Abstractions 2: Files

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CS 162: Operating Systems and System Programming

Lecture 4

https://inst.eecs.berkeley.edu/~cs162/su20

Read: A&D 3.2-3, 11.1-2

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) 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

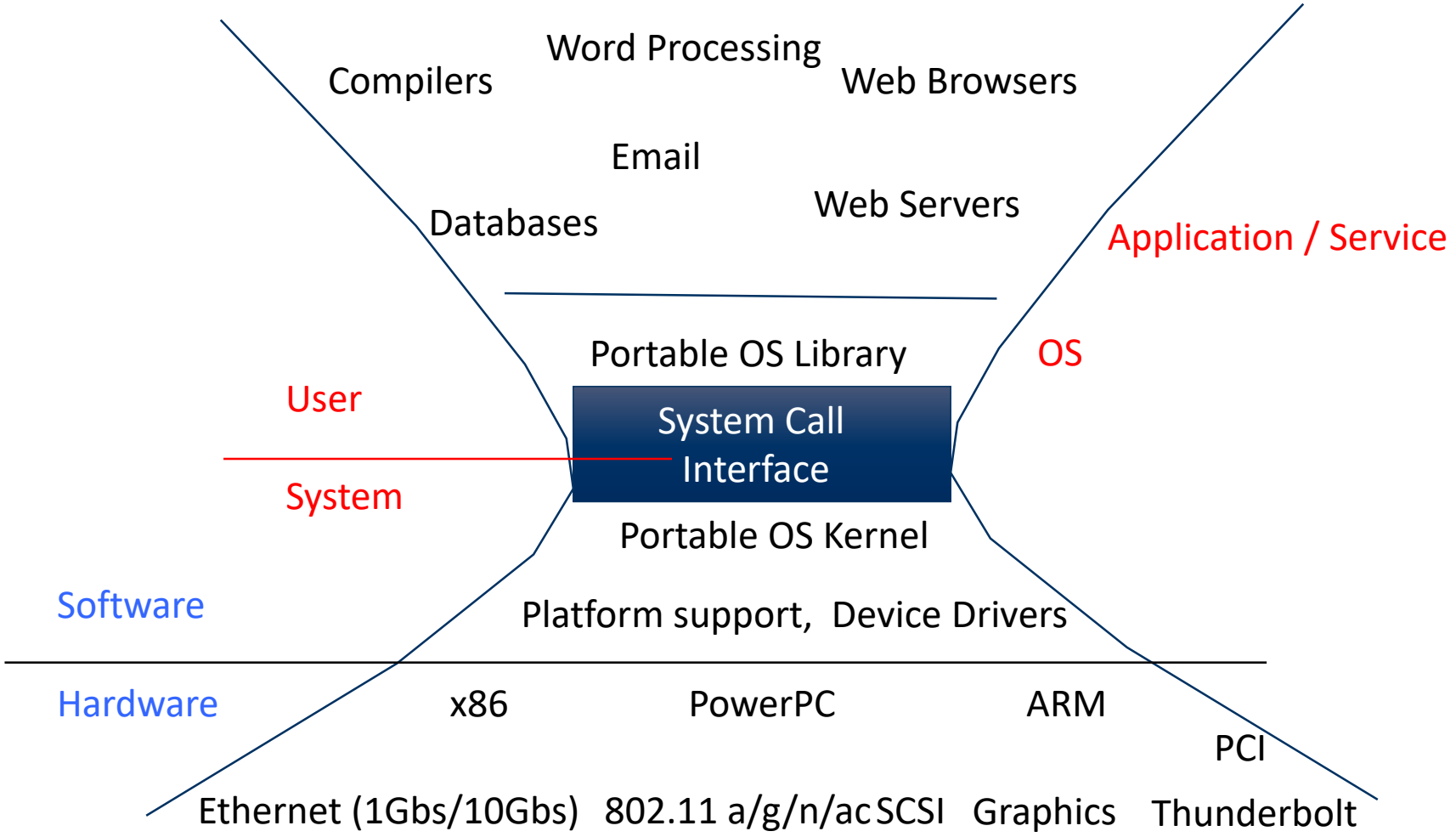
Recall: Synchronization

- **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

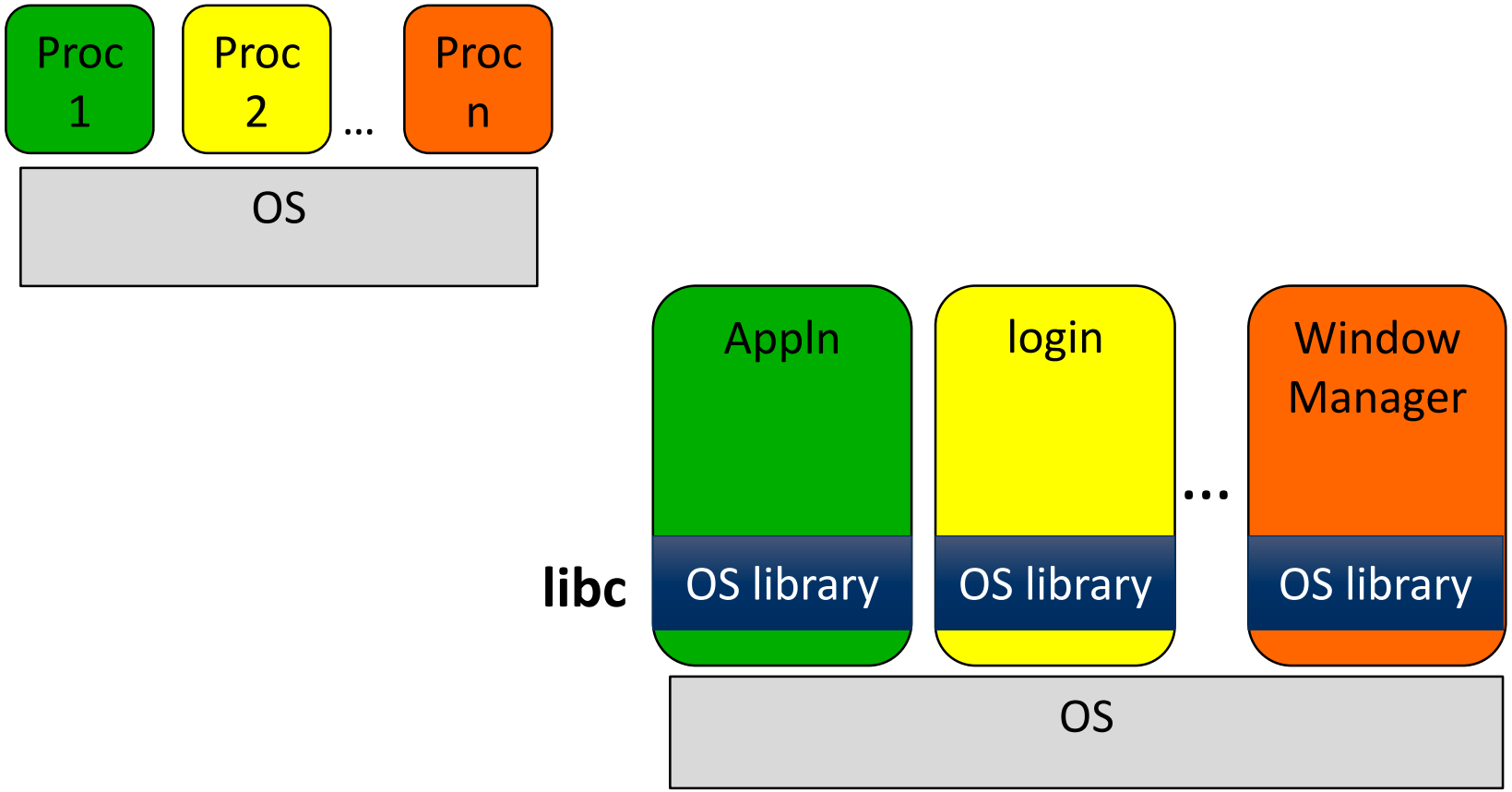
Recall: Processes

- 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**

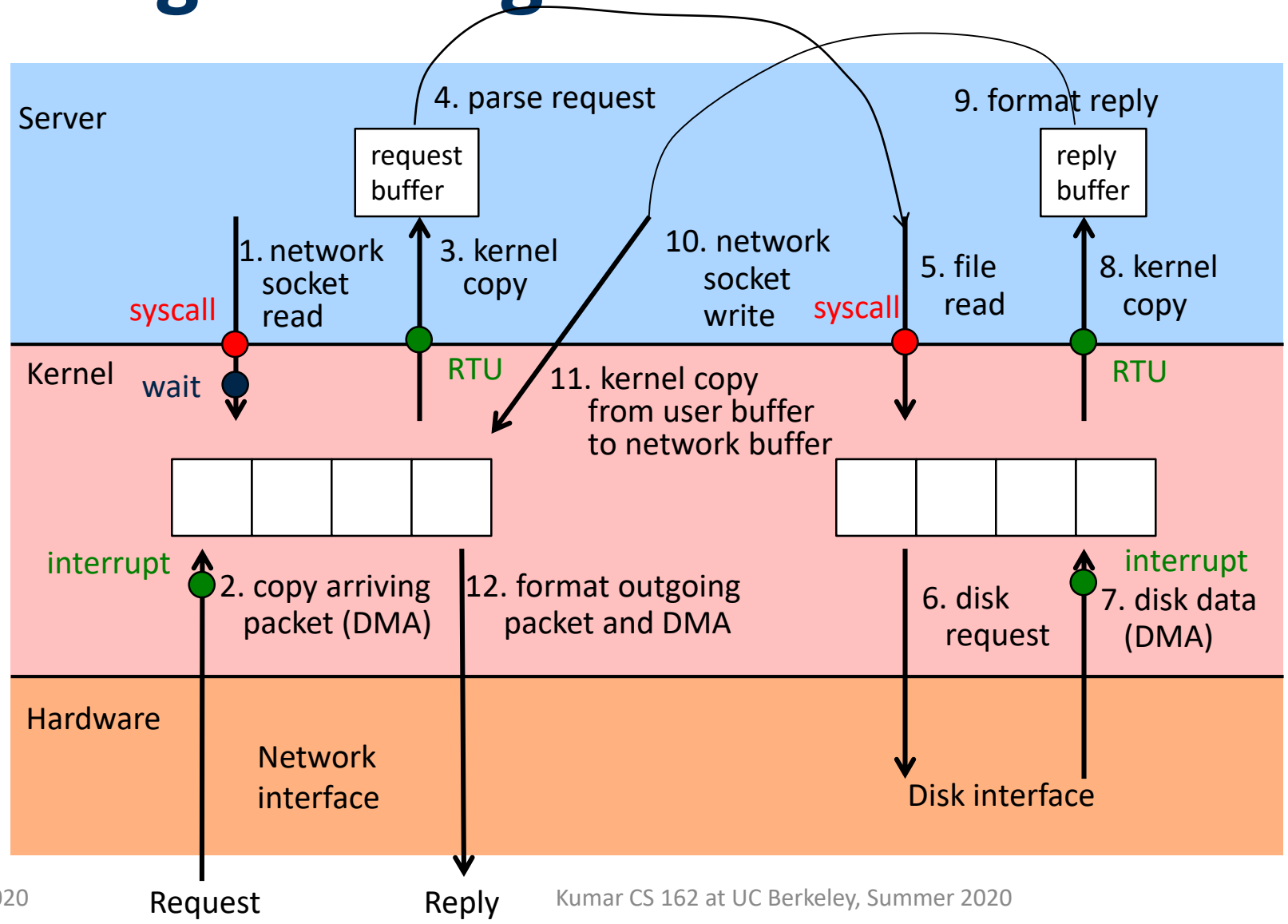
Recall: System Calls ("Syscalls")



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

Unix/POSIX Idea: 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()**

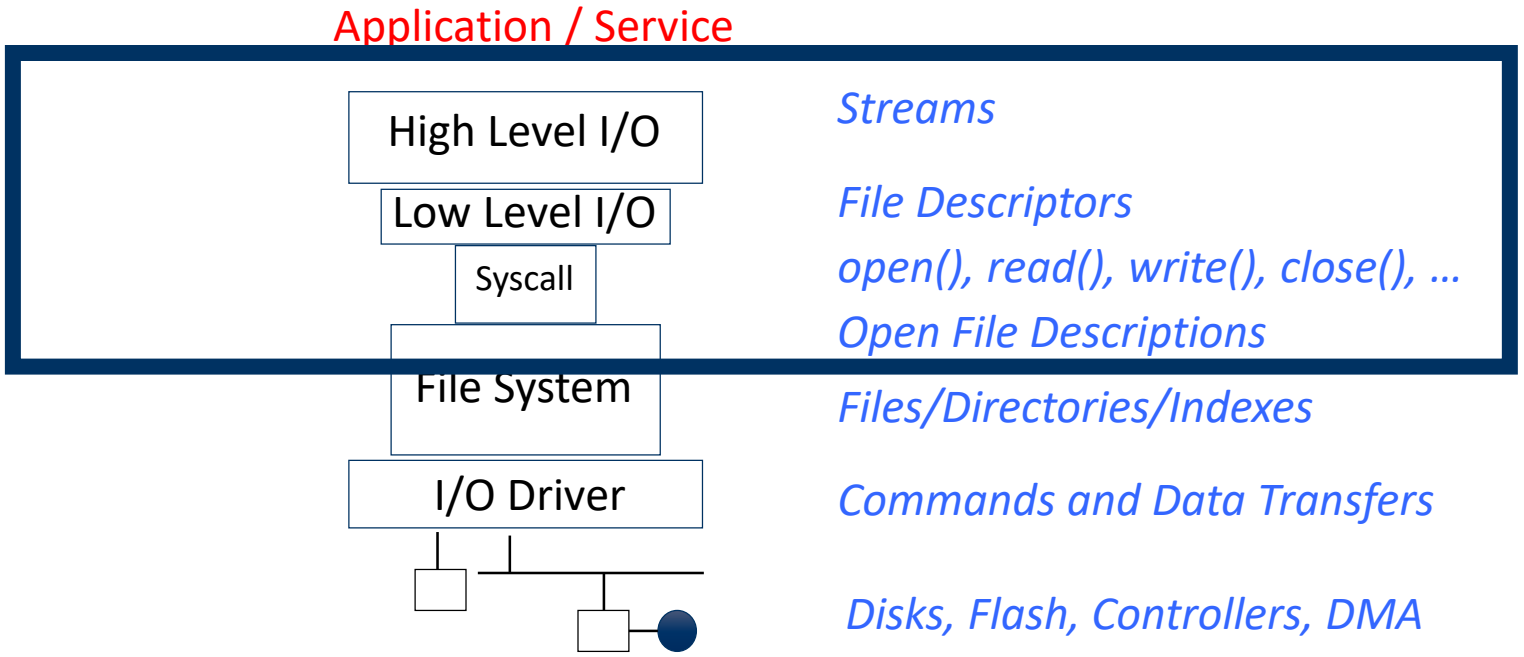
The File System Abstraction

- 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
    - Size, Modification Time, Owner, Security info, Access control
- Directory
  - “Folder” containing files & directories
  - Hierachical (graphical) naming
    - Path through the directory graph
    - Uniquely identifies a file or directory
      - /home/ff/cs162/public_html/fa14/index.html
  - Links and Volumes (later)

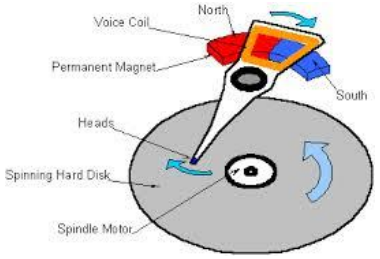
Connecting Processes, File Systems, and Users

- **Every process has a *current working directory***
- Absolute paths
  - /home/oski/cs162
- 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, ~cs162/index.html
    - Refers to index.html in the home directory

I/O and Storage Layers



Focus of today's lecture



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

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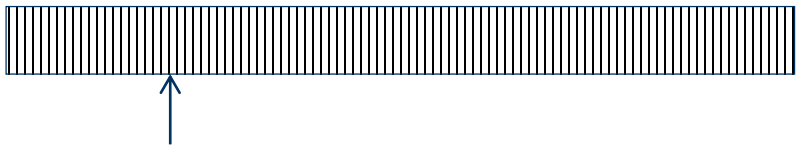
C High-Level File API – Streams

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



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

Mode Text	Binary	Descriptions
r	rb	Open existing file for reading
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.
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.
  - `FILE *stdin` – normal source of input, can be redirected
  - `FILE *stdout` – normal source of output, can 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( const char *s, FILE *fp );   // rtn > 0 or EOF

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

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

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

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);
}
```

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

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);
  fclose(input);
  fclose(output);
}
```

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

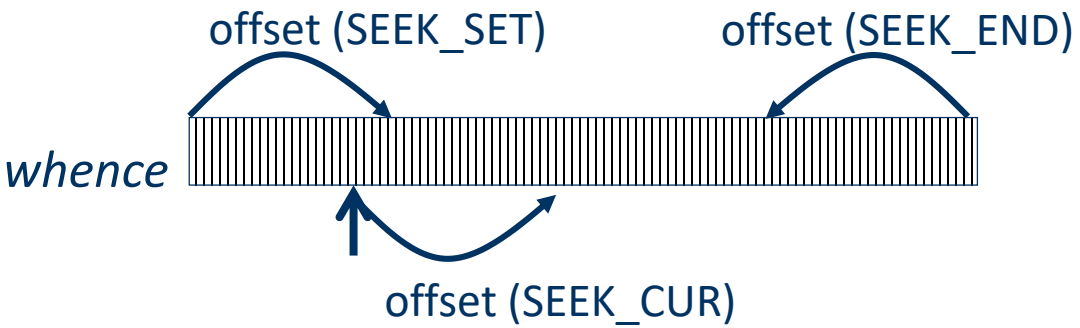
- Systems programmers are paranoid
- We should really be writing things like:

```
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

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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 filedes, const char *opentype)
```

Low-Level File API

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

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

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

- returns bytes written

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

Example: `lowio.c`

```
int main() {
  char buf[1000];
  int     fd = open("lowio.c", O_RDONLY, 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 looks the same, read blocks yielding processor to other task
- Kernel buffered writes
  - Completion of out-going transfer decoupled from the application, allowing it to continue
- Explicit close

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

- C review session tonight
  - 6-7 PM
- Quiz 0 solutions posted
- Homework 0 due tonight
- Homework 1 out tonight
- Project 0 out
  - We'll set up an open Zoom room to help you find groups

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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("and end of line \n", 16);
```

Outputs "Beginning of line" 10 seconds earlier

What's in a `FILE`?

- 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
  - 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

```
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 see end of file (in which case x will remain ‘c’)

Example

```
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);
```

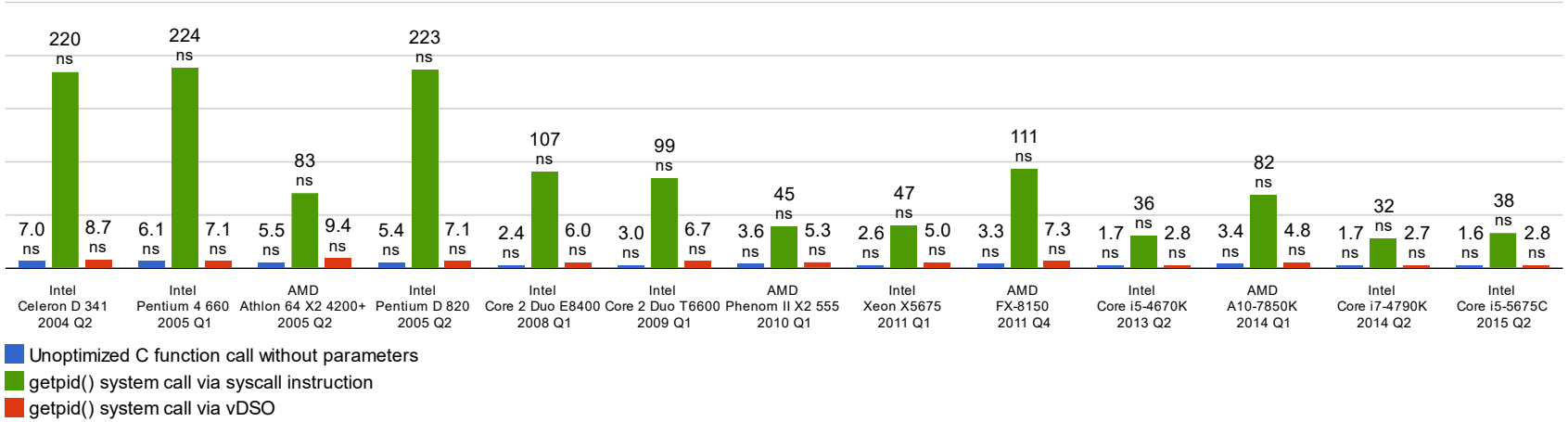
- Now, the call to fread will see the latest write ‘b’

Writing Correct Code with `FILE`

- Your code should behave correctly regardless of when 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

Break

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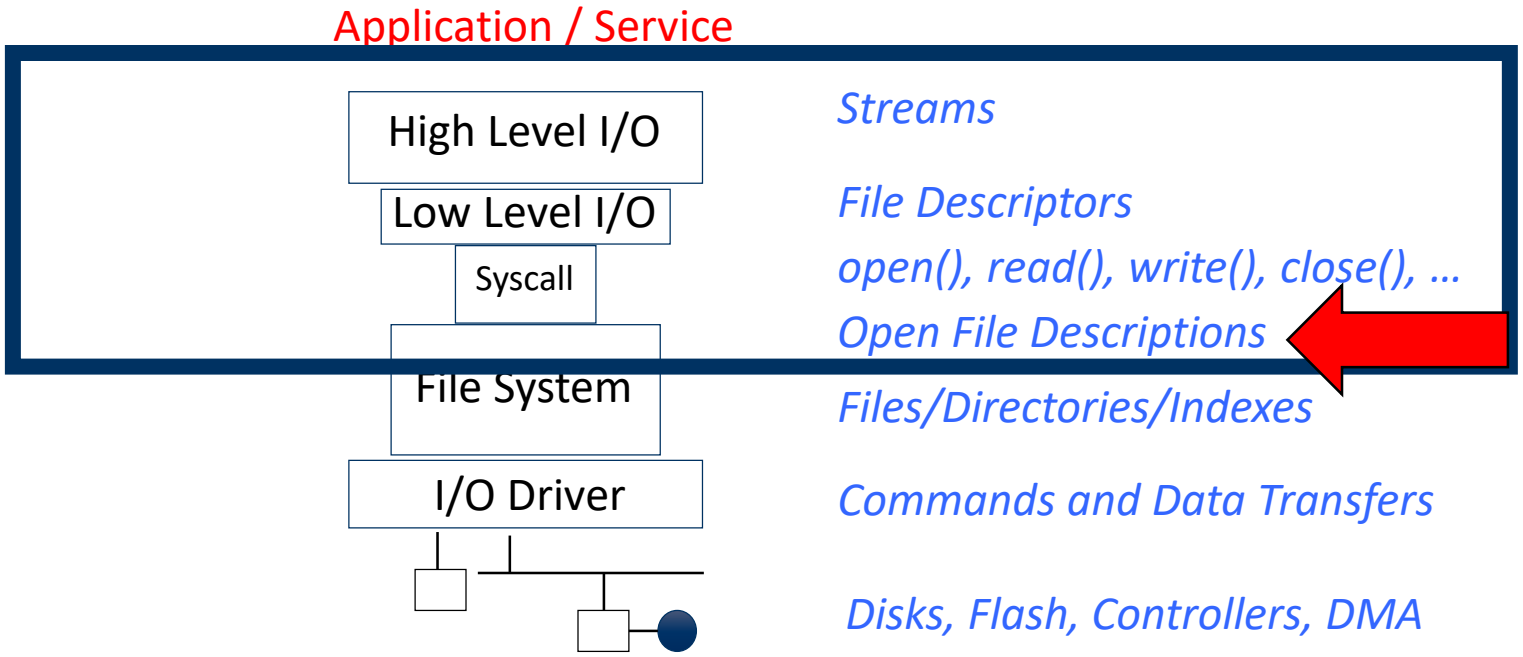
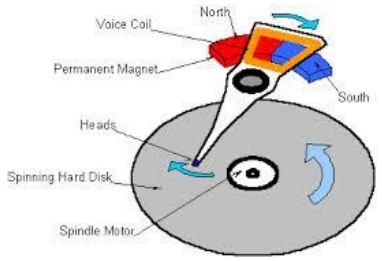
I/O and Storage Layers



Focus of today's lecture



Kernel Maintains State

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

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

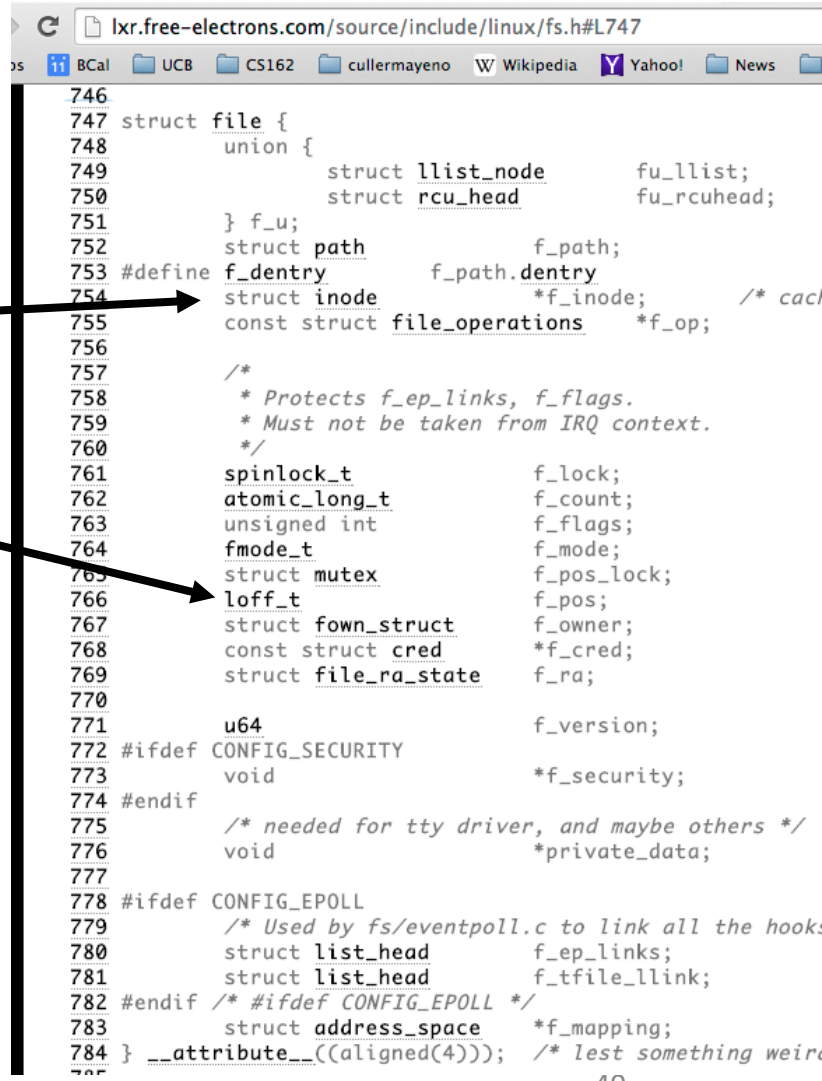
For each process, the kernel maintains a mapping from *file descriptor* to *open file description*

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

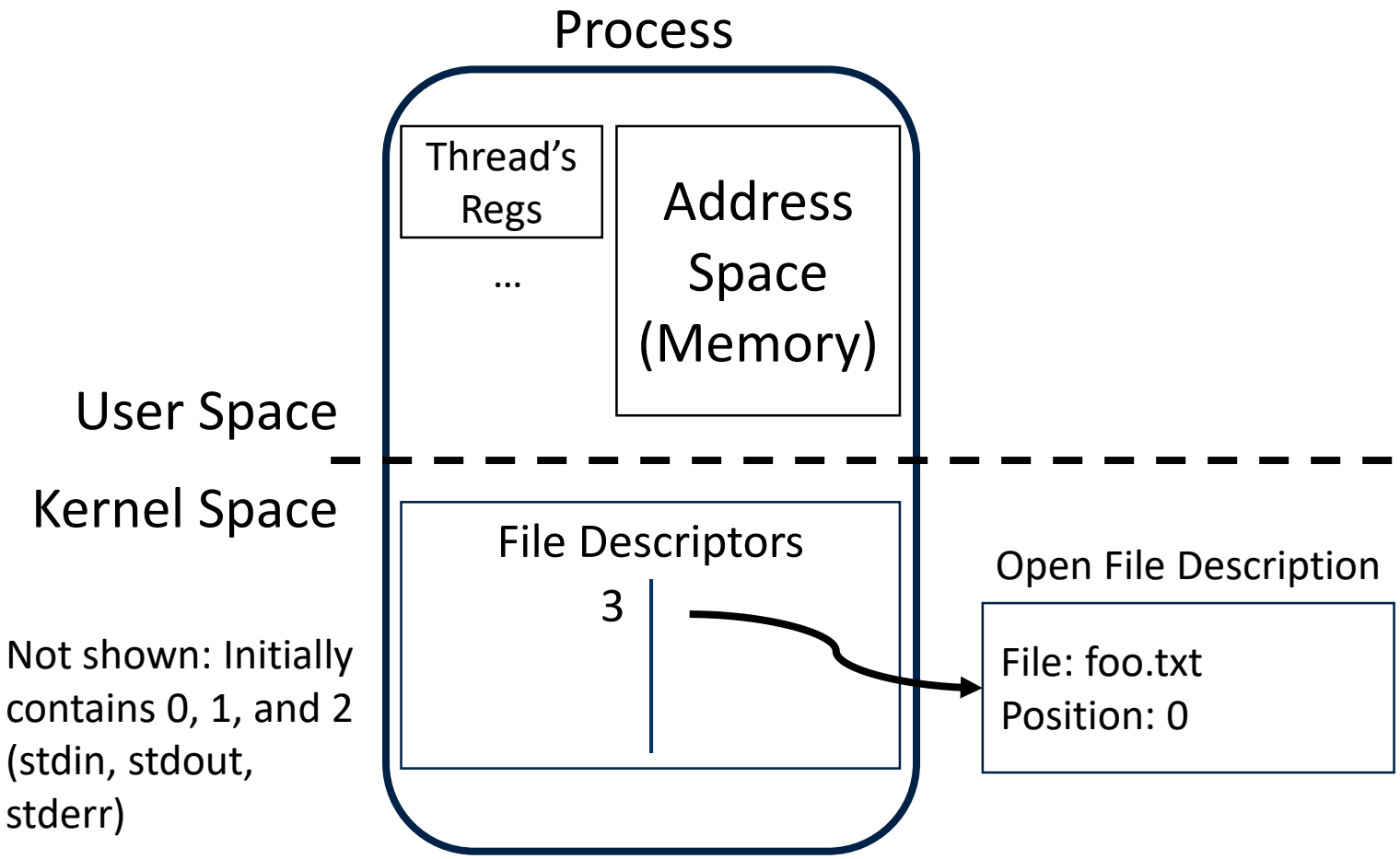
What's in an Open File Description?

For our purposes, the two most important things are:

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



Abstract Representation of a Process

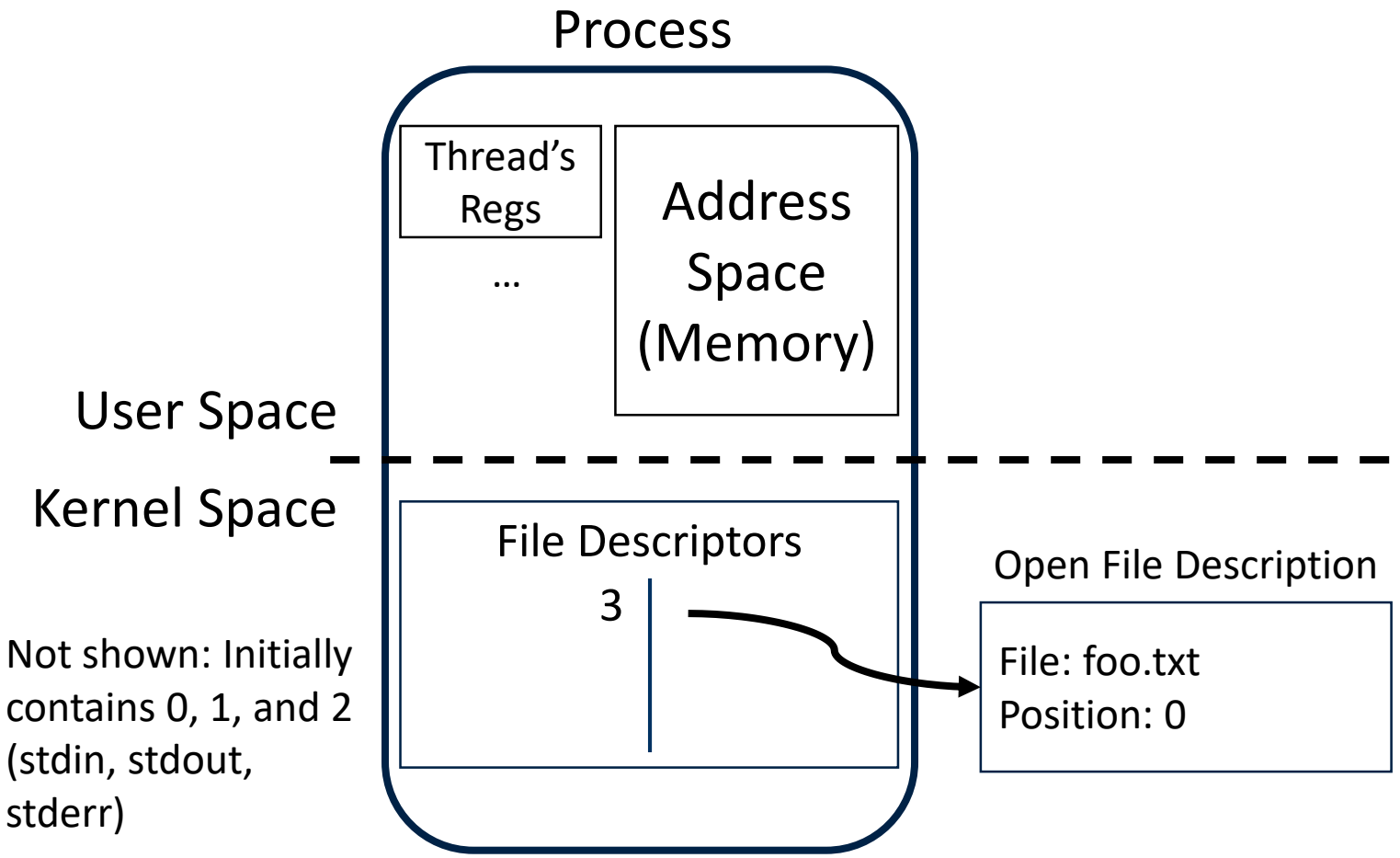


Suppose that we execute

`open("foo.txt")`

and that the result is 3

Abstract Representation of a Process



Suppose that we execute

`open("foo.txt")`

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Next, suppose that we execute

`read(3, buf, 100)`

and that the result is 100

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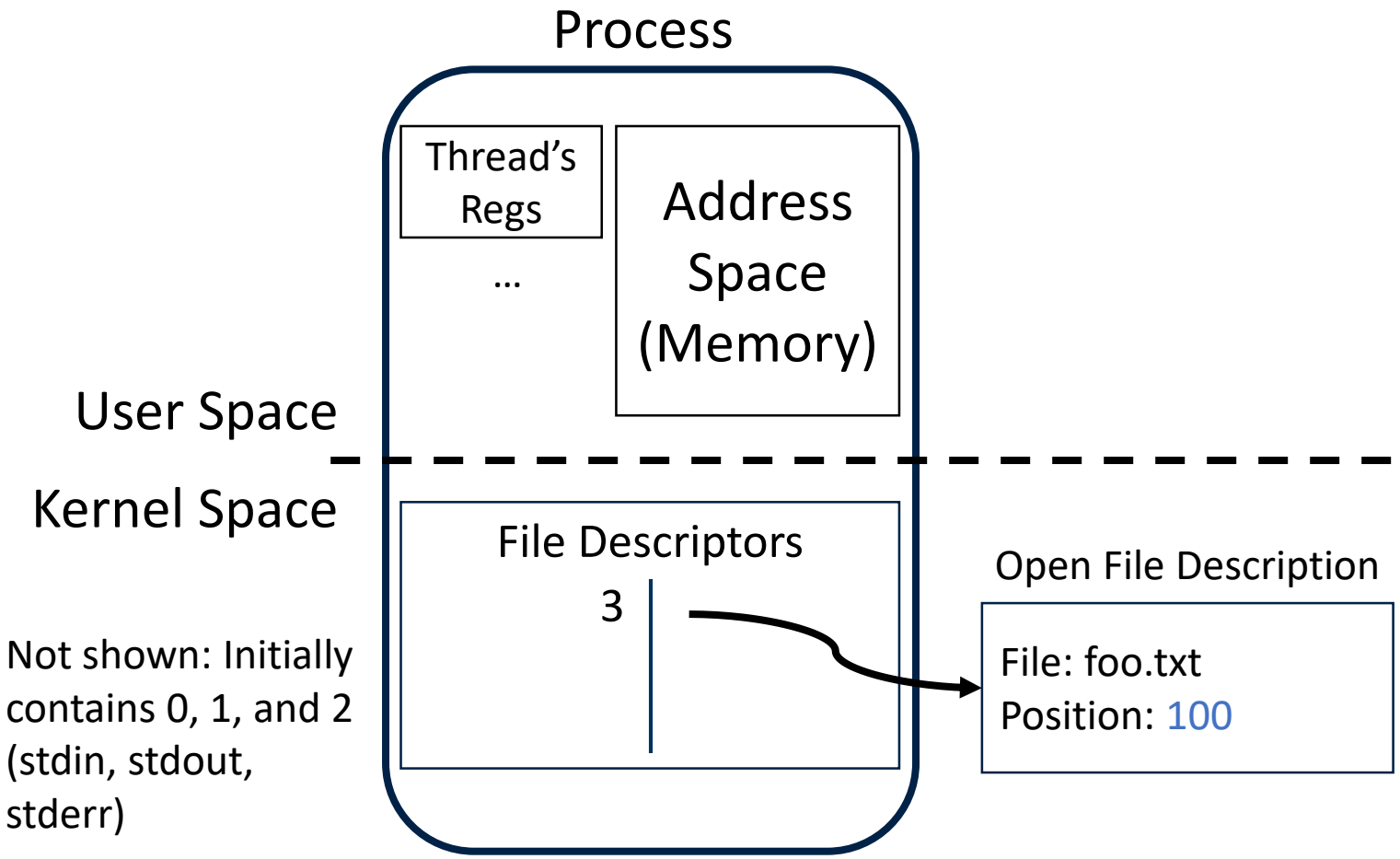

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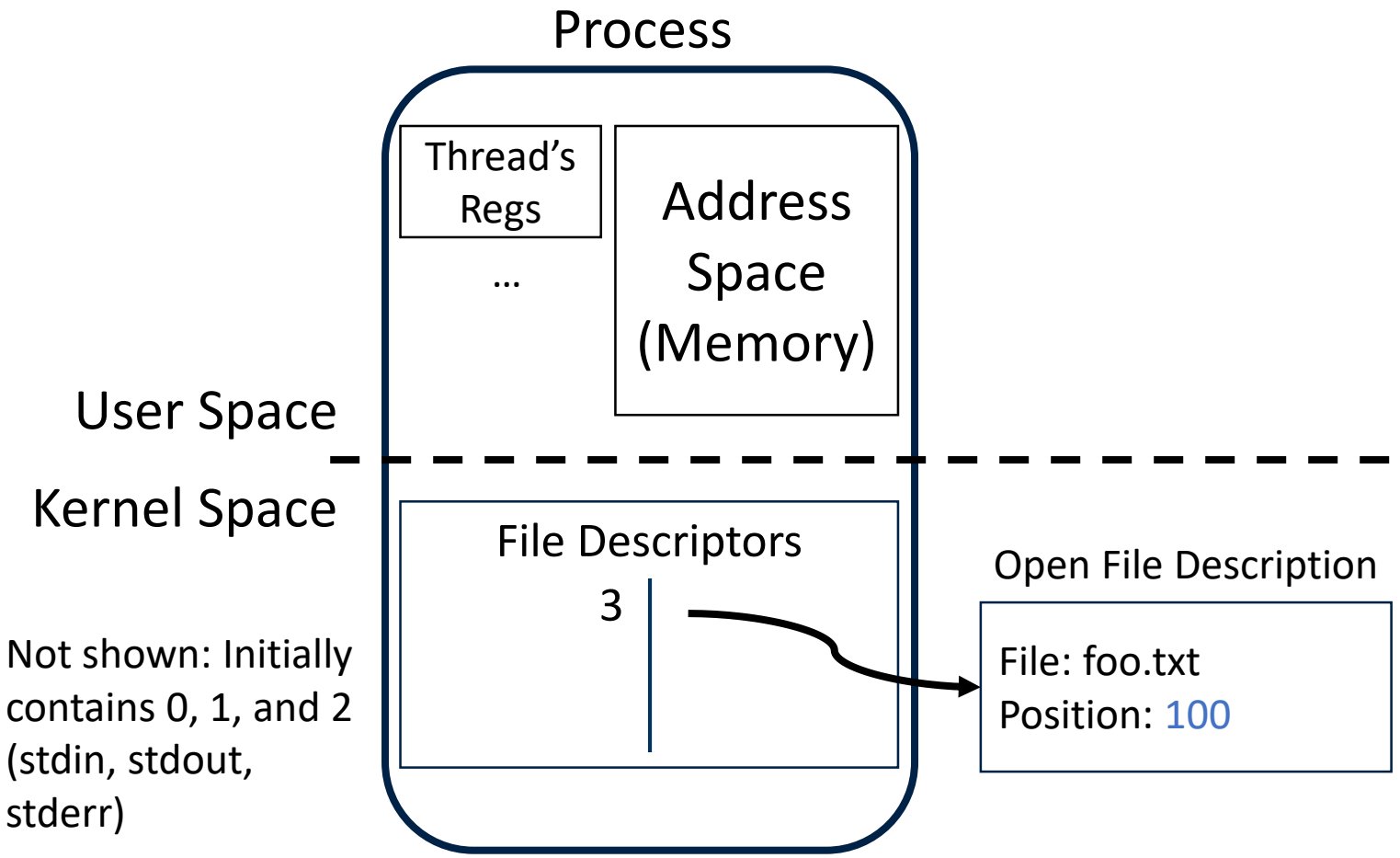
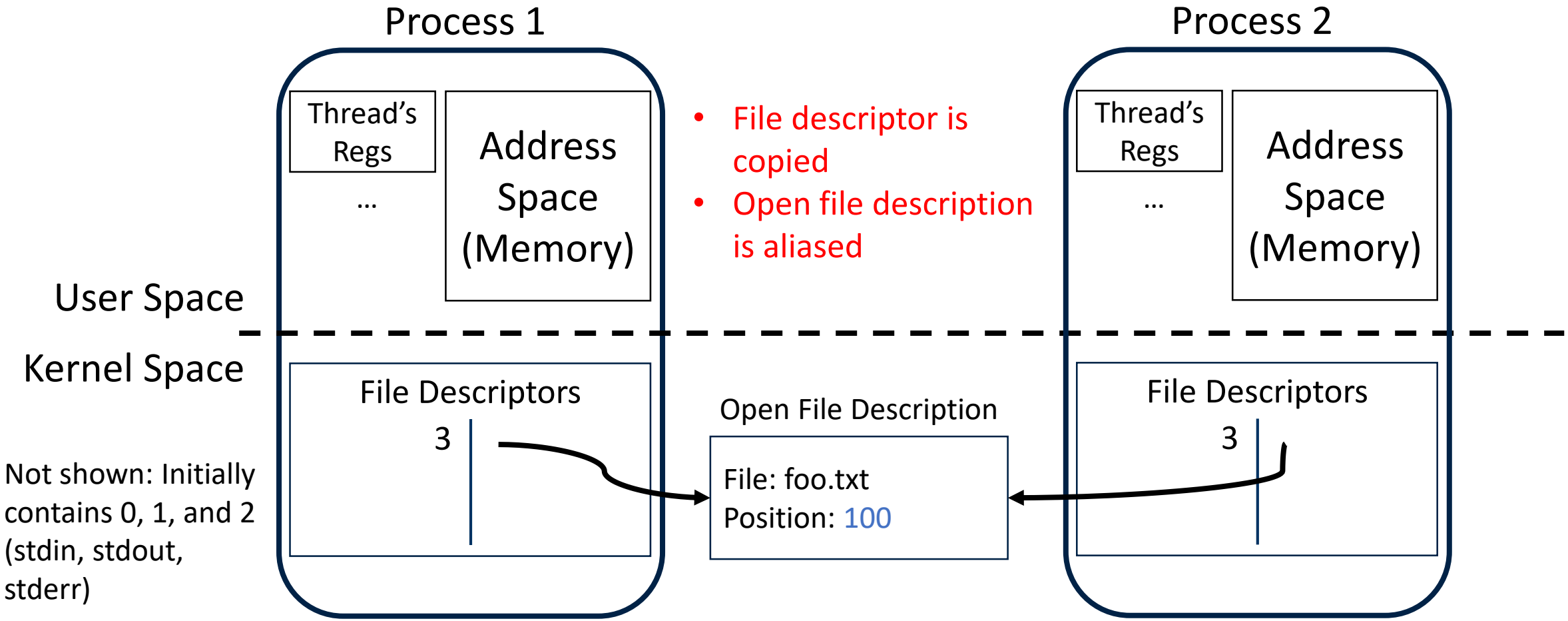


Suppose that we execute
`open("foo.txt")`
and that the result is 3

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

Finally, suppose that we execute
`close(3)`

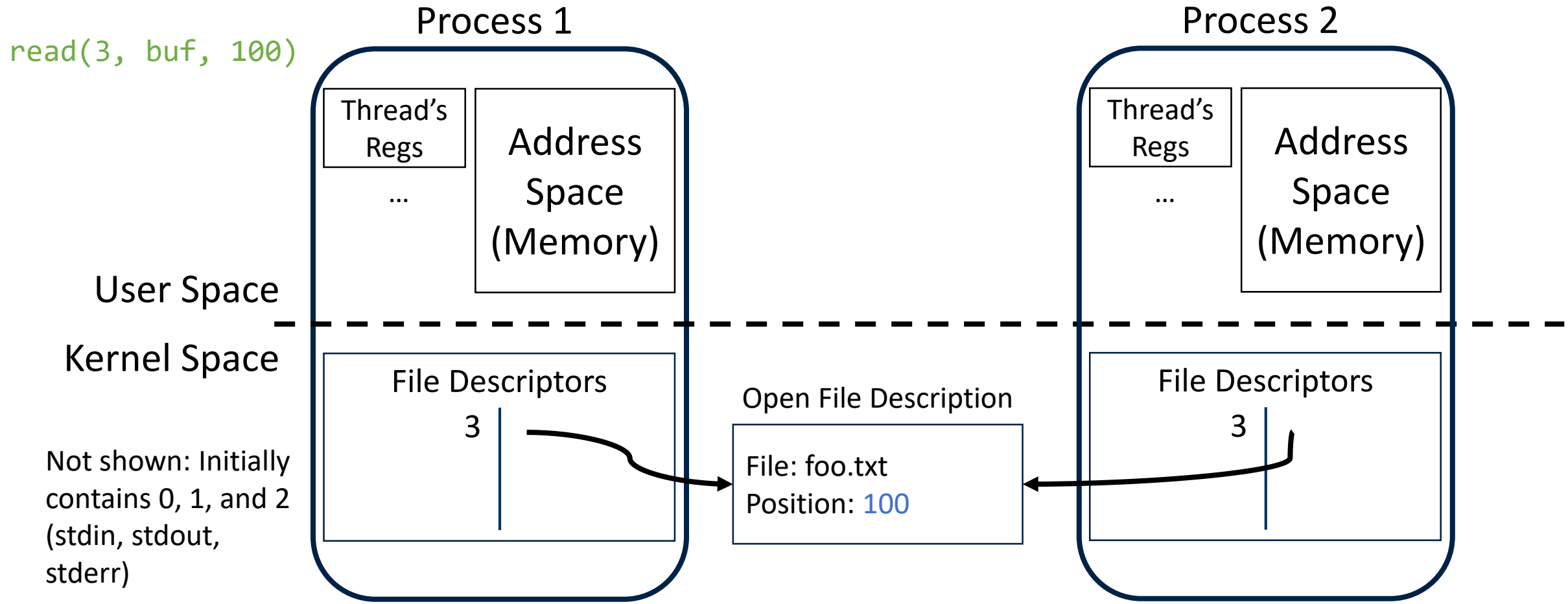
Now, let's fork()!



- 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*



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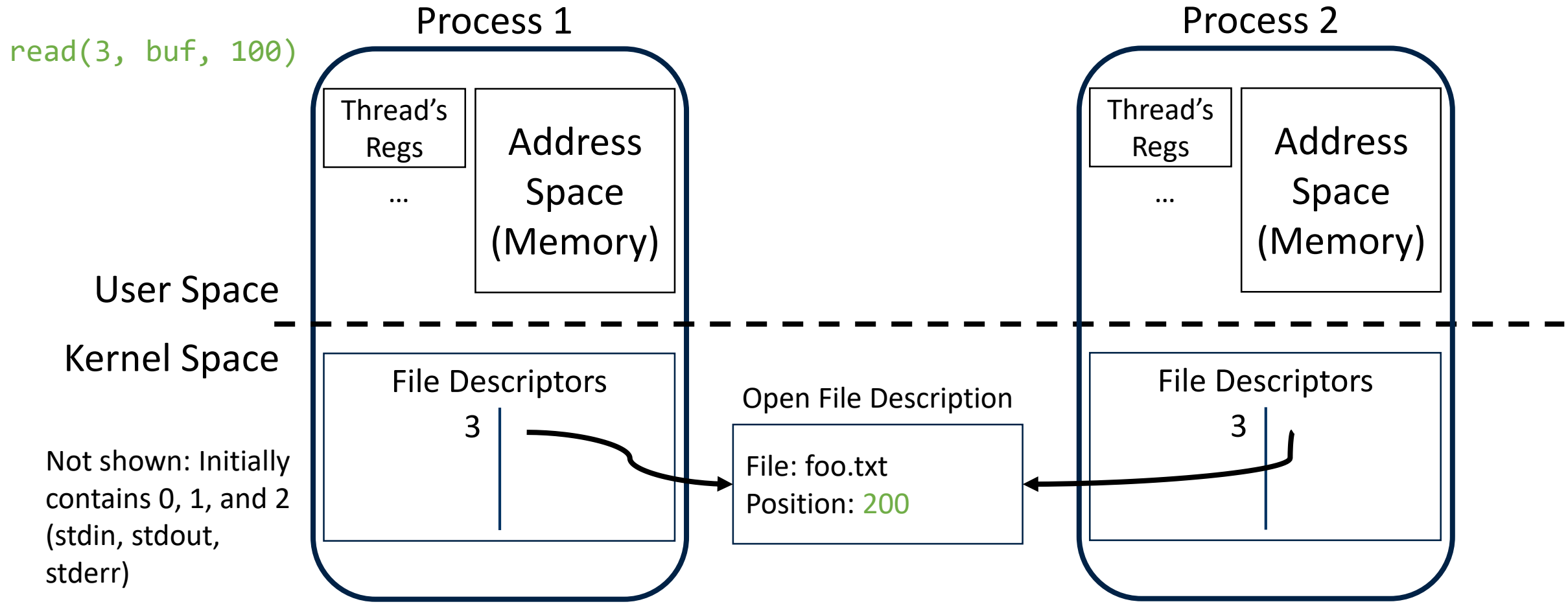

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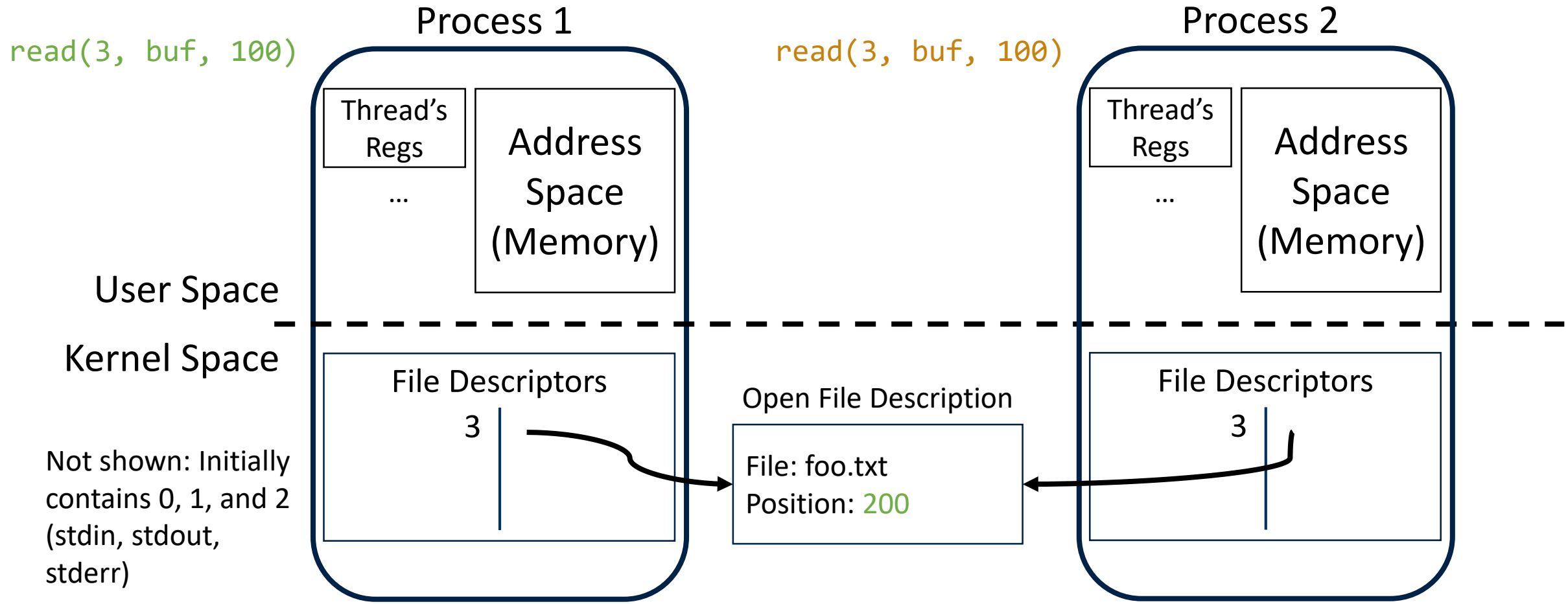
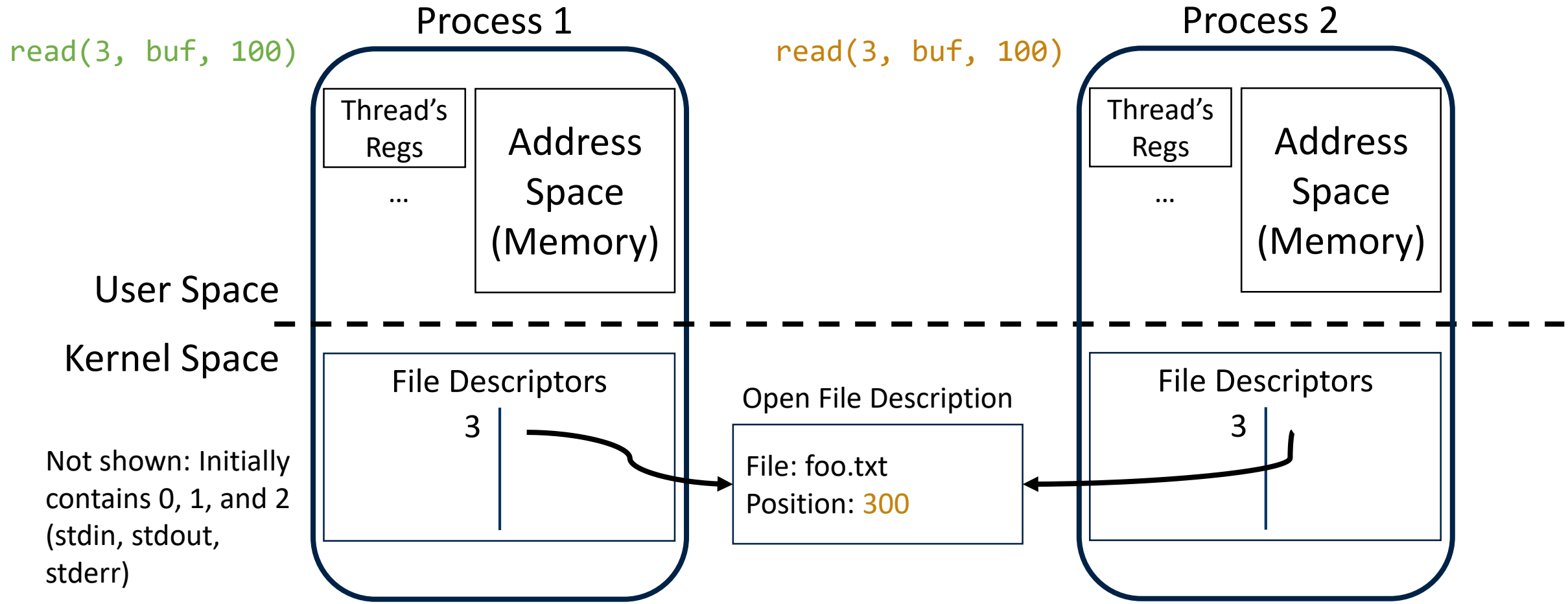
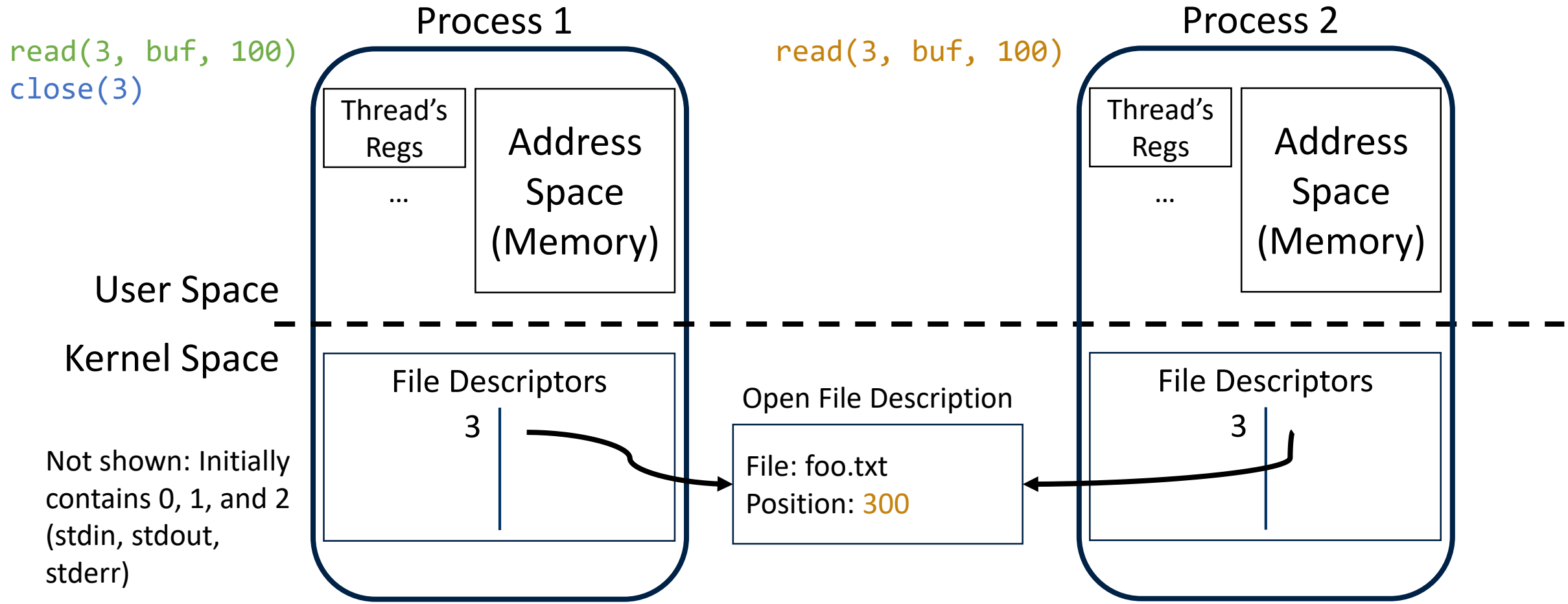


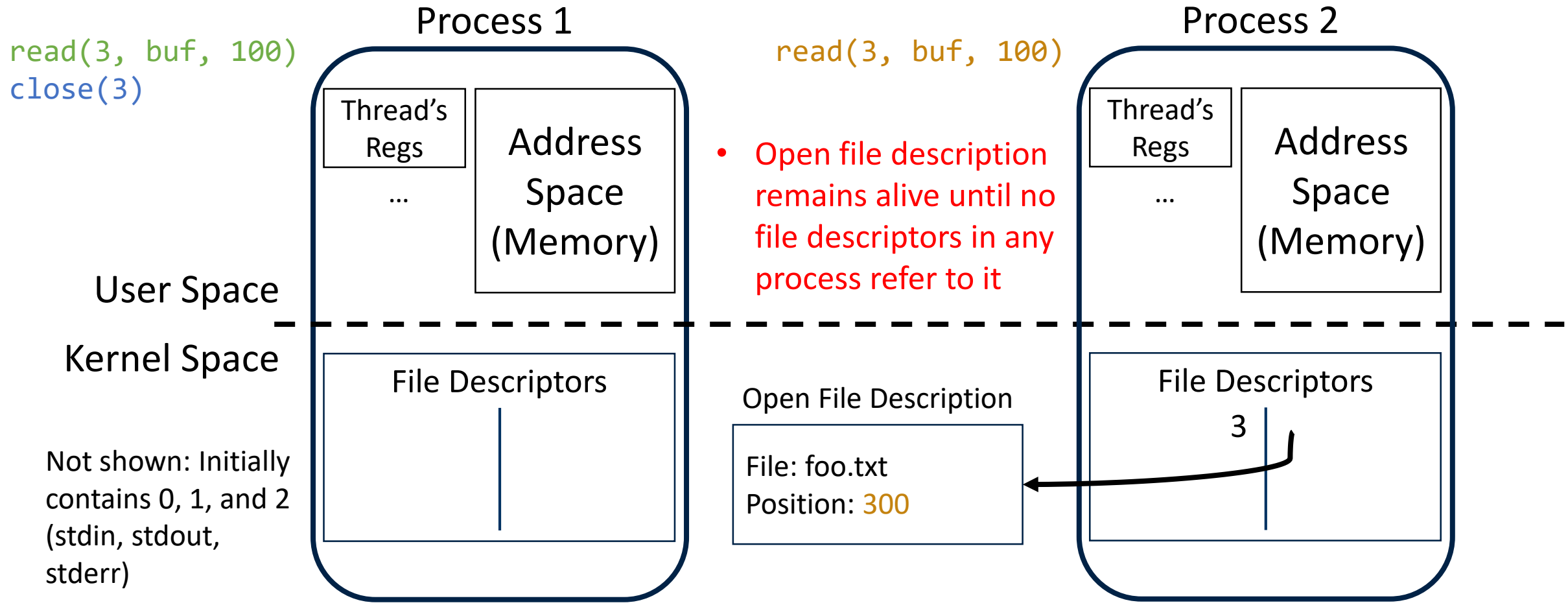
Open File Description is *Aliased*



File Descriptor is *Copied*



File Descriptor is *Copied*



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

Why is Aliasing the Open File Description a Good Idea?

- It allows for *shared resources* between processes

Recall: In POSIX, Everything is a "File"

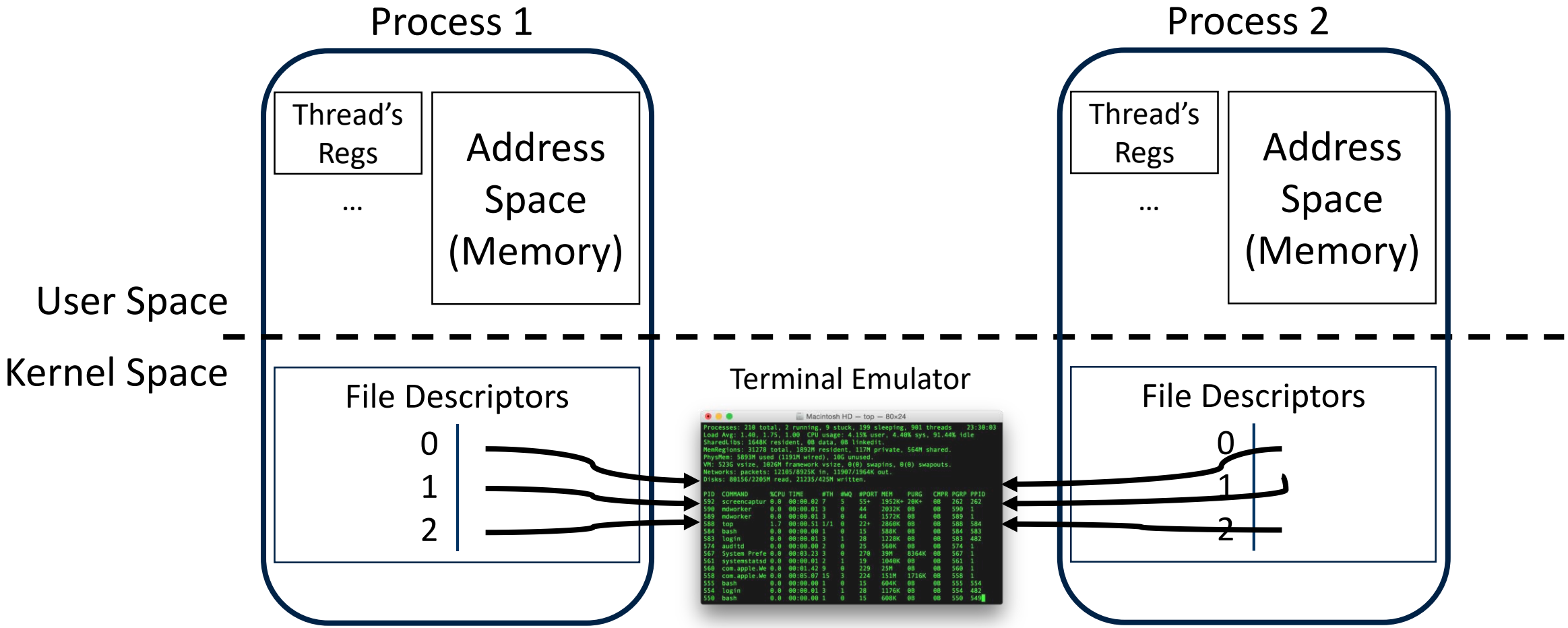
- Identical interface for:
  - Files on disk
  - Devices (terminals, printers, etc.)
  - Regular files on disk
  - Networking (sockets)
  - Local interprocess communication (pipes, sockets)

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

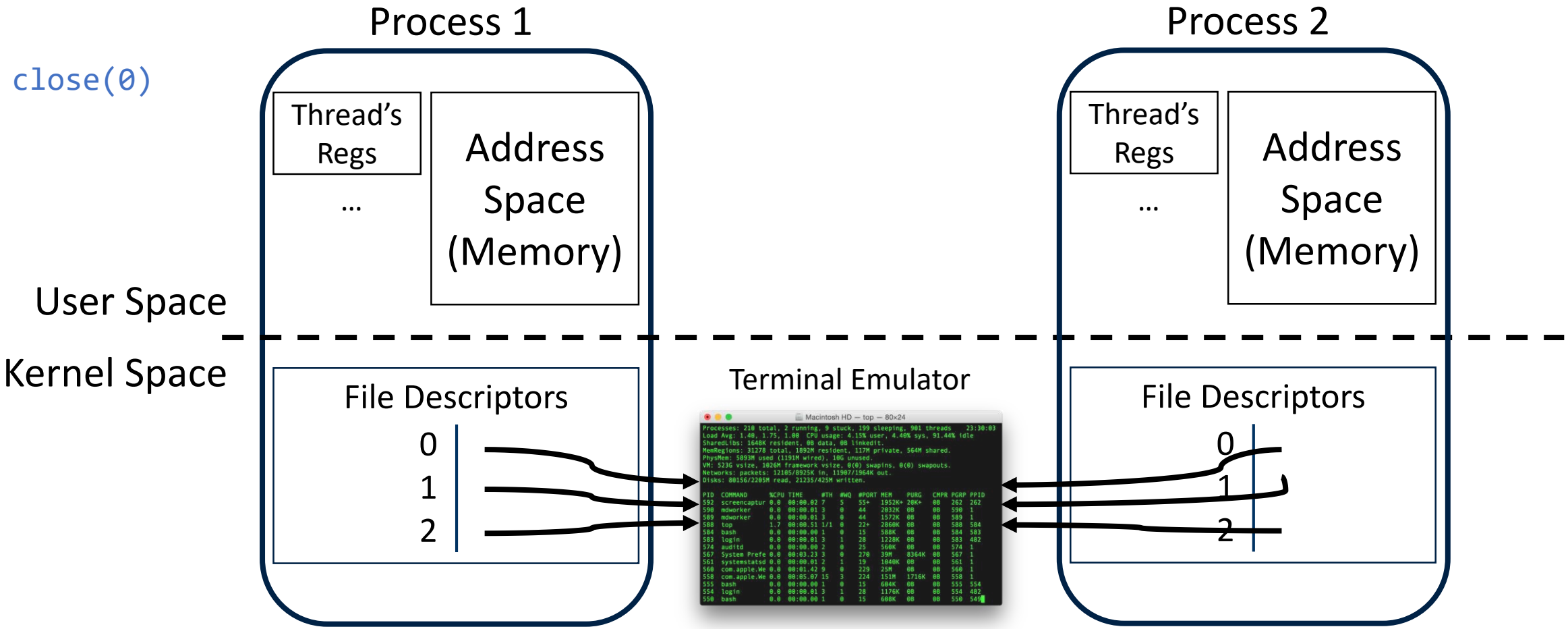
Example: Shared Terminal Emulator

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

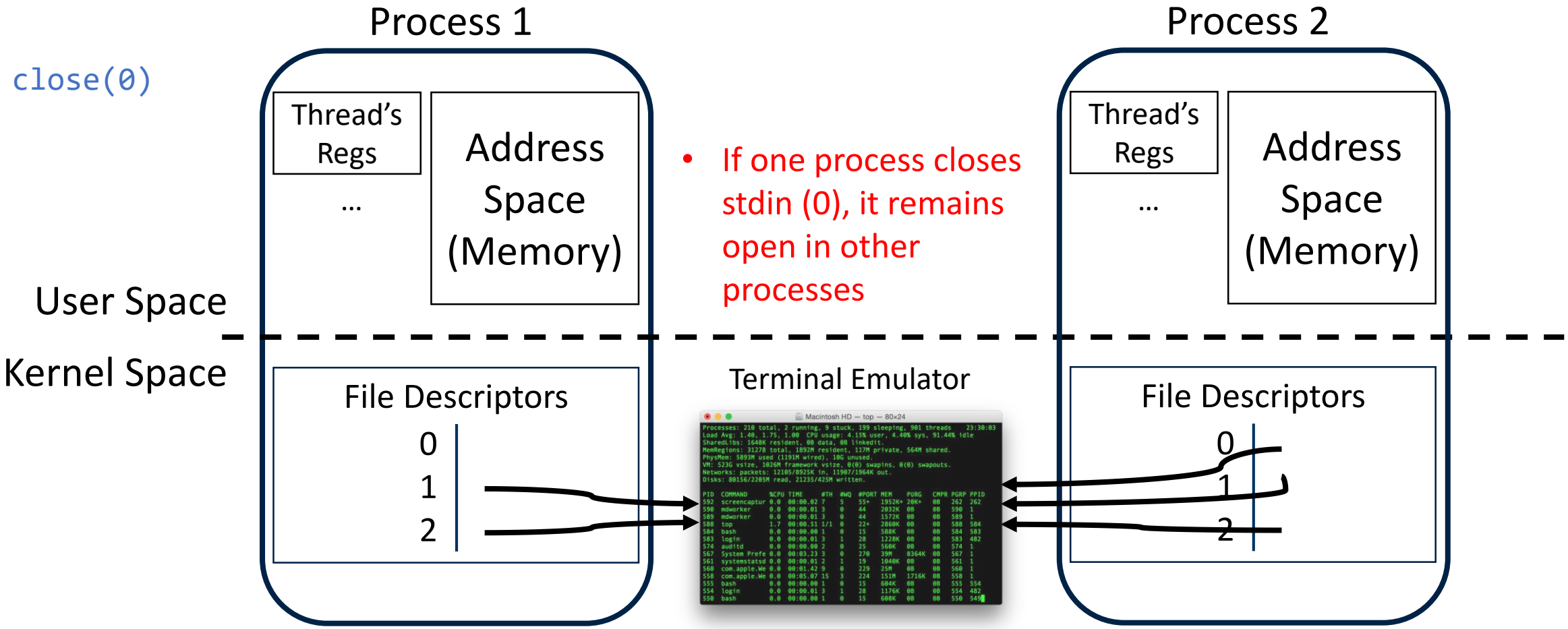
Example: Shared Terminal Emulator



Example: Shared Terminal Emulator



Example: Shared Terminal Emulator



Other Examples

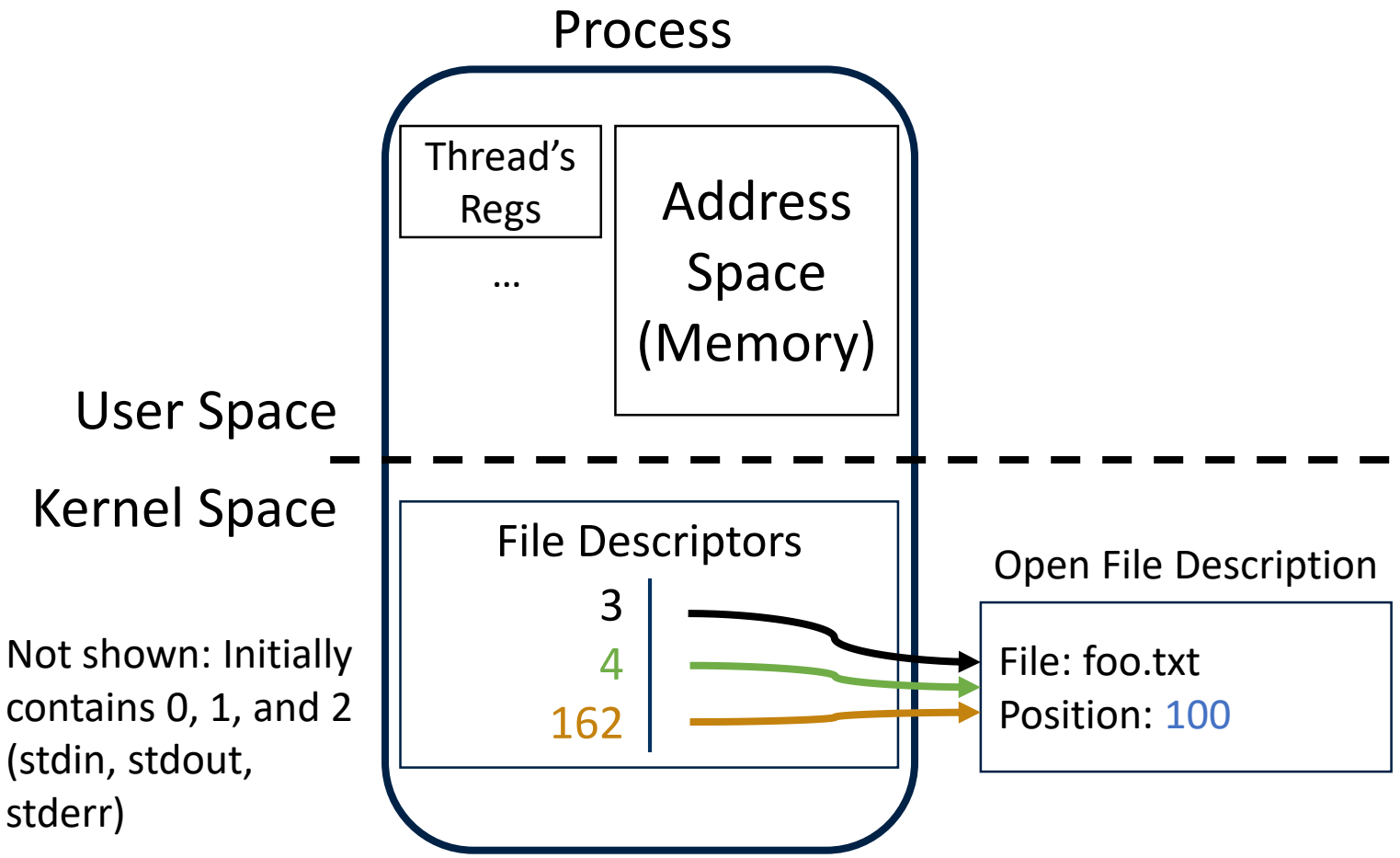
- Shared network connections after `fork()`
  - Allows handling each connection in a separate process
  - We'll explore this next time

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

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, 162)`

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

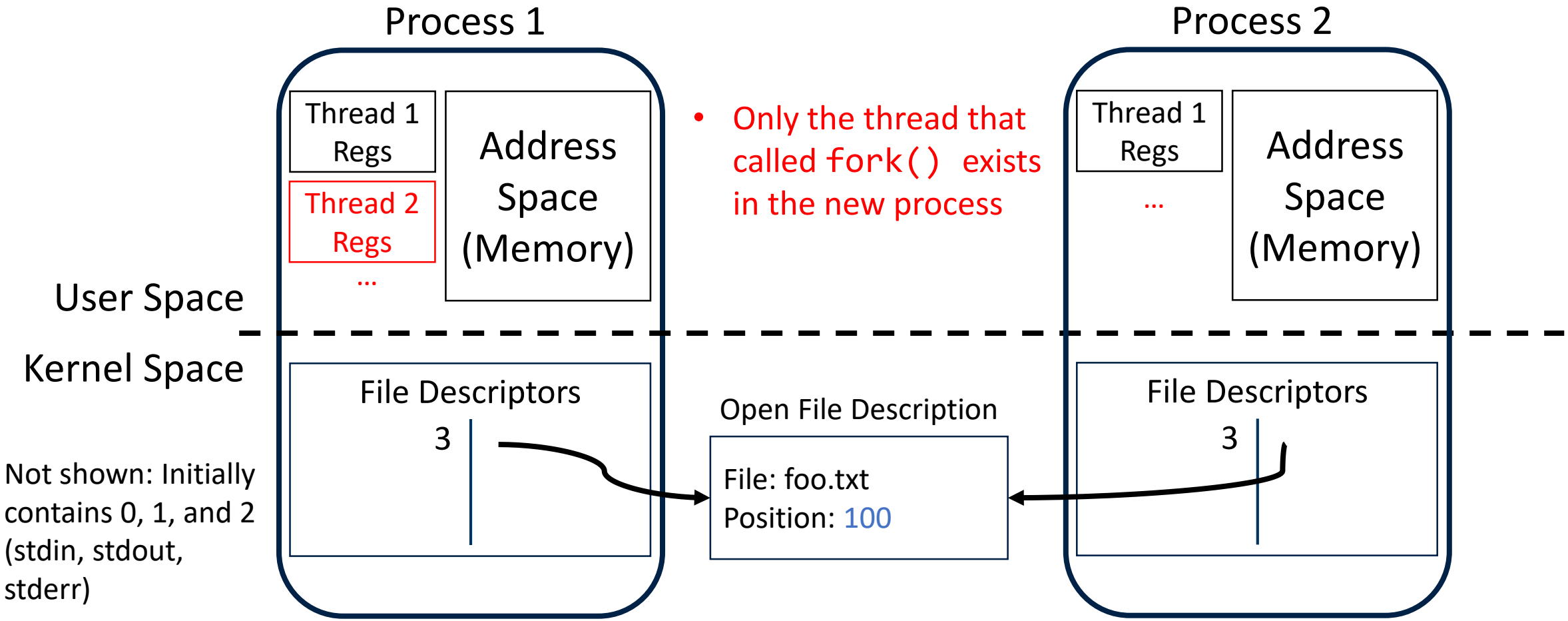
Unless you plan to call `exec()` in the child process

`fork()` in Multithreaded Processes

- The child process always has just a single thread
  - The thread in which `fork()` was called

- The other threads just vanish

fork() in a Multithreaded Processes



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

```
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
```

- Which bytes from the file are read into y?
  A. Bytes 0 to 9
  B. Bytes 10 to 19
  C. None of these?

Avoid Mixing FILE* and File Descriptors

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char x[10];
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- Which bytes from the file are read into y?
  A. Bytes 0 to 9
  B. Bytes 10 to 19
  C. 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);
```

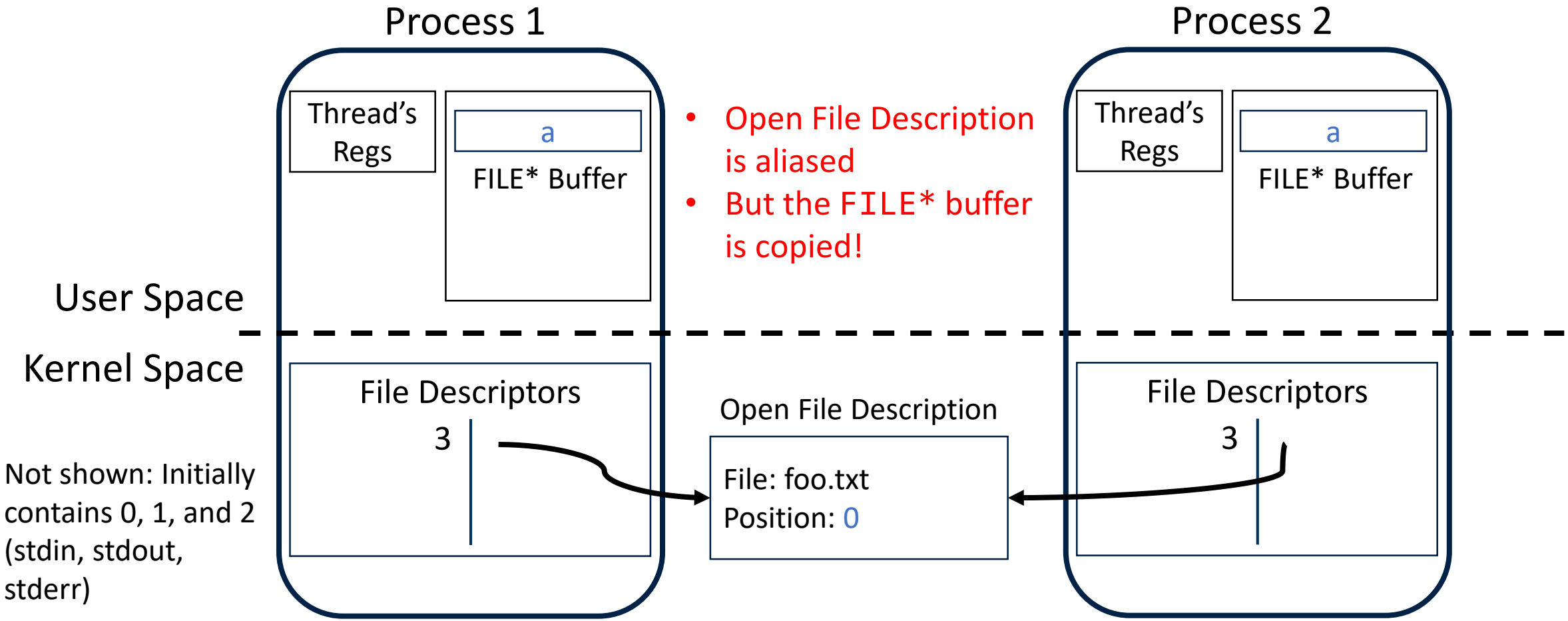
- Depends on whether this `fwrite` call flushes…

After all processes exit, what is in `foo.txt`?

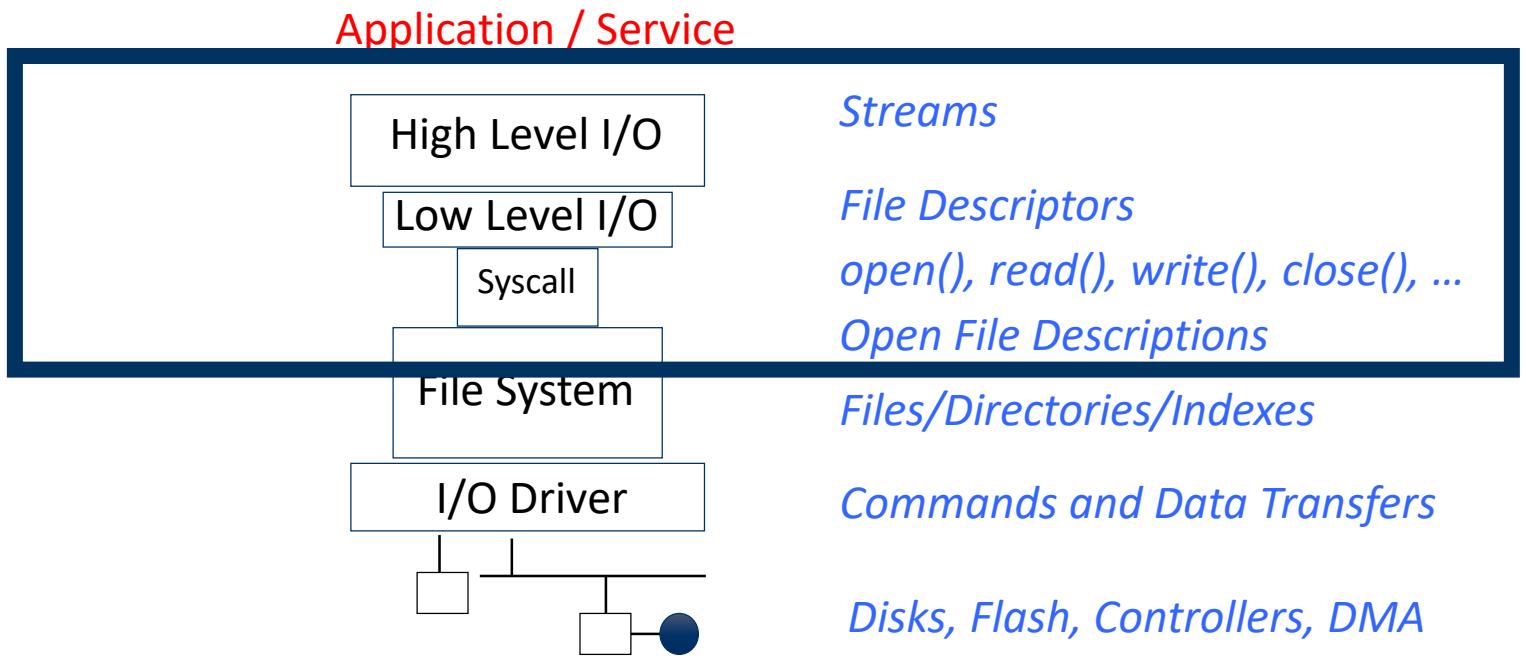
Could be either `a` or `aa`

- Usually `aa` based on what I've observed in Linux…

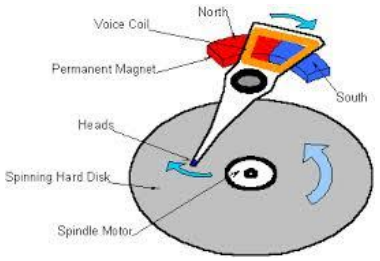
Be Careful Using fork() with FILE*



Conclusion



Focus of today's lecture



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