CS-202 Exercises on File Systems (L06 - L07)

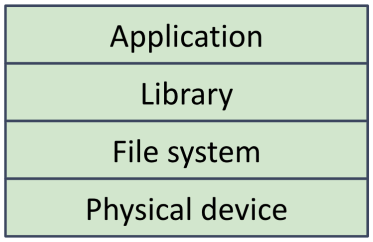
17.03.2025

This exercise set covers concepts related to file systems. We advise that you work through it sequentially, referring back to lecture slides or videos as necessary. If anything is unclear, or if you could benefit from discussing a particular concept in depth, please seek an assistant's help.

Exercise 1: File system abstractions

Fill in the blanks with terminology related to file system abstractions. The figure on the right is the file system abstraction stack, which you can refer to for hints.

- ______ code uses primitives like `fopen` and `fread`, which are implemented by ______ code. These primitives take as input and return objects of type ______.
- ______ code uses syscalls (e.g., `open`, `read`, `lseek`). These take as input and return ______, which are numerical values used to index open file metadata stored in a table. There is one such table for each ______.



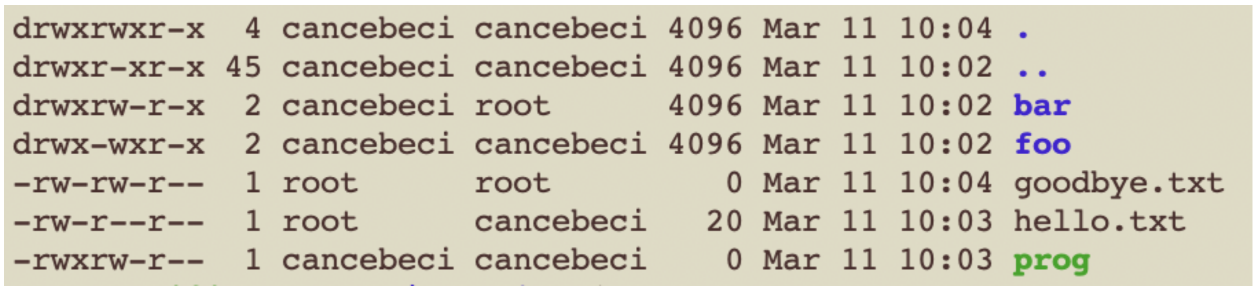
Exercise 2: File system basics

Mark the following sentences about inodes as true (T) or false (F).

( ) Inodes store metadata related to files.
( ) There may be many inodes in a file system storing information related to the same file.
( ) Among other things, an inode stores the name of the file it is related to.
( ) Multiple filenames can map to the same inode.
( ) A process can insert entries to a directory inode using a write syscall. (Hint: "Look again at slides 32-35 that discuss the file-system interface. According to those slides, how does a process add a file to a directory?")

Exercise 3: Permission bits

Below, you are given the current directory for a process, run by user ‘cancebeci’, and the file descriptor table for the process. You can use the `man` command on your terminal to look up the semantics of specific syscalls and flags.



```
drwxrwxr-x  4 cancebeci cancebeci 4096 Mar 11 10:04 .
drwxr-xr-x 45 cancebeci cancebeci 4096 Mar 11 10:02 ..
drwxrw-r-x  2 cancebeci root      4096 Mar 11 10:02 bar
drwx-wxr-x  2 cancebeci cancebeci 4096 Mar 11 10:02 foo
-rw-rw-r--  1 root      root         0 Mar 11 10:04 goodbye.txt
-rw-r--r--  1 root      cancebeci   20 Mar 11 10:03 hello.txt
-rwxrw-r--  1 cancebeci cancebeci    0 Mar 11 10:03 prog
```

0	STDIN
1	STDOUT
2	STDERR
3	Inode: 55, offset: 32, mode: read
4	closed
5	Inode: 22, offset: 4918, mode: read/write

Indicate whether each syscall will succeed or fail. Assume buf is a large enough buffer and the open files are large enough that reads never reach the end of a file.

- `open(“./out.txt”,  O_RDWR | O_TRUNC, S_IRWXU);`
- `open(“./out.txt”, O_CREAT | O_RDWR | O_TRUNC, S_IRWXU);`
- `open(“goodbye.txt”, O_RDWR | O_TRUNC, 0);`
- `open(“hello.txt”, O_RDWR | O_TRUNC, 0);`
- `open(“hello.txt”, O_RDONLY | O_TRUNC, 0);`
- `close(5);`
- `close(4);`
- `read(3, buf, 10);`
- `write(3, buf, 10);`
- `write(5, buf, 10);`

Exercise 4: Path resolution (inode walk)

The figure below depicts a disk organization consisting of 16 blocks (numbered 0-15), where the inode for the root directory ("/") is at inode 1. Block 0 is the superblock. Blocks 1-3 store the inode table, each block storing 4 inodes (block 1 stores inodes 0-4, block 2 stores inodes 4-7 and block 3 stores inodes 8-12.)

4.1: *Write down the sequence of blocks that will be read when the user asks to read the first character of "/hello/world.txt", and identify the character that will be read.*

0	1	2	3	4	5	6	7
	[... (inode 1: Location: 12 …), (inode 2: Location: 14 …)]	[….]	[… (inode 8: Location: 7 …), …]		"This block stores a text file … "	"00101010 010101010 010101110 01011…"	"its.me": inode 4 "world.txt": inode 2 "baz": inode 12
8	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	"etc": inode 4 "pwd": inode 5	"This block stores another text file … "		"foo": inode 3 "bar": inode 7 "hello": inode 8		"!\nabcdefg …"	

4.2: *Which of these reads will actually trigger an interaction with the disk? Which of them may be served by a block cache?*

Exercise 5: File allocation: contiguous, linked

Below you are given the contents of the root directory in a file system.

```
root
    ├── phantom_thread.mov
    └── secrets
        └── never_cursed.txt
```

The file system is stored on a disk consisting of 24 blocks of size 4KB. Block 0 is the superblock, blocks 1-7 store inodes, and 8-23 are data blocks. The size of phantom_thread.mov is 12KB, and the size of never_cursed.txt is 8KB.

5.1.1: *Assume the file system is using contiguous allocation. Draw what the organization of the disk may look like. Clearly label each block with its contents (Which file, directory do they store? Do they include any metadata?). You can assume that directories are smaller than 4KB.*

0	1	2	3	4	5	6	7
	inodes	inodes	inodes	inodes	inodes	inodes	inodes
8	9	10	11	12	13	14	15
16	17	18	19	20	21	22	23

5.1.2: *What happens if the user needs to append 4KB of data to phantom_thread.mov?*

5.2.1: *Assume the file system is using linked blocks for file allocation. Draw what the organization of the disk may look like. Clearly label each block with its contents (Which file, directory do they store? Do they include any metadata?). You can assume that directories are smaller than 4KB.*

0	1	2	3	4	5	6	7
	inodes	inodes	inodes	inodes	inodes	inodes	inodes
8	9	10	11	12	13	14	15
16	17	18	19	20	21	22	23

5.2.2: *Assume the user asked to append 4KB of data to phantom_thread.mov, and then append 4KB of data to never_cursed.txt. Draw the organization of the disks after both operations are completed.*

0	1	2	3	4	5	6	7
	inodes	inodes	inodes	inodes	inodes	inodes	inodes
8	9	10	11	12	13	14	15
16	17	18	19	20	21	22	23

Exercise 6: File allocation: multi-level indexing

Consider the multi-level indexing approach discussed in Lecture 7. Below is a brief recap and some problem parameters.

- Each disk block is 4KB
- Each inode contains 15 pointers.
  - 12 of these directly point to data blocks.
  - The 13th is a single-indirect pointer. It points to a block, which contains pointers to data blocks
  - The 14th is a double-indirect pointer and the 15th is a triple-indirect pointer.
- Each "pointer" is 4 bytes. (By pointer, here we mean a disk block index, not C pointers - which are typically 8 bytes).

Answer the following questions.

6.1: *What is the maximum file size that can be represented by an inode?*

6.2: *How many block accesses does it take to read a data byte, including the initial access to the inode? You can assume that the inode walk has already been done (i.e., we already know the number of the inode related to the file). The answer depends on which data block the byte resides in.*

- Which one requires more block accesses, reading the first byte of the first block, or the last byte of the last block (assuming the file's size is the maximum you computed in 7.1)
- What is the minimum number of block accesses?
- What is the maximum number of block accesses?
- Assuming the maximum file size, if all bytes are accessed uniformly randomly, what is the average number of block accesses?

6.3: *If we were to change the approach slightly, such that an inode contains 11 direct pointers to data blocks instead of 12, and in exchange, it contains an additional quadruple-indirect pointer (four levels of indirection), what would the maximum file size be? What is the trade-off here?*

Exercise 7: File system API

Below is a C program using the file system system call API. Show the contents of the file descriptor table of the process running this program after each syscall.

```c
int main(int argc, char *argv[]) {
    int fd = open("file.txt", O_RDONLY);
    char buf[10];
    read(fd, buf, 5);
    lseek(fd, 0, SEEK_SET);
    close(fd);
    return 0;
}
```

Exercise 8 (Advanced): File system API + fork

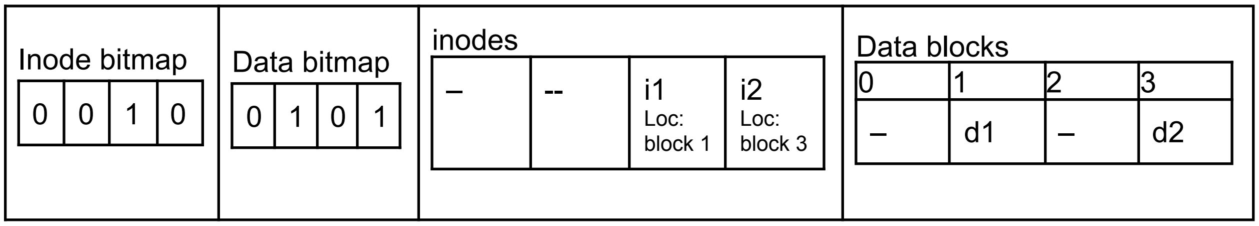
Write the output of the following program. Remember that when a process forks, the file descriptor table is copied as-is to the child process.

```c
int main(int argc, char *argv[]) {
    int pid1 = 0; int pid2 = 0;
    int fd = open("file.txt", O_RDONLY);
    assert(fd >= 0);
    pid1 = fork();
    if (pid1 == 0) {
        int off = lseek(fd, 10, SEEK_SET);
        printf("statement1: offset %d\n", off);
        pid2 = fork();
    } else if (pid1 > 0) {
        (void) wait(NULL);
        printf("statement2: offset %d\n", (int) lseek(fd, 20, SEEK_CUR));
    }
    if (pid2 == 0) {
        printf("statement3: offset %d\n", (int) lseek(fd, 0, SEEK_SET));
    }
    return 0;
}
```

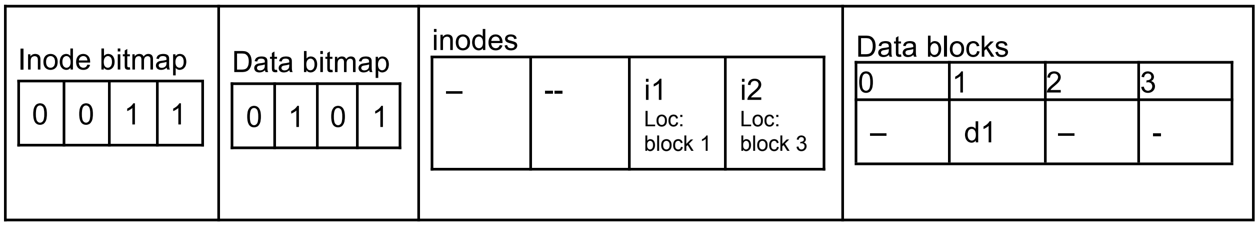
Exercise 9 (Advanced): Crash consistency

Below, you are given two disk states. Both contain inconsistencies introduced by a crash. For each example, identify the inconsistency and propose a fix.

9.1:



9.2:



Exercise 10 (Optional): Redirecting STDOUT

Below is a C program that prints “Hello World!”. Add a few lines of code at the beginning of the main function, such that this program writes “Hello World!” to a new file, hello.txt, instead of printing to the terminal. Do not change the existing code; the goal is to get the exact same printf statement to write to a file. (Hint: what happens if you close STDOUT? Try writing a program and running it to understand this better.)

```
#include <stdio.h>

int main() {
    // add code here

    printf("Hello World!");
    return 0;
}
```