File System Implementation

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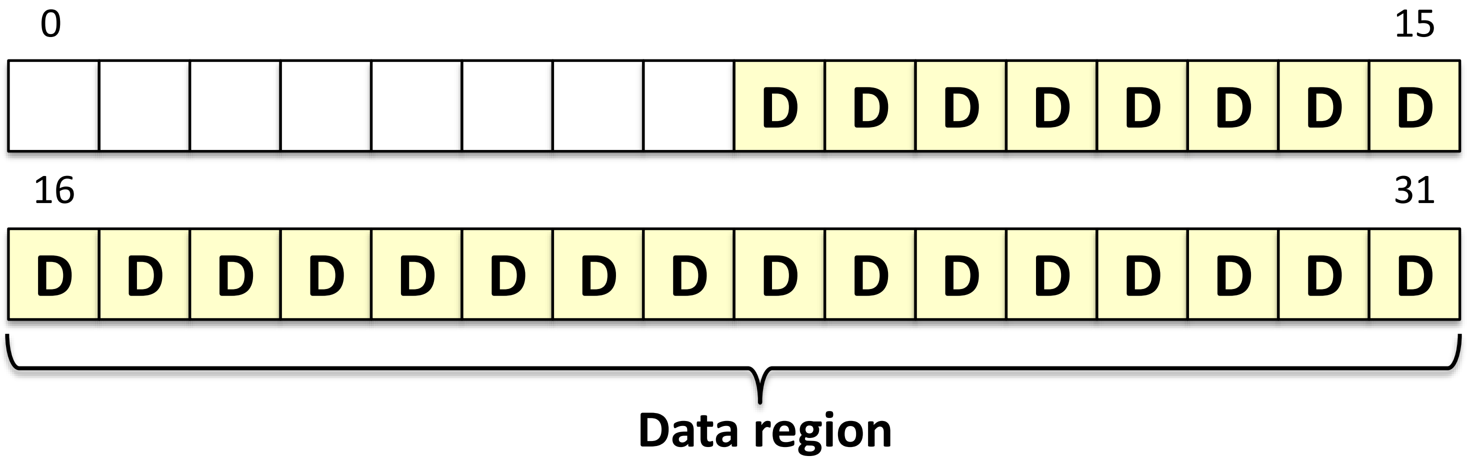
Implementing a File System

- On-disk structures
  - How does file system represent files and directories?
  - How to manage various file system metadata?

- Access methods
  - What steps should be taken for various file system APIs?
  - `open()`, `read()`, `write()`, `close()`, …

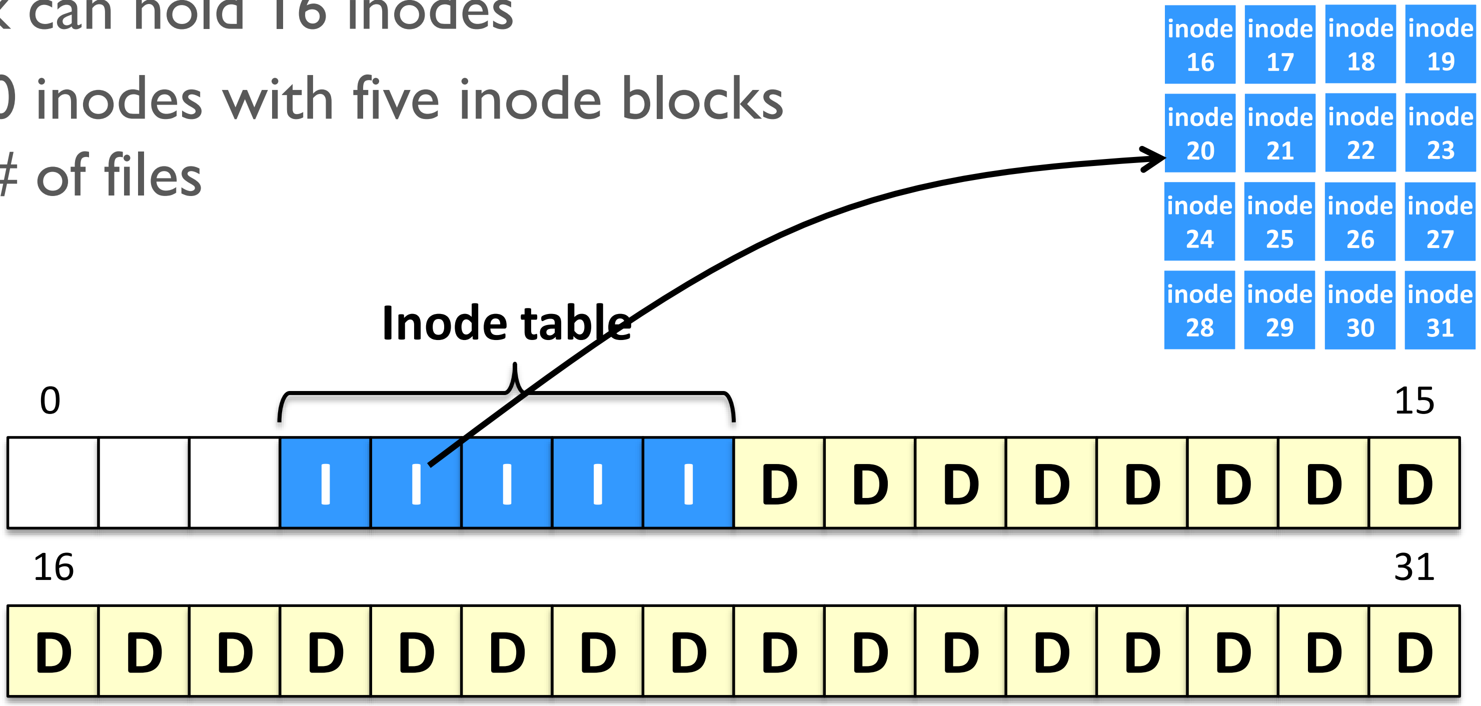
VSFS: Data Blocks

- "Very Simple File System"
  - Divide the disk into blocks (e.g., 4KB)
  - Block size is a multiple of sector size
  - Most of disk blocks are used for storing user data
  - A small portion of the disk is reserved for file system metadata



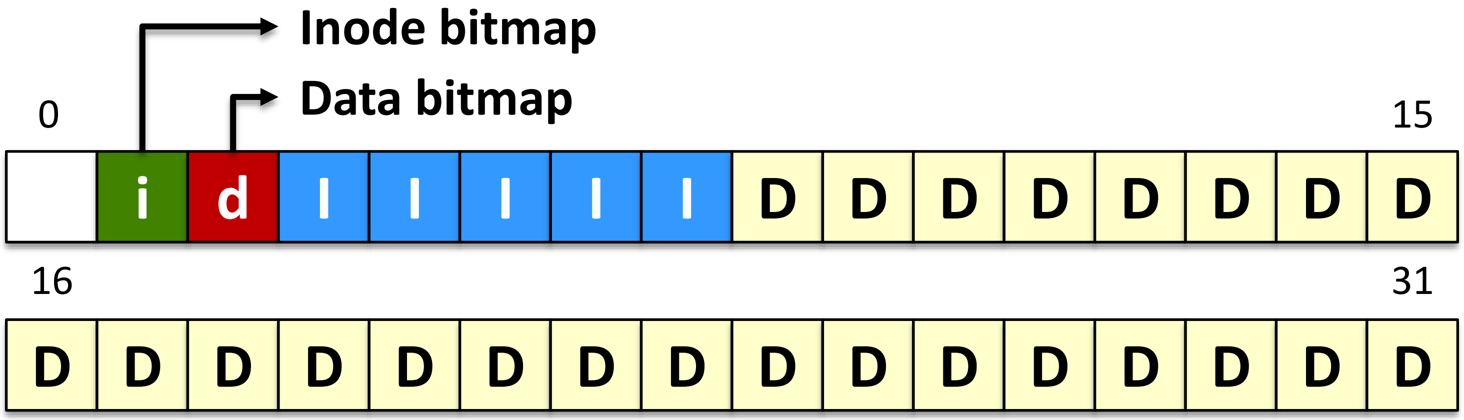
VSFS: Inodes

- Each inode holds file metadata
  - The size of an inode is fixed (typically, 128B ~ 256B)
  - For 256B per inode,
    a 4KB block can hold 16 inodes
  - The total 80 inodes with five inode blocks
    = the max # of files



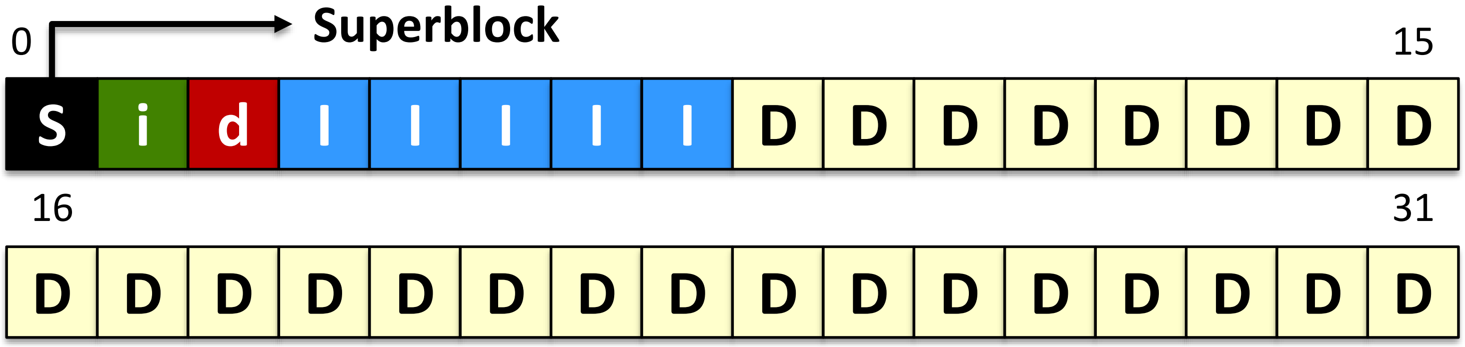
VSFS: Bitmaps

- Data bitmap & Inode bitmap
  - Each bit indicates whether the corresponding block/inode is free (0) or in-use (1)
  - One data bitmap (or inode bitmap) block can support up to 4096*8 data blocks (or inodes)



VSFS: Superblock

- Superblock holds file system metadata
  - File system type
  - Block size
  - Total number of blocks
  - Number of inodes
  - Number of data / inode bitmap blocks, …



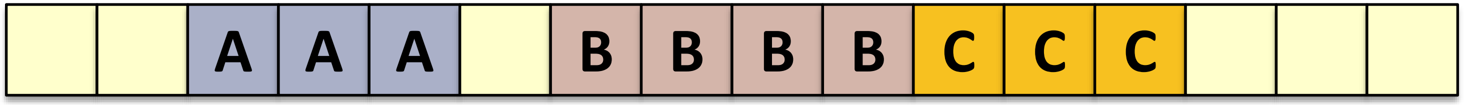
Allocation Strategies

- How to map files to disk blocks?
  - Similar to mapping variable-sized address spaces to physical memory
  - Same principle: map logical abstraction to physical resources

- Issues
  - The amount of fragmentation (mostly ___________)
  - Ability to grow file over time
  - Performance of sequential accesses
  - Speed to find data blocks for random accesses
  - Metadata overhead to track data blocks

Contiguous Allocation

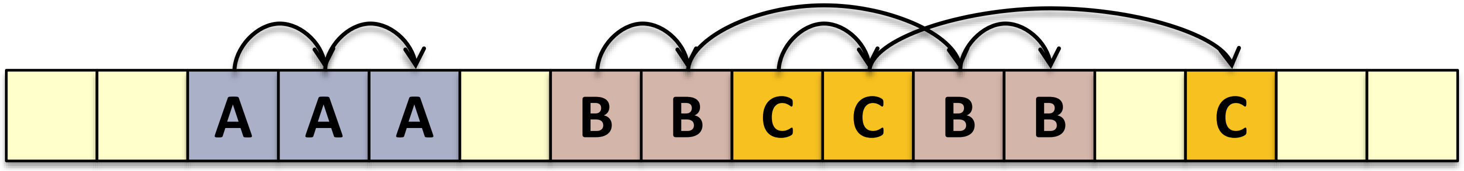
- Allocate each file to contiguous blocks on disk
  - Metadata: <starting block #, length>
  - Feasible and widely used for CD-ROMs
  - Example: IBM OS/360



  - Horrible external fragmentation (needs periodic compaction)
  - May not be able to grow file without moving
  - Excellent performance for sequential accesses
  - Simple calculation to perform random accesses
  - Little overhead for metadata

Linked Allocation

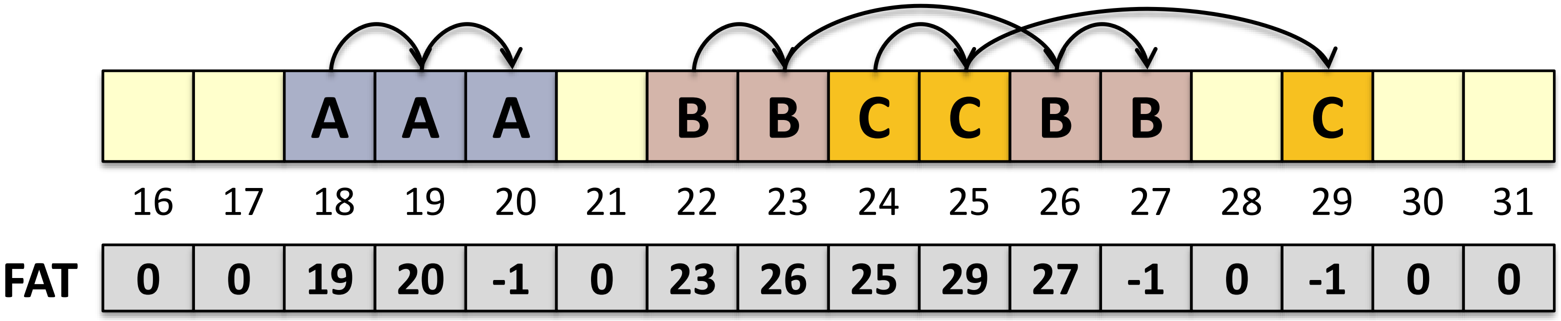
- Allocate linked-list of fixed-sized blocks
  - Metadata: <starting block #>
  - Each block contains pointer to next block
  - Example: TOPS-10, Alto



  - No external fragmentation
  - File can grow easily
  - Sequential access performance depends on data layout
  - Poor __________ access performance
  - Waste pointer per block (fragile -- it can be lost or damaged)

File Allocation Table (FAT)

- Variation of linked allocation
  - Keep linked-list information for all files in on-disk FAT
  - FAT is cached in main memory to avoid disk seeks
  - Metadata: <starting block #> + FAT
  - Example: MS-DOS, Windows (FAT12, FAT16, FAT32)



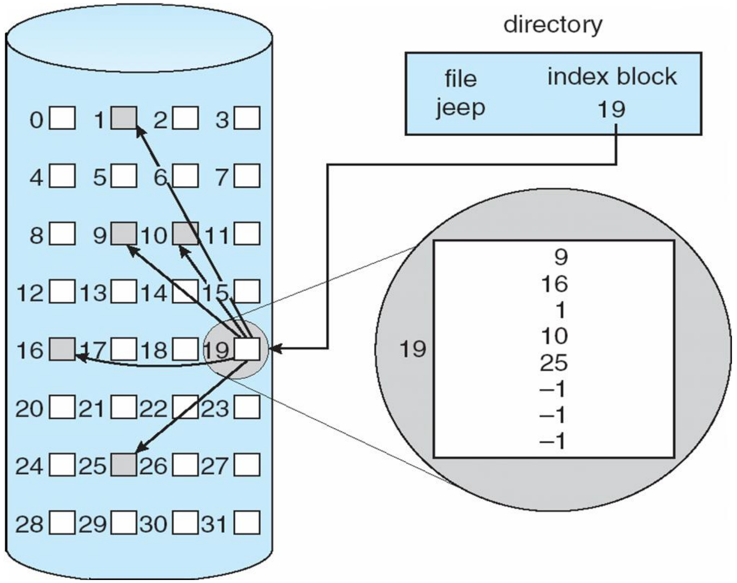
	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
			A	A	A		B	B	C	C	B	B		C		
FAT	0	0	19	20	-1	0	23	26	25	29	27	-1	0	-1	0	0

  - Improved random access performance
  - Scalability with larger file systems?

Indexed Allocation

- Allocate fixed-size blocks for each file
  - Metadata: An array of block pointers
  - Each block pointer points to the corresponding data block

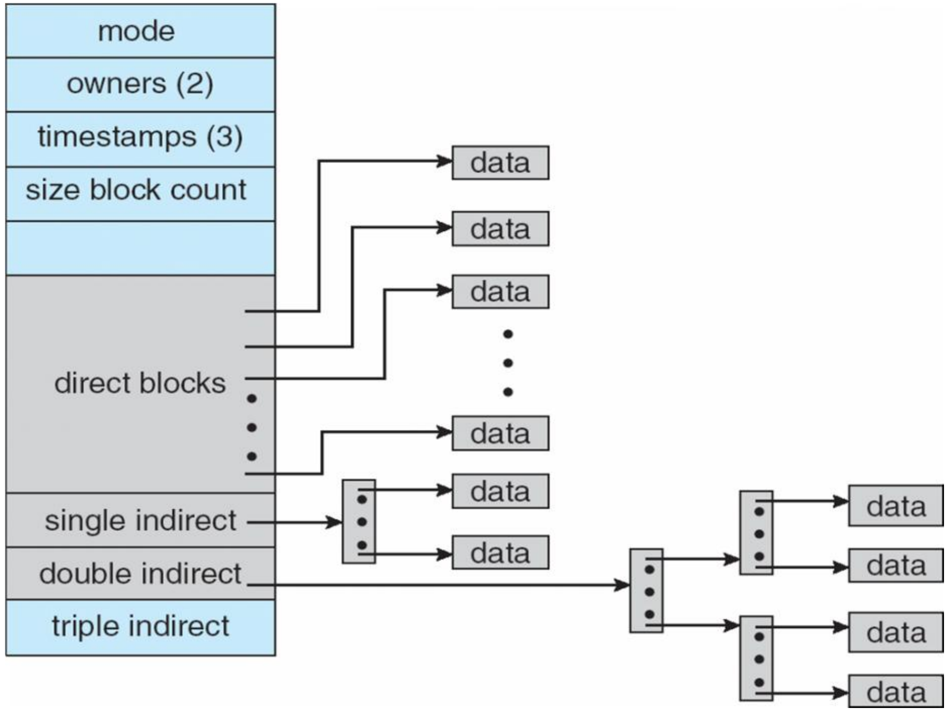
  - No external fragmentation
  - File can grow easily up to max file size
  - Sequential access performance depends on data layout
  - Random accesses supported
  - Large overhead for metadata:
    wasted space for unneeded pointers
    (most files are small)



Multi-level Indexing

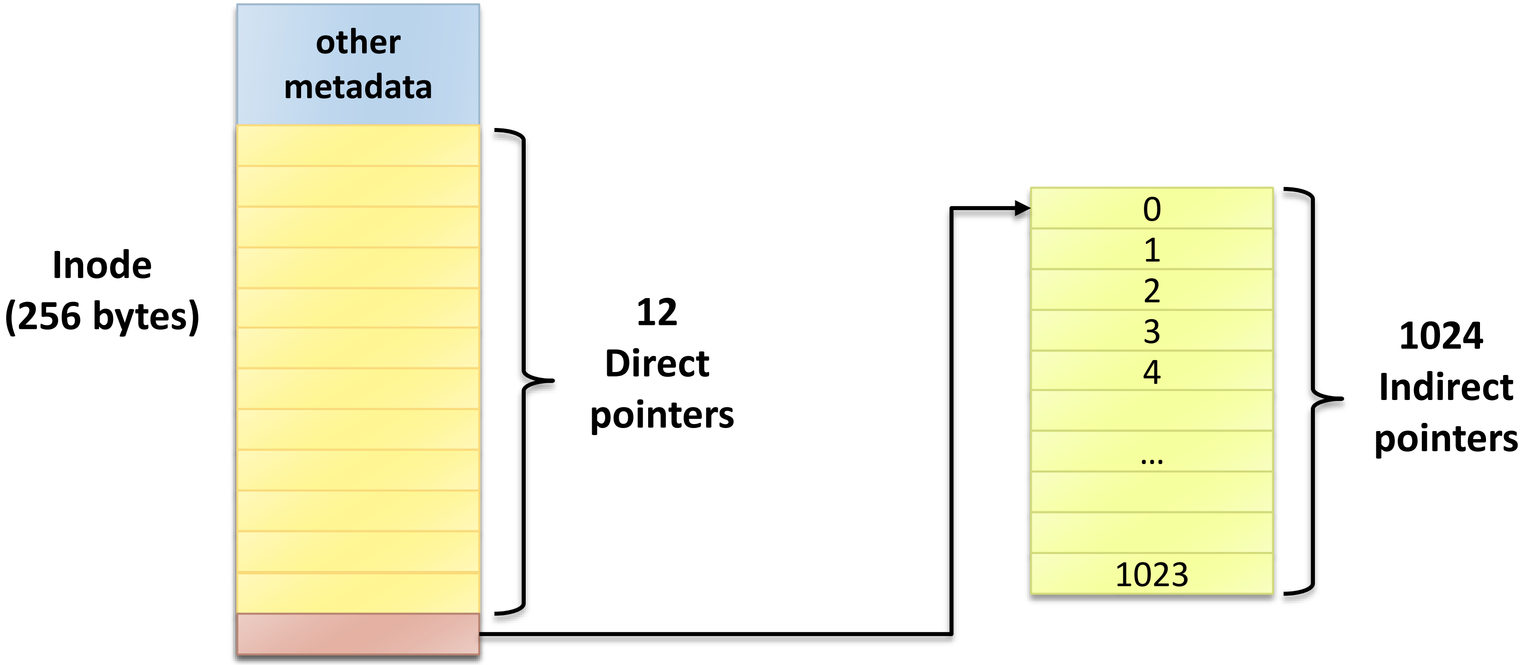
- Variation of indexed allocation
  - Dynamically allocate hierarchy of pointers to data blocks
  - Metadata: small number of direct pointers + indirect pointers
  - Example: Unix FFS, Linux Ext2/3

  - Does not waste space for unneeded pointers
  - Need to read indirect blocks of pointers to calculate addresses (extra disk read)
    - Keep indirect blocks cached in main memory



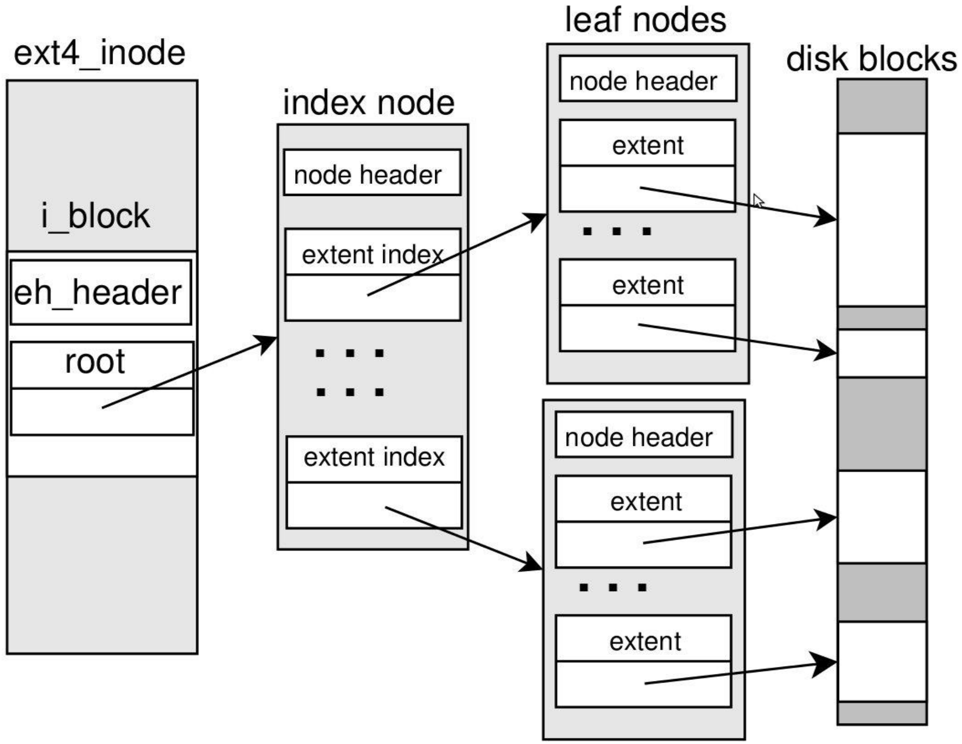
Multi-level Indexing in VSFS

- Configurations
  - An inode has 12 direct pointers and 1 single indirect pointer
  - 4-byte disk address: 1024 pointers per 4KB block
  - Max file size = (12 + 1024) * 4KB = 4144KB



Extent-based Allocation

- Allocate multiple contiguous regions (extents) per file
  - Organize extents into multi-level tree structure (e.g., B+tree)
  - Each leaf node: <logical block #, physical block #, extent size>
  - Example: Linux Ext4



  - Reasonable amount of external fragmentation
  - Still good sequential performance
  - Some calculations needed for random accesses
  - Relatively small metadata overhead

Directory Organization

- Common design
  - Directory is a special file containing directory entries
  - Large directories just use multiple data blocks
  - Use bits in inode to distinguish directories from files
- Table (fixed length entries) or linear list:
  - Requires a linear search to find an entry
- Tree:
  - Entries may be sorted to decrease the average search time and to produce a sorted directory listing easily
- Hash table:
  - Fast, but should be scalable as the number of files increases

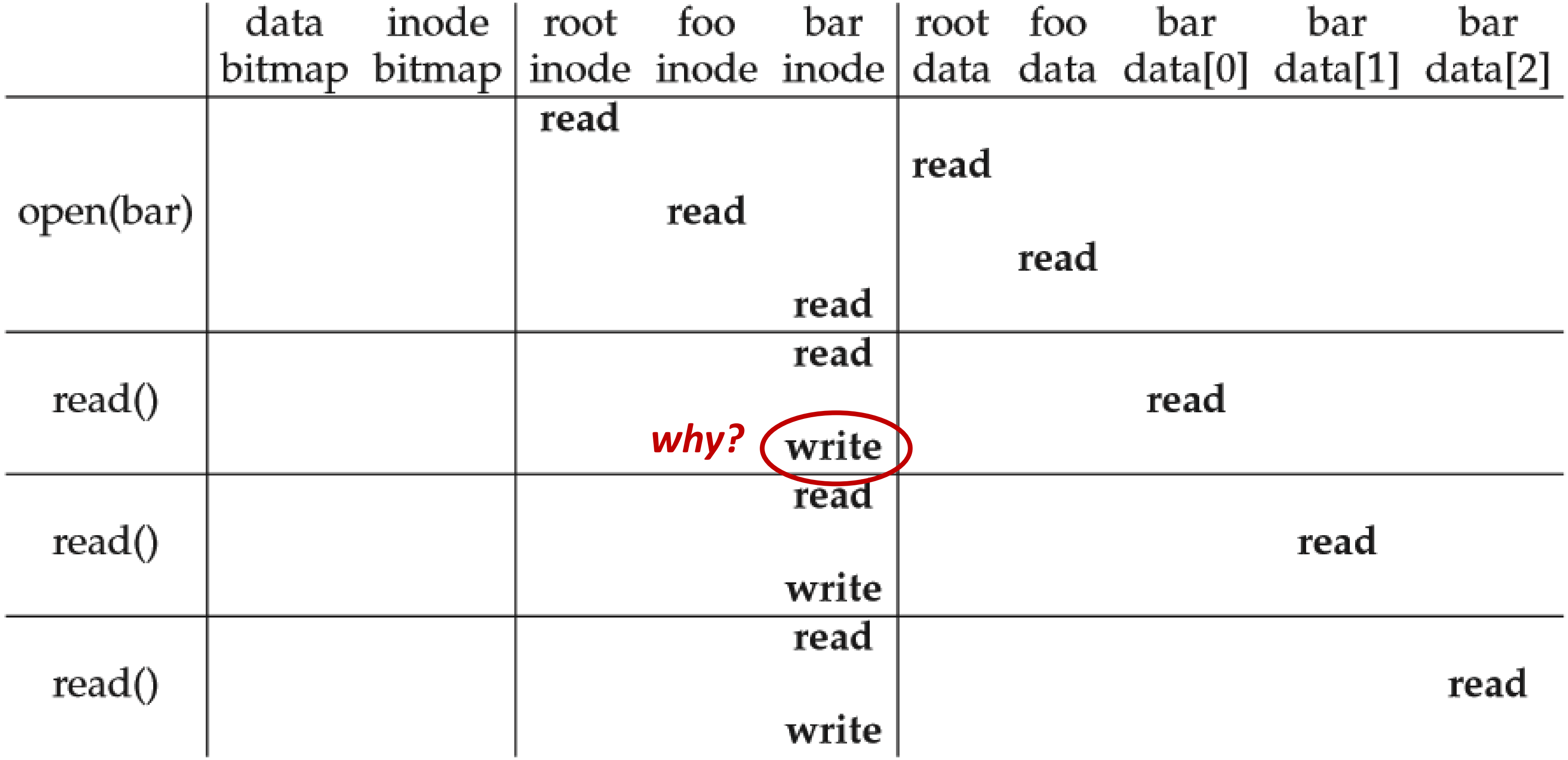
VSFS: Directory

- A linear list of <file name, inode number>
  - Similar to Linux Ext2 directory
  - Supports variable-sized names
  - Example: `/dir`
    - Inode number for `/dir`?
    - Inode number for the root directory?

inode number	record length	name length	name	
5	12	2	. \0 \0 \0	
2	12	3	. . \0 \0	
12	12	4	f o o \0	
0	12	4	b a r \0	*<deleted entry>*
24	16	7	f o o b a r \0 \0	

Reading a File

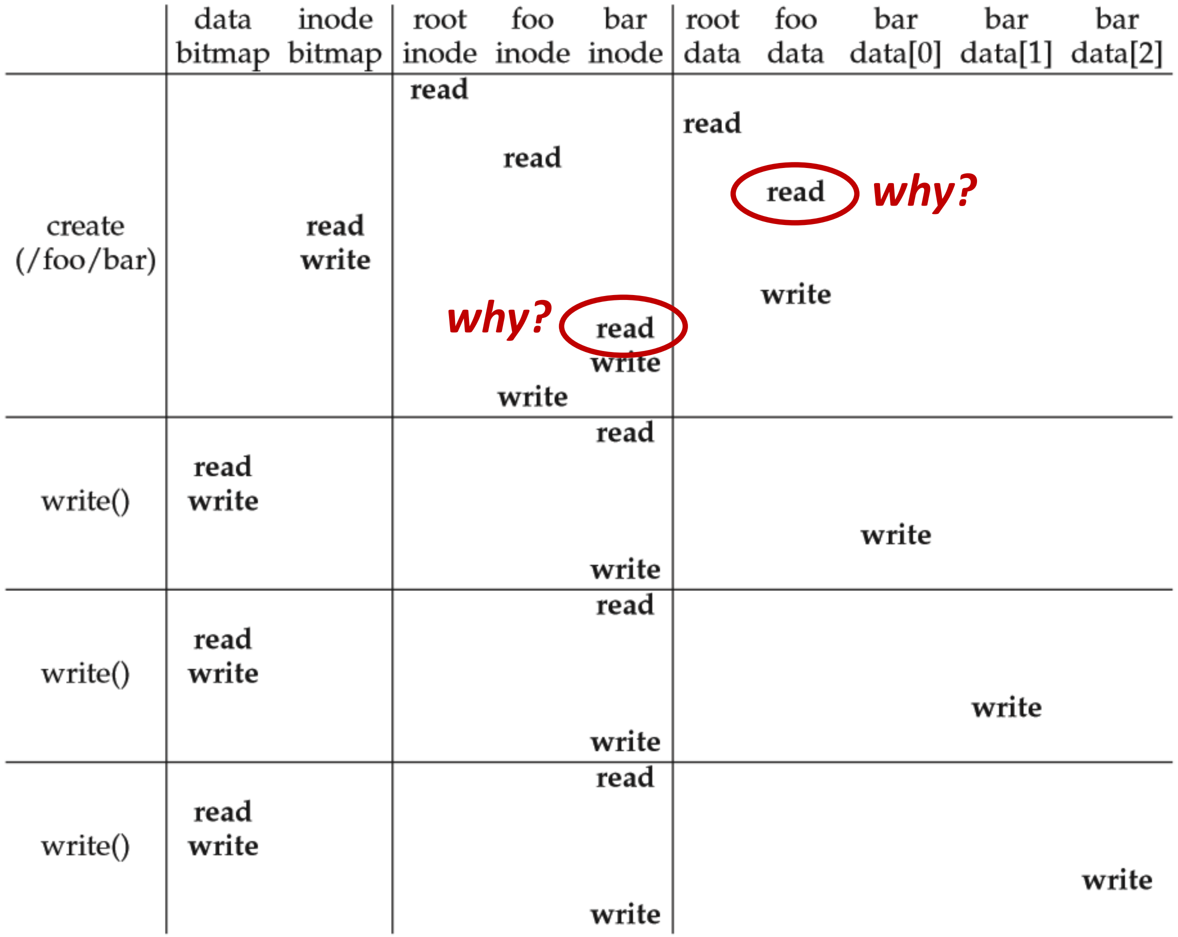
- Open `/foo/bar` and read three blocks



	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		
				why?	write					
read()					read					
									read	
					write					
read()					read					
										read
					write					

Writing a File

- Create /foo/bar and write three blocks



	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	why?		
		read								
		write								
							write			
				why?	read					
					write					
				write						
write()					read					
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