NOTICE

- Deadlines
  - (4/27 11:59 PM) Programming assignment 2
  - Midterm Quiz 2 will be online by tomorrow morning 8 am
    - Cover materials from Apr 8 to Apr 27

CS 344: Operating Systems I
Filesystem Internals

M/W 12:00 – 1:50 PM (LINC #200)

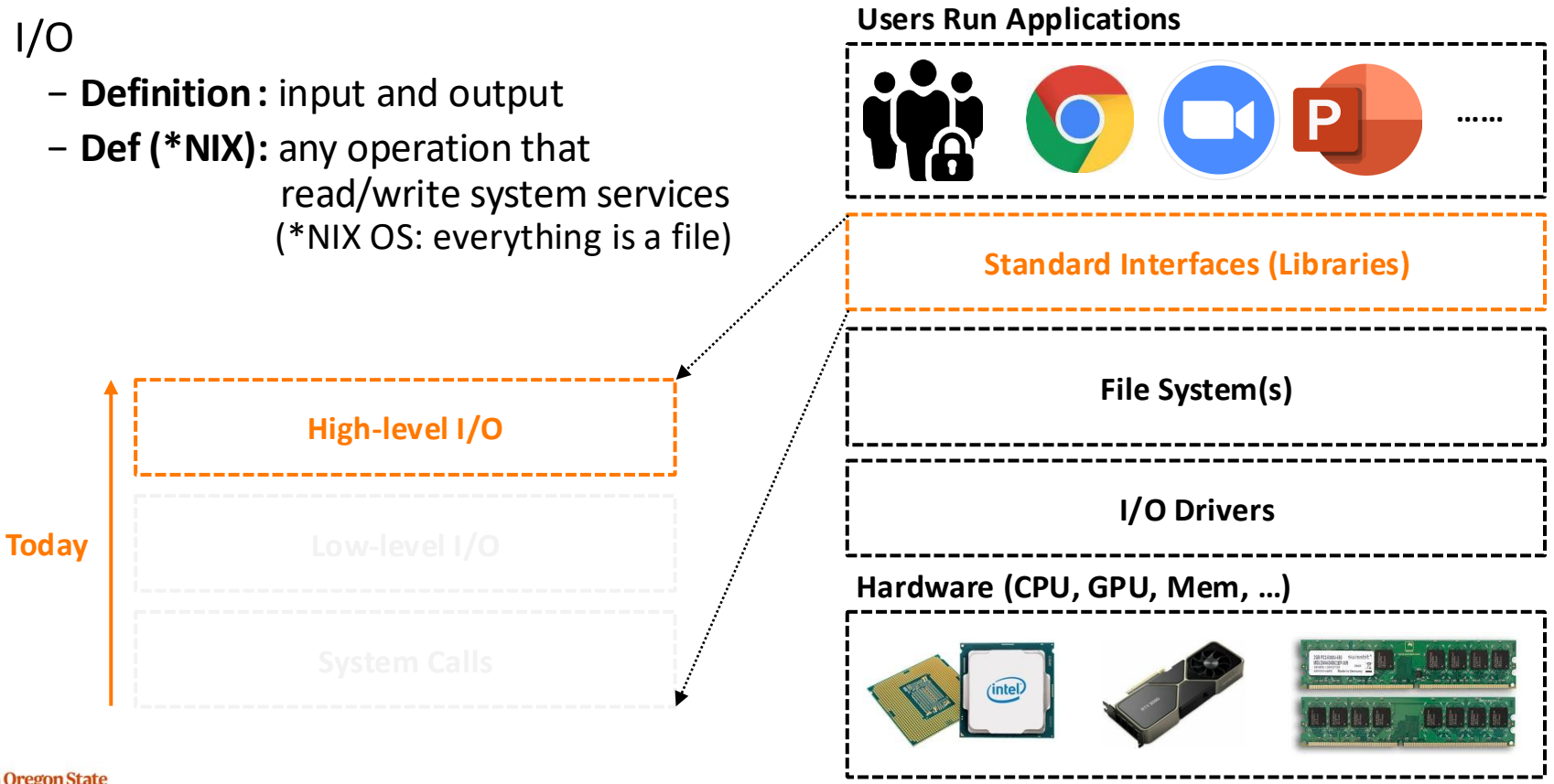
Sanghyun Hong
sanghyun.hong@oregonstate.edu

RECAP

- Part II: I/Os
  - Provide abstractions
    - What is I/O?
  - Offer standard interface
    - How can we do low-level I/O?
    - How can we do high-level I/O?
  - Manage resources
    - How does OS manage (file) I/O internally?

RECAP: HIGH-LEVEL I/O

- I/O
  - **Definition :** input and output
  - **Def (*NIX):** any operation that read/write system services (*NIX OS: everything is a file)



RECAP: HIGH-LEVEL I/O

- File as a stream
  - **Definition:** an unformatted sequence of bytes **with a position**
  - **Functions:**
    - FILE *fopen(const char *filename, const char *mode)
    - int fclose(FILE *fp)
  - **Standard streams:**
    - FILE *stdin : normal source of input, can b
    - FILE *stdout: normal source of output; redirection can be done
    - FILE *stderr : output errors
  - **Standard streams in Terminal:**
    - Each stream has numbers: 0 (stdin), 1 (stdout), 2 (stderr)
    - An example command : $ ./movie movie.csv > ./output 2>&1

Redirects the stdout from "./movie movie.csv" to "./output" file. "printf" outputs will be stored.

Errors won't be stored to "./output" "2>&1" redirects stderr output to stdin; stored to the file

RECAP: READ/WRITE FROM/TO A STREAM

- Character(byte)-level API
  - int fputc(int c, FILE *fp)
  - int fputs(const char *s, FILE *fp)
  - int fgetc(FILE *fp)
  - char *fgets(char *buf, int n, FILE *fp)
- Block-level API
  - size_t fread(void *ptr, size_t size_of_elements, size_t number_of_elements, FILE *fp)
  - size_t fwrite(void *ptr, size_t size_of_elements, size_t number_of_elements, FILE *fp)
- Note
  - fread(buf, sizeof(char), 100, fp) is not the same as
  - fread(buf, 100, sizeof(char), fp)

RECAP: READ/WRITE FROM/TO A STREAM

- Character(byte)-level API
  - int fputc(int c, FILE *fp)
  - int fputs(const char *s, FILE *fp)
  - int fgetc(FILE *fp)
  - char *fgets(char *buf, int n, FILE *fp)
- Block-level API
  - size_t fread(void *ptr, size_t size_of_elements, size_t number_of_elements, FILE *fp)
  - size_t fwrite(void *ptr, size_t size_of_elements, size_t number_of_elements, FILE *fp)
- (More convenient) API allows formatting
  - int fprintf(FILE *restrict stream, const char *restrict format, …);
  - int fscanf(FILE *restrict stream, const char *restrict format, …);

RECAP: HIGH-LEVEL I/O

- Example C code:

```c
#define BUFFER_SIZE    256

int main(void) {
   FILE *input;
   char *buffer = (char *) calloc(BUFFER_SIZE, sizeof(char));
   size_t len = 0;

   input = fopen("input.txt", "r");
   if (input == NULL) {
      printf("Cannot open the input.txt file, abort.\n");
      return -ENOENT;
   }

   len = fread(buffer, sizeof(char), BUFFER_SIZE, input);
   while (len > 0) {
      printf("[CHAR] read: %c\n", buffer[--len]);
   }

   fclose(input);
   return 0;
}
```

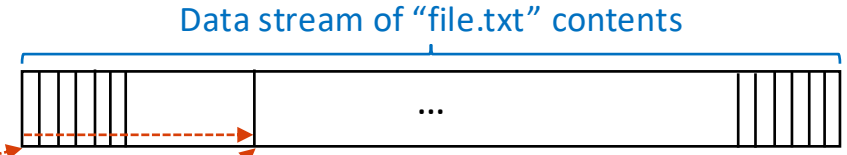
Macros (some predefineds):
You can define any numbers, strings, etc.
Or you can use what C already defines

fopen / fread system calls:
Open a file and read the contents, 256 bytes,
The file will be open for reading-only. If the contents are less than 256 bytes. It will return all

RECAP: HIGH-LEVEL I/O

- Example C code:

```
#define BUFFER_SIZE     256

int main(void) {
   FILE *input;
   char *buffer = (char *) calloc(BUFFER_SIZE, sizeof(char));
   size_t len = 0;

   input = fopen("input.txt", "r");
   if (input == NULL) {
      printf("Cannot open the input.txt file, abort.\n");
      return -ENOENT;
   }

   len = fread(buffer, sizeof(char), BUFFER_SIZE, input);
   while (len > 0) {
      printf("[CHAR] read: %c\n", buffer[--len]);
   }

   fclose(input);
   return 0;
}
```



The next fread/fwrite will be performed from the new location!

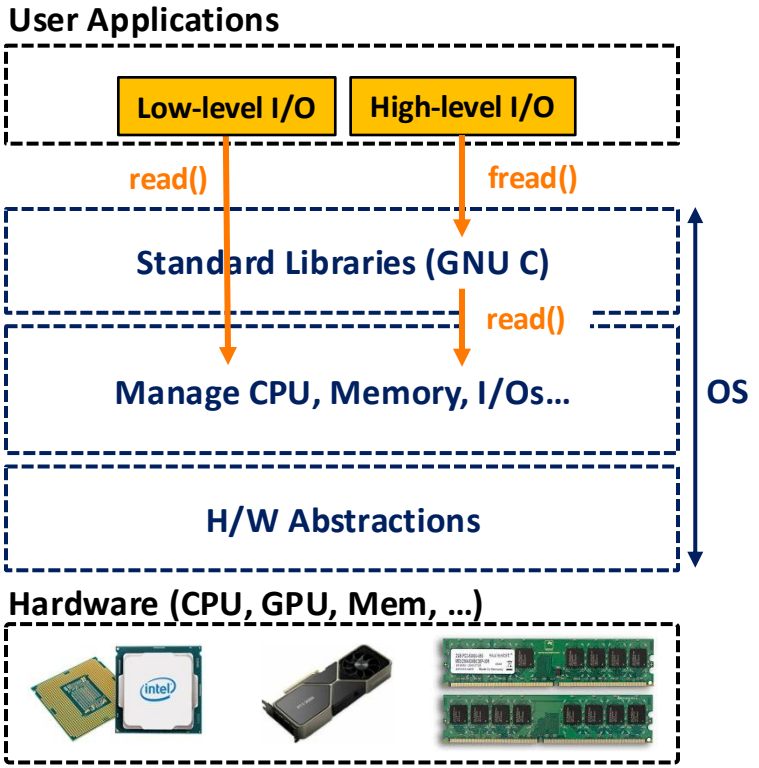
RECAP: POSITION CONTROL

- Position control API
  - int fseek(FILE *fp, long offset, int whence)
  - int ftell(FILE *fp)

- *examples*
  - fseek(fp, 0, SEEK_SET): move the stream position to the first
  - fseek(fp, 0, SEEK_END): move the stream position to the end

RECAP: HIGH-LEVEL VS. LOW-LEVEL I/OS

- Low-level I/O uses system calls, while high-level I/Os are **not**
  - **System calls**
    - They directly request OS services/resources
    - e.g., open(), read(), write(), and close()
  - **Standard libraries in C**
    - They are offered by C libraries
    - C libraries eventually do system calls
    - e.g., fopen(), fread(), fwrite(), and fclose()



RECAP: HIGH-LEVEL = LOW-LEVEL I/O + ADDITIONAL FN

High-level I/O calls

size_t fread(...) {

You can do something (fill buffer, error ctrl, ...) at here!

asm code ... syscall <number> into %eax
put <syscall args> into registers %ebx
special trap instruction

Kernel:
get <syscal args> from %ebx
dispatch to system func
do the work to read from the file
store return value in %eax

get return values from regs

You can do something (fill buffer, error ctrl, ...) at here!

}

Low-level I/O calls

ssize_t read(...) {

asm code ... syscall <number> into %eax
put <syscall args> into registers %ebx
special trap instruction

Kernel:
get <syscal args> from %ebx
dispatch to system func
do the work to read from the file
store return value in %eax

get return values from regs

}

High-level I/O calls also use system calls!

RECAP: WHY HIGH-LEVEL I/O?

- Given the functionalities we've learned:
  - fopen() anyway uses open() system call
  - fopen() may make users (or developers) more confusing which one to use (open?, fopen?)

- **Problem**
  - System calls are **25x slower** than the standard function call
  - System calls need the ctx switch btw user and kernel
  - Solutions?

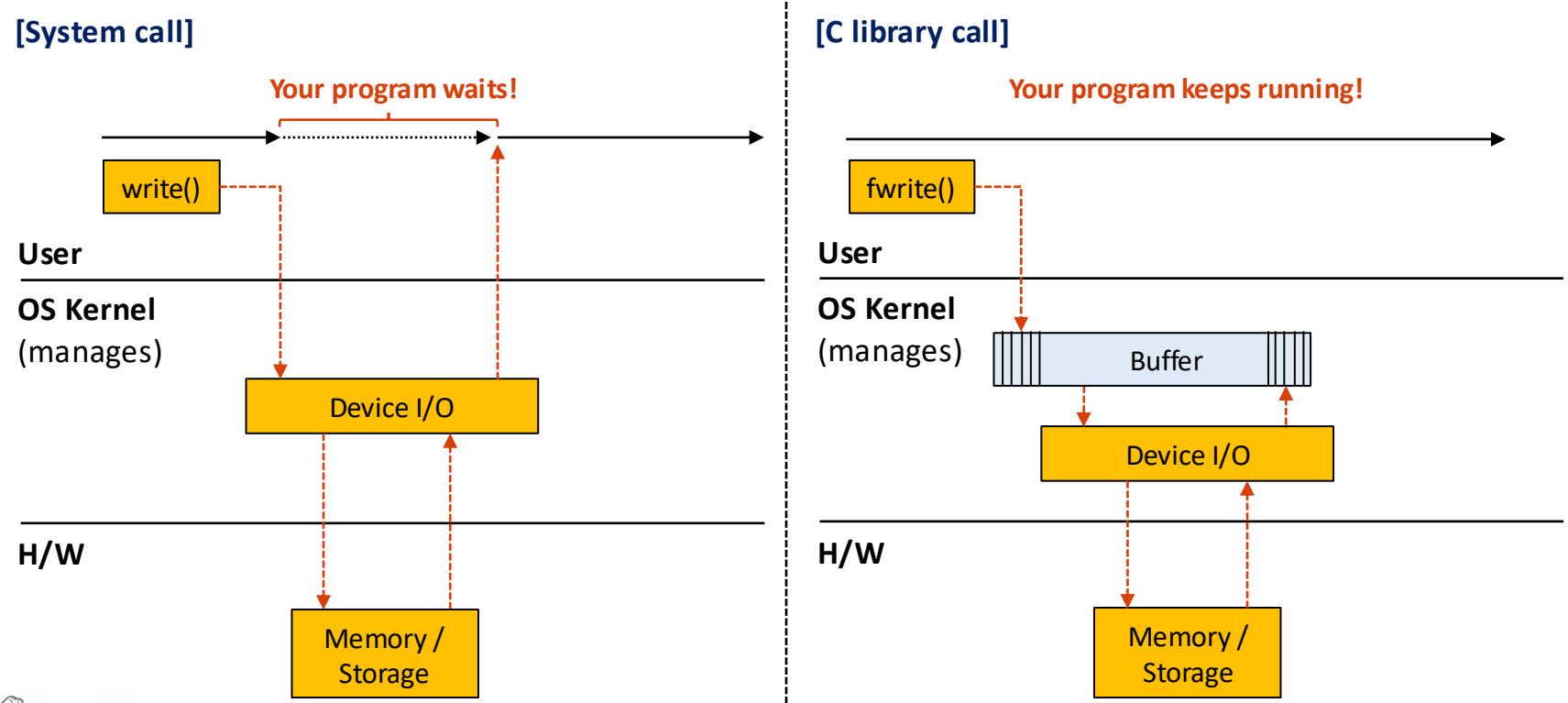
- **Kernel buffering**
  - Create a buffer in user-space (heap, managed by kernel)
  - Read/write data asynchronously
    - Read whatever amount of data in the buffer
    - Write the data to devices when the buffer is full

Recall the read() system call:

```
ssize_t read(...) {
   asm code ... syscall <number> into %eax
   put <syscall args> into registers %ebx
   special trap instruction

   Kernel:
      get <syscal args> from %ebx
      dispatch to system func
      do the work to read from the file
      store return value in %eax

   get return values from regs
}
```

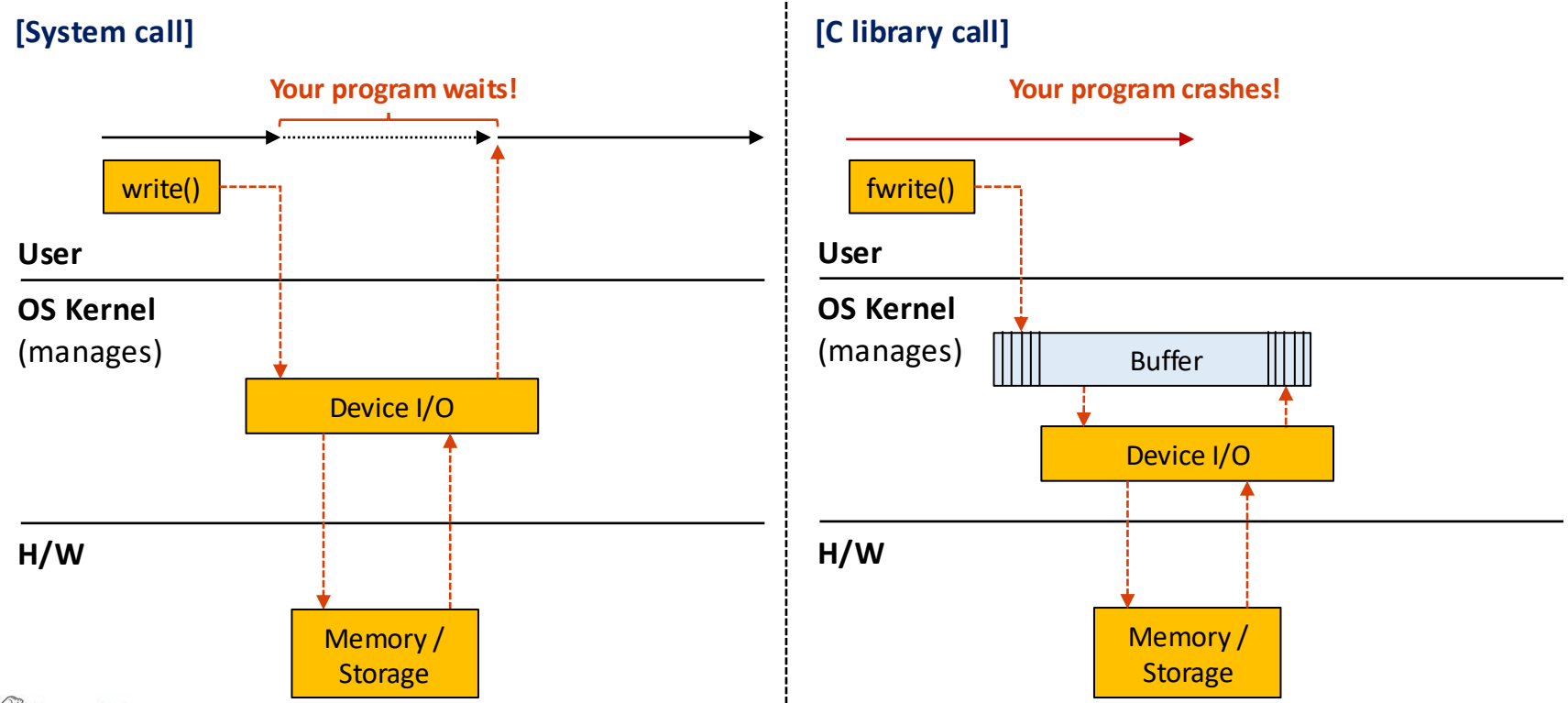
RECAP: AN EXAMPLE OF "SOMETHING"

- **Kernel buffering**



RECAP: AN EXAMPLE OF "SOMETHING"

- **Kernel buffering:** what happens when a program crashes?



RECAP: AN EXAMPLE OF "SOMETHING"

- When fwrite flushes the buffer?
  - When we write data to the buffer, but it is full
  - When we close the stream, *i.e.*, fclose(FILE *fp)
  - When the program that has called fwrite() finished its execution (*i.e.*, terminated)
  - When a new line (*i.e.*, \n) is written to the buffer
  - When a program reads data from a file (not from the buffer)
  - …

- Or if you explicitly call fflush()
  - int fflush(FILE *fp);
  - fflush(NULL): close all the streams opened for a process

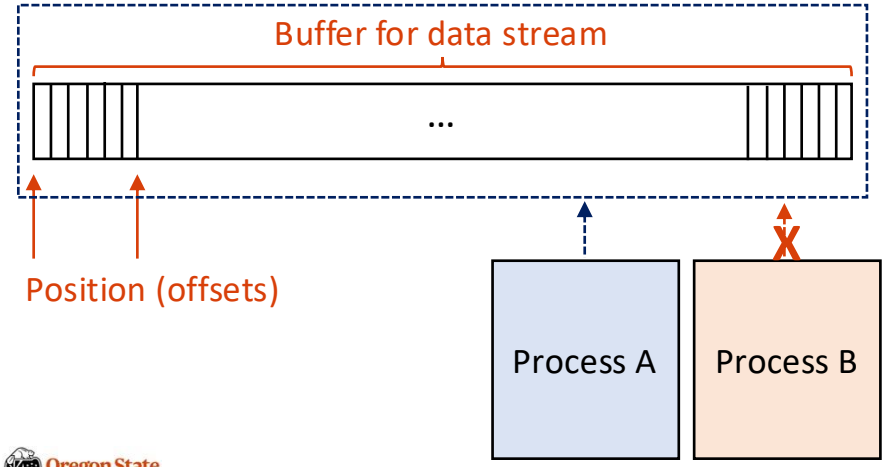
TOPICS FOR TODAY

- Part II: Filesystem internals
  - Manage resources
    - How does OS manage high-level I/O internally?
    - How does OS manage low-level I/O internally?

HIGH-LEVEL API INTERNALS: HOW?

- FILE data structure contents (code)
  - File descriptor (**fd**), from open()
  - **Offsets**, a position to read/write data
  - **Buffer** (an array of bytes to read/write data)
  - **Lock** (only one process can access data)

- FILE (Diagram)




```
49  struct _IO_FILE
50  {
51    int _flags;           /* High-order word is _IO_MAGIC; rest is flags. */
52
53    /* The following pointers correspond to the C++ streambuf protocol. */
54    char *_IO_read_ptr;   /* Current read pointer */
55    char *_IO_read_end;   /* End of get area. */
56    char *_IO_read_base;  /* Start of putback+get area. */
57    char *_IO_write_base; /* Start of put area. */
58    char *_IO_write_ptr;  /* Current put pointer. */
59    char *_IO_write_end;  /* End of put area. */
60    char *_IO_buf_base;   /* Start of reserve area. */
61    char *_IO_buf_end;    /* End of reserve area. */
62
63    /* The following fields are used to support backing up and undo. */
64    char *_IO_save_base; /* Pointer to start of non-current get area. */
65    char *_IO_backup_base;  /* Pointer to first valid character of backup area */
66    char *_IO_save_end; /* Pointer to end of non-current get area. */
67
68    struct _IO_marker *_markers;
69
70    struct _IO_FILE *_chain;
71
72    int _fileno;
73    int _flags2;
74    __off_t _old_offset; /* This used to be _offset but it's too small.  */
75
76    /* 1+column number of pbase(); 0 is unknown. */
77    unsigned short _cur_column;
78    signed char _vtable_offset;
79    char _shortbuf[1];
80
81    _IO_lock_t *_lock;
.....
89    __off64_t _offset;
90    /* Wide character stream stuff.  */
91    struct _IO_codecvt *_codecvt;
92    struct _IO_wide_data *_wide_data;
93    struct _IO_FILE *_freeres_list;
94    void *_freeres_buf;
95    size_t __pad5;
96    int _mode;
97    /* Make sure we don't get into trouble again.  */
98    char _unused2[15 * sizeof (int) - 4 * sizeof (void *) - sizeof (size_t)];
99  };
```

HIGH-LEVEL API INTERNALS: HOW?

- Exercise

```
… many #include …

int main(void) {
   char name[8] = "Sanghyun";
   char desc[28] = "is an instructor of CS 374\n";

   fwrite(name, sizeof(char), strlen(name), stdout);
   sleep(10);
   fwrite(desc, sizeof(char), strlen(desc), stdout);
   return 0;
}
```

```
… many #include …

int main(void) {
   char name[8] = "Sanghyun";
   char desc[28] = "is an instructor of CS 374\n";

   write(STDOUT_FILENO, name, strlen(name));
   sleep(10);
   write(STDOUT_FILENO, desc, strlen(desc));
   return 0;
}
```

  - Before the sleep(10), what message you'll see in your terminal?
  - After the sleep(10), what message you'll see in your terminal?

HIGH-LEVEL API INTERNALS: HOW?

- Exercise

```
… many #include …

int main(void) {
   char x = 'S';

   FILE *fp1 = fopen("input.txt", "w");
   fwrite("H", sizeof(char), 1, fp1);

   FILE *fp2 = fopen("input.txt", "r");
   fread(&x, sizeof(char), 1, fp2);

   printf("I read %c\n", x);
   return 0;
}
```

- **Case I – X**
  - "H" is written to the file by fwrite()
  - fread() will read "H" from the file
  - Print "H"
- **Case II – O**
  - "H" is in the kernel buffer
  - fread() won't read anything from the file
  - Print "S"

HIGH-LEVEL API INTERNALS: HOW?

- Exercise

```
… many #include …

int main(void) {
   char x = 'S';

   FILE *fp1 = fopen("input.txt", "w");
   fwrite("H", sizeof(char), 1, fp1);
   fflush(fp1);

   FILE *fp2 = fopen("input.txt", "r");
   fread(&x, sizeof(char), 1, fp2);

   printf("I read %c\n", x);
   return 0;
}
```

- **Case I – X**
  - "H" is written to the file by fwrite()
  - fread() will read "H" from the file
  - Print "H"
- **Case II – O**
  - "H" is in the kernel buffer
  - fread() won't read anything from the file
  - Print "S"
- **Case with fflush()**
  - "H" is written to the buffer
  - It will be flushed to the file by fflush()
  - fread() will read "H" from the file
  - Print "H"

TOPICS FOR TODAY

- Part II: Filesystem internals
  - Manage resources
    - How does OS manage high-level I/O internally?
    - How does OS manage low-level I/O internally?

LOW-LEVEL API INTERNALS

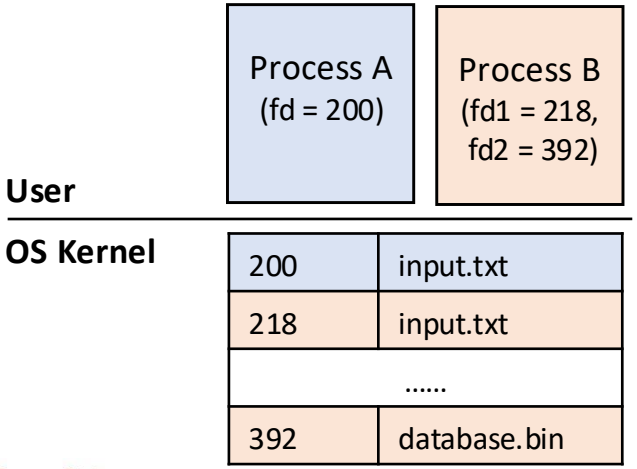
- File descriptors (fd)
  - **Definition** : an integer that uniquely identifies an open file in Linux
  - **System calls:** (fctrl.h)
    - int open(const char *filename, int flags, mode_t *mode)
  - Magic behind the open()
    - open() creates an *open file descriptor table* for each process (fd is here)
    - open() also creates an *entry* in system-wide table of open files (offset are here)
    - *open file description object* in the kernel represents an *instance of an actual open file*
  - Reserved fd
    - stdin/stdout/stderr: 0, 1, and 2

```
… many #include …

int main(void) {
   int fd = open("file.txt", O_RDONLY);
   printf("fd = %d\n", fd);
   return 0;
}
```

LOW-LEVEL API INTERNALS: HOW?

- File descriptor (code) in Linux kernel
  - **iNode**, a structure that holds data on disk
  - **Offsets**, a position to read/write data
  - **No buffer**

- File descriptor (Diagram)

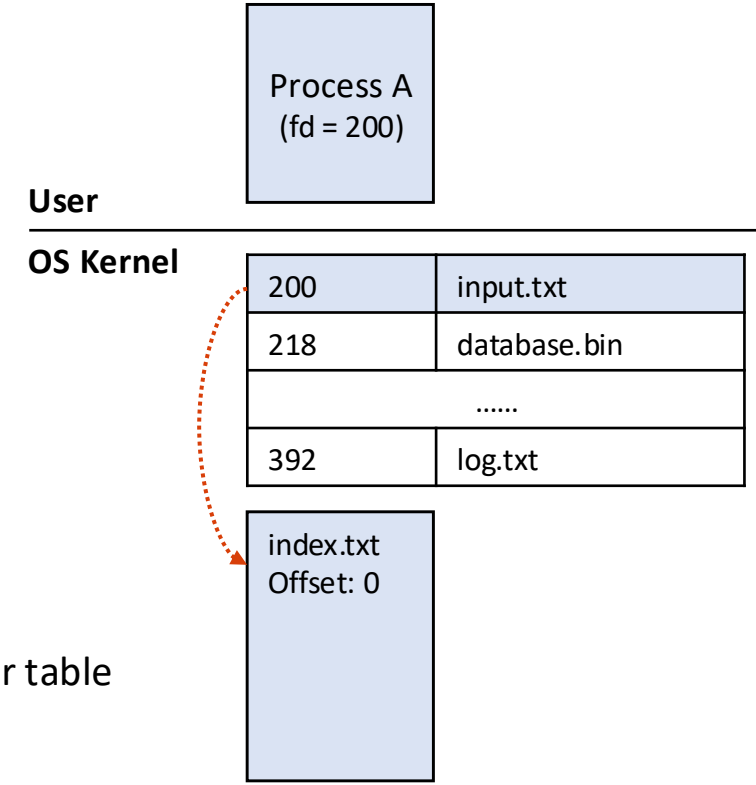



```
932 struct file {
933         union {
934                 struct llist_node       fu_llist;
935                 struct rcu_head         fu_rcuhead;
936         } f_u;
937         struct path             f_path;
938         struct inode            *f_inode;       /* cached value */
939         const struct file_operations    *f_op;
940
941         /*
942          * Protects f_ep, f_flags.
943          * Must not be taken from IRQ context.
944          */
945         spinlock_t              f_lock;
946         atomic_long_t           f_count;
947         unsigned int            f_flags;
948         fmode_t                 f_mode;
949         struct mutex            f_pos_lock;
950         loff_t                  f_pos;
951         struct fown_struct      f_owner;
952         const struct cred       *f_cred;
953         struct file_ra_state    f_ra;
954
955         u64                     f_version;
956 #ifdef CONFIG_SECURITY
957         void                    *f_security;
958 #endif
959         /* needed for tty driver, and maybe others */
960         void                    *private_data;
961
962 #ifdef CONFIG_EPOLL
963         /* Used by fs/eventpoll.c to link all the hooks to this file */
964         struct hlist_head       *f_ep;
965 #endif /* #ifdef CONFIG_EPOLL */
966         struct address_space    *f_mapping;
967         errseq_t                f_wb_err;
968         errseq_t                f_sb_err; /* for syncfs */
969 } __randomize_layout
970   __attribute__((aligned(4)));  /* lest something weird decides that 2 is OK */
```

LOW-LEVEL API INTERNALS: HOW?

- Let's check with the following program

```
... many #include ...
#define   BSIZE   100

int main(void) {
   char buf1[BSIZE];
   char buf2[BSIZE];
   int fd = open("input.txt", O_RDONLY);

   read(fd, buf1, BSIZE);
   read(fd, buf2, BSIZE);
   return 0;
}
```



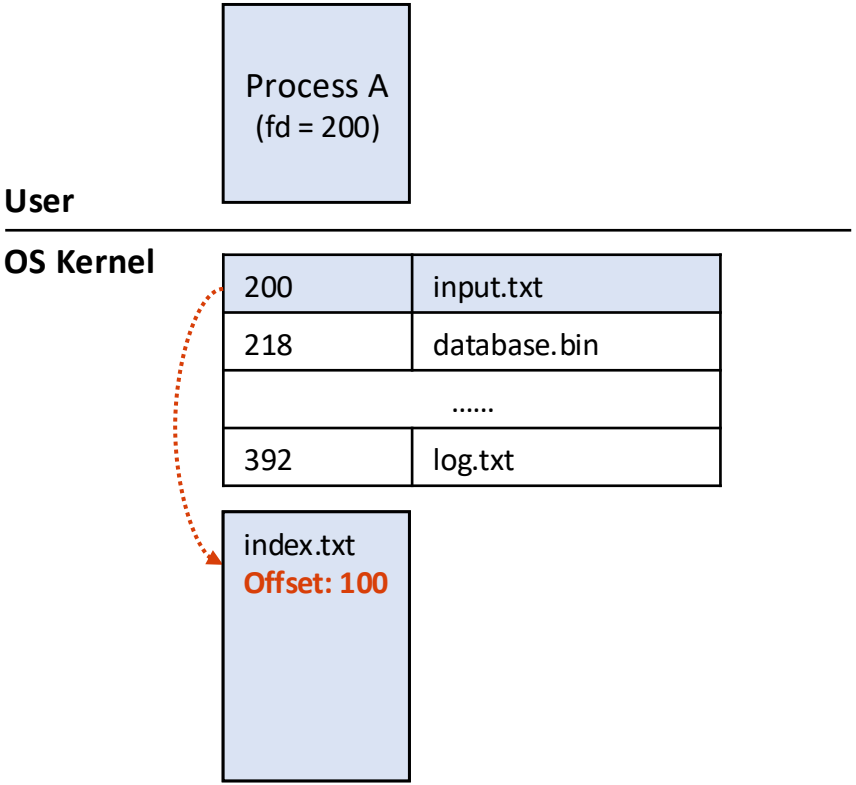
- Note
  - Process A opens a file "input.txt"
  - OS Kernel opens the file, offset is 0
  - OS Kernel create an entry to the descriptor table
  - OS Kernel returns fd = 200

LOW-LEVEL API INTERNALS: HOW?

- Let's check with the following program

```
... many #include ...
#define   BSIZE   100

int main(void) {
   char buf1[BSIZE];
   char buf2[BSIZE];
   int fd = open("input.txt", O_RDONLY);

   read(fd, buf1, BSIZE);
   read(fd, buf2, BSIZE);
   return 0;
}
```

- Note
  - Process A read the file
  - OS Kernel reads the file, 100 bytes
  - OS Kernel moves the offset to 100
  - OS Kernel returns the data to Process A

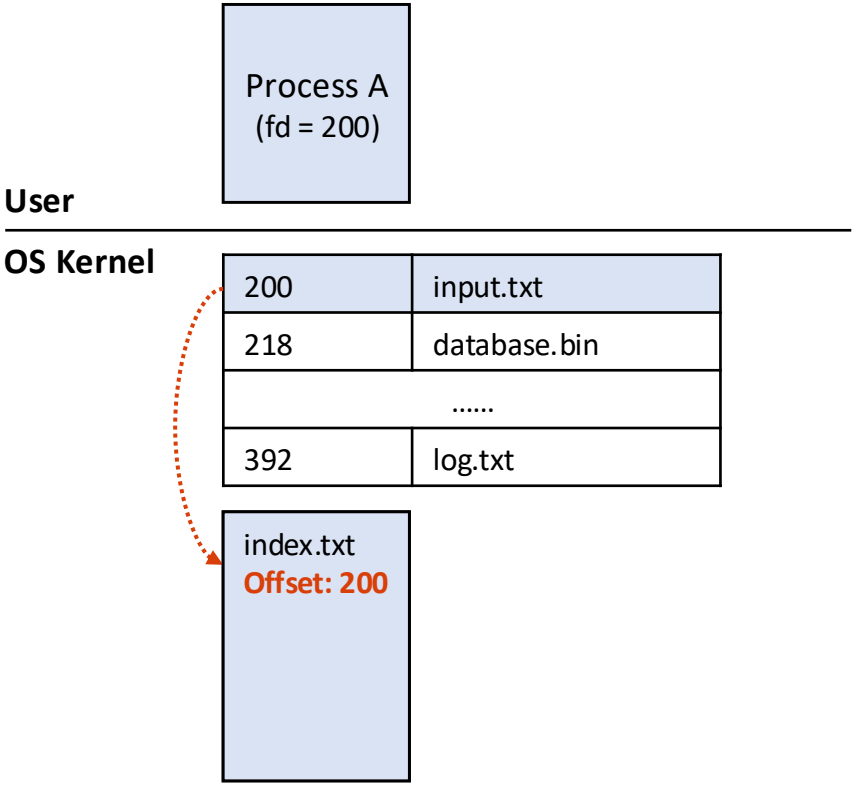


LOW-LEVEL API INTERNALS: HOW?

- Let's check with the following program

```
... many #include ...
#define   BSIZE   100

int main(void) {
   char buf1[BSIZE];
   char buf2[BSIZE];
   int fd = open("input.txt", O_RDONLY);

   read(fd, buf1, BSIZE);
   read(fd, buf2, BSIZE);
   return 0;
}
```

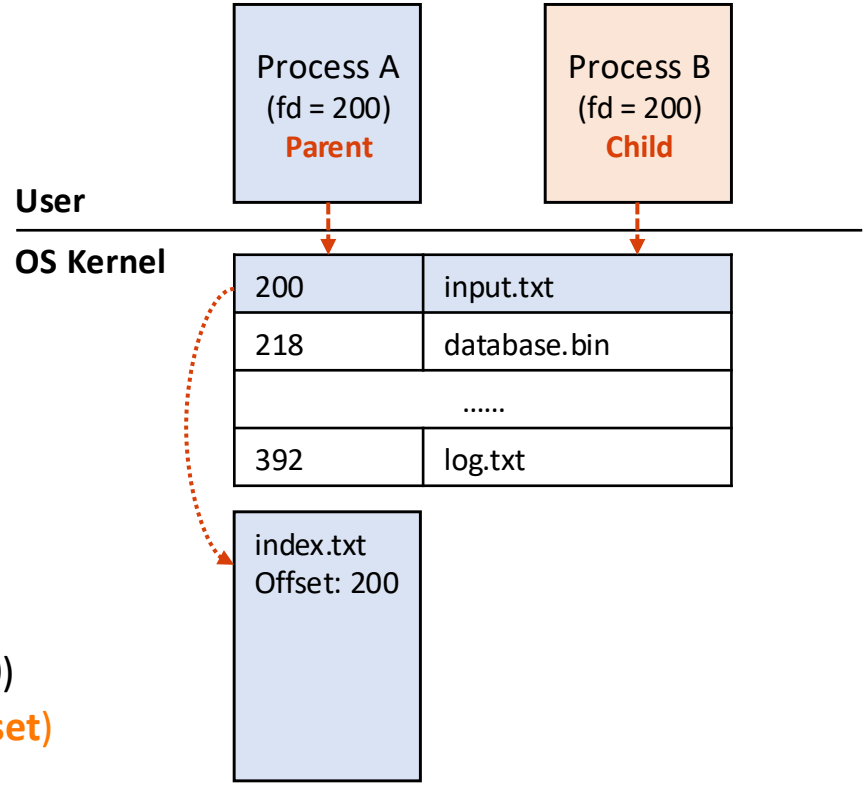
- Note
  - Process A read the file
  - OS Kernel reads the file, 100 bytes
  - OS Kernel moves the offset to 100
  - OS Kernel returns the data to Process A



LOW-LEVEL API INTERNALS: HOW?

- Let's do more exercise

```
... many #include ...
#define   BSIZE   100

int main(void) {
   char buf1[BSIZE];
   char buf2[BSIZE];
   int fd = open("input.txt", O_RDONLY), pid;

   read(fd, buf1, BSIZE);
   read(fd, buf2, BSIZE);

   switch (pid = fork()) {
```

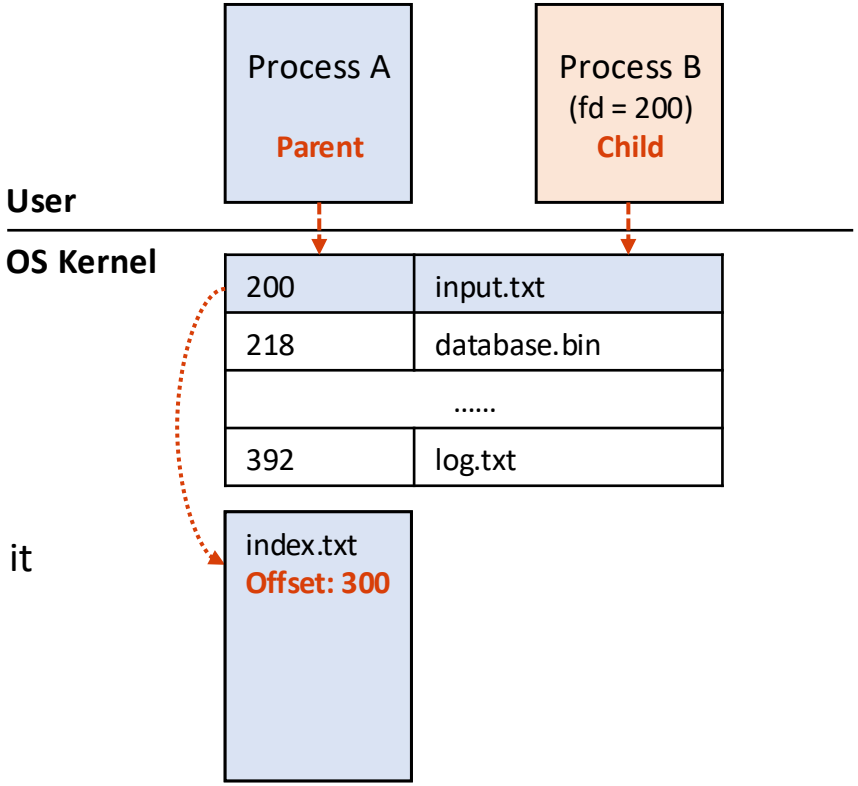


- Note
  - Process A fork()!
  - Process B is created (a child)
  - Process B has the same file descriptor (200)
  - The fd is **copied** and **aliased** (share the **offset**)

LOW-LEVEL API INTERNALS: HOW?

- Let's do more exercise

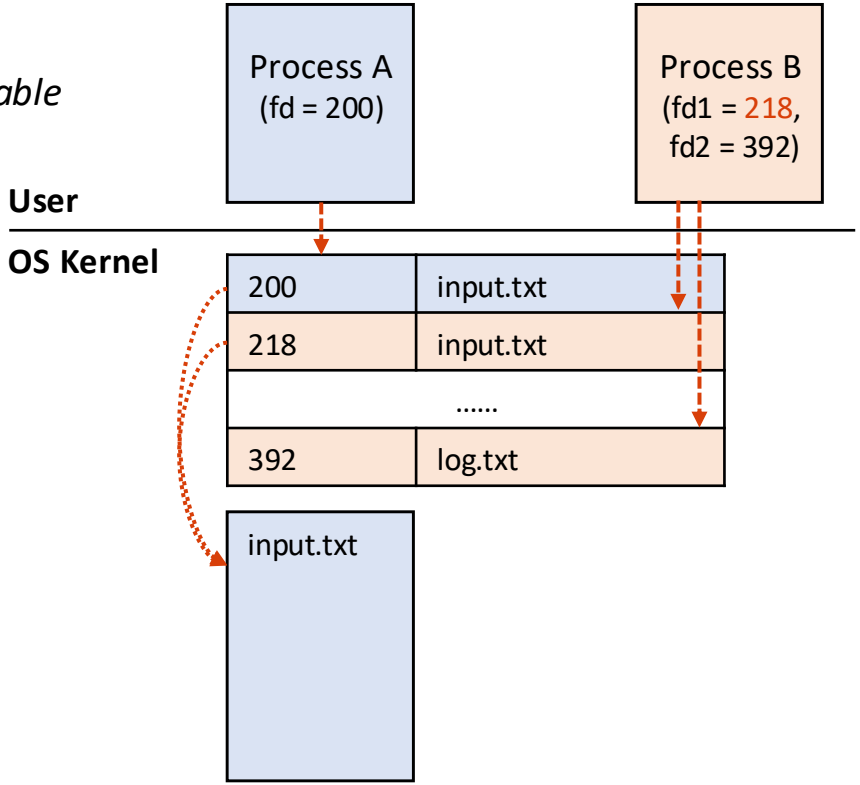
```
... many #include ...
#define   BSIZE   100

int main(void) {
   ...
   switch (pid = fork()) {
      case 0:
         sleep(3); read(fd, buf1, BSIZE);
         break;
      default:
         read(fd, buf1, BSIZE);
         close(fd);
```



- Note
  - Proc A (parent) read data from fd and close it
  - The fd will **remain available** to Proc B

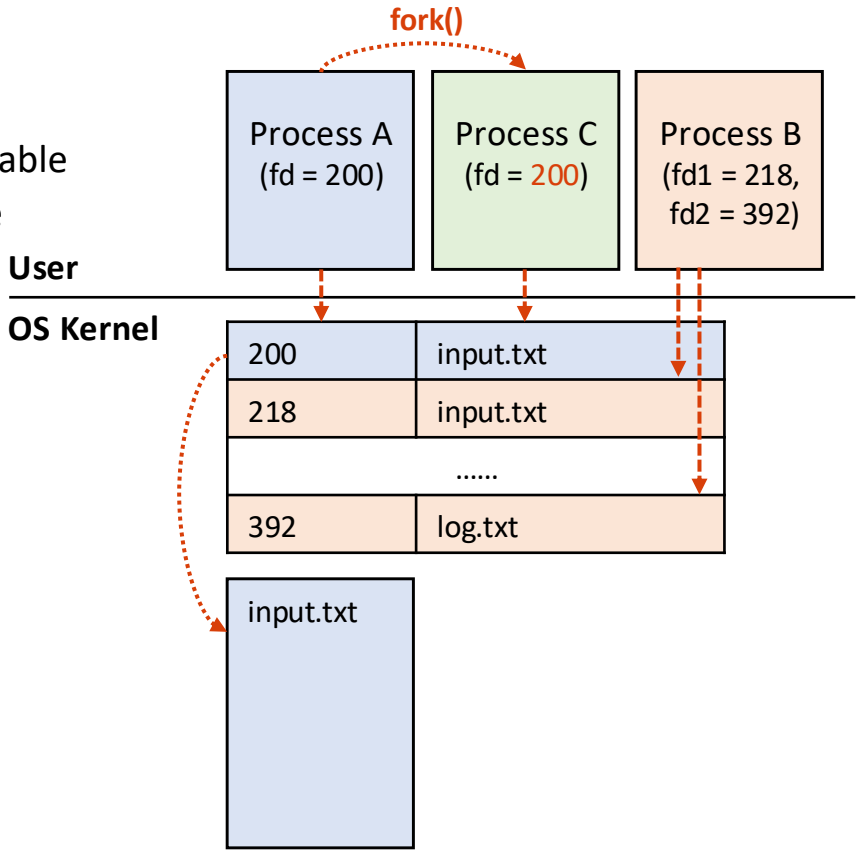
LOW-LEVEL API INTERNALS: SUMMARY

- File descriptors (fd)
  - A unique identifier for an open file
    - Each process has an *open file descriptor table*
    - OS also has a *system-wide desciptor table*
  - Properties of file descriptors
    - The fd can **point to the same file**



LOW-LEVEL API INTERNALS: SUMMARY

- File descriptors (fd)
  - A unique identifier for an open file
    - Each process has an open file descriptor table
    - OS also has a system-wide desciptor table
  - Properties of file descriptors
    - The fd can **point to the same file**
    - The fd can be **copied and aliased**
      - Proc A and C share the offset
      - Proc A and B do not



TOPICS FOR TODAY

- Part II: Filesystem internals
  - Manage resources
    - How OS manages high-level I/O internally?
    - How OS manages low-level I/O internally?

Thank You!

M/W 12:00 – 1:50 PM (LINC #200)

Sanghyun Hong

sanghyun.hong@oregonstate.edu