Abstractions 2: Files

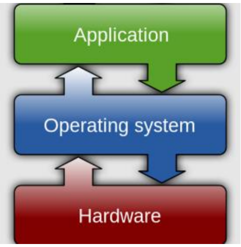
Lecture 4

Hartmut Kaiser

https://teaching.hkaiser.org/spring2026/csc4103/

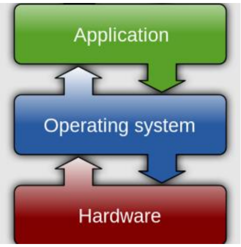
Recall: Threads

- Independently schedulable execution sequence that runs concurrently with other threads
  - It can block waiting for something while others progress
  - It can work in parallel with others
- Has local state (its stack, registers) and shares static data and heap with other threads in the same process
- In the absence of synchronization operations, arbitrary interleaving of threads may occur



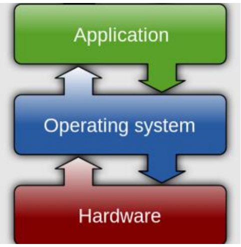
Recall: Synchronization

- Mutual Exclusion: Ensuring only one thread does a particular thing at a time (one thread excludes the others)
- Critical Section: Code exactly one thread can execute at once
  - Result of mutual exclusion
- Lock: An object only one thread can hold at a time
  - Provides mutual exclusion
  - Offers two atomic operations:
    - Lock.Acquire() – wait until lock is free; then grab
    - Lock.Release() – Unlock, wake up waiters
- Need other tools for “cooperation”
  - e.g., semaphores



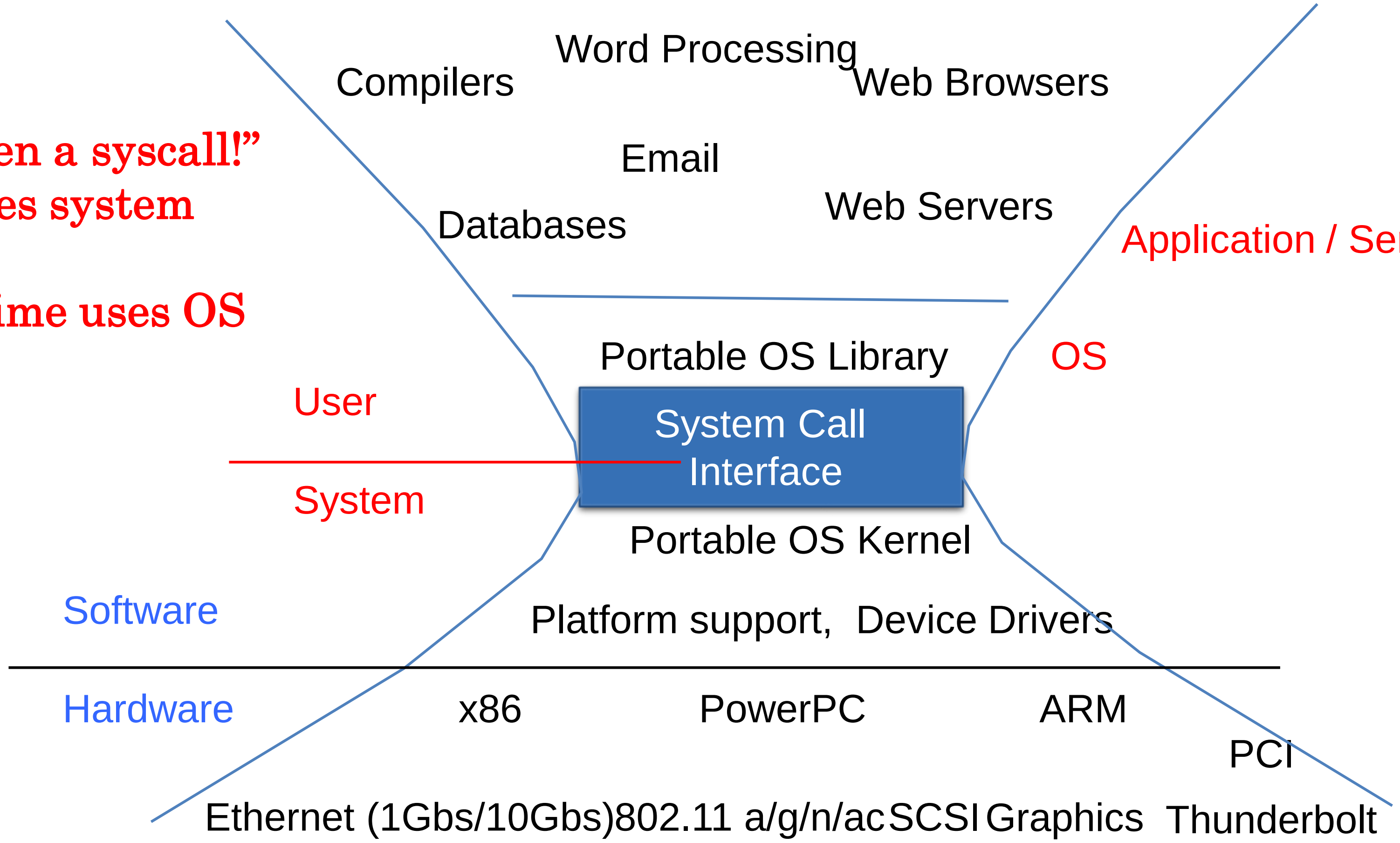
Recall: Processes

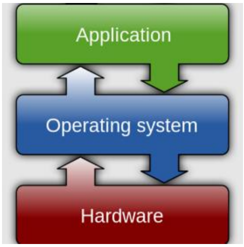
- Definition: execution environment with restricted rights
  - One or more threads executing in a single address space
  - Owns file descriptors, network connections
- Instance of a running program
  - When you run an executable, it runs in its own process
  - Application: one or more processes working together
- Protected from each other; OS protected from them
- In modern OSes, anything that runs outside of the kernel runs in a process



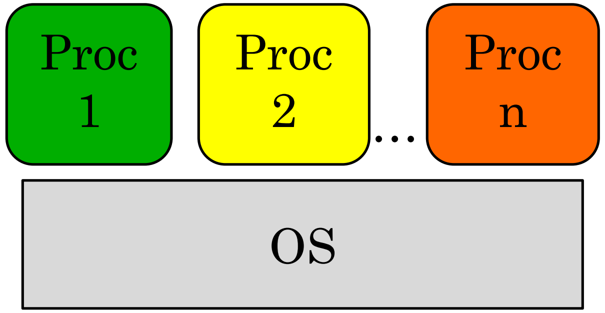
Recall: System Calls ("Syscalls")

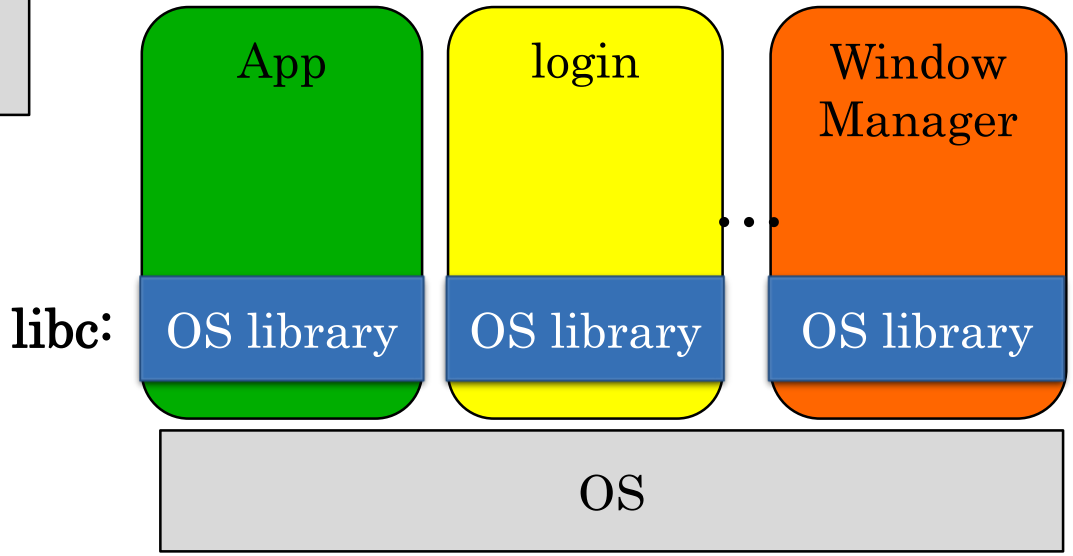
"But, I've never seen a syscall!"
- OS library issues system call
- Language runtime uses OS library…

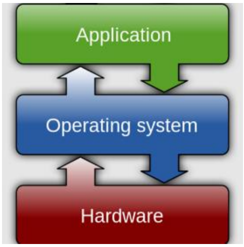




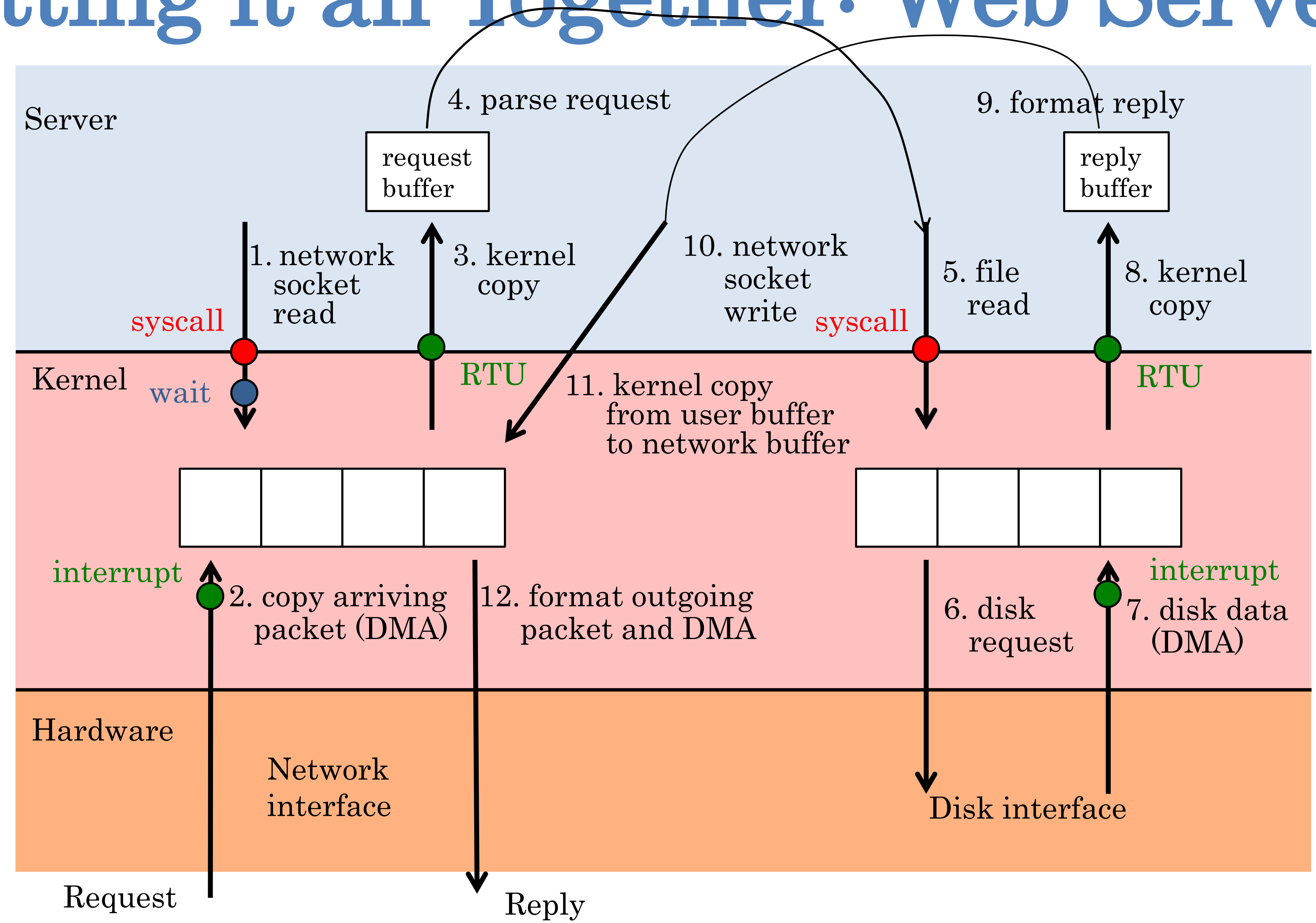
Recall: OS Library Issues Syscalls

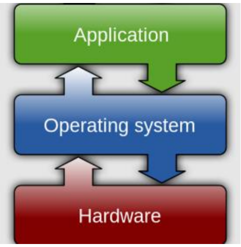






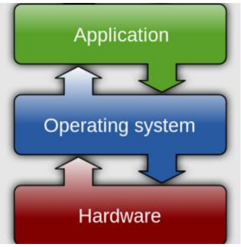
Putting it all Together: Web Server





What does pthread stand for?

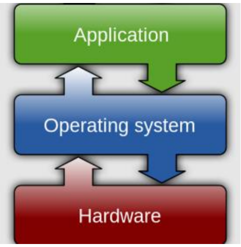
- `pthread` library: POSIX thread library
- POSIX: Portable Operating System Interface (X?)
  - Interface for application programmers (mostly)
  - Defines the term "Unix," derived from AT&T Unix
  - Created to bring order to many Unix-derived OSes, so applications are portable
  - Requires standard system call interface



Files

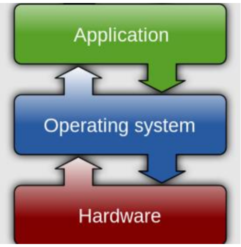
Unix/POSIX Idea: Everything is a "File"

- Identical interface for:
  - Files on disk
  - Devices (terminals, printers, etc.)
  - Networking (sockets)
  - Local inter-process communication (pipes, sockets)
- Based on the system calls `open()`, `read()`, `write()`, and `close()`



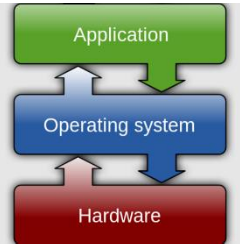
The File System Abstraction

- File
  - Named collection of data in a file system
  - POSIX File data: sequence of bytes
    - Could be text, binary, serialized objects, …
  - File Metadata: information about the file (in addition to its name)
    - Size, Modification Time, Owner, Security info, Access control
- Directory
  - "Folder" containing files & directories
  - Hierarchical (graphical) naming
    - Path through the directory graph
    - Uniquely identifies a file or directory
      - /home/ff/csc4103/public_html/fa14/index.html
- Links and Volumes (later)



Connecting Processes, File Systems, and Users

- Every process has a current working directory
  - Stored in the process control block (PCB)
- Absolute paths
  - /home/csc4103
- Relative paths
  - index.html, ./index.html
    - Refers to index.html in current working directory
  - ../index.html
    - Refers to index.html in parent of current working directory
  - ~/index.html, ~csc4103/index.html
    - Refers to index.html in the home directory



I/O and Storage Layers

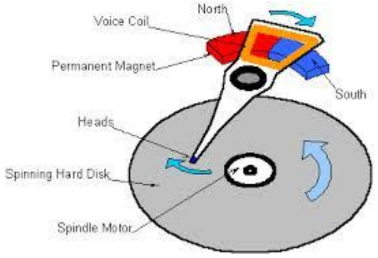
Focus of today's lecture

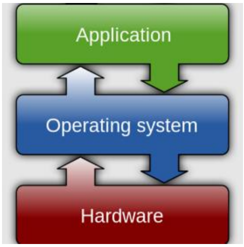
Application / Service

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



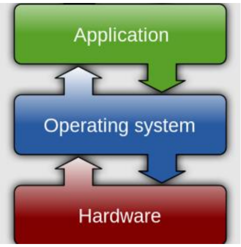




Today: The File Abstraction

- High-Level File I/O: Streams
- Low-Level File I/O: File Descriptors
- How and Why of High-Level File I/O
- Process State for File Descriptors
- Common Pitfalls with OS Abstractions

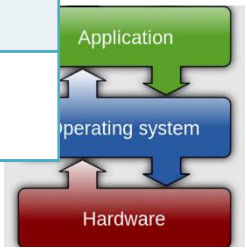


C High-Level File API – Streams

- Operates on “streams” – sequence of bytes, either text or data, with a position

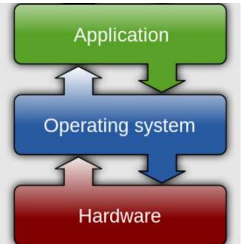
```
#include <stdio.h>
FILE* fopen(char const* filename, char const* mode);
int fclose(FILE* fp);
```

Mode Text	Binary	Descriptions
"r"	"rb"	Open existing file for reading; fails if file doesn’t exist
"w"	"wb"	Open for writing; created if does not exist
"a"	"ab"	Open for appending; created if does not exist
"r+"	"rb+"	Open existing file for reading & writing; fails if file doesn’t exist
"w+"	"wb+"	Open for reading & writing; truncated to zero if exists, create otherwise
"a+"	"ab+"	Open for reading & writing. Created if does not exist. Read from beginning, write as append



C API Standard Streams – stdio.h

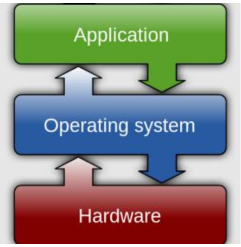
- Three predefined streams are opened implicitly when the program is executed (by C standard library)
  - `FILE* stdin` – normal source of input, can be redirected
  - `FILE* stdout` – normal source of output, can be redirected too
  - `FILE* stderr` – diagnostics and errors
- `STDIN` / `STDOUT` enable composition in Unix
- All can be redirected
  - `cat hello.txt | grep "World!"`
  - `cat`'s `stdout` goes to `grep`'s `stdin`



C High-Level File API

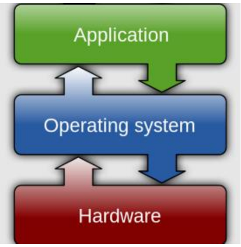
```
// character oriented
int fputc(int c, FILE* fp);                 // rtn c or EOF on err
int fputs(char const* s, FILE* fp);         // rtn > 0 or EOF

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* stream, char const* format, ...);
int fscanf(FILE* stream, char const* format, ... );
```



C Streams: Char-by-Char I/O

```
int main(void) {
  FILE* input = fopen("input.txt", "r");
  FILE* output = fopen("output.txt", "w");
  int c;

  c = fgetc(input);
  while (c != EOF) {
    fputc(output, c);
    c = fgetc(input);
  }
  fclose(input);
  fclose(output);
}
```



C High-Level File API

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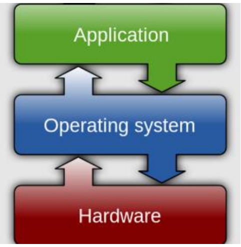
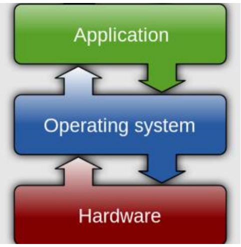


C Streams: Block-by-Block I/O

```
#define BUFFER_SIZE 1024
int main(void) {
  FILE* input = fopen("input.txt", "r");
  FILE* output = fopen("output.txt", "w");
  char buffer[BUFFER_SIZE];
  size_t length;
  length = fread(buffer, BUFFER_SIZE, sizeof(char), input);
  while (length > 0) {
    fwrite(buffer, length, sizeof(char), output);
    length = fread(buffer, BUFFER_SIZE, sizeof(char), input);
  }
  fclose(input);
  fclose(output);
}
```

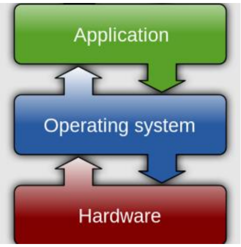


Aside: System Programming

- Systems programmers are paranoid
- We should really be writing things like:

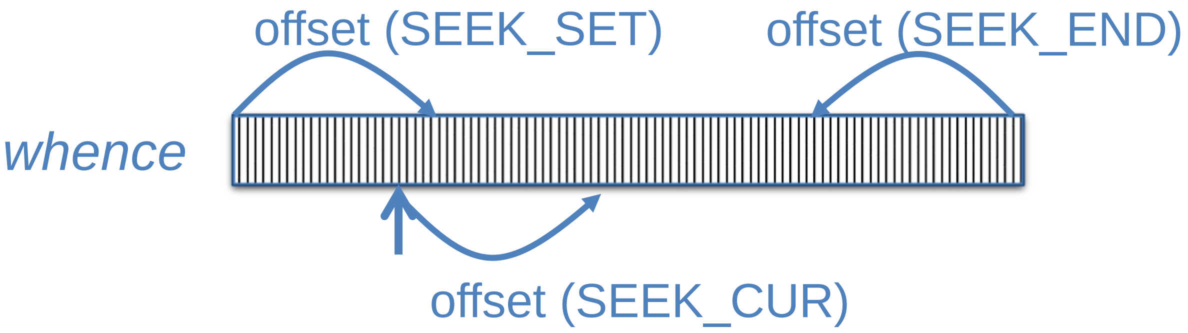
```
FILE* input = fopen("input.txt", "r");
if (input == NULL) {
  // Prints our string and error msg.
  perror("Failed to open input file");
}
```

- Be thorough about checking return values
  - Want failures to be systematically caught and dealt with

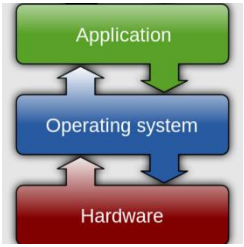


C High-Level File API: Positioning

- `int fseek(FILE* stream, long int offset, int whence);`
- `long int ftell (FILE* stream)`
- `void rewind (FILE* stream)`



- Preserves high level abstraction of a uniform stream of objects



Today: The File Abstraction

- High-Level File I/O: Streams
- Low-Level File I/O: File Descriptors
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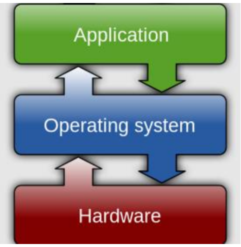


Low-Level File I/O

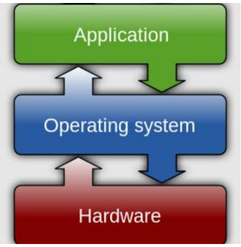
- Operations on file descriptors
  - Integer that corresponds to an object in the kernel called an open file description
  - Open file description object in the kernel represents an instance of an open file
  - Why not just use a pointer?

```
#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



C Low-Level Standard Descriptors

```
#include <unistd.h>
```

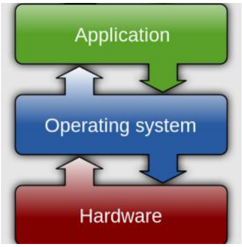
`STDIN_FILENO` - macro has value 0

`STDOUT_FILENO` - macro has value 1

`STDERR_FILENO` - macro has value 2

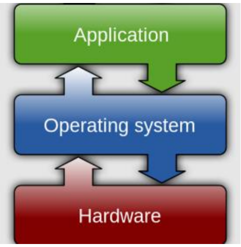
```
int fileno (FILE* stream);
```

```
FILE* fdopen (int fileno, const char* opentype);
```



Low-Level File API

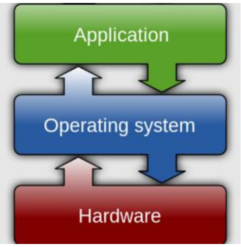
- `ssize_t read (int filedesc, void* buffer, size_t maxsize)`
  - Reads up to `maxsize` bytes – might actually read less!
  - Returns bytes read, 0 => `EOF`, -1 => error
- `ssize_t write (int filedesc, const void* buffer, size_t size)`
  - Returns bytes written
- `off_t lseek (int filedesc, off_t offset, int whence)`
  - Moves current position



Example: lowio.c

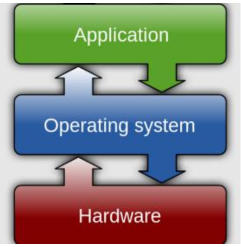
```
int main() {
  char buf[1000];
  int     fd = open("lowio.c", O_RDONLY | O_CREAT, S_IRUSR | S_IWUSR);
  ssize_t rd = read(fd, buf, sizeof(buf));
  int    err = close(fd);
  ssize_t wr = write(STDOUT_FILENO, buf, rd);
}
```

- How many bytes does this program read?



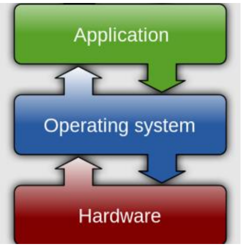
POSIX I/O: Design Patterns

- 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



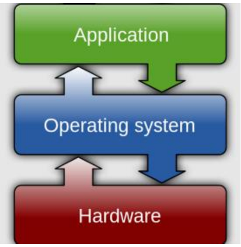
POSIX I/O: Kernel Buffering

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



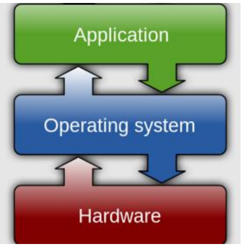
Key Unix I/O Design Concepts

- 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 look the same, reading blocks yields processor to other task
- Kernel buffered writes
  - Completion of out-going transfer decoupled from the application, allowing it to continue
- Explicit close



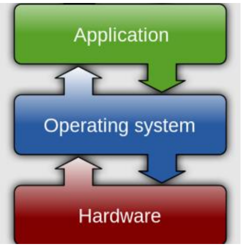
Low-Level I/O: Other Operations

- 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



Announcements

- Project 0 deadline is next Monday
- Assignment 1 out, deadline February 24
  - You should be working on this!



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- High-Level File I/O: Streams
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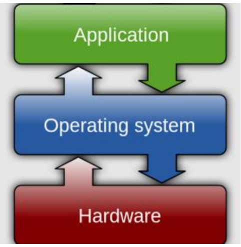


High-Level vs. Low-Level File API

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:

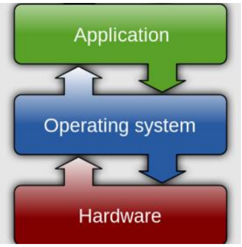
```
ssize_t read(…) {

    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

};
```



High-Level vs. Low-Level File API

- Streams are buffered in user memory:

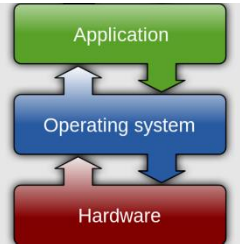
```
printf("Beginning of line ");
sleep(10); // sleep for 10 seconds
printf("and end of line\n");
```

- Prints out everything at once

- Operations on file descriptors are visible immediately

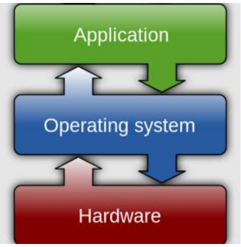
```
write(STDOUT_FILENO, "Beginning of line ", 18);
sleep(10);
write(STDOUT_FILENO, "and end of line \n", 16);
```

- Outputs "Beginning of line" 10 seconds earlier



What's in a FILE*?

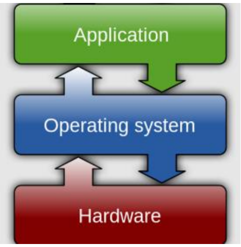
- FILE instance lives in user space, `fopen` returns pointer to it
- What's in the `FILE*` returned by `fopen`?
  - File descriptor (from call to `open`)
  - Buffer (array)
  - Lock (in case multiple threads use the `FILE` concurrently)
- Of course there's other stuff in a `FILE` too…
- … but this is useful model to have



FILE Buffering

- When you call `fwrite`, what happens to the data you provided?
  - It gets written to the `FILE`'s buffer (in user space)
  - If the `FILE`'s buffer is full, then it is flushed
    - Which means it's written to the underlying file descriptor
  - The C standard library may flush the `FILE` more frequently
    - e.g., if it sees a certain character in the stream

- When you write code, make the weakest possible assumptions about how data is flushed from `FILE` buffers



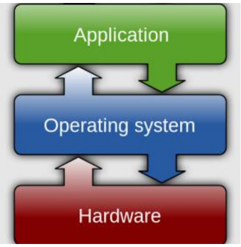
Example

- What will x be after the following code execution?

```
char x = 'c';
FILE* f1 = fopen("file.txt", "w");
fwrite("b", sizeof(char), 1, f1);

FILE* f2 = fopen("file.txt", "r");
fread(&x, sizeof(char), 1, f2);
```

- The call to `fread` might see the latest write `'b'`
- Or it might miss it, seeing the end of file (in which case `x` will remain `'c'`)



Example

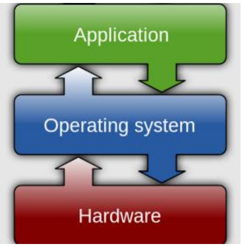
- What will x be after the following code execution?

```
char x = 'c';
FILE* f1 = fopen("file.txt", "wb");
fwrite("b", sizeof(char), 1, f1);

fflush(f1);

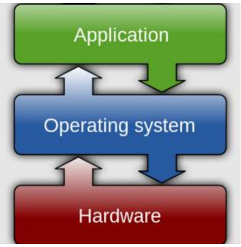
FILE* f2 = fopen("file.txt", "rb");
fread(&x, sizeof(char), 1, f2);
```

- Now, the call to `fread` will see the latest write `'b'`



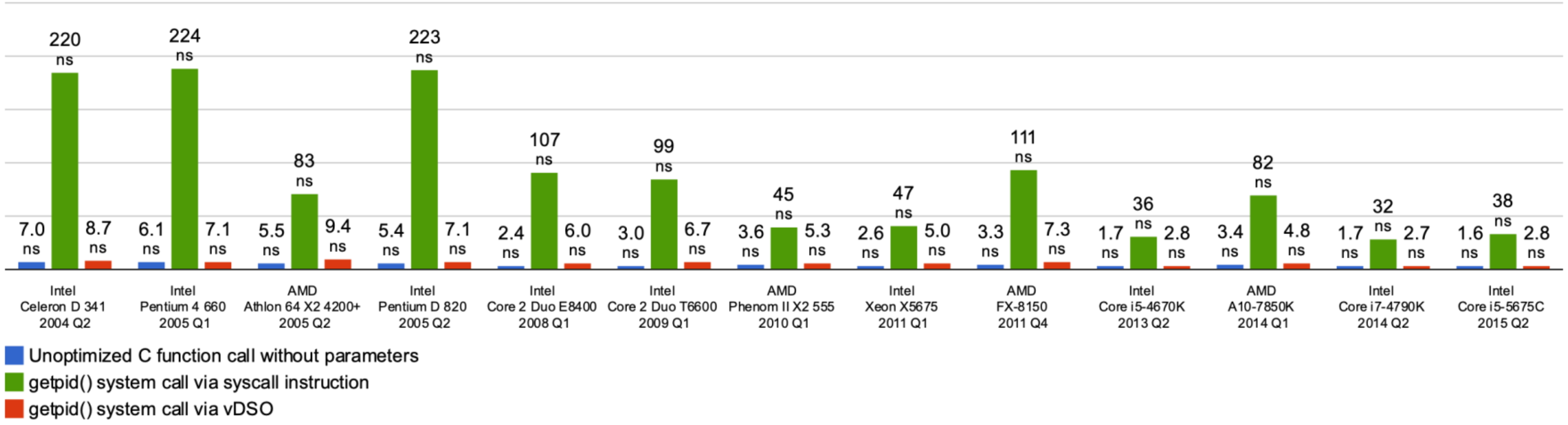
Writing Correct Code with FILE

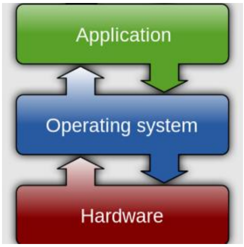
- Your code should behave correctly regardless of when/if C Standard Library flushes its buffer
  - Add your own calls to `fflush` so that data is written when you need to
  - Calls to `fclose` flush the buffer before deallocating memory and closing the file descriptor
- With the low-level file API, we don't have this problem
  - After write completes, data is visible to any subsequent reads



Why Buffer in Userspace? Overhead!

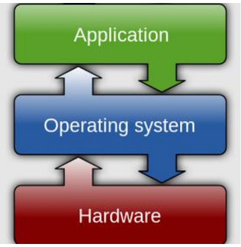
- Syscalls are 25x more expensive than function calls (~100 ns)
- `read`/`write` a file byte by byte? Max throughput of ~10MB/second
- With `fgetc`? Keeps up with your SSD





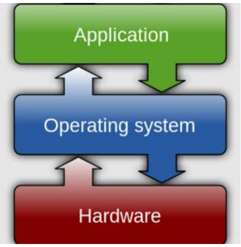
Why Buffer in Userspace? Functionality!

- System call operations less capable
  - Simplifies operating system
- Example: No “read until new line” operation
  - Solution: Make a big `read` syscall, find first new line in userspace



Today: The File Abstraction

- High-Level File I/O: Streams
- Low-Level File I/O: File Descriptors
- How and Why of High-Level File I/O
- Process State for File Descriptors
- Some Pitfalls with OS Abstractions [if time]

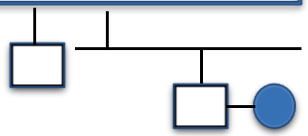


I/O and Storage Layers

Focus of today's lecture

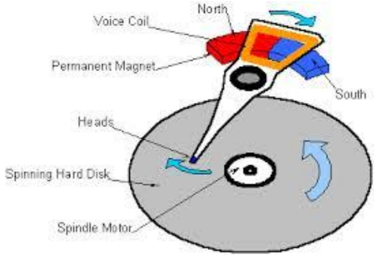
Application / Service

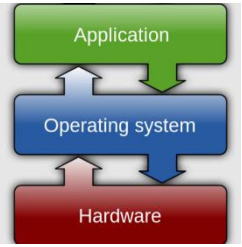
High Level I/O	*Streams*
Low Level I/O	*File Descriptors*
Syscall	*open(), read(), write(), close(), …* *Open File Descriptions*
File System	*Files/Directories/Indexes*
I/O Driver	*Commands and Data Transfers*
	Disks, Flash, Controllers, DMA









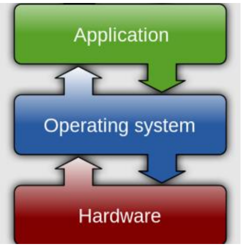



Kernel Maintains State

```
char buffer1[100];
char buffer2[100];
int fd = open("foo.txt", O_RDONLY);
read(fd, buffer1, 100);
read(fd, buffer2, 100);
close(fd);
```

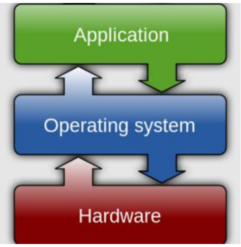
The kernel remembers that the int it receives (stored in `fd`) corresponds to foo.txt

The kernel picks up where it left off in the file



State Maintained by the Kernel

- On a successful call to `open()`:
  - A file descriptor (`int`) is returned to the user
  - An open file description is created in the kernel
- For each process, the kernel maintains a mapping from a file descriptor to an open file description
- On future system calls (e.g., `read()`), the kernel looks up the open file description corresponding to the provided file descriptor and uses it to service the system call
- A call to `close()` removes the file descriptor mapping and deallocates the file description (if no other processes refer to it)



What's in an Open File Description?

- For our purposes, the two most important things are:
  - Where to find the file data on disk
  - The current position within the file

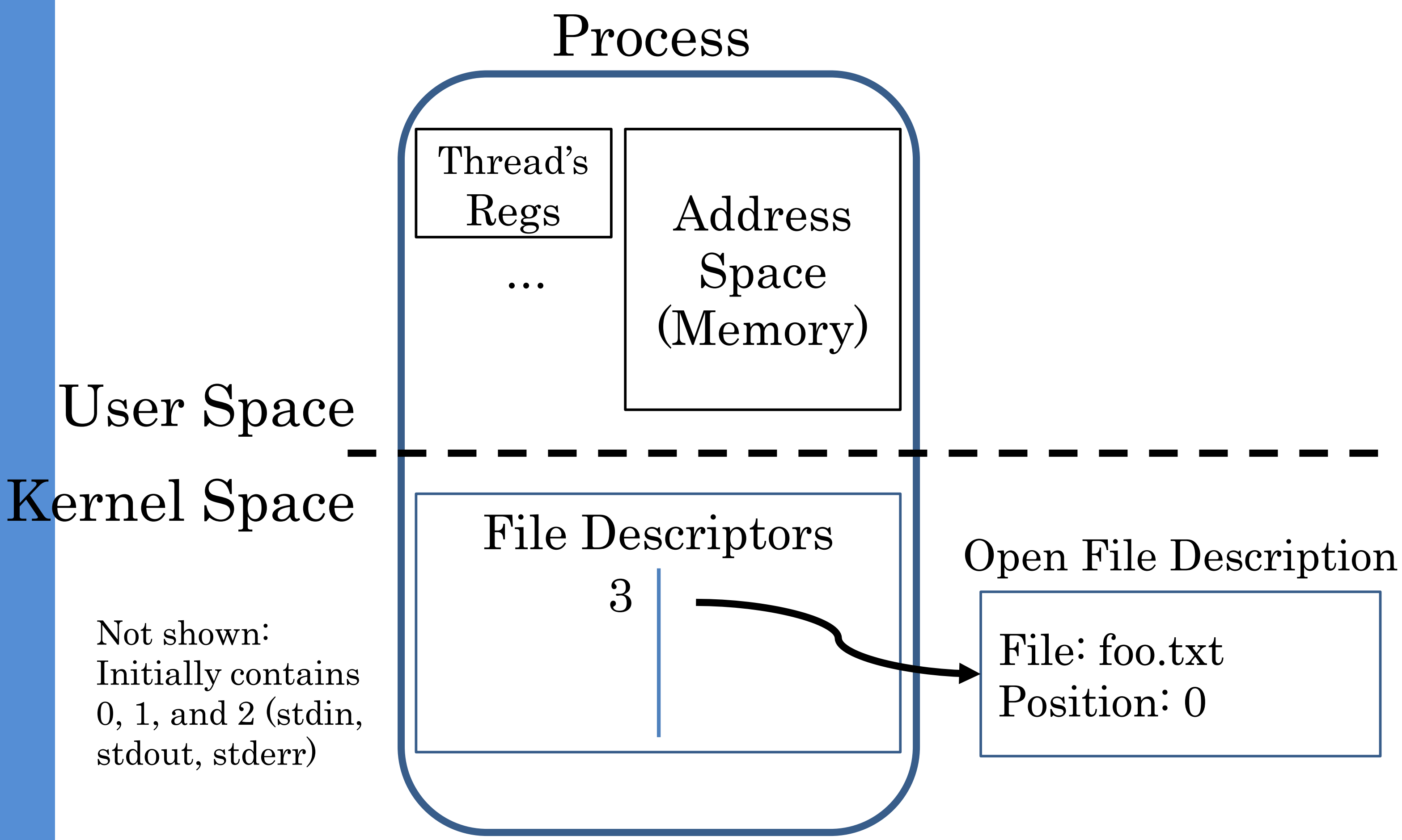

```
struct file {
        union {
                struct llist_node       fu_llist;
                struct rcu_head         fu_rcuhead;
        } f_u;
        struct path             f_path;
#define f_dentry        f_path.dentry
        struct inode            *f_inode;       /* cac
        const struct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

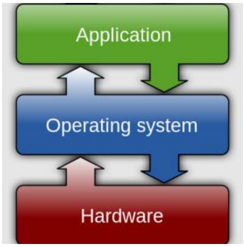
        u64                     f_version;
#ifdef CONFIG_SECURITY
        void                    *f_security;
#endif
        /* needed for tty driver, and maybe others */
        void                    *private_data;

#ifdef CONFIG_EPOLL
        /* Used by fs/eventpoll.c to link all the hooks
        struct list_head        f_ep_links;
```

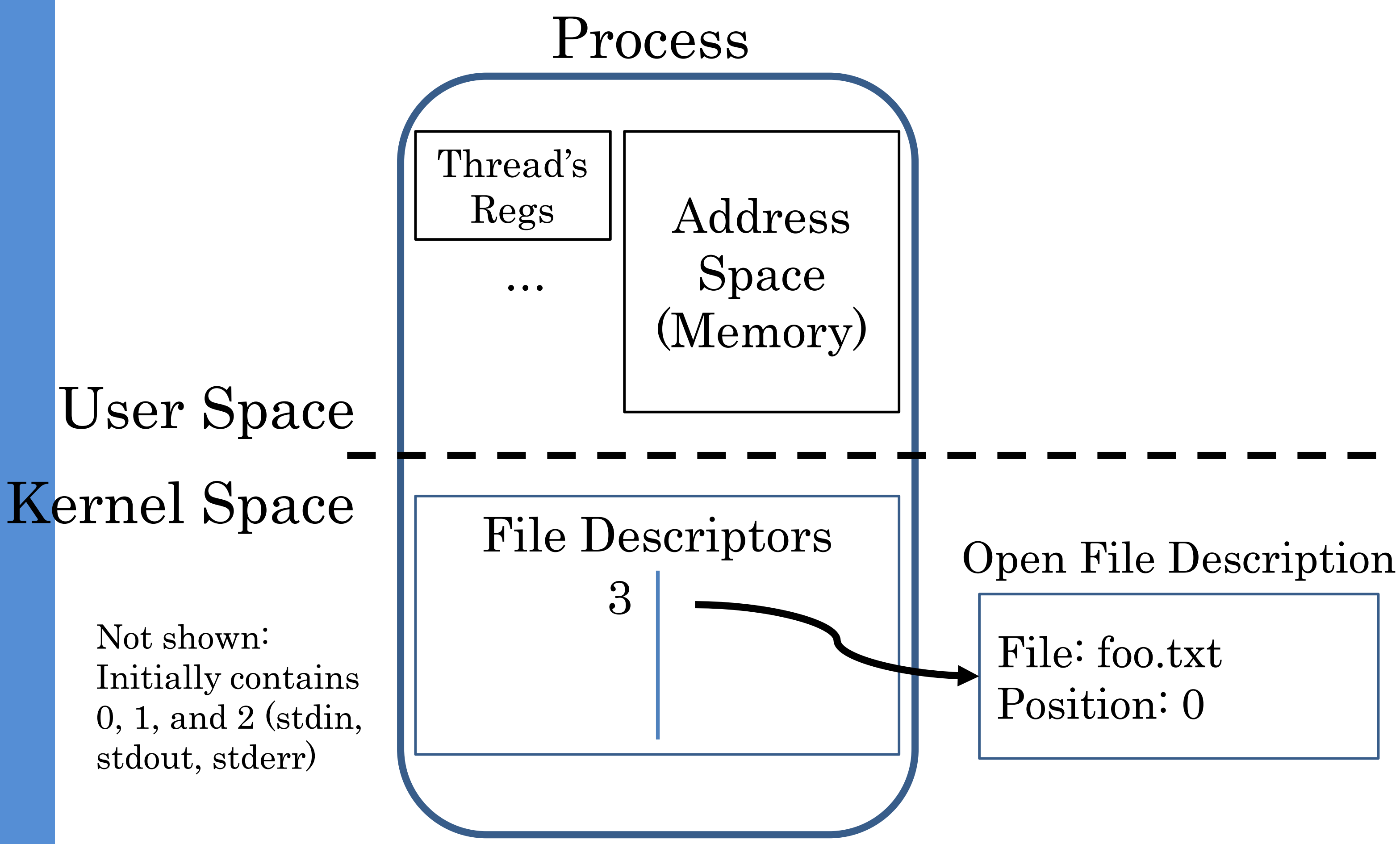
Abstract Representation of a Process



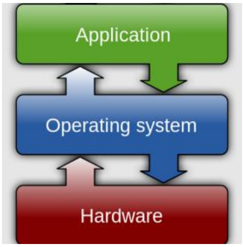
- Suppose that we execute `open("foo.txt", ...)`
- and that the result is 3



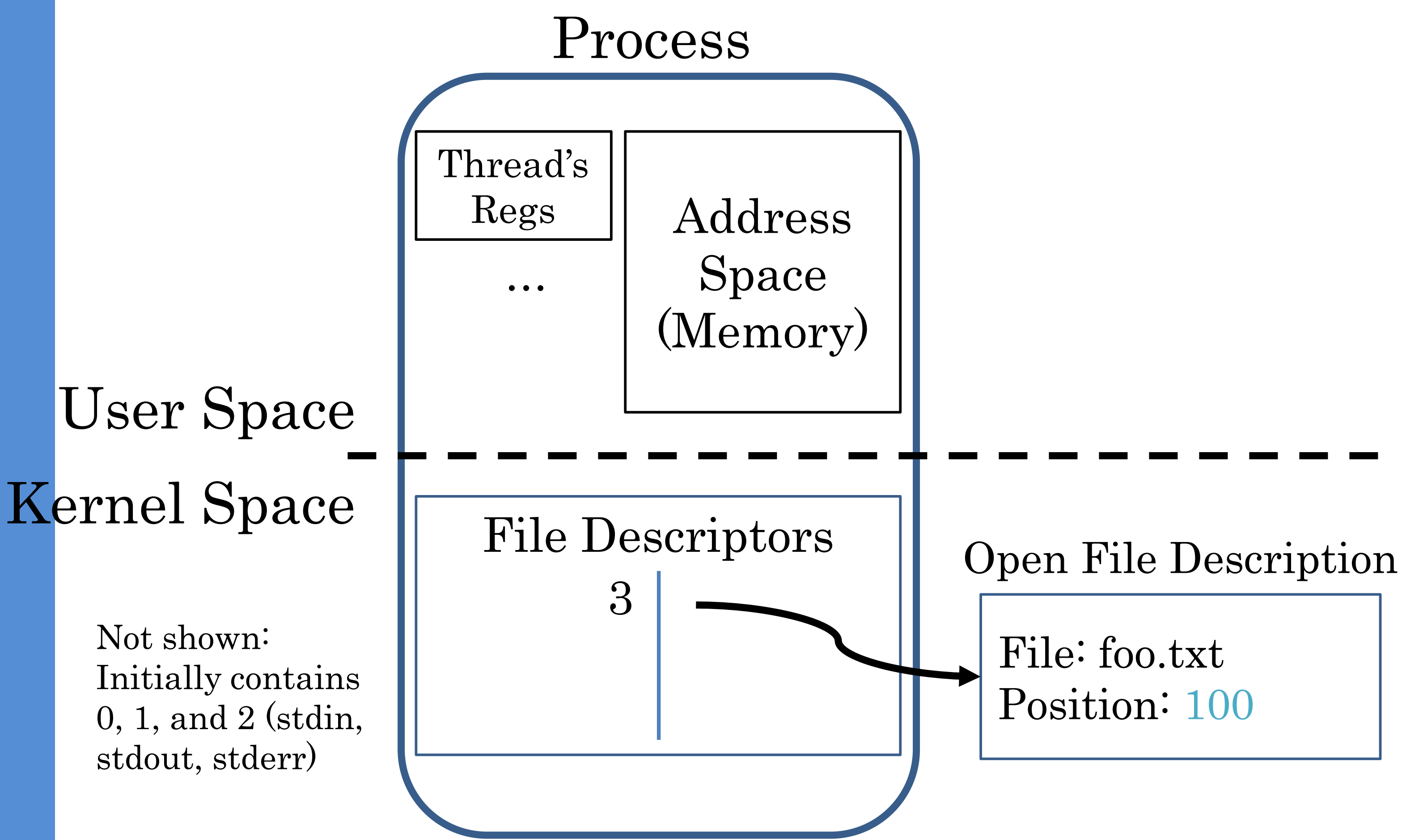
Abstract Representation of a Process



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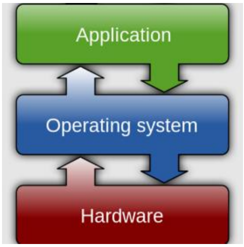
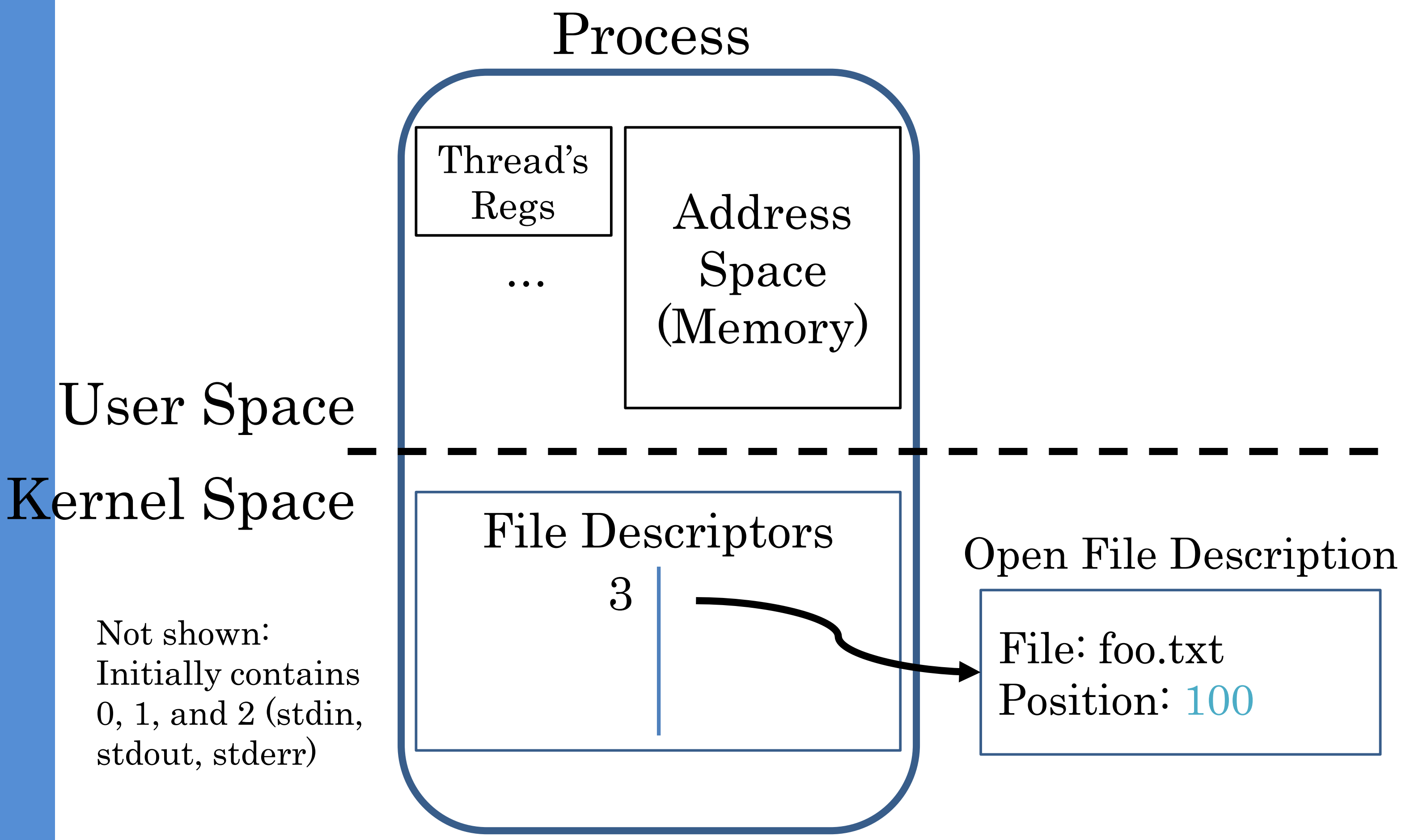
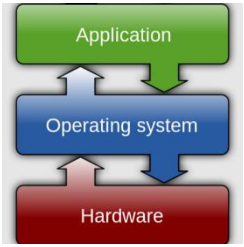
- Next, suppose that we execute
  `read(3, buf, 100)`
- and that the result is 100



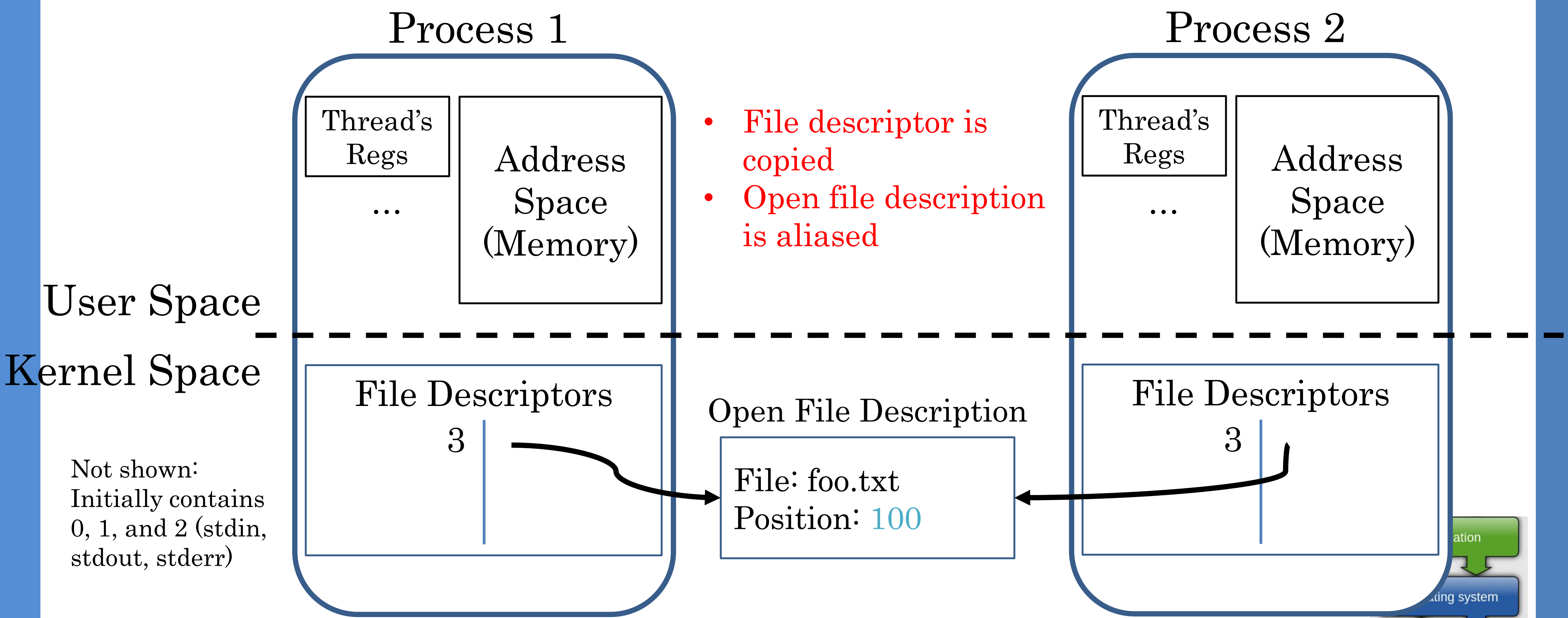
Abstract Representation of a Process



- 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)`

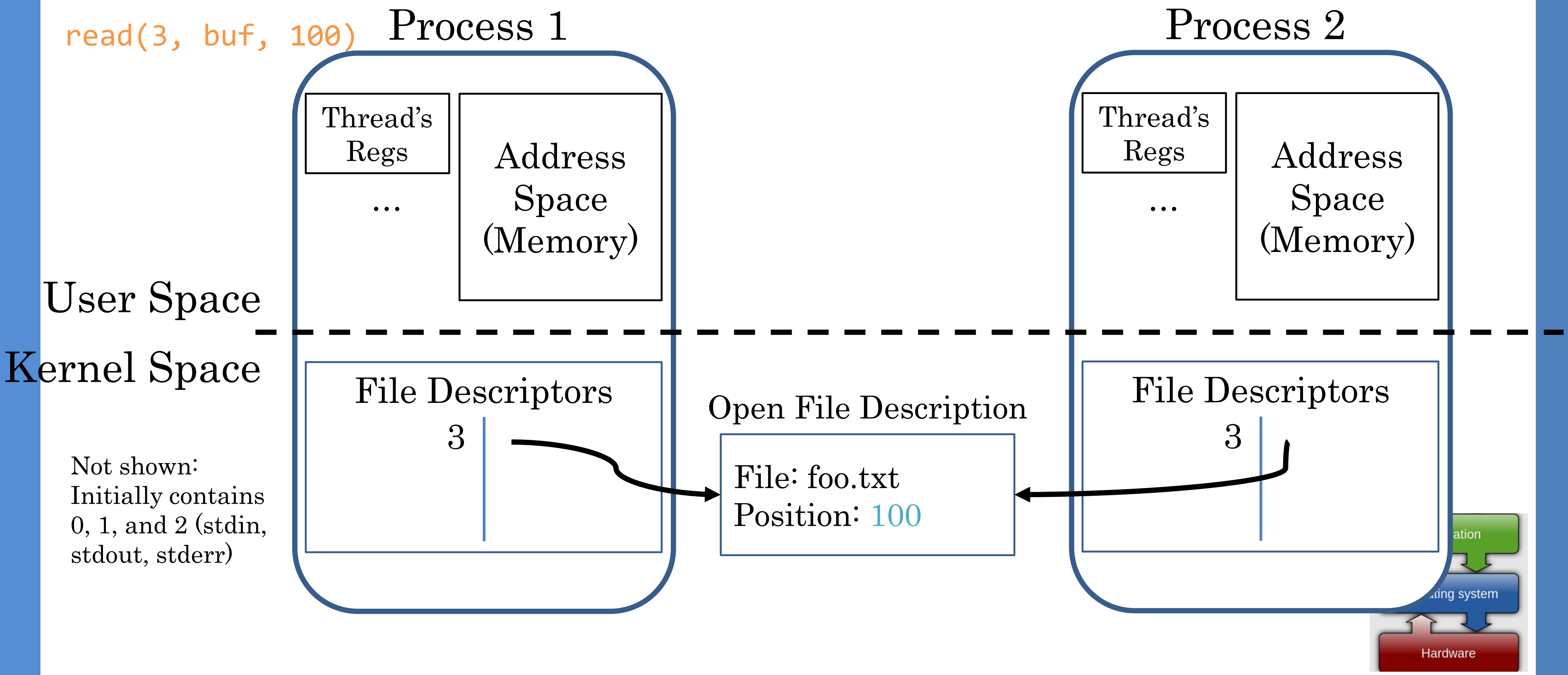


Now, let's fork()!



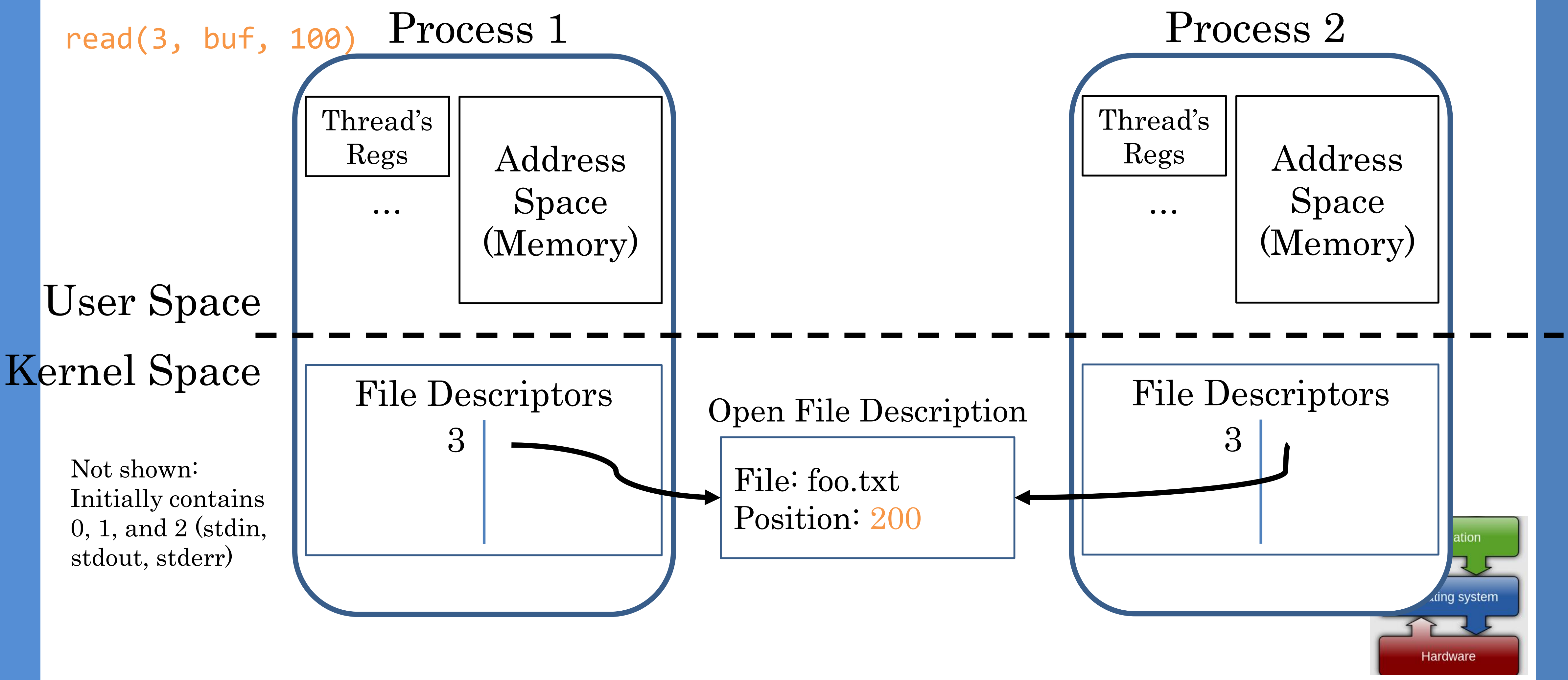
Open File Description is Aliased

`read(3, buf, 100)`



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

Open File Description is Aliased



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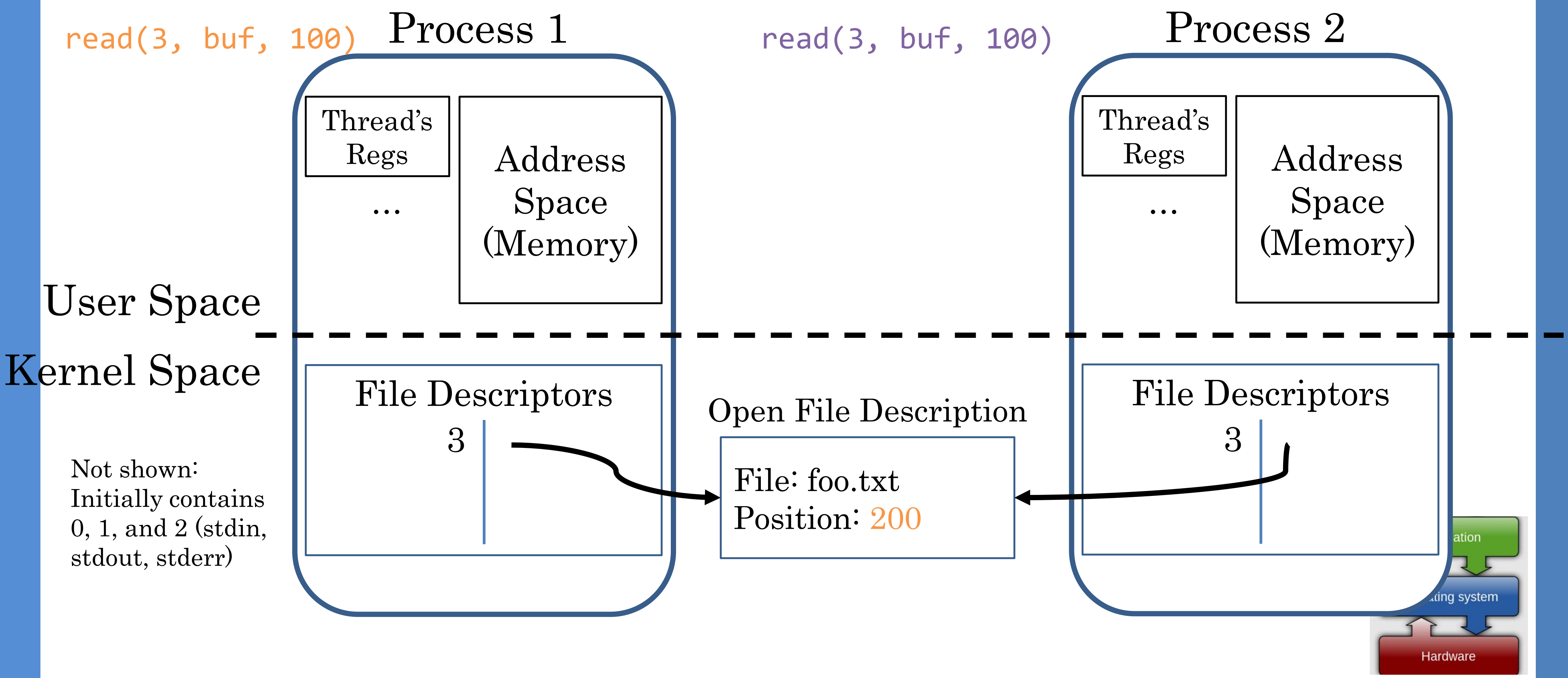
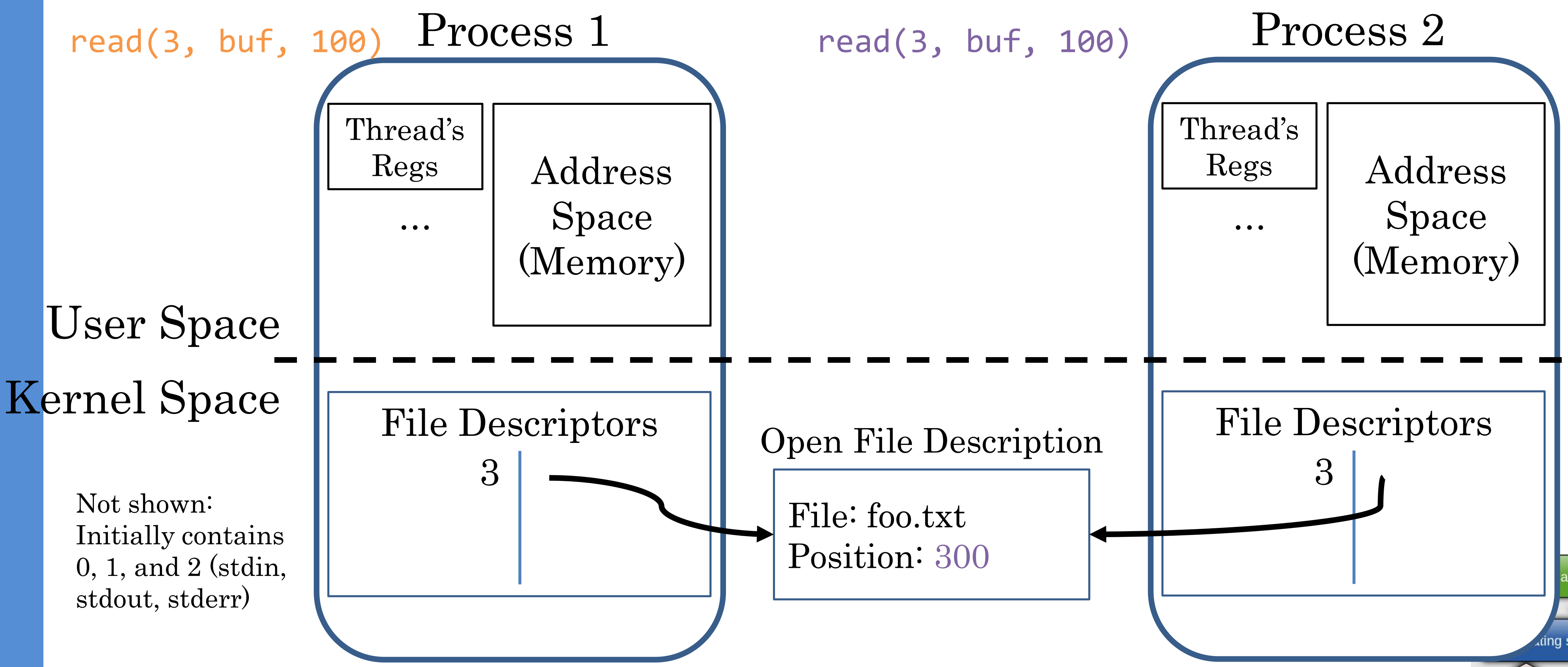
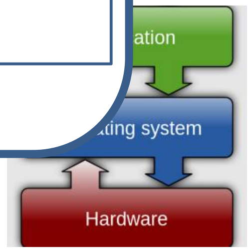
Open File Description is Aliased

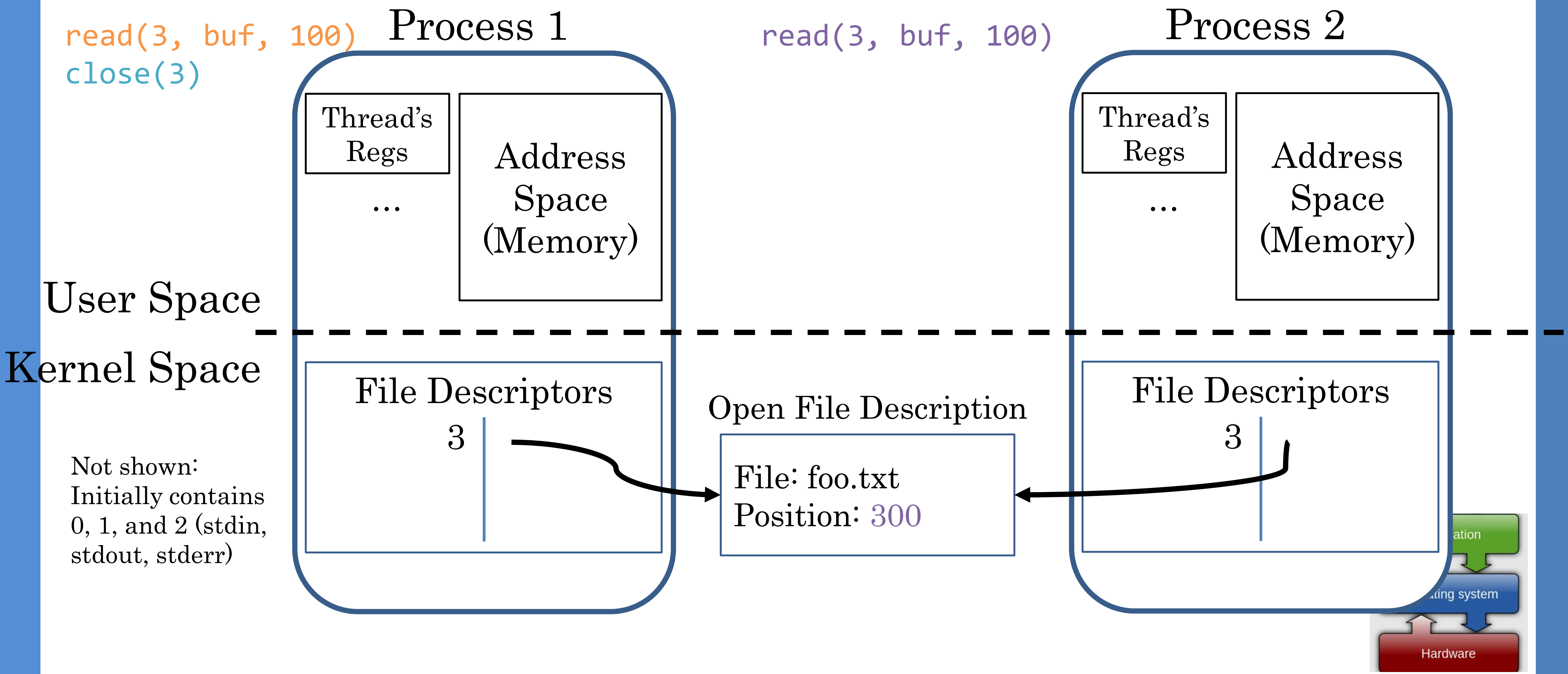


Open File Description is Aliased

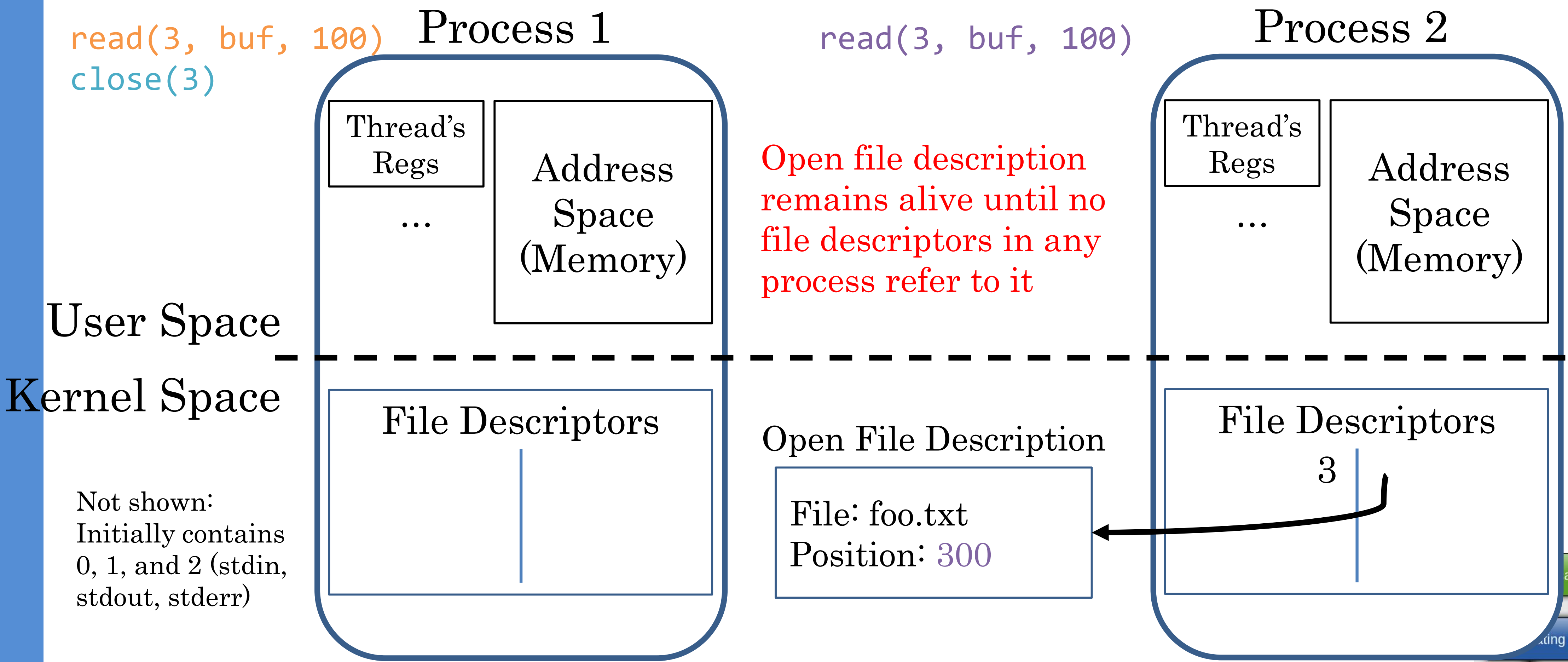


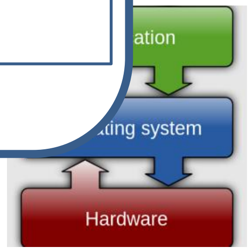


File Descriptor is Copied



File Descriptor is Copied



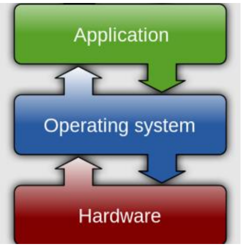


Why is Aliasing the Open File Description a Good Idea?

It allows for shared resources between processes

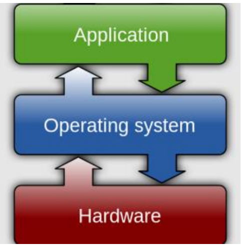
Recall: In POSIX, Everything is a "File"

- 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)

File Descriptors

0
1
2

Process 2

Thread's Regs

…

Address Space (Memory)

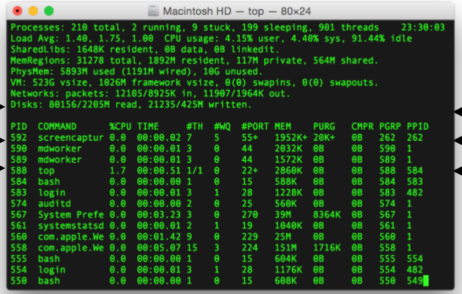
File Descriptors

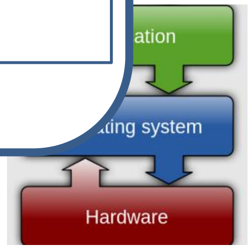
0
1
2

User Space

Kernel Space

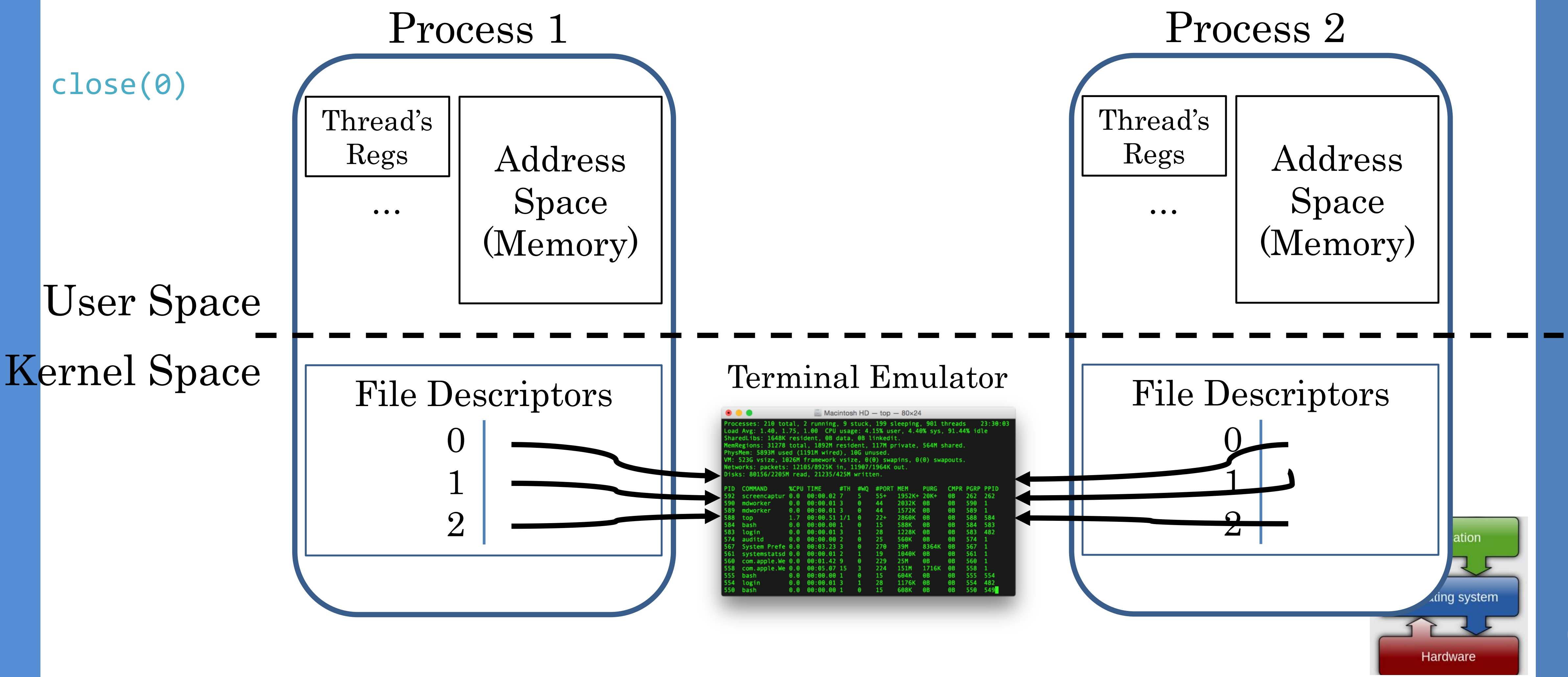
Terminal Emulator





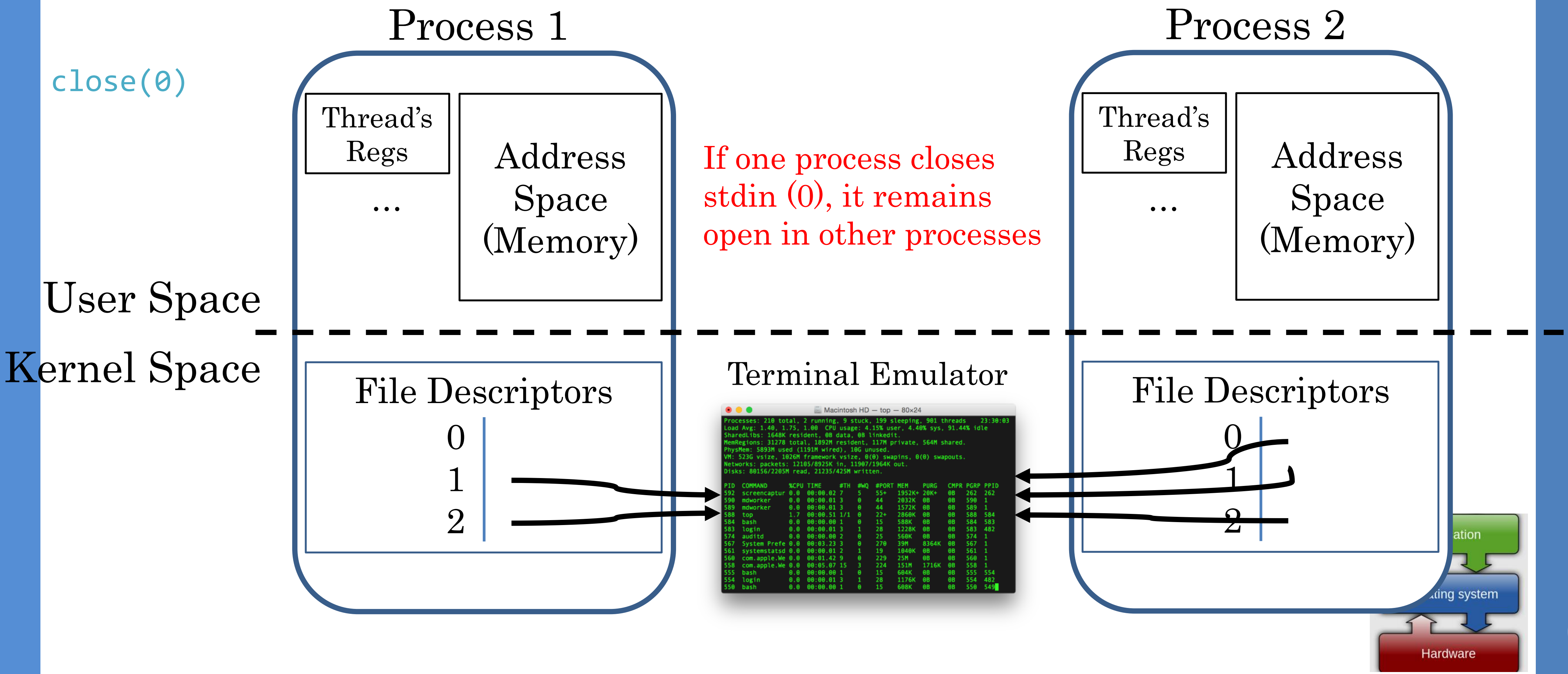
Example: Shared Terminal Emulator

`close(0)`



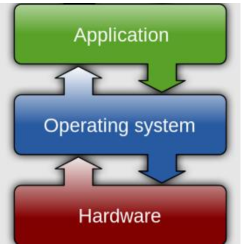
Example: Shared Terminal Emulator

`close(0)`



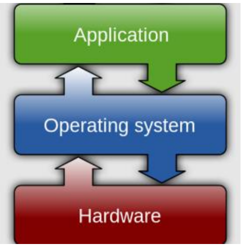
Other Examples

- 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 (Assignment 2)

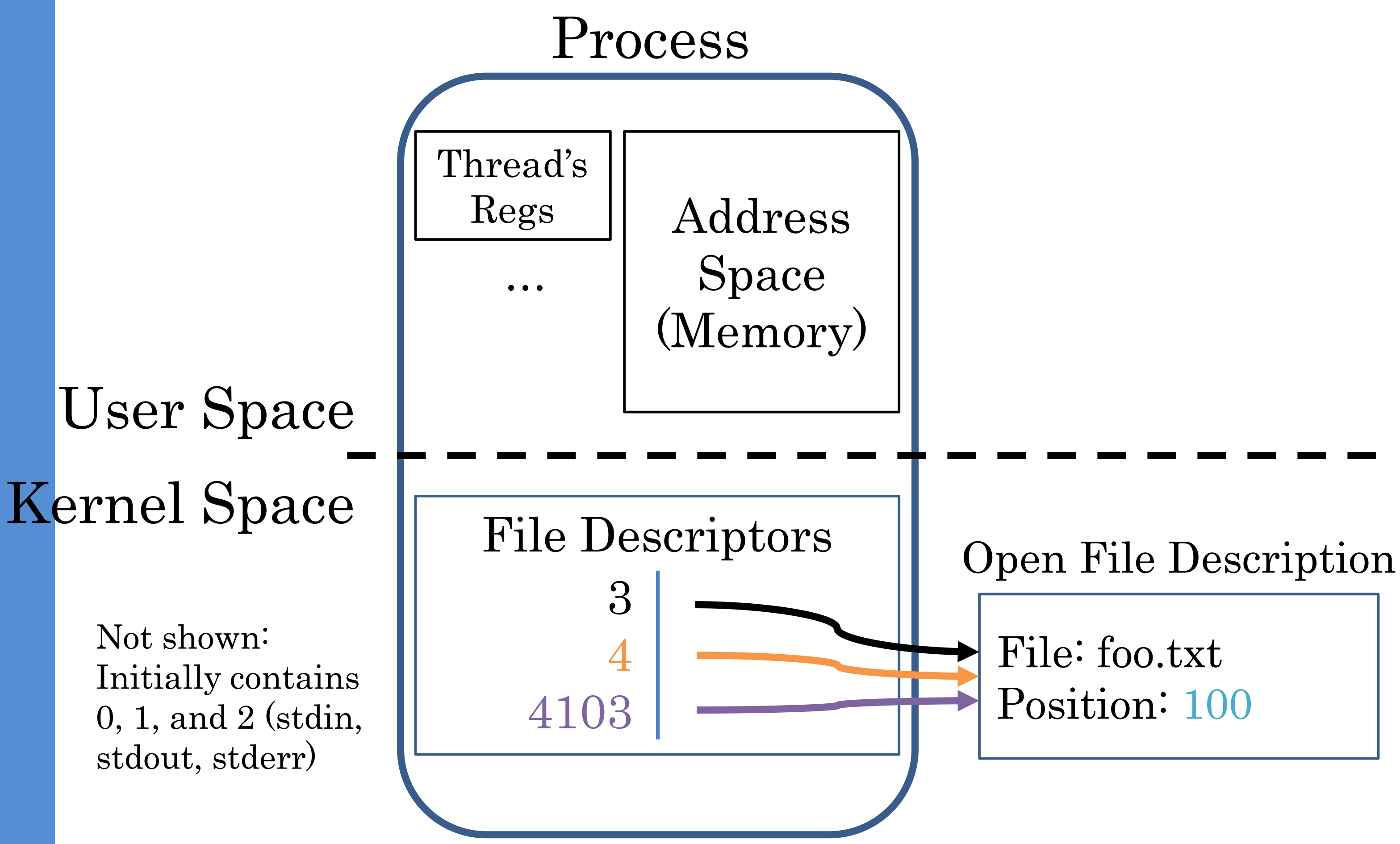


Other Syscalls: dup and dup2

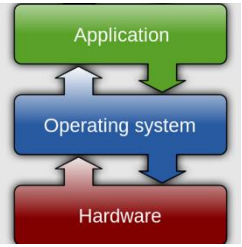
- They allow you to duplicate the file descriptor
- But the open file description remains aliased



Other Syscalls: dup and dup2

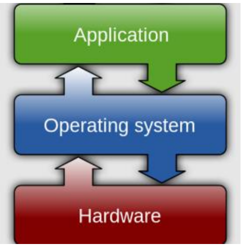


- Suppose that we execute `open("foo.txt")`
- and that the result is 3
- Next, suppose that we execute `read(3, buf, 100)`
- and that the result is 100
- Next, suppose that we execute `dup(3)`
- And that the result is 4
- Finally, suppose that we execute `dup2(3, 4103)`



Today: The File Abstraction

- High-Level File I/O: Streams
- Low-Level File I/O: File Descriptors
- How and Why of High-Level File I/O
- Process State for File Descriptors
- Some Pitfalls with OS Abstractions [if time]

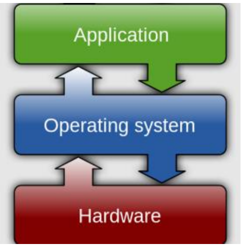


Don't fork() in a process that already has multiple threads

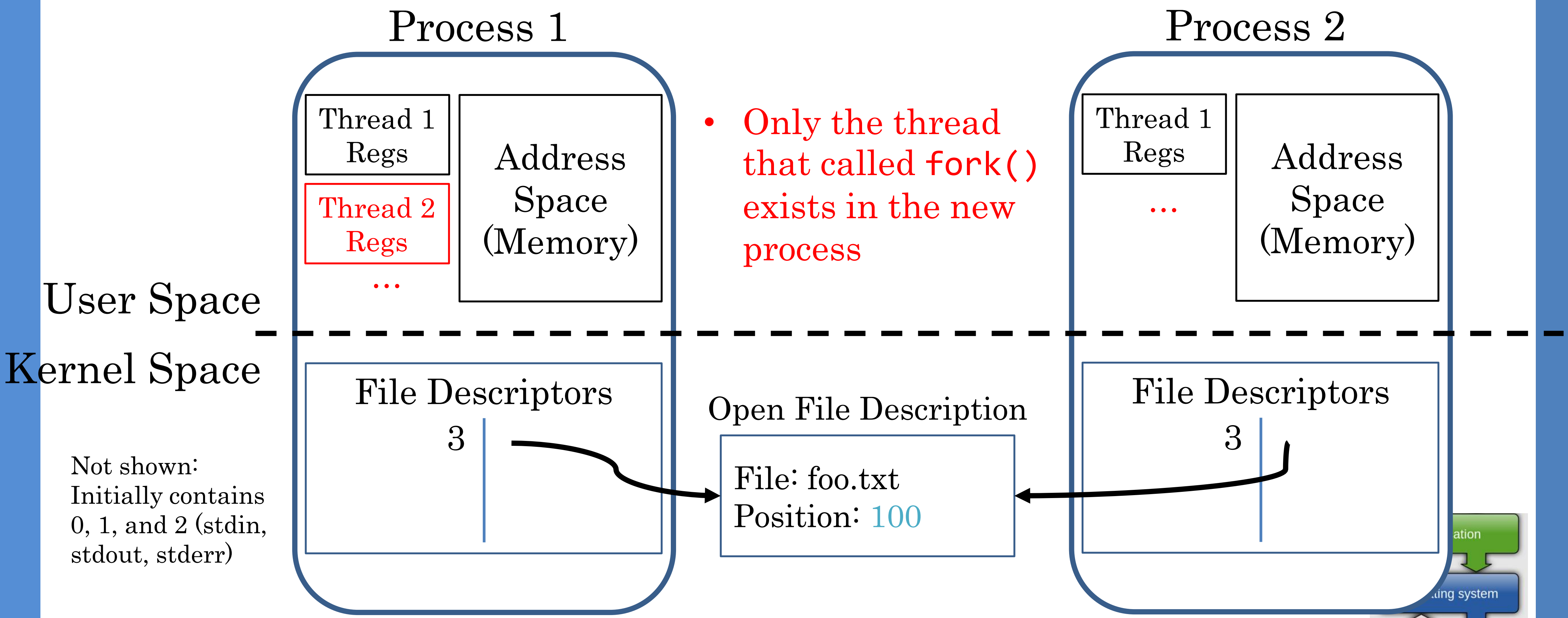
Unless you plan to call `exec()` in the child process

fork() in Multithreaded Processes

- The child process always has just a single thread
  - The thread in which `fork()` returns
- The other threads just vanish



fork() in a Multithreaded Processes

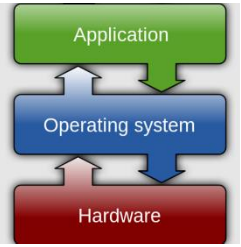


- Only the thread that called `fork()` exists in the new process

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

Possible Problems with Multithreaded fork()

- When you call `fork()` in a multithreaded process, the other threads (the ones that didn't call `fork()`) just vanish
  - What if one of these threads was holding a lock?
  - What if one of these threads was in the middle of modifying a data structure?
  - No cleanup happens!
- It's safe if you call `exec()` in the child
  - Replacing the entire address space



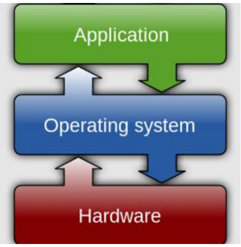
Don’t carelessly mix low-level and high-level file I/O

Avoid Mixing FILE* and File Descriptors

- What is the value has y after executing the following code?

```
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 10
```

- Bytes 0 to 9
- Bytes 10 to 19
- None of these?



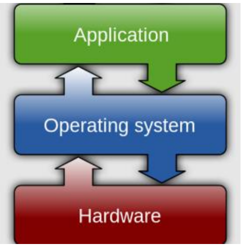
Be careful with fork() and FILE*

Be Careful Using fork() with FILE*

```
FILE* f = fopen("foo.txt", "w");
fwrite("a", 1, 1, f);
fork();
fclose(f);
```

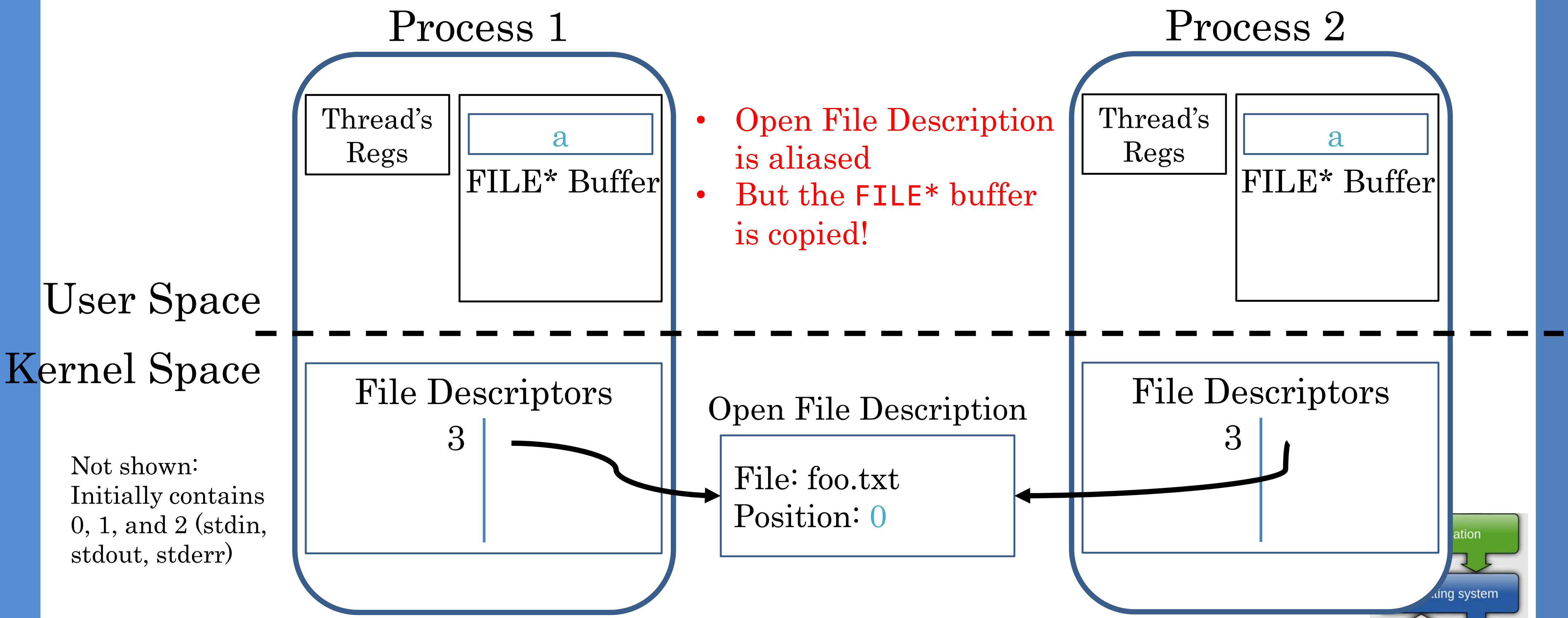
Depends on whether this `fwrite` call flushes…

- After all processes exit, what is in foo.txt?
  - Could be either `a` or `aa`
- Usually `aa` based on what I've observed in Linux…



Be Careful Using fork() with FILE*

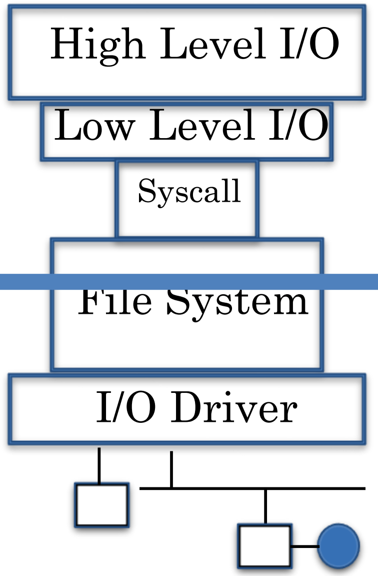
- Open File Description is aliased
- But the `FILE*` buffer is copied!



Conclusion

Focus of today's lecture

Application / Service



Streams

File Descriptors

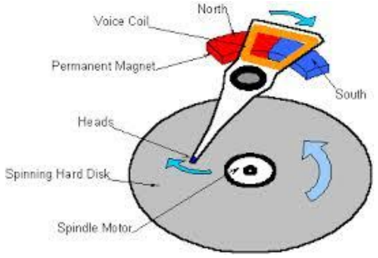
open(), read(), write(), close(), …

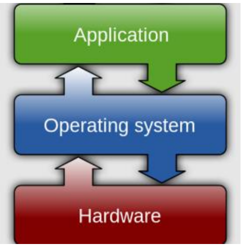
Open File Descriptions

Files/Directories/Indexes

Commands and Data Transfers

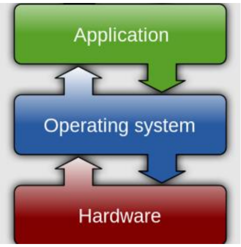
Disks, Flash, Controllers, DMA

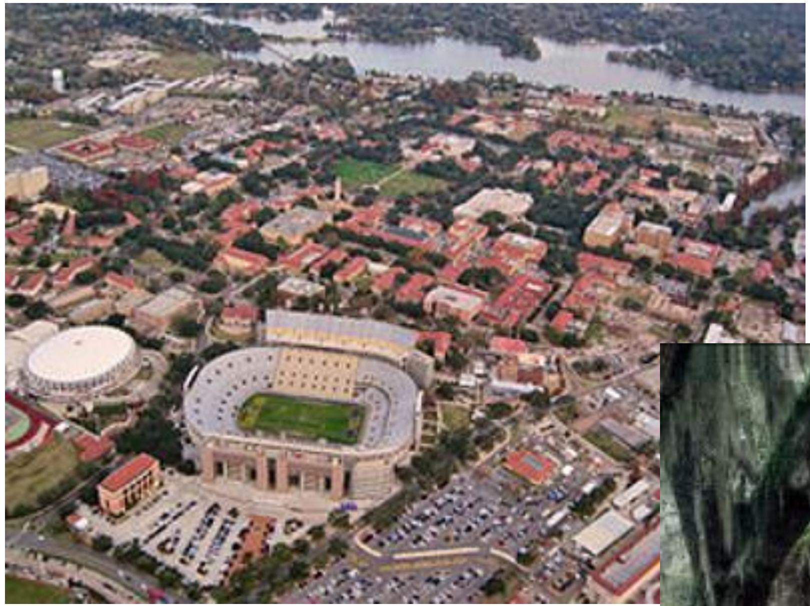




Conclusion

- POSIX idea: "everything is a file"
- All sorts of I/O managed by open/read/write/close
- We added two new elements to the PCB:
  - Mapping from file descriptor to open file description
  - Current working directory





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