Operating System Labs

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Operating System Labs

- Project 4 (multi-thread & lock):
  - Due: 10 Dec
    - Code & experiment report
- 18 Dec.
  - Oral test (proj 4): 9:30am
  - Lectures: Q&A
- Project 5:
  - Due: 31 Dec
  - Oral test: 8 Jan, 9:30am

Operating System Labs

- Overview of file system
  - File system API
  - File system implementation
- Project 5

File System API

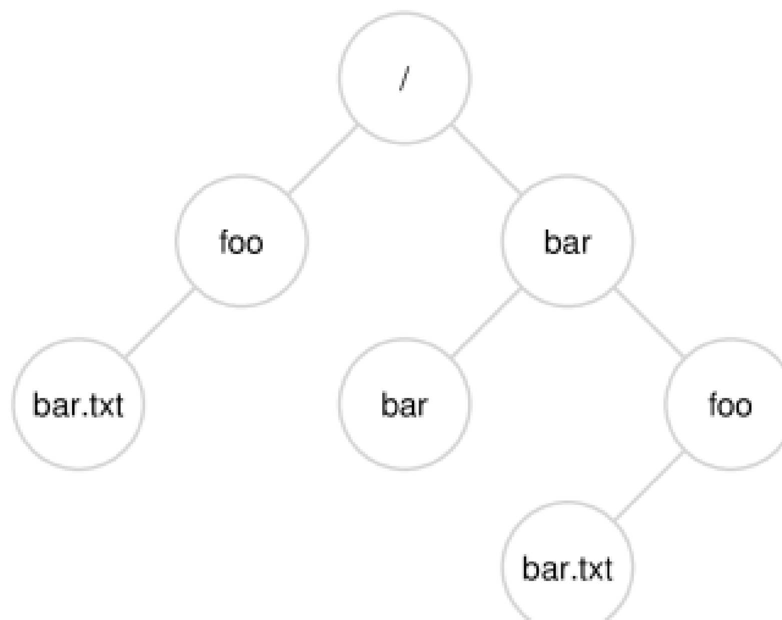
- Previous
  - CPU: process, thread
  - Memory: address space, virtual memory management
- Now
  - File system: persistent storage

File System API

- Regular File
  - File name: user readable
  - **inode number**: low-level file name
  - Contents: figure, text, video
- Directory
  - Directory name: user readable
  - **inode number**: low-level directory name
  - Contents: file and sub-directories

File System API

- Directories
  - Content :
    - tuples: (user-readable name, inode number)
  - Directory tree



File System API

- File System APIs
  - Basic I/O interface (lecture2)
    - File descriptor
    - open, read, write, close, lseek
    - buffer
  - strace

```
% strace cat foo
```

  - Other APIs

File System API

- Renaming files

```
% strace mv foo bar
```

```
#include <stdio.h>

int rename(char *old, char *new)
```

File System API

- Renaming files
  - Atomic
    - the system can crash during renaming
    - either old name or new name

```
int fd = open("foo.txt.tmp", O_WRONLY|O_CREAT|O_TRUNC);
write(fd, buffer, size); // write out new version of file
fsync(fd);
close(fd);
rename("foo.txt.tmp", "foo.txt");
```

File System API

- Get information about files
  - **meta data**

```
#include <sys/stat.h>

int fstat(int fildes, struct stat *buf);
```

```
% stat bar
```

```
struct stat {
  dev_t       st_dev;         // ID of device containing file
  ino_t       st_ino;         // inode number
  mode_t      st_mode;        // protection
  nlink_t     st_nlink;       // number of hard links
  uid_t       st_uid;         // user ID of owner
  gid_t       st_gid;         // group ID of owner
  dev_t       st_rdev;        // device ID (if special file)
  offset_t    st_size;        // total size, in bytes
  blksize_t   st_blksize;     // blocksize for filesystem I/O
  blkcnt_t    st_blocks;      // number of blocks allocated
  time_t      st_atime;       // time of last access
  time_t      st_mtime;       // time of last modification
  time_t      st_ctime;       // time of last status change
};
```

File System API

- Removing file

```
% strace rm bar
```

```
#include <unistd.h>

int unlink(const char *pathname);
```

File System API

- Making Directories

```
% strace mkdir foo
```

```
#include <unistd.h>

int mkdir(const char *pathname);
```

File System API

- Reading Directories

```
% strace ls
```

```
int getdents(unsigned int fd,
                    struct linux_dirent *dirp,
                    unsigned int count);
// no glibc wrappers (with the same name) for it
```

File System API

- Reading Directories
  - Glibc: DIR stream (recall the FILE stream)

```
#include <sys/types.h>
#include <dirent.h>

DIR *opendir(const char *name);
int closedir(DIR *dirp);
```

```
#include <dirent.h>

struct dirent *readdir(DIR *dirp);
```

File System API

- Reading Directories

```
struct dirent {
  char              d_name[256];    //filename
  ino_t             d_ino;          //inode number
  off_t             d_off;          //opaque value
  unsigned short  d_reclen;       //length of this record
  unsigned char  d_type;          //type of file
};
```

File System API

- Reading Directories
  - A simple ls

```
int main(int argc, char *argv[]) {
    DIR *dp = opendir(".");
    assert(dp != NULL);
    struct dirent *d;
    while ((d = readdir(dp)) != NULL) {
        printf("%d %s\n", (int) d->d_ino, d->d_name);
    }
    closedir(dp);
    return 0;
}
```

File System API

- Remove Directories

```
% strace rmdir
```

```
int rmdir(const char* name);
// remove empty directory
```

File System API

- Hard links
  - Link(): create a new way to refer the same file

```
#include <unistd.h>

int link(const char* old, const char* new);
```

```
% cat file
% ln file file1
% cat file1
% ls -i file file1
```

File System API

- Hard links
  - unlink(): the reverse of link()

```
#include <unistd.h>

int unlink(const char* filename);
```

```
% rm file
% cat file1
% ls -i file1
```

File System API

- Hard links
  - A field in inode structure: reference count

```
% ln file file1
% stat file
% ln file1 file2
% stat file
% ln file2 file3
% stat file
% rm file1
% stat file
```

File System API

- Symbolic links
  - Limitations of hard links
    - Can not link directories → cycles are not allowed
    - Can not hard link across partitions
  - Symbolic links
    - A new file type (regular file, directory, symbolic link)
    - Different from the original file
    - The content of a symbolic links
      - Pathname of the linked-to file

File System API

- Symbolic links

```
% ln -s file file1
% stat file
% stat file1
% ls -al
% rm file
% cat file1

% echo hello > verylongfile
% ln -s verylongfile file
% ls -al
```

File System API

- Making and Mounting file systems
  - mkfs:
    - Input: a partition and a fs type
    - Output: a file system
  - Mount:
    - Put the new file system in the current directory tree

File System API

- Summary
  - File, directory, symbolic link
  - open(), read(), write(), lseek(), close()
  - link(), unlink()
  - readdir(), mkdir()

File System Implementation

- A very simple file system (vsfs)
  - pure software (different from process/vm)
- The way to think about a file system
  - Data structures
  - Access methods

File System Implementation

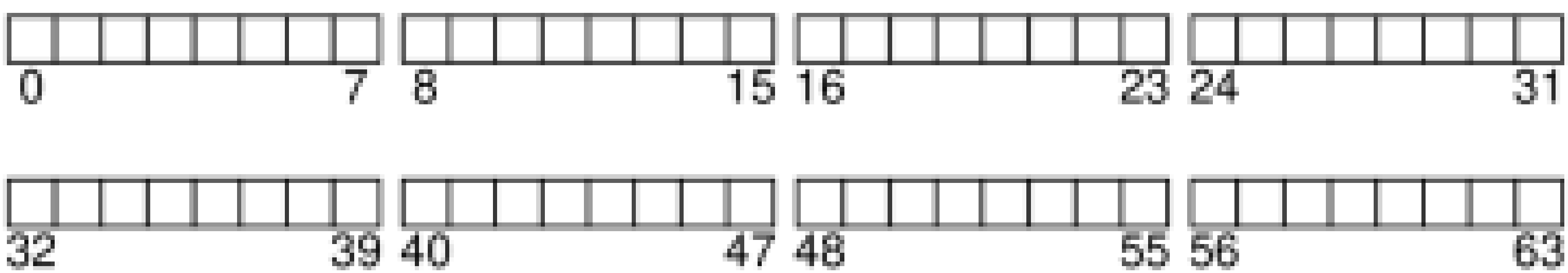
- The way to think about a file system
  - Data structures
    - How to organize files?
  - Things to manage
    - Files
    - Meta data of files (inode)
    - Free space

File System Implementation

- The way to think about a file system
  - Access methods
    - open(), read(), write()
    - opendir(), readdir()
    - link(), unlink()

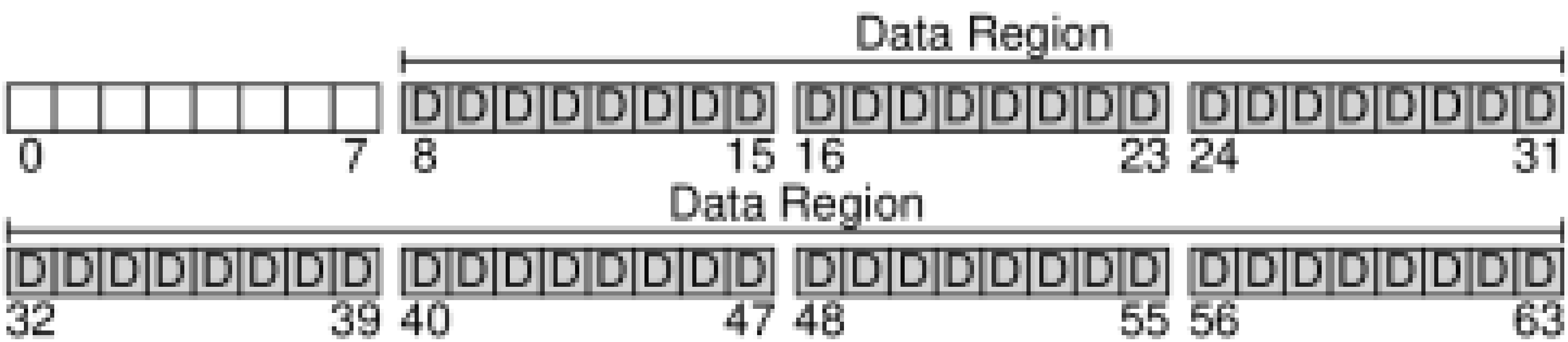
File System Implementation

- Data structure: overall organization
  - Block
    - A file system manipulate blocks (not byte)
    - Commonly used: 4KB
  - We have a disk with 64 blocks (256KB)



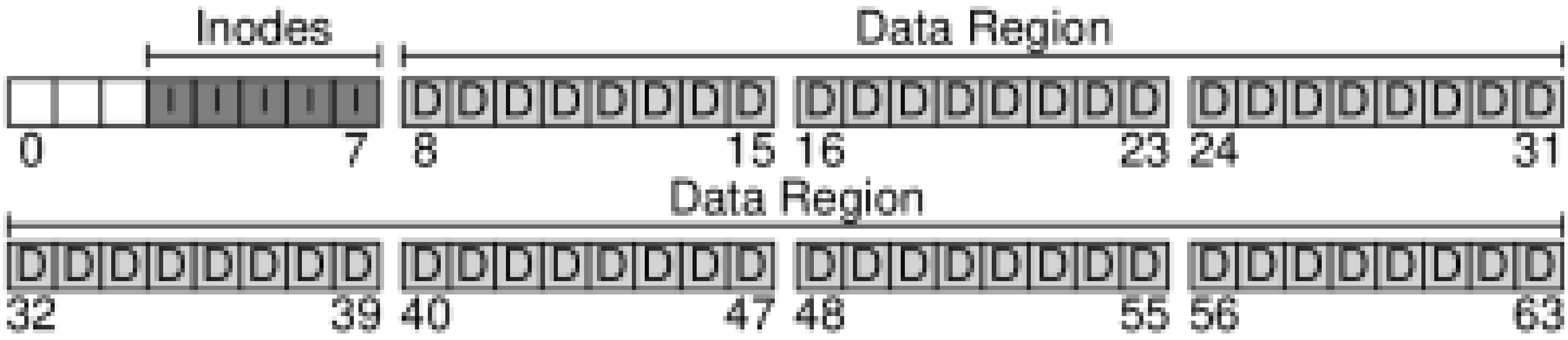
File System Implementation

- Data structure: overall organization
  - Data region
  - We have 56 blocks for storing data (D)



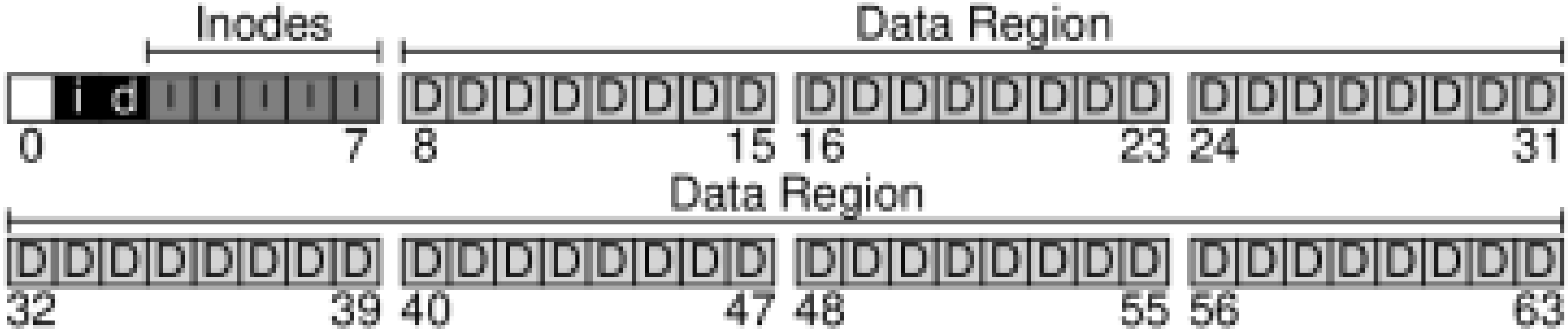
File System Implementation

- Data structure: overall organization
  - Meta data: information about files
    - size, reference count, protection, access time
    - Inode
  - We have 5 blocks for inodes (I)
    - Assume each inode 256B (16 inodes per block)
    - We can handle 80 files



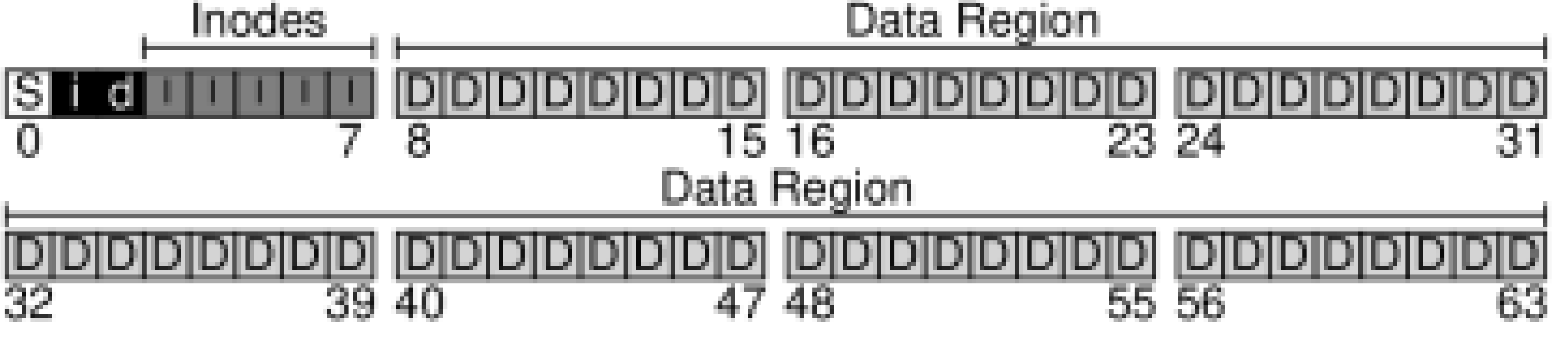
File System Implementation

- Data structure: overall organization
  - Allocation structures (free list)
    - Which blocks are allocated?
  - We will use the “bitmap”
    - Each bit indicates whether a block is used
    - one for data region (d), one for inode table (i)
    - What are sizes of the bitmaps?



File System Implementation

- Data structure: overall organization
  - Superblock
    - Metadata of the whole file system
    - How many inodes and data blocks?
    - The start of inode table/data region
  - We use the left 1 block as superblock (S)

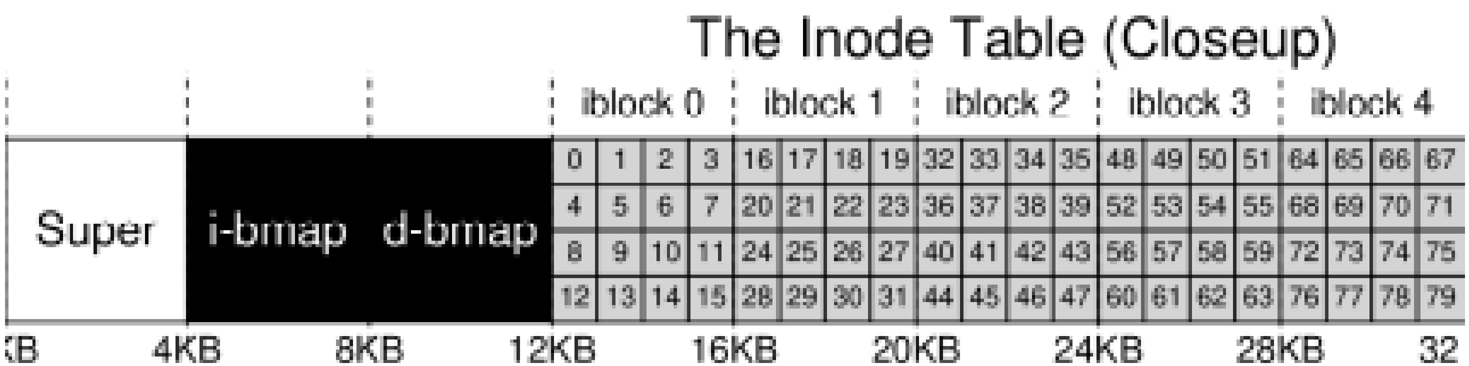


File System Implementation

- Summary
  - Data structure: overall organization
    - Data region
    - Inode table
    - Bitmaps
    - Superblock

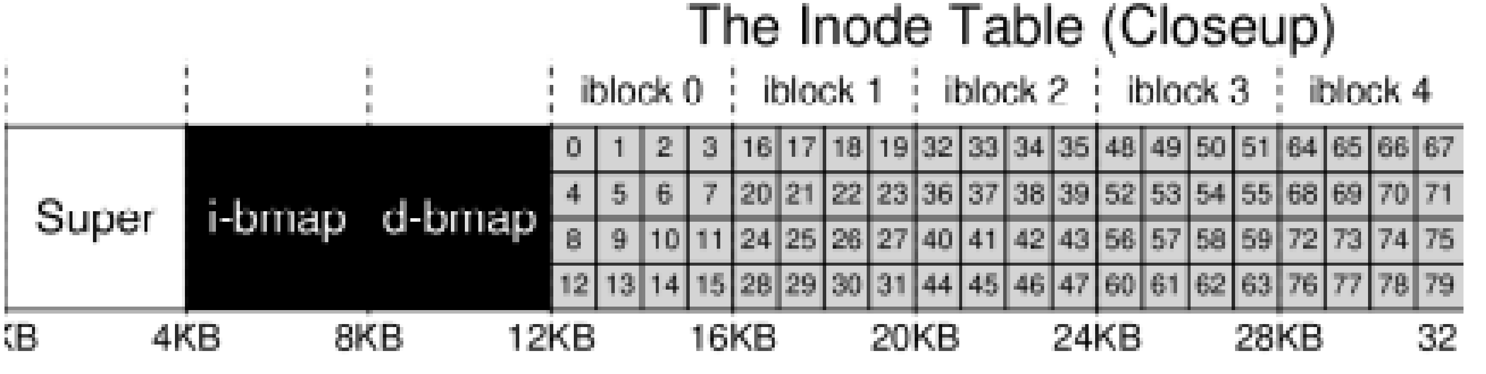
File System Implementation

- Data structure: the inode
  - Inode number:
    - its index in the inode table
    - Low-level name of the file



File System Implementation

- Data structure: the inode
  - Locating an inode through inode number
  - Example: file with inode number 32
    - Offset: 32*256 + 12K = 8K + 12K = 20K
    - For a read from disk (only read *sectors*)
      - Sector size: 512
    - Finally the disk will read sector: 40 (20K/512)



File System Implementation

- Data structure: the inode
  - An inode contains
    - The data blocks
    - Type (file/directory/symbolic link)
    - Reference count (link/unlink)
    - Size (#blocks)
    - Protection
    - Time information

- The Ext2 inode

Size	Name	What is this inode field for?
2	mode	can this file be read/written/executed?
2	uid	who owns this file?
4	size	how many bytes are in this file?
4	time	what time was this file last accessed?
4	ctime	what time was this file created?
4	mtime	what time was this file last modified?
4	dtime	what time was this inode deleted?
2	gid	which group does this file belong to?
2	links_count	how many hard links are there to this file?
4	blocks	how many blocks have been allocated to this file?
4	flags	how should ext2 use this inode?
4	osd1	an OS-dependent field
60	block	a set of disk pointers (15 total)
4	generation	file version (used by NFS)
4	file_acl	a new permissions model beyond mode bits
4	dir_acl	called access control lists
4	faddr	an unsupported field
12	i_osd2	another OS-dependent field

File System Implementation

- Data structure: the inode
  - An inode contains
    - The data blocks
    - Type (file/directory/symbolic link)
    - Reference count (link/unlink)
    - Size (#blocks)
    - Protection
    - Time information

How to organize data blocks in inodes?

File System Implementation

- Data structure: the inode
  - How to locate data blocks
    - direct pointers in inode structure
    - Can not hold large files
  - The multi-level Index
    - Indirect pointers
    - Point to data blocks which contain direct pointers

File System Implementation

- Data structure: the inode
  - Example of multi-level Index
    - An inode contains 12 direct pointers
    - 1 indirect pointers
      - Block size: 4K
      - Block number: an int (4 Bytes)
      - #direct pointers per block: 1K
    - #direct pointers: 12 + 1K
    - File size: (12 + 1K)*4K = 4144KB

File System Implementation

- Data structure: the inode
  - Double indirect pointer
    - # direct pointers: 1024 * 1024 = 1M
    - File size: $(12 + 1024 + 1024^2) * 4K \approx 4G$
  - Triple indirect pointer
  - An imbalanced tree
    - Most files are small

File System Implementation

- Summary
  - Data structure: the inode
    - Inode number
    - Locating an inode
    - Contents of an inode
    - How to index data blocks

File System Implementation

- Data structure: directory
  - Again: a directory is a file!
    - An inode
    - Data blocks
  - The contents of its data blocks
    - List of (entry name, inode number)
    - Other data structures: B-trees, hash tables

File System Implementation

- Data structure: directory
  - Example
    - Directory: dir(5)
    - Files: dir/foo(12), dir/bar(13), dir/foobar(24)

inum	reclen	strlen	name
5	4	2	.
2	4	3	..
12	4	4	foo
13	4	4	bar
24	8	7	foobar

  - Delete a file in the directory
    - Can we reuse the entries?

File System Implementation

- Data structure: free space management
  - Bitmaps
    - Inode table
    - Data region
  - Other data structures: B-tree
  - Pre-allocation

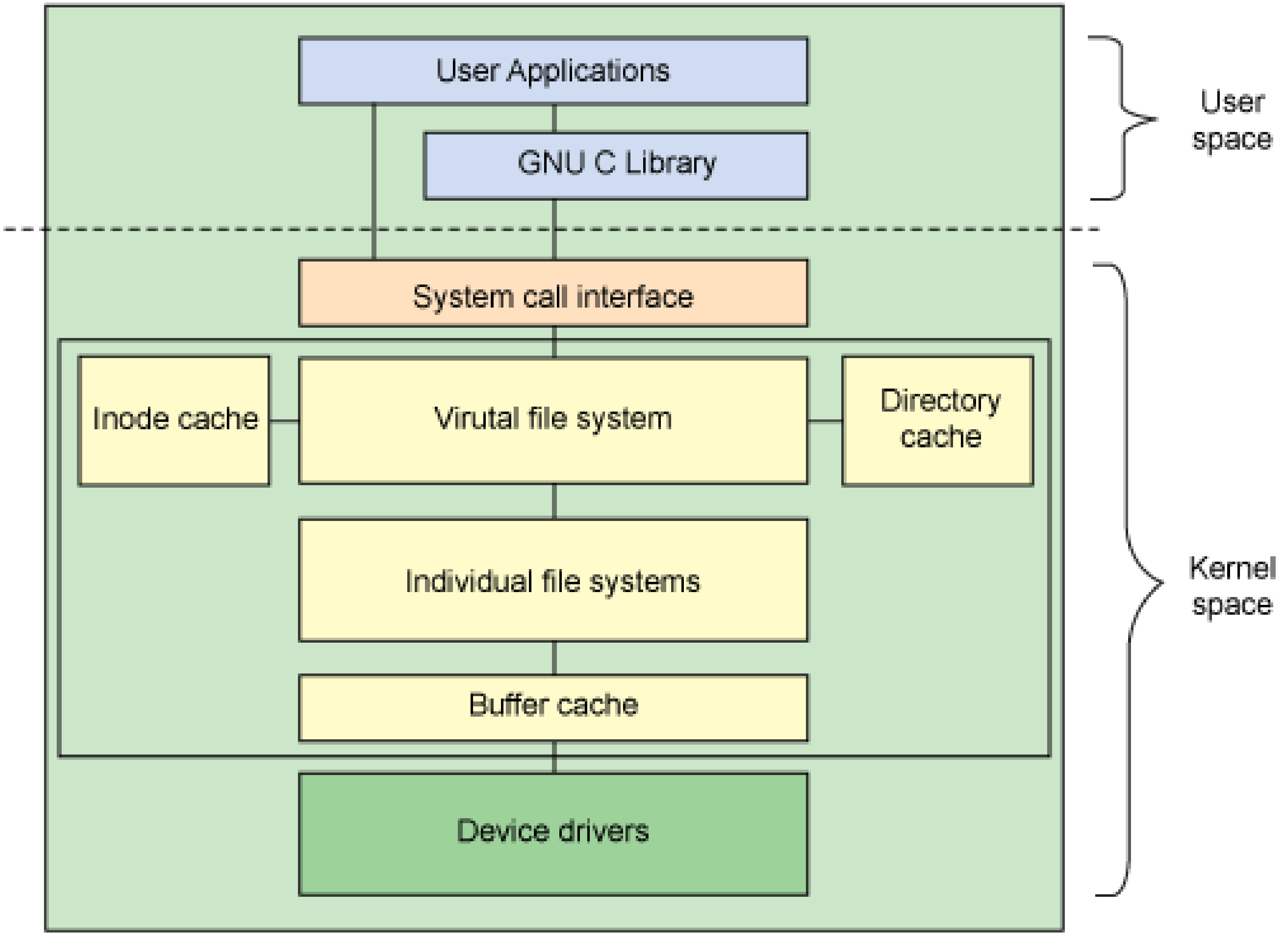
File System Implementation

- Summary
  - Data structures for implementing an fs
    - Overall organization
    - Inode
    - Directory
    - Free list management

File System Implementation

- Different types of fs
  - ext2, ext3, ext4, proc, cgroup
  - The concept: *virtual file system*
    - Provide unified view of different file systems
  - For each file system
    - Data structures: Inode, dentry, superblock
    - Operations:
      - Superblock operations: alloc_inode(), distroy_inode(), read_inode(), write_inode();
      - inode operations: create_inode(), lookup(), mkdir(), rename()
      - File operations: read(), write(), open(); close(); lseek()

File System Implementation



File System Implementation

- Access methods
  - read(), write()
  - readdir()
  - link(), unlink()

File System Implementation

- Access methods: read a file
  - open("/foo/bar", O RDONLY); and read it

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[2]
open(bar)			**read**							
						read				
				read						
							read			
					read					
read()					**read**					
								read		
					write					
read()					**read**					
									read	
					write					
read()					**read**					
										read
					write					

File System Implementation

- Access methods: create and write a file
  - open("/foo/bar", O RDONLY); and write it

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[2]
create (/foo/bar)			read							
						read				
				read						
							read			
		read								
		write								
							write			
					read					
					write					
				write						
write()					read					
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write()					read					
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					write					
write()					read					
	read									
	write									
										write
					write					

There are more operations!

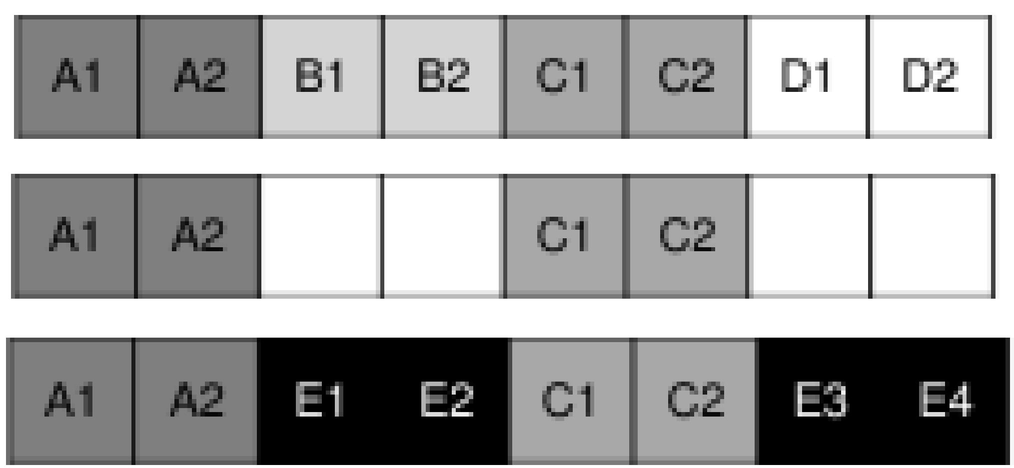
Can we change the order?

File System Implementation

- Access methods: how to speed up?
  - Cache
  - Buffering

File System Implementation

- Summary
  - The way to think about a file system
    - Data structures
    - Access methods
- Problems
  - Locality is not preserved



File System Implementation

- Project 5
  - defragmentation