

40. File system Implementation.

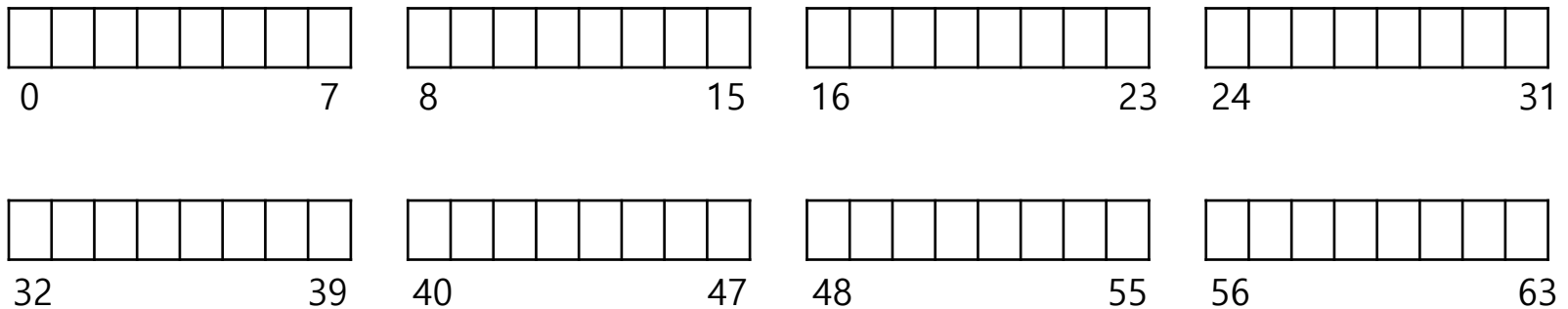
Operating System: Three Easy Pieces

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?

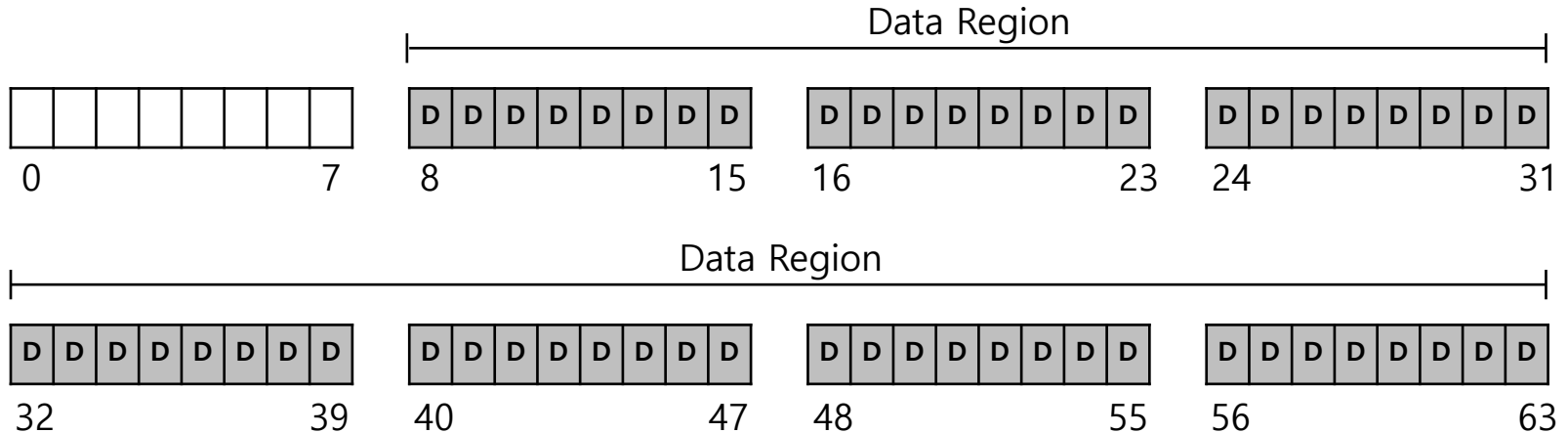
Overall Organization of VSFS (Very Simple FS)

- 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

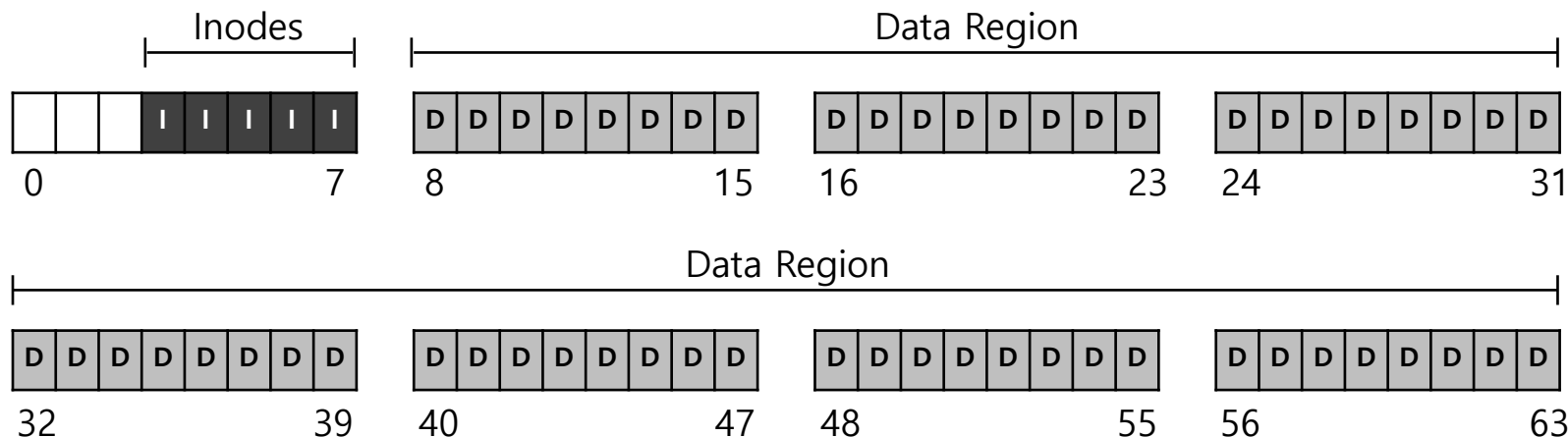


- File system has to track which data block comprise a file, the size of the file, its owner, etc.

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

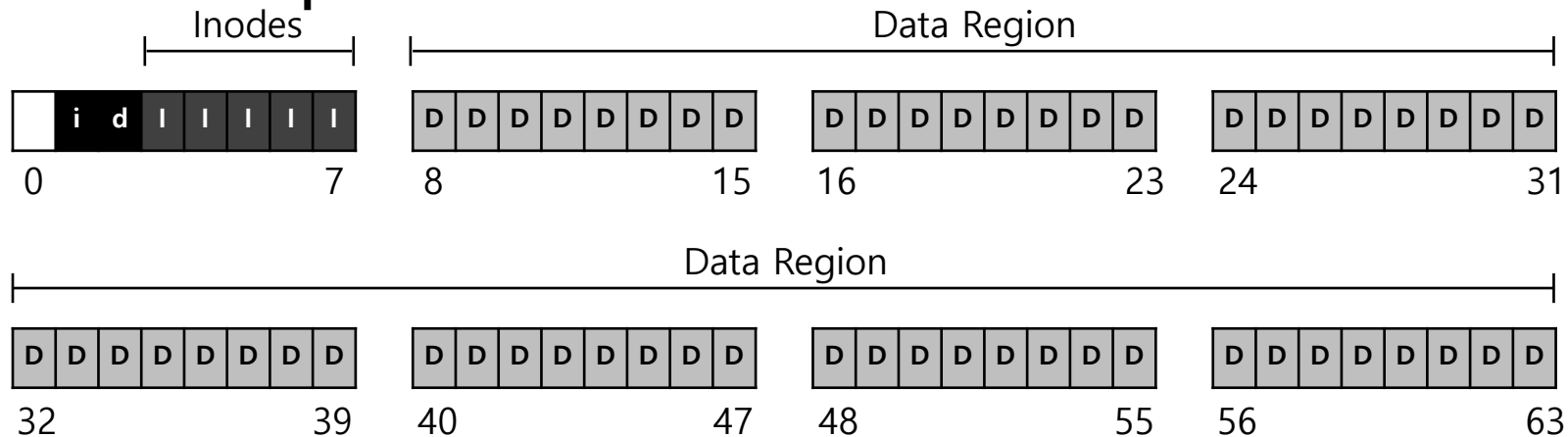
Inode table in file system

- 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.
 - The filesystem contains 80 inodes. (maximum number of files)



Allocation Structures

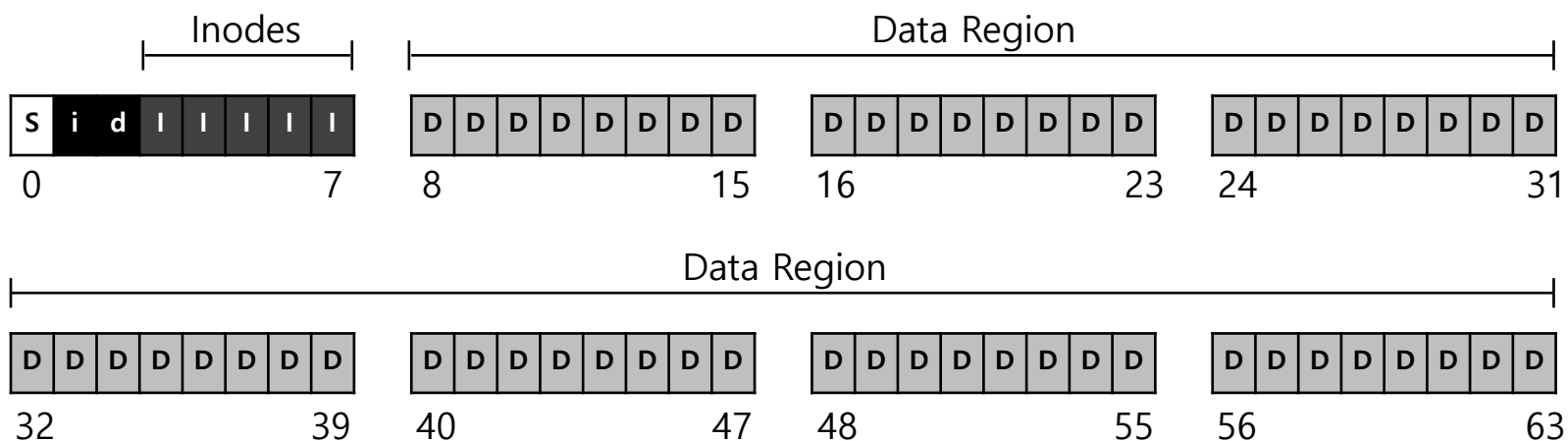
- This is to track whether inodes or data blocks are free or allocated.
- Free-list approach is way too slow
- Use **bitmap**, each bit indicates free(0) or in-use(1)
 - ◆ **data bitmap**: for data region for data region
 - ◆ **inode bitmap**: for inode table



Superblock

- Super block contains this **information** for **particular file system**

- Ex) The number of inodes, begin location of inode table. etc



- Thus, when mounting a file system, OS will read the superblock first, to initialize various information.

File Organization: The inode

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

The Inode table

Super				i-bmap				d-bmap				iblock 0				iblock 1				iblock 2				iblock 3				iblock 4			
								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: The inode (Cont.)

- ▣ Disk 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 : (inumber * sizeof(inode)) / blocksize`
 - `sector : (blk * blocksize) + inodeStratAddr) /sectorsize`

The Inode table

				iblock 0				iblock 1				iblock 2				iblock 3				iblock 4								
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: The inode (Cont.)

- `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 owns the file, who can access, etc).
 - ◆ Time information.
 - ◆ Etc.

File Organization: The inode (Cont.)

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

The EXT2 Inode

The Multi-Level Index

- ▣ To support bigger files, we use multi-level index.
- ▣ **Indirect pointer** points to a block that contains (only) more pointers.
 - ◆ inode have fixed number of direct pointers (v.gr., 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 (assuming 4byte addresses)

The Multi-Level Index (Cont.)

- ❑ **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 $(12+1024+1024^2) \times 4\text{KB}$
- ❑ 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 (conceptually similar to Segments in VM)

The Multi-Level Index (Cont.)

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

Aside: Linked-based approaches

- Use linked list
 - ◆ Only a pointer inside the inode
- Might perform poorly in certain tasks
 - ◆ Ex) Read the last inode block of a file
 - ◆ Some systems use an in-memory table of link information (kept in persistent storage too!)
- File-allocation table (FAT) uses this approach

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 finale permissions, allocate a file descriptor for this process and returns file descriptor to user.

Access Paths: Reading a File From Disk (Cont.)

- ▣ 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 (Cont.)

	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 (Cont.)

	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	read			
write()	read write			write	read write			write		
write()	read write				read write				write	
write()	read write				read write					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 (Cont.)

- ❑ 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.

- Disclaimer: This lecture slide set is used in AOS course at University of Cantabria by V.Puente. Was initially developed for Operating System course in Computer Science Dept. at Hanyang University. This lecture slide set is for OSTEP book written by Remzi and Andrea Arpaci-Dusseau (at University of Wisconsin)