Operating Systems
(Honor Track)

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

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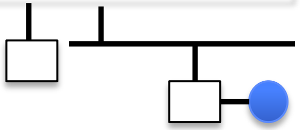
Recap: Key Unix I/O Design Concepts

- 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

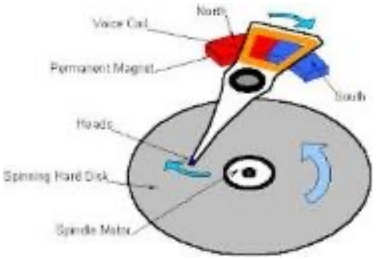
Recap: I/O and Storage Layers

Application / Service

High Level I/O	*Streams*
Low Level I/O	*File Descriptors*
Syscall	*open(), read(), write(), close(), …*
	Open File Descriptions
File System	*Files/Directories/Indexes*
I/O Driver	*Commands and Data Transfers*



Disks, Flash, Controllers, DMA



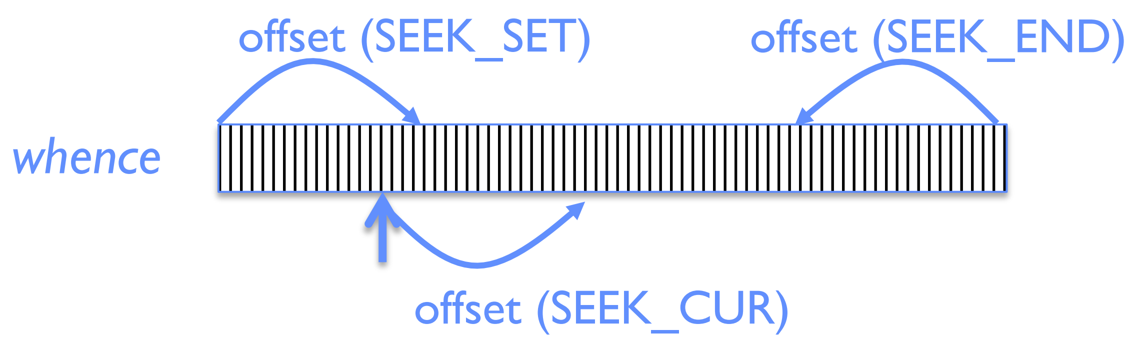
Recap: C High-Level File API

```
// character oriented
int fputc( int c, FILE *fp );               // rtn c or EOF on err
int fputs( const char *s, FILE *fp );       // rtn > 0 or EOF

int fgetc( FILE * fp );
char *fgets( char *buf, int n, FILE *fp );

// block oriented
size_t fread(void *ptr, size_t size_of_elements,
             size_t number_of_elements, FILE *a_file);
size_t fwrite(const void *ptr, size_t size_of_elements,
             size_t number_of_elements, FILE *a_file);

// formatted
int fprintf(FILE *restrict stream, const char *restrict format, ...);
int fscanf(FILE *restrict stream, const char *restrict format, ... );
```

Recap: C High-Level File API: Positioning The Pointer

```
int fseek(FILE *stream, long int offset, int whence); // Reposition stream position indicator
long int ftell (FILE *stream) // Get current position in stream
void rewind (FILE *stream) // Set position of stream to the beginning
```

- For `fseek()`, the `offset` is interpreted based on the `whence` argument (constants in `stdio.h`):
  - `SEEK_SET`: Then offset interpreted from beginning (position 0)
  - `SEEK_END`: Then offset interpreted backwards from end of file
  - `SEEK_CUR`: Then offset interpreted from current position



- Overall preserves high-level abstraction of a uniform stream of objects

Recap: Low-Level File API

- Read data from open file using file descriptor:

```
ssize_t read (int filedes, void *buffer, size_t maxsize)
```

  - Reads up to `maxsize` bytes – **might actually read less!**
  - returns bytes read, 0 => EOF, -1 => error

- Write data to open file using file descriptor

```
ssize_t write (int filedes, const void *buffer, size_t size)
```

  - returns number of bytes written

- Reposition file offset within kernel (this is independent of any position held by high-level FILE descriptor for this file!)

```
off_t lseek (int filedes, off_t offset, int whence)
```

Recap: High-Level vs. Low-Level File API

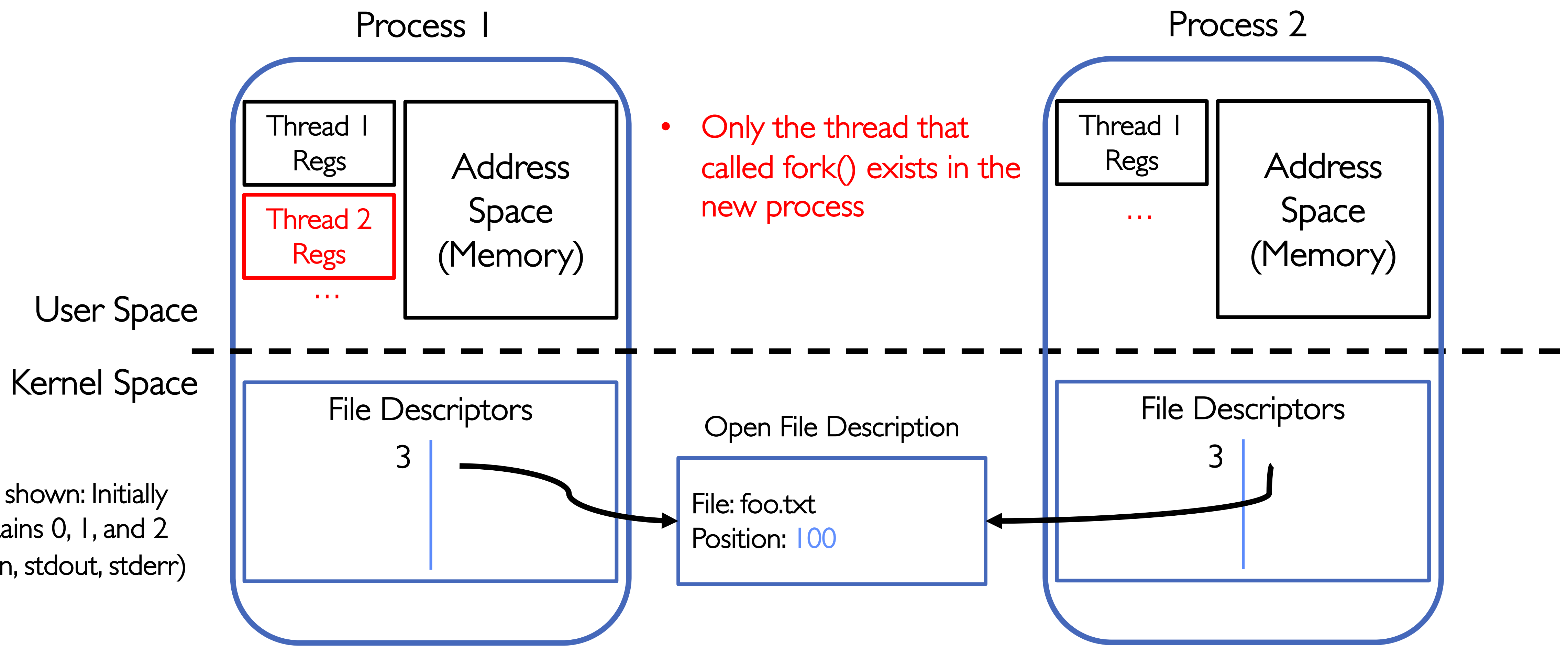
High-Level Operation:

```
size_t fread(…) {
  Do some work like a normal fn…

  asm code … syscall # into %eax
  put args into registers %ebx, …
  special trap instruction
      Kernel:
        get args from regs
        dispatch to system func
        Do the work to read from the file
        Store return value in %eax
  get return values from regs
  Do some more work like a normal fn…
};
```

Low-Level Operation:

```
ssize_t read(…) {

  asm code … syscall # into %eax
  put args into registers %ebx, …
  special trap instruction
      Kernel:
        get args from regs
        dispatch to system func
        Do the work to read from the file
        Store return value in %eax
  get return values from regs

};
```

Recap: `fork()` in a Multithreaded Processes



- Only the thread that called fork() exists in the new process

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

Recap: Avoid Mixing FILE* and File Descriptors

```
char x[10];
char y[10];
FILE* f = fopen(“foo.txt”, “rb”);
int fd = fileno(f);
fread(x, 10, 1, f); // read 10 bytes from f
read(fd, y, 10); // assumes that this returns data starting at offset 10
```

- Which bytes from the file are read into y?
  A. Bytes 0 to 9
  B. Bytes 10 to 19
  C. None of these?
- Answer: C! None of the above.
  - The `fread()` reads a big chunk of file into user-level buffer
  - Might be all of the file!

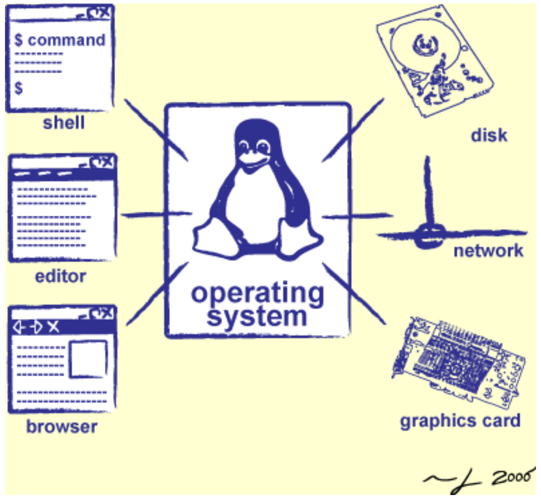
Group Discussion

- Topic: High-level vs. low-level File API
  - What are the differences between high-level and low-level file APIs?
  - What are the pros and cons of high-level and low-level file APIs?
  - When to use high-level file API? When to use low-level file API?
  - How are you going to design file API?

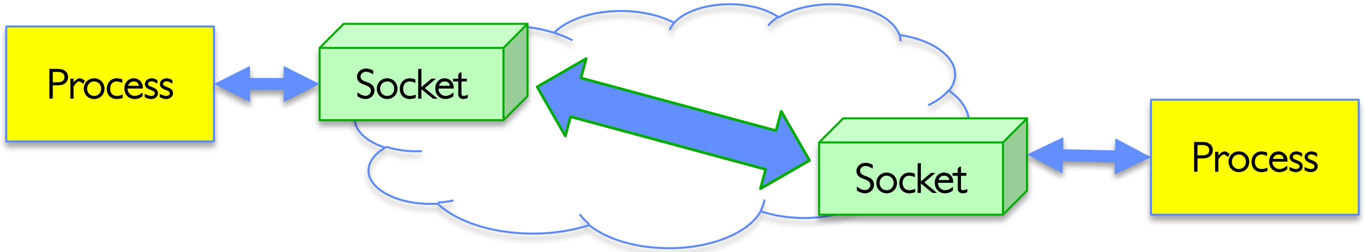
- Discuss in groups of two to three students
  - Each group chooses a leader to summarize the discussion
  - In your group discussion, please do not dominate the discussion, and give everyone a chance to speak

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);
```

Communication Between Processes

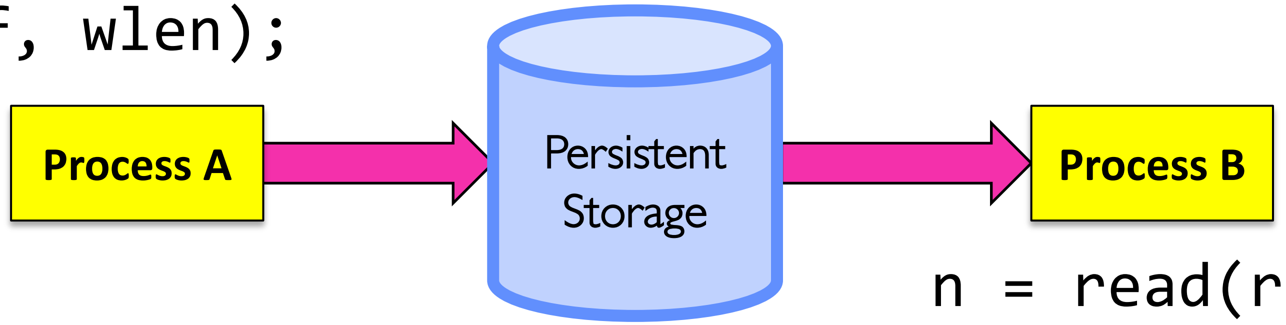
- What if processes wish to communicate with one another?
  - Why? Shared Task, Cooperative Venture with Security Implications
- Process Abstraction Designed to Discourage Inter-Process Communication!
  - Prevent one process from interfering with/stealing information from another
- So, must do something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

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);
```



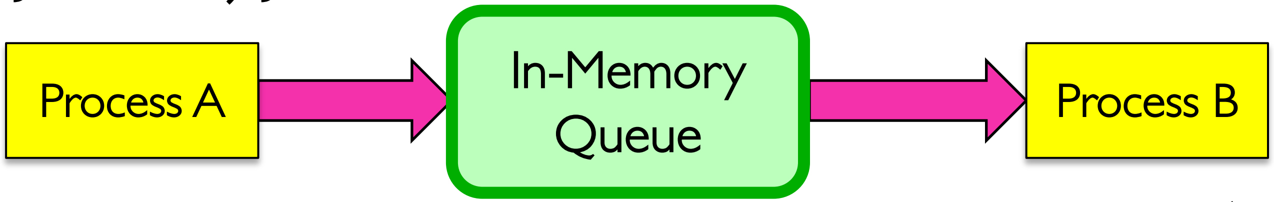

```
n = read(rfd, rbuf, rmax);
```

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

Communication Between Processes

- 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)

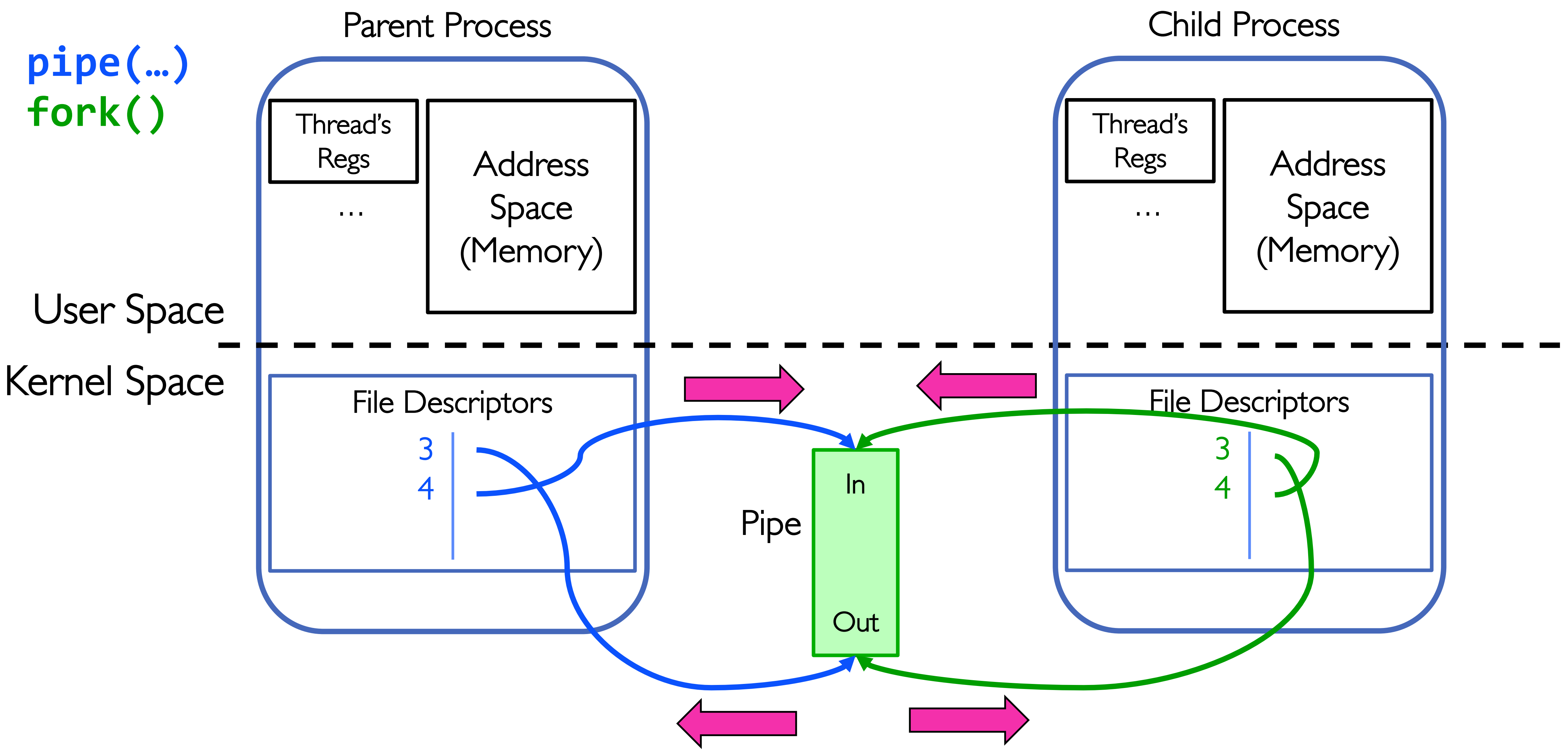
```
int pipe(int fileds[2]);
```

- 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", buf, readlen);

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

Pipes *Between* Processes

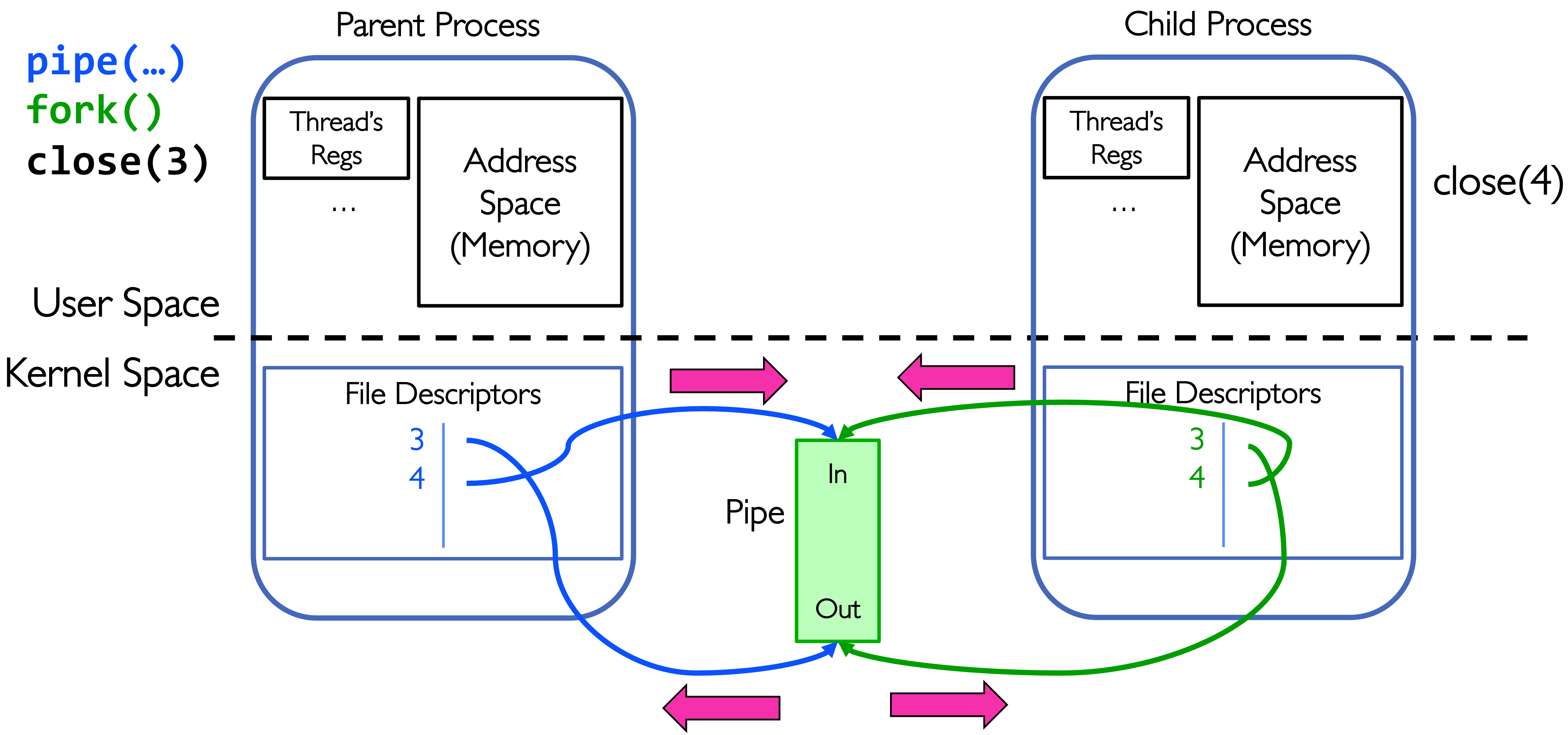


Inter-Process Communication (IPC): Parent ⇒ Child

```c
// 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", buf, readlen);
  close(pipe_fd[1]);
}
```

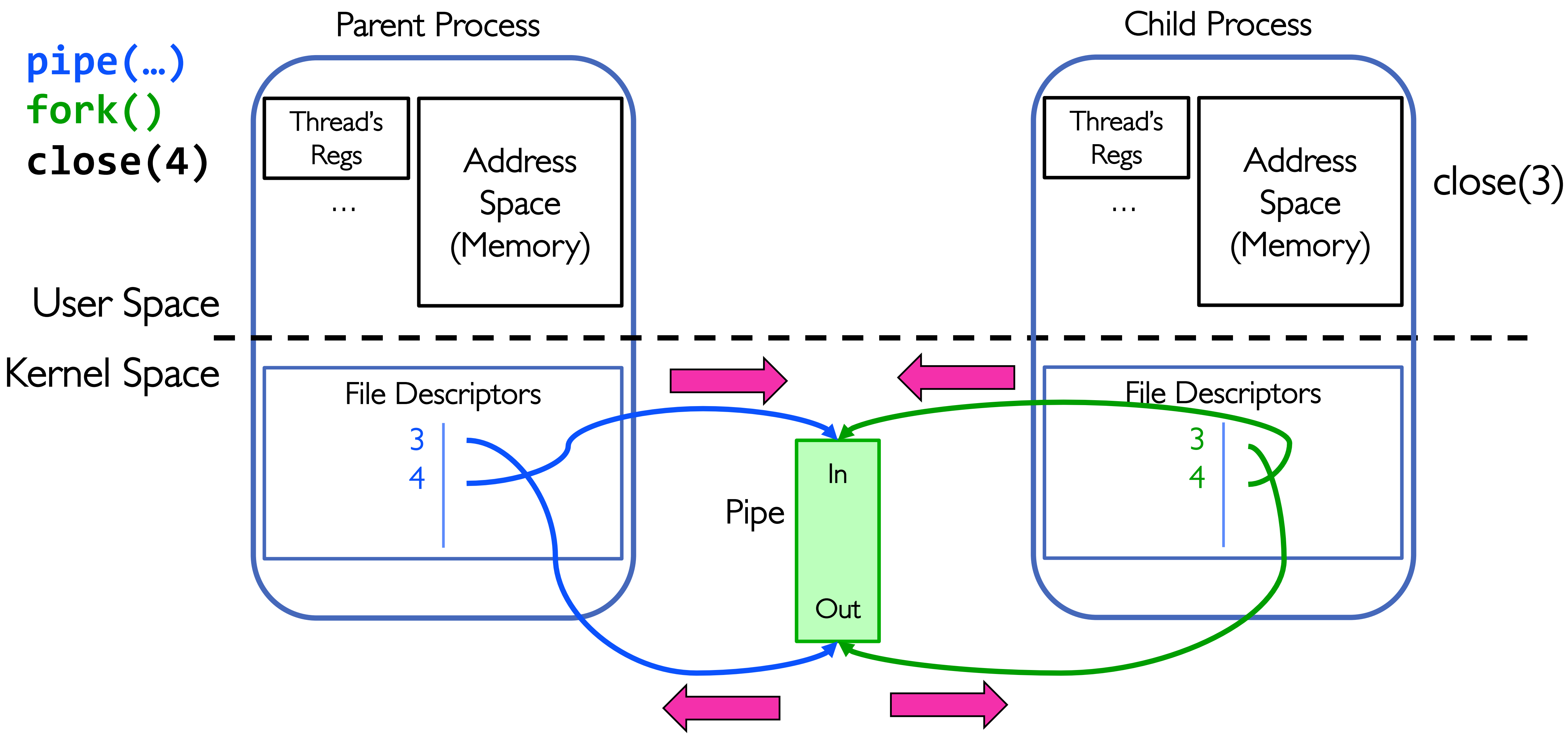
Channel from Parent ⇒ Child

`pipe(…)`
`fork()`
`close(3)`



Instead: Channel from Child ⇒ Parent

```
pipe(…)
fork()
close(4)
```

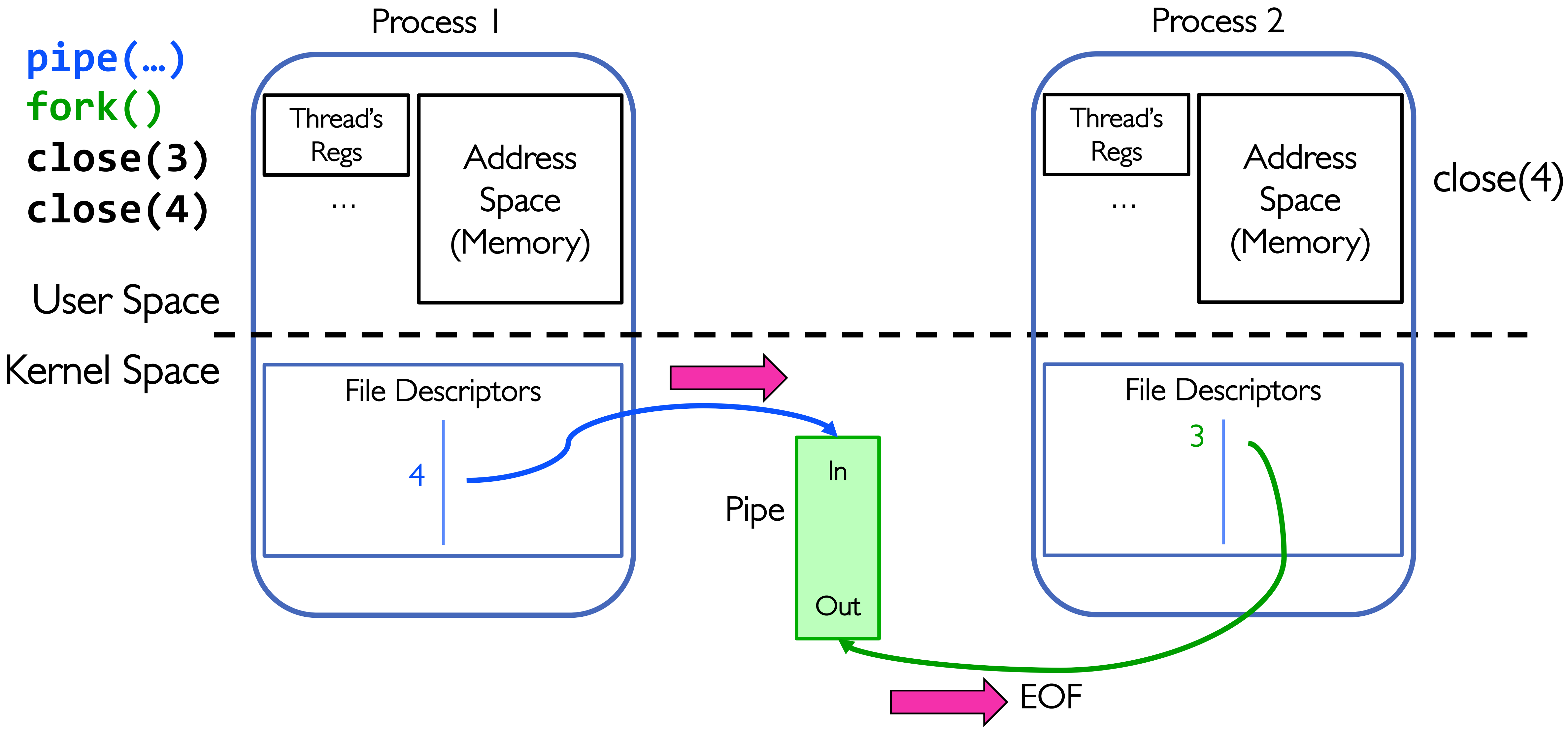


When do we get EOF on a pipe?

- 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)
```



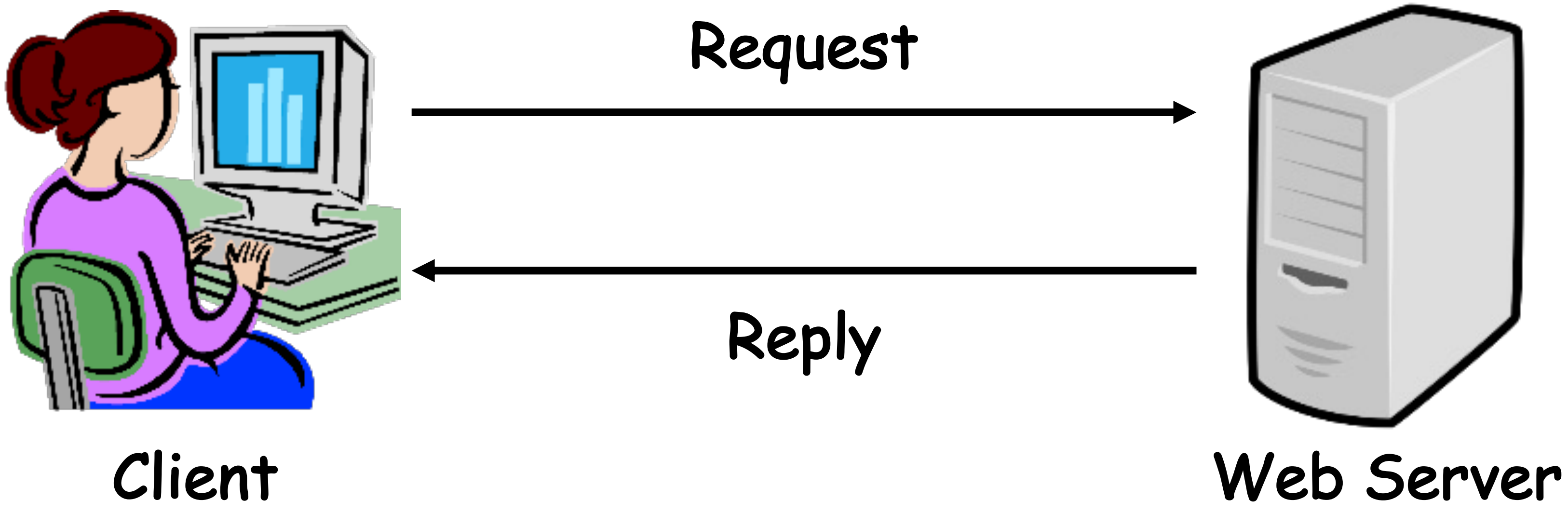
Once we have communication, we need a *protocol*

- 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
- In fact, across network may need a way to translate between different representations for numbers, strings, etc.
  - Such translation typically part of a Remote Procedure Call (RPC) facility
  - Don't worry about this now, but it is clearly part of the *protocol*

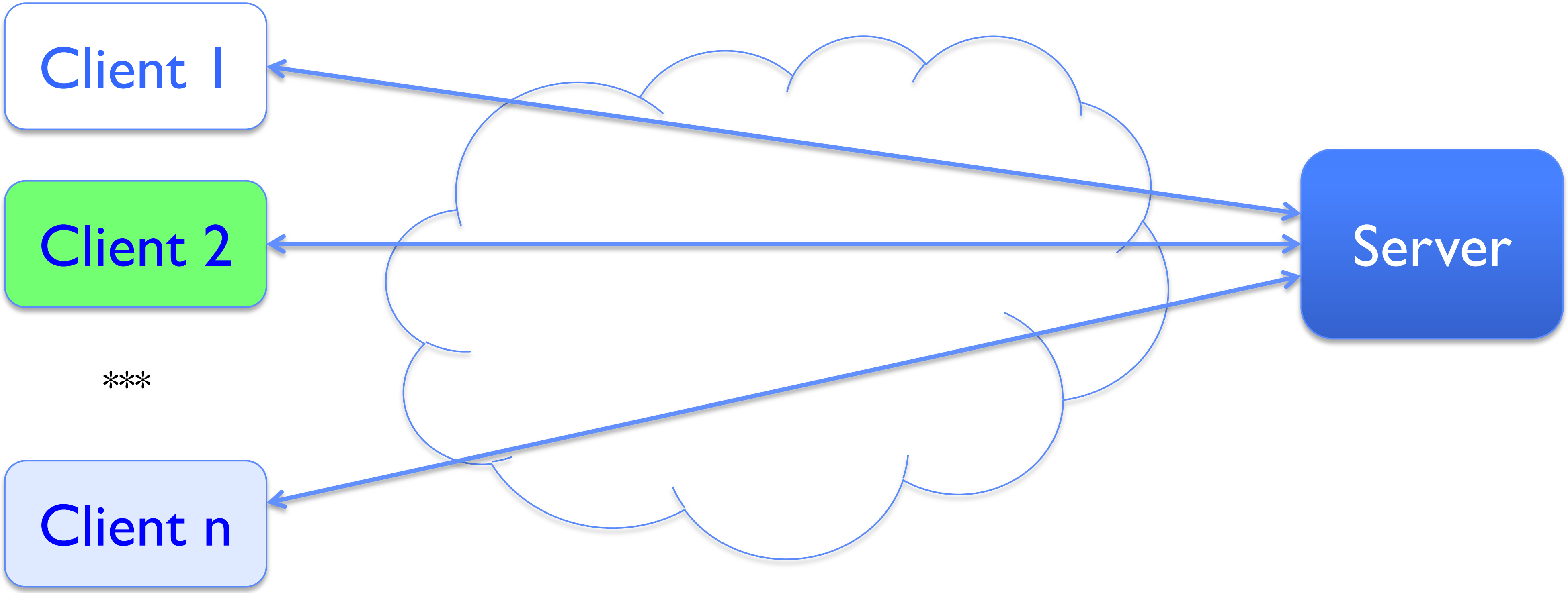
Examples of Protocols in Human Interaction

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 John….”
   Or: “Hi, it’s me” (what’s that about?)
8. Caller: “Hey, do you think … blah blah blah …” pause
9. Callee: “Yeah, blah blah blah …” **pause**
10. Caller: Bye
11. Callee: Bye
12. Hang up

Web Server



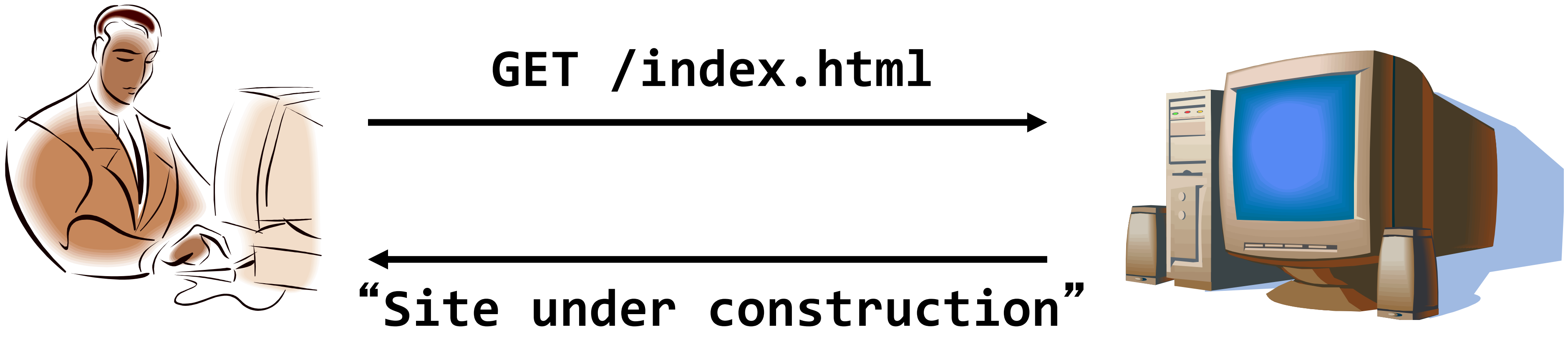
Client-Server Protocols: Cross-Network IPC



- 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.pku.edu.cn`
  - Doesn’t initiate contact with clients
  - Needs a fixed, well-known address



What is a Network Connection?

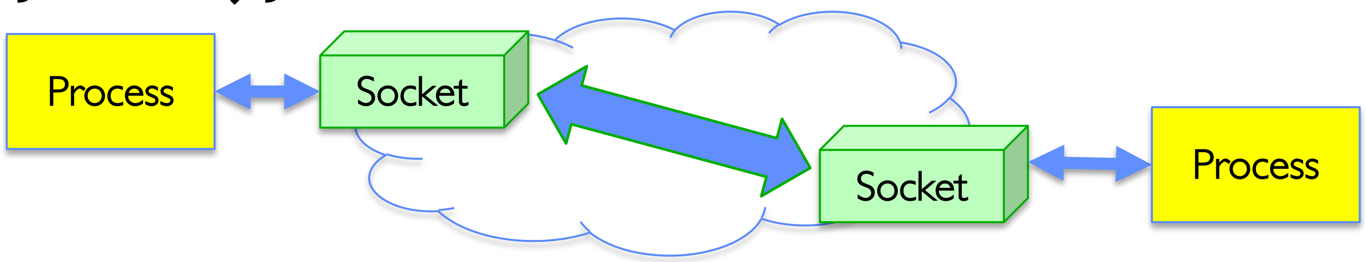
- Bidirectional *stream* of bytes between two processes on possibly different machines
  - For now, we are discussing "TCP Connections"

- 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 ⇒ IPC over network!
  - How to **open()**?
  - What is the namespace?
  - How are they connected in time?

Sockets: More Details

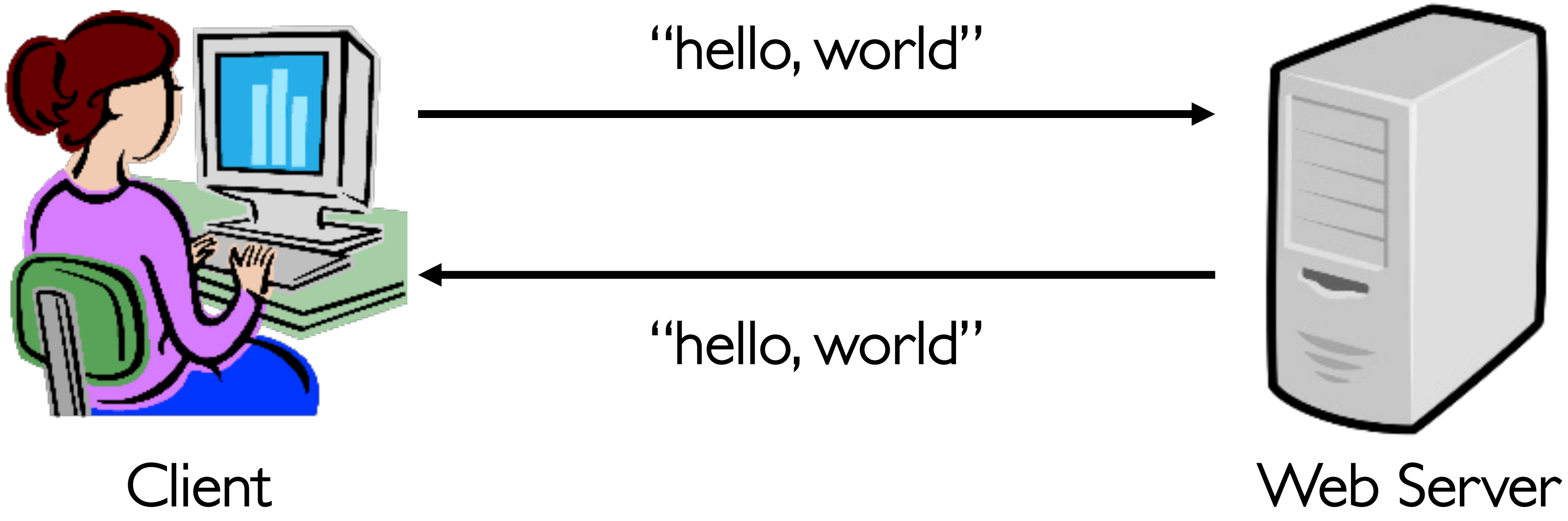
- **Socket:** An abstraction for one endpoint of a network connection
  - Another mechanism for **inter-process communication**
  - Most operating systems (Linux, Mac OS X, Windows) provide this, even if they don't copy rest of UNIX I/O
  - Standardized by POSIX
- First introduced in 4.2 BSD (Berkeley Software/Standard Distribution) Unix
- 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

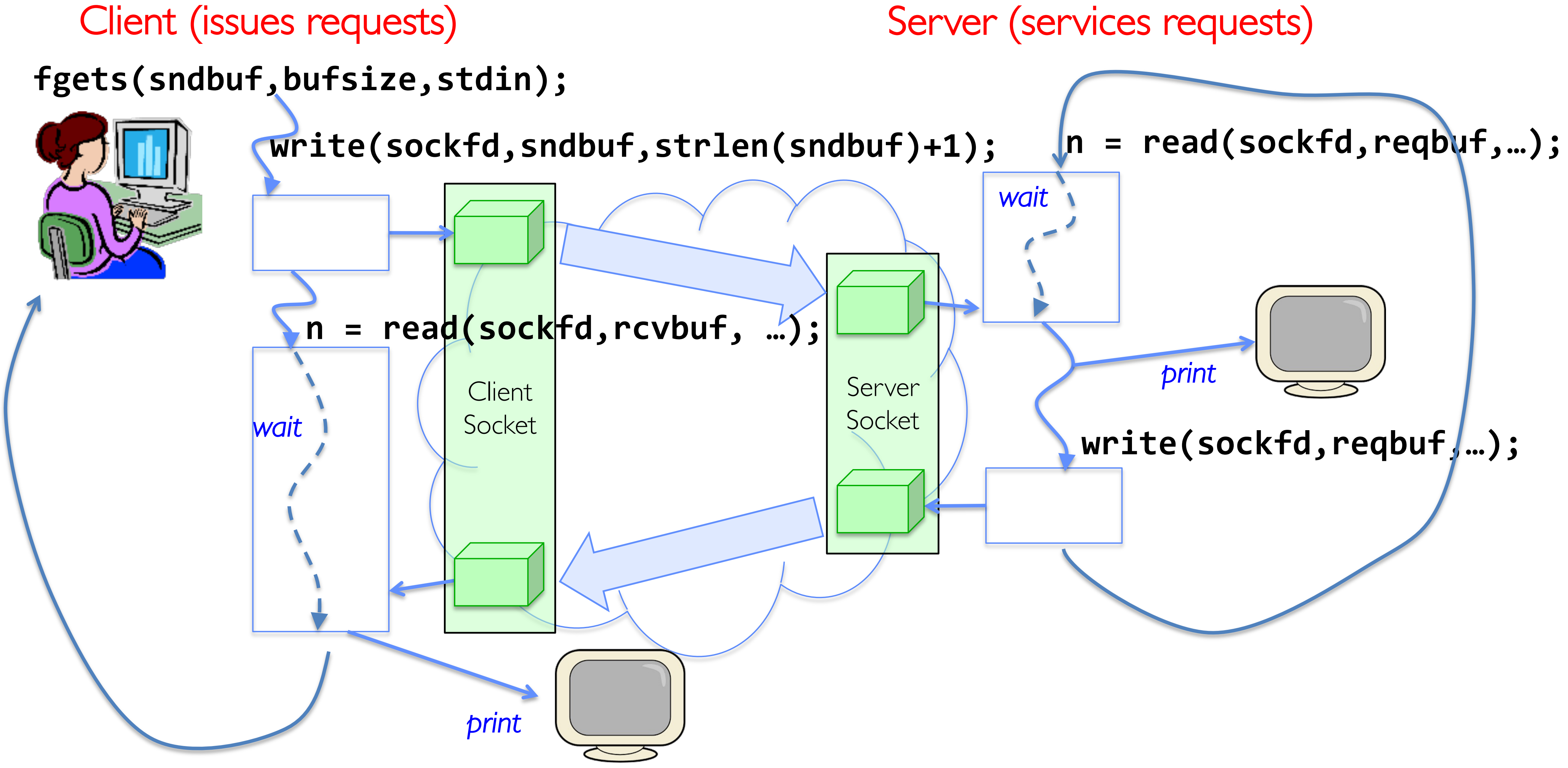
- Looks just like a file with a **file descriptor**
  - Corresponds to a network connection (*two* queues)
  - **`write`** adds to output queue (queue of data destined for other side)
  - **`read`** removes from input queue (queue of data destined for this side)
  - Some operations do not work, e.g.,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

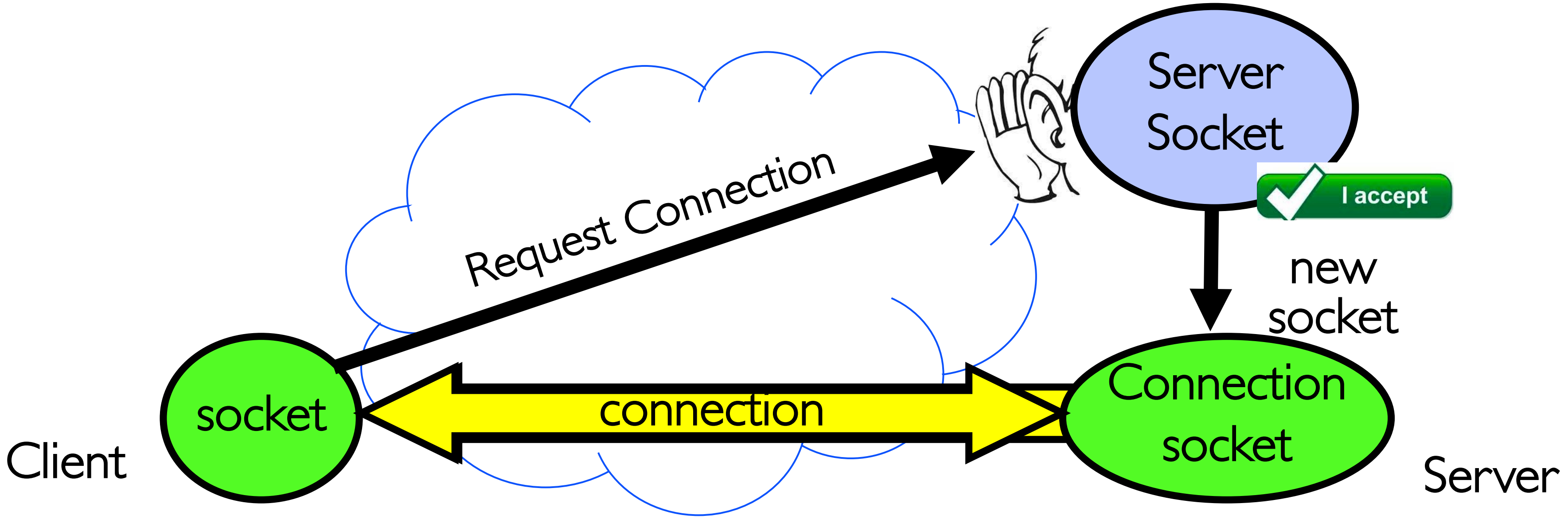
Socket Creation

- 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 opening?
  - How do these completely independent programs know that the other wants to "talk" to them?

Namespaces for Communication over IP

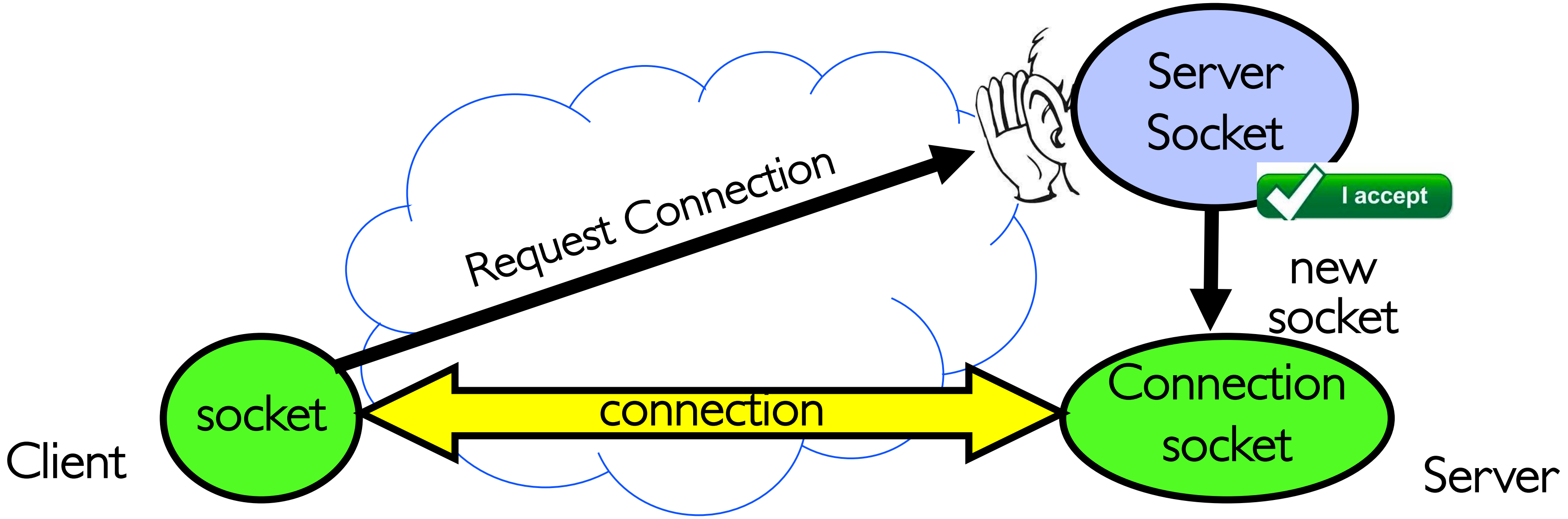
- Hostname
  - www.pku.edu.cn
- IP address
  - 128.32.244.172 (IPv4, 32-bit Integer)
  - 2607:f140:0:81:e:f (IPv6, 128-bit Integer)
- Port Number
  - 0-1023 are "well known" or "system" ports
    - » Superuser privileges to bind to one
  - 1024 – 49151 are "registered" ports (registry)
    - » Assigned 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

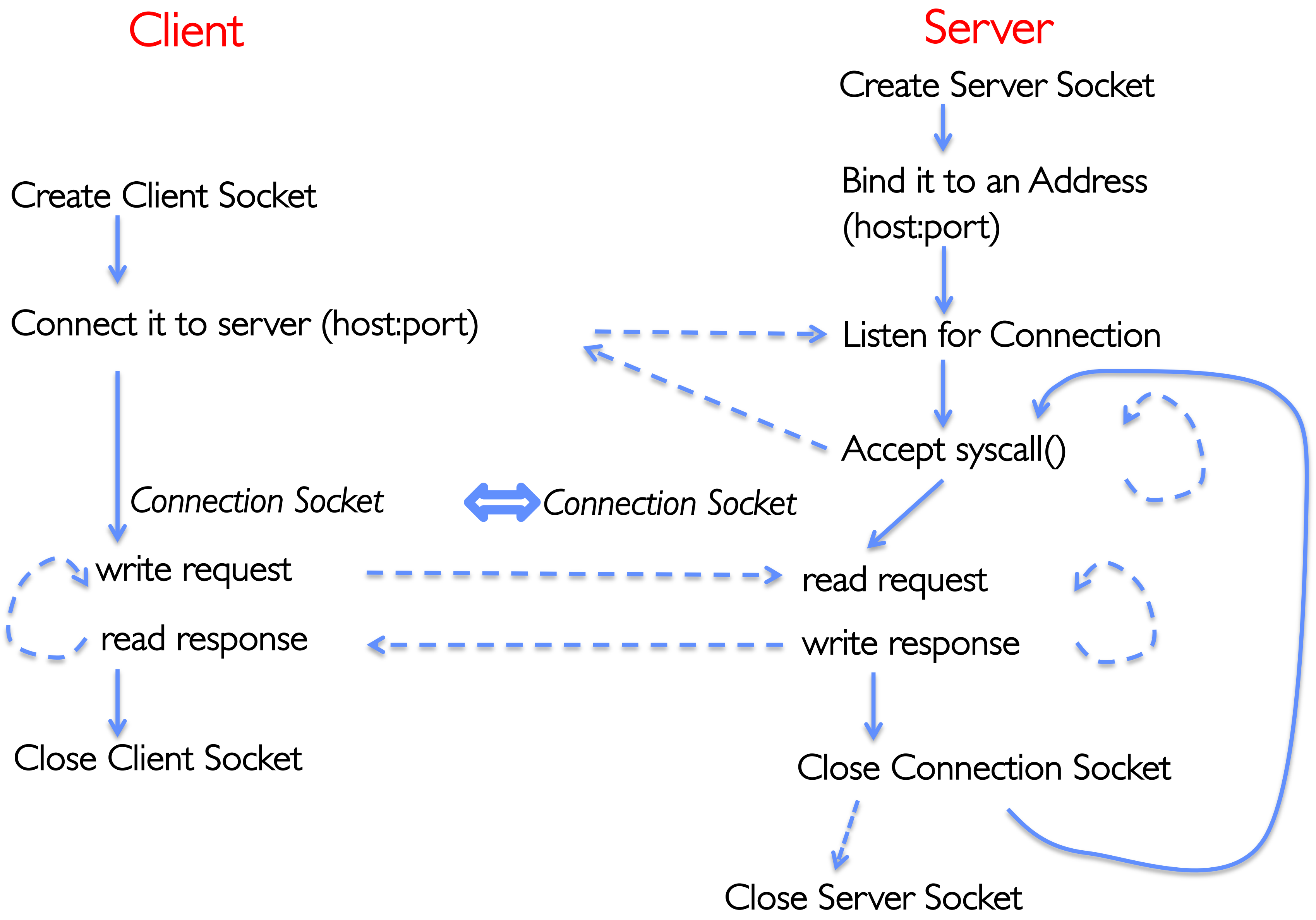
Connection Setup over TCP/IP



- 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

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);
```

Address family, e.g.,
- AF_INET (IPv4)
- AF_INET6 (IPv6)

Socket type, e.g.,
- SOCK_STEAM
- SOCK_DGRAM

Protocol type, e.g.,
- IPPROTO_TC
- 0 (any protocol)

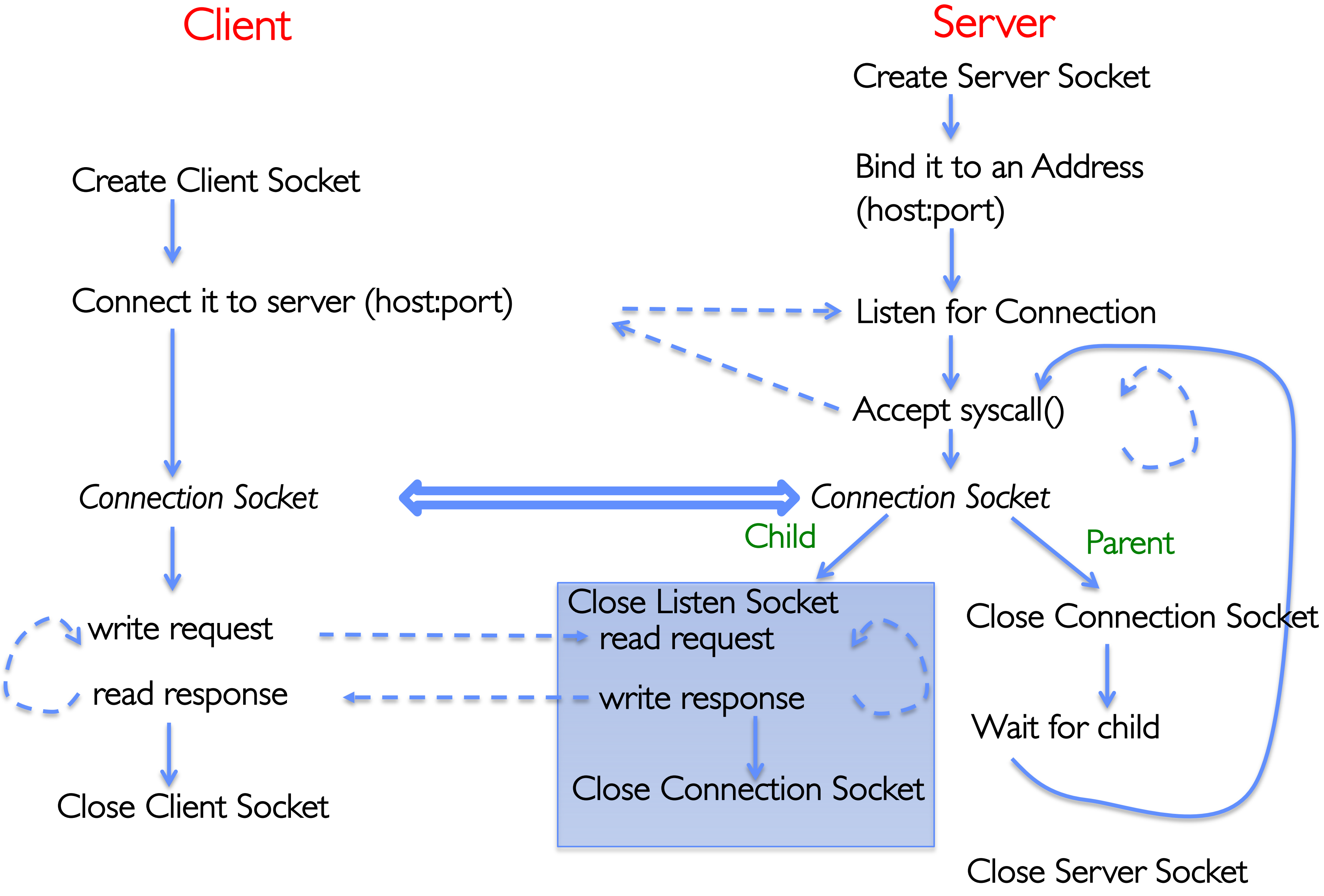
Server Protocol (v1)

```
// 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);
```

How Could the Server Protect Itself?

- Handle each connection in a separate process

Sockets With Protection (each connection has own process)



Server Protocol (v2)

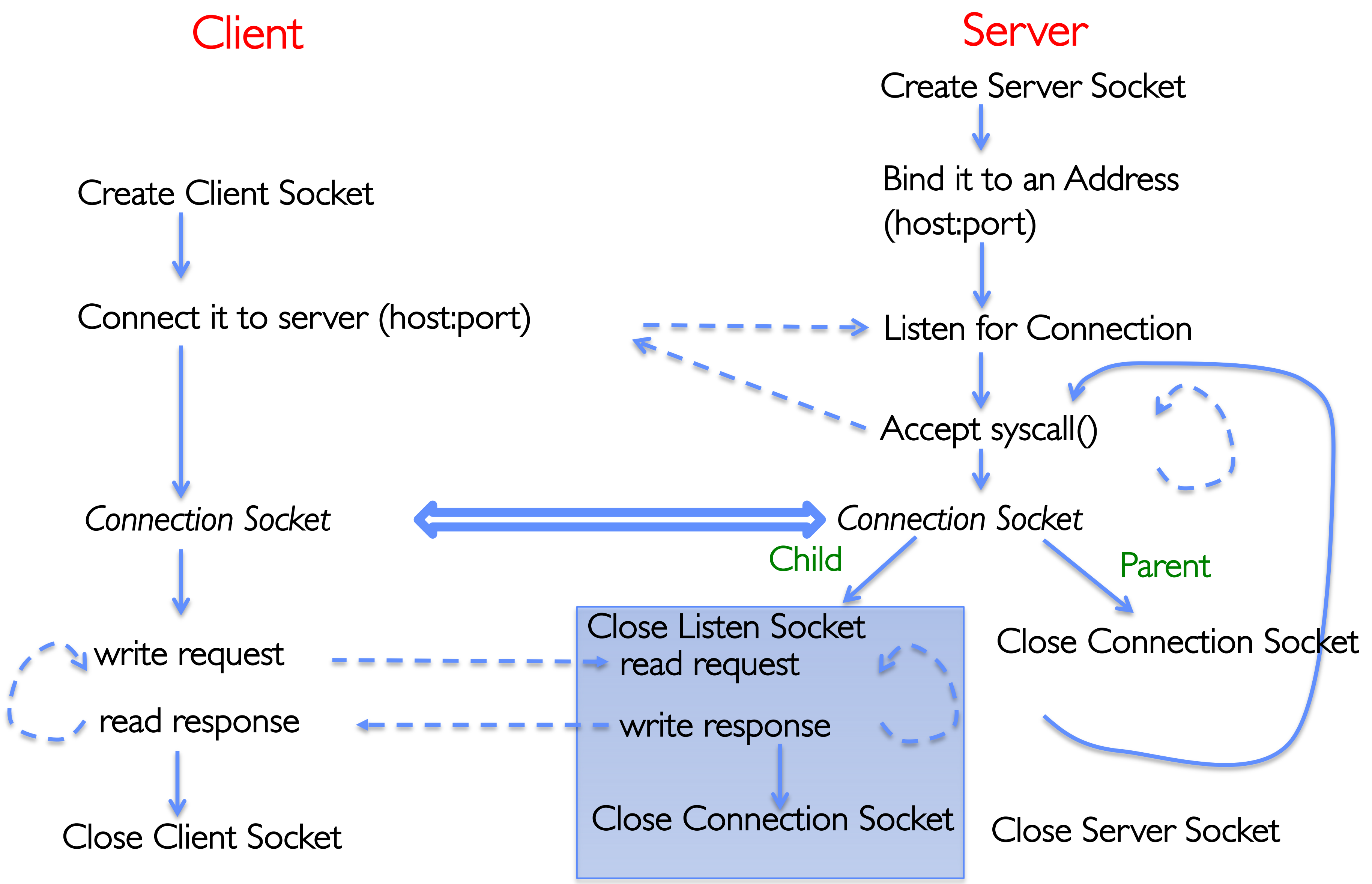
```
// Socket setup code elided…
while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);
  pid_t pid = fork();
  if (pid == 0) {
    close(server_socket);
    serve_client(conn_socket);
    close(conn_socket);
    exit(0);
  } else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

Sockets With Protection and Concurrency



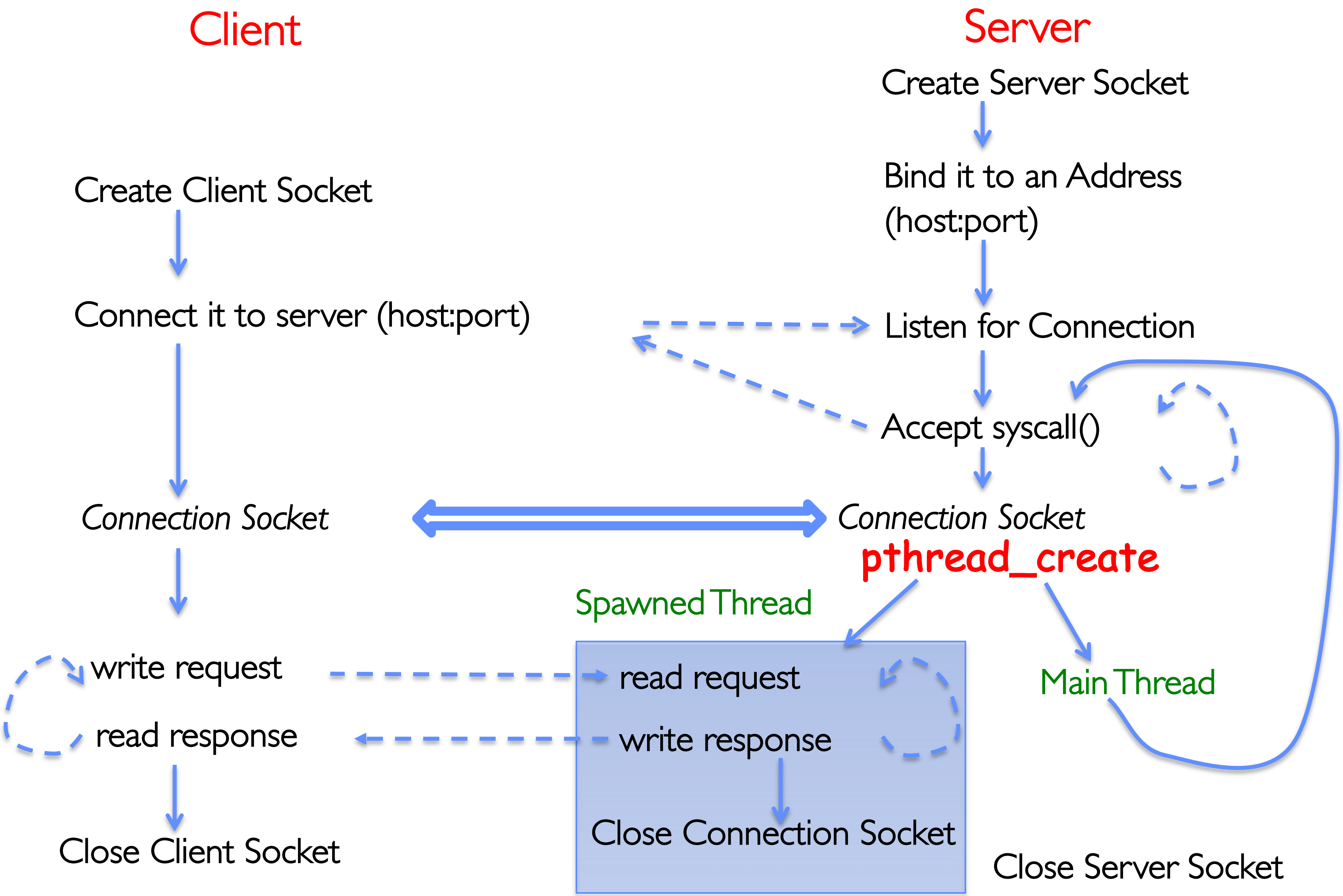
Server Protocol (v3)

```
// 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);
```

Concurrent Server without Protection

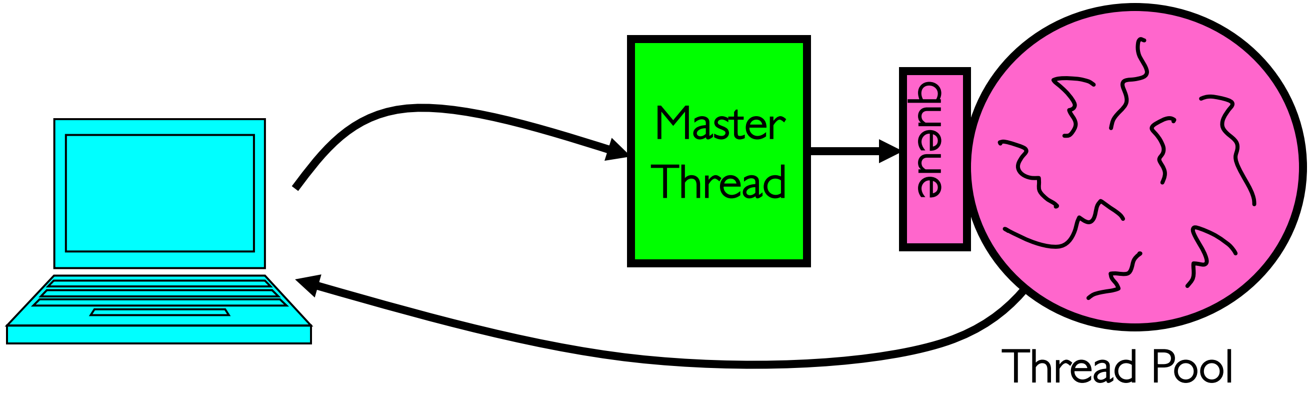
- Spawn a new thread to handle each connection
- Main thread initiates new client connections without waiting for previously spawned threads
- Why give up the protection of separate processes?
  - More efficient to create new threads
  - More efficient to switch between threads

Sockets with Concurrency, without Protection



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




```
master() {
   allocThreads(worker,queue);
   while(TRUE) {
      con=AcceptCon();
      Enqueue(queue,con);
      wakeUp(queue);
   }
}
```

```
worker(queue) {
   while(TRUE) {
      con=Dequeue(queue);
      if (con==null)
         sleepOn(queue);
      else
         ServiceWebPage(con);
   }
}
```

Summary

- 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