CS162
Operating Systems and
Systems Programming
Lecture 5

Device Drivers, Sockets and IPC (Finished)
Concurrency: Processes and Threads

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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)
```

Bit vector of:

- **Access modes (Rd, Wr, …)**
- **Open Flags (Create, …)**
- **Operating modes (Appends, …)**

Bit vector of Permission Bits:

- **User|Group|Other X R|W|X**

- Integer return from `open()` is a *file descriptor*
  - *Error indicated by return < 0:* the global `errno` variable set with error (see man pages)
- Operations on *file descriptors*:
  - Open system call created an *open file description* entry in system-wide table of open files
  - *Open file description* object in the kernel represents an instance of an open file
  - Why give user an integer instead of a pointer to the file description in kernel?

Recall: Example: lowio.c

```
int main() {
  char buf[1000];

  int     fd = open("lowio.c", O_RDONLY, S_IRUSR | S_IWUSR);
  if (fd < 0) {
     /* Error!  errno variable contains specification of which error */
     exit(1);
  }

  ssize_t rd = read(fd, buf, sizeof(buf));
  if (fd < 0) {
     /* Error!  errno variable contains specification of which error */
     exit(1);
  }

  int    err = close(fd);
  /* check for errors */

  ssize_t wr = write(STDOUT_FILENO, buf, rd);
  /* check for errors */
}
```

- How many bytes does this program read?

Low-Level I/O: Other Operations

- Operations specific to terminals, devices, networking, …
  - e.g., `ioctl`
- Duplicating descriptors
  - `int dup2(int old, int new);`
  - `int dup(int old);`
- Pipes – channel
  - `int pipe(int pipefd[2]);`
  - `Writes to pipefd[1] can be read from pipefd[0]`
- File Locking
- Memory-Mapping Files
- Asynchronous I/O

POSIX I/O: Design Patterns

- Open before use
  - Access control check, setup happens here
- Byte-oriented
  - Least common denominator
  - OS responsible for hiding the fact that real devices may not work this way (e.g. hard drive stores data in blocks)
- Explicit close

POSIX I/O: Kernel Buffering

- Reads are buffered inside kernel
  - – Part of making everything byte-oriented
  - – Process is **blocked** while waiting for device
  - – Let other processes run while gathering result
- Writes are buffered inside kernel
  - – Complete in background (more later on)
  - – Return to user when data is “handed off” to kernel

- This buffering is part of global buffer management and caching for block devices (such as disks)
  - – Items typically cached in quanta of disk block sizes
  - – We will have many interesting things to say about this buffering when we dive into the kernel

Low-Level vs High-Level file API

- Low-level direct use of syscall interface: `open(), read(), write(), close()`
- Opening of file returns file descriptor:

  `int myfile = open(…);`
- File descriptor only meaningful to kernel
  - Index into process (PDB) which holds pointers to kernel-level structure ("file description") describing file.
- Every `read()` or `write()` causes syscall no matter how small (could read a single byte)
- Consider loop to get 4 bytes at a time using `read()`:
  - Each iteration enters kernel for 4 bytes.

- High-level buffered access: `fopen(), fread(), fwrite(), fclose()`
- Opening of file returns ptr to FILE:

  `FILE *myfile = fopen(…);`
- FILE structure is user space contains:
  - a chunk of memory for a buffer
  - the file descriptor for the file (`fopen()` will call `open()` automatically)
- Every `fread()` or `fwrite()` filters through buffer and may not call `read()` or `write()` on every call.
- Consider loop to get 4 bytes at a time using `fread()`:
  - First call to `fread()` calls `read()` for block of bytes (say 1024). Puts in buffer and returns first 4 to user.
  - Subsequent `fread()` grab bytes from buffer

Low-Level vs. High-Level File API

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

  Return data to caller

};
```

High-Level Operation:

```
ssize_t fread(…) {
  Check buffer for contents
  Return data to caller if available
    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
  Update buffer with excess data
  Return data to caller
};
```

High-Level vs. Low-Level File API

- Streams are buffered in user memory:

```
printf("Beginning of line ");
sleep(10); // sleep for 10 seconds
printf("and end of line\n");
```

Prints out everything at once

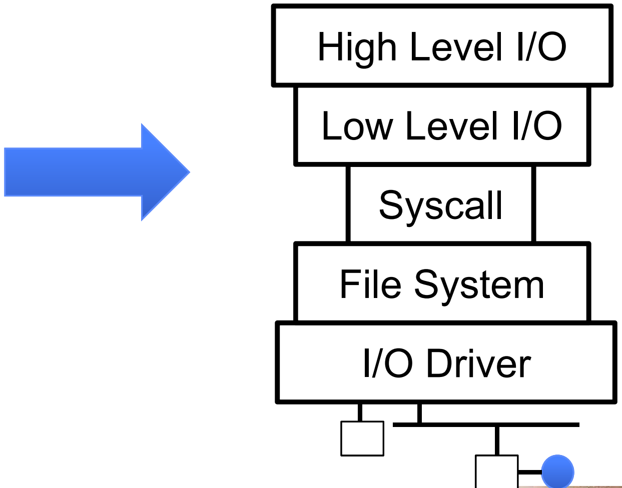
- Operations on file descriptors are visible immediately

```
write(STDOUT_FILENO, "Beginning of line ", 18);
sleep(10);
write("and end of line \n", 16);
```

Outputs "Beginning of line" 10 seconds earlier than “and end of line”

What’s below the surface ??

Application / Service



High Level I/O — streams

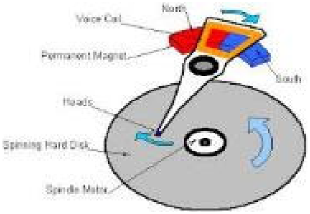
Low Level I/O — handles

Syscall — registers

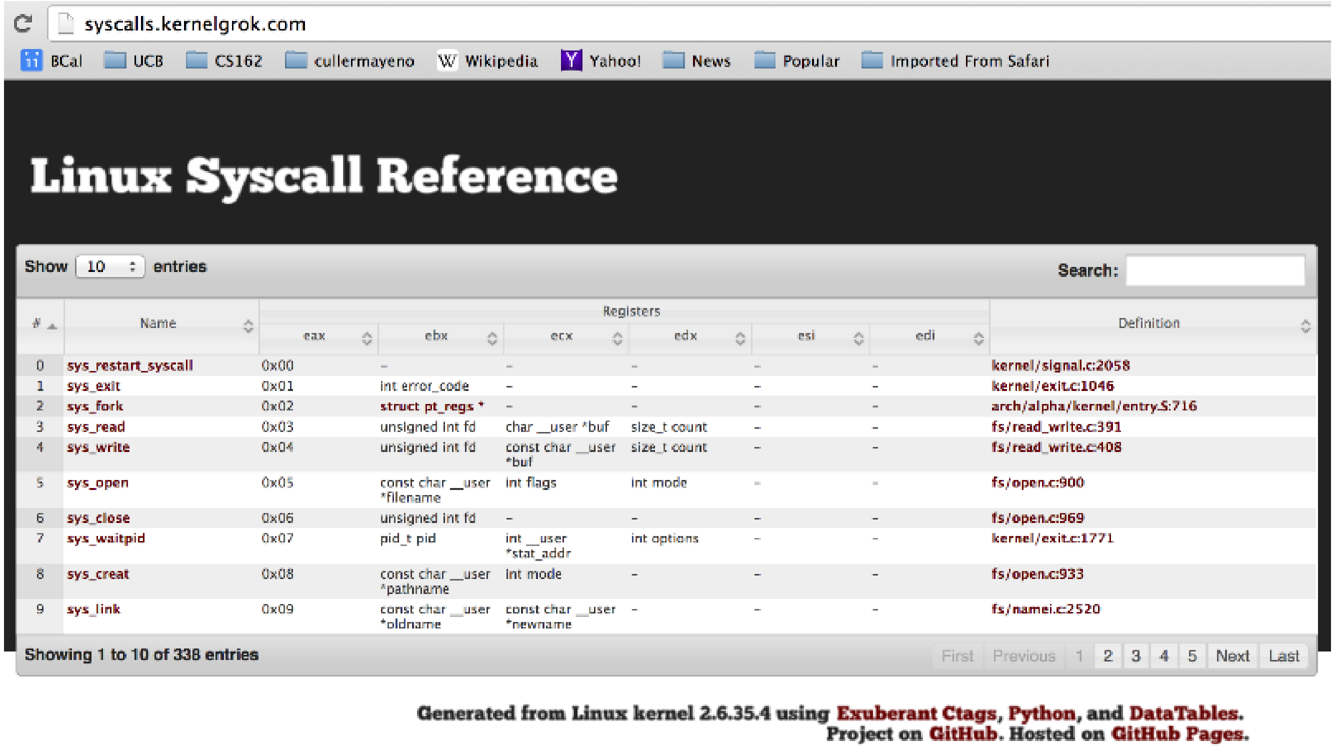
File System — descriptions

I/O Driver — Commands and Data Transfers

Disks, Flash, Controllers, DMA



Recall: SYSCALL



Linux Syscall Reference

Show 10 entries

Search:

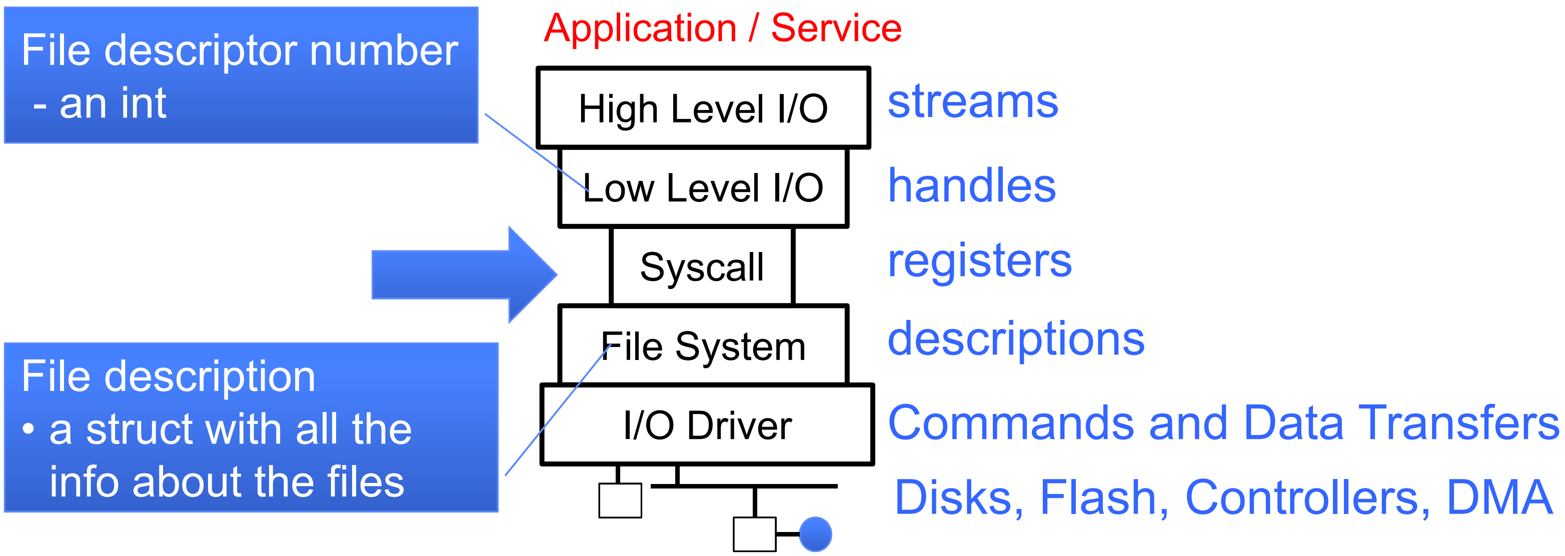
#	Name	Registers						Definition
		eax	ebx	ecx	edx	esi	edi	
0	sys_restart_syscall	0x00	-	-	-	-	-	kernel/signal.c:2058
1	sys_exit	0x01	int error_code	-	-	-	-	kernel/exit.c:1046
2	sys_fork	0x02	struct pt_regs *	-	-	-	-	arch/alpha/kernel/entry.S:716
3	sys_read	0x03	unsigned int fd	char __user *buf	size_t count	-	-	fs/read_write.c:391
4	sys_write	0x04	unsigned int fd	const char __user *buf	size_t count	-	-	fs/read_write.c:408
5	sys_open	0x05	const char __user *filename	int flags	int mode	-	-	fs/open.c:900
6	sys_close	0x06	unsigned int fd	-	-	-	-	fs/open.c:969
7	sys_waitpid	0x07	pid_t pid	int __user *stat_addr	int options	-	-	kernel/exit.c:1771
8	sys_creat	0x08	const char __user *pathname	int mode	-	-	-	fs/open.c:933
9	sys_link	0x09	const char __user *oldname	const char __user *newname	-	-	-	fs/namei.c:2520

Showing 1 to 10 of 338 entries

Generated from Linux kernel 2.6.35.4 using Exuberant Ctags, Python, and DataTables.
Project on GitHub. Hosted on GitHub Pages.

- Low level lib parameters are set up in registers and syscall instruction is issued
  - A type of synchronous exception that enters well-defined entry points into kernel

What’s below the surface ??



File descriptor number
- an int

Application / Service

High Level I/O — streams

Low Level I/O — handles

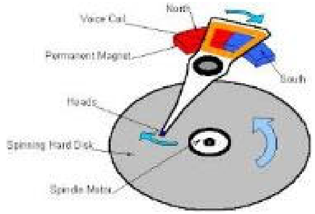
Syscall — registers

File System — descriptions

I/O Driver — Commands and Data Transfers

Disks, Flash, Controllers, DMA

File description
- a struct with all the info about the files

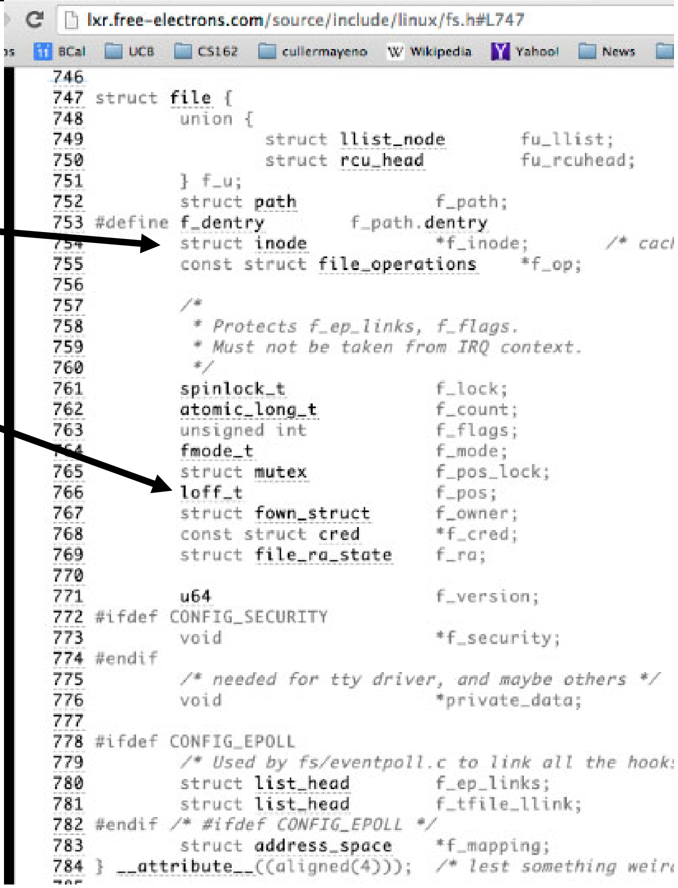


What’s in an Open File Description?

Inside Kernel!

For our purposes, the two most important things are:

- Where to find the file data on disk
- The current position within the file



```
struct file {
        union {
                struct llist_node       fu_llist;
                struct rcu_head         fu_rcuhead;
        } f_u;
        struct path             f_path;
#define f_dentry        f_path.dentry
        struct inode            *f_inode;       /* cac
        const struct file_operations    *f_op;

        /*
         * Protects f_ep_links, f_flags.
         * Must not be taken from IRQ context.
         */
        spinlock_t              f_lock;
        atomic_long_t           f_count;
        unsigned int            f_flags;
        fmode_t                 f_mode;
        struct mutex            f_pos_lock;
        loff_t                  f_pos;
        struct fown_struct      f_owner;
        const struct cred       *f_cred;
        struct file_ra_state    f_ra;

        u64                     f_version;
#ifdef CONFIG_SECURITY
        void                    *f_security;
#endif
        /* needed for tty driver, and maybe others */
        void                    *private_data;

#ifdef CONFIG_EPOLL
        /* Used by fs/eventpoll.c to link all the hook
        struct list_head        f_ep_links;
        struct list_head        f_tfile_llink;
#endif /* #ifdef CONFIG_EPOLL */
        struct address_space    *f_mapping;
} __attribute__((aligned(4)));  /* lest something weir
```

File System: from syscall to driver

In `fs/read_write.c`

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return
  if (!file->f_op || (!file->f_op->read &&
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, bu
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

- Read up to “count” bytes from “file” starting from “pos” into “buf”.
- Return error or number of bytes read.

File System: from syscall to driver

In `fs/read_write.c`

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) ret
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Make sure we are allowed to read this file

File System: from syscall to driver

In `fs/read_write.c`

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Check if file has read methods

File System: from syscall to driver

In `fs/read_write.c`

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, c
    else
      ret = do_sync_read(file, buf, count
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

- Check whether we can write to buf (e.g., buf is in the user space range)
- unlikely(): hint to branch prediction this condition is unlikely

File System: from syscall to driver

In `fs/read_write.c`

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, po
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Check whether we read from a valid range in the file.

File System: from syscall to driver

In fs/read_write.c

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

If driver provide a read function (f_op->read) use it; otherwise use do_sync_read()

File System: from syscall to driver

In fs/read_write.c

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->re
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Notify the parent of this file that the file was read (see http://www.fieldses.org/~bfields/kernel/vfs.txt)

File System: from syscall to driver

In `fs/read_write.c`

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, po
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Update the number of bytes read by "current" task (for scheduling purposes)

File System: from syscall to driver

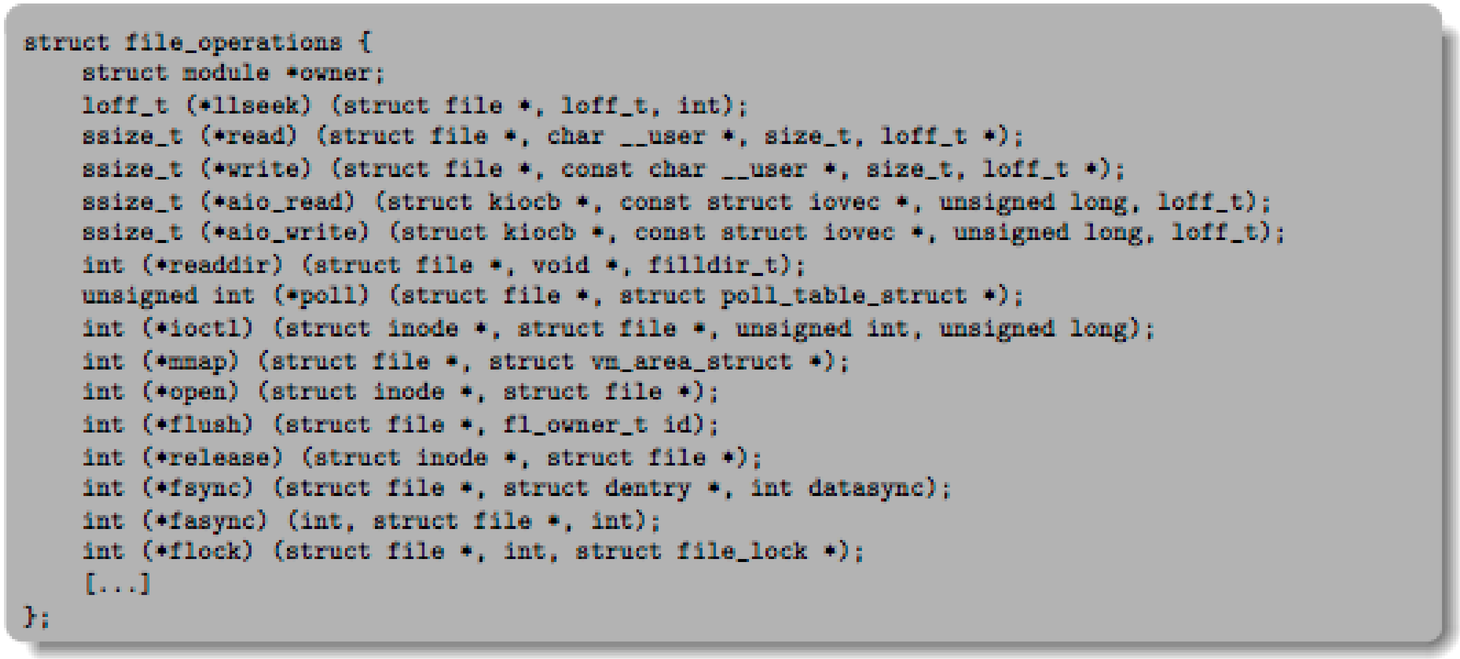
In fs/read_write.c

```
ssize_t vfs_read(struct file *file, char __user *buf, size_t count, loff_t *pos)
{
  ssize_t ret;
  if (!(file->f_mode & FMODE_READ)) return -EBADF;
  if (!file->f_op || (!file->f_op->read && !file->f_op->aio_read))
    return -EINVAL;
  if (unlikely(!access_ok(VERIFY_WRITE, buf, count))) return -EFAULT;
  ret = rw_verify_area(READ, file, pos, count);
  if (ret >= 0) {
    count = ret;
    if (file->f_op->read)
      ret = file->f_op->read(file, buf, count, pos);
    else
      ret = do_sync_read(file, buf, count, pos);
    if (ret > 0) {
      fsnotify_access(file->f_path.dentry);
      add_rchar(current, ret);
    }
    inc_syscr(current);
  }
  return ret;
}
```

Update the number of read syscalls by “current” task (for scheduling purposes)

Lower Level Driver

- Associated with particular hardware device
- Registers / Unregisters itself with the kernel
- Handler functions for each of the file operations



```
struct file_operations {
    struct module *owner;
    loff_t (*llseek) (struct file *, loff_t, int);
    ssize_t (*read) (struct file *, char __user *, size_t, loff_t *);
    ssize_t (*write) (struct file *, const char __user *, size_t, loff_t *);
    ssize_t (*aio_read) (struct kiocb *, const struct iovec *, unsigned long, loff_t);
    ssize_t (*aio_write) (struct kiocb *, const struct iovec *, unsigned long, loff_t);
    int (*readdir) (struct file *, void *, filldir_t);
    unsigned int (*poll) (struct file *, struct poll_table_struct *);
    int (*ioctl) (struct inode *, struct file *, unsigned int, unsigned long);
    int (*mmap) (struct file *, struct vm_area_struct *);
    int (*open) (struct inode *, struct file *);
    int (*flush) (struct file *, fl_owner_t id);
    int (*release) (struct inode *, struct file *);
    int (*fsync) (struct file *, struct dentry *, int datasync);
    int (*fasync) (int, struct file *, int);
    int (*flock) (struct file *, int, struct file_lock *);
    [...]
};
```

Device Drivers

- Device Driver: Device-specific code in the kernel that interacts directly with the device hardware
  - Supports a standard, internal interface
  - Same kernel I/O system can interact easily with different device drivers
  - Special device-specific configuration supported with the `ioctl()` system call
- Device Drivers typically divided into two pieces:
  - Top half: accessed in call path from system calls
    - implements a set of standard, cross-device calls like `open()`, `close()`, `read()`, `write()`, `ioctl()`, `strategy()`
    - This is the kernel's interface to the device driver
    - Top half will *start* I/O to device, may put thread to sleep until finished
  - Bottom half: run as interrupt routine
    - Gets input or transfers next block of output
    - May wake sleeping threads if I/O now complete

Life Cycle of An I/O Request

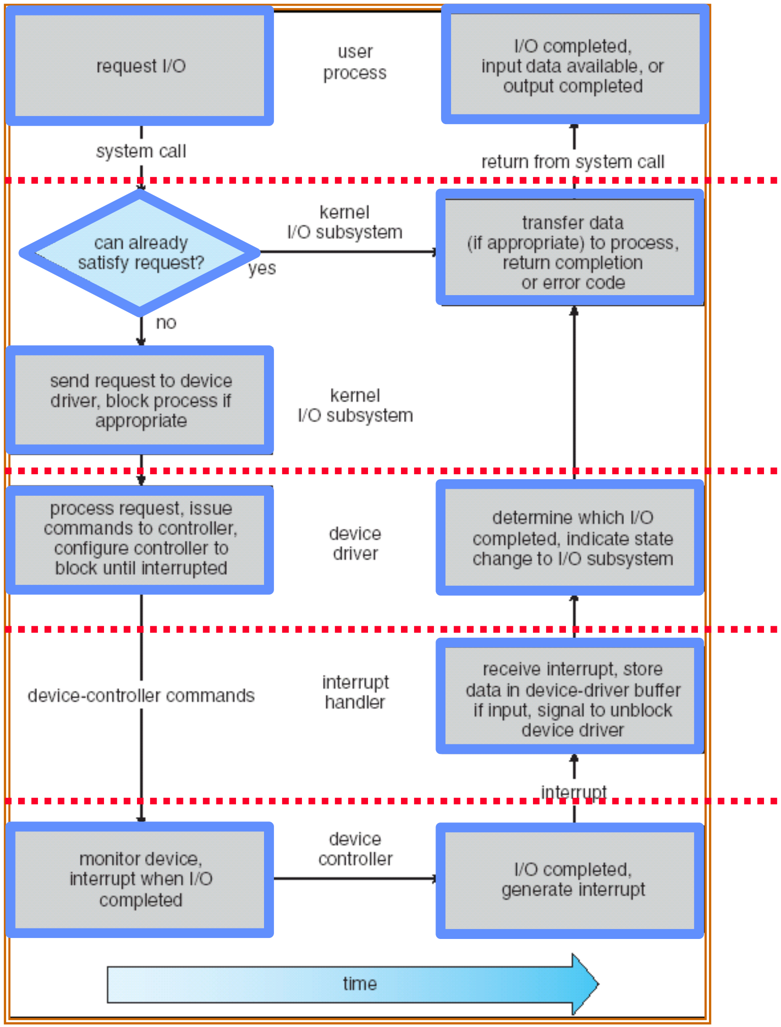
User Program

Kernel I/O Subsystem

Device Driver Top Half

Device Driver Bottom Half

Device Hardware



request I/O

user process

I/O completed, input data available, or output completed

system call

return from system call

can already satisfy request?

yes

no

kernel I/O subsystem

transfer data (if appropriate) to process, return completion or error code

send request to device driver, block process if appropriate

kernel I/O subsystem

process request, issue commands to controller, configure controller to block until interrupted

device driver

determine which I/O completed, indicate state change to I/O subsystem

device-controller commands

interrupt handler

receive interrupt, store data in device-driver buffer if input, signal to unblock device driver

interrupt

monitor device, interrupt when I/O completed

device controller

I/O completed, generate interrupt

time

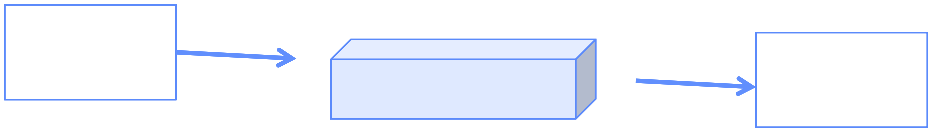
Administrivia

- Kubiatowicz Office Hours:
  - 2-3pm, Monday & Wednesday
- Friday was drop deadline. If you forgot to drop, we can't help you!
  - You need to speak with advisor services in your department about how to drop
- Recommendation: Read assigned readings *before* lecture
- Group sign up should have happened already
  - If you don't have 4 members in your group, we will try to find you other partners
  - Want everyone in your group to have the same TA
  - Go to your assigned section on Friday, starting this week!
- Midterm 1 conflicts
  - Watch for announcements on EdStem (remember: MT1 is 2/16)

Communication between processes

- Can we view files as communication channels?

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

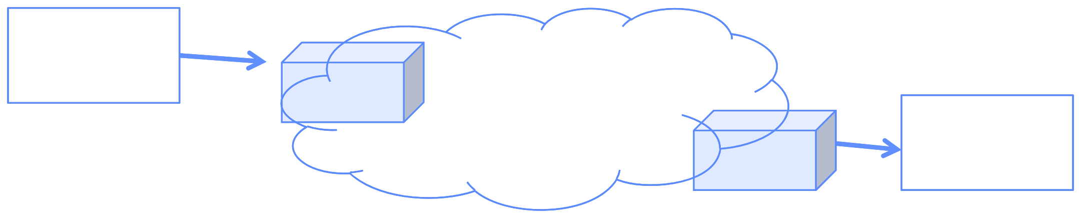


```
n = read(rfd,rbuf,rmax);
```

- Producer and Consumer of a file may be distinct processes
  – May be separated in time (or not)
- However, what if data written once and consumed once?
  – Don’t we want something more like a queue?
  – Can still look like File I/O!

Communication Across the world looks like file IO!

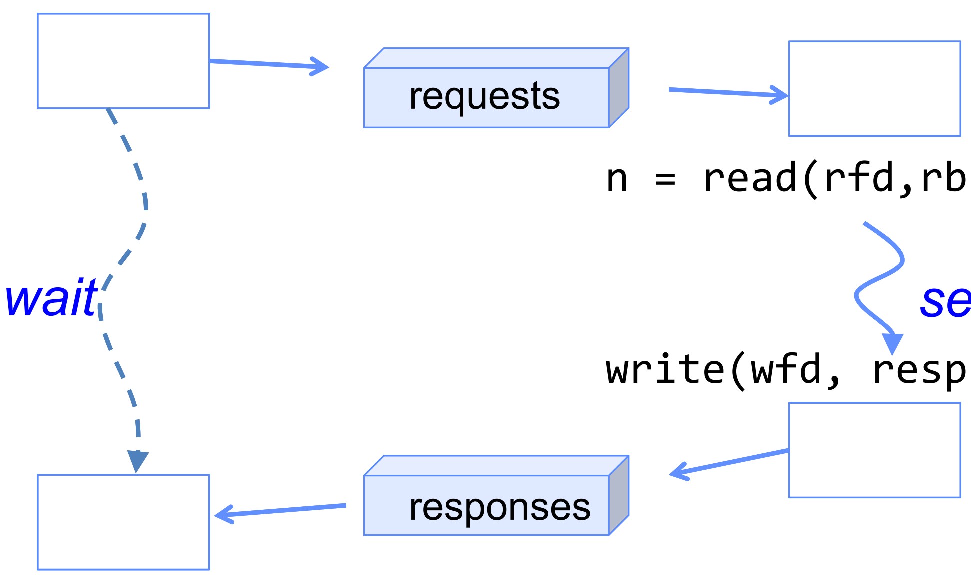
```
write(wfd, wbuf, wlen);
```



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

- Connected queues over the Internet
  - – But what’s the analog of open?
  - – What is the namespace?
  - – How are they connected in time?

Request Response Protocol



Client (issues requests)

Server (performs operations)

```
write(rqfd, rqbuf, buflen);
```

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

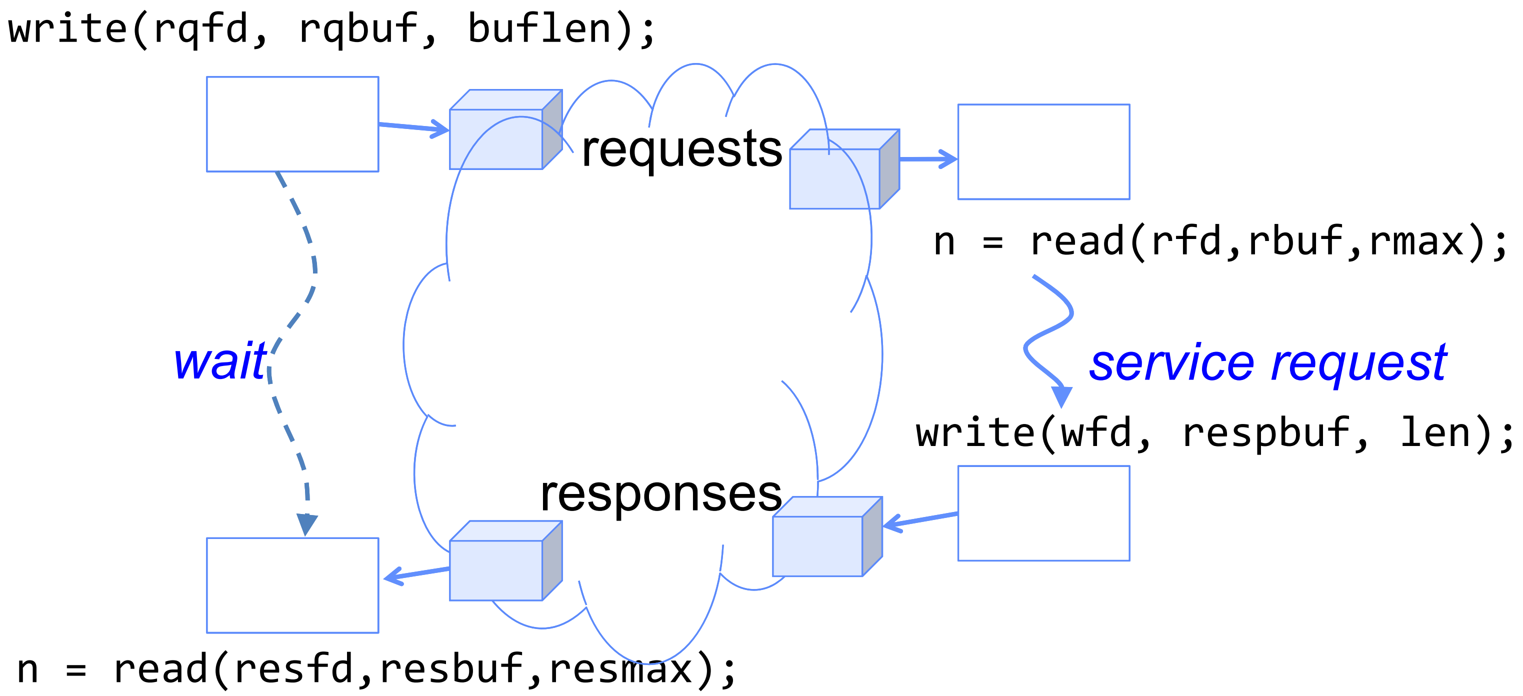
```
write(wfd, respbuf, len);
```

```
n = read(resfd,resbuf,resmax);
```

Request Response Protocol: Across Network

Client (issues requests)

Server (performs operations)



```
write(rqfd, rqbuf, buflen);
```

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

service request

```
write(wfd, respbuf, len);
```

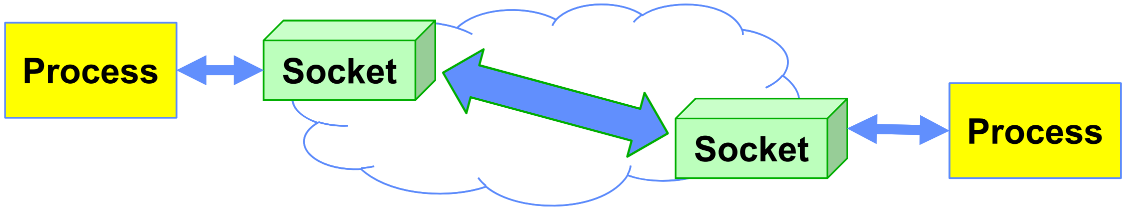
wait

```
n = read(resfd,resbuf,resmax);
```

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

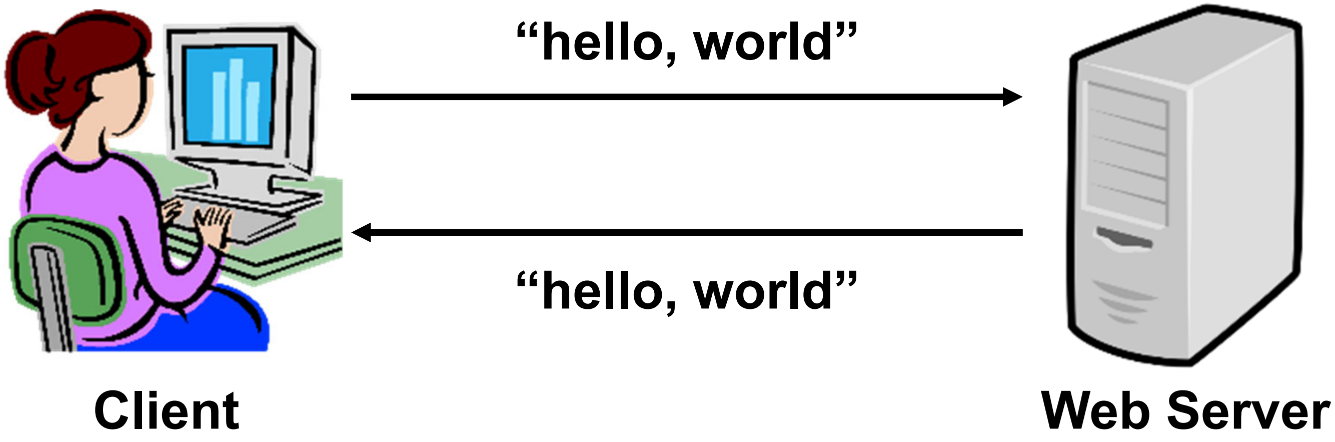
- **Socket:** An abstraction for one endpoint of a network connection
  - Another mechanism for **inter-process communication**
  - Most operating systems (Linux, Mac OS X, Windows) provide this, even if they don't copy rest of UNIX I/O
  - Standardized by POSIX
- First introduced in 4.2 BSD (Berkeley Standard Distribution) Unix
  - This release had some huge benefits (and excitement from potential users)
  - Runners waiting at release time to get release on tape and take to businesses
- 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 it 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



“hello, world”

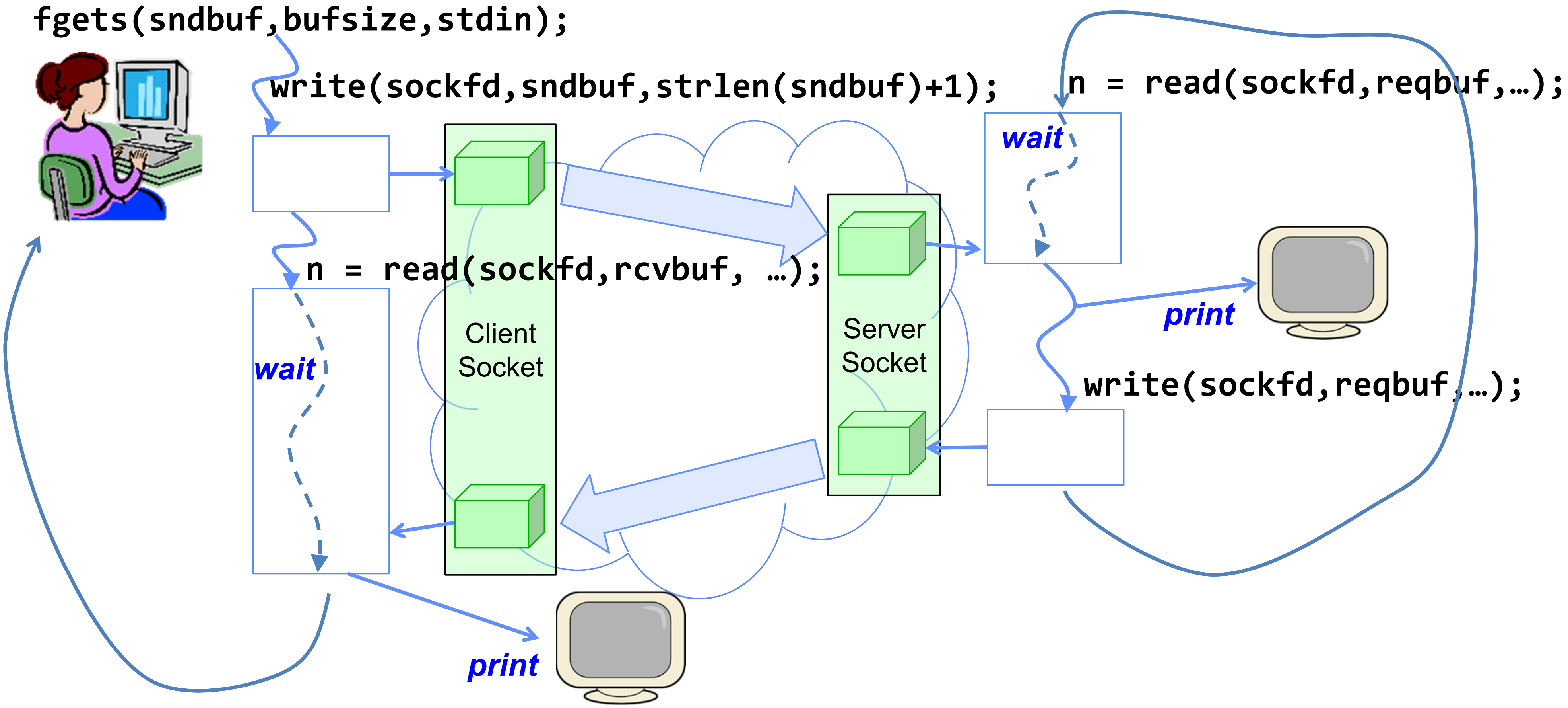
“hello, world”

Client

Web Server

Simple Example: Echo Server

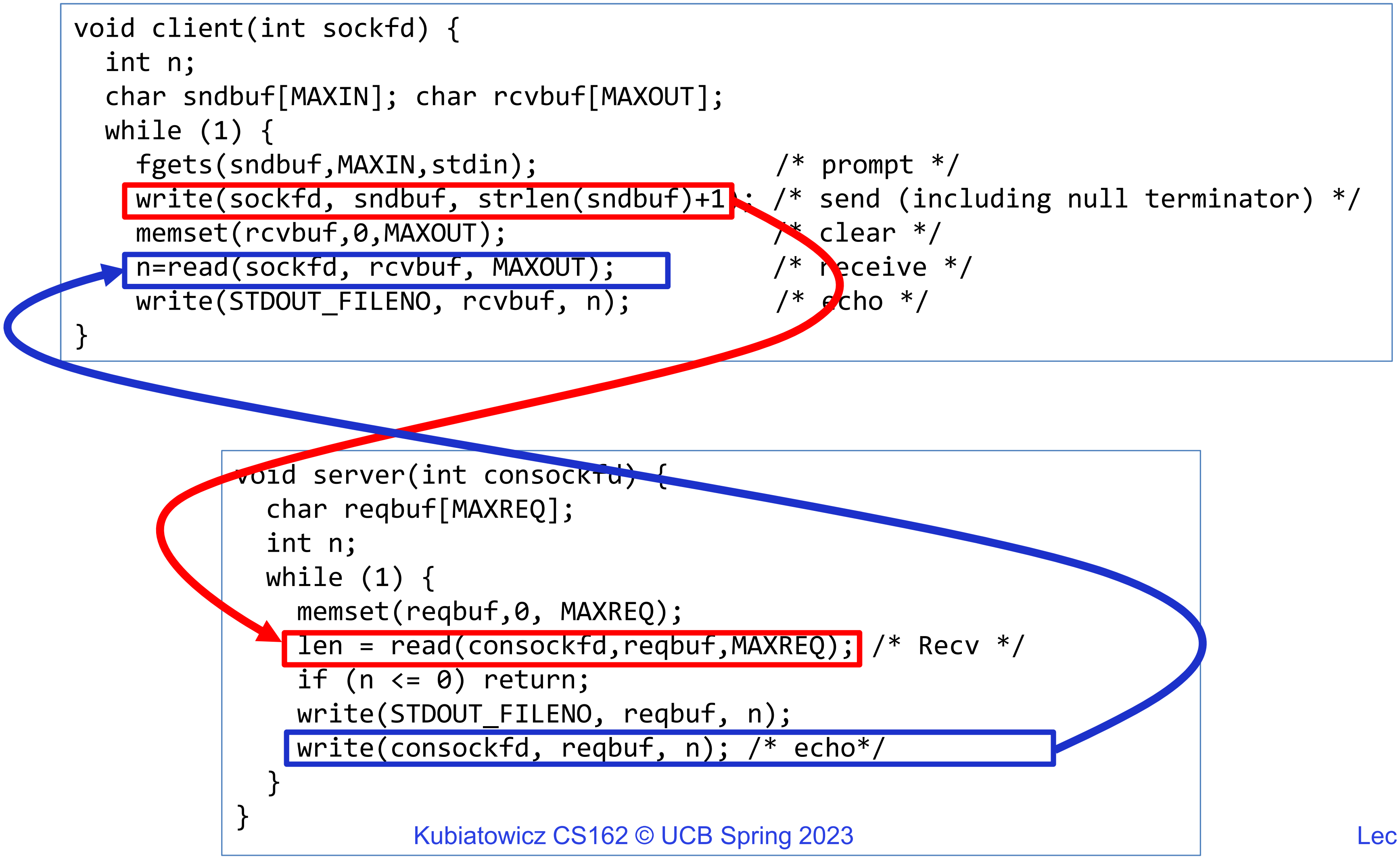
Client (issues requests) **Server (services requests)**



```
fgets(sndbuf,bufsize,stdin);
write(sockfd,sndbuf,strlen(sndbuf)+1);
n = read(sockfd,rcvbuf, …);
```

```
n = read(sockfd,reqbuf,…);
write(sockfd,reqbuf,…);
```

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.

- 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
    - » Actually need to loop and read until we receive the terminator ('\0')
  - Assumes writing already took place
  - Blocks if nothing has arrived yet

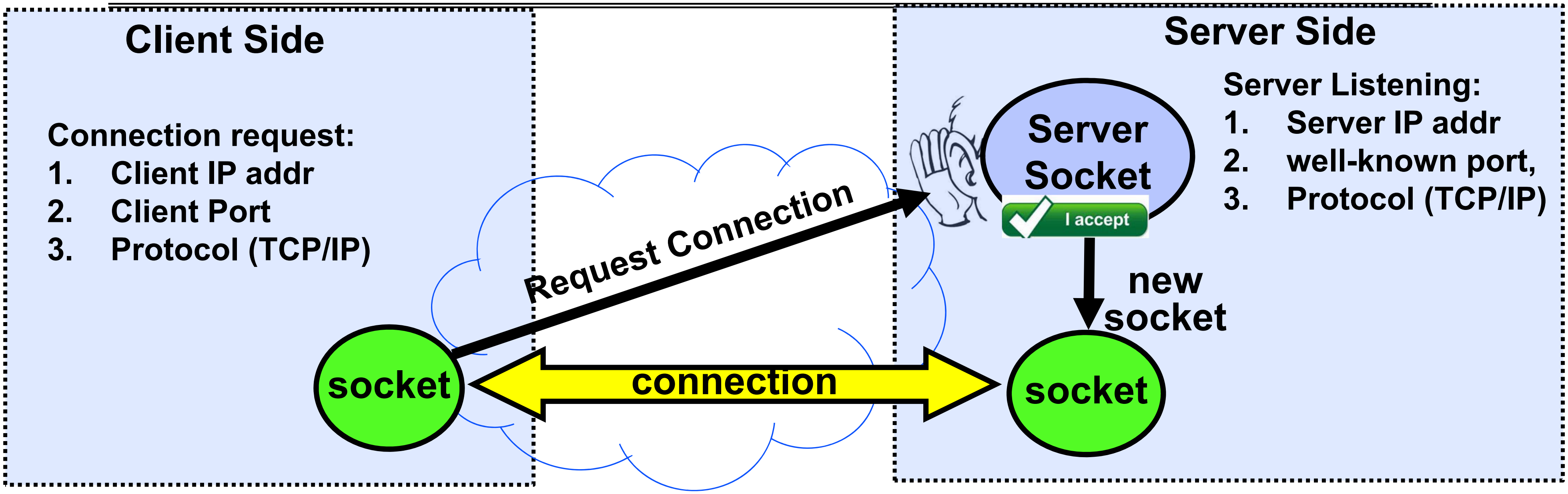
Socket Creation

- 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.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

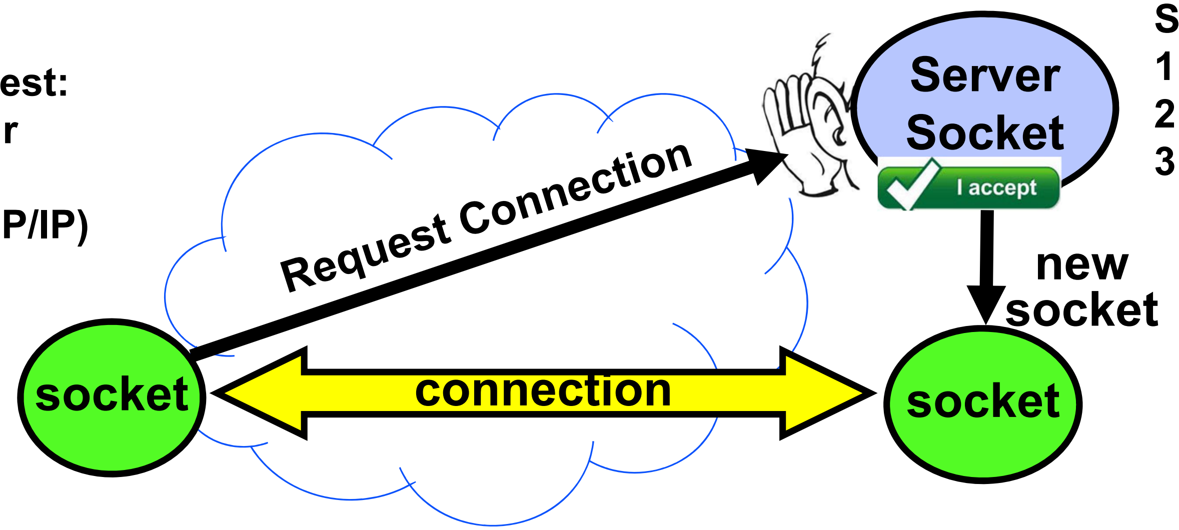
Connection Setup over TCP/IP

Client Side

Connection request:
1. **Client IP addr**
2. **Client Port**
3. **Protocol (TCP/IP)**

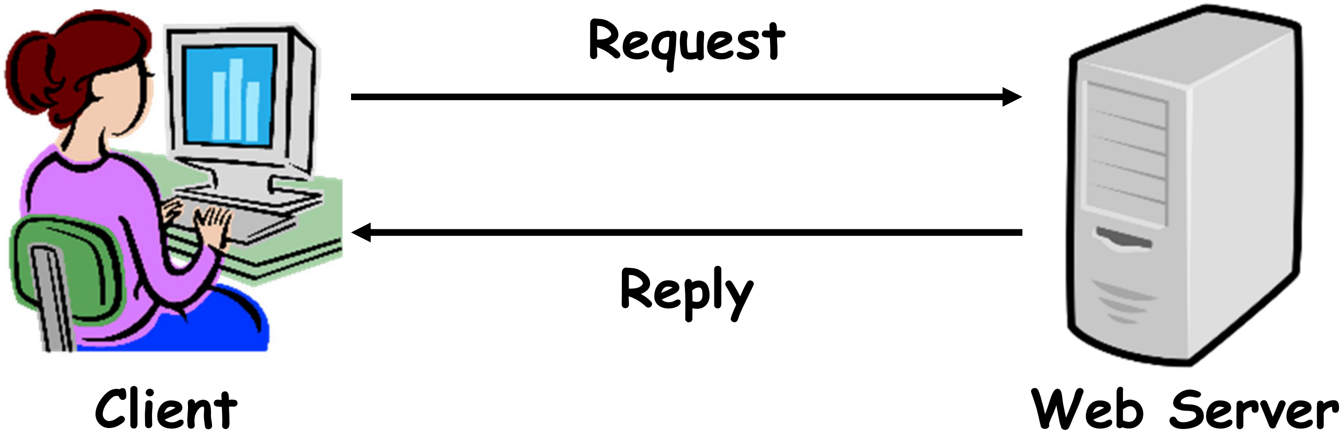
Server Side

Server Listening:
1. **Server IP addr**
2. **well-known port,**
3. **Protocol (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

Web Server



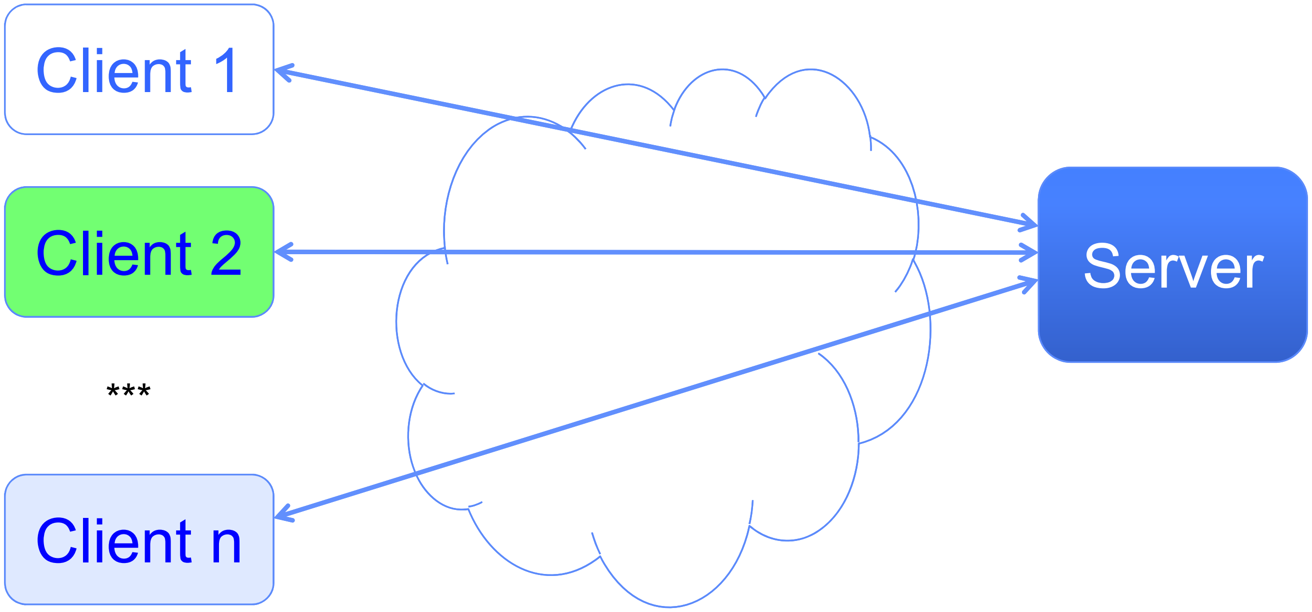
Request

Reply

Client

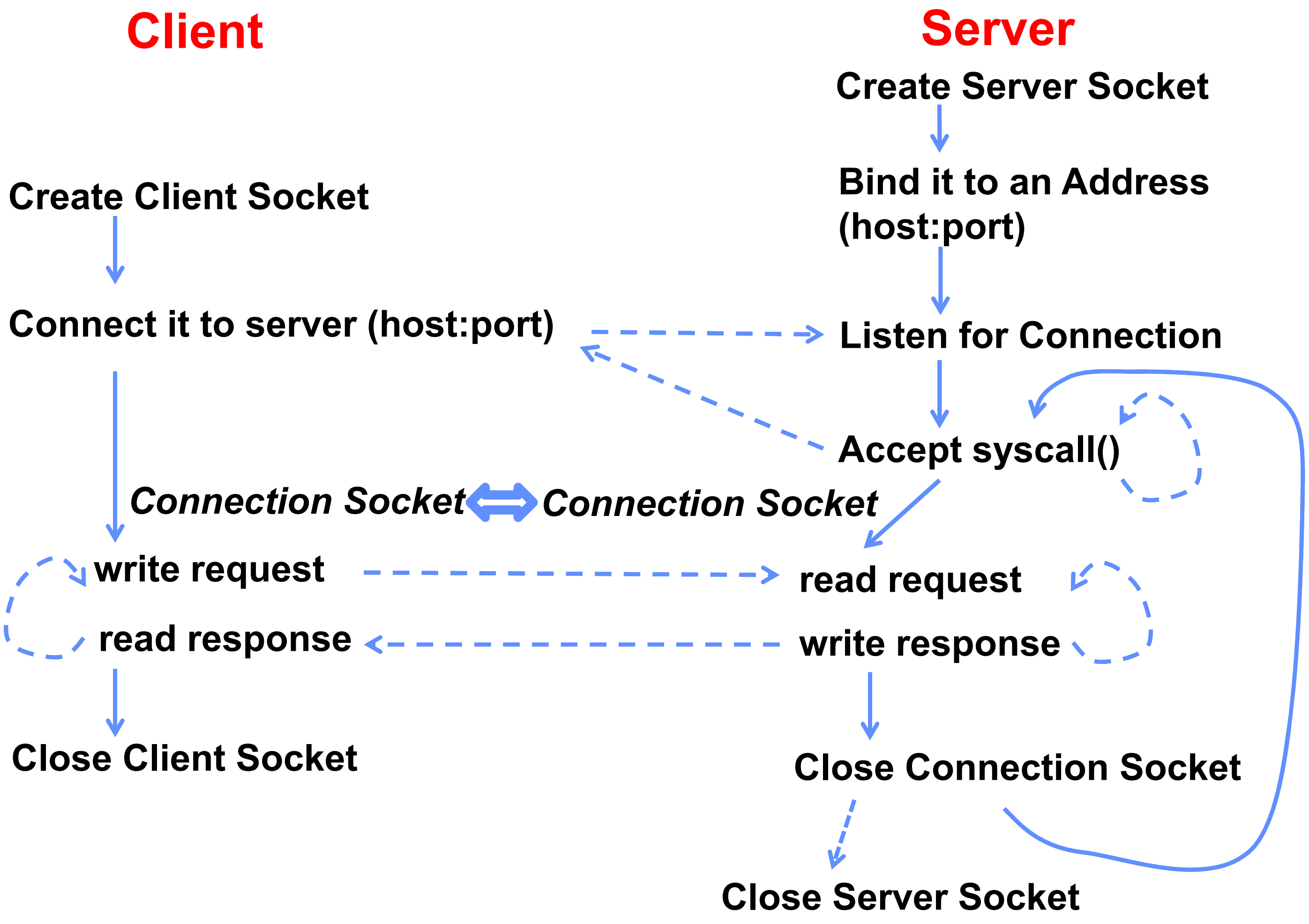
Web Server

Client-Server Models



- File servers, web, FTP, Databases, …
- Many clients accessing a common server

Sockets in concept



Client

Server

Create Server Socket

Bind it to an Address (host:port)

Create Client Socket

Connect it to server (host:port)

Listen for Connection

Accept syscall()

Connection Socket ⟺ ***Connection Socket***

write request

read request

read response

write response

Close Client Socket

Close Connection Socket

Close Server Socket

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);
```

Client: Getting the Server Address

```
struct addrinfo *lookup_host(char *host_name, char *port) {
  struct addrinfo *server;
  struct addrinfo hints;
  memset(&hints, 0, sizeof(hints));
  hints.ai_family = AF_UNSPEC;         /* Includes AF_INET and AF_INET6 */
  hints.ai_socktype = SOCK_STREAM;     /* Essentially TCP/IP */

  int rv = getaddrinfo(host_name, port_name,
                       &hints, &server);
  if (rv != 0) {
    printf("getaddrinfo failed: %s\n", gai_strerror(rv));
    return NULL;
  }
  return server;
}
```

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);
```

Server Address: Itself (wildcard IP), Passive

```
struct addrinfo *setup_address(char *port) {
  struct addrinfo *server;
  struct addrinfo hints;
  memset(&hints, 0, sizeof(hints));
  hints.ai_family = AF_UNSPEC;           /* Includes AF_INET and AF_INET6 */
  hints.ai_socktype = SOCK_STREAM;       /* Essentially TCP/IP */
  hints.ai_flags = AI_PASSIVE;           /* Set up for server socket */

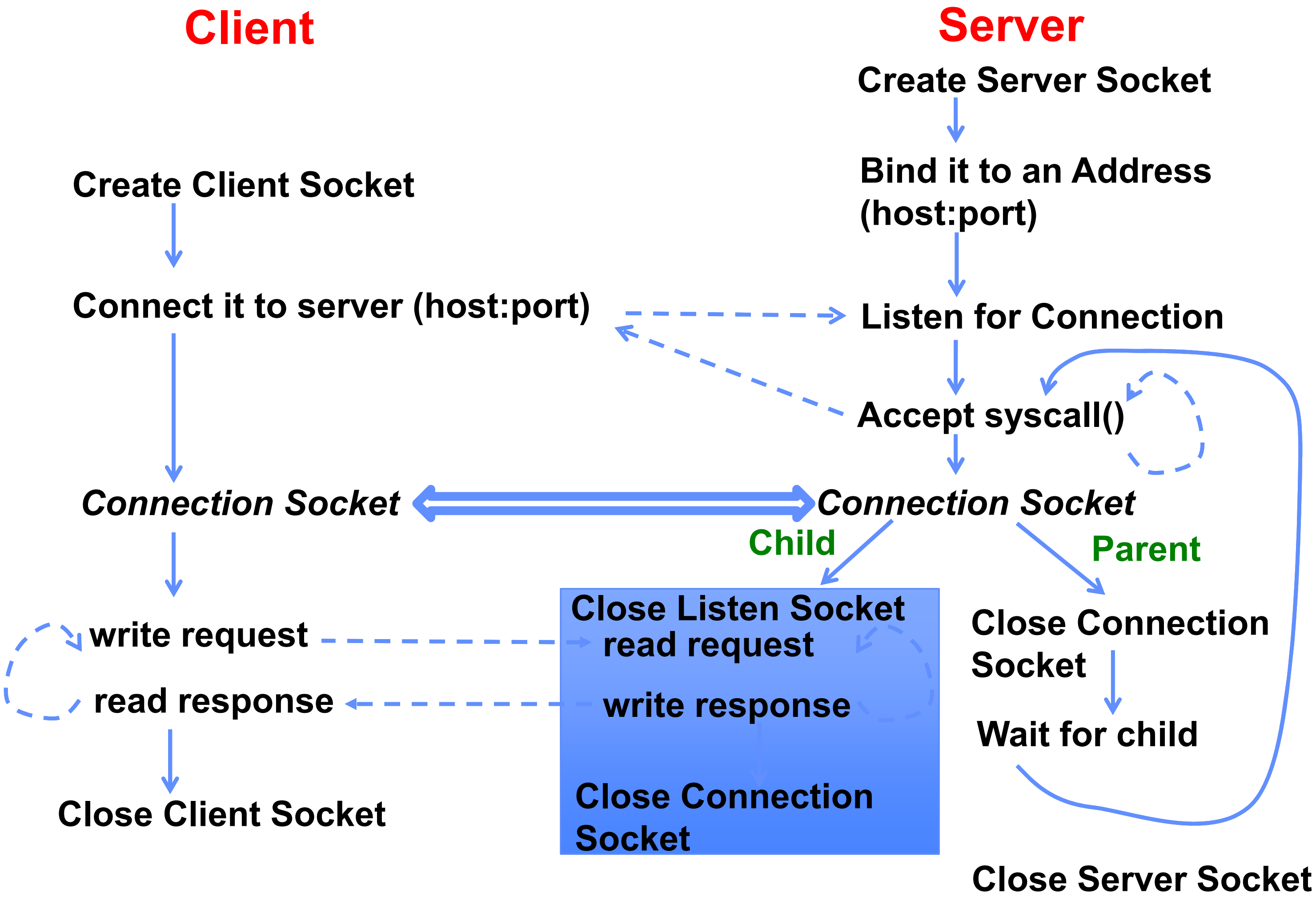
  int rv = getaddrinfo(NULL, port, &hints, &server);  /* No address! (any local IP) */
  if (rv != 0) {
    printf("getaddrinfo failed: %s\n", gai_strerror(rv));
    return NULL;
  }
  return server;
}
```

- **Accepts any connections on the specified port**

How Could the Server Protect Itself?

- Handle each connection in a separate process
  - This will mean that the logic serving each request will be “sandboxed” away from the main server process

Sockets With Protection (each connection has own process)



Client

Create Client Socket

Connect it to server (host:port)

Connection Socket

write request

read response

Close Client Socket

Server

Create Server Socket

Bind it to an Address (host:port)

Listen for Connection

Accept syscall()

Connection Socket

Child

Close Listen Socket

read request

write response

Close Connection Socket

Parent

Close Connection Socket

Wait for child

Close Server Socket

Server Protocol (v2)

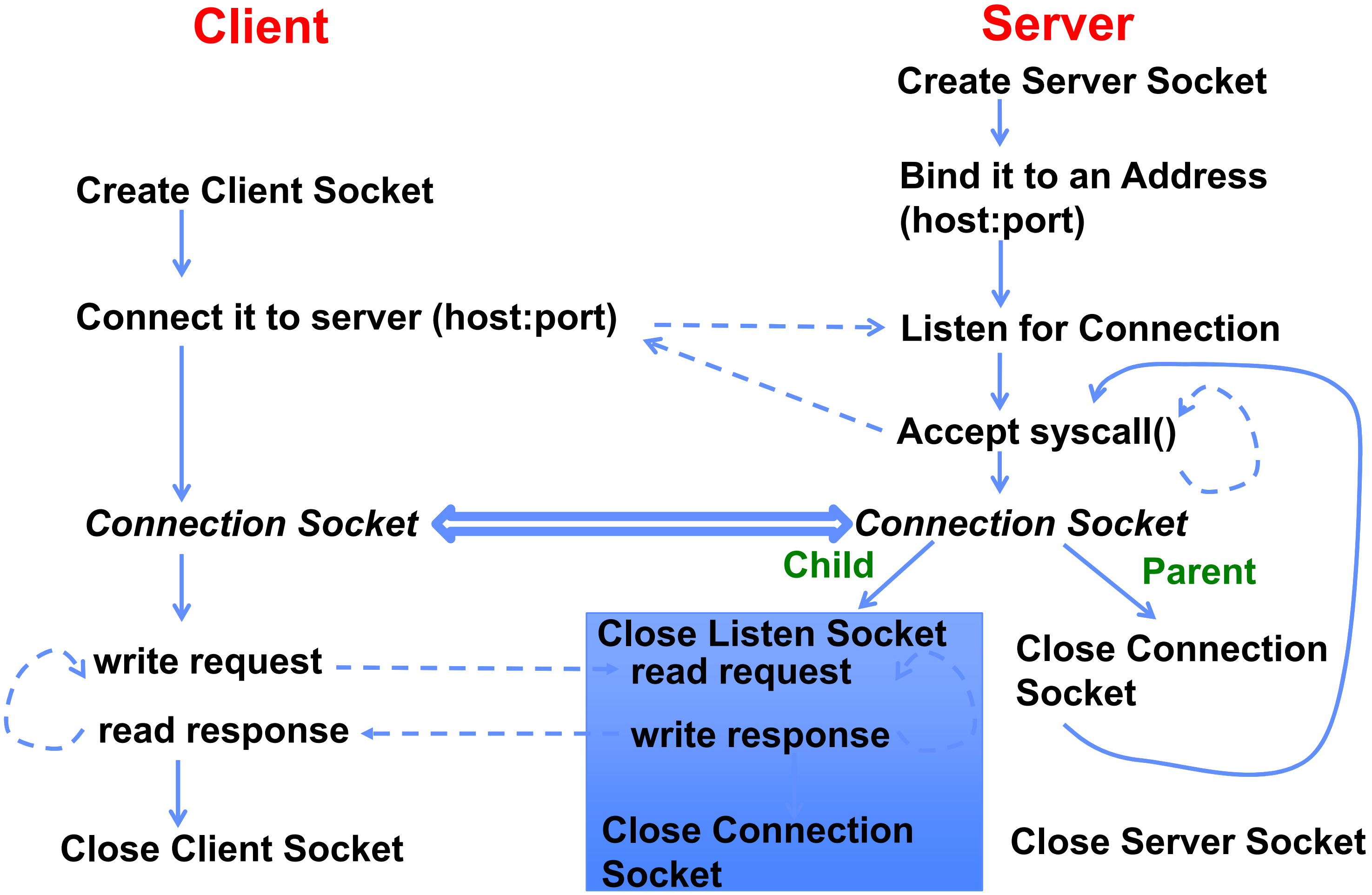
```
// Socket setup code elided…
listen(server_socket, MAX_QUEUE);
while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);
  pid_t pid = fork();
  if (pid == 0) {
    close(server_socket);
    serve_client(conn_socket);
    close(conn_socket);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



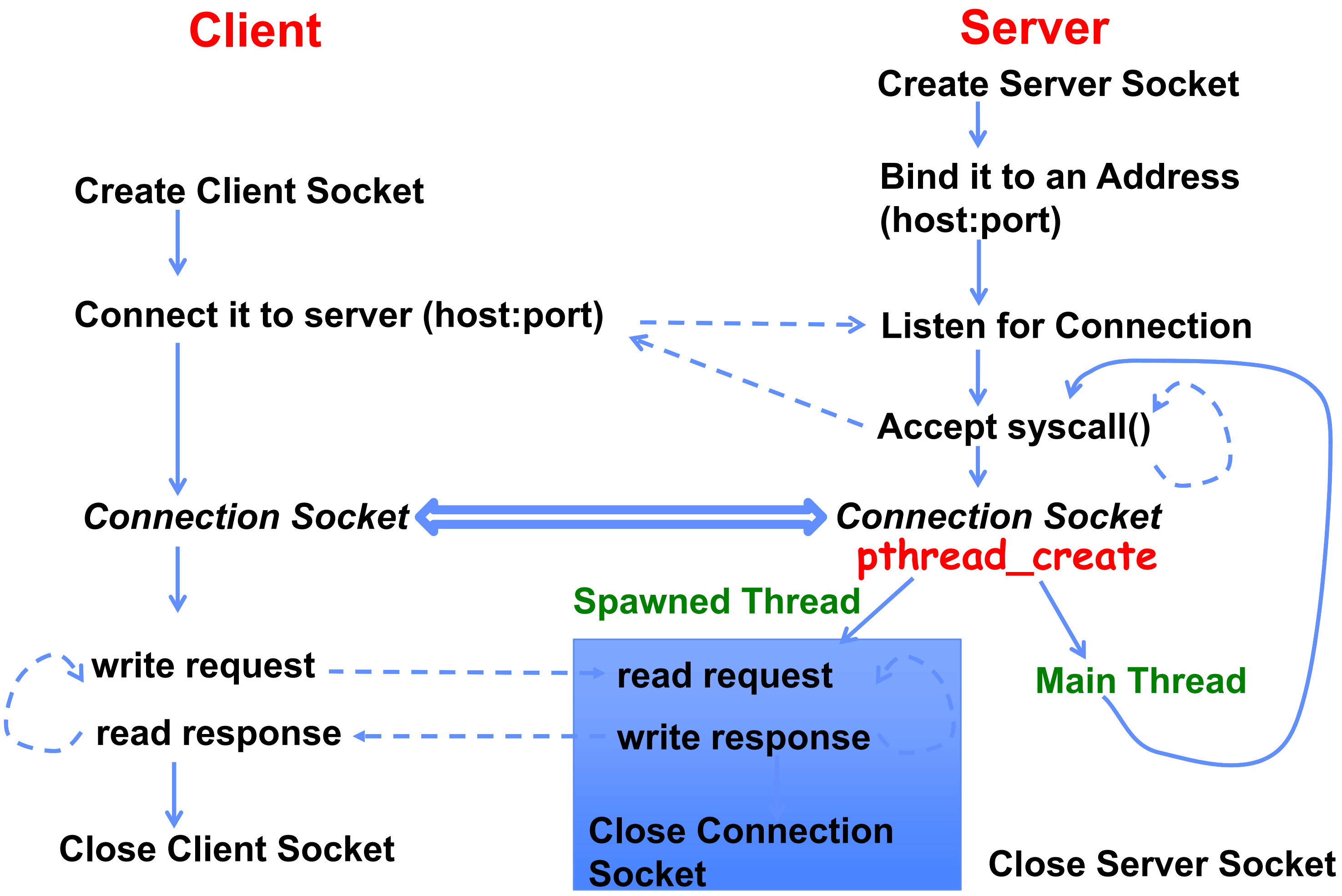
Server Protocol (v3)

```
// Socket setup code elided…
listen(server_socket, MAX_QUEUE);
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



Client

Create Client Socket

Connect it to server (host:port)

Connection Socket

write request

read response

Close Client Socket

Server

Create Server Socket

Bind it to an Address (host:port)

Listen for Connection

Accept syscall()

Connection Socket

pthread_create

Spawned Thread

read request

write response

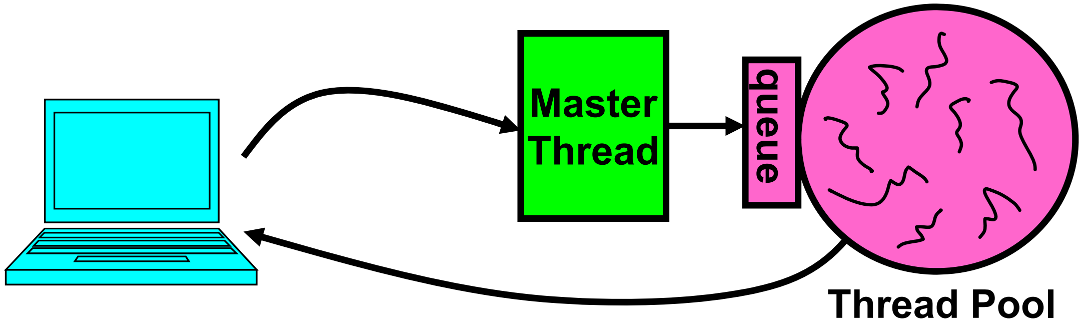
Close Connection Socket

Main Thread

Close Server Socket

Thread Pools: More Later!

- 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

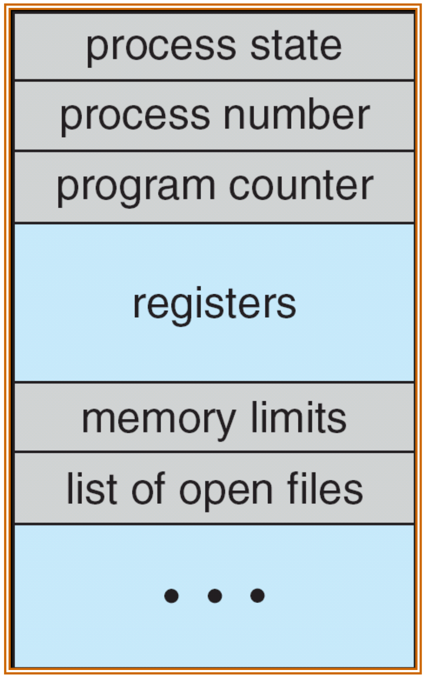


```
master() {
   allocThreads(worker,queue);
   while(TRUE) {
      con=AcceptCon();
      Enqueue(queue,con);
      wakeUp(queue);
   }
}
```

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

Recall: The Process Control Block

- Kernel represents each process as a process control block (PCB)
  - Status (running, ready, blocked, …)
  - Register state (when not ready)
  - Process ID (PID), User, Executable, Priority, …
  - Execution time, …
  - Memory space, translation, …
- Kernel *Scheduler* maintains a data structure containing the PCBs
  - Give out CPU to different processes
  - This is a Policy Decision
- Give out non-CPU resources
  - Memory/IO
  - Another policy decision



process state

process number

program counter

registers

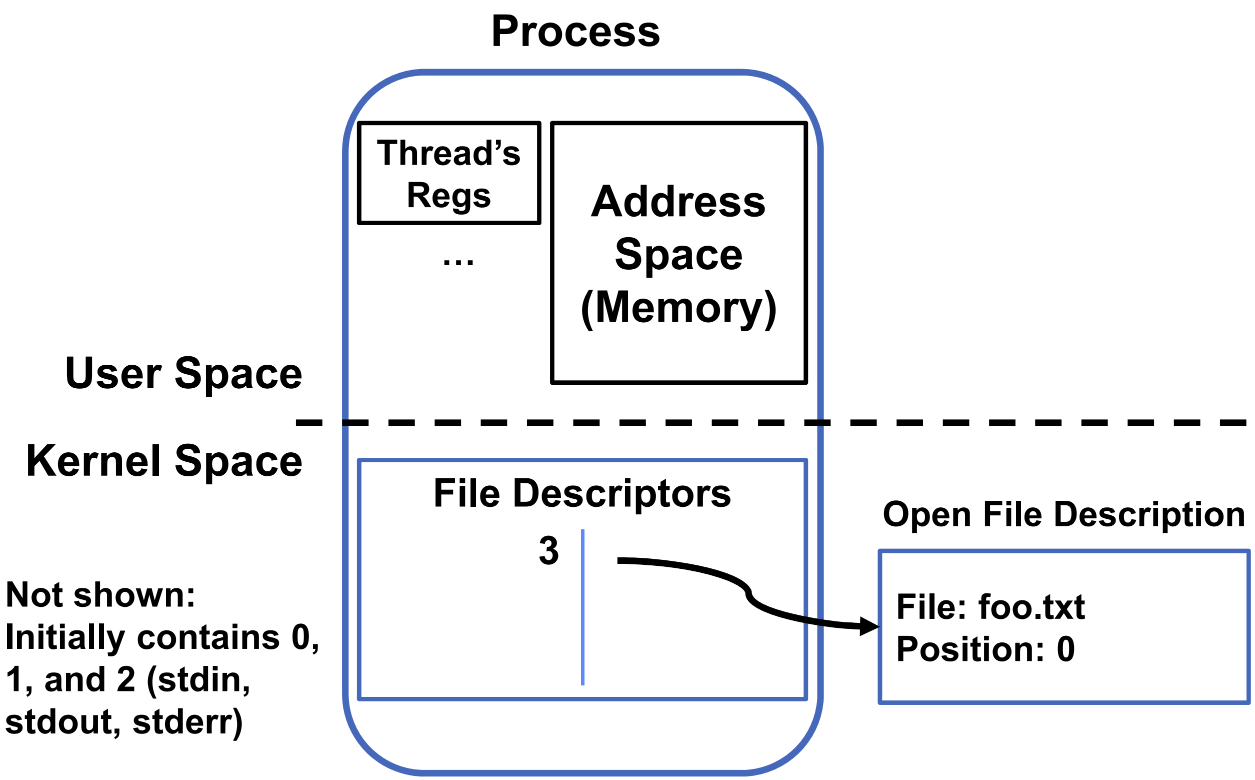
memory limits

list of open files

• • •

Process
Control
Block

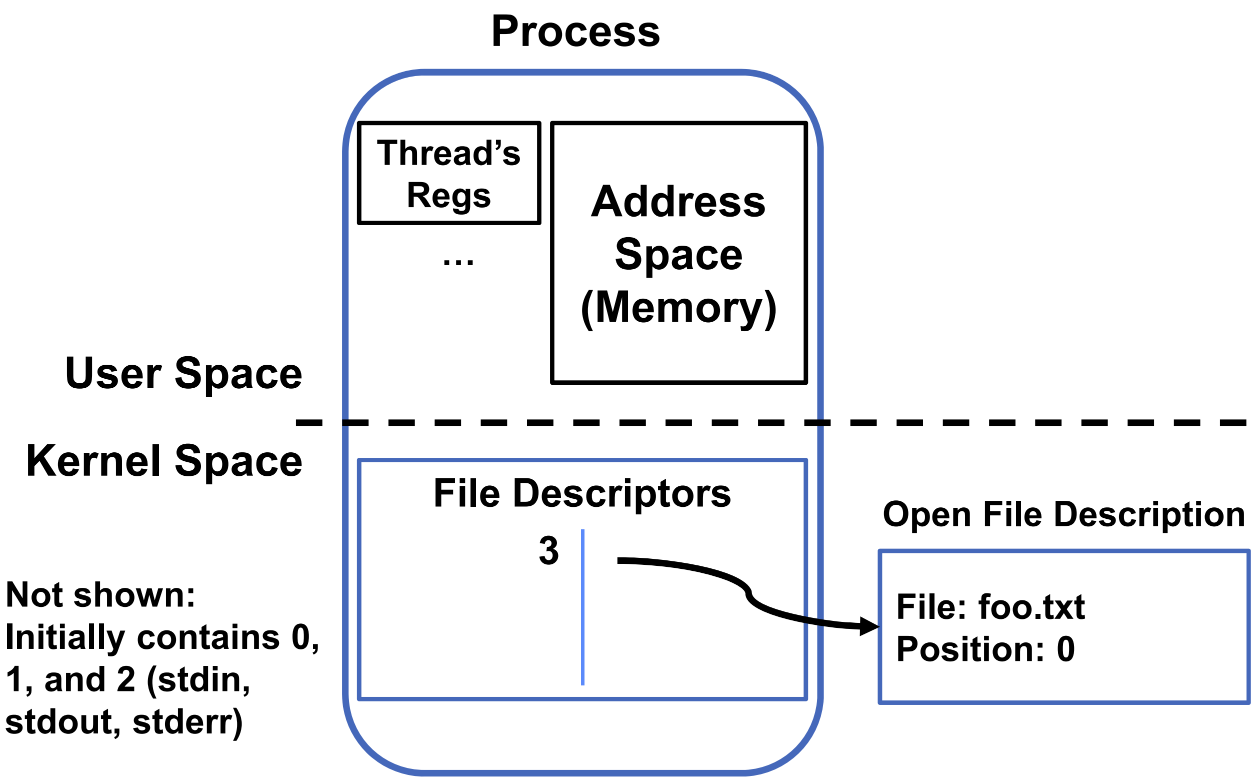
Abstract Representation of a Process



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

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

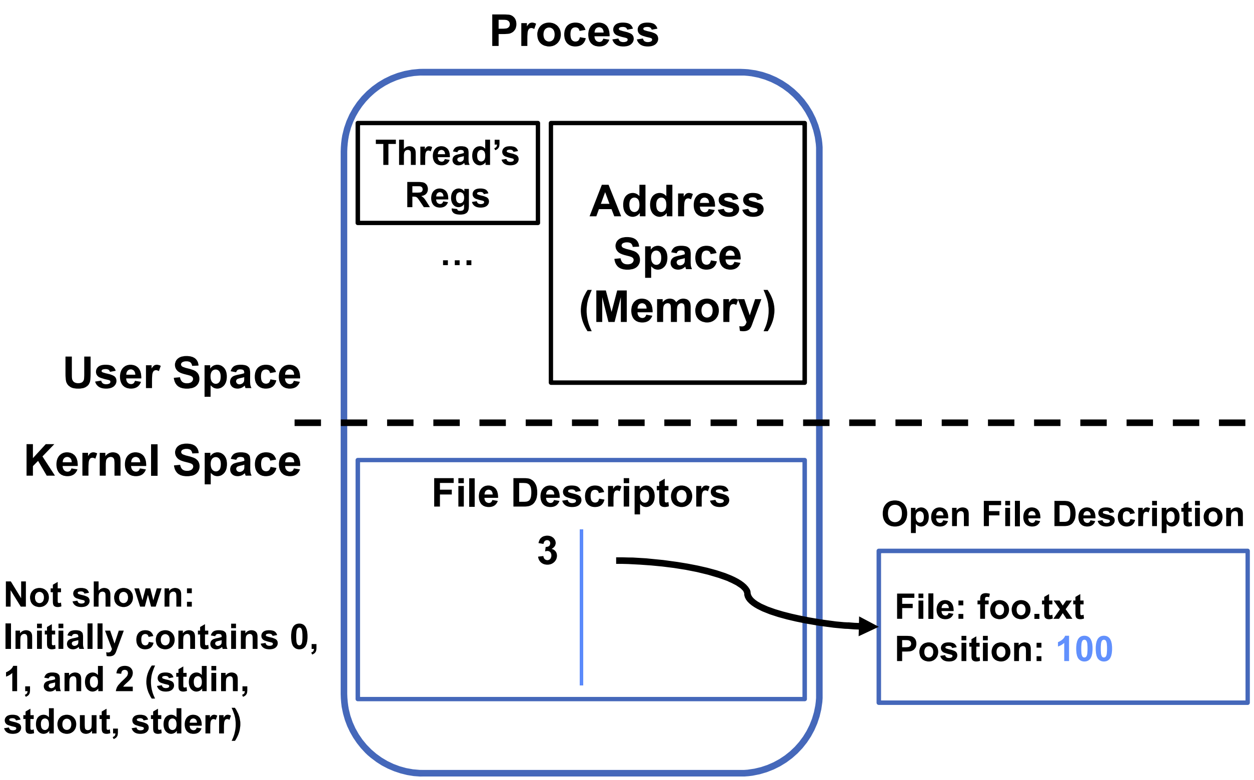
Abstract Representation of a Process



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

Next, suppose that we execute
read(3, buf, 100)
and that the result is 100

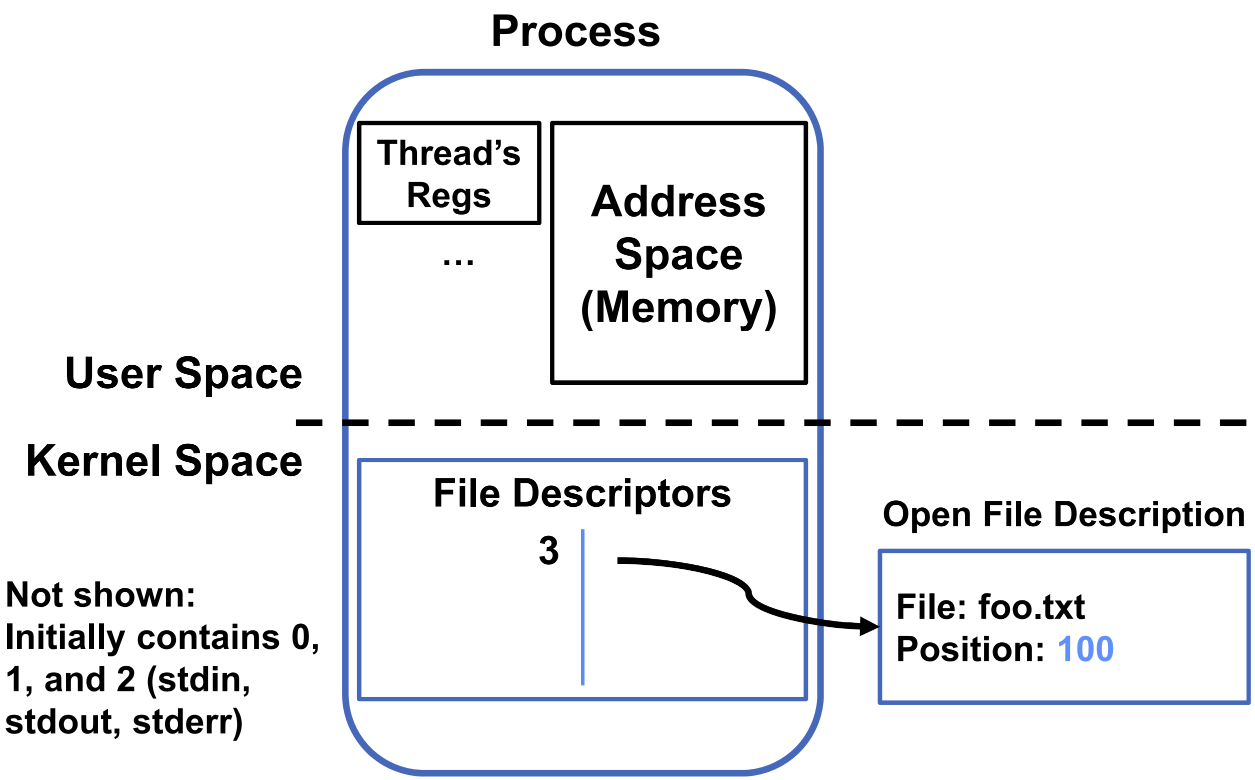
Abstract Representation of a Process



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

Next, suppose that we execute
read(3, buf, 100)
and that the result is 100

Abstract Representation of a Process

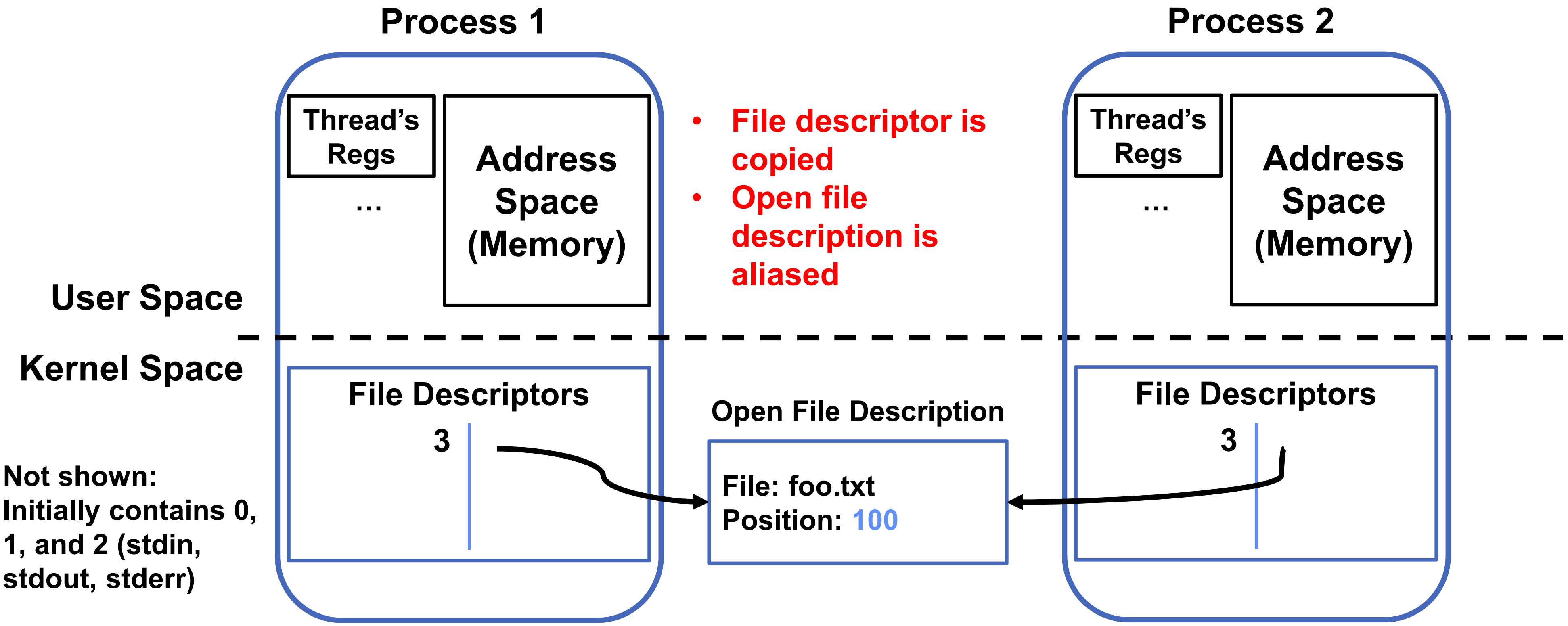


Suppose that we execute
open("foo.txt")
and that the result is 3

Next, suppose that we execute
read(3, buf, 100)
and that the result is 100

Finally, suppose that we execute
close(3)

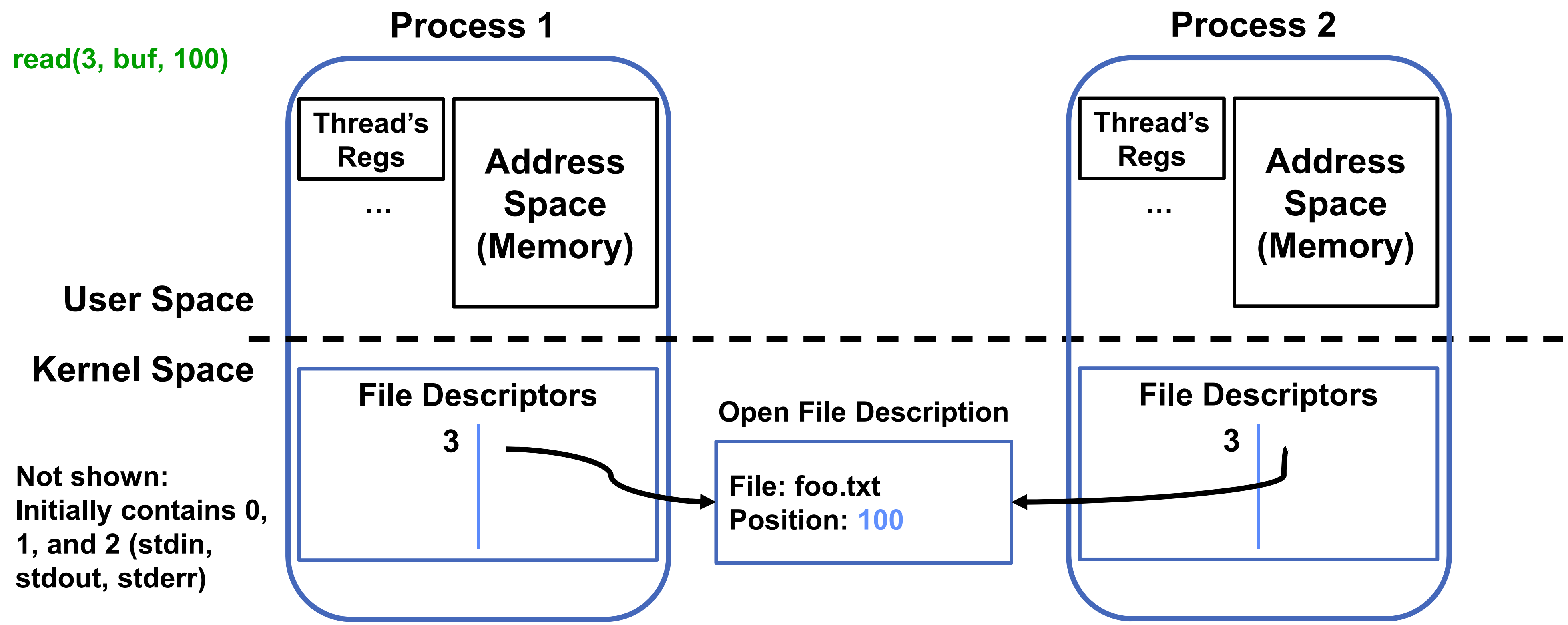
Instead of Closing, let’s `fork()`!



- File descriptor is copied
- Open file description is aliased

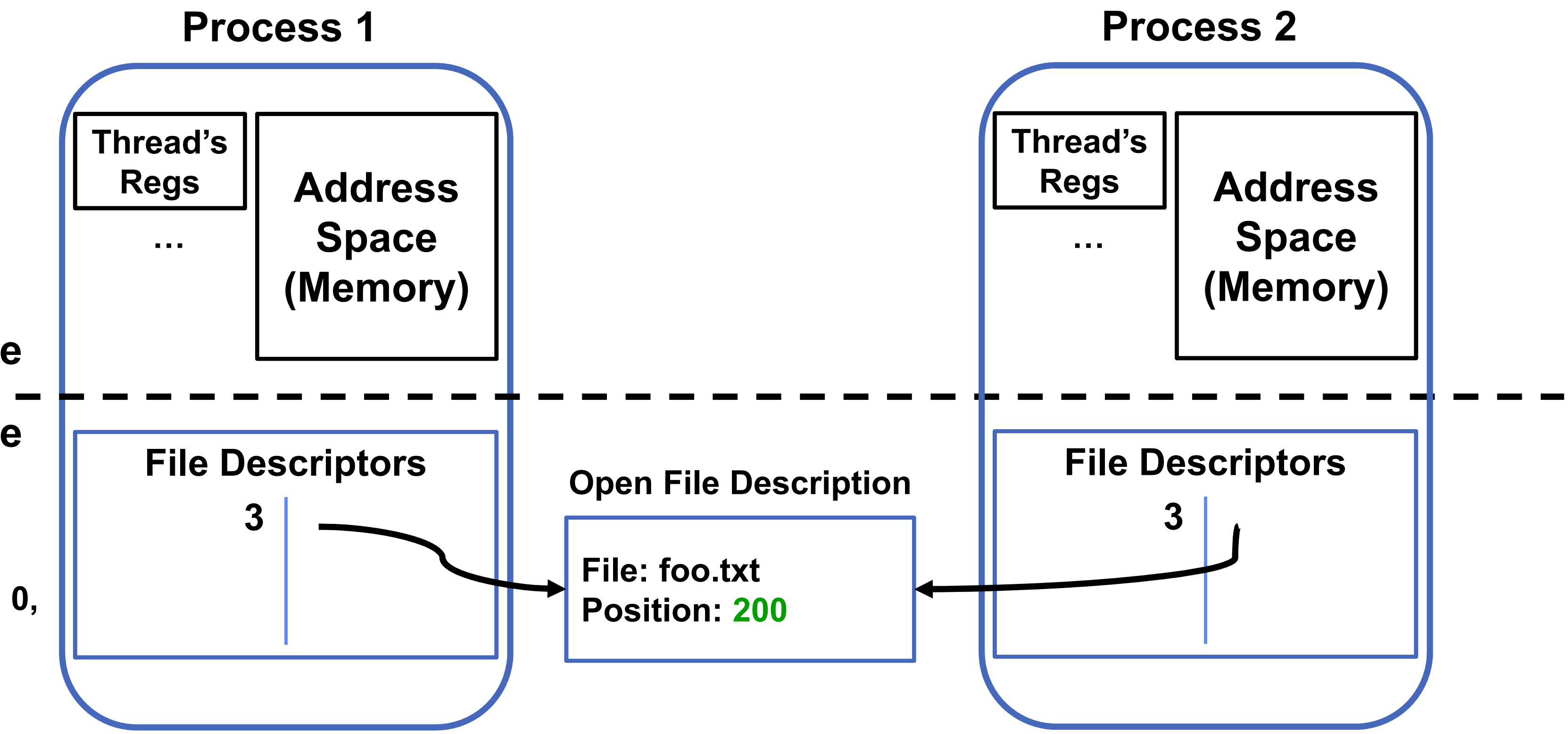
Not shown: Initially contains 0, 1, and 2 (stdin, stdout, stderr)

Open File Description is *Aliased*



Open File Description is *Aliased*

read(3, buf, 100)



Process 1

Process 2

Thread's Regs

…

Address Space (Memory)

User Space

Kernel Space

File Descriptors

3

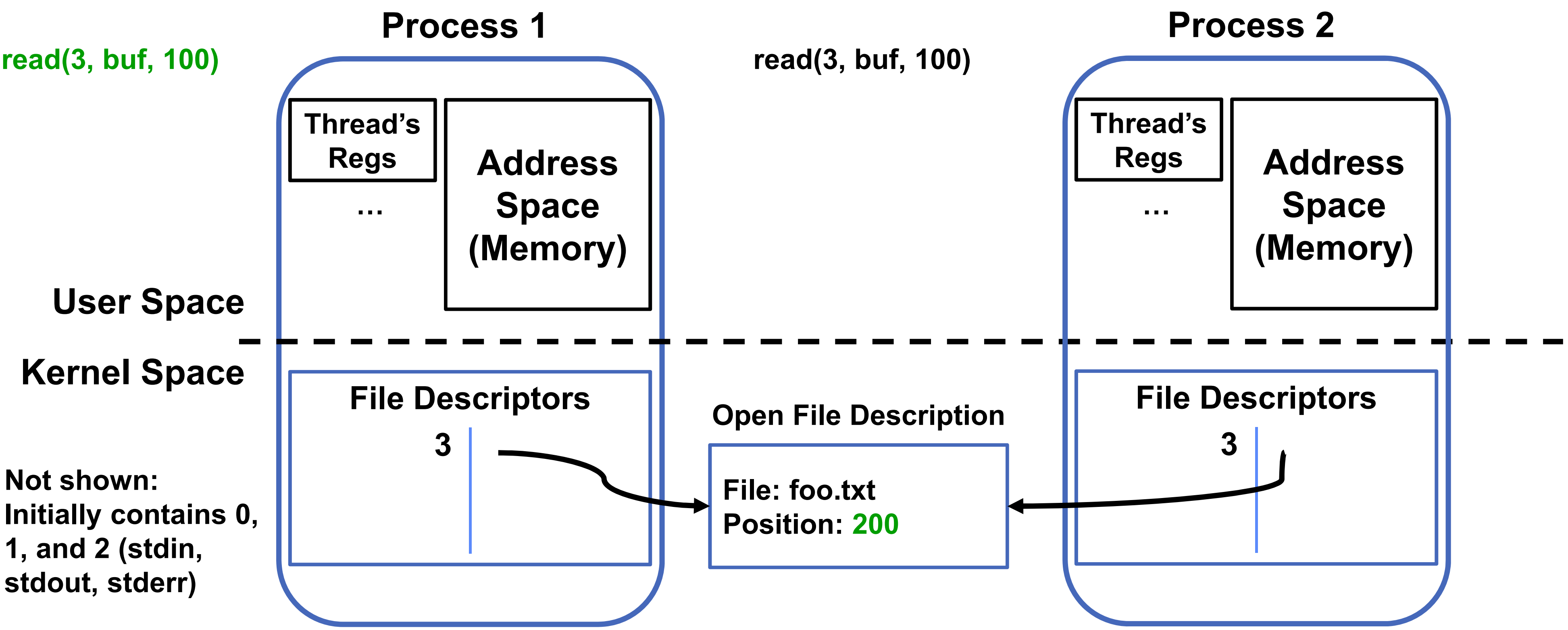
Open File Description

File: foo.txt
Position: 200

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

Open File Description is *Aliased*

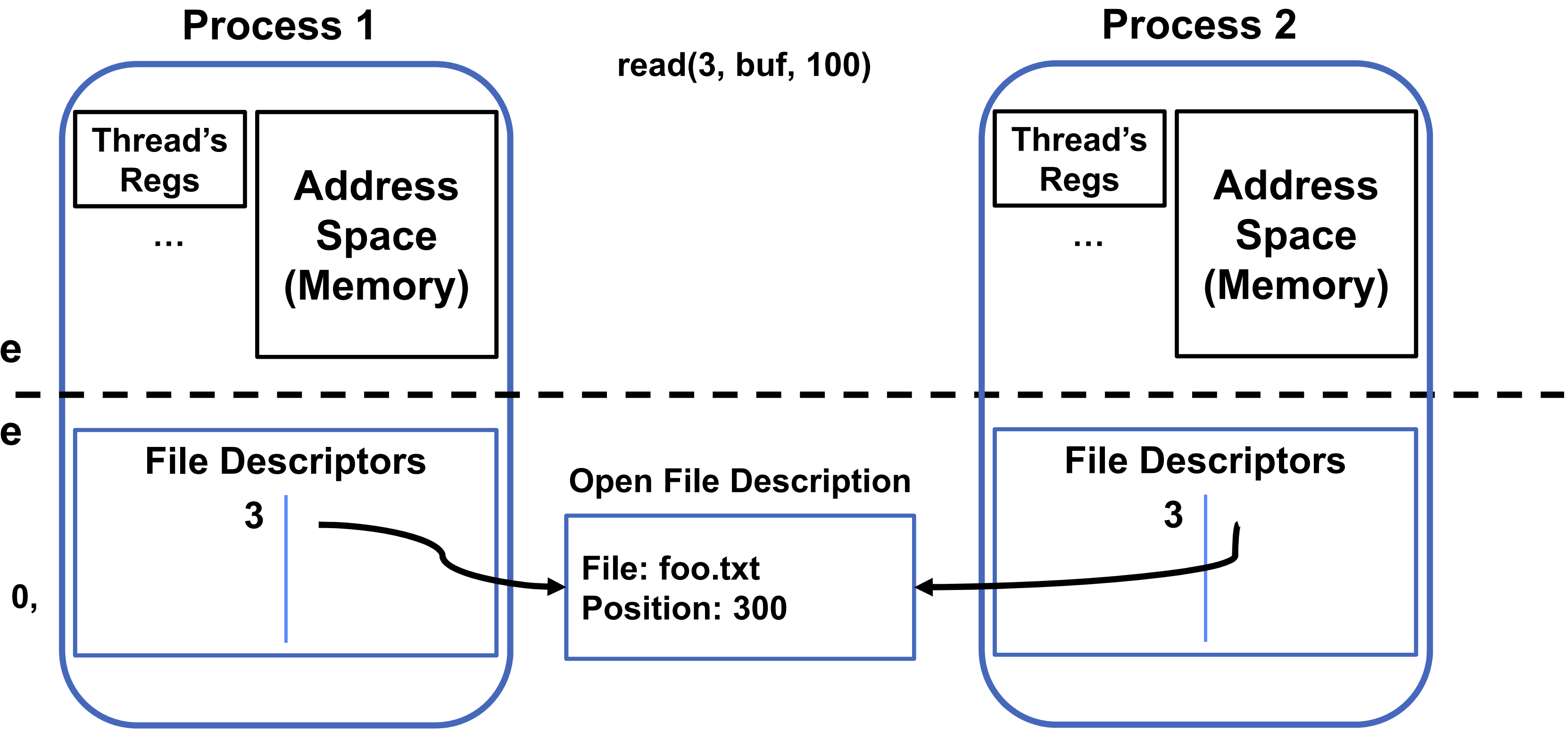
read(3, buf, 100)



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

Open File Description is *Aliased*

read(3, buf, 100)

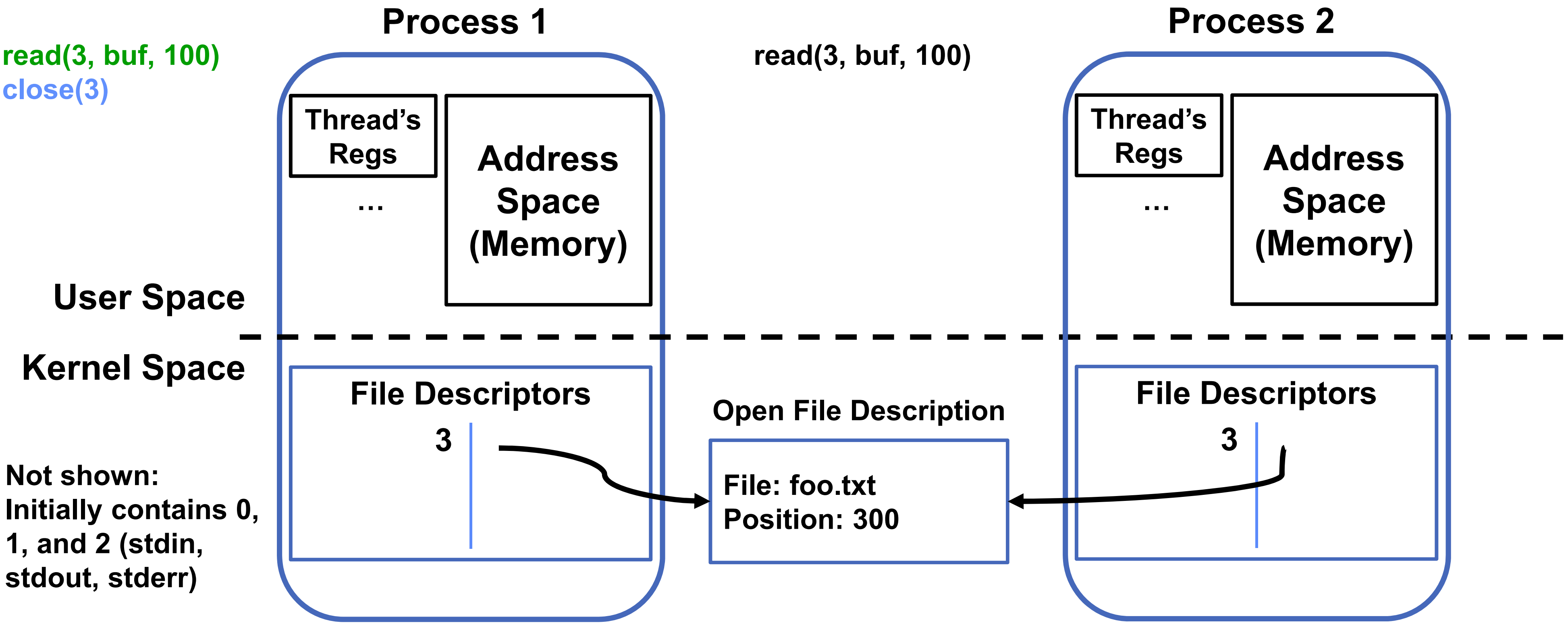


User Space

Kernel Space

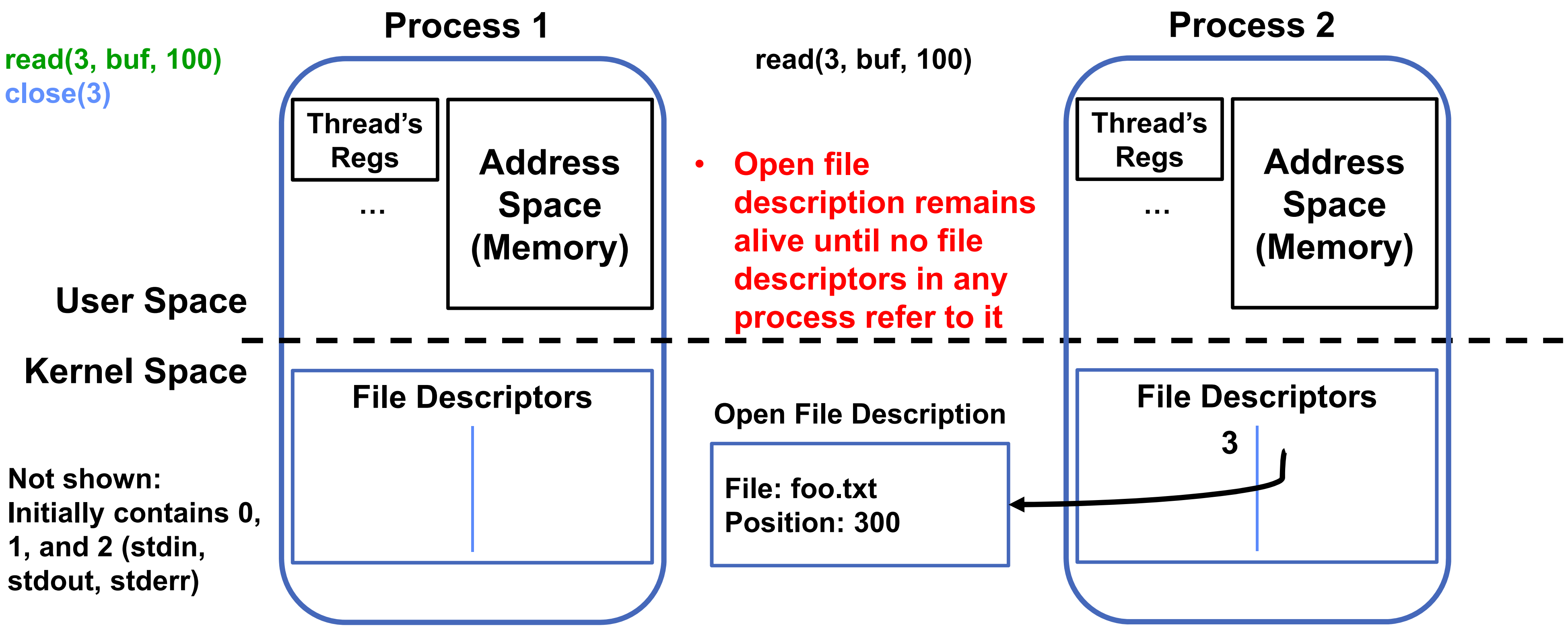
Not shown:
Initially contains 0, 1, and 2 (stdin, stdout, stderr)

File Descriptor is *Copied*



File Descriptor is *Copied*

read(3, buf, 100)
close(3)



- Open file description remains alive until no file descriptors in any process refer to it

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

Why is Aliasing the Open File Description a Good Idea?

- It allows for *shared resources* between processes

Recall: In POSIX, Everything is a "File"

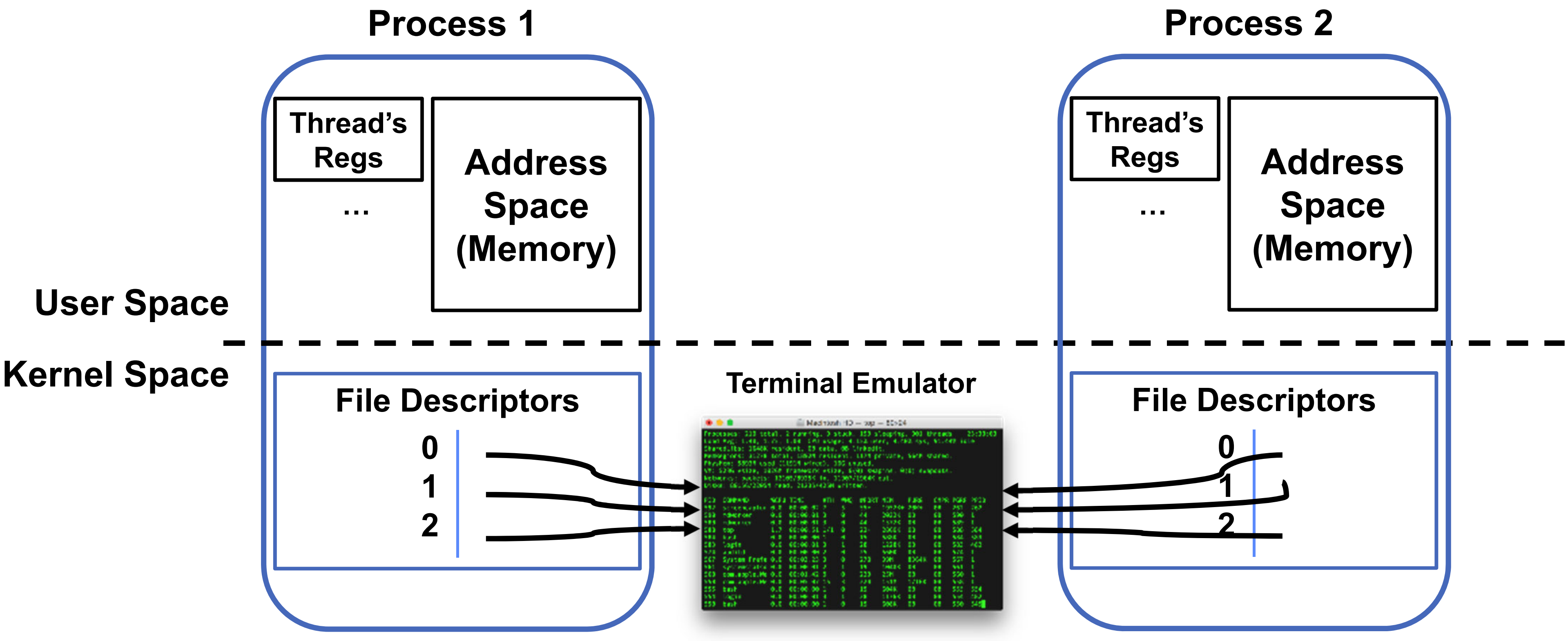
- Identical interface for:
  - – Files on disk
  - – Devices (terminals, printers, etc.)
  - – Regular files on disk
  - – Networking (sockets)
  - – Local interprocess communication (pipes, sockets)

- Based on the system calls **open()**, **read()**, **write()**, and **close()**

Example: Shared Terminal Emulator

- When you `fork()` a process, the parent's and child's `printf` outputs go to the same terminal

Example: Shared Terminal Emulator



Process 1

Thread's Regs

…

Address Space (Memory)

User Space

Kernel Space

File Descriptors

0

1

2

Terminal Emulator

Process 2

Thread's Regs

…

Address Space (Memory)

File Descriptors

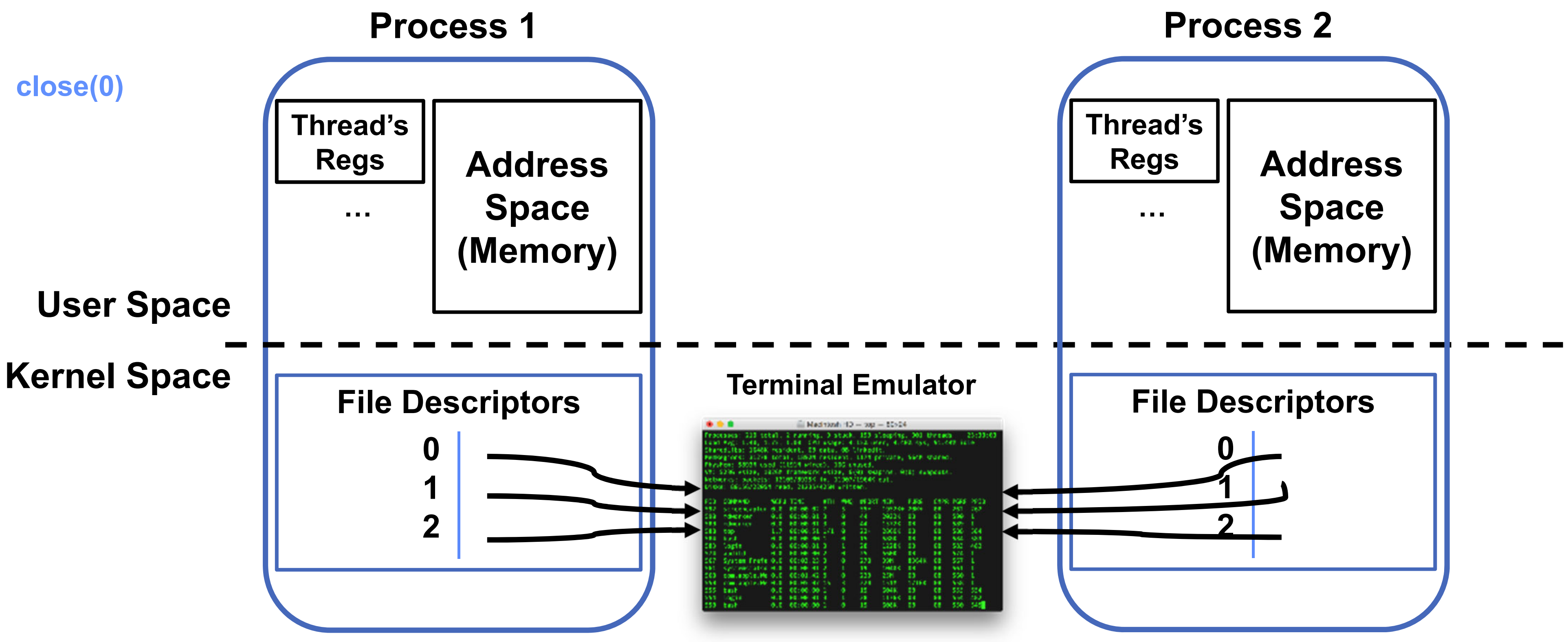
0

1

2

Example: Shared Terminal Emulator

close(0)



Process 1

Thread's Regs

…

Address Space (Memory)

Process 2

Thread's Regs

…

Address Space (Memory)

User Space

Kernel Space

File Descriptors

0
1
2

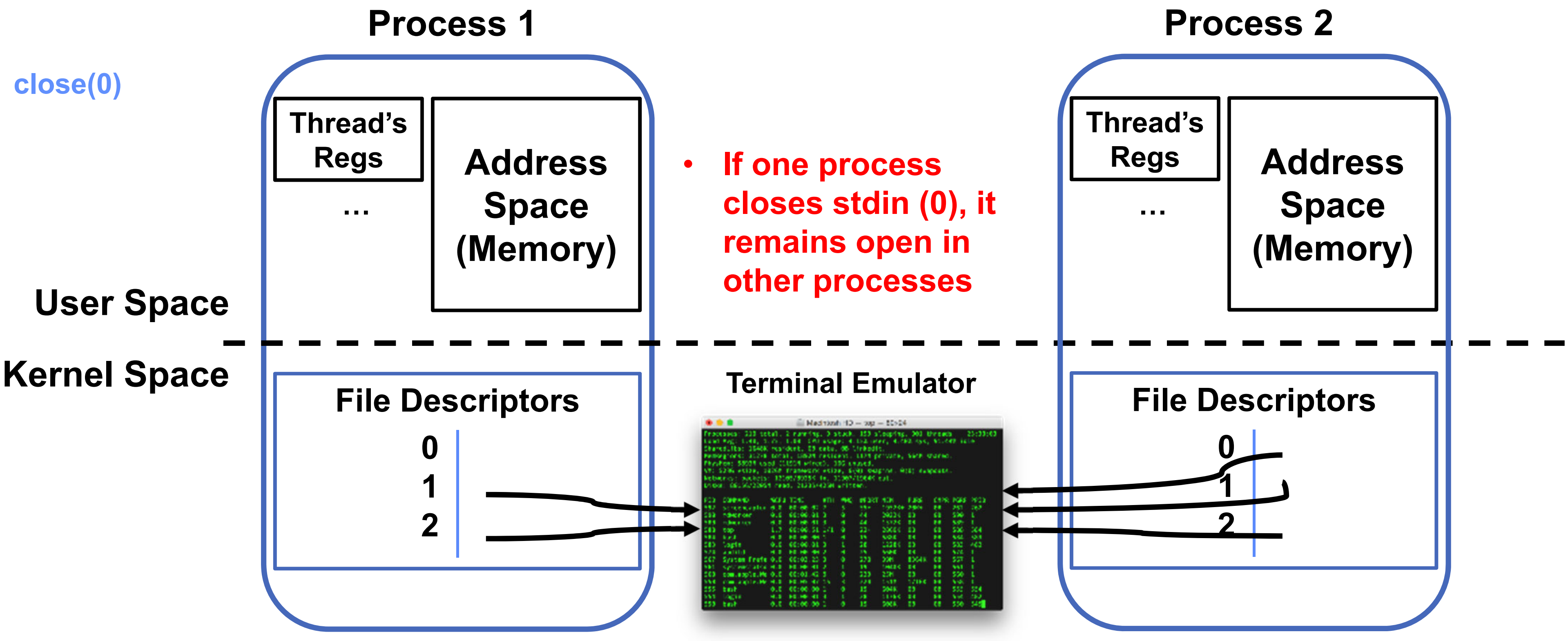
Terminal Emulator

File Descriptors

0
1
2

Example: Shared Terminal Emulator

close(0)



Process 1

Process 2

Thread's Regs

…

Address Space (Memory)

User Space

Kernel Space

File Descriptors

0
1
2

Terminal Emulator

- If one process closes stdin (0), it remains open in other processes

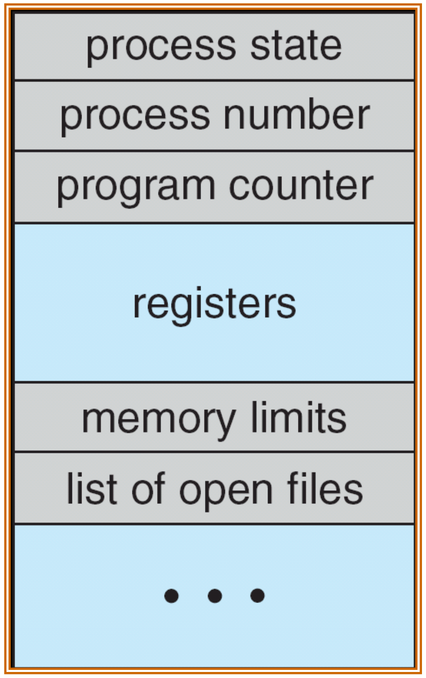
Other Examples

- Shared network connections after `fork()`
  - Allows handling each connection in a separate process
  - We'll explore this next time

- Shared access to pipes
  - Useful for interprocess communication
  - And in writing a shell (Homework 2)

Recall: How do we Multiplex Processes?

- The current state of process held in a process control block (PCB):
  - This is a “snapshot” of the execution and protection environment
  - Only one PCB active at a time
- Give out CPU time to different processes (Scheduling):
  - Only one process “running” at a time
  - Give more time to important processes
- Give pieces of resources to different processes (Protection):
  - Controlled access to non-CPU resources
  - Example mechanisms:
    - » Memory Trnslation: Give each process their own address space
    - » Kernel/User duality: Arbitrary multiplexing of I/O through system calls


process state

process number

program counter

registers

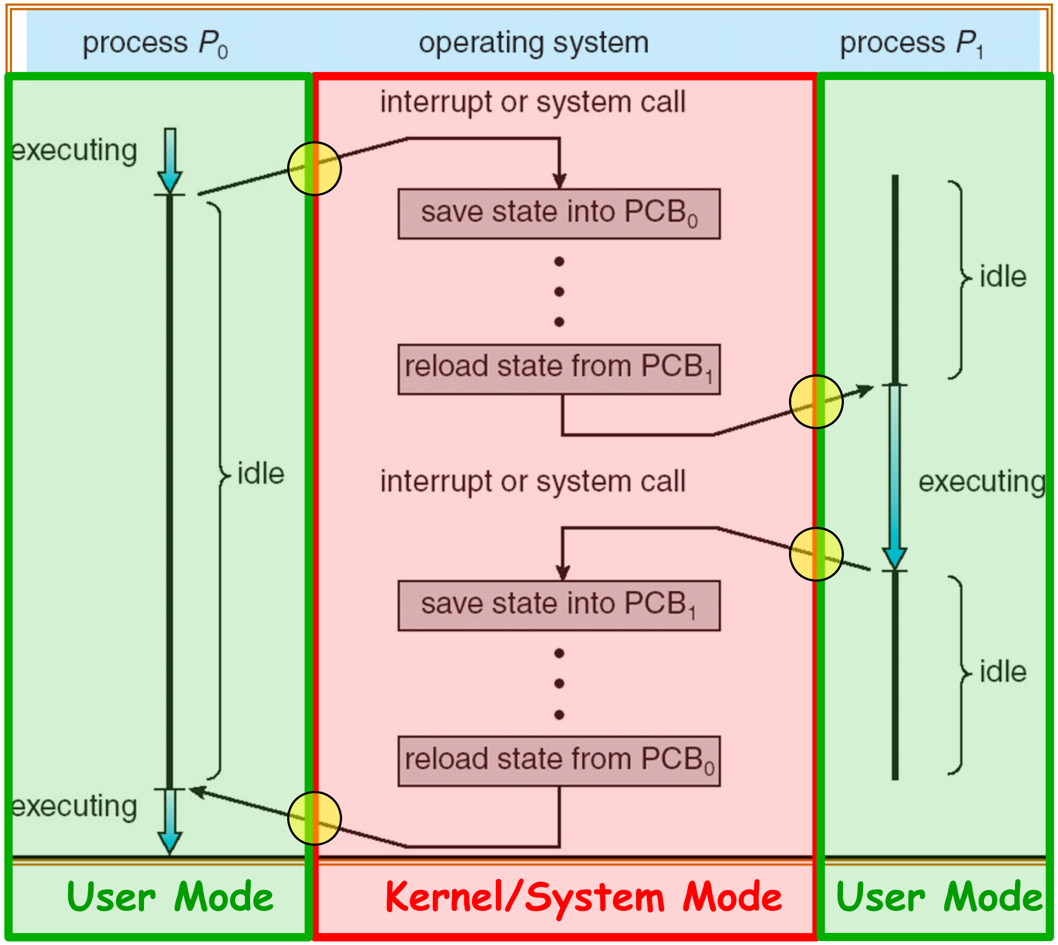
memory limits

list of open files

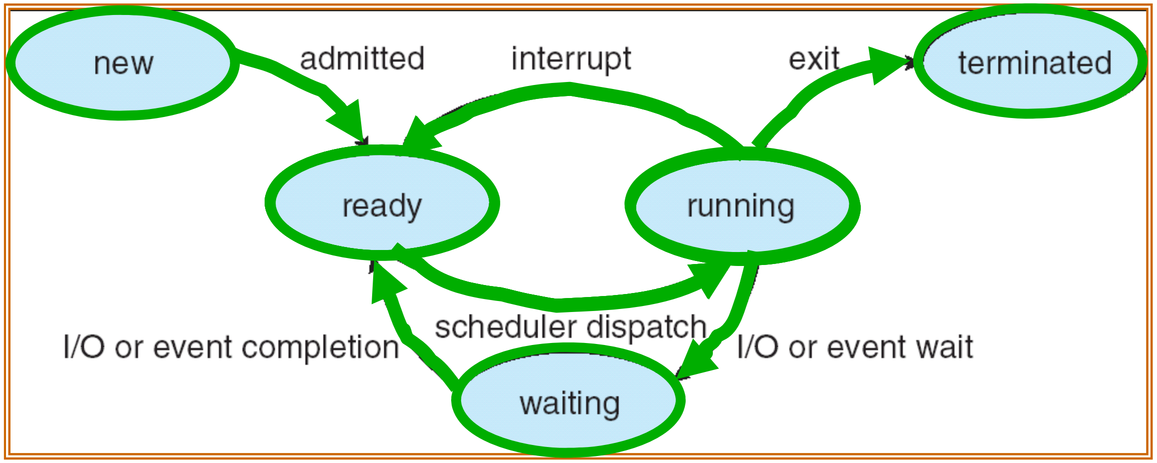
• • •

Process Control Block

Recall: CPU Switch From Process A to Process B

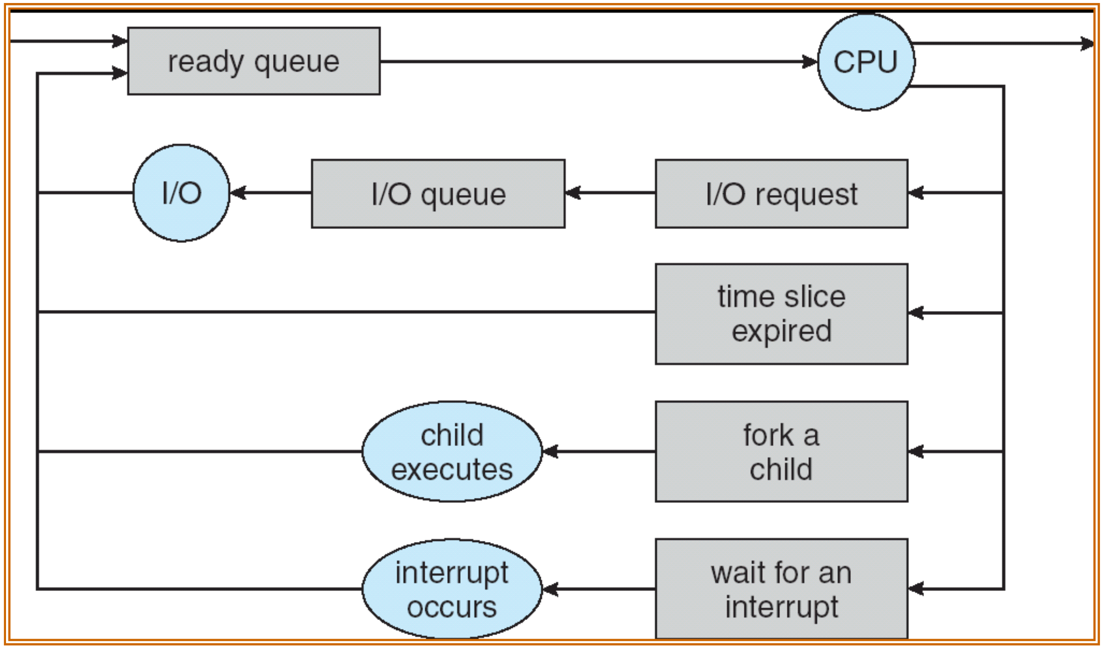


Lifecycle of a Process



- As a process executes, it changes state:
  - new: The process is being created
  - ready: The process is waiting to run
  - running: Instructions are being executed
  - waiting: Process waiting for some event to occur
  - terminated: The process has finished execution

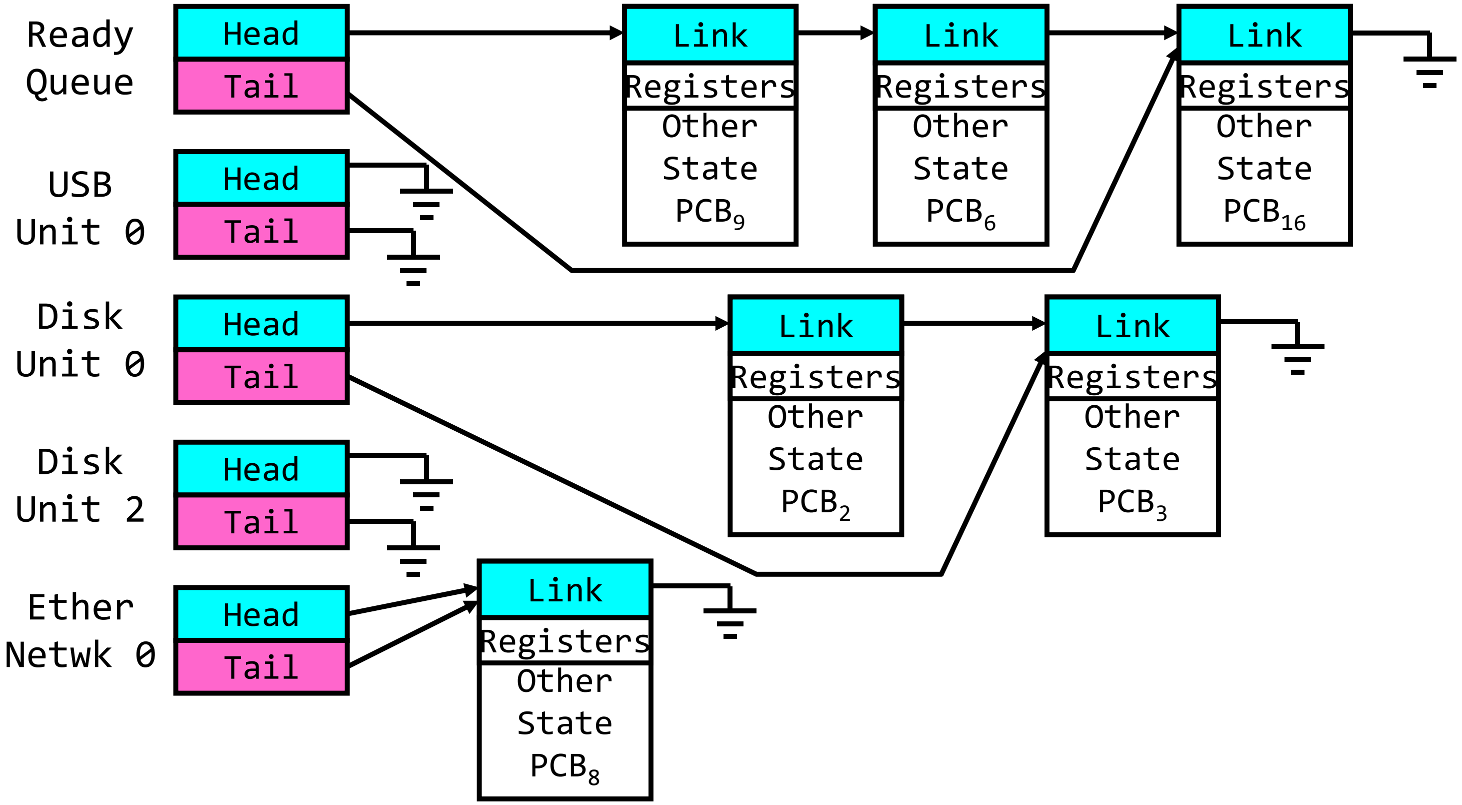
Process Scheduling



- PCBs move from queue to queue as they change state
  - Decisions about which order to remove from queues are Scheduling decisions
  - Many algorithms possible (few weeks from now)

Ready Queue And Various I/O Device Queues

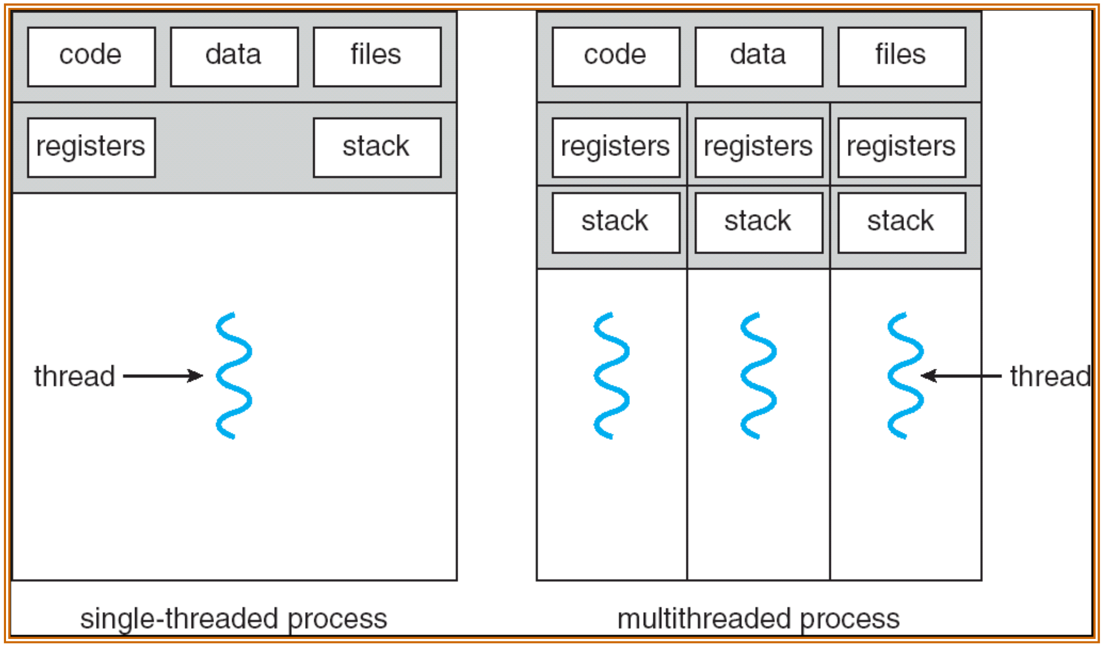
- Process not running ⇒ PCB is in some scheduler queue
  - – Separate queue for each device/signal/condition
  - – Each queue can have a different scheduler policy



Modern Process with Threads

- Thread: *a sequential execution stream within process* (Sometimes called a "Lightweight process")
  - Process still contains a single Address Space
  - No protection between threads
- Multithreading: *a single program made up of a number of different concurrent activities*
  - Sometimes called multitasking, as in Ada …
- Why separate the concept of a thread from that of a process?
  - Discuss the "thread" part of a process (concurrency)
  - Separate from the "address space" (protection)
  - Heavyweight Process ≡ Process with one thread

Single and Multithreaded Processes



- Threads encapsulate concurrency: “Active” component
- Address spaces encapsulate protection: “Passive” part
  - – Keeps buggy program from trashing the system
- Why have multiple threads per address space?

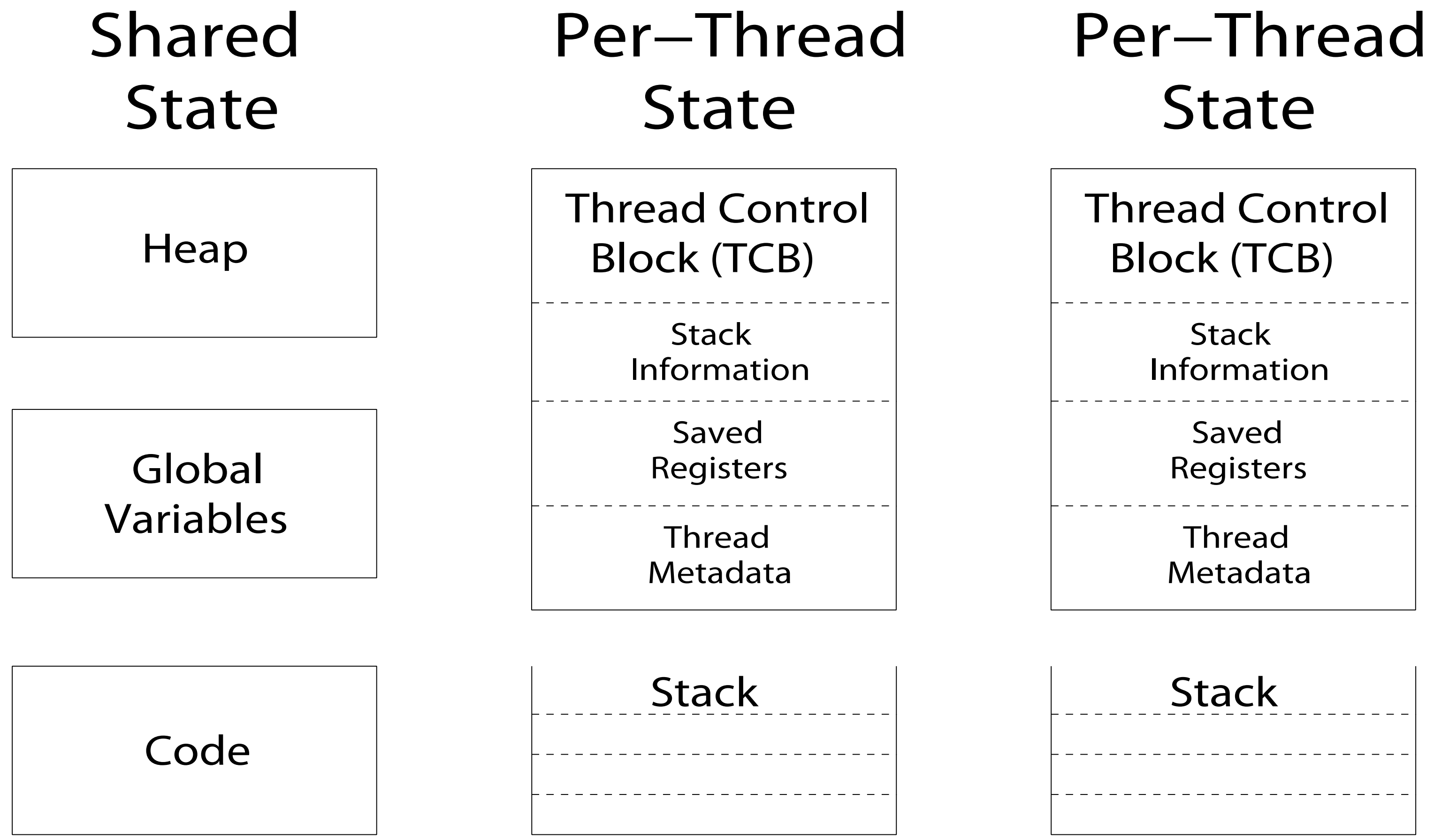
Thread State

- State shared by all threads in process/address space
  - Content of memory (global variables, heap)
  - I/O state (file descriptors, network connections, etc)

- State "private" to each thread
  - Kept in TCB ≡ Thread Control Block
  - CPU registers (including, program counter)
  - Execution stack – what is this?

- Execution Stack
  - Parameters, temporary variables
  - Return PCs are kept while called procedures are executing

Shared vs. Per-Thread State



Shared State

Heap

Global Variables

Code

Per–Thread State

Thread Control Block (TCB)

Stack Information

Saved Registers

Thread Metadata

Stack

Per–Thread State

Thread Control Block (TCB)

Stack Information

Saved Registers

Thread Metadata

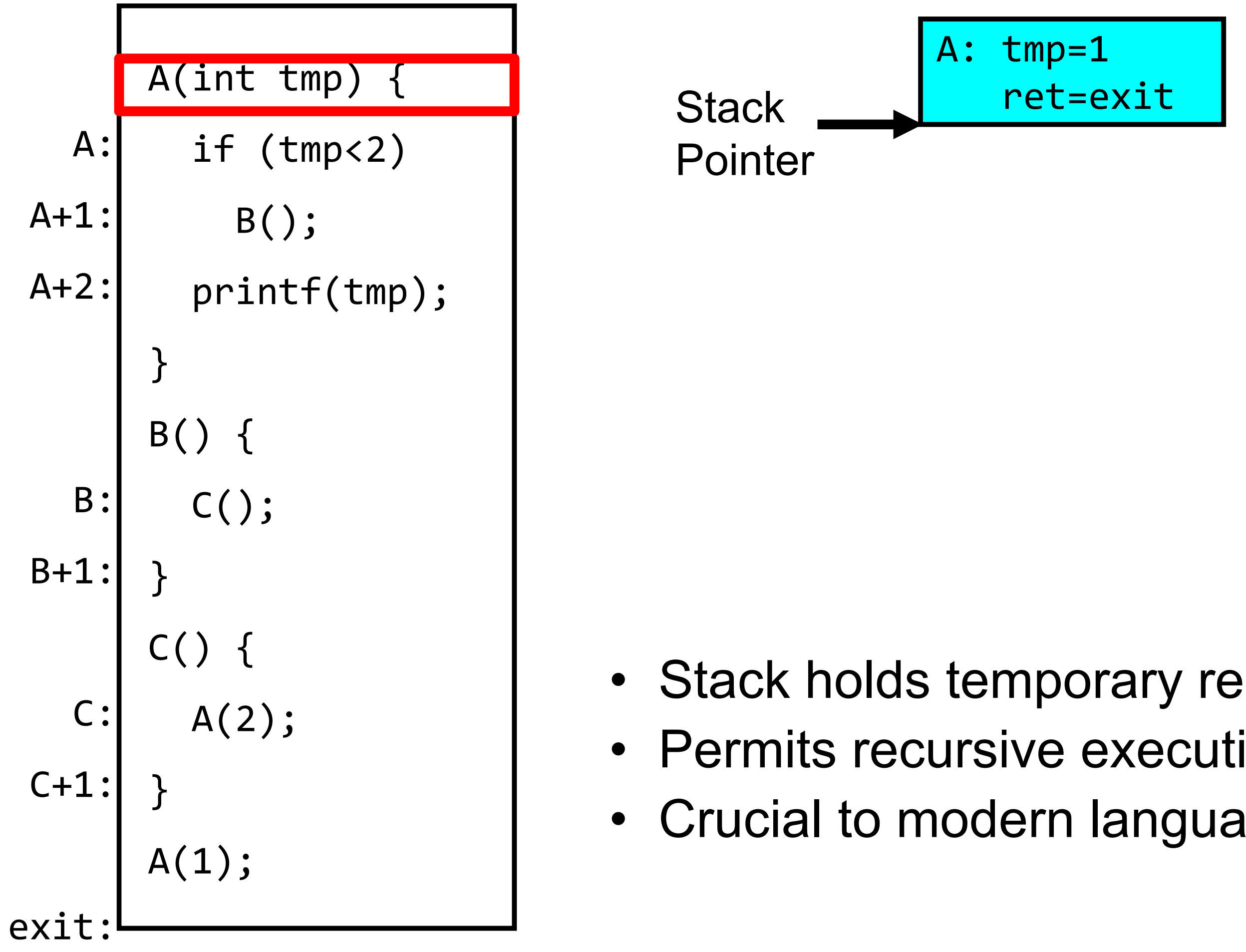
Stack

Execution Stack Example

```
      A(int tmp) {
   A:   if (tmp<2)
 A+1:     B();
 A+2:   printf(tmp);
      }
      B() {
   B:   C();
 B+1: }
      C() {
   C:   A(2);
 C+1: }
      A(1);
exit:
```

- Stack holds temporary results
- Permits recursive execution
- Crucial to modern languages

Execution Stack Example



```
      A(int tmp) {
A:      if (tmp<2)
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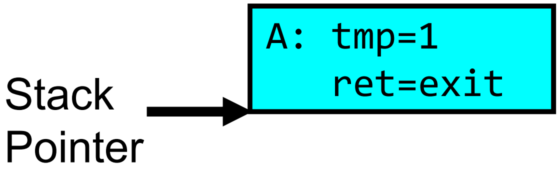

Stack Pointer

```
A: tmp=1
   ret=exit
```

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Execution Stack Example

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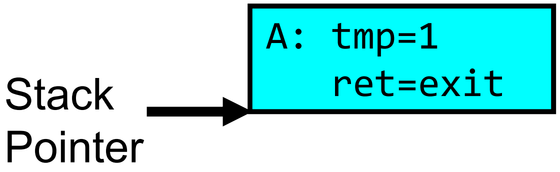

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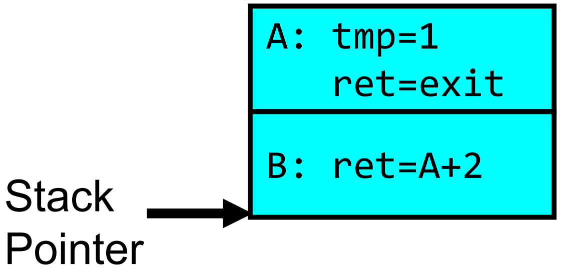
```



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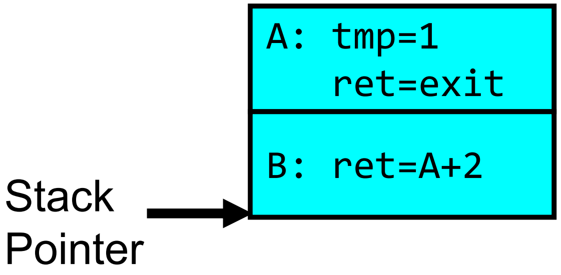
```



A: tmp=1
ret=exit

B: ret=A+2

Stack Pointer

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Execution Stack Example

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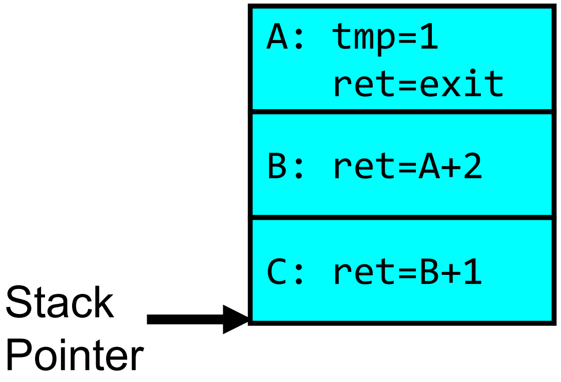
```



A: tmp=1
ret=exit

B: ret=A+2

C: ret=B+1

Stack Pointer

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Execution Stack Example

```
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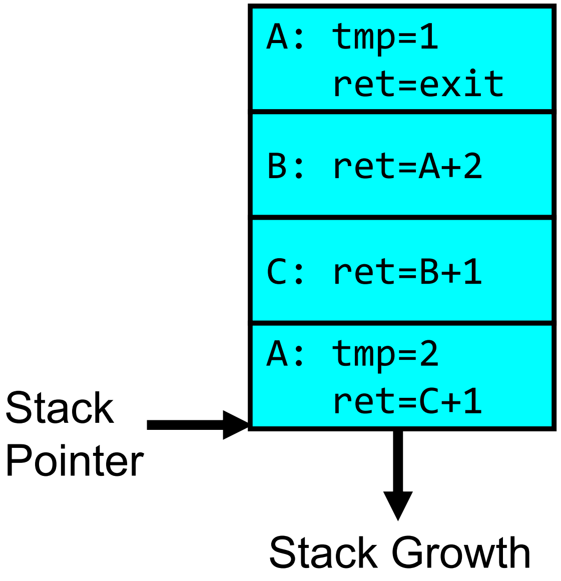
```



A: tmp=1
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B: ret=A+2

C: ret=B+1

A: tmp=2
ret=C+1

Stack Pointer

Stack Growth

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Execution Stack Example

```
        A(int tmp) {
A:        if (tmp<2)
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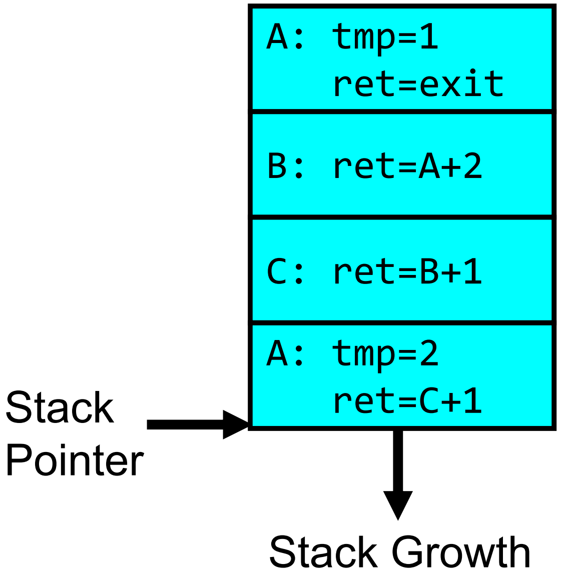
A+2:      printf(tmp);
        }
        B() {
B:        C();
B+1:    }
        C() {
C:        A(2);
C+1:    }
        A(1);
exit:
```



A: tmp=1
ret=exit

B: ret=A+2

C: ret=B+1

A: tmp=2
ret=C+1

Output: `>2`

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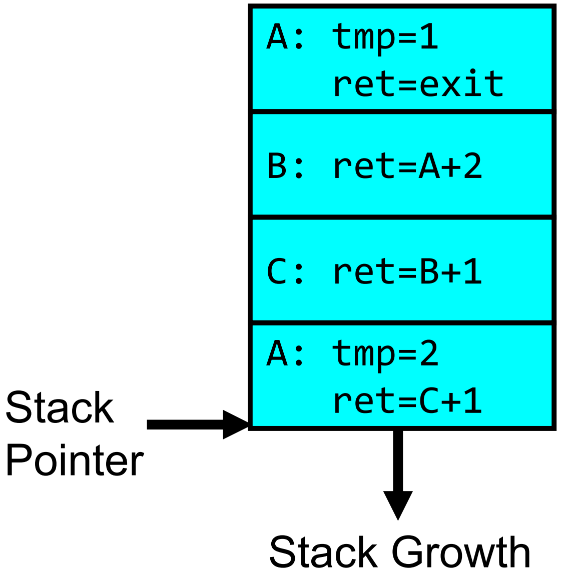

A: tmp=1
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A: tmp=2
ret=C+1

Output:

```
>2
```

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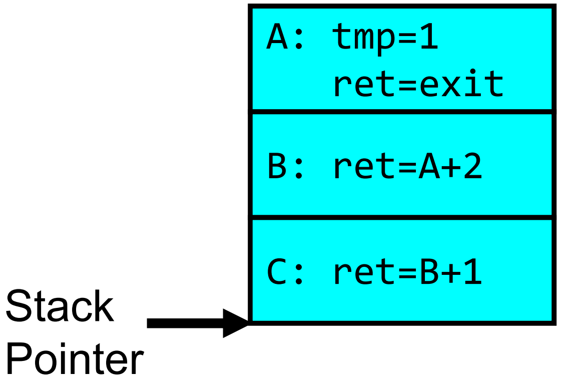

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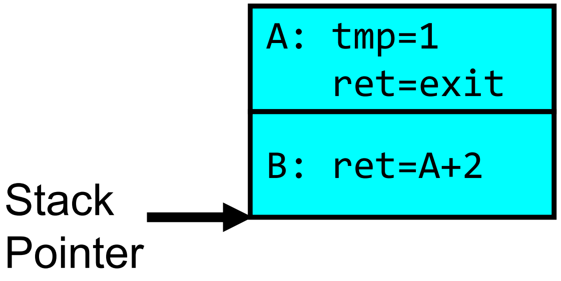

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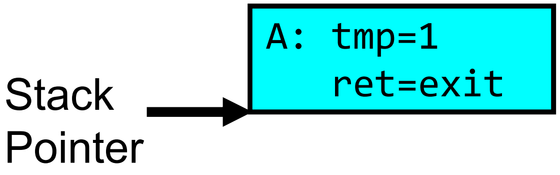

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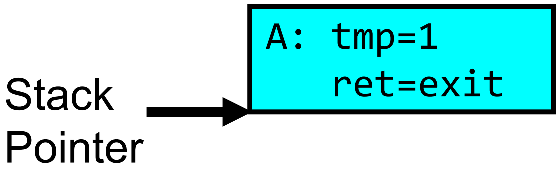

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```
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```

```
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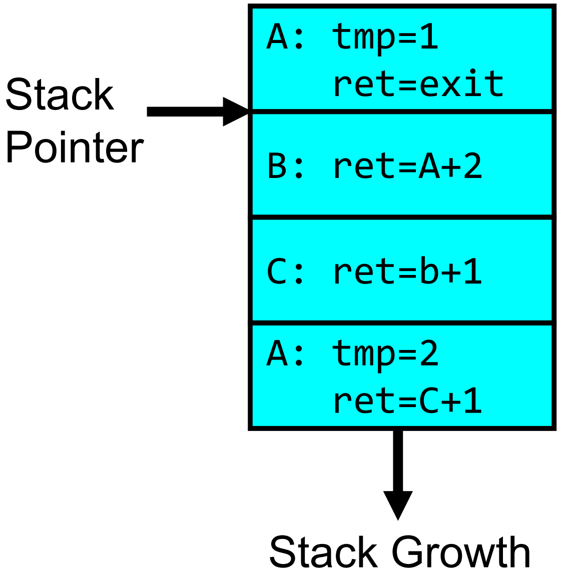

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Motivational Example for Threads

- Imagine the following C program:

```
main() {
   ComputePI(“pi.txt”);
   PrintClassList(“classlist.txt”);
}
```

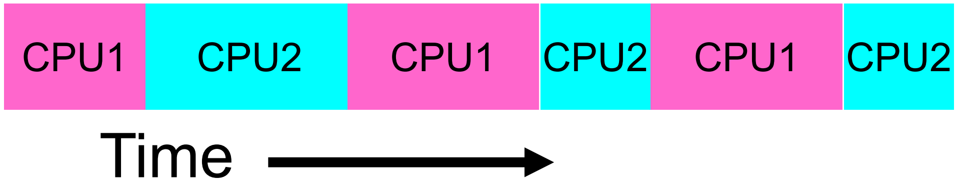
- What is the behavior here?
  - Program would never print out class list
  - Why? `ComputePI` would never finish

Use of Threads

- Version of program with Threads (loose syntax):

```
main() {
   ThreadFork(ComputePI, “pi.txt” ));
   ThreadFork(PrintClassList, “classlist.txt”));
}
```

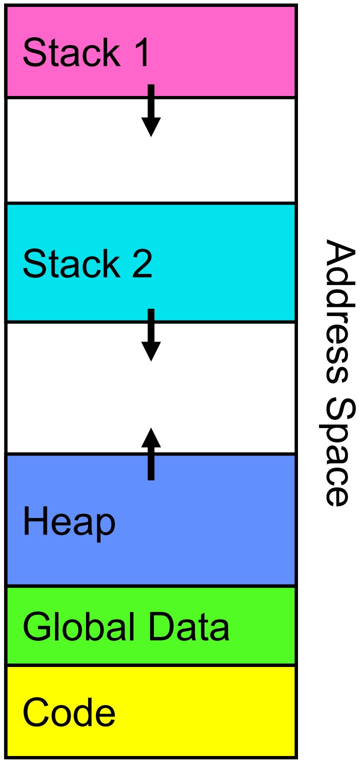
- What does `ThreadFork()` do?
  - Start independent thread running given procedure
- What is the behavior here?
  - Now, you would actually see the class list
  - This *should* behave as if there are two separate CPUs



Memory Footprint: Two-Threads

- If we stopped this program and examined it with a debugger, we would see
  - Two sets of CPU registers
  - Two sets of Stacks

- Questions:
  - How do we position stacks relative to each other?
  - What maximum size should we choose for the stacks?
  - What happens if threads violate this?
  - How might you catch violations?



OS Library API for Threads: *pthreads*

pThreads: POSIX standard for thread programming
[POSIX.1c, Threads extensions (IEEE Std 1003.1c-1995)]

```
int pthread_create(pthread_t *thread, const pthread_attr_t *attr,
                   void *(*start_routine)(void*), void *arg);
```

- thread is created executing *start_routine* with *arg* as its sole argument.
- return is implicit call to pthread_exit

```
void pthread_exit(void *value_ptr);
```

- terminates the thread and makes *value_ptr* available to any successful join

```
int pthread_yield();
```

- causes the calling thread to yield the CPU to other threads

```
int pthread_join(pthread_t thread, void **value_ptr);
```

- suspends execution of the calling thread until the target *thread* terminates.
- On return with a non-NULL *value_ptr* the value passed to *pthread_exit()* by the terminating thread is made available in the location referenced by *value_ptr*.

prompt% man pthread
https://pubs.opengroup.org/onlinepubs/7908799/xsh/pthread.h.html

Conclusion

- Device Driver: Device-specific code in the kernel that interacts directly with the device hardware
  - Supports a standard, internal interface
  - Same kernel I/O system can interact easily with different device drivers
- File abstraction works for inter-processes communication (local or Internet)
- Socket: an abstraction of a network I/O queue (IPC mechanism)

- Processes have two parts
  - One or more Threads (Concurrency)
  - Address Spaces (Protection)
- Stack is an essential part of a computation stream
  - Every thread has a stack!