// Create a socket
struct addrinfo *server = lookup_host(host_name, port_name);
int sock_fd = socket(server->ai_family, server->ai_socktype,
                     server->ai_protocol);

// Connect to specified host and port
connect(sock_fd, server->ai_addr, server->ai_addrlen);

// Carry out Client-Server protocol
run_client(sock_fd);

/* Clean up on termination */
close(sock_fd);
```

Server Protocol (v1)

```
// Create socket to listen for client connections
char *port_name;
struct addrinfo *server = setup_address(port_name);
int server_socket = socket(server->ai_family,
      server->ai_socktype, server->ai_protocol);
// Bind socket to specific port
bind(server_socket, server->ai_addr, server->ai_addrlen);
// Start listening for new client connections
listen(server_socket, MAX_QUEUE);

while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);
  serve_client(conn_socket);
  close(conn_socket);
}
close(server_socket);
```

What's wrong here?

- Sequential
- Running code from different users in the same process => no protection

- Solution: Handle each connection in a separate process

Server Protocol (v2)

```
// Socket setup code elided…
while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);
  pid_t pid = fork();
  if (pid == 0) {
    close(server_socket);
    serve_client(conn_socket);
    close(conn_socket);
    exit(0);
  } else {
    close(conn_socket);
    wait(NULL);
  }
}
close(server_socket);
```

Concurrent Server

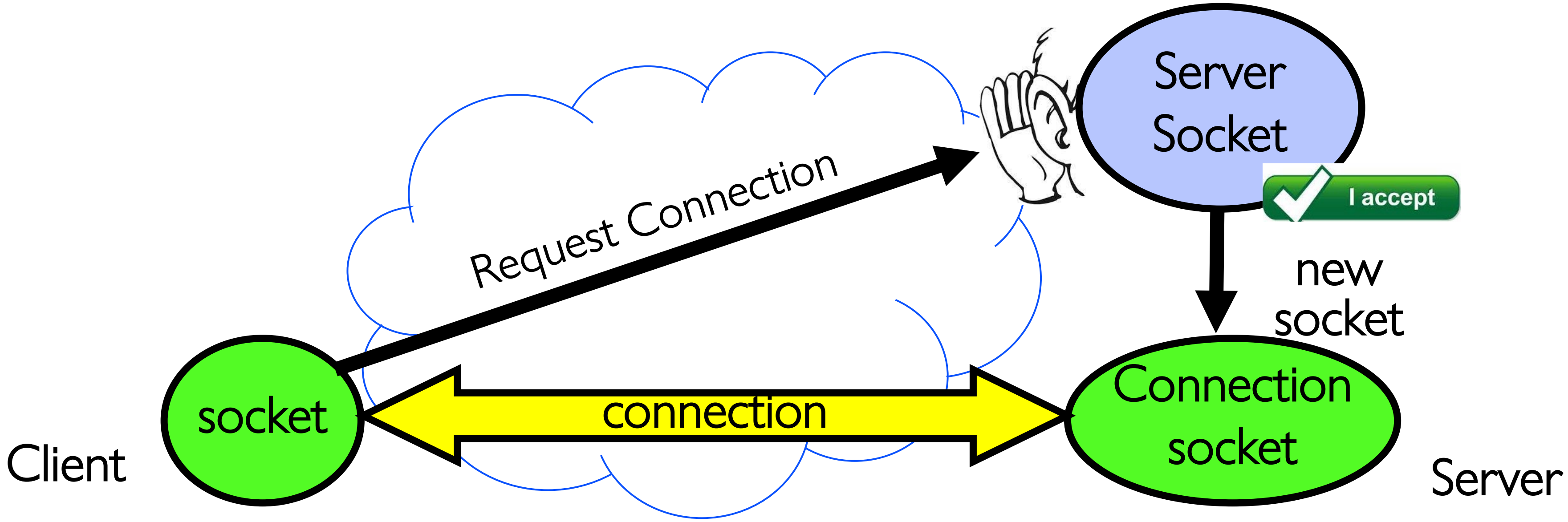
- So far, in the server:
  - Listen will queue requests
  - Buffering present elsewhere
  - But server waits for each connection to terminate before servicing the next

- A concurrent server can handle and service a new connection before the previous client disconnects

Server Protocol (v3)

```
// Socket setup code elided…
while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);
  pid_t pid = fork();
  if (pid == 0) {
    close(server_socket);
    serve_client(conn_socket);
    close(conn_socket);
    exit(0);
  } else {
    close(conn_socket);
    //wait(NULL);
  }
}
close(server_socket);
```

Connection Setup over TCP/IP



- 5-Tuple identifies each connection:
  1. Source IP Address
  2. Destination IP Address
  3. Source Port Number
  4. Destination Port Number
  5. Protocol (always TCP here)
- Often, Client Port "randomly" assigned
  - Done by OS during client socket setup
- Server Port often "well known"
  - 80 (web), 443 (secure web), 25 (sendmail), etc
  - Well-known ports from 0—1023

Concurrent Server without Protection

- Spawn a new thread to handle each connection
- Main thread initiates new client connections without waiting for previously spawned threads
- Why give up the protection of separate processes?
  - More efficient to create new threads
  - More efficient to switch between threads

Thread Pools

- Problem with previous version: Unbounded Threads
  - When web-site becomes too popular – throughput sinks
- Instead, allocate a bounded "pool" of worker threads, representing the maximum level of multiprogramming
- When service a request, use a thread from the pool. If no thread available, queue request

Conclusion

- Interprocess Communication (IPC)
  - Communication facility between protected environments (i.e. processes)

- Pipes are an abstraction of a single queue
  - One end write-only, another end read-only
  - Used for communication between multiple processes on one machine
  - File descriptors obtained via inheritance

- Sockets are an abstraction of two queues, one in each direction
  - Can read or write to either end
  - Used for communication between multiple processes on different machines
  - File descriptors obtained via socket/bind/connect/listen/accept
  - Inheritance of file descriptors on fork() facilitates handling each connection in a separate process

- Both support read/write system calls, just like File I/O