



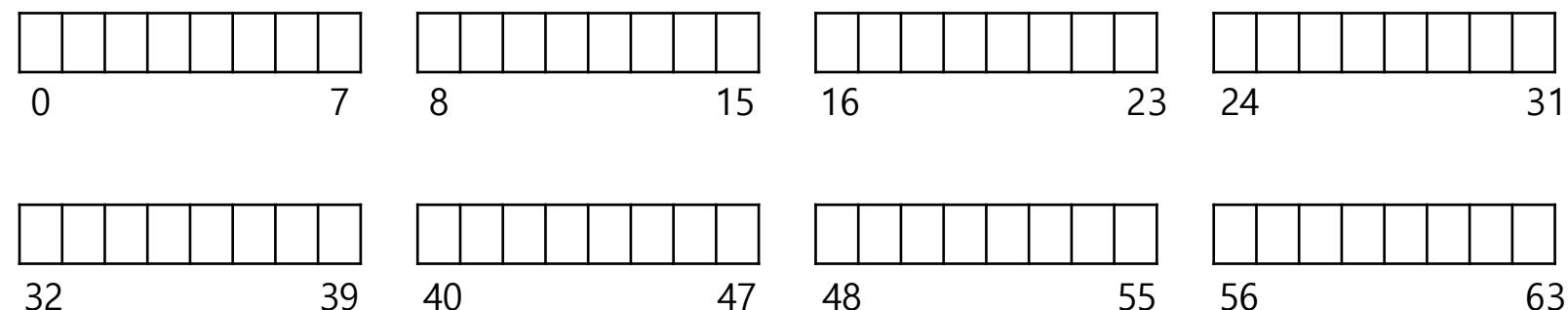
File System Design

The Way To Think

- There are two different aspects to implement file system
 - **Data structures**
 - What types of on-disk structures are utilized by the file system to organize its data and metadata?
 - **Access methods**
 - How does it map the calls made by a process as `open()`, `read()`, `write()`, etc.
 - Which structures are read during the execution of a particular system call?

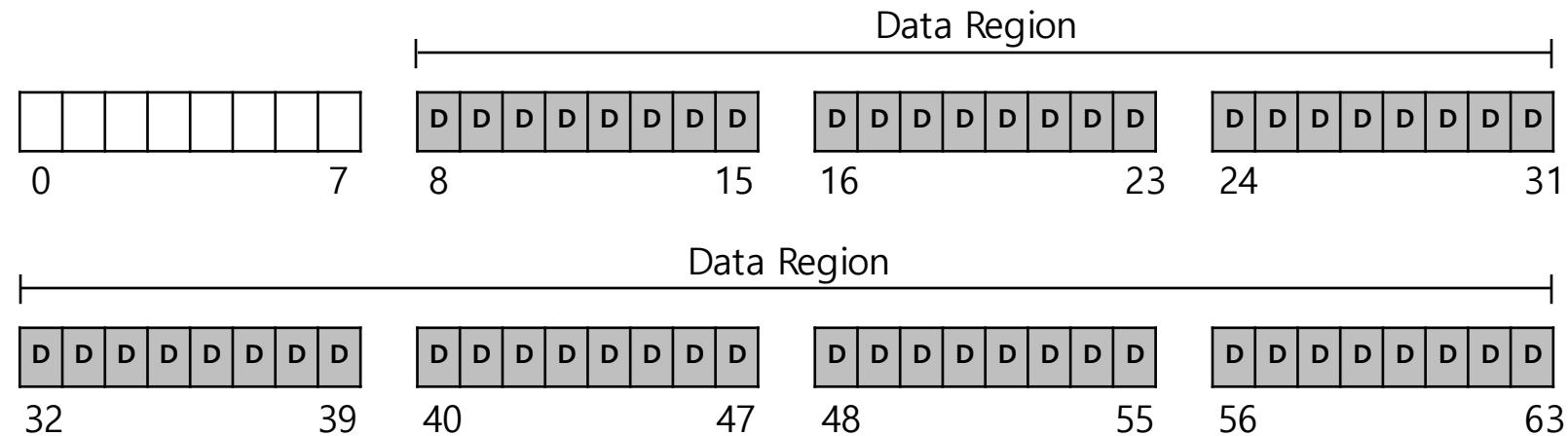
Overall Organization

- Let's develop the overall organization of the file system data structure
- Divide the disk into **blocks**
 - Block size is 4 KB
 - The blocks are addressed from 0 to $N - 1$



Data Region in File System

- Reserve **data region** to store user data

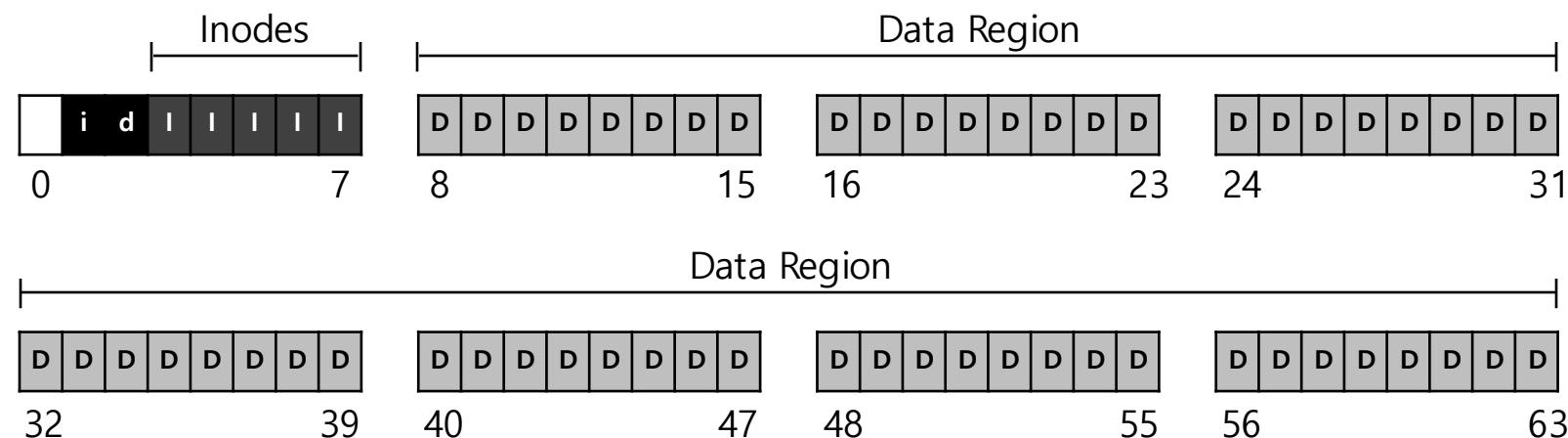


- File system has to track which data block comprise a file, the size of the file, its owner, etc

How we store these **inodes** in file system?

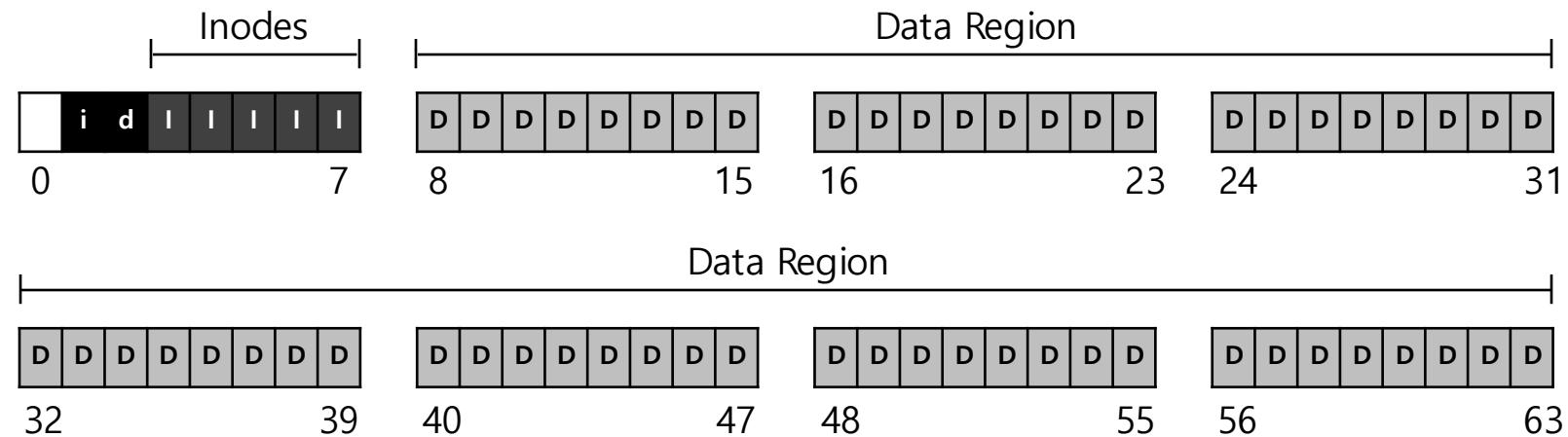
Inode Table in File System

- Reserve some space for **inode table**
 - This holds an array of on-disk inodes
 - Ex) inode tables : 3 ~ 7, inode size : 256 bytes
 - 4-KB block can hold 16 inodes
 - File system contains 80 inodes (maximum number of files)



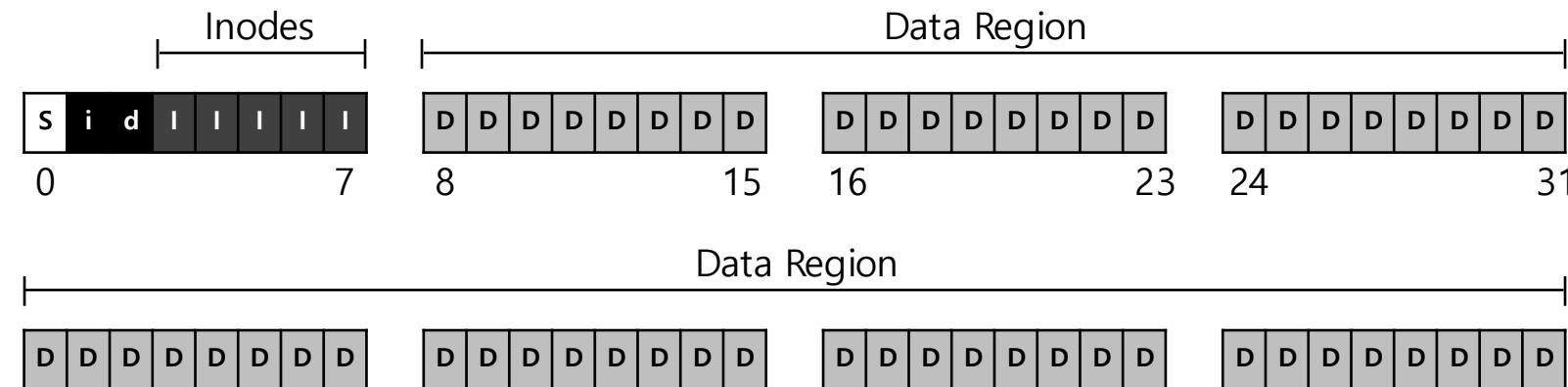
Allocation Structures

- This is to track whether inodes or data blocks are free or allocated
- Use **bitmap**, each bit indicates free(0) or in-use(1)
 - **Data bitmap**: for data region
 - **inode bitmap**: for inode table



Superblock

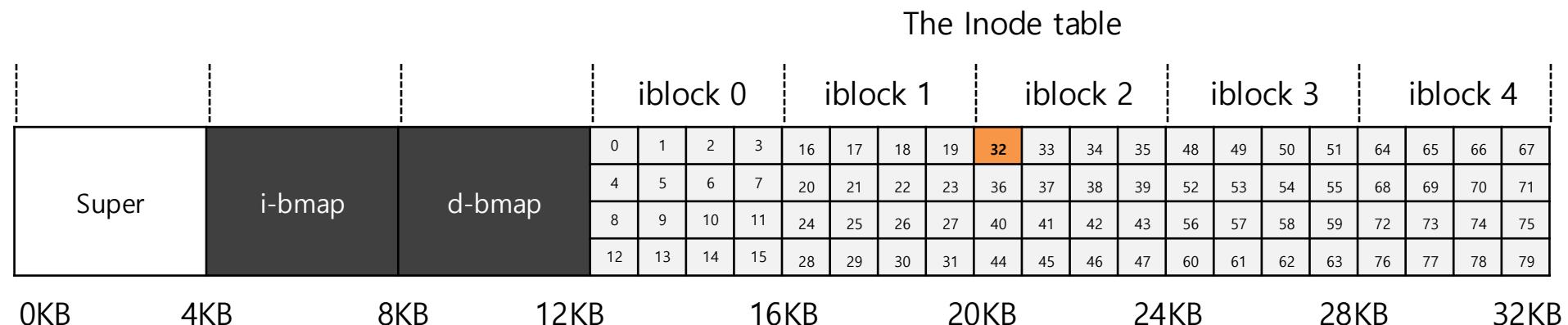
- Super block contains **information** about a **particular file system**
 - Ex) The number of inodes, begin location of inode table, etc



- Thus, when³² mounting a³⁹ file⁴⁰ system, OS⁴⁷ will⁴⁸ read the superblock first, to initialize various information^{55, 56}, to⁶³ initialize various information

File Organization: inode

- Each inode is referred to by inode number
 - With inode number, a file system calculates where the inode is on the disk
 - Ex) inode number: 32
 - Calculate the offset into the inode region
 $32 \times \text{sizeof(inode)} (256 \text{ bytes}) = 8192$
 - Add start address of the inode table(12 KB) + inode region(8 KB) = 20 KB



File Organization: inode

- Disks are not byte addressable, sector addressable
- Disk consist of a large number of addressable sectors (512 bytes)
 - Ex) Fetch the block of inode (inode number: 32)
 - Sector address iaddr of the inode block:
 - blk : $(\text{inumber} * \text{sizeof(inode)}) / \text{blocksize}$
 - sector : $(\text{blk} * \text{blocksize}) + \text{inodeStartAddr} / \text{sectorsize}$

The Inode table

						iblock 0				iblock 1				iblock 2				iblock 3				
Super	i-bmap	d-bmap	0	1	2	3	16	17	18	19	32	33	34	35	48	49	50	51	64	65	66	67
			4	5	6	7	20	21	22	23	36	37	38	39	52	53	54	55	68	69	70	71
			8	9	10	11	24	25	26	27	40	41	42	43	56	57	58	59	72	73	74	75
			12	13	14	15	28	29	30	31	44	45	46	47	60	61	62	63	76	77	78	79

0KB 4KB 8KB 12KB 16KB 20KB 24KB 28KB 32KB

File Organization: inode

- inode have all of the information about a file
 - File type (regular file, directory, etc.)
 - Size, the number of blocks allocated to it
 - Protection information(who ones the file, who can access, etc)
 - Time information
 - Etc.

File Organization: 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?
4	gid	which group does this file belong to?
2	links_count	how many hard links are there to this file?
2	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

EXT2 Inode

Multi-Level Index

- To support bigger files, we use multi-level index
- **Indirect pointer** points to a block that contains more pointers
 - inode have fixed number of direct pointers (12) and a single indirect pointer
 - If a file grows large enough, an indirect block is allocated, inode's slot for an indirect pointer is set to point to it
 - $(12 + 1024) \times 4\text{ K}$ or 4144 KB

Multi-Level Index

- Double indirect pointer points to a block that contains indirect blocks
 - Allow file to grow with an additional 1024×1024 or 1 million 4KB blocks
- Triple indirect pointer points to a block that contains double indirect blocks
- Multi-Level Index approach to pointing to file blocks
 - Ex) twelve direct pointers, a single and a double indirect block
 - over 4GB in size $(12+1024+1024^2) \times 4KB$
- Many file system use a multi-level index
 - Linux EXT2, EXT3, NetApp's WAFL, Unix file system
 - Linux EXT4 use **extents** instead of simple pointers

Multi-Level Index

- Most files are small**
- Average file size is growing**
- Most bytes are stored in large files**
- File systems contains lots of files**
- File systems are roughly half full**
- Directories are typically small**

- Roughly 2K is the most common size
- Almost 200K is the average
- A few big files use most of the space
- Almost 100K on average
- Even as disks grow, file system remain ~50% full
- Many have few entries; most have 20 or fewer

File System Measurement Summary

Directory Organization

- Directory contains a list of (entry name, inode number) pairs
- Each directory has two extra files ."dot" for current directory and .."dot-dot" for parent directory
 - For example, `dir` has three files (`foo`, `bar`, `foobar`)

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

on-disk for dir

Free Space Management

- File system track which inode and data block are free or not
- In order to manage free space, we have two simple bitmaps
 - When file is newly created, it allocated inode by searching the inode bitmap and update on-disk bitmap
 - Pre-allocation policy is commonly used for allocate contiguous blocks

Access Paths: Reading a File From Disk

- Issue an `open("/foo/bar", O_RDONLY)`
 - Traverse the pathname and thus locate the desired inode.
 - Begin at the root of the file system (/)
 - In most Unix file systems, the root inode number is 2
 - Filesystem reads in the block that contains inode number 2
 - Look inside of it to find pointer to data blocks (contents of the root)
 - By reading in one or more directory data blocks, It will find "foo" directory
 - Traverse recursively the path name until the desired inode ("bar")
 - Check final permissions, allocate a file descriptor for this process and returns file descriptor to user

Access Paths: Reading a File From Disk

- Issue `read()` to read from the file
 - Read in the first block of the file, consulting the inode to find the location of such a block
 - Update the inode with a new last accessed time
 - Update in-memory open file table for file descriptor, the file offset
- When file is closed
 - File descriptor should be deallocated, but for now, that is all the file system really needs to do. No disk I/Os take place

Access Paths: Reading a File From Disk

	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			
read()				read				read		
read()				read					read	

File Read Timeline (Time Increasing Downward)

Access Paths: Writing to Disk

- Issue `write()` to update the file with new contents
- File may allocate a block (unless the block is being overwritten)
 - Need to update data block, data bitmap
 - It generates five I/Os:
 - one to read the data bitmap
 - one to write the bitmap (to reflect its new state to disk)
 - two more to read and then write the inode
 - one to write the actual block itself
 - To create file, it also allocate space for directory, causing high I/O traffic

Access Paths: Writing to Disk

	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		
write()	read write			read				write		
write()	read write			read					write	
write()	read write			read						write

File Creation Timeline (Time Increasing Downward)

Caching and Buffering

- Reading and writing files are expensive, incurring many I/Os
 - For example, long pathname(/1/2/3/..../100/file.txt)
 - One to read the inode of the directory and at least one read its data
 - Literally perform hundreds of reads just to open the file
- In order to reduce I/O traffic, file systems aggressively use system memory(DRAM) to cache
 - Early file system use fixed-size cache to hold popular blocks
 - Static partitioning of memory can be wasteful
 - Modern systems use **dynamic partitioning approach**, unified page cache
- Read I/O can be avoided by large cache

Caching and Buffering

- Write traffic has to go to disk for persistent, Thus, cache does not reduce write I/Os
- File system use write buffering for write performance benefits
 - delaying writes (file system batch some updates into a smaller set of I/Os)
 - By buffering a number of writes in memory, the file system can then schedule the subsequent I/Os
 - By avoiding writes
- Some application force flush data to disk by calling `fsync()` or direct I/O