# Operating System Labs

Yuanbin Wu
CS@ECNU

# Operating System Labs

- Project 4 (multi-thread & lock):
  - Due: 10 Dec
    - Code & experiment report
- 18 Dec.
  - Oral test of project 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

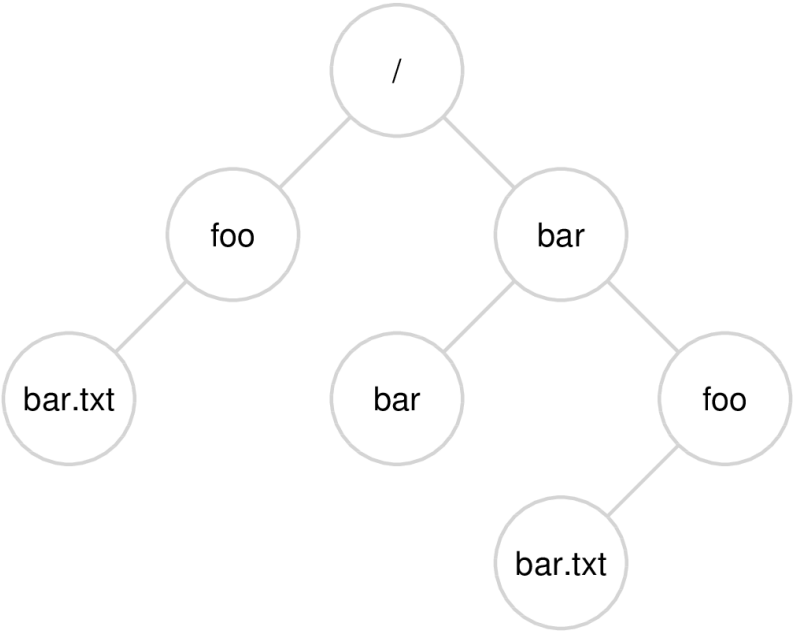
- Previous
  - CPU: process, thread
  - Memory: address space, virtual memory management
- Now
  - File system: persistent storage

# File System API

- Regular File
  - File name: user readable
  - Low-level file name: **inode number**
  - Contents: figure, text, video
- Directory
  - Directory name: user readable
  - Low-level directory name: **inode number**
  - 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 may 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);
// There are no glibc wrappers for these system calls;
```

# File System API

- Reading Directories
  - Glibc: DIR stream (c.f., 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

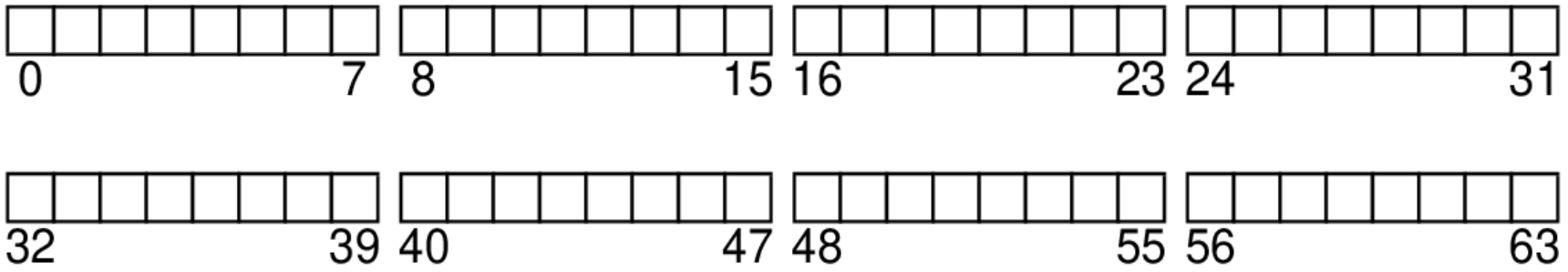
- The way to think about a file system
  - Data structures
    - How to organize files?
  - Things to manage
    - Files
    - Meta data of files (inode)
    - Free space

# File System Implementation

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

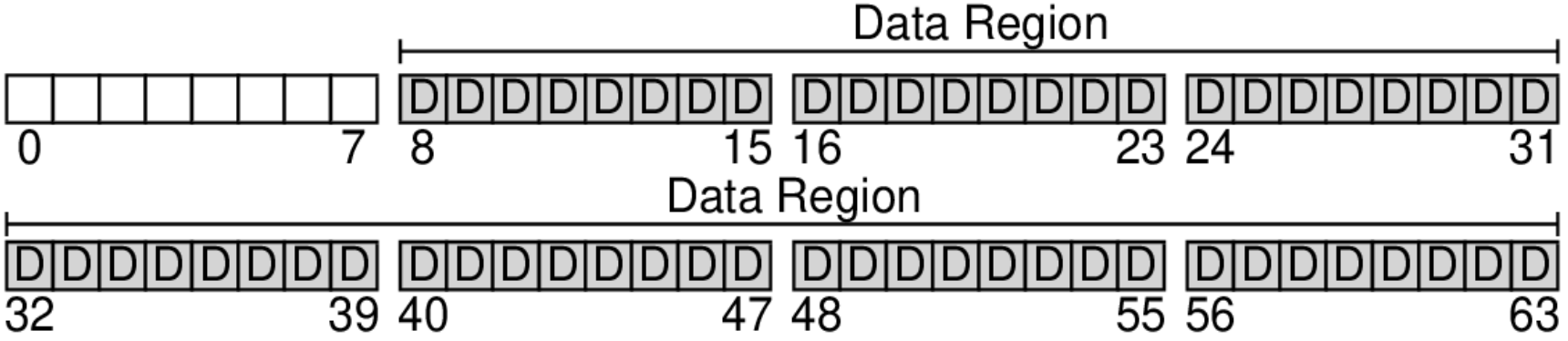
# File System Implementation

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



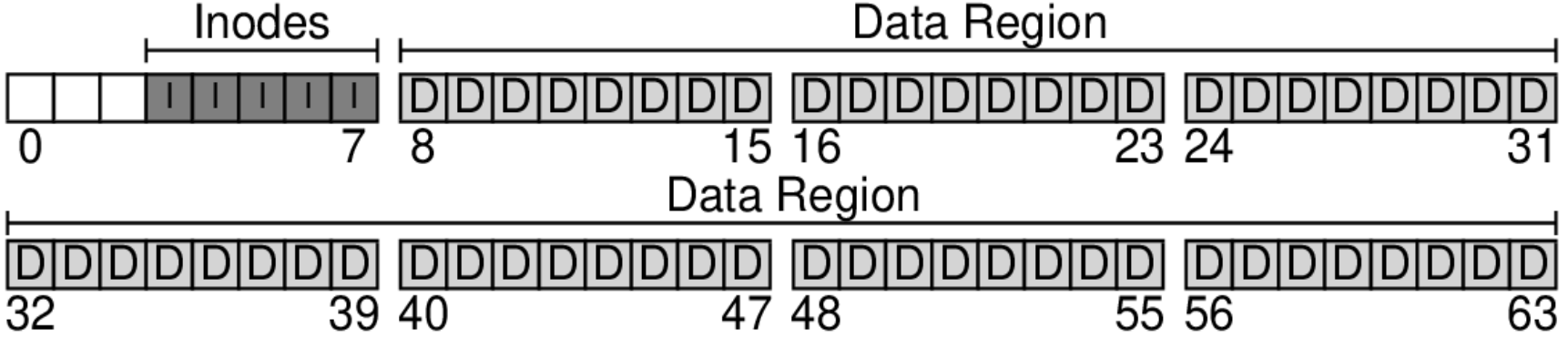
# File System Implementation

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



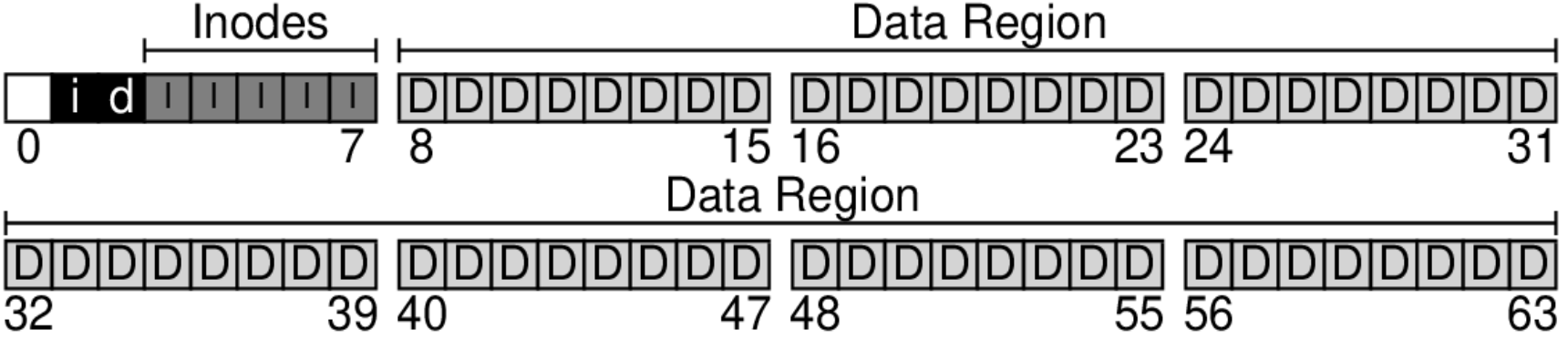
# File System Implementation

- 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



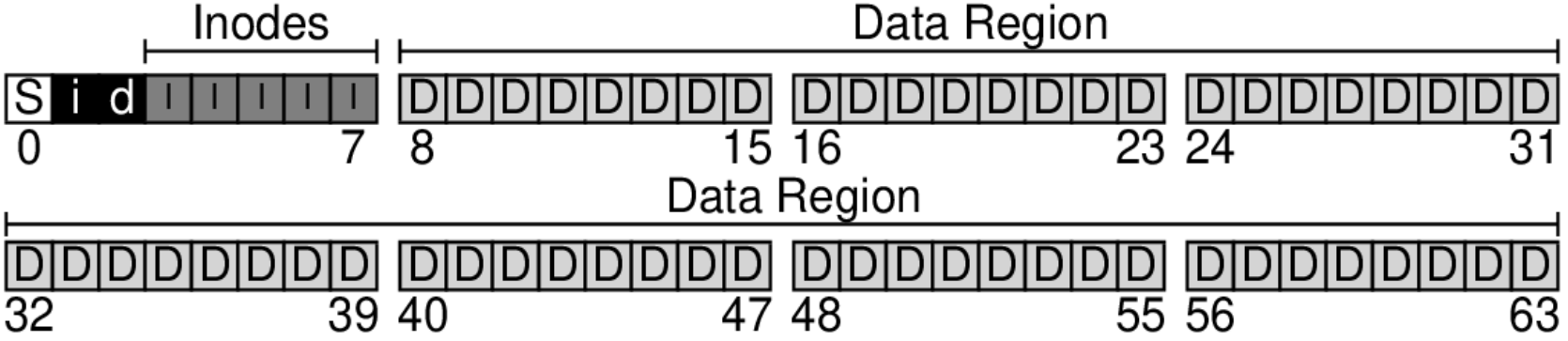
# File System Implementation

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



# 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)

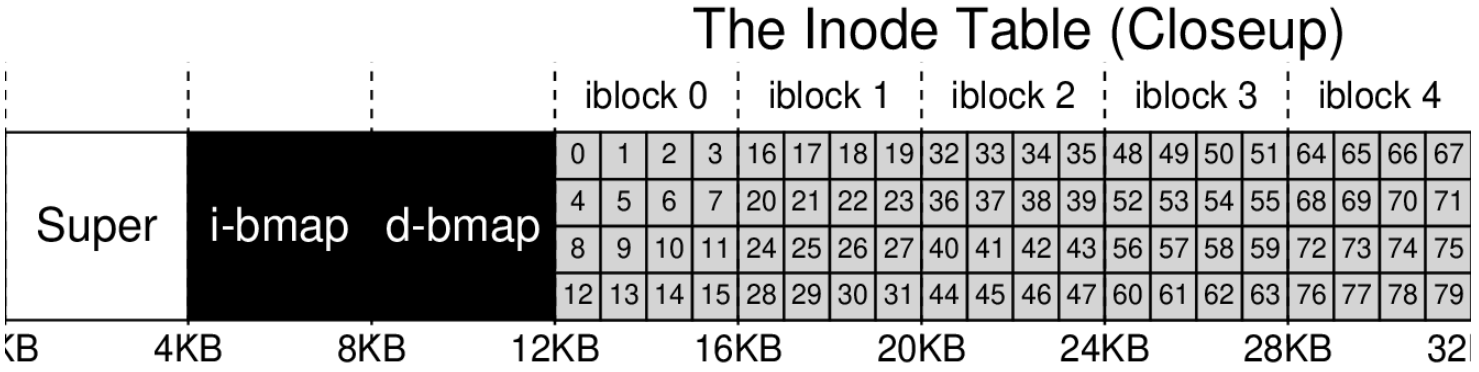


# File System Implementation

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

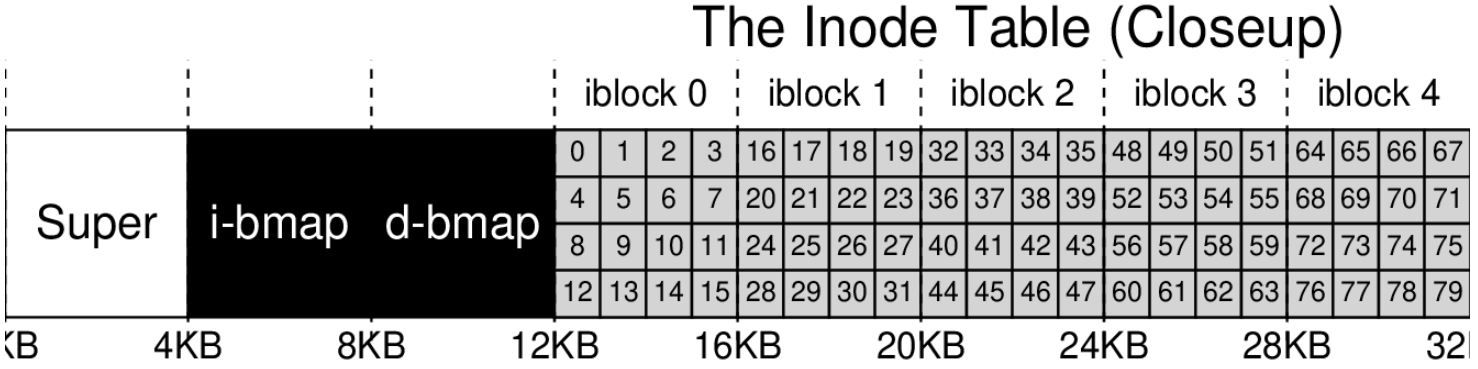
# File System Implementation

- 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

# 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?

- 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
  - 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

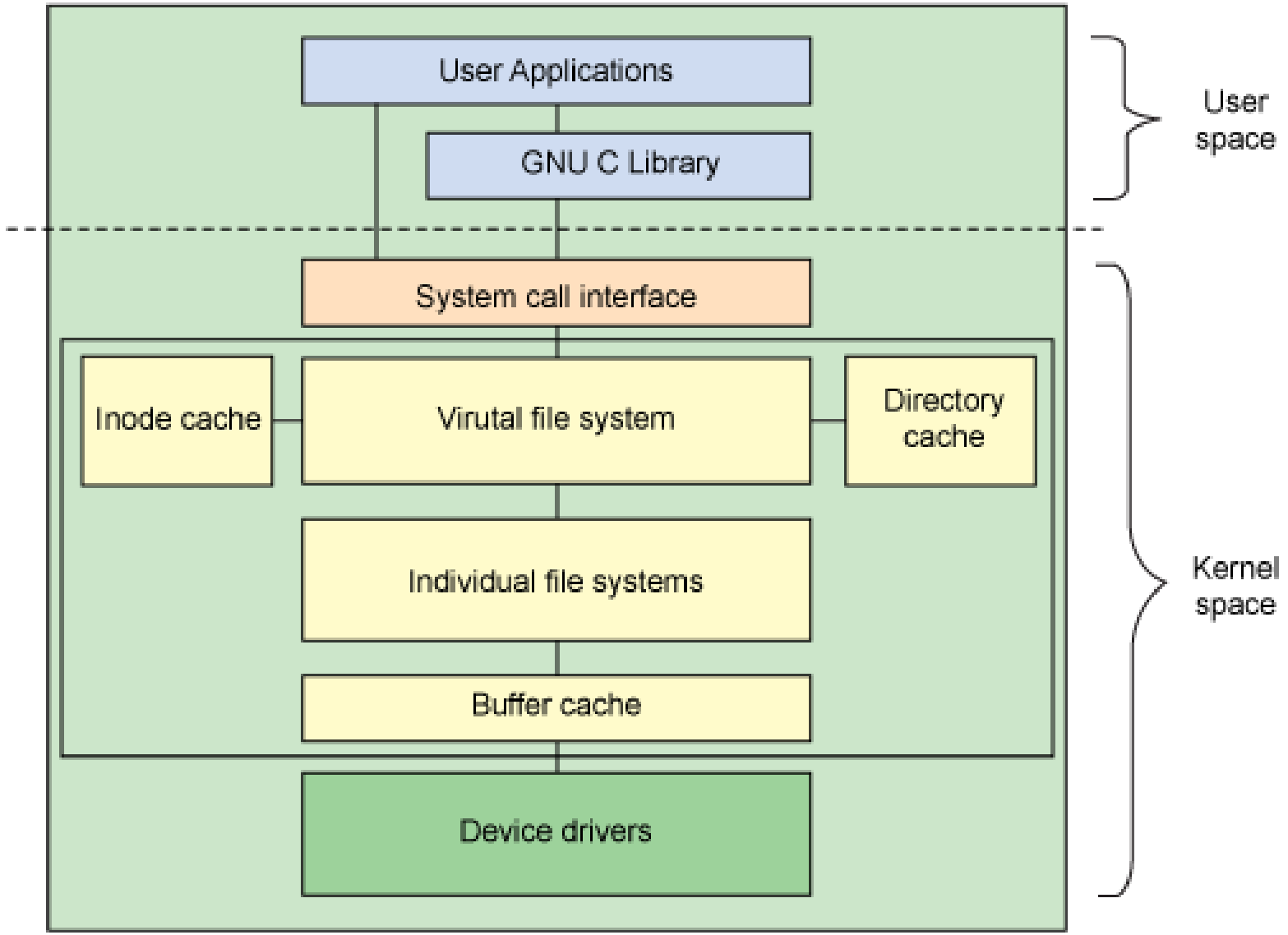
# File System Implementation

- 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** **write** | **read** | **read** | **read** **write** | **read** | **read** | **write** | | |
| write() | **read** **write** | | | | **read** **write** | | | **write** | | |
| write() | **read** **write** | | | | **read** **write** | | | | **write** | |
| write() | **read** **write** | | | | **read** **write** | | | | | **write** |

This is not all!

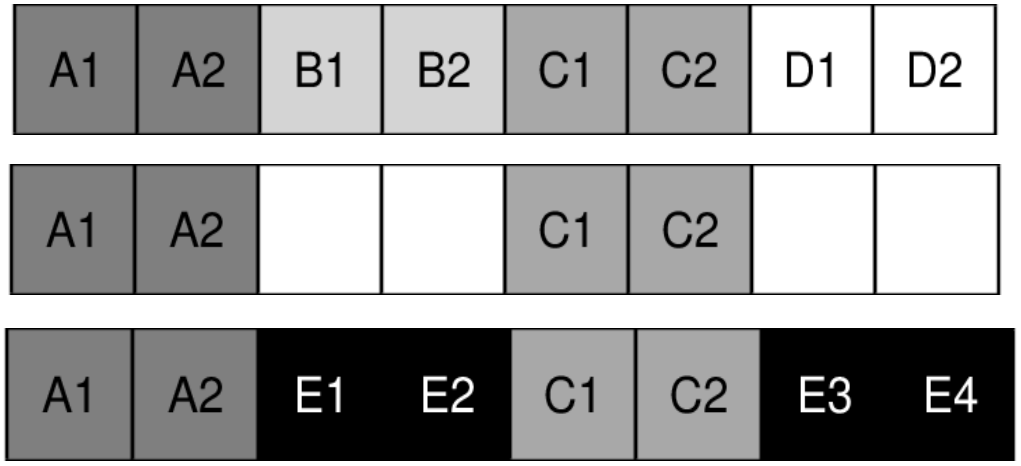
Can we change the order?

# 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