File Systems

INF 551
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Roadmap

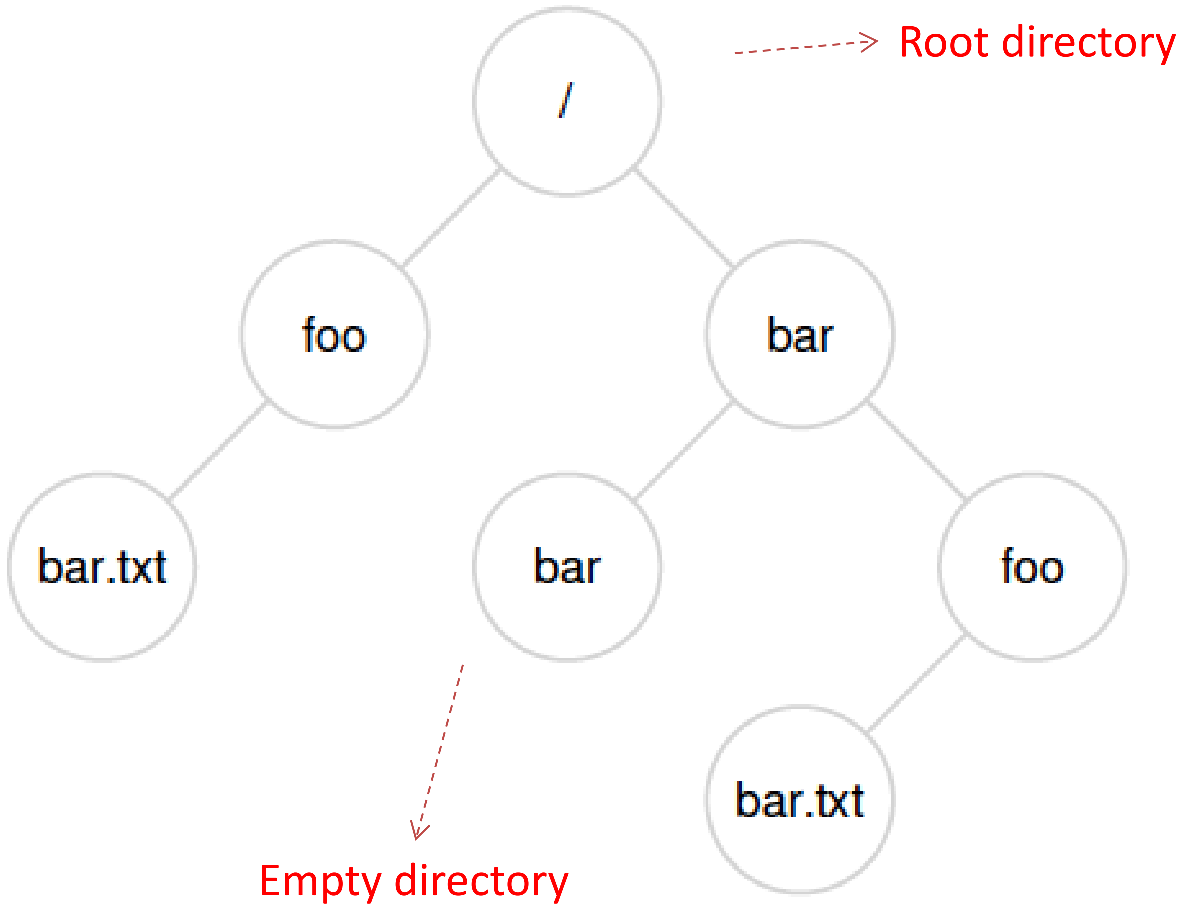
- Files and directories
  - CRUD operations
- How to implement them
  - Data structures
  - Access methods

Files and directories

- File: stored in blocks on storage device
  - Has user defined name: hello.txt
  - & low-level name, e.g., inode number: 410689

- Files are organized into directories (folders)
  - each may have a list of files and/or subdirectories
  - That is, directories can be nested

Example


Root directory
/
foo
bar
bar.txt
bar
foo
bar.txt
Empty directory

Operations on files

- Create
- Read
- Update
- Delete

Create

- User interface, e.g., via GUI
- Implementation, e.g., via a C program with a call to system function open()

|: Bitwise OR operator

- int fd = open("foo", O_CREAT | O_WRONLY | O_TRUNC);
  - Open with flags indicating the specifics
  - O_CREATE: create a file
  - O_WRONLY: write only
  - O_TRUNC: remove existing contents if exits

File descriptor

- Note open() returns a file descriptor
  - Typically an integer
  - Reserved fds: stdin 0, stdout, 1, stderr 2

Read

- read(fd, buffer, size)
  - Read from file "fd" <*size*> number of bytes
  - And store them in *buffer*

- Read starts from the current offset of fd
  - Initially 0

Write

- write(fd, buffer, size)
  - Write to file *fd* <*size*> number of bytes stored in buffer
  - Also start writing from the current offset

Random read and write

- off_t lseek(int fd, off_t offset, int whence)
  - If whence is SEEK_SET, the offset is set to <offset> bytes from the beginning of file
  - If whence is SEEK_CUR, the offset is set to its current location plus <offset> bytes
  - If whence is SEEK_END, the offset is set to the size of the file plus <offset> bytes (typically offset is negative, e.g., -8 for 8 bytes from the end)

- whence: from where

```c
#define BUF_SIZE 8192

int main(int argc, char* argv[]) {

    int input_fd, output_fd;     /* Input and output file descriptors */
    ssize_t ret_in, ret_out;     /* Number of bytes returned by read() and write() */
    char buffer[BUF_SIZE];       /* Character buffer */

    /* Are src and dest file name arguments missing */
    if(argc != 3){
        printf ("Usage: cp file1 file2\n");
        return 1;
    }

    /* Create input file descriptor */
    input_fd = open (argv [1], O_RDONLY);
    if (input_fd == -1) {
            perror ("open");
            return 2;
    }

    /* Create output file descriptor */
    /* WRONLY will truncate file to zero length if exists */
    output_fd = open(argv[2], O_WRONLY | O_CREAT, 0644);
    if(output_fd == -1){
        perror("open");
        return 3;
    }

    /* Copy process */
    while((ret_in = read (input_fd, &buffer, BUF_SIZE)) > 0){
            ret_out = write (output_fd, &buffer, (ssize_t) ret_in);
            if(ret_out != ret_in){
                /* Write error */
                perror("write");
                return 4;
```

Copy a file

"0" starts an octal number
=> permissions:
110 (owner) rw-
100 (group) r--
100 (others) r--

Pointer to a character array

File permission mode

```
Vincent@Vincent-PC ~/usc/551-fa16/Amazon
$ copy2
Usage: cp file1 file2

Vincent@Vincent-PC ~/usc/551-fa16/Amazon
$ copy2 copy2.c copy2-a.c

Vincent@Vincent-PC ~/usc/551-fa16/Amazon
$ ls -l
total 95
-rwxrwx---+ 1 Vincent None     3 Aug 30 18:04 a.txt
-rwxrwx---+ 1 Vincent None     0 Aug 30 18:04 a.txt~
-rwxrwx---+ 1 Vincent None  1568 Jan 31  2016 copy2.c
-rwxrwxr-x+ 1 Vincent None 64289 Sep 10 11:45 copy2.exe
-rw-r--r--+ 1 Vincent None  1568 Sep 10 11:45 copy2-a.c
-rwxrwx---+ 1 Vincent None   426 Aug 31 15:18 HelloWorld.class
-rwxrwx---+ 1 Vincent None   239 Aug 30 18:02 HelloWorld.java
-r--------+ 1 Vincent None  1698 Aug 23 17:18 inf551.pem
-rwxrwx---+ 1 Vincent None  1464 Aug 23 20:56 inf551.ppk
-r--------+ 1 Vincent None  1694 Aug 31 14:48 inf551-a.pem
-r--------+ 1 Vincent None  1698 Aug 31 17:28 inf551-b.pem
-rwxrwx---+ 1 Vincent None  1464 Aug 31 17:39 inf551-b.ppk
```

rw-r--r–

=> 110 (owner permission) 100 (group) 100 (others)

Resources for system calls

- https://en.wikipedia.org/wiki/System_call
- open: https://en.wikipedia.org/wiki/Open_(system_call)
- read: https://en.wikipedia.org/wiki/Read_(system_call)
- write: https://en.wikipedia.org/wiki/Write_(system_call)
- close: https://en.wikipedia.org/wiki/Close_(system_call)

Resources for system calls

- man –S 2 read
  - Find it in the Section 2 of the manual

Install gcc on EC2

- sudo yum groupinstall "Development Tools"
  – Will install other dev. tools too
  – E.g., perl, bison, flex, automake, autoconf

- Usage:
  – gcc -o copy2 copy2.c

File and directory

- When creating a file
  - Bookkeeping data structure (inode) created: recording size of file, location of its blocks, etc.
  - Linking a human-readable name to the file
  - Putting the link in a directory

Info about file (stored in inode)

```
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) */
    off_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; /* last time file content was examined */
    time_t st_mtime; /* last time file content was changed */
    time_t st_ctime; /* last time inode was changed */
};
```

inode

- Stores metadata/attributes about the file
- Also stores locations of blocks holding the content of the file

Example

- a.txt

  abc def

  abc def

  abc def

Device id

Block size

# of blocks allocated

of (hard) links

Inode #

```
[ec2-user@ip-172-31-52-194 inf551]$ stat a.txt
  File: ‘a.txt’
  Size: 24              Blocks: 8          IO Block: 4096   regular file
Device: ca01h/51713d    Inode: 410837      Links: 1
Access: (0770/-rwxrwx---)  Uid: (  500/ec2-user)   Gid: (  500/ec2-user)
Access: 2016-09-10 23:57:57.757982711 +0000
Modify: 2016-09-10 23:57:57.869981750 +0000
Change: 2016-09-10 23:57:57.869981750 +0000
 Birth: -
[ec2-user@ip-172-31-52-194 inf551]$
```

Access permission

User id

Group id

Working with directories

- Create: mkdir() system call
  - Used to implement command, e.g., mkdir xyz
- Read: opendir(), readdir(), closedir()
  - ls xyz
- Delete: rmdir()

Roadmap

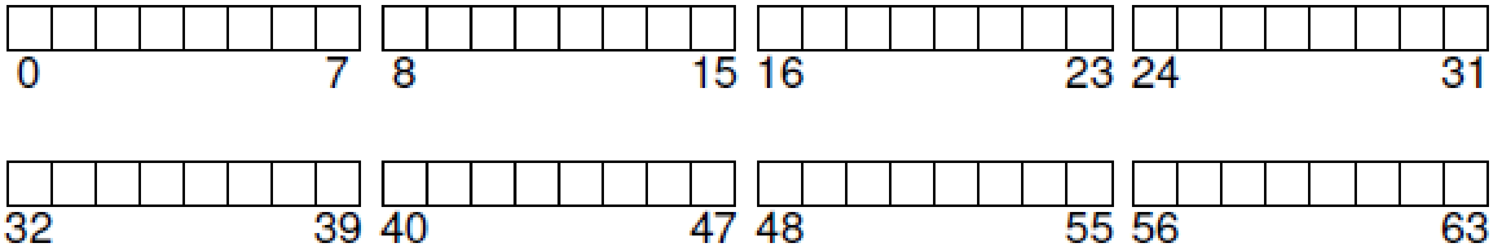
- Files and directories
  - CRUD operations
- Implementation
  - Data structures: how to organize the blocks
  - Access methods: map system calls to operations on data structures

Organization of blocks

- Array-based
  - Disk consists of a list of blocks
  - We will assume this
- Tree-based, e.g., SGI XFS
  - Blocks are organized into variable-length extents
  - Use B+-tree to quickly find free extents

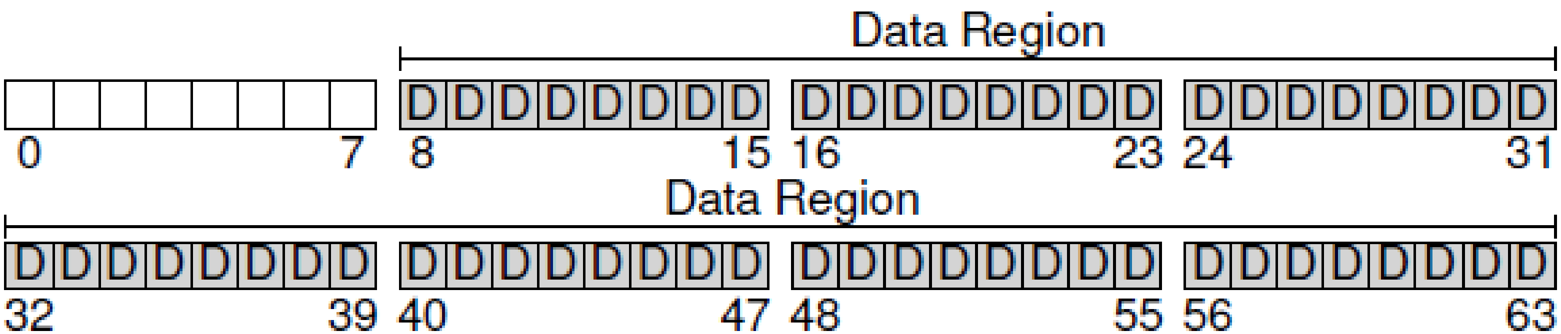
Blocks

- Consider a disk with 64 blocks
  - 4KB/block
  - 512B/sector (we assume this in this lecture)
- So there are $2^{12}/2^{9} = 2^{3} = 8$ sectors/block
  - Capacity of disk = 64 * 4KB = 256KB



Data region

- 56 blocks used to store data (files)
  - Blocks # 8 – 63



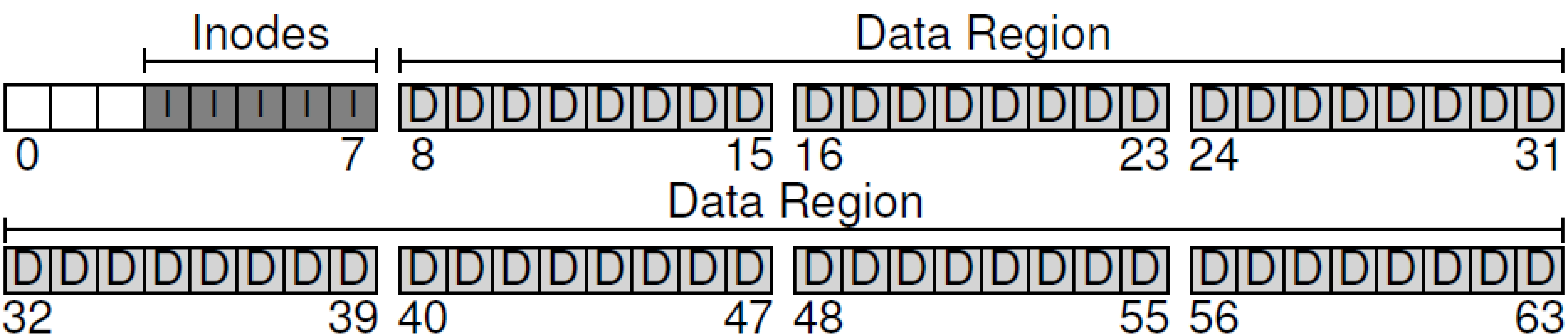
Metadata

- For each file, file system keeps track of
  - Location of the blocks that comprise the file
  - Size of the file
  - Owner and access rights
  - Access and modify times
  - Etc. (see the stat struct a couple of slides back…)

- These metadata are stored in an **inode** (index node)

inodes

- Index nodes
- Stored in blocks #3 -- #7 (i.e., 5 blocks)
- Together they are called inode table



How many inodes are there?

- 256 bytes/inode
- 5 blocks, 4KB/block

=> 16 inodes/block (4K/256 = $2^{12}/2^{8}$)

=> 5 blocks, 5 * 16 = 80 inodes

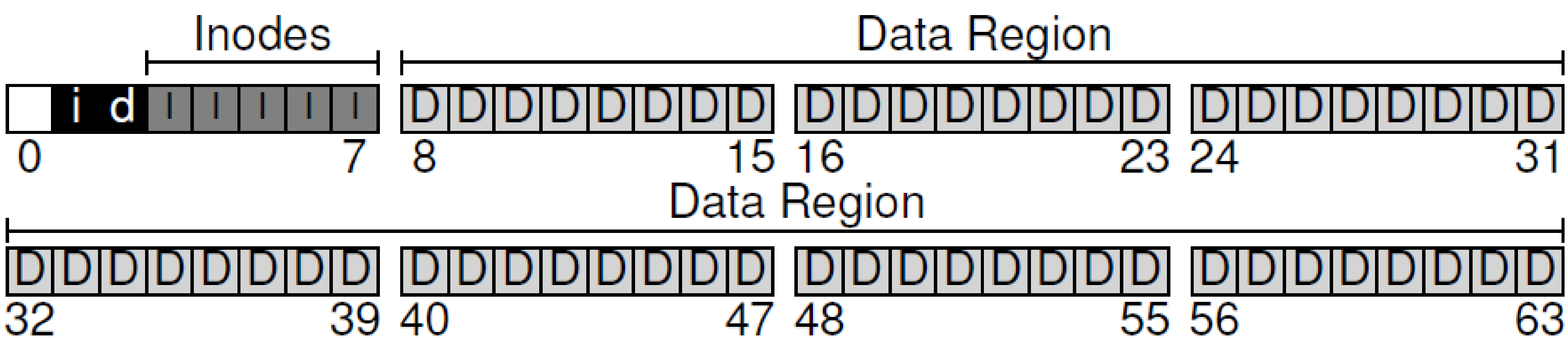
=> File system can store at most 80 files

Free space management using bitmaps

- Bitmap: a vector of bits
  - 0 for free (inode/block), 1 for in-use
- Inode bitmap (imap)
  - keep track of which inodes in the inode table are available
- Data bitmap (dmap)
  - Keep track of which blocks in data region are available

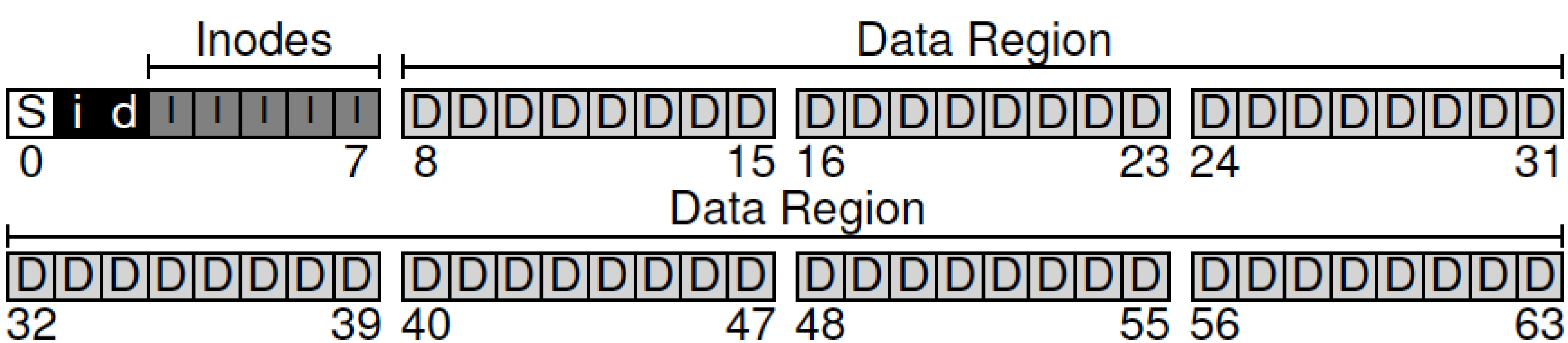
Bitmaps

- Each bitmap is stored in a block
  - Block "i": keep track of 80 inodes (could track 32K)
  - Block "d": keep track of the 56 data blocks



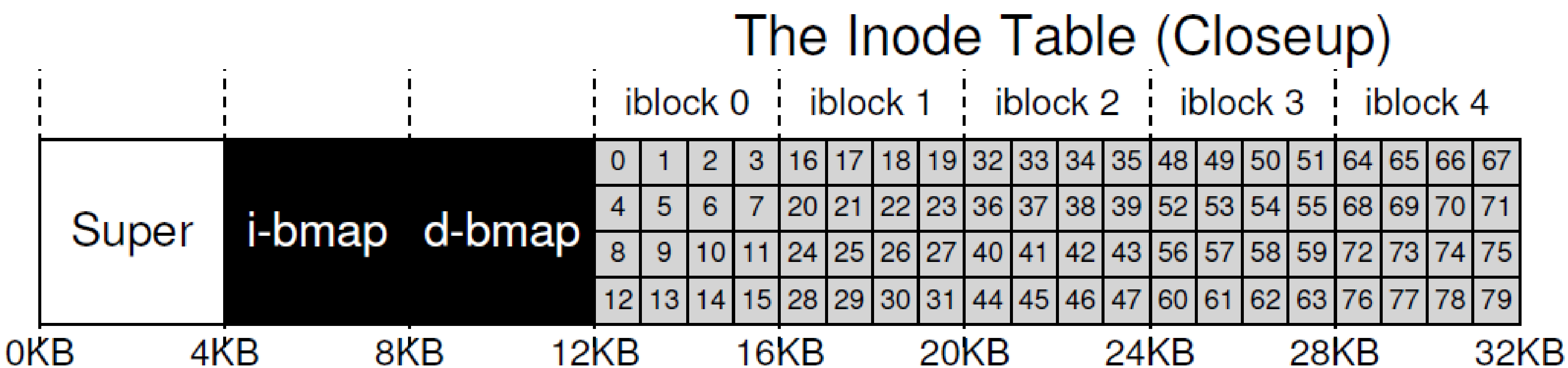
Superblock

- Track where i/d blocks and inode table are
  - E.g., inode table starts at block 3; there are 80 inodes and 56 data blocks, etc.
- Indicate type of file system
- Will be read first when file system is mounted



inumber

- Each inode is identified by a number
  - Low-level number of file name
- Can figure out location of inode from inumber

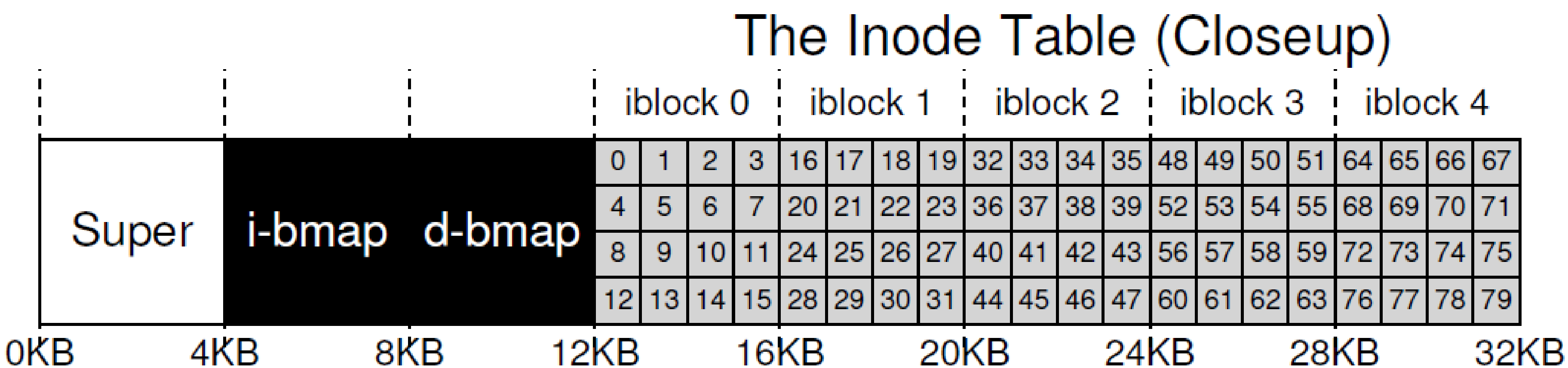


inumber => location

- inumber = 32

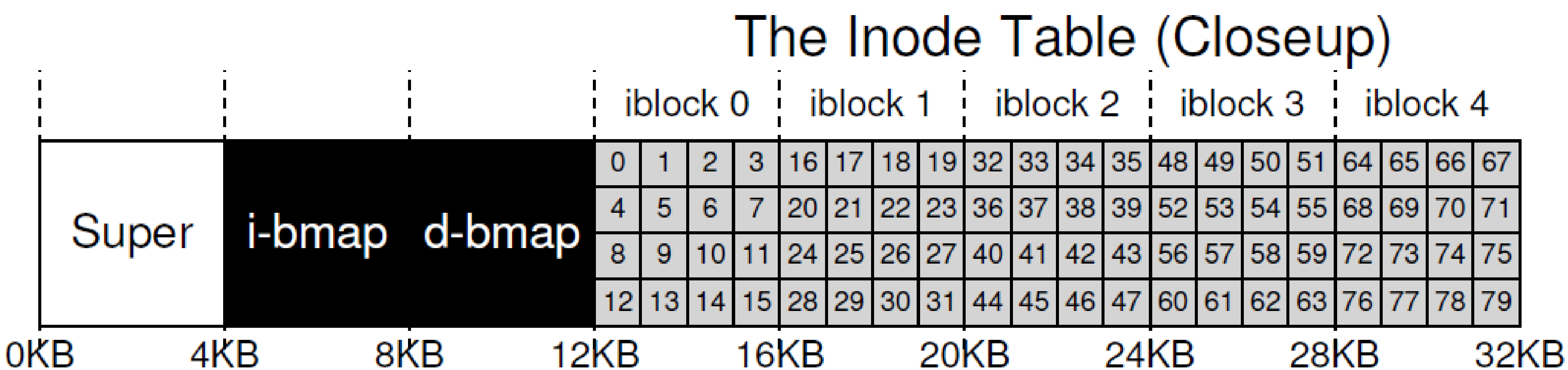
=> address: offset in bytes from the beginning

=> which sector?



inumber => location of inode

- Address: 12K + 32 * 256 = 20K
- Sector #: 20K/512 = 40
  - more generally
  - $\lfloor(\text{inodeStartAddress} + \text{inumber} * \text{inode size})/\text{sector size}\rfloor$



inode => location of data blocks

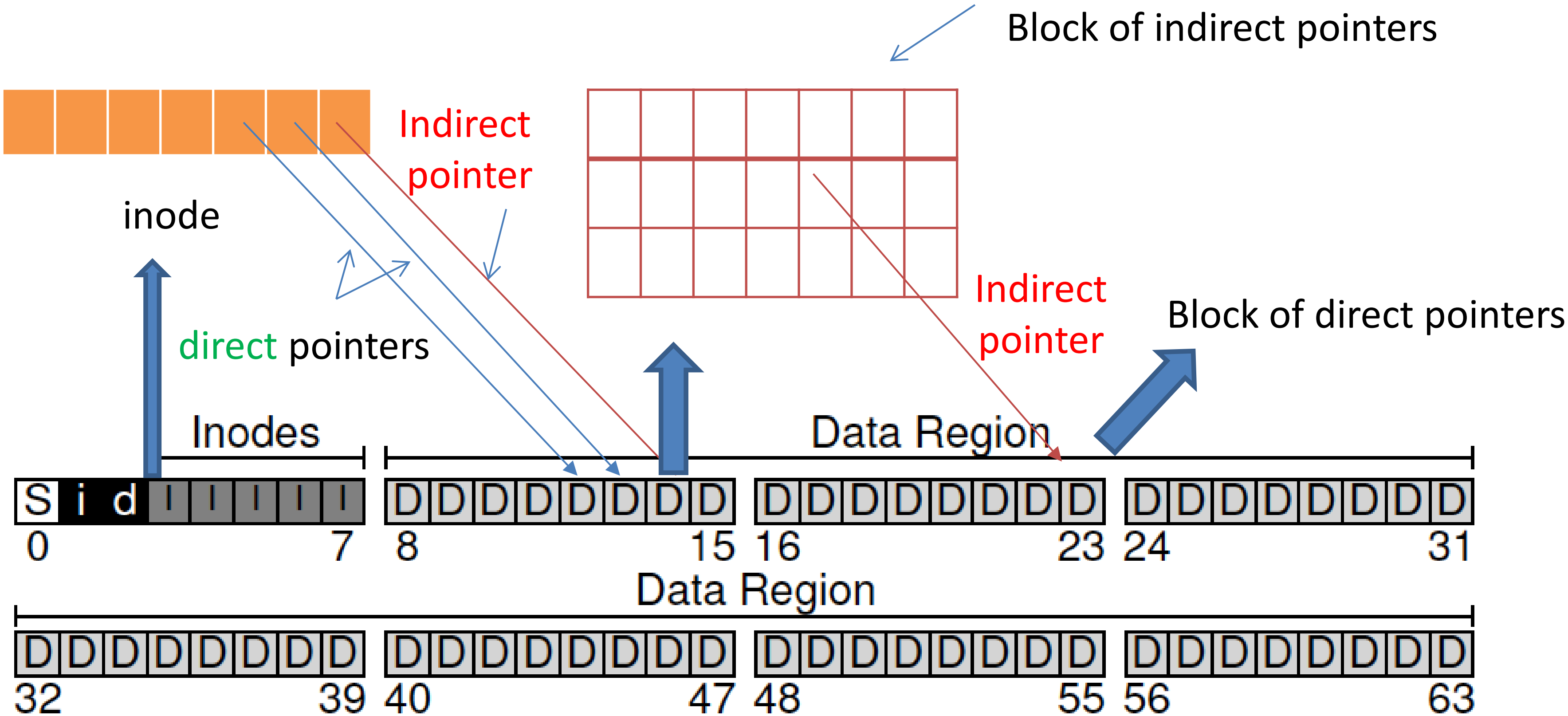
- A number of direct pointers
  - E.g., 8 pointers, each points to a data block
  - Enough for 8*4K = 32K size of file

- Also has a slot for indirect pointer
  - Pointing to a data block storing direct pointers
  - Assume 4 bytes for block address (e.g., represented in CHS), so 1024 pointers/block
  - Now file can have (8 + 1024) blocks or 4,128KB

Multi-level index

- Pointers may be organized into multiple levels
  - Indirect pointer (as in previous slide)
    - Inode (pointer1, pointer2, …, indirect pointer)
    - Indirect pointer -> a block of direct pointers
  - Double indirect pointers
    - Inode (pointer1, pointer2, …, indirect pointer)
    - Indirect pointer -> a block of indirect pointers instead
      -> each points to a block of direct pointers
  - Triple indirect pointers
    - Indirect pointer -> a block of indirect pointers
      -> each points to a block of indirect pointers
      -> each points to a block of direct pointers

Double Indirect Pointers



Advantages of multi-level index

- Grow to more levels as needed

- Direct pointers handle most of the cases
  - Many files are small

Directory organization

- Directory itself stored as a file
- For each file in the directory, it stores:
  - name, inumber, record length, string length

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

Actual length

Record length vs string length

- String length = # of characters in file name + 1 (for \0: end of string)
- Record length >= string length
  - Due to entry reuse

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

Reusing directory entries

- If file is deleted (using rm command) or a name is unlinked (using unlink command)
  - File is finally deleted when its last (hard) link is removed
- Then inumber in its directory entry set to 0 (reserved for empty entry)
  - So we know it can be reused

Storing a directory

- Also as a file with its own inode + data block

- inode:
  - file type: directory (instead of regular file)
  - pointer to block(s) in data region storing directory entries

Roadmap

- Files and directories
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  - Access methods: turn system calls to operations on data structures

Open for read

- fd = open("/foo/bar", O_RDONLY)

mode

bar inode
↓
foo content
↓
foo inode
↓
root content → root inode.
↓
mount (super block)

Open for read

- fd = open("/foo/bar", O_RDONLY)
  – Need to locate inode of the file "/foo/bar"
  – Assume inumber of root, say 2, is known (e.g., when the file system is mounted)

Open for read

1. Read inode and content of / (2 reads)
   – Look for "foo" in / -> foo's inumber

2. Read inode and content of /foo (2 reads)
   – Look for "bar" in /foo -> bar's inumber

3. Read inode of /foo/bar (1 read)
   – Permission check + allocate file descriptor

Cost of open()

- Need 5 reads of inode/data block

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

Reading the file

- read(fd, buffer, size)
  - Note fd is maintained in per-process open-file table
  - Table translates fd -> inumber of file

File-open table per process

File descriptor	File name	Inumber	Position offset	…
3	/foo/bar	32382	0	
4	/foo/more	48482	512	…

Reading the file

- read(fd, buffer, size)

1. Consult bar's inode to locate its 1^{st} block
2. Read the block
3. Update inode with newest file access time
4. Update open-file table with new offset
5. Continue steps 2, 3, 4 until done
6. Deallocate file descriptor

Cost for reading a block

- 3 I/O's:
  - read inode, read data block, write inode

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

Open for write

- int fd = open("/foo/bar", O_WRONLY)
  - Assume bar is a new file under foo
  - (note the difference from reading chapter!)

Open for write

- int fd = open("/foo/bar", O_WRONLY)

1. Read '/' inode & content
   – obtain foo's inumber

2. Read '/foo' inode & content
   – check if bar exists

Open for write

3. Read imap, to find a free inode for bar
4. Update imap, setting 1 for allocated inode
5. Write bar's inode

Open for write

6. Update foo's content block
   – Adding an entry for bar

7. Update foo's inode
   – Update its modification time

Cost for "open for write"

- int fd = open("/foo/bar", O_WRONLY)
- Need 9 I/O's

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

Writing the file: /foo/bar

1. Read inode of bar (by looking up its inumber in the file-open table)
2. Allocate new data block
   - Read and write bmap
3. Write to data block of bar
4. Update bar inode
   - new modified time, add pointer to block

Cost of writing /foo/bar

- 5 I/O's for write a block

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

Caching for read

- First read may be slow
  – But subsequent ones will speed up
- Good idea to cache popular blocks
  – e.g., determined via LRU strategy

Buffering for delayed write

- Improve write performance via:
  - Batching (e.g., two updates to the same imap)
  - Scheduling (reordering for better performance)
  - Avoiding writes (if file created, then quickly deleted)
- Problem: update may be lost when system crashes

Example file systems

- NTFS
  - New technology file system, Microsoft proprietary
- FAT
  - File allocation table
  - FAT 16, 32, …
  - 32 bits = # of sectors a file can occupy

    512B/sector => 2TB limit on file size

    4KB/sector => 16TB limit
- Ext4
  - fourth extended file system, common in Linux