Sistemi Operativi

Corso di Laurea in Informatica

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SAPIENZA
UNIVERSITÀ DI ROMA

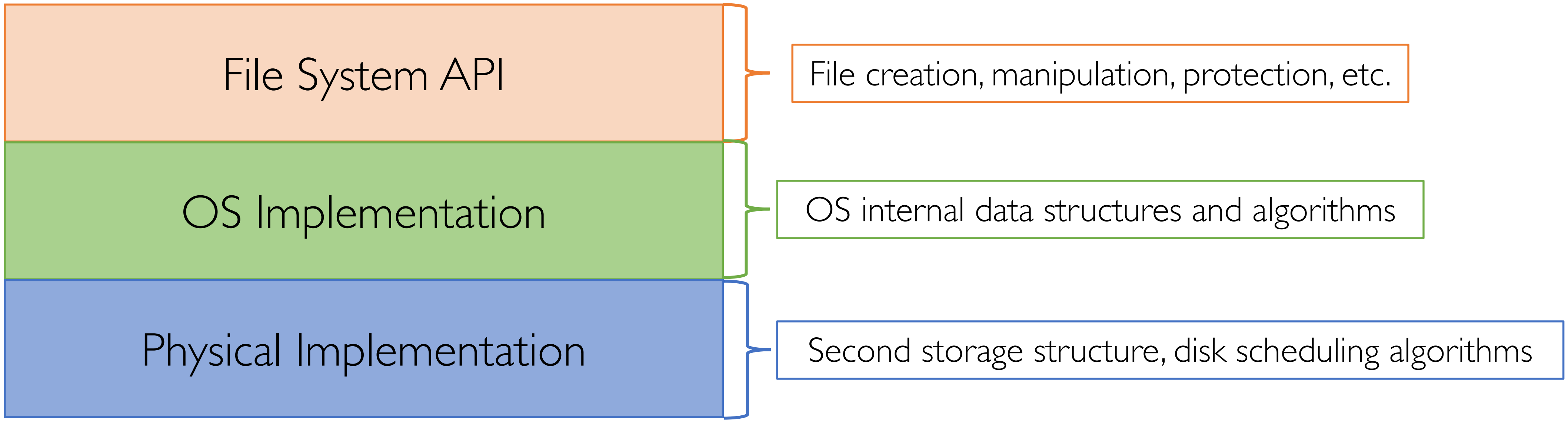
Gabriele Tolomei

Dipartimento di Informatica

Sapienza Università di Roma

tolomei@di.uniroma1.it

File System's Logical View



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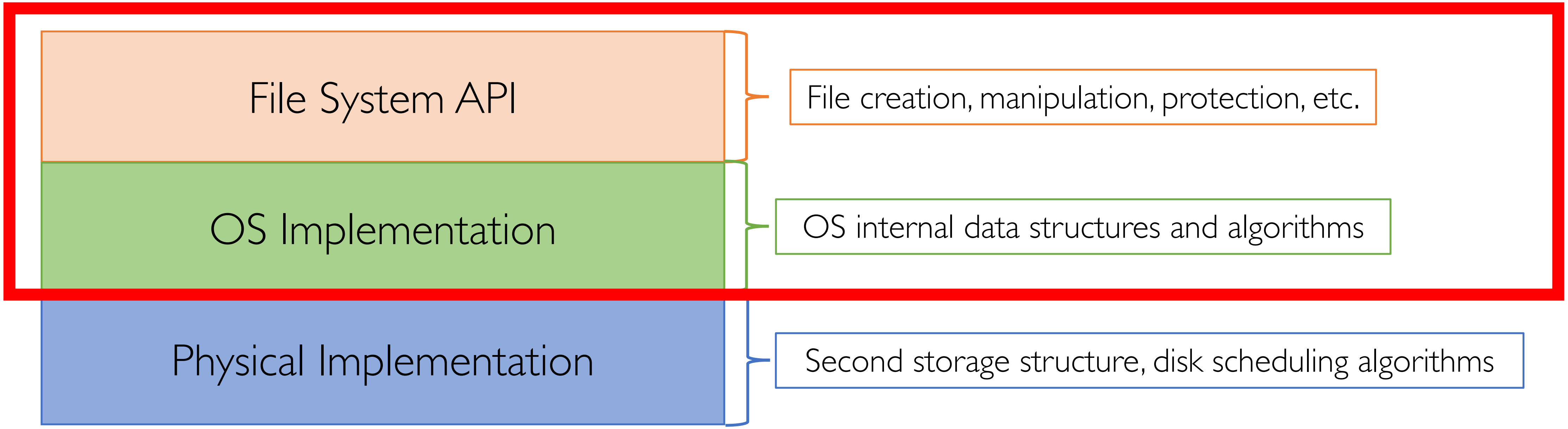
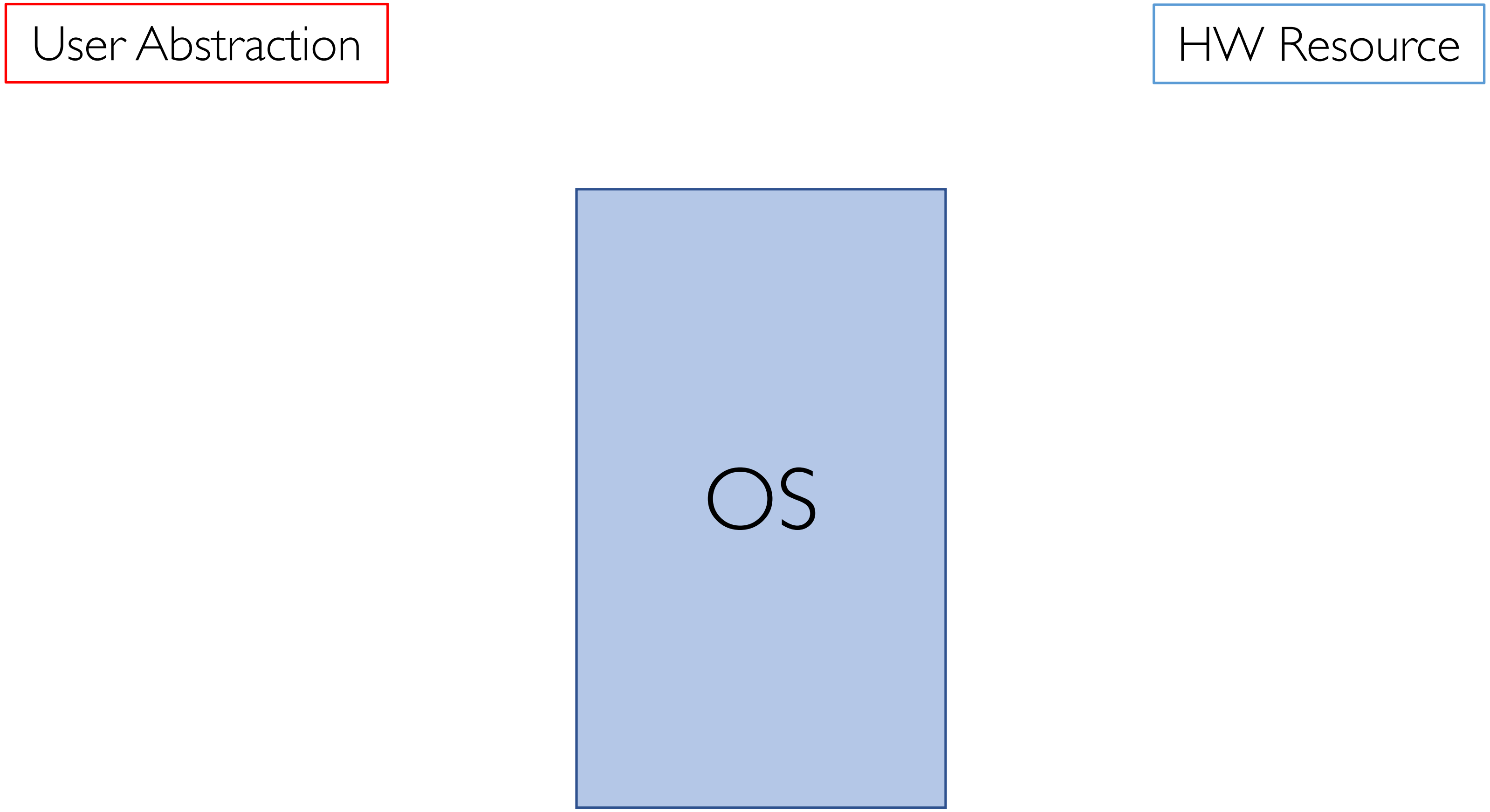


Abstraction



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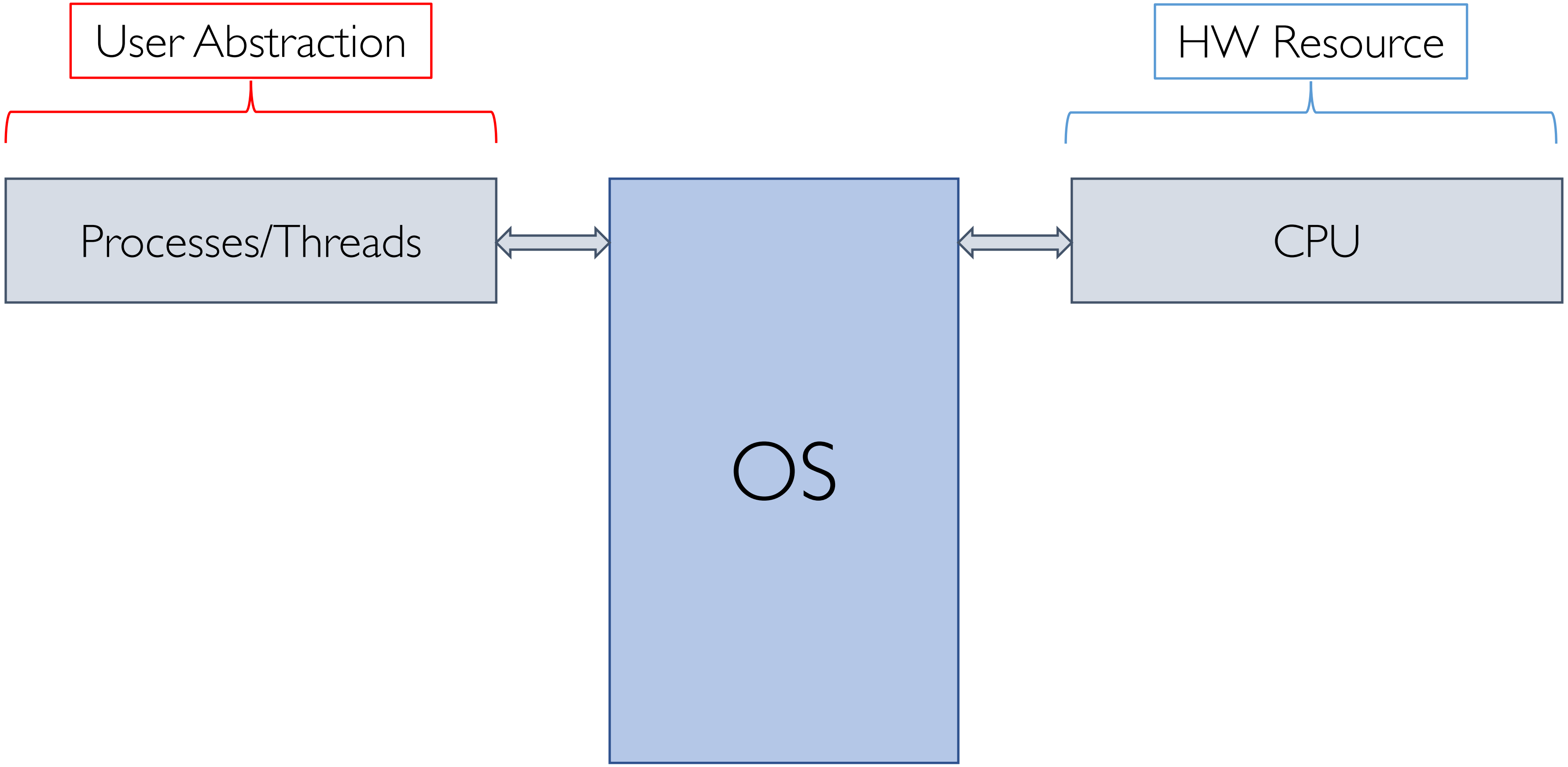

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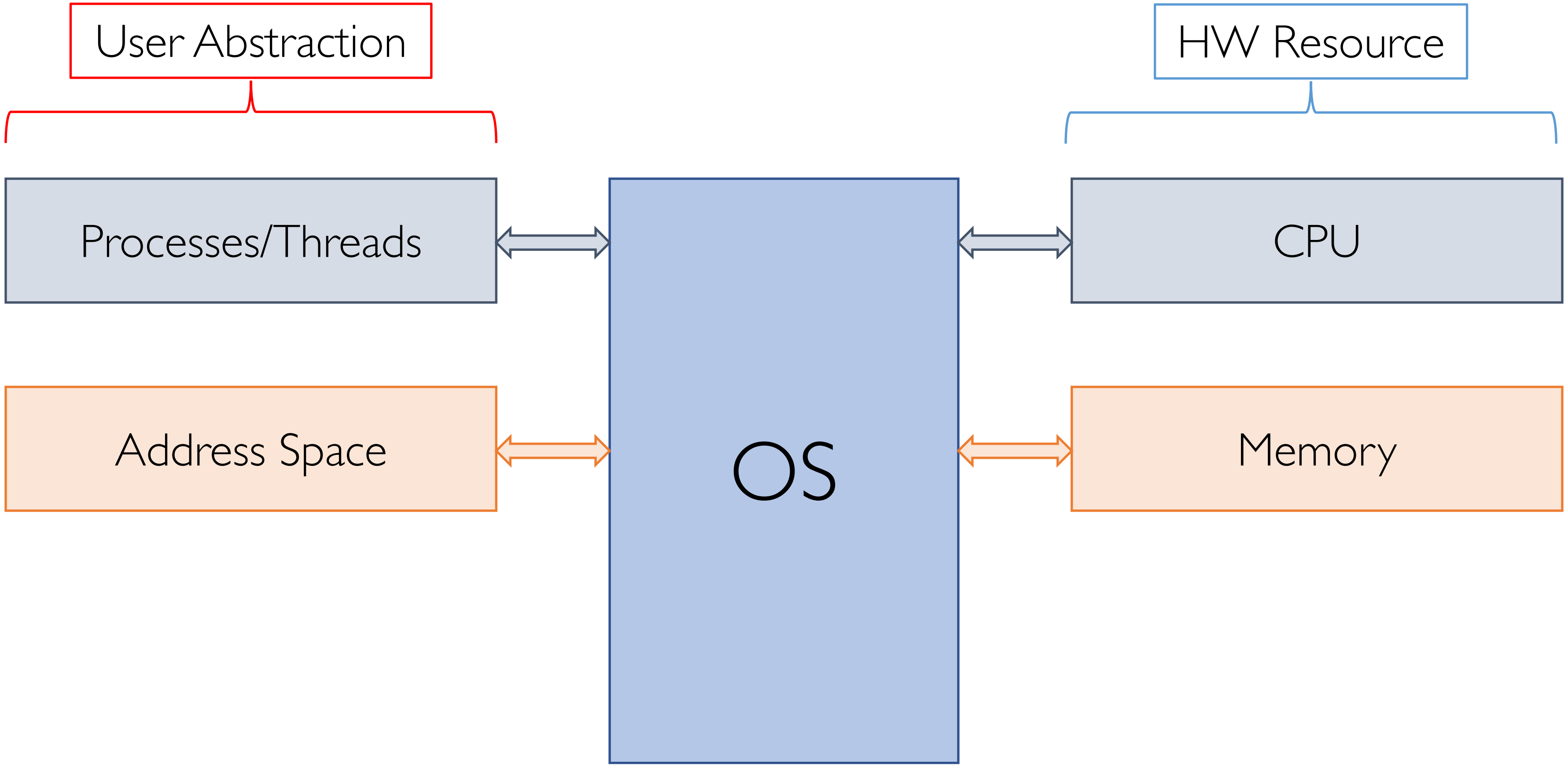

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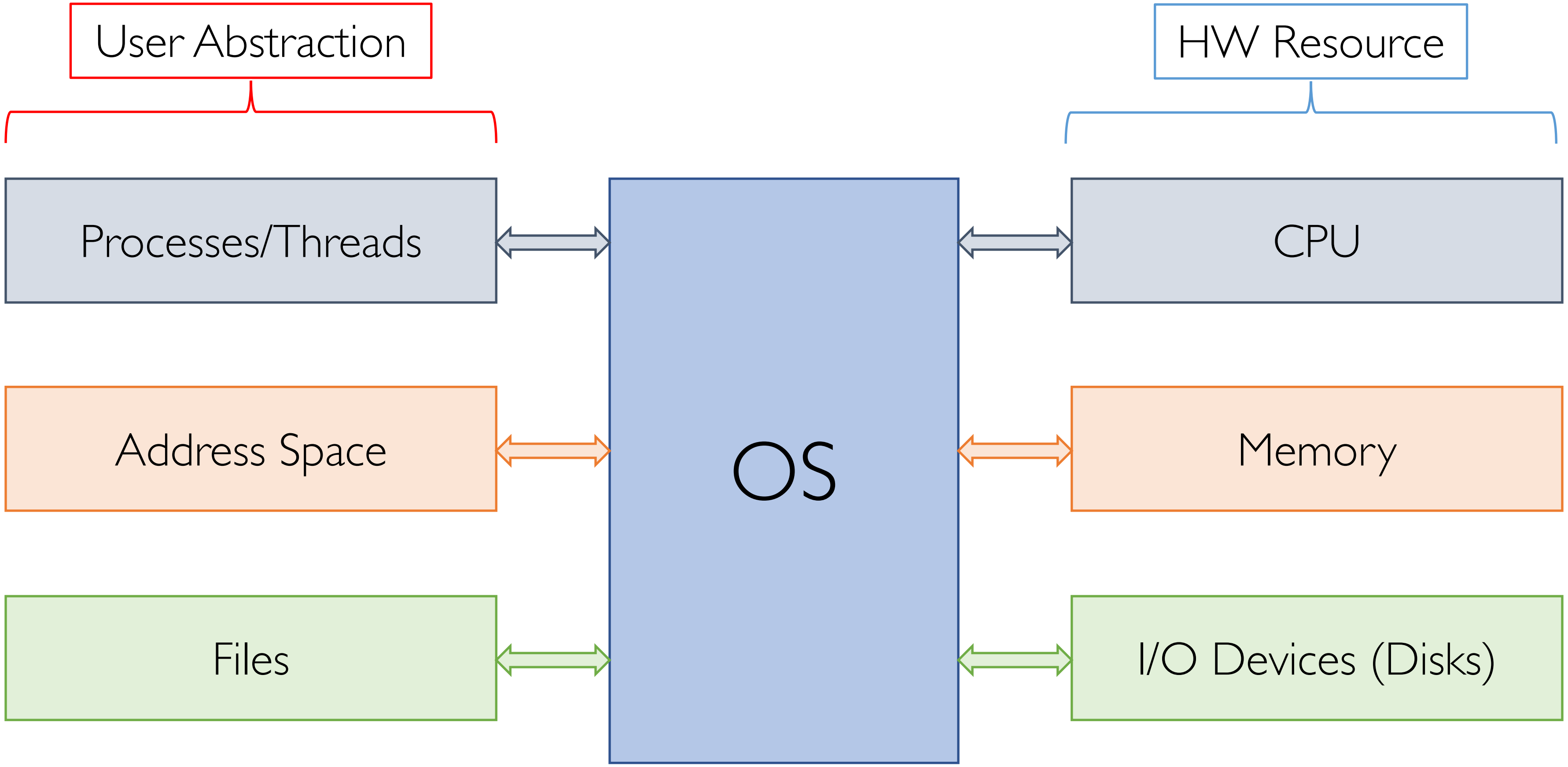

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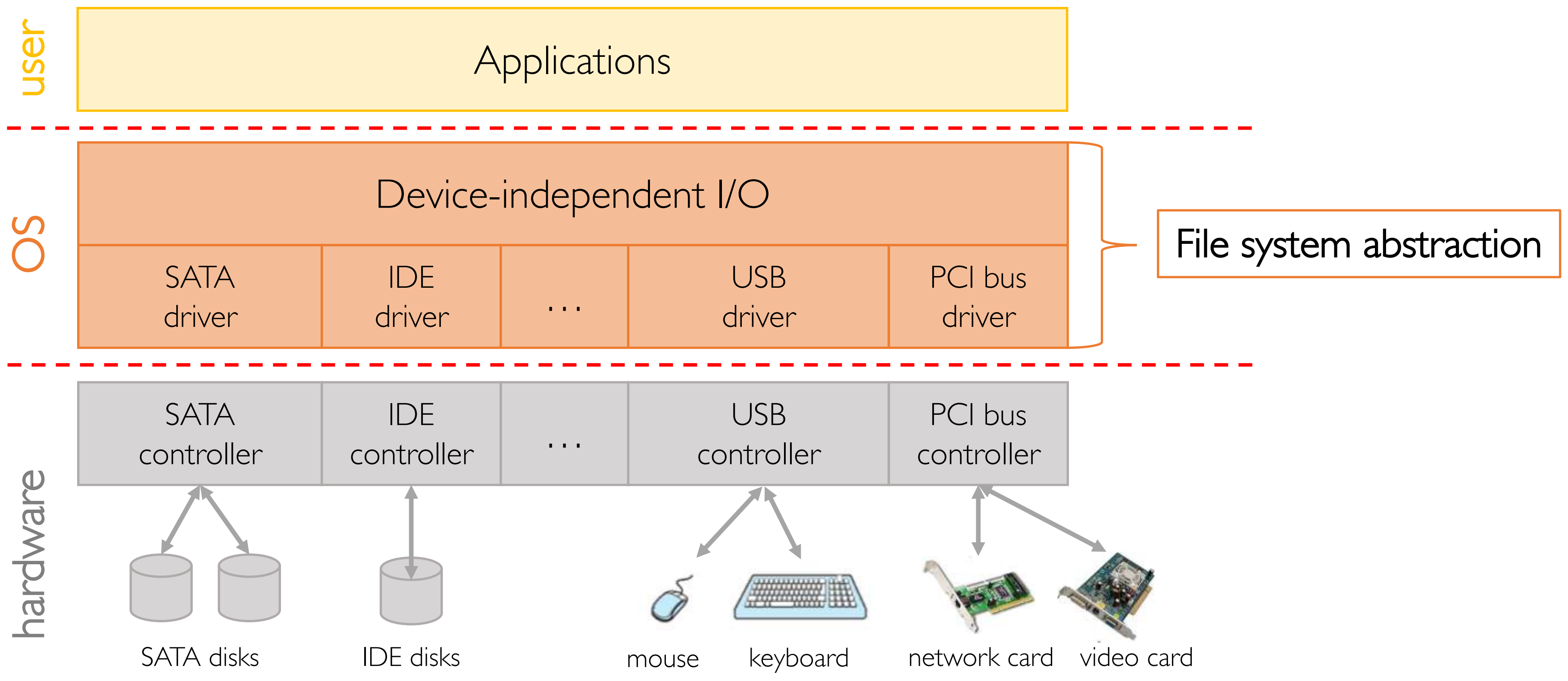

User Requirements on Data

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- Sharing/Protection → Data can be shared where appropriate
- Ease of Use → Data should be easily found, examined, modified, etc.

HW vs. OS Capabilities

- HW provides:
  - Persistence: Disks are non-volatile storage devices
  - Speed (somewhat): Disks enable direct/random access
  - Size: Disks keep getting bigger (order of TBs on today's laptop)

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- OS provides:
  - Persistence: Redundancy mechanisms
  - Sharing/Protection: Permissions (e.g., UNIX **`rwx`** privileges)
  - Ease of Use: named files, directories, search tools (e.g., Spotlight in macOS)

What's a File?

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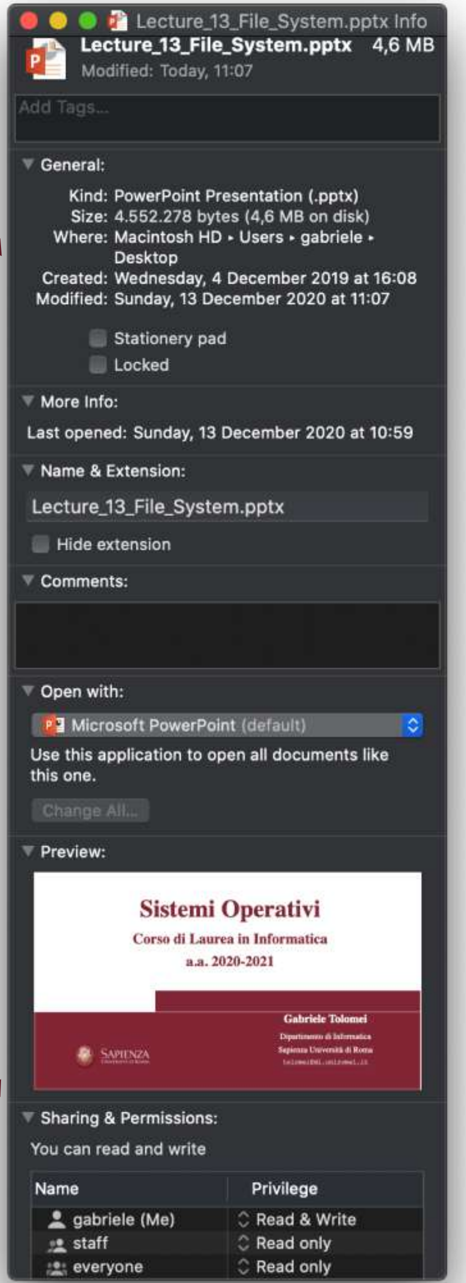
- Files are mapped by the OS onto physical storage devices (e.g., disks)
  - Such devices are non-volatile (their content persist across reboots)
- Files can contain programs (source, binary) or data
  - Examples: **`main.cpp`**, **`test.exe`**, **`doc.txt`**

Files: Attributes (Metadata)

- Different OSs keep track of different file attributes
- Examples:
  - Name: human-friendly identifier
  - Identifier: how the OS actually identifies the file (e.g., **`inode`** number)
  - Type: text, executable, other binary, etc.
  - Location (on the hard drive)
  - Size
  - Protection
  - Time & Date
  - User ID

Files: Attributes (Example)

All the information displayed are metadata associated with *this* file



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  - make symbolic links (**`ln`**)
  - etc.

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  - etc.

Those are all system calls typically wrapped within a user library

OS (Kernel) File Data Structures

Global Open File Table

- shared by all the processes with an open file
- one entry for each open file
- multiple processes may have the same file open (counter)
- file attributes (ownership, protection, etc.)
- location of each file on disk
- pointers to location of each file on disk

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Local Per-Process File Table

- one table for each process
- for each open file of this process:
  - pointer to the entry in the global table
  - current position in the file (offset)
  - open mode (r, w, r/w)

Files Operations: `create(filename)`

- Allocate disk space, also checking disk quotas and permissions
- Create a file descriptor for the file including:
  - **`filename`**
  - location on disk
  - other attributes
- Add the file descriptor to the directory that contains the file

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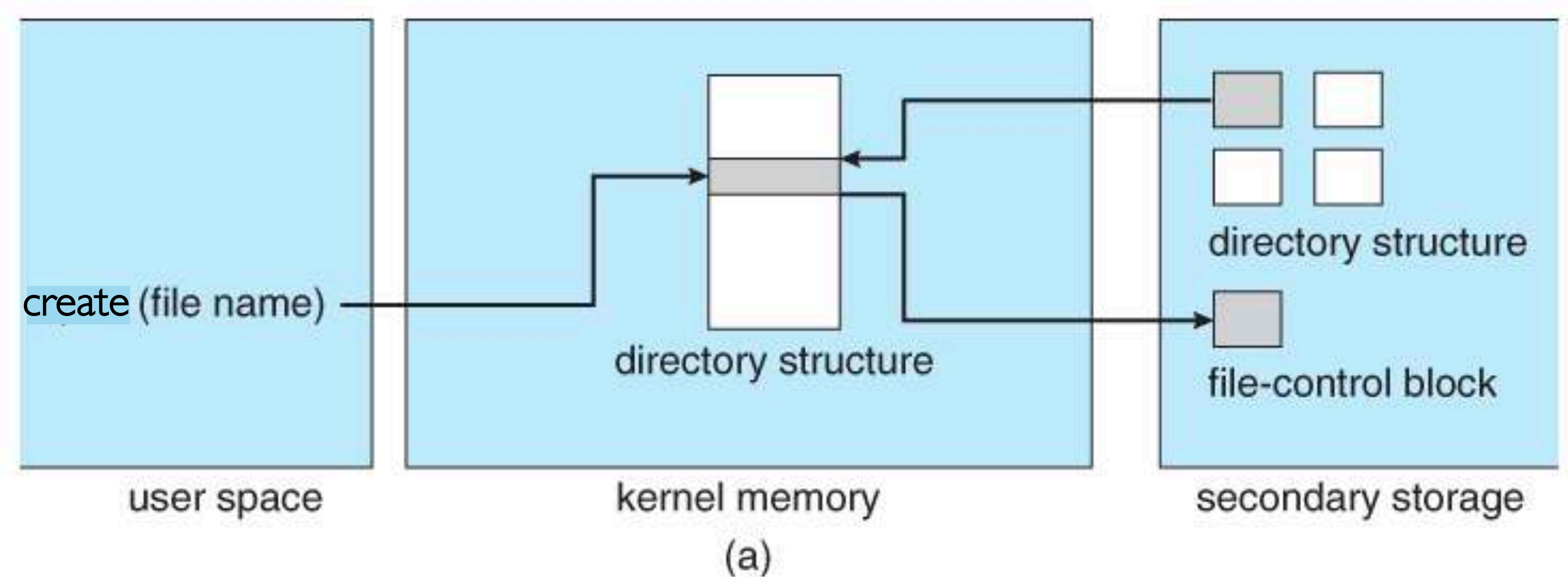


Files Operations: `create(filename)`

- Optional file attribute: file type (MS Word, executable, etc.):
  - better error detection
  - specialized default operations (e.g., double-click triggers the right application)
  - storage layout optimization
  - more complex filesystem and OS
  - less flexibility (what if we want to change the file type)
- In UNIX no file type, Windows and Mac opt for user-friendliness

Files Operations: `delete(filename)`

- Find the directory containing the file
- Free the disk blocks used by the file
- Remove the file descriptor from the directory
- Behavior dependent on hard links (more on this later)

Files Operations: `open(filename,mode)`

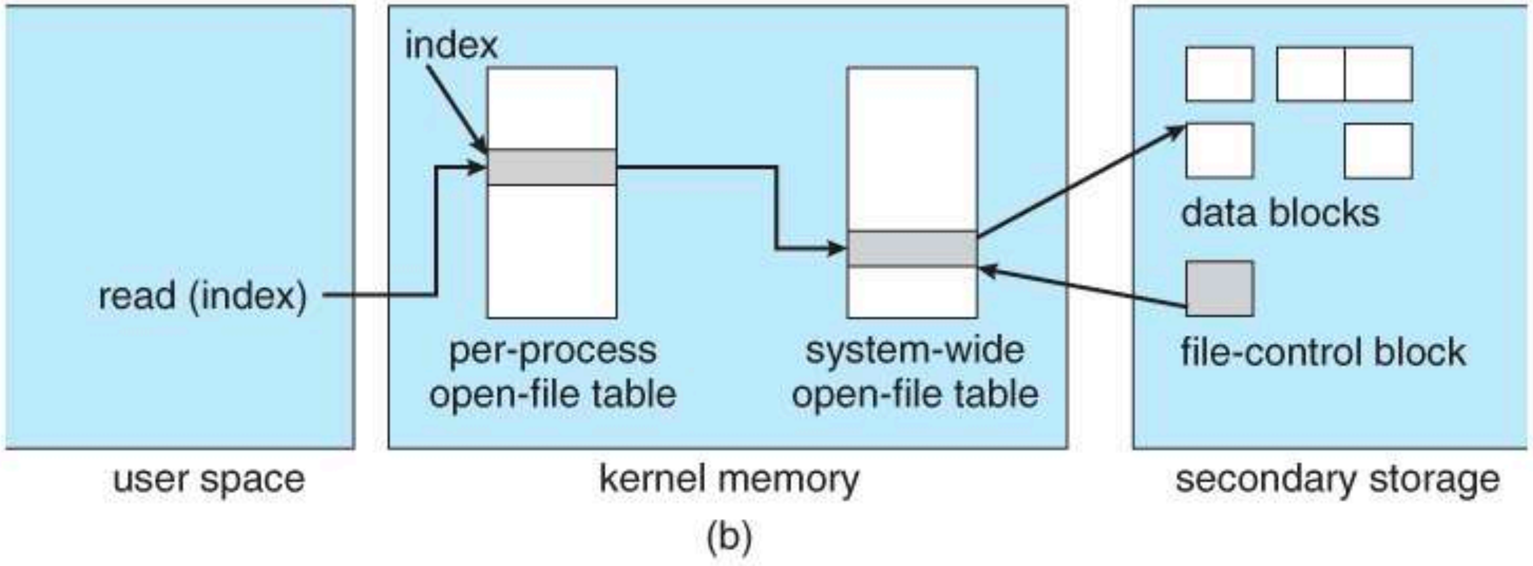
- Returns the **`fileID`** the OS associated with that **`filename`**
- Check the global open file table if the file is already open by another process, if not:
  - Find the file and copy the file descriptor into the global open file table
- Check protection of the file against the mode, if not ok abort
- Increment the open count
- Create an entry in the process' file table pointing to the entry of the global table, and initialize the file pointer to the beginning of the file

Files Operations: `close(fileID)`

- Remove the entry for the file in the process' file table
- Decrement the open count of this file on the global file table
- If the open count gets to 0 → no processes have this file open
  - The corresponding entry in the global table can be safely removed

Files Operations: `read(fileID)`

- Read a file given the index (file descriptor) returned by the **`open`** call
- In order for a file to be read, it must therefore be open!



Files Operations: Read

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- random/direct access → hard drives (or main memory)
  - Can access to a specific disk block (memory address)
- sequential access → devices which do not support direct access (e.g., tape drives)
  - Need to go all the way through the desired position

Files Operations: Read (Random Access)

- **`read(fileID, from, size, bufAddress)`**
  - OS reads **`size`** bytes from file position **`from`** into **`bufAddress`**

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```
for (i = from; i < from + size; ++i) {
    bufAddress[i - from] = fileID[i];
}
```

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```
for (i = 0; i < size; ++i) {

    bufAddress[i] = fileID[fp + i];

}
fp += size;
```

Files Operations: Other Operations

- **`write`** → similar to **`read`** but copies from buffer to the file
- **`seek`** → just updates the file position (no need to actual I/O)
- **`mmap`** → Memory mapping a file
  - Map (a part of) the virtual address space to a file
  - Read from/write to that portion of memory implies OS reads from/writes to the corresponding location in the file (stored on disk)
  - File accesses are greatly simplified (no read/write system calls are necessary)
  - No need to copy from/to the buffer in kernel space at each operation

File Access Methods: Programmer's Perspective

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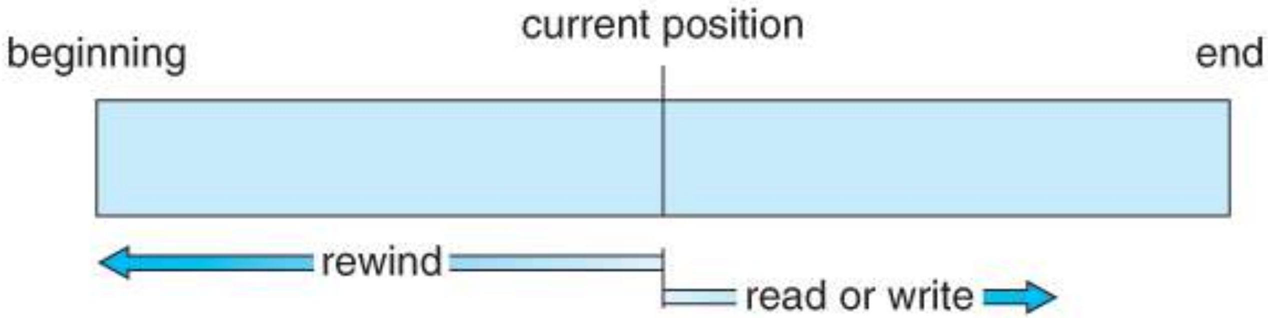
  - Example: text editor "goto line" feature
- Keyed/Indexed → Data is accessed based on a key
  - Example: database search

File Access Methods: OS's Perspective

Sequential

Keep a pointer to the next byte in the file, and update the pointer on each read/write operation



File Access Methods: OS's Perspective

Direct/Random

Address any block of data directly given its offset within the file

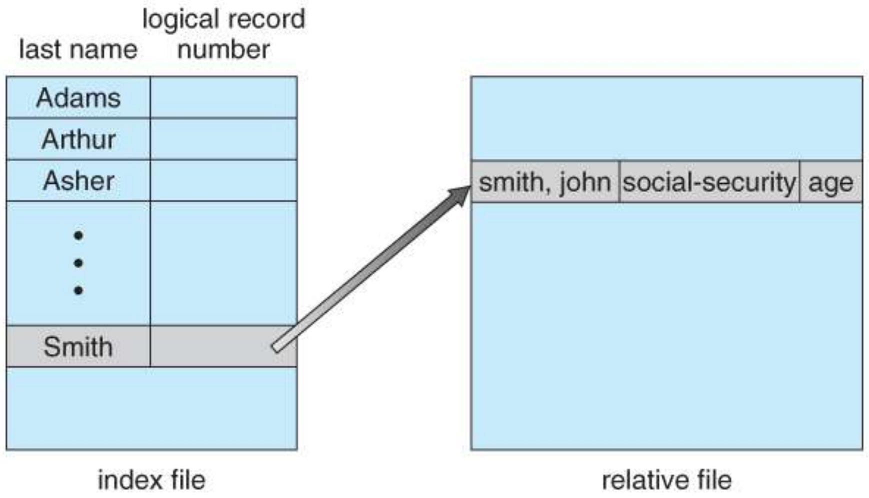
sequential access	implementation for direct access
reset	cp = 0;
read_next	read cp ; cp = cp + 1;
write_next	write cp; cp = cp + 1;

simulating sequential access using direct access

File Access Methods: OS's Perspective

<u>Keyed/Indexed</u>

Address any block of data directly given a key



implemented on top of direct access

Naming and Directories

- Need a method to getting back files that are located on disk
- OS uses unique numbers to identify files
- Users would rather use human-friendly names to refer to files
- Directory → OS data structure which maps file names to descriptors

Directory: Overview

- Directory operations to be supported include:
  - Search for a file
  - Create a file (add it to the directory)
  - Delete a file (erase it from the directory)
  - List a directory (possibly ordered in different ways)
  - Rename a file (may change sorting order)
  - Traverse the file system

Directory: Naming Strategies

- Single-Level Directory
  - One name space for the entire disk
  - Every filename must be unique
  - Use a special area of disk to hold the directory
  - Directory contains (name, index) pairs
  - If one user uses a name, no one else can
  - Used by early personal computers because their disks were very small

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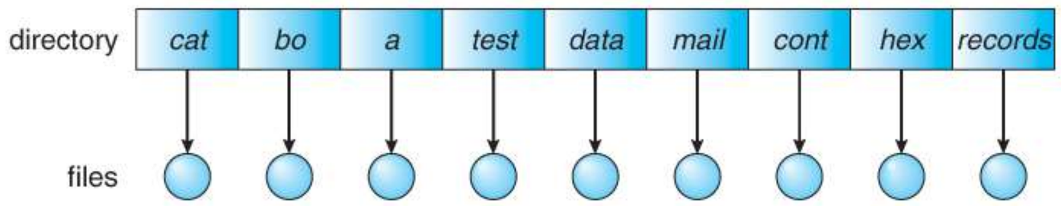

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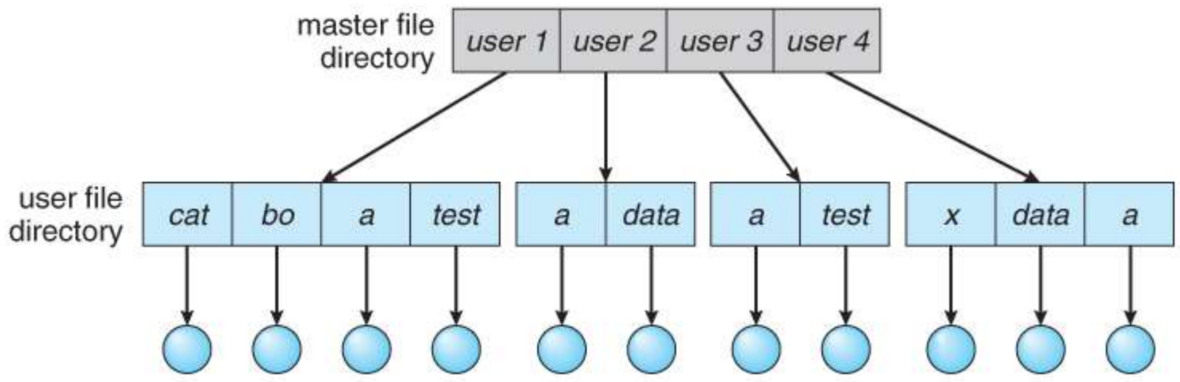

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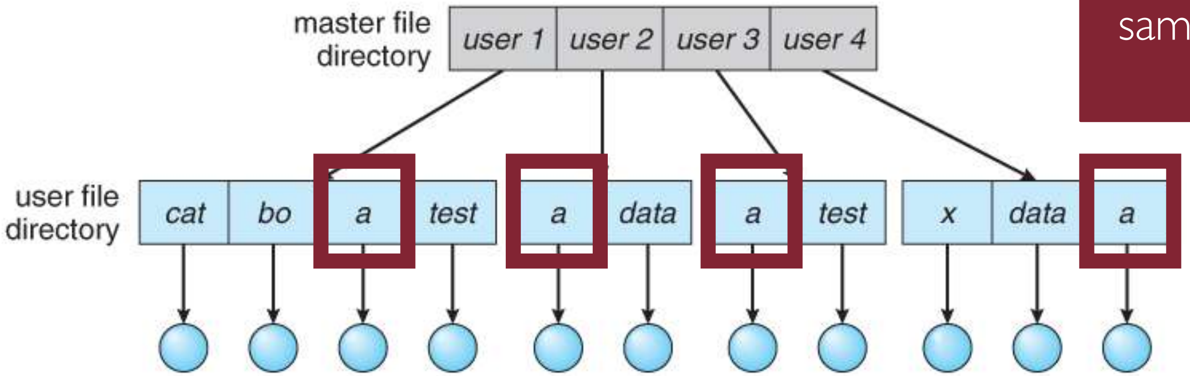
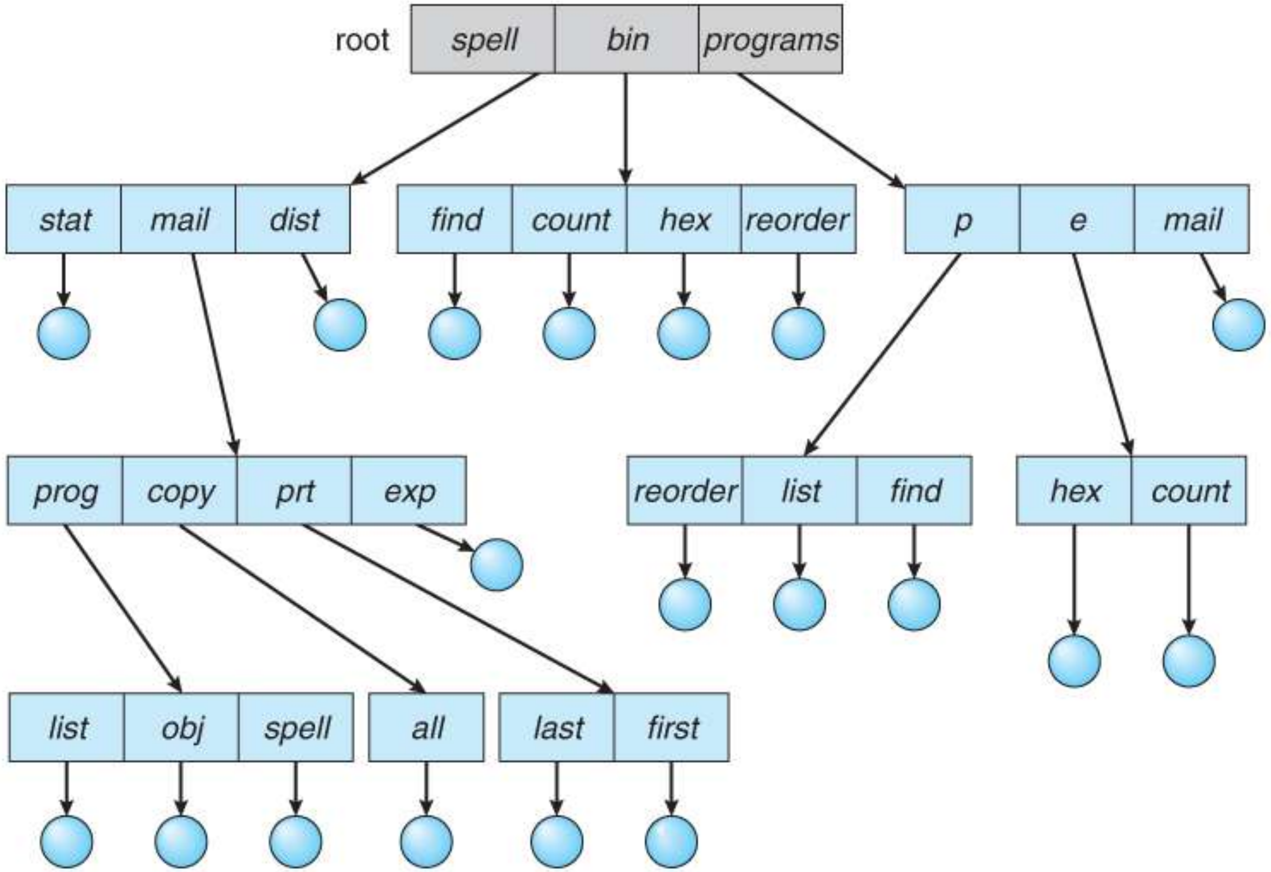


same user directories (possibly same filenames too!) yet underneath different master directories

Directory: Naming Strategies

- Multi-Level (Tree-based) Directory
  - An obvious extension to the two-tiered directory structure
  - Each user/process has the concept of a current directory from which all (relative) searches take place
  - Files may be accessed using either absolute pathnames (relative to the root of the tree) or relative pathnames (relative to the current directory)
  - Directories are stored the same as any other file in the system, except there is a bit that identifies them as directories
  - Used by most modern OSs (UNIX/Linux, Windows, and macOS)

Directory Tree



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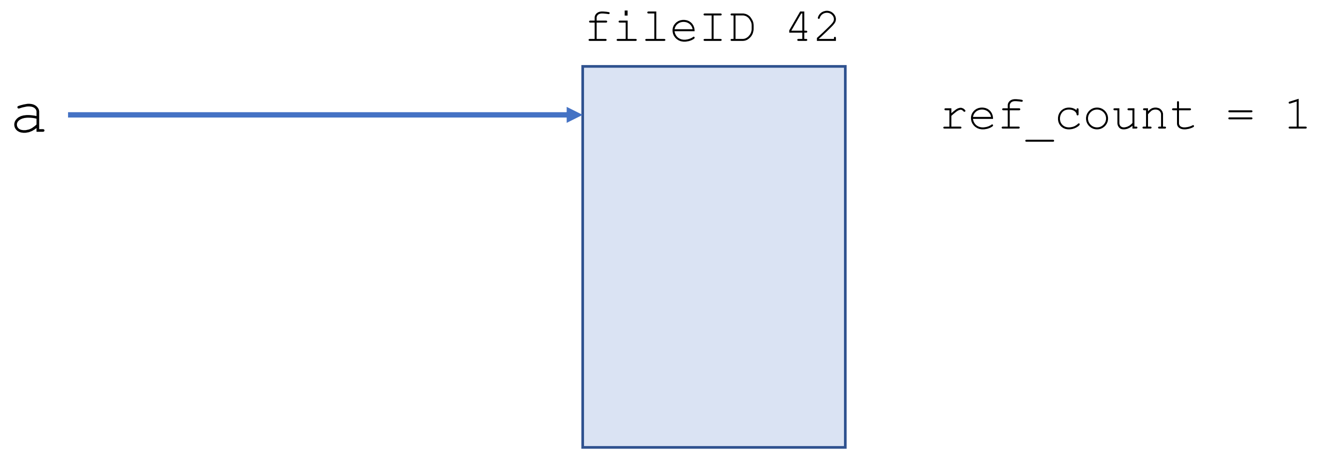
- UNIX provides 2 types of links via the **`ln`** command:
  - hard link → multiple directory entries that refer to the same file
  - symbolic link → an alias to the linked file

Referential Naming: Hard Links



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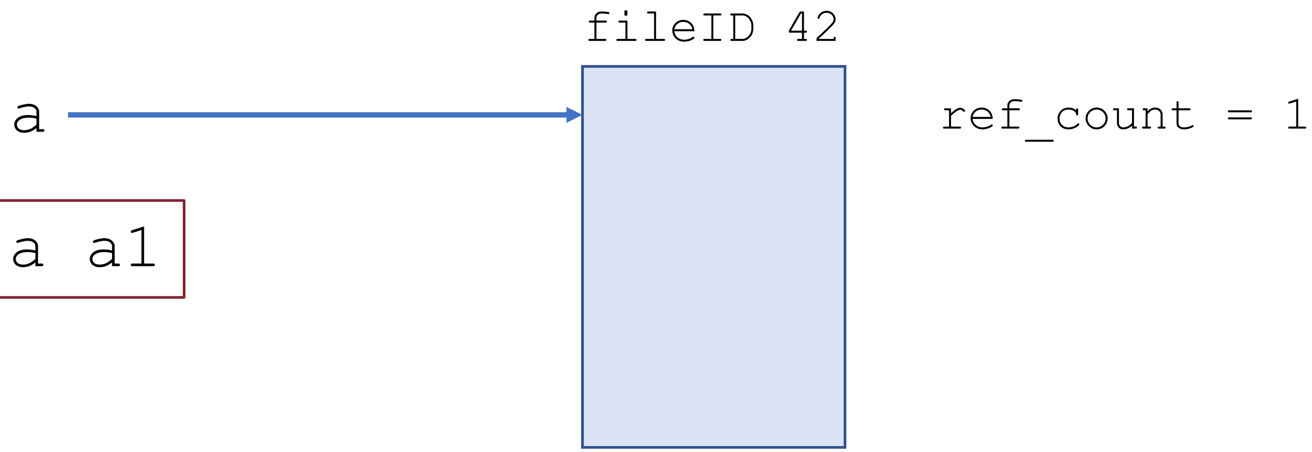
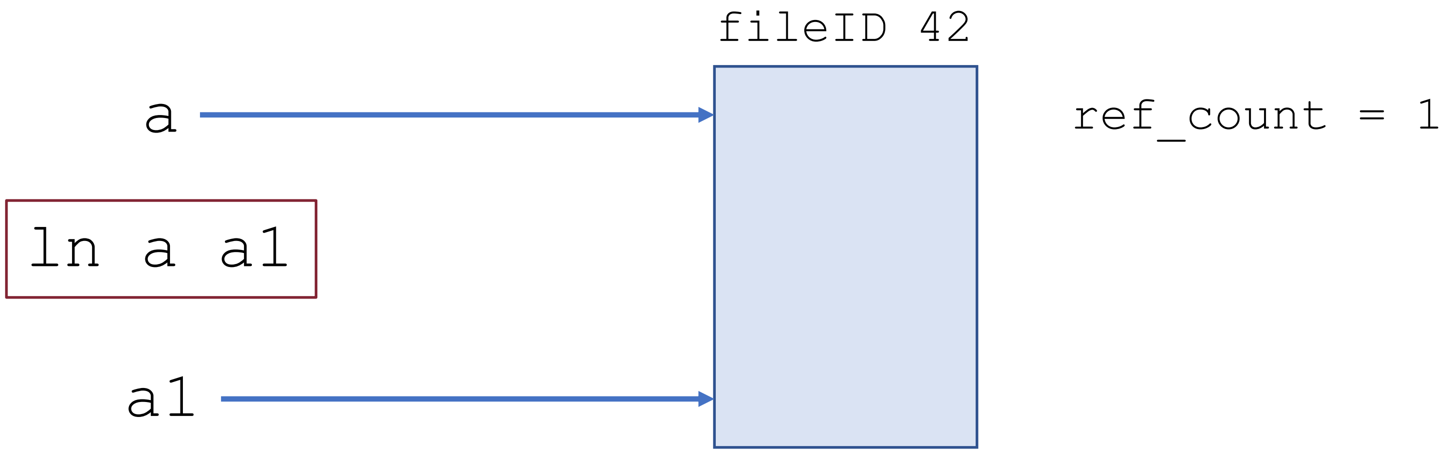



```
ln a a1
```

Referential Naming: Hard Links



Adds a second connection to a file

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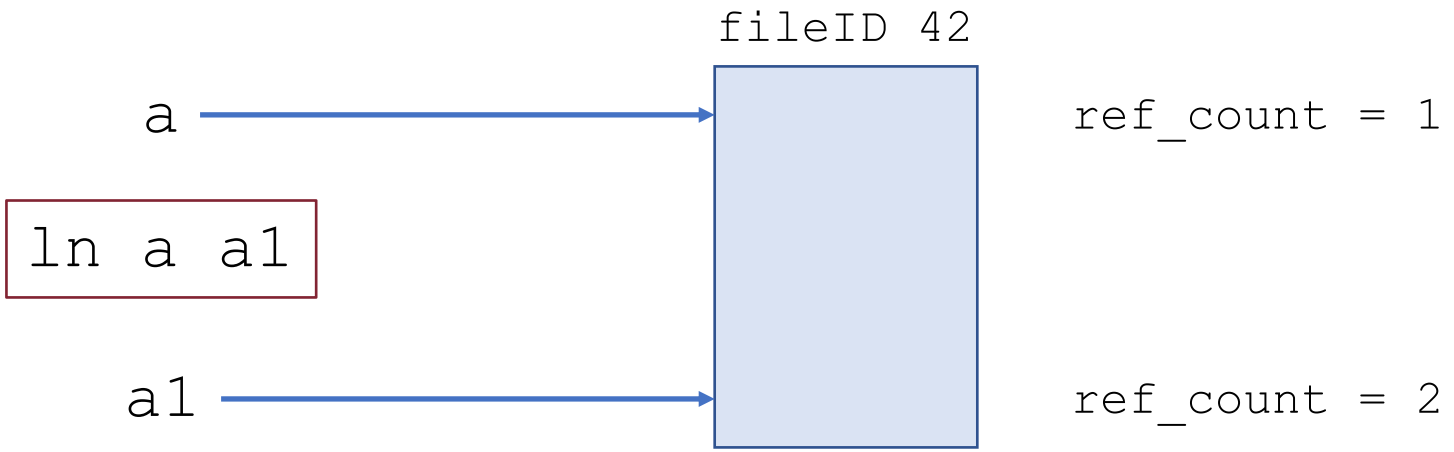
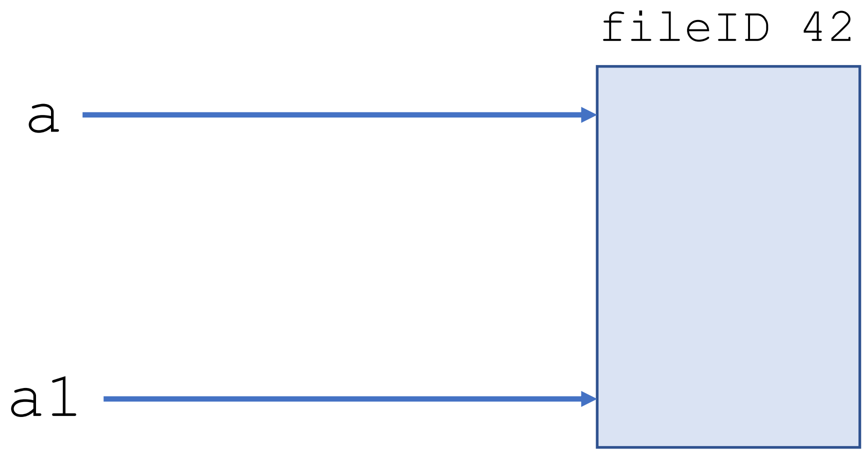


Adds a second connection to a file

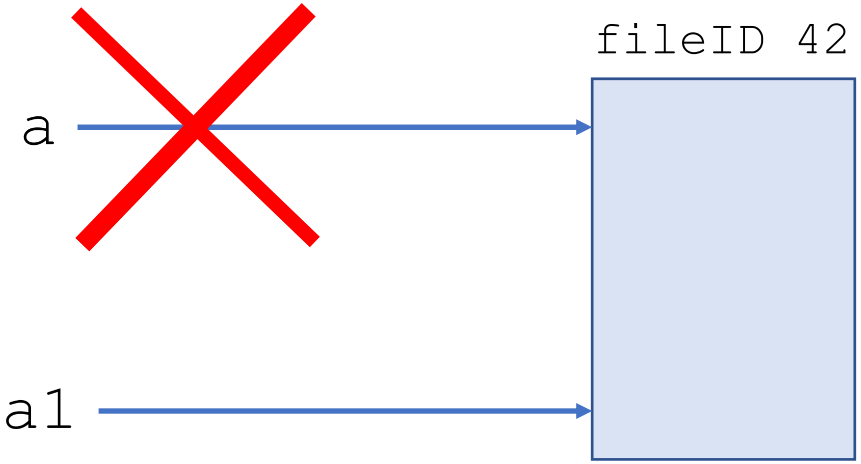
OS maintains reference counts, so it will delete a file only when the last hard link is deleted

Referential Naming: Hard Links



Change to the file using any of its hard links is reflected globally

Referential Naming: Hard Links



Removing a reference **does not** affect others!

as long as reference count > 0

Referential Naming: Hard Links

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Hard links to directories may cause circular links which prevent the OS from claiming back disk space

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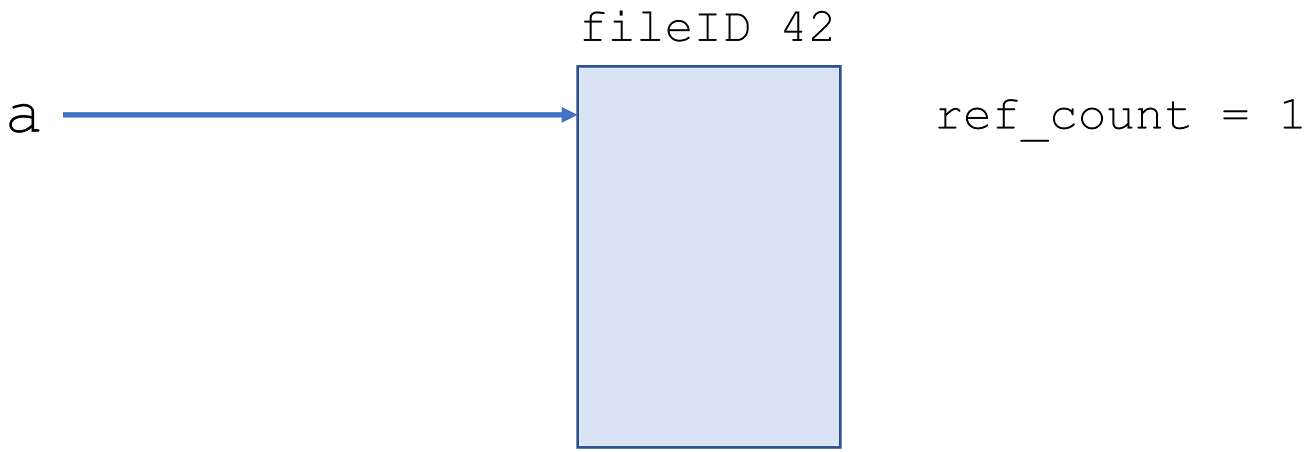
Solution

Do not allow hard links to directories at all!
Hard links to files are safe since files are leaves of the tree

Referential Naming: Soft Links



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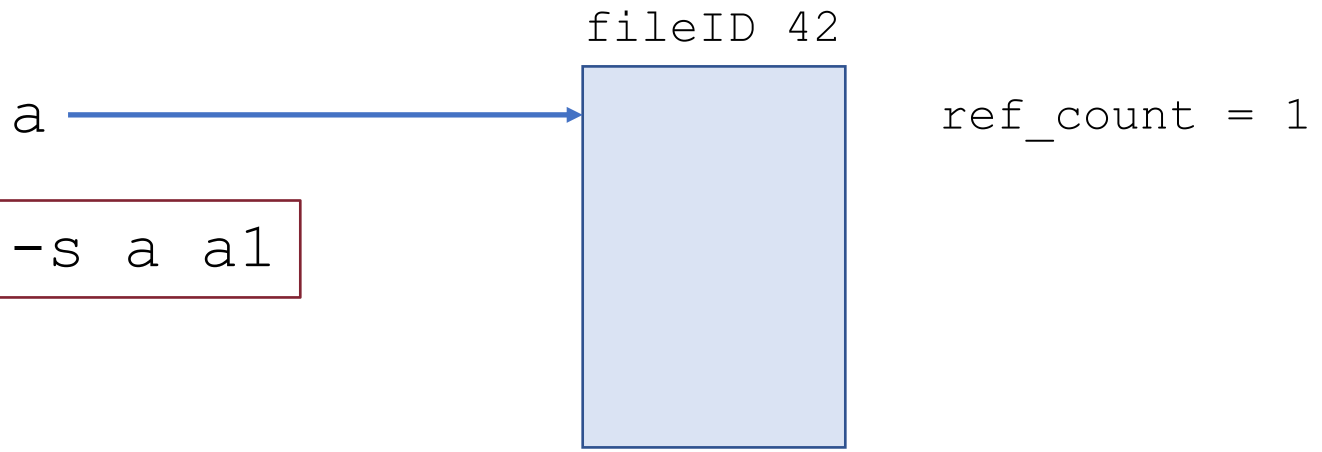
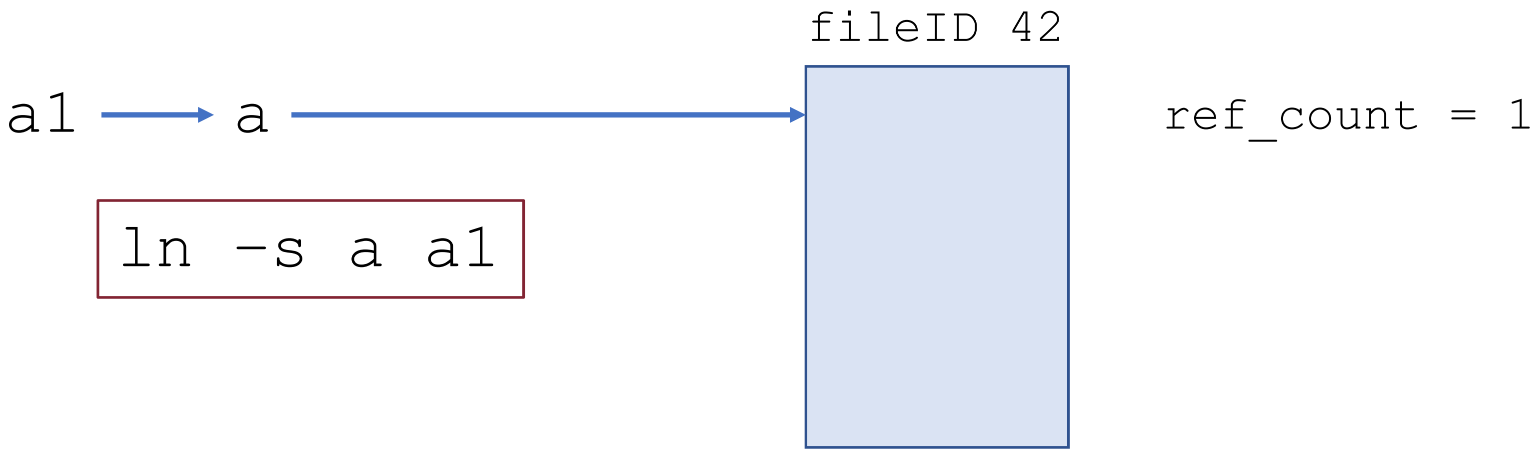


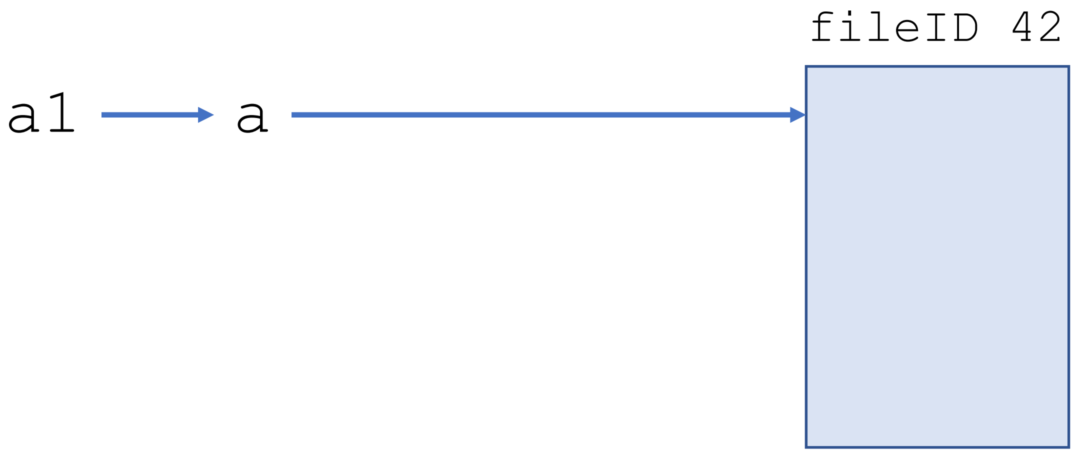

```
ln -s a a1
```

Referential Naming: Hard Links



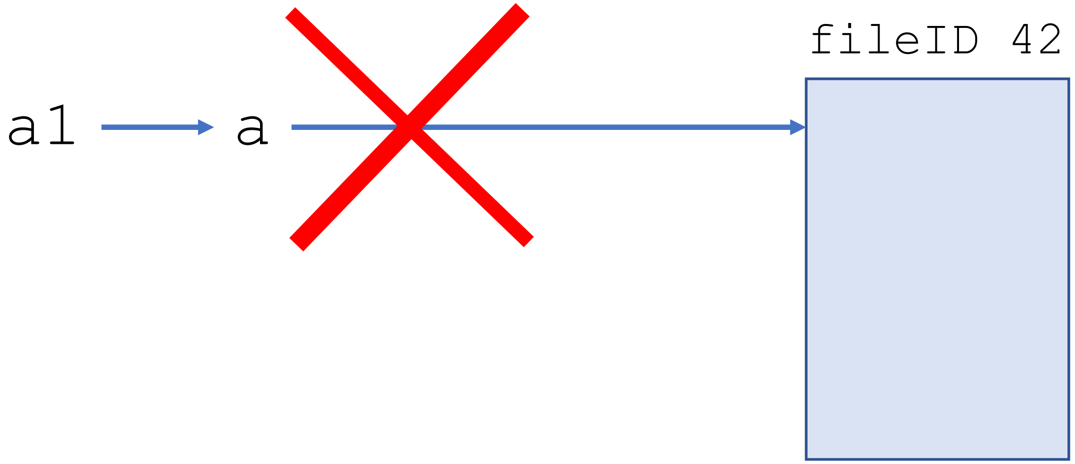
Adds a symbolic pointer to a file

Referential Naming: Soft Links



Change to the file using soft link is reflected globally

Referential Naming: Soft Links



Removing a reference affects all the symbolic links pointing to the file!

`a1` remains in the directory but its content no longer exists (dangling pointer)

File Protection

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- Control access to files: grant or deny access to file operations depending on protection information
- 2 different approaches:
  - access lists and groups (Windows NT)
  - access control bits (UNIX/Linux)

File Protection: Access Lists

- Keep an access list for each file with user name and type of access
- PRO: Highly flexible solution
- CON: Lists can become large and tedious to maintain

File Protection: Access Control Bits

- 3 categories of users: (`owner`, `group`, `world`)
- 3 types of access privileges: (`read`, `write`, `execute`)
- Keep one bit for each privilege on each category

(`111101000` = `rwxr-x---`)

- PRO: Easy to implement and maintain
- CON: Less accurate

File System Implementation

How do we actually lay down data on disk?

Recap: Disk Overheads

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- **Bandwidth:** once a transfer is initiated, the rate of the I/O transfer

File Organization on Disk

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- From the OS's perspective:
  - Disk is just an array of blocks
- We can think of a block as a disk sector
  - In practice, a block may be a multiple of a sector (e.g., 4 sectors)
- How it should work:
  - The OS requests for `fileID 42`, `block 73` (contiguous integer addressing)
  - The disk responds with the corresponding (head, cylinder, sector) triple

File Organization on Disk

- Disk Access:
  - Must be able to support both sequential and direct/random access
- File information on disk:
  - Data structure to maintain file location information
- File location on disk:
  - Physically deploy file on disk

On-Disk Data Structures: File Descriptor

- Per-file data structure used to describe where the file is located on disk
- Contains also file attributes (i.e., file metadata)
- Must be stored on disk as regular files
- Also known as File Control Block (FCB)
- A copy of each FCB is stored also in the OS's Global Open File Table

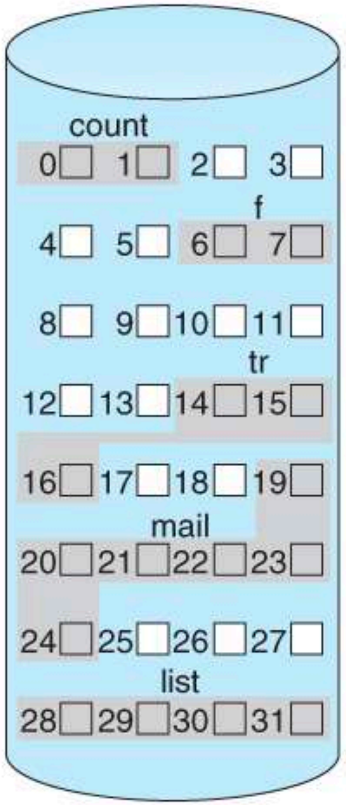
Considerations on Files

- Most files in a system are typically very small
- The vast majority of disk space is taken up by few but very large files
- Disk I/O operations target both small and large files
- Per-file cost must be low (and large files must be handled efficiently)

Option 1: Contiguous Allocation

- Sounds familiar with how basic memory allocation is done
- The OS keeps track of a list of free disk blocks
- When a file is created the OS allocates a sequence of free blocks
- File descriptor needs only to store the start location and size
- Examples: IBM/360, write-once disks, early PCs

Option 1: Contiguous Allocation



directory

file	start	length
count	0	2
tr	14	3
mail	19	6
list	28	4
f	6	2

Contiguous Allocation: PROs and CONs

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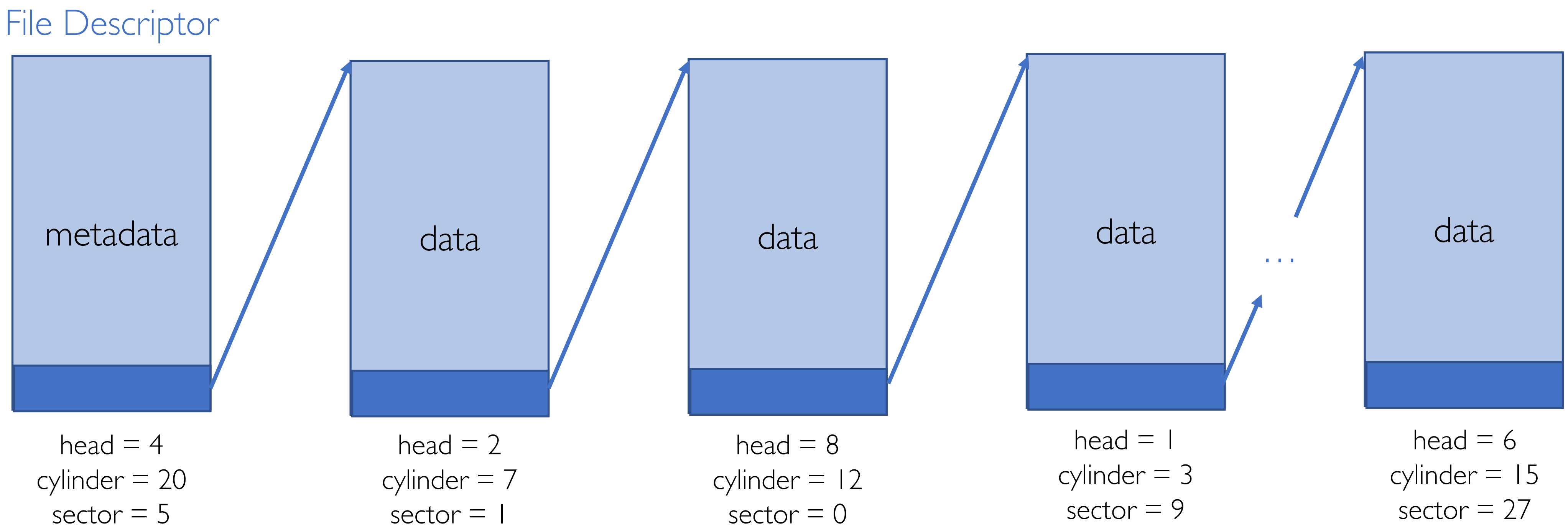
- CONs:
  - Hard to change file size (may need to re-allocate it entirely to another location)
  - Fragmentation (may need to run compaction/defragmentation)

Option 2: Linked Files

- The OS keeps a linked list of free (not necessarily contiguous) blocks
- The OS keeps also a linked list of where subsequent blocks are located
- This frees the file to be physically located sequentially
- Keep a pointer to the first block of the file in the file descriptor
- Keep a pointer to the next block in each sector
- Examples: FAT, MS-DOS

Option 2: Linked Files



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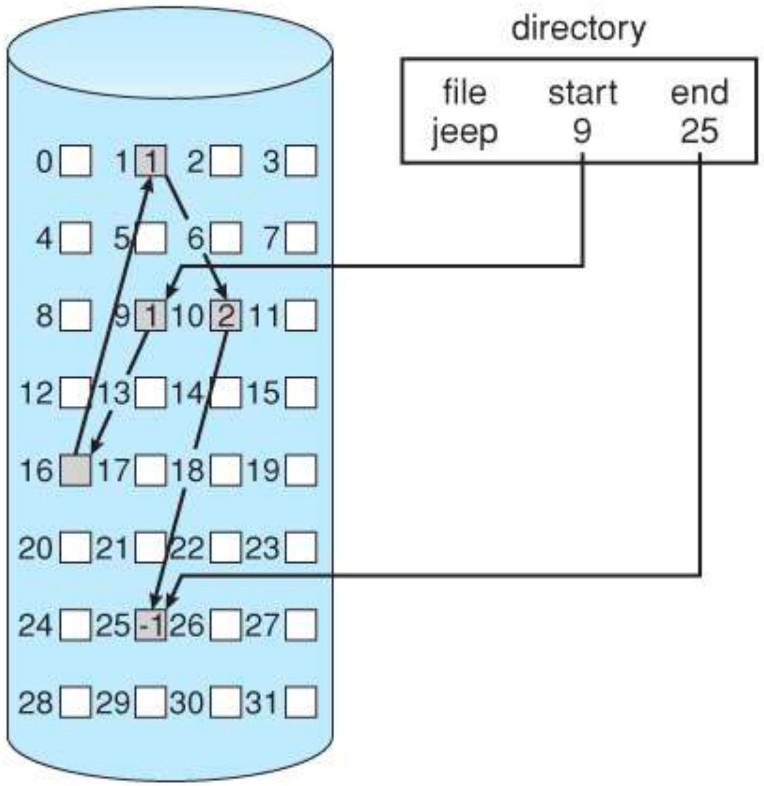

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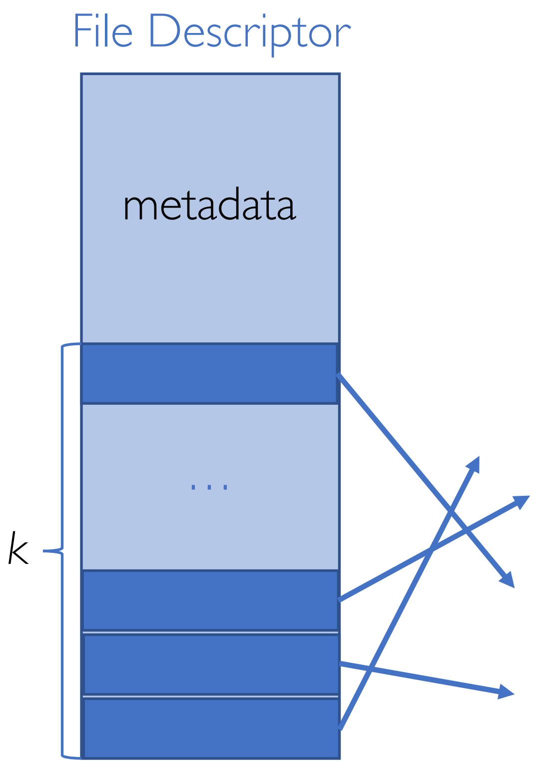
- CONs:
  - Inefficient sequential access: need to traverse the whole linked list (may need n seeks + n rotational delays for n-block files)
  - Inefficient random access: basically, as above (of course the exact cost depends on the specific block referenced)

Option 3: Indexed Files

- The file descriptor contains a block of pointers (vs. only 1 pointer as in the linked list approach)
- The user or OS must declare the maximum length of the file when it is created
- OS allocates an array to hold the pointers to all the blocks when it creates the file, but allocates the blocks only on demand
- OS fills in the pointers as it allocates blocks
- Example: Nachos

Option 3: Indexed Files



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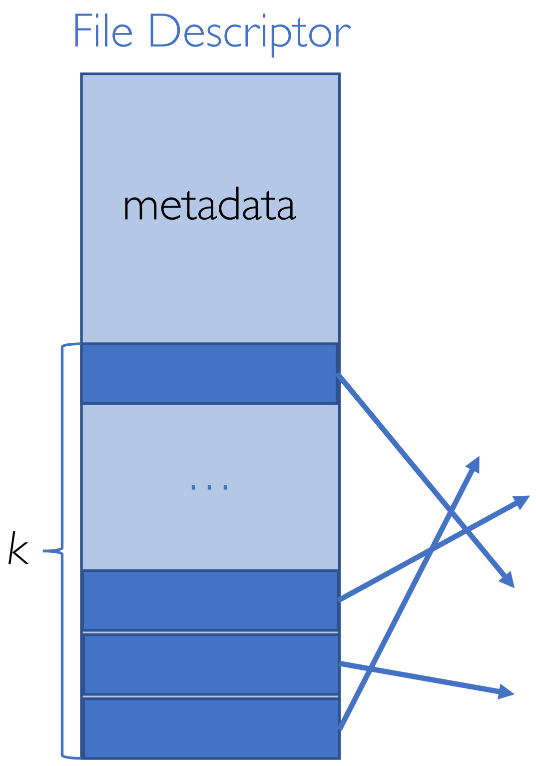

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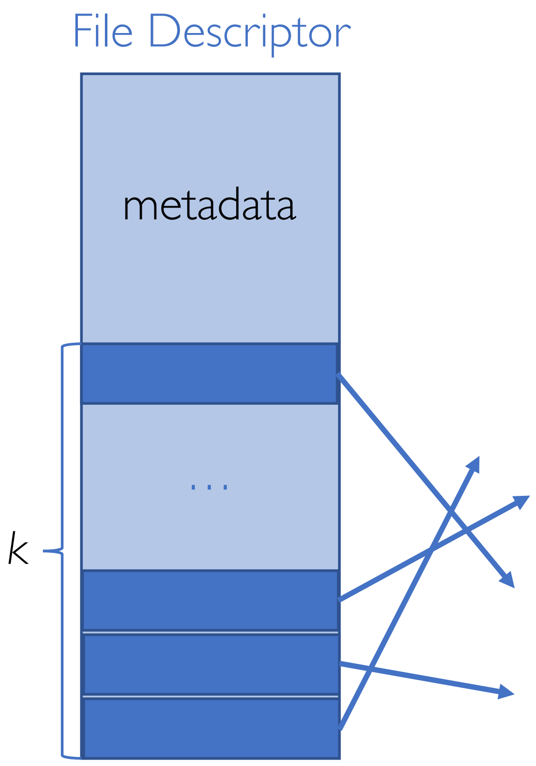

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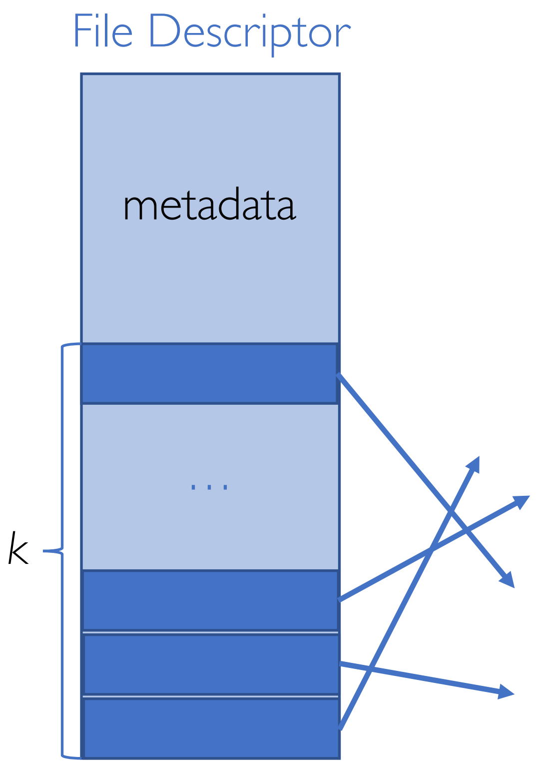

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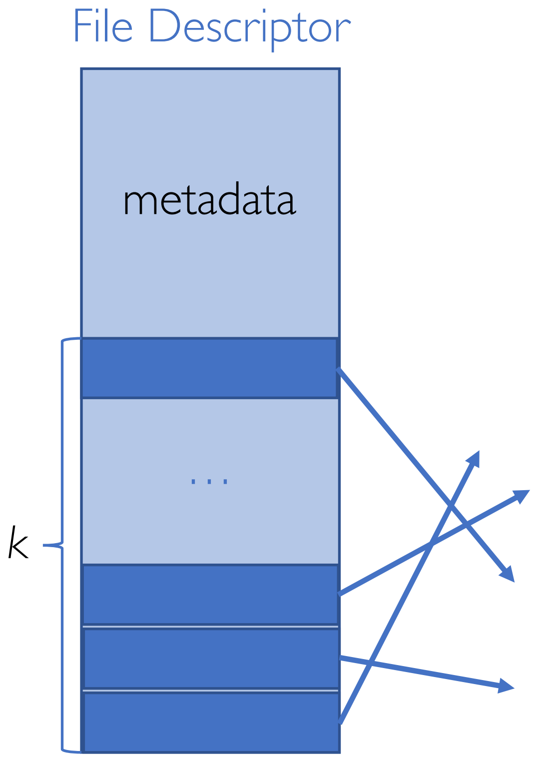

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Of course, only pointers to blocks are allocated on the file descriptor, not the blocks themselves!

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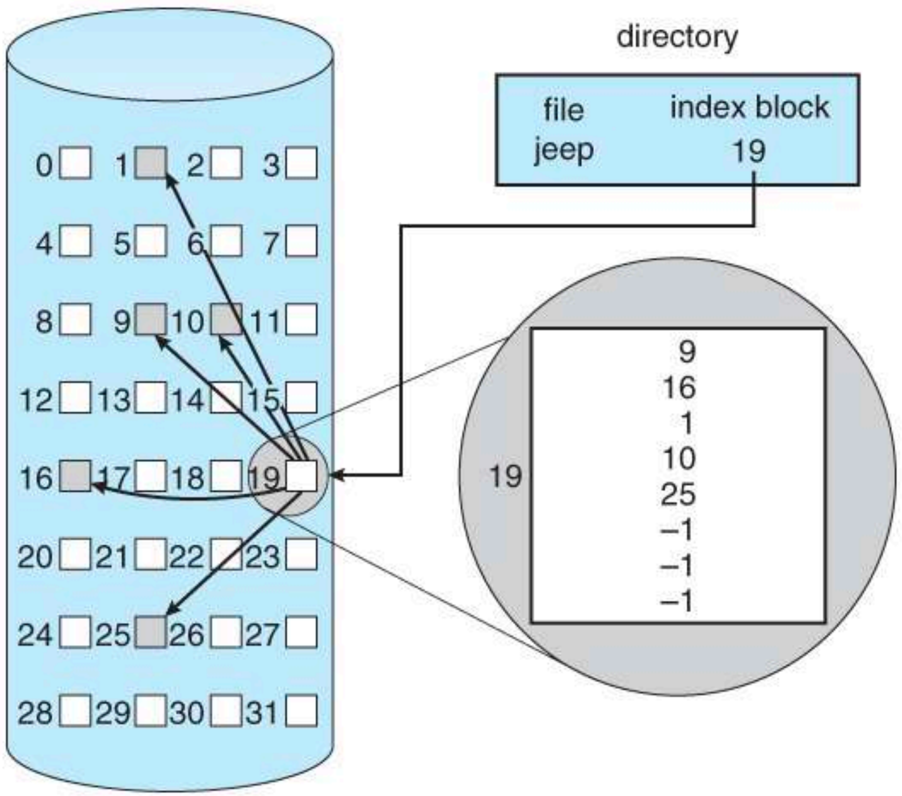

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  - Efficient random access: just follow the correct pointer (1 seek + 1 rotation)
- CONs:
  - Waste some space on the file descriptor
  - Max file size to be set upfront (things change very quickly!)
  - Inefficient sequential access: as for the linked files approach, it may need n seeks + n rotational delays for n-block files

Option 4: Multi-Level Indexed Files

- Each file descriptor contains a number of block pointers (e.g., 14)
- The first 12 of those point to data blocks
- The 13th pointer points to another block of, say, 1024 block pointers
  - Each of those pointer points to a specific file data block
- The 14th pointer points to another block of, say, 1024 pointers
  - Each of those pointer points to, say, 1024 block pointers, which in turn point to file data blocks
- Example: UNIX BSD 4.3

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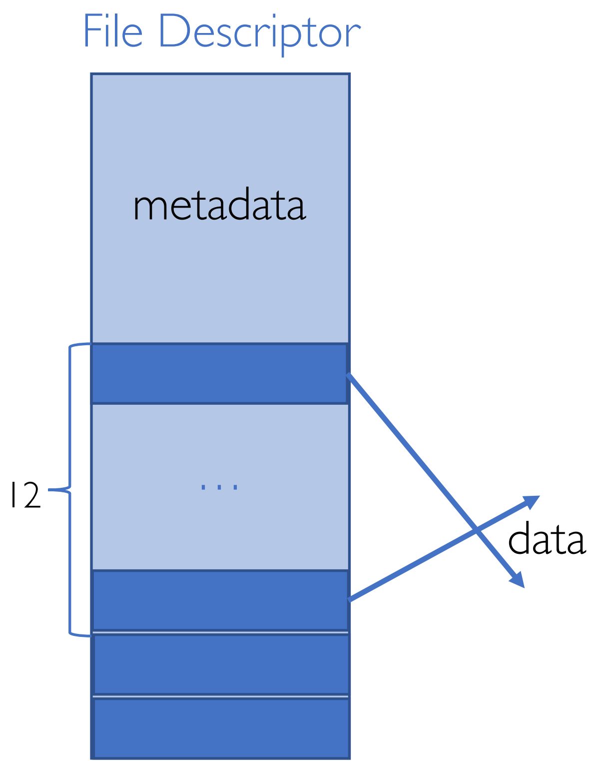

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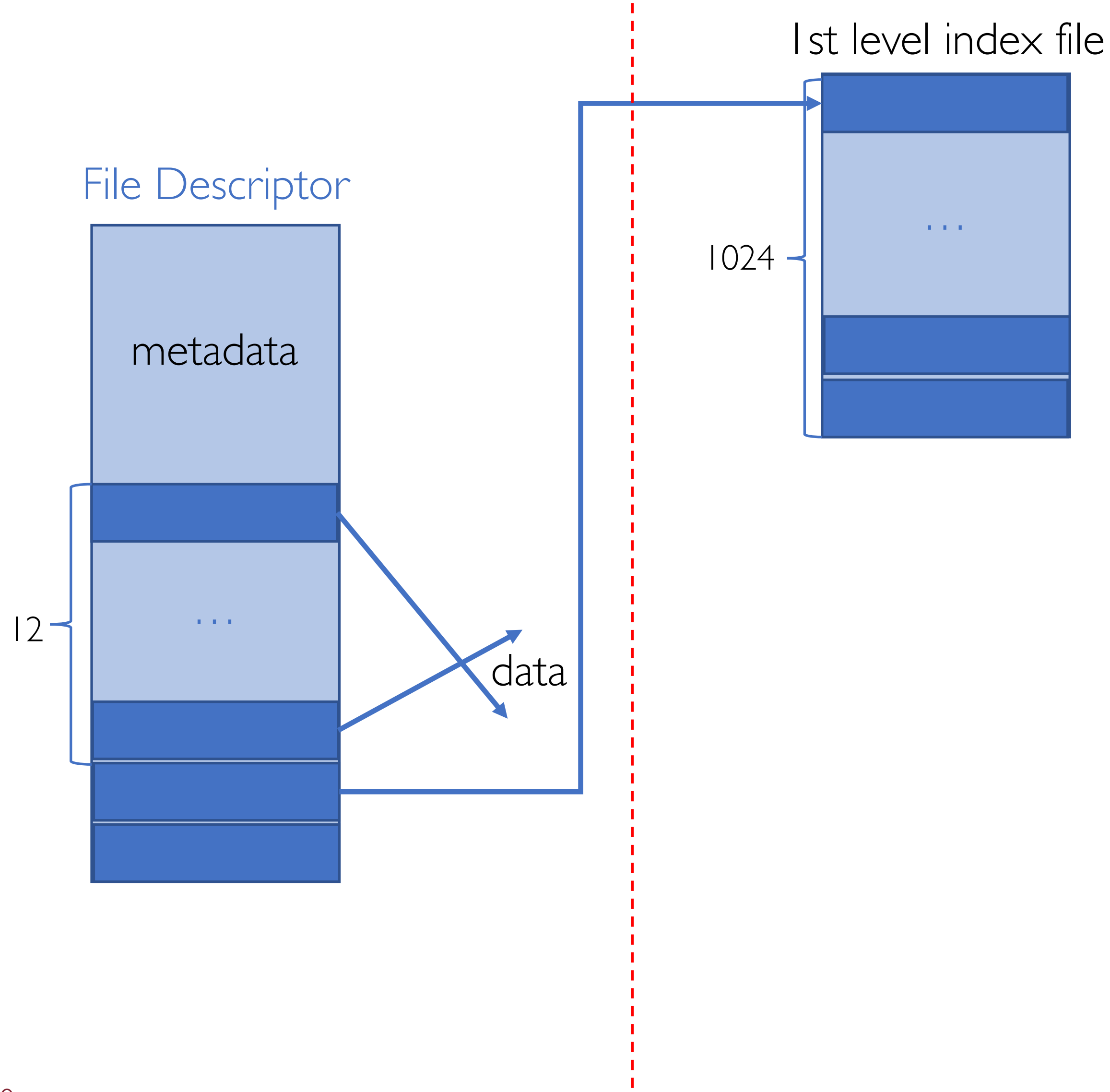

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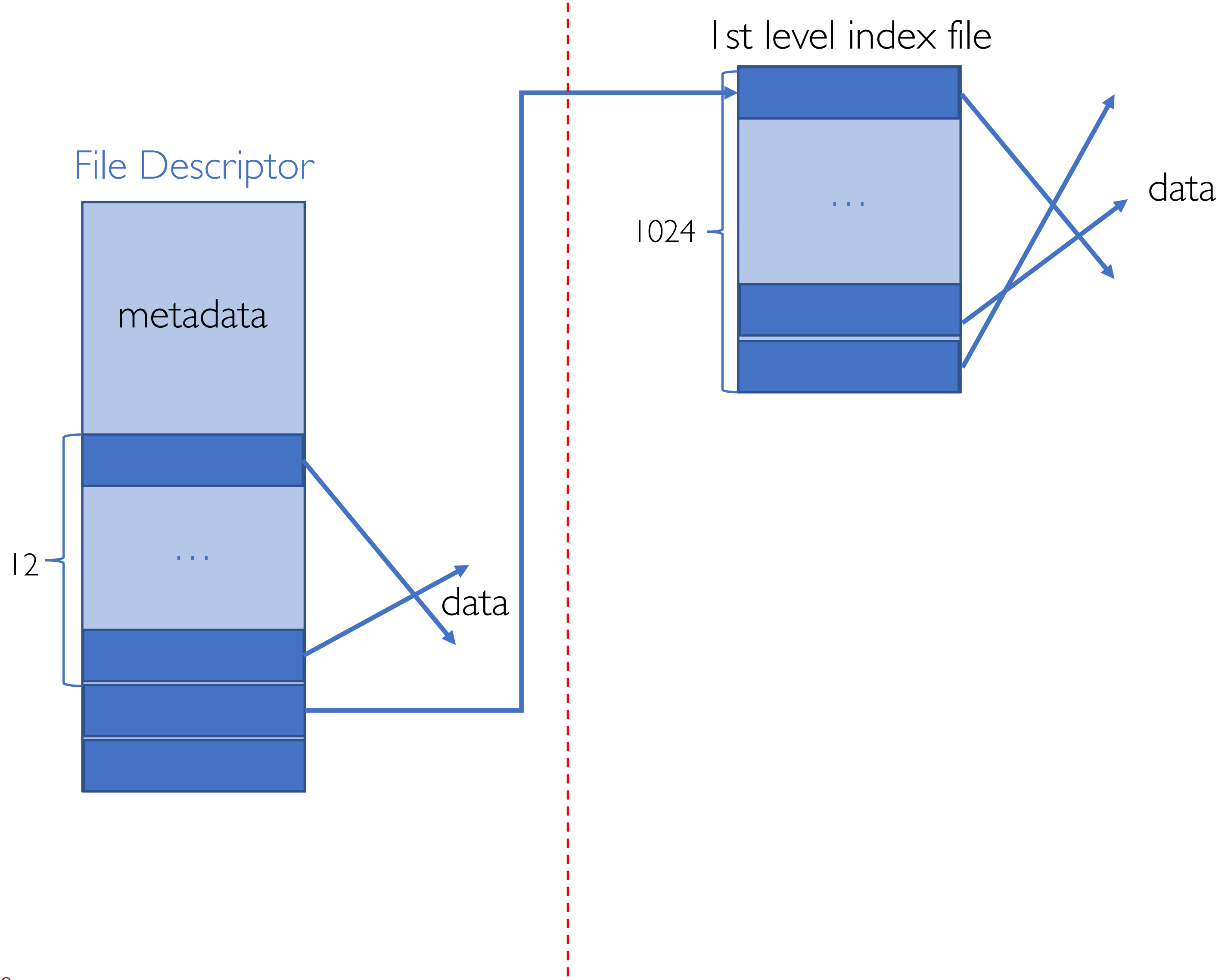

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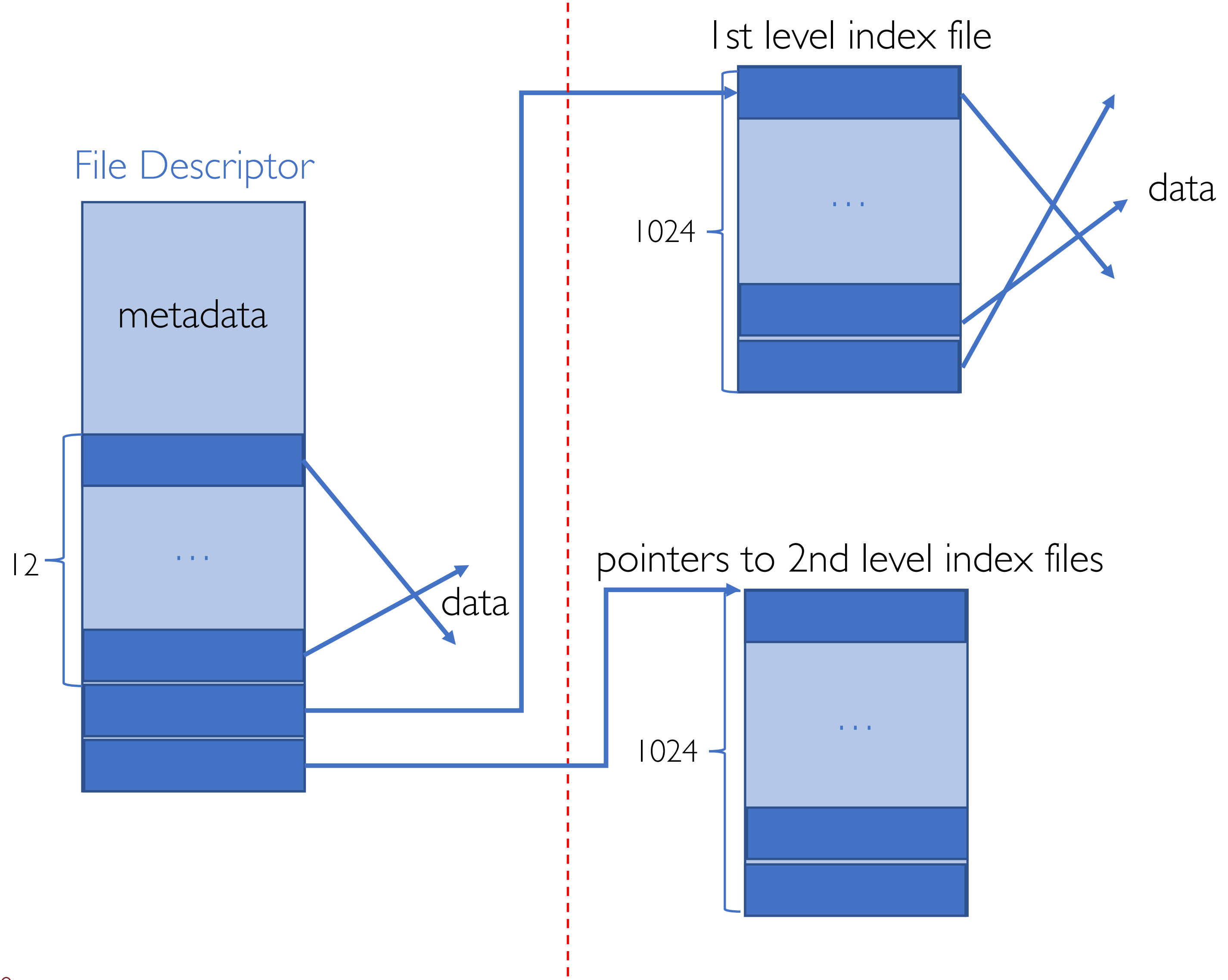

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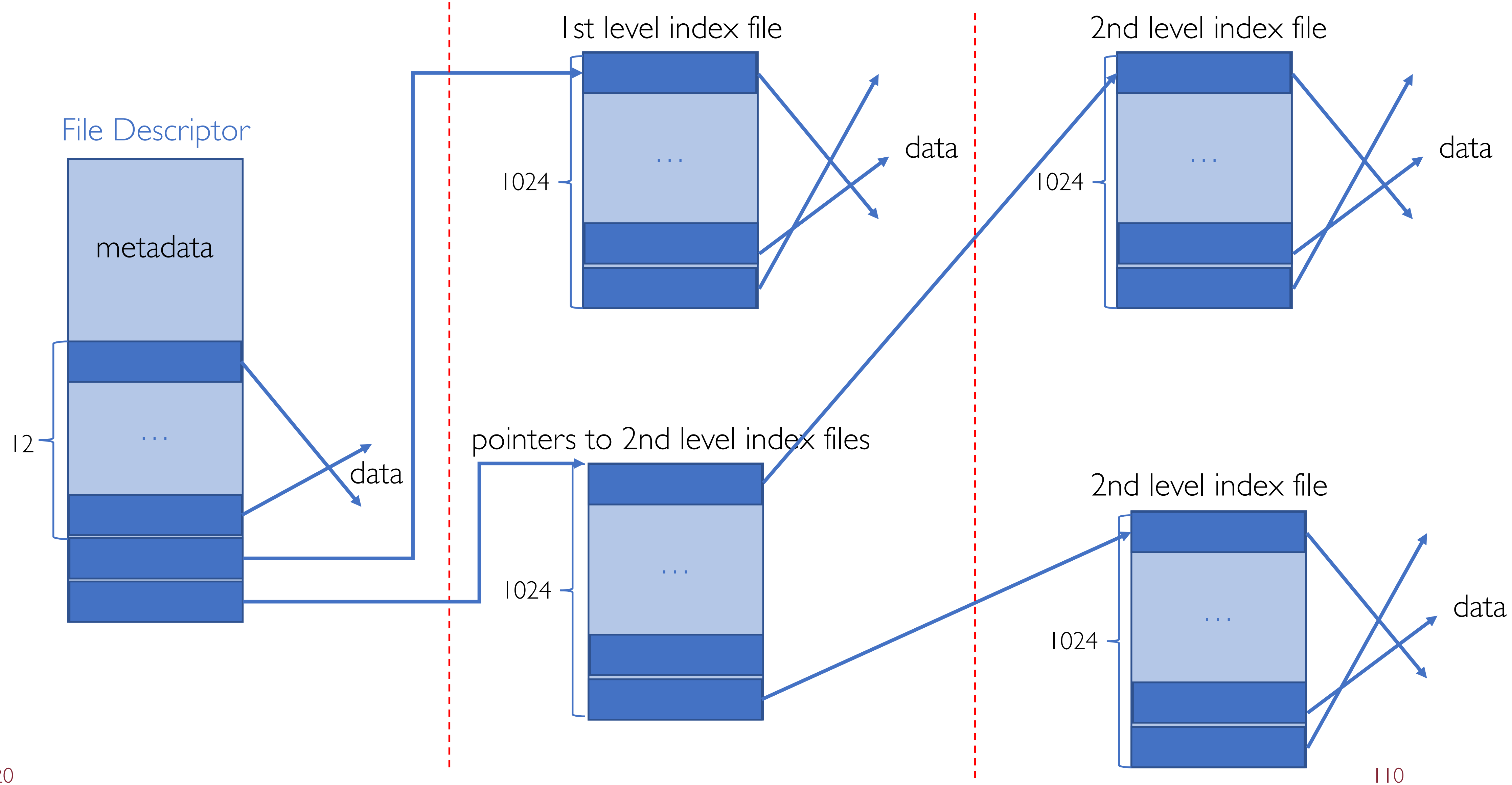

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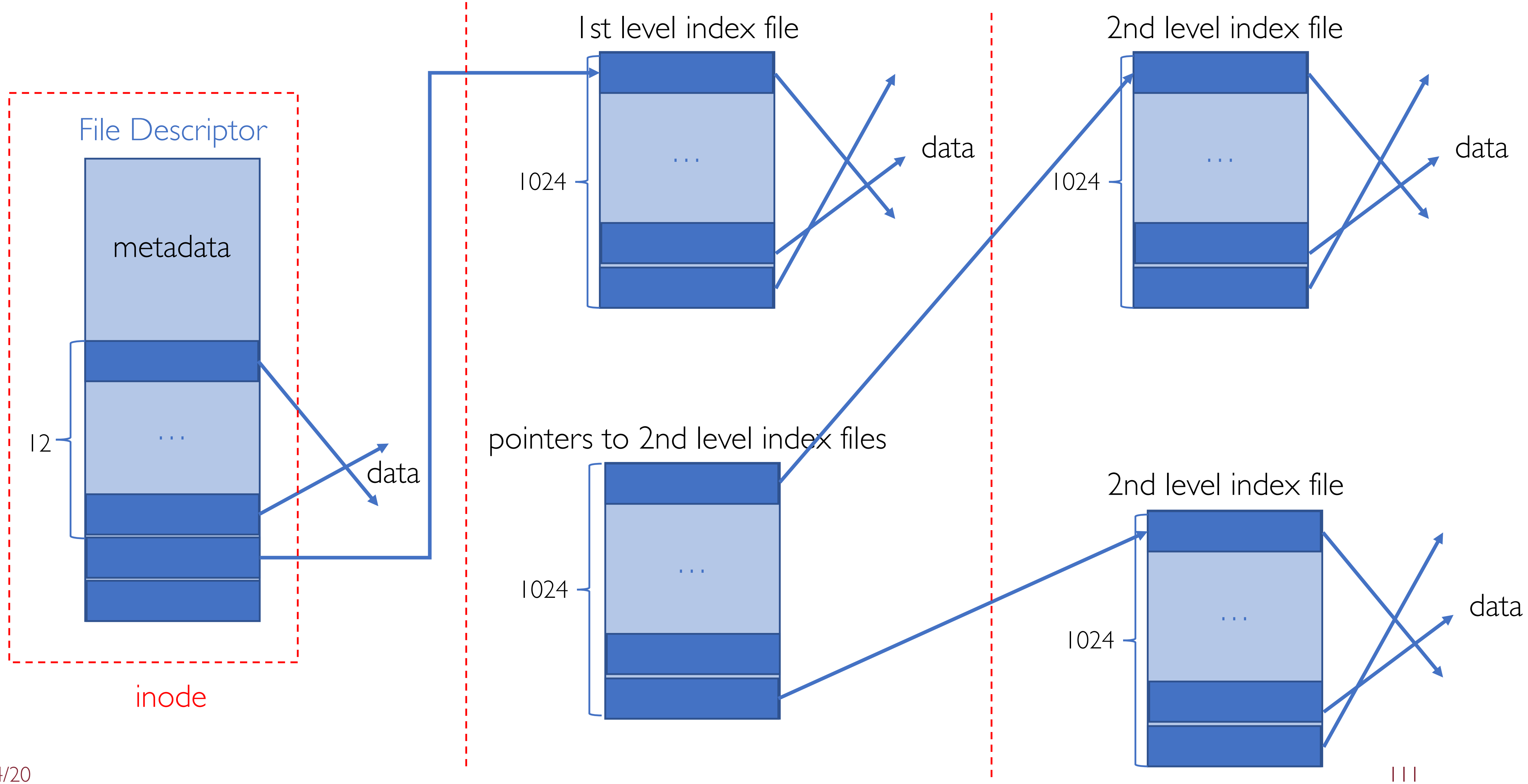

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In general, $\sim k^l$ if k = n. of block pointers and l = n. of levels

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- CONs:
  - Still inefficient sequential/random access yet better than linked files
  - Lots of seeks because of non-contiguous allocation

Free Space Management: Bitmap

- Need a free-space list to keep track of which disk blocks are free (just as we need for main memory)
- Need to be able to find free space quickly and release space quickly
- The bitmap has one bit for each block on the disk
- If the bit is 1 the block is free, otherwise (0) the block is allocated

Free Space Management: Bitmap

- Use a 32-bit bitmap (i.e., a typical CPU-word size)
- Can quickly determine if any block in the next 32 is free, by comparing the word to 0
- If the bitmap is 0, all the pages are in use
- Otherwise, use bit operations to find an empty block
- Marking a block as freed is simple since the block number can be used to index into the bitmap to set a single bit

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~4,000,000,000 bitmap entries = 500,000,000 bytes = 500MB

Free Space Management: Linked List

- If most of the disk is in use, it will be expensive to find free blocks with a bitmap
- An alternative implementation is to link together the free blocks
- The head of the list is cached in kernel memory
- Each block contains a pointer to the next free block
- Allocating/Deallocating blocks by modifying pointers of this list

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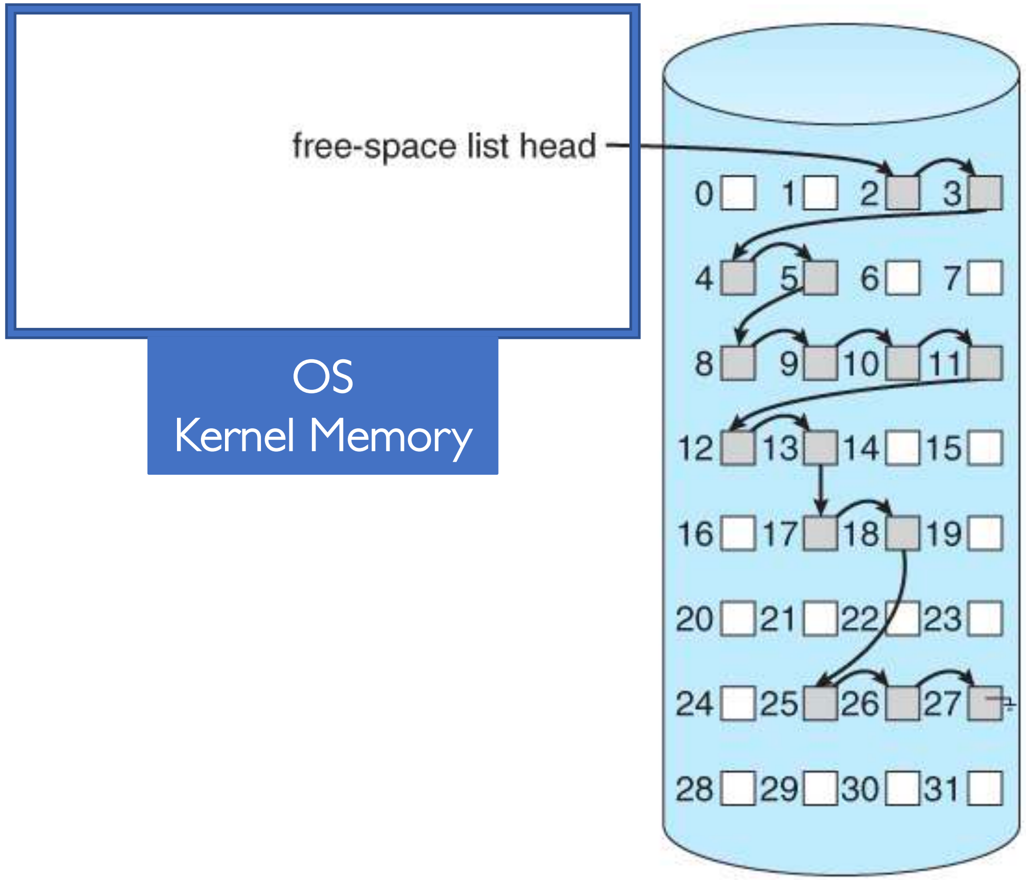

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Summary

- Many of the concerns of file system implementation are similar to those of virtual memory implementation
- Contiguous allocation is simple, but suffers from external fragmentation, the need for compaction, and the need to move files as they grow
- Indexed allocation is very similar to page tables
  - A table maps from logical file blocks to physical disk blocks
- Free space can be managed using a bitmap or a linked list