

Sistemi Operativi

Corso di Laurea in Informatica

a.a. 2020-2021



SAPIENZA
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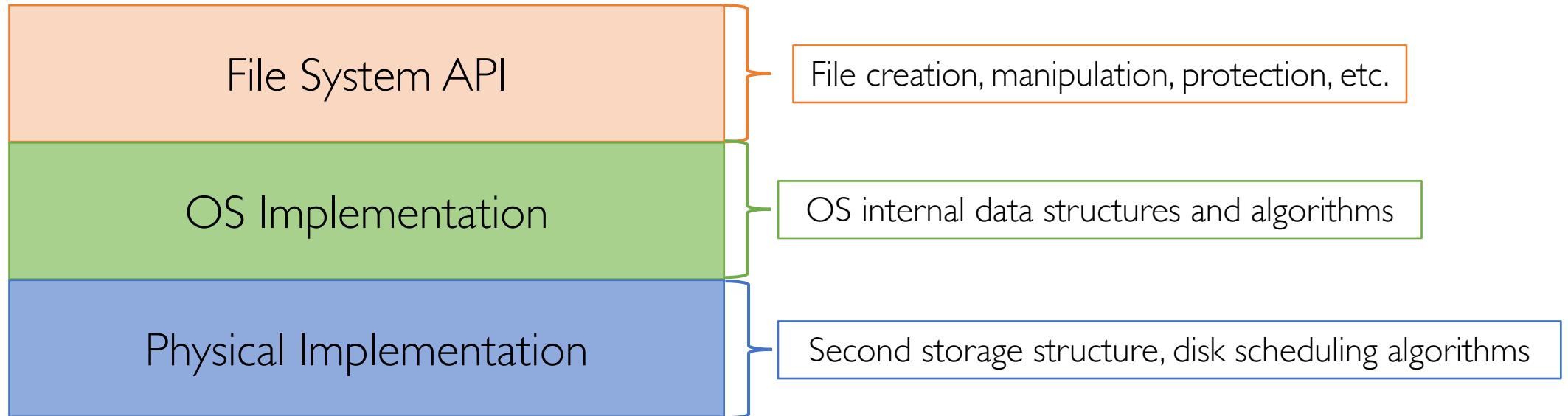
Gabriele Tolomei

Dipartimento di Informatica

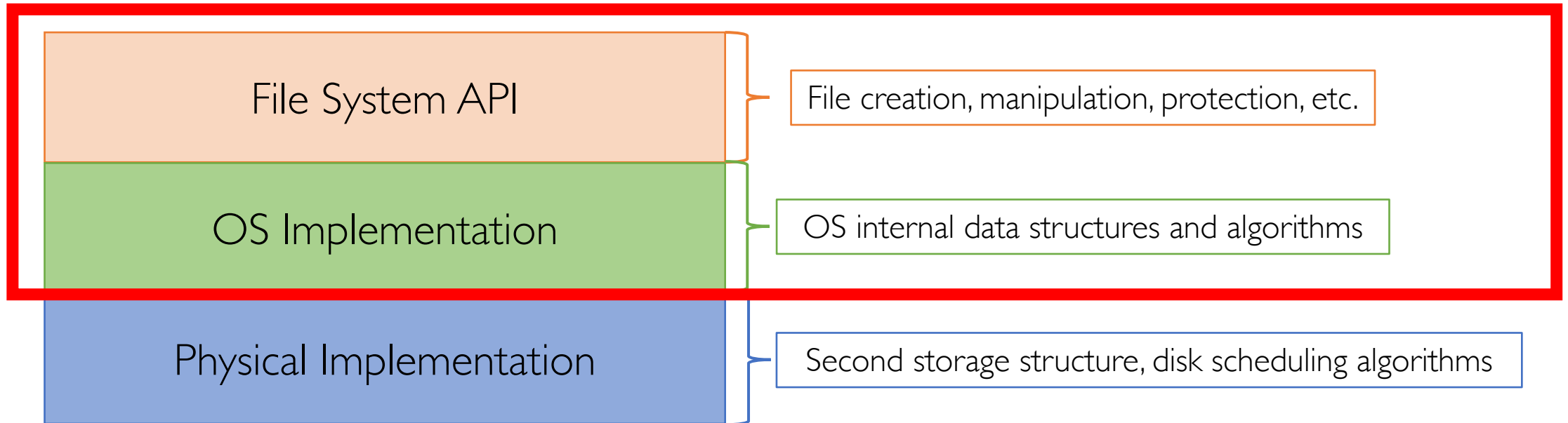
Sapienza Università di Roma

tolomei@di.uniroma1.it

File System's Logical View



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Abstraction

User Abstraction

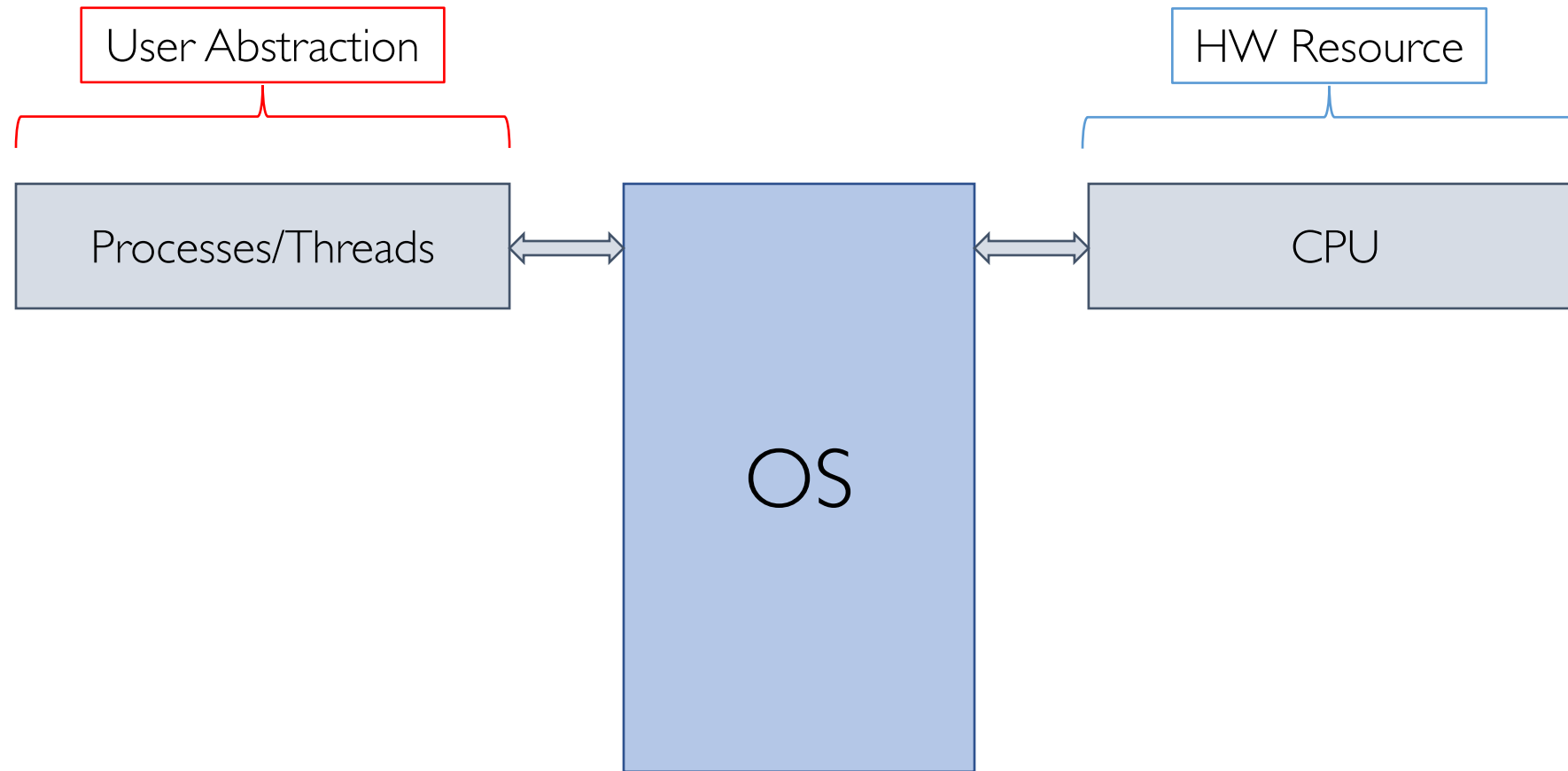
HW Resource



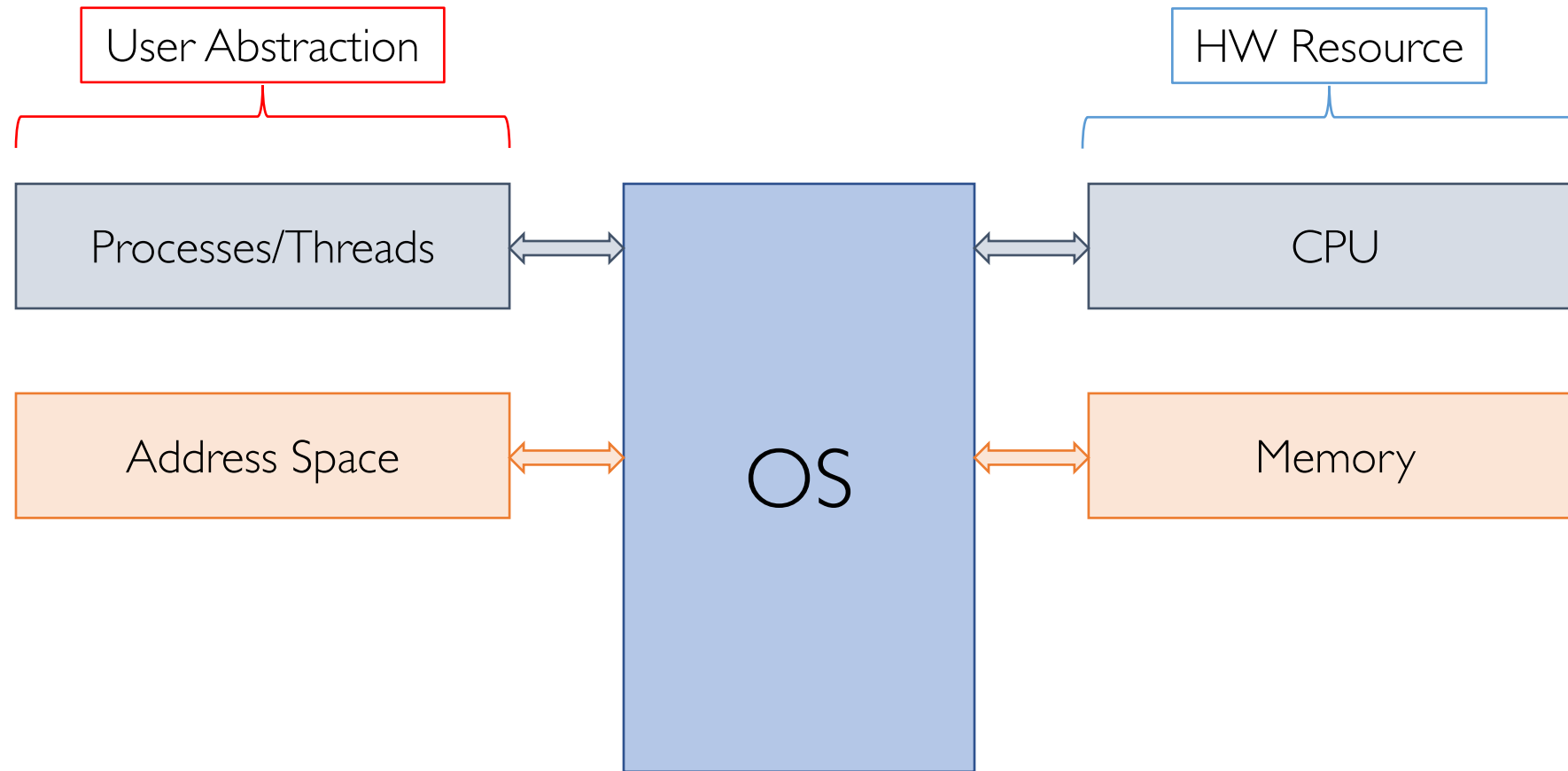
OS

The diagram illustrates the concept of abstraction in operating systems. It features three main components: 'User Abstraction' (a red-outlined box at the top left), 'OS' (a large blue-outlined rectangle in the center), and 'HW Resource' (a blue-outlined box at the top right). The 'OS' box is positioned between the 'User Abstraction' and 'HW Resource' boxes, suggesting it acts as an intermediary or abstraction layer between user-level operations and the underlying hardware resources.

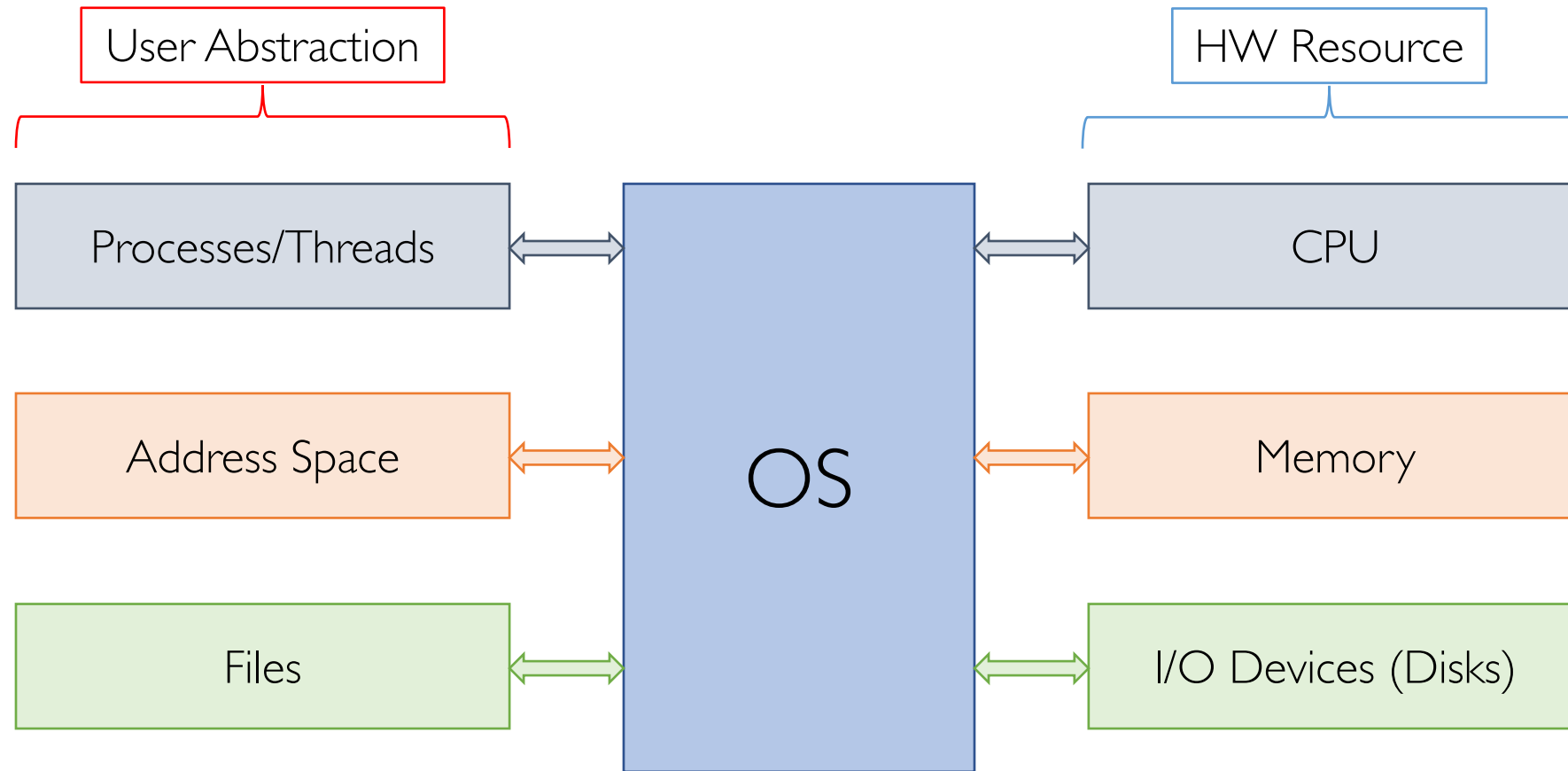
Abstraction



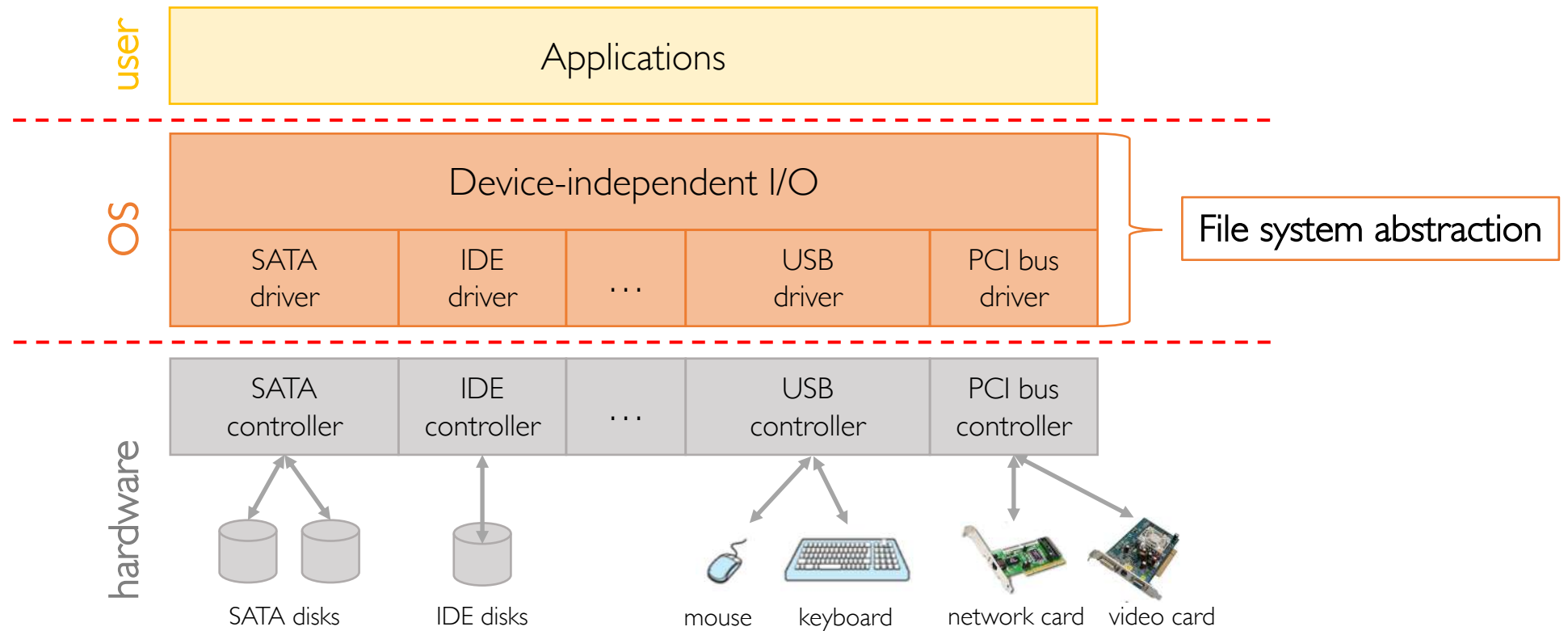
Abstraction



Abstraction



File System Abstraction



User Requirements on Data

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- **Ease of Use** → Data should be easily found, examined, modified, etc.

HW vs. OS Capabilities

- HW provides:
 - Persistence: Disks are non-volatile storage devices
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- OS provides:
 - Persistence: Redundancy mechanisms
 - Sharing/Protection: Permissions (e.g., UNIX **rw~~x~~** privileges)
 - Ease of Use: named files, directories, search tools (e.g., Spotlight in macOS)

What's a File?

- The abstraction used by the OS to refer to the logical unit of data on a storage device
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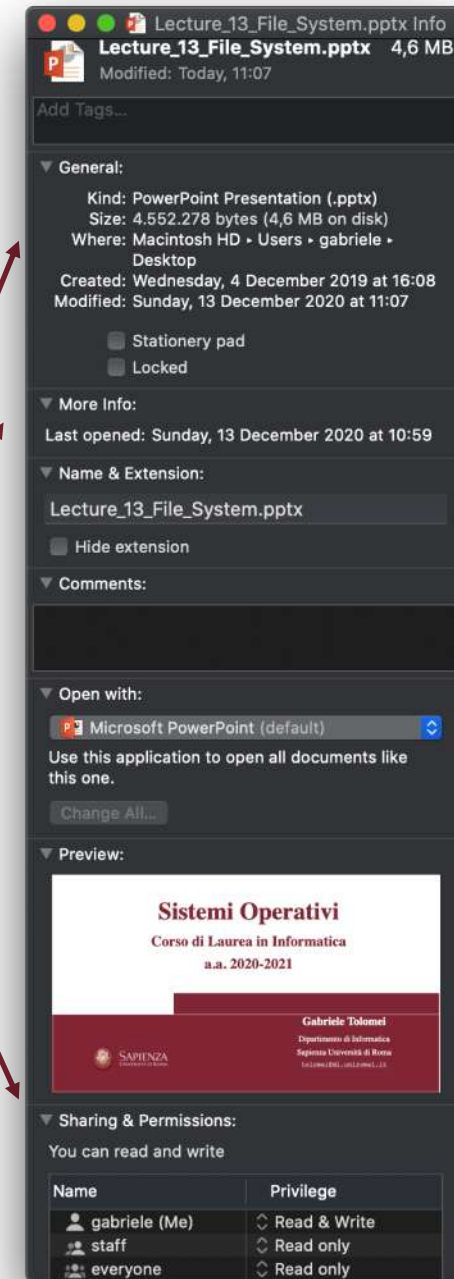
- The abstraction used by the OS to refer to the logical unit of data on a storage device
 - Named collection of related information stored on secondary memory
- Files are mapped by the OS onto physical storage devices (e.g., disks)
 - Such devices are non-volatile (their content persist across reboots)
- 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



Files: Operations (User Interface to File System)

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 - 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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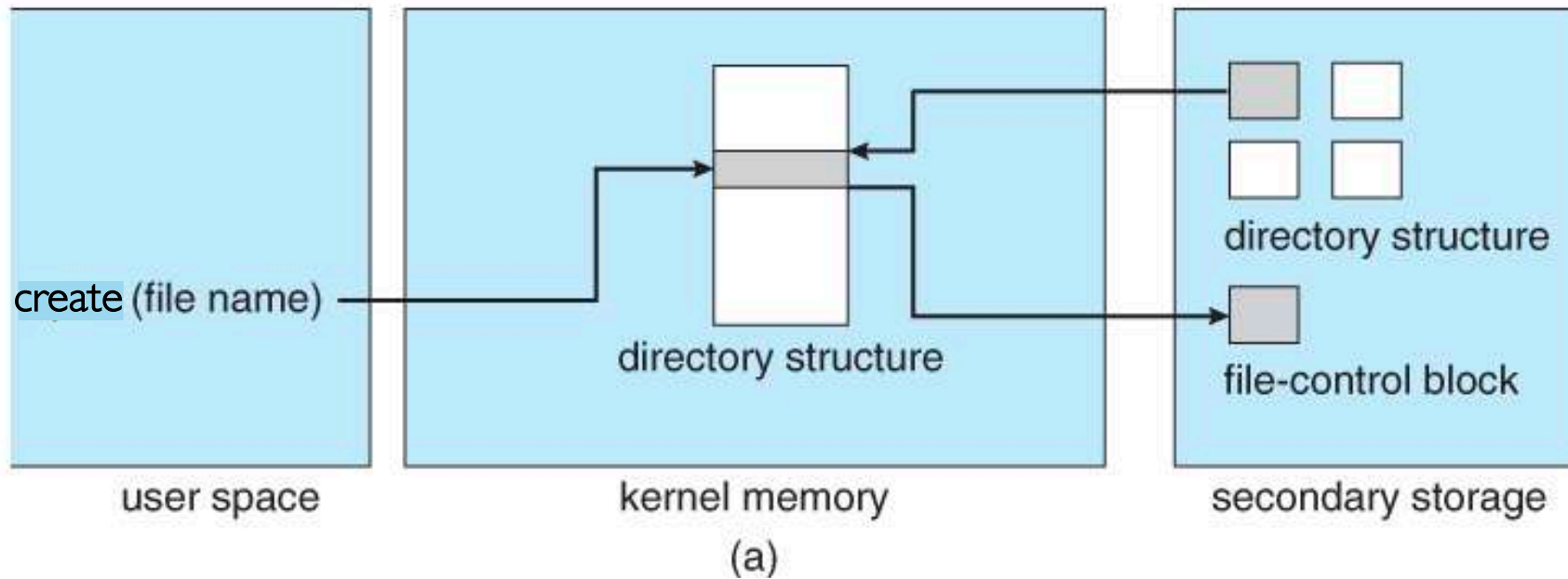
Local Per-Process File Table

- 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

Files Operations: `create (filename)`



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)**

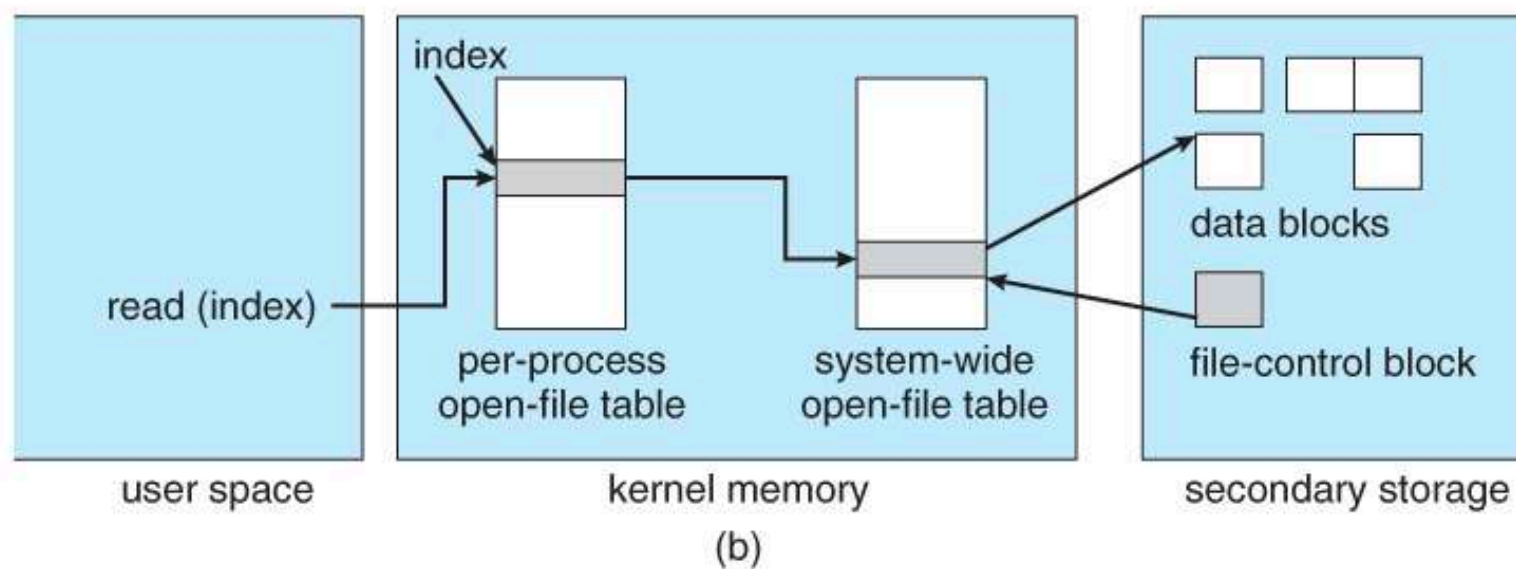
- Returns the **fileID** the OS associated with that **filename**
- Check the global open file table if the file is already open by another process, if not:
 - Find the file and copy the file descriptor into the global open file table
- Check protection of the file against the mode, if not ok abort
- 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!



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- 2 possible ways of reading a file:
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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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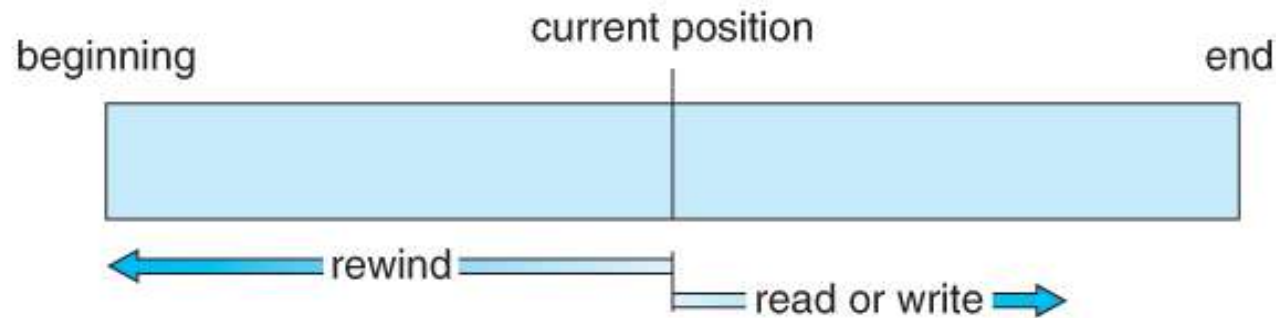
File Access Methods: Programmer's Perspective

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- **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

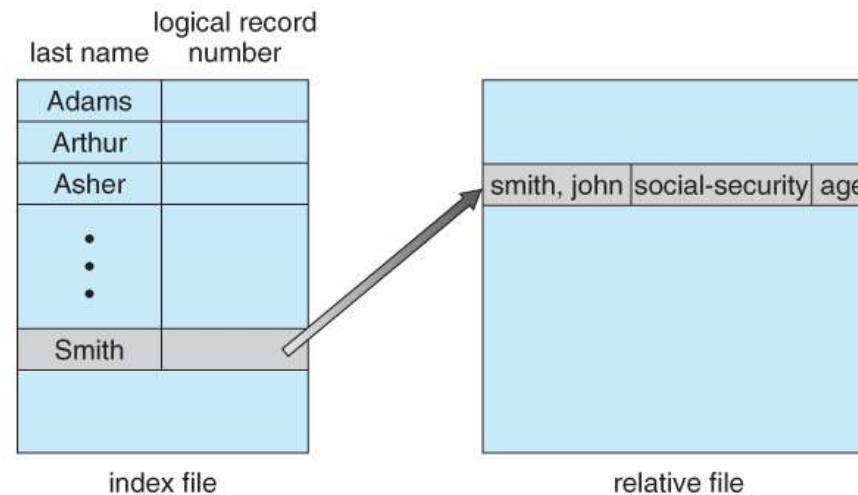
sequential access	implementation for direct access
reset	cp = 0;
read_next	read cp ; cp = cp + 1;
write_next	write cp ; cp = cp + 1;

simulating sequential access using direct access

File Access Methods: OS's Perspective

Keyed/Indexed

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

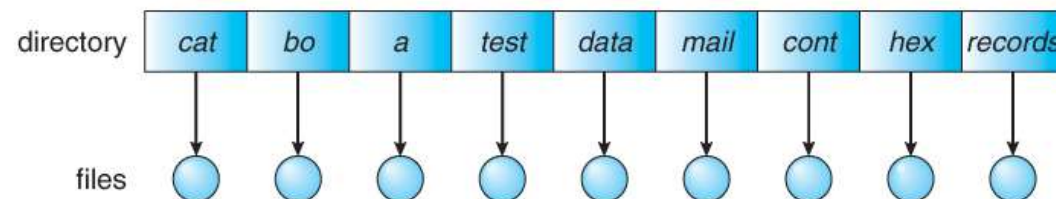
- Directory operations to be supported include:
 - Search for a file
 - Create a file (add it to the directory)
 - Delete a file (erase it from the directory)
 - List a directory (possibly ordered in different ways)
 - Rename a file (may change sorting order)
 - Traverse the file system

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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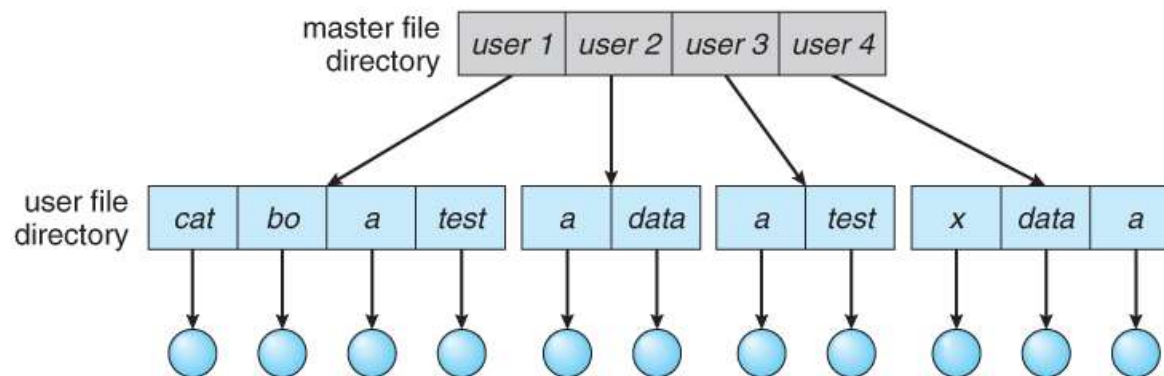
Directory: Naming Strategies

- Two-Level Directory
 - Each user gets their own directory space
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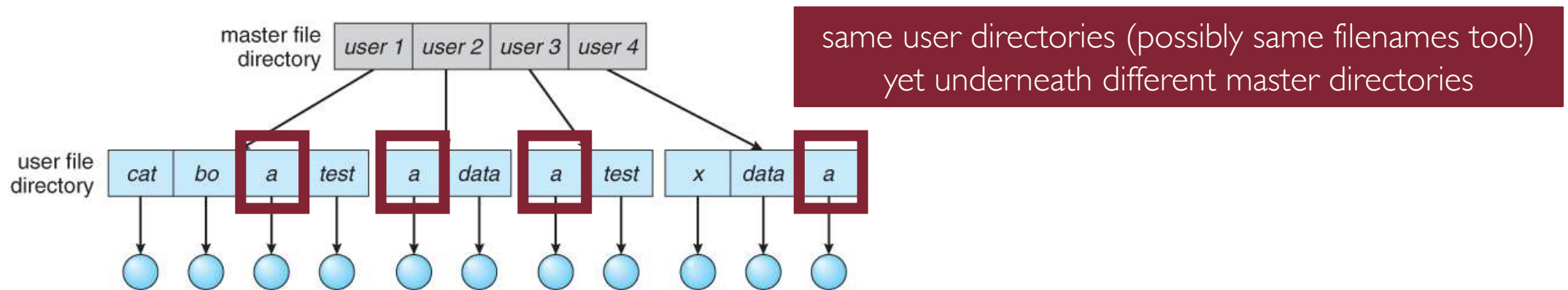
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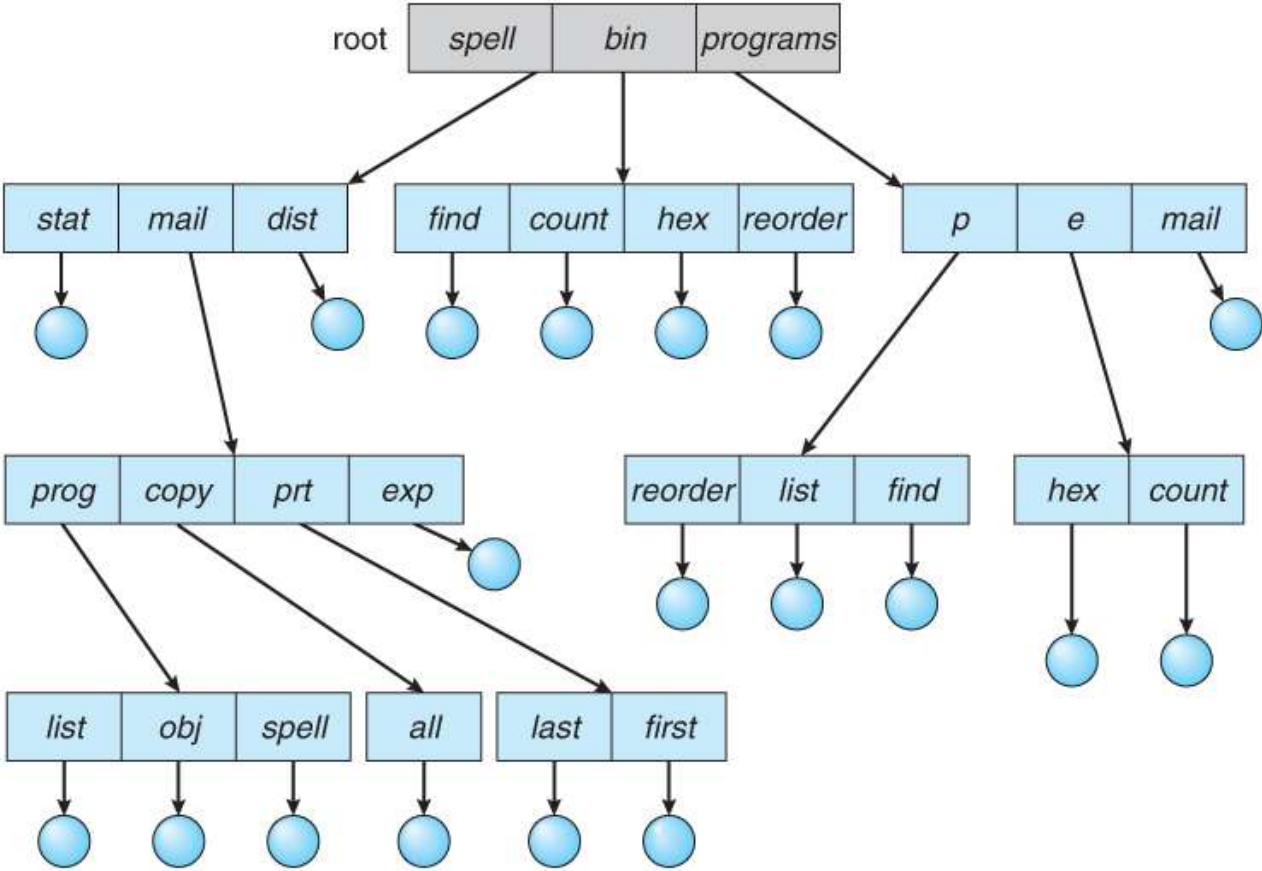
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Directory: Naming Strategies

- 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



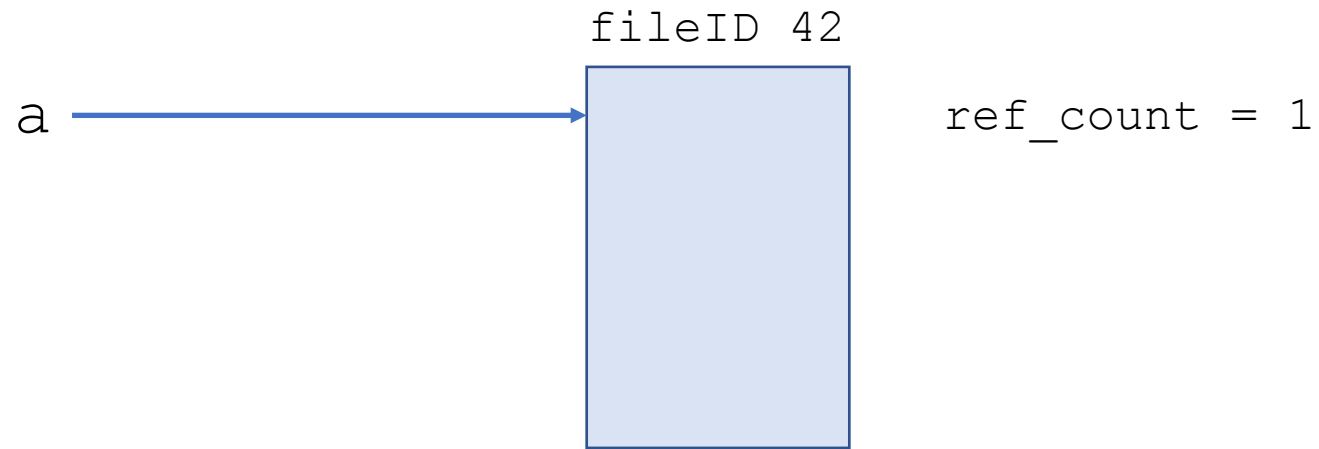
Referential Naming

- Sharing files between different user's directory trees may be complicated

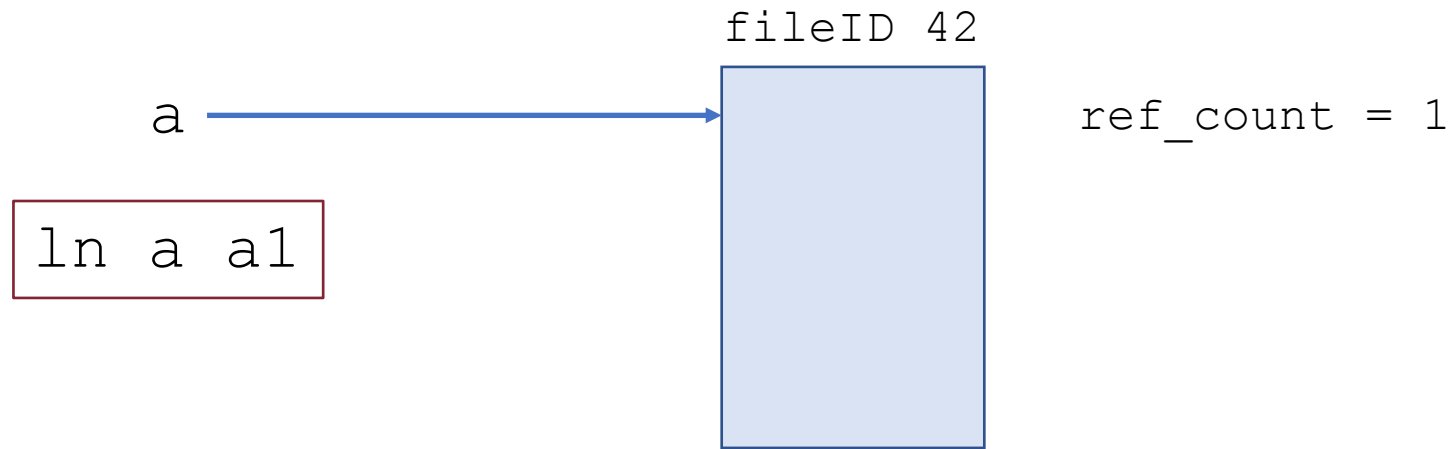
Referential Naming

- Sharing files between different user's directory trees may be complicated
- 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

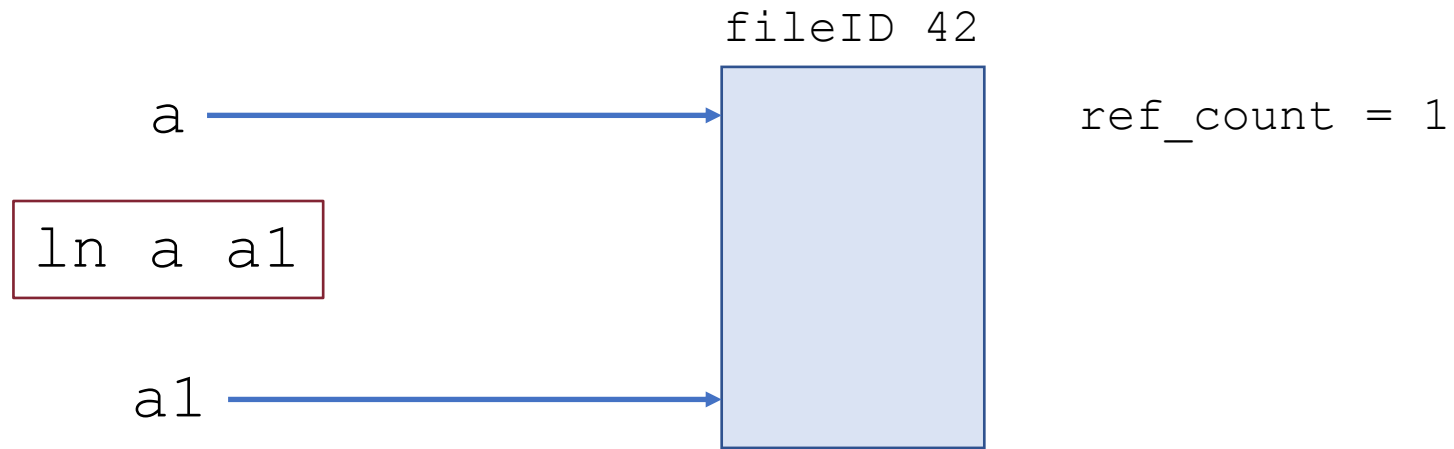
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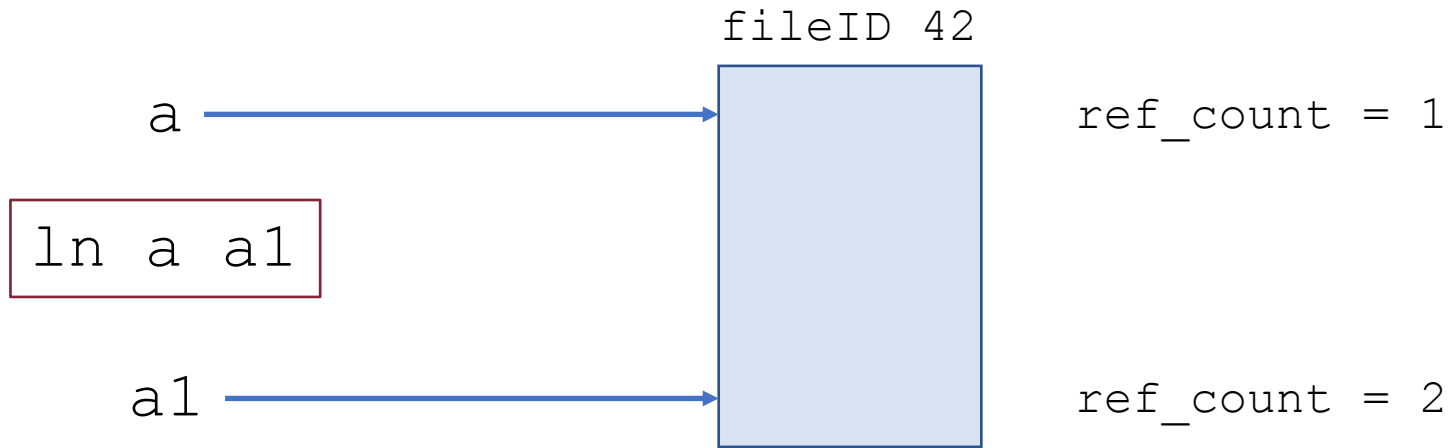


Referential Naming: Hard Links



Adds a second connection to a file

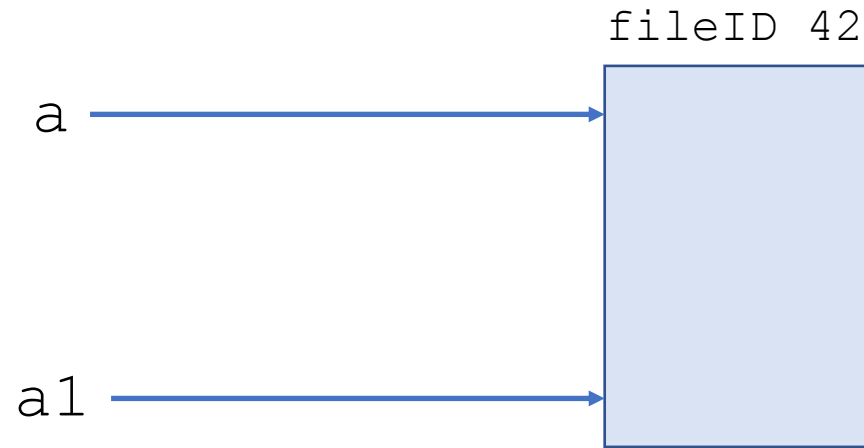
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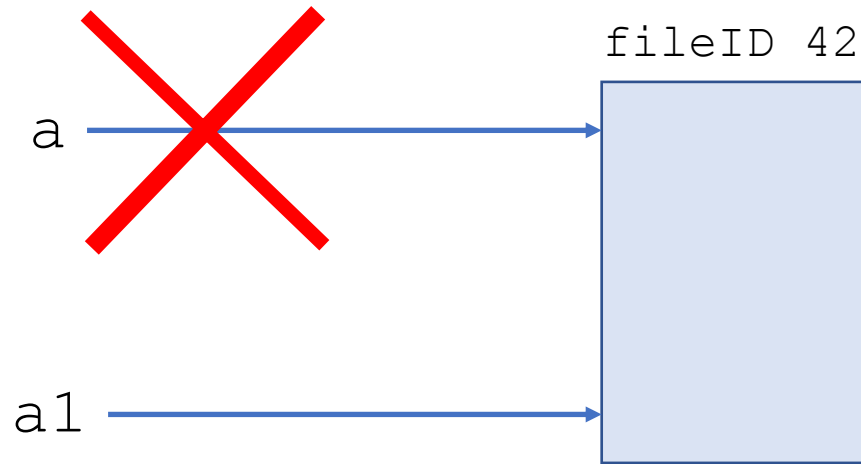
OS maintains reference counts, so it will delete a file only when the last hard link is deleted

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

Problem

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

Referential Naming: Hard Links

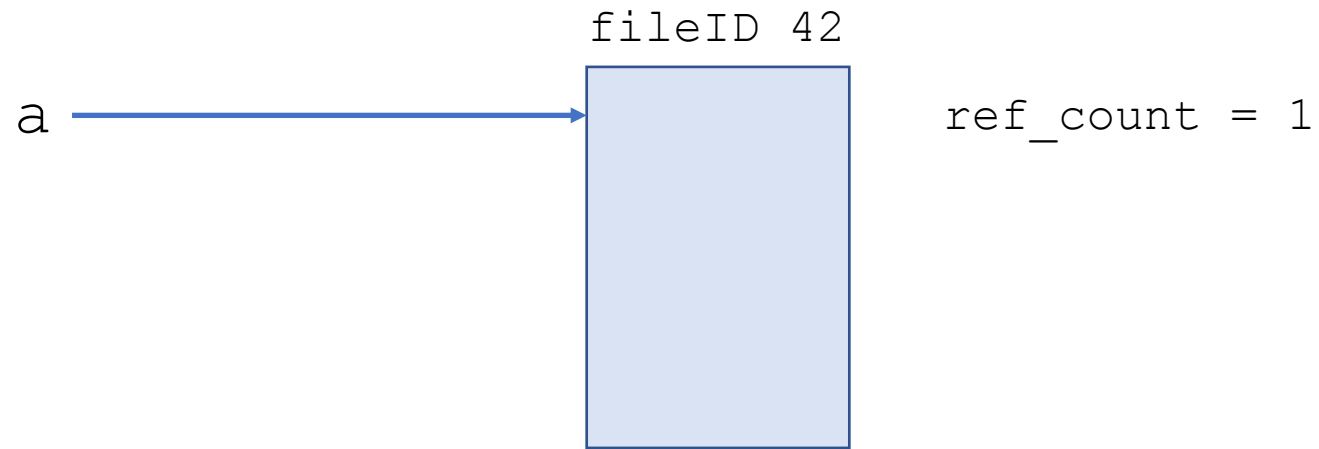
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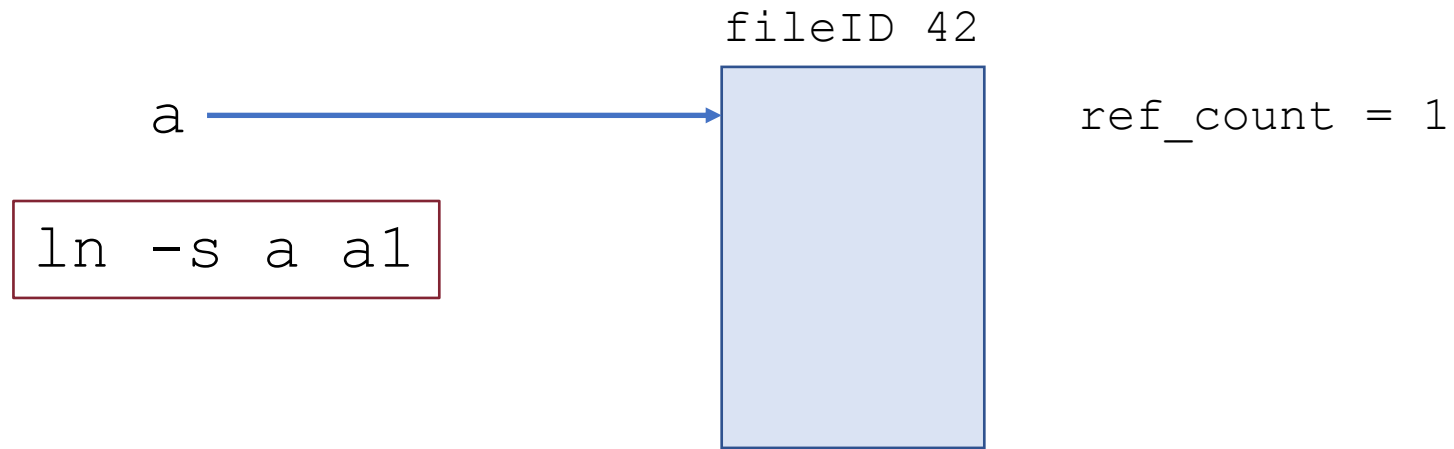
Solution

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

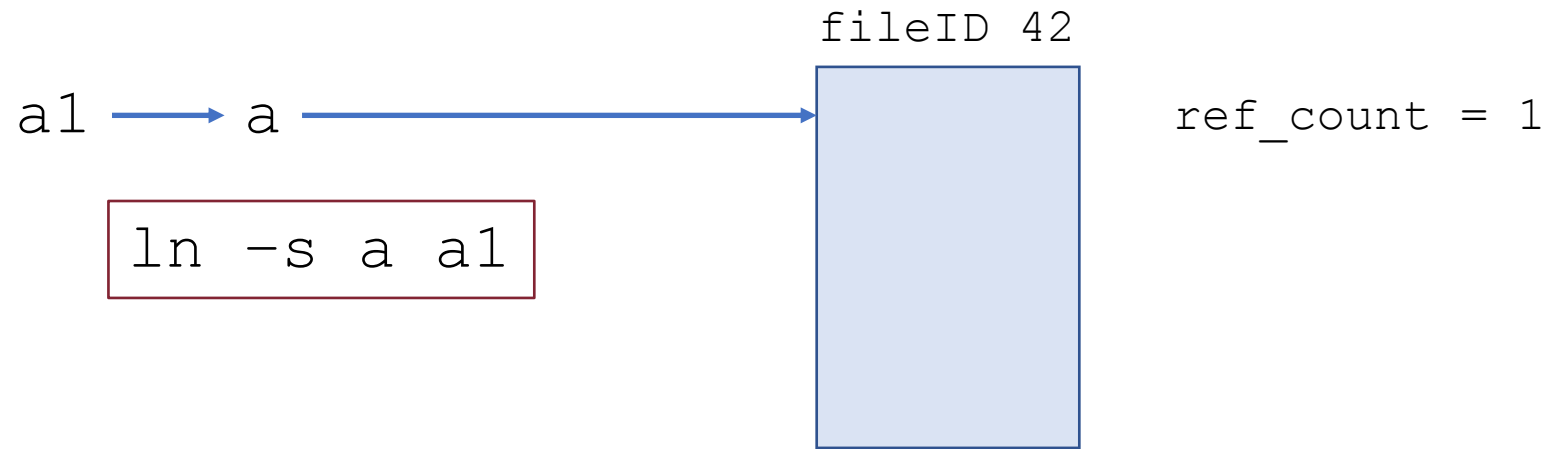
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Referential Naming: Hard Links



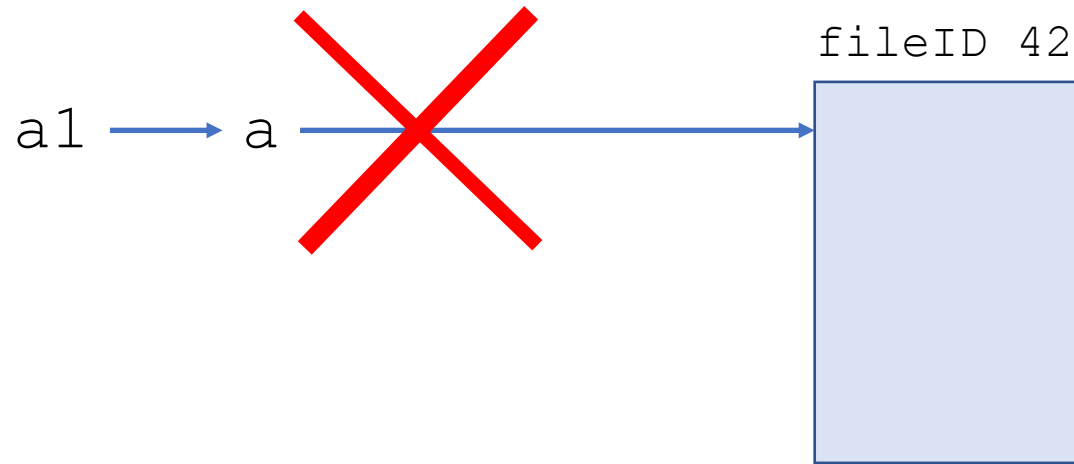
Adds a symbolic pointer to a file

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)

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- 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?

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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

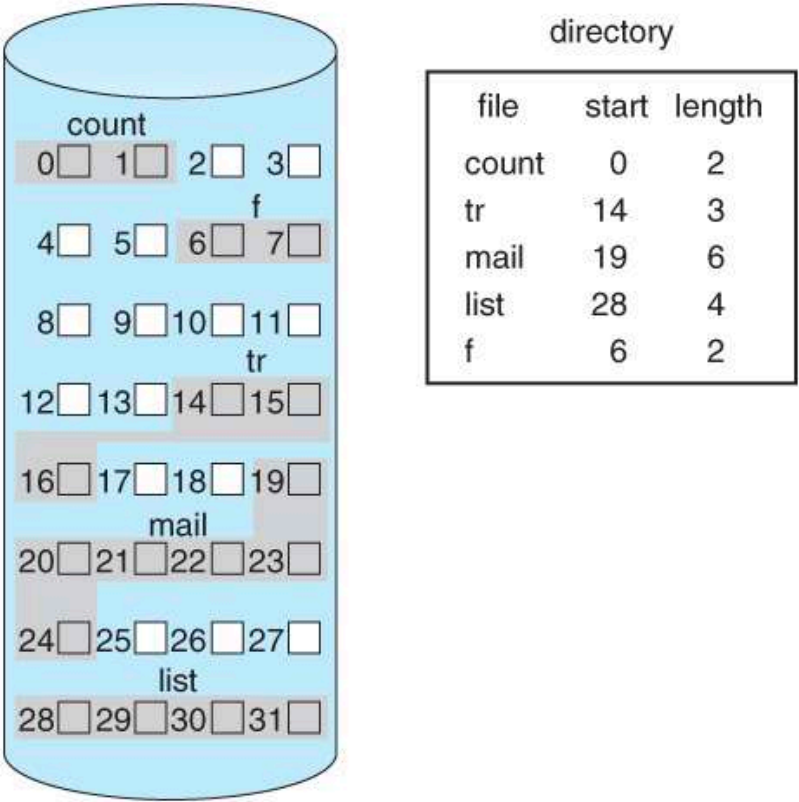
Considerations on Files

- 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



Contiguous Allocation: PROs and CONs

- PROs:
 - Very simple
 - Best possible choice for sequential access (only 1 disk seek) and random access (1 disk seek + rotational time to get to the correct block)

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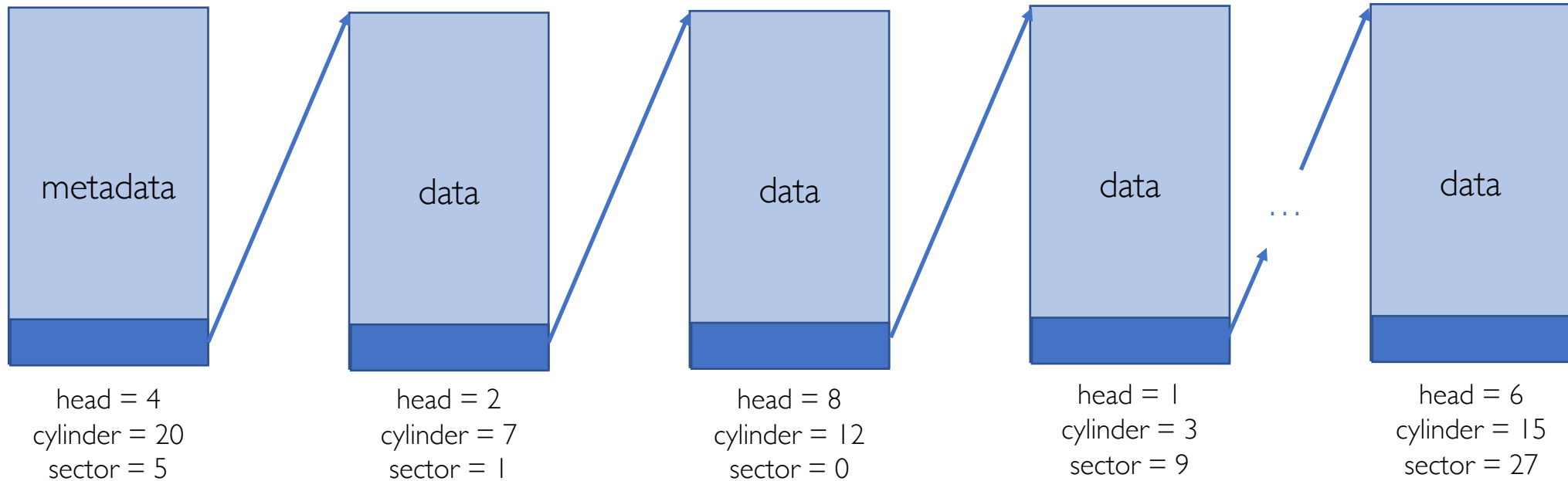
- Hard to change file size (may need to re-allocate it entirely to another location)
- Fragmentation (may need to run compaction/defragmentation)

Option 2: Linked Files

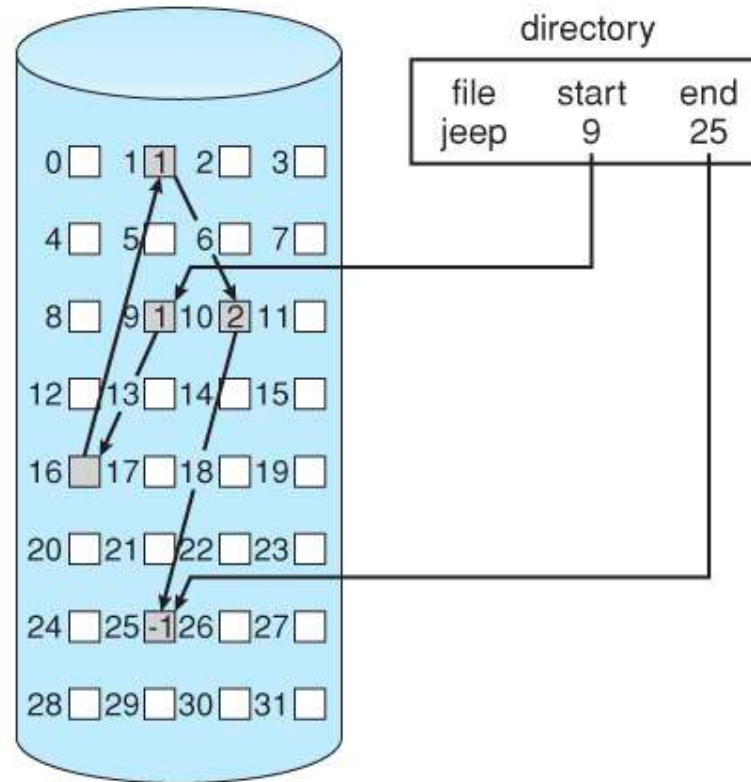
- The OS keeps a linked list of free (not necessarily contiguous) blocks
- The OS keeps also a linked list of where subsequent blocks are located
- This frees the file to be physically located sequentially
- Keep a pointer to the first block of the file in the file descriptor
- Keep a pointer to the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

Option 2: Linked Files

File Descriptor



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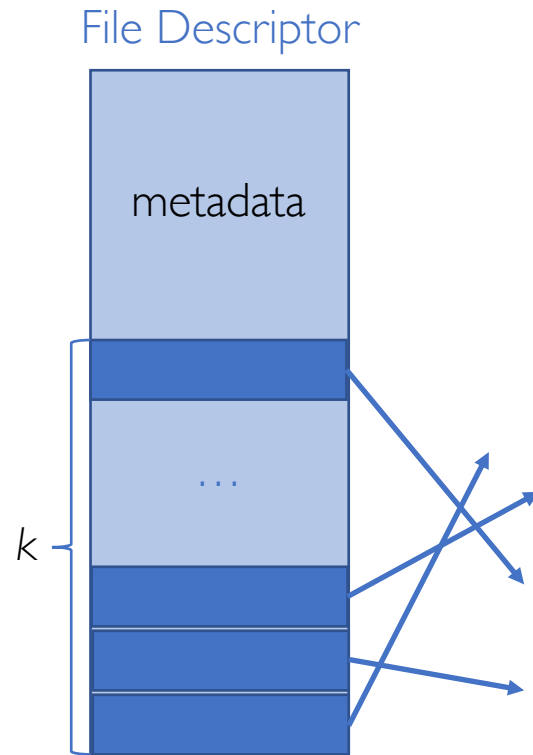
- CONs:

- 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

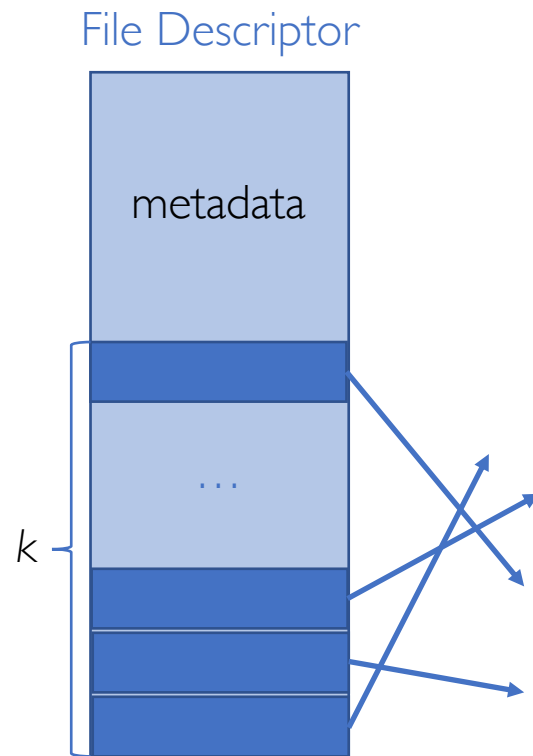
- The file descriptor contains a block of pointers (vs. only 1 pointer as in the linked list approach)
- The user or OS must declare the maximum length of the file when it is created
- OS allocates an array to hold the pointers to all the blocks when it creates the file, but allocates the blocks only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

Option 3: Indexed Files



The number of block pointers k determine the maximum file size the system can manage

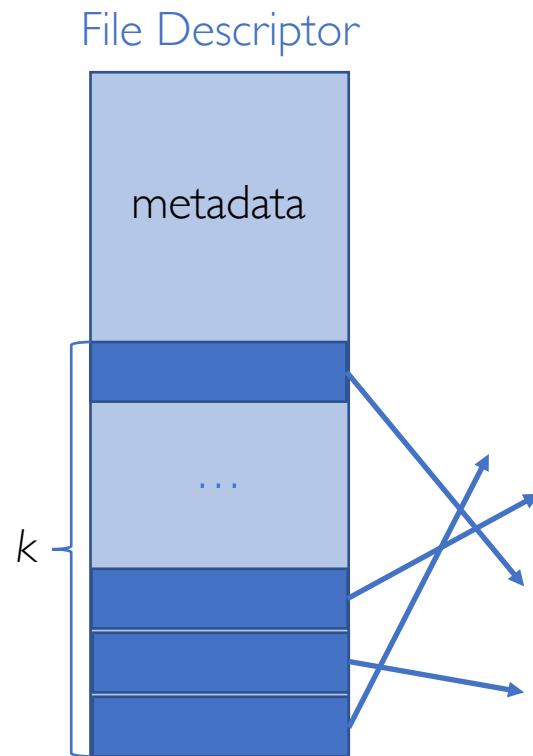
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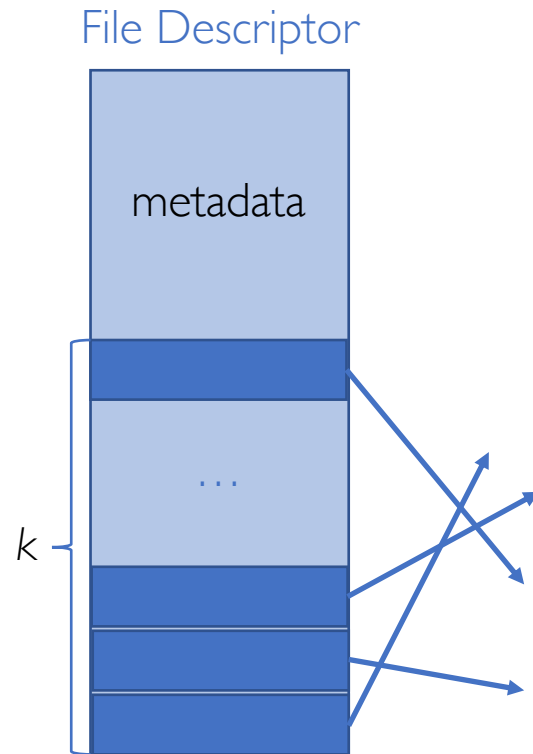


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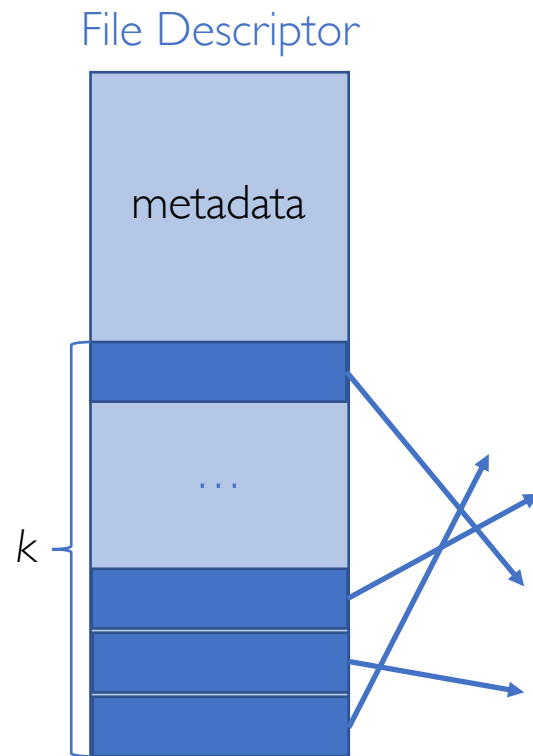
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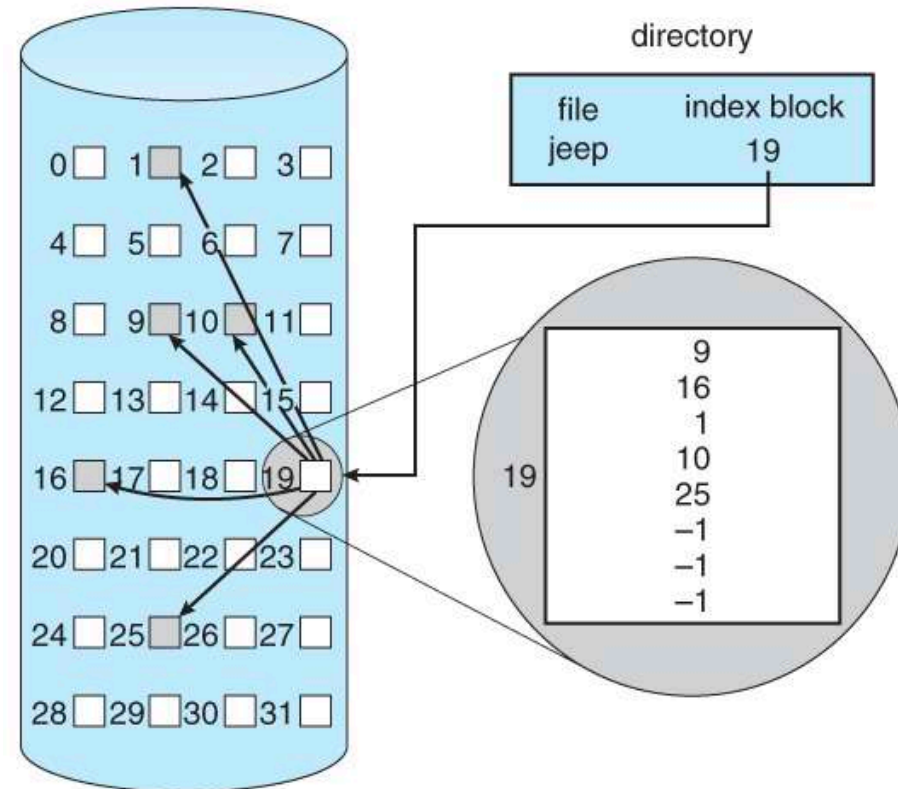
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Of course, only pointers to blocks are allocated on the file descriptor, not the blocks themselves!

Option 3: Indexed Files



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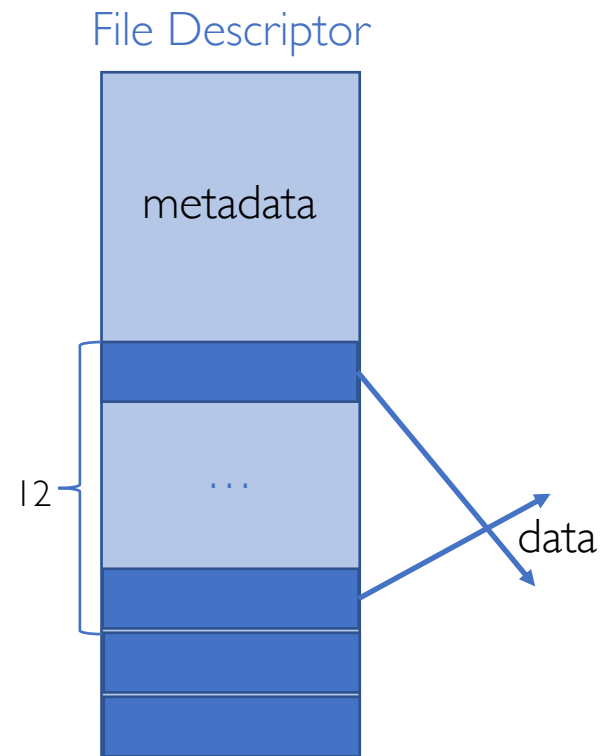
- CONs:

- 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

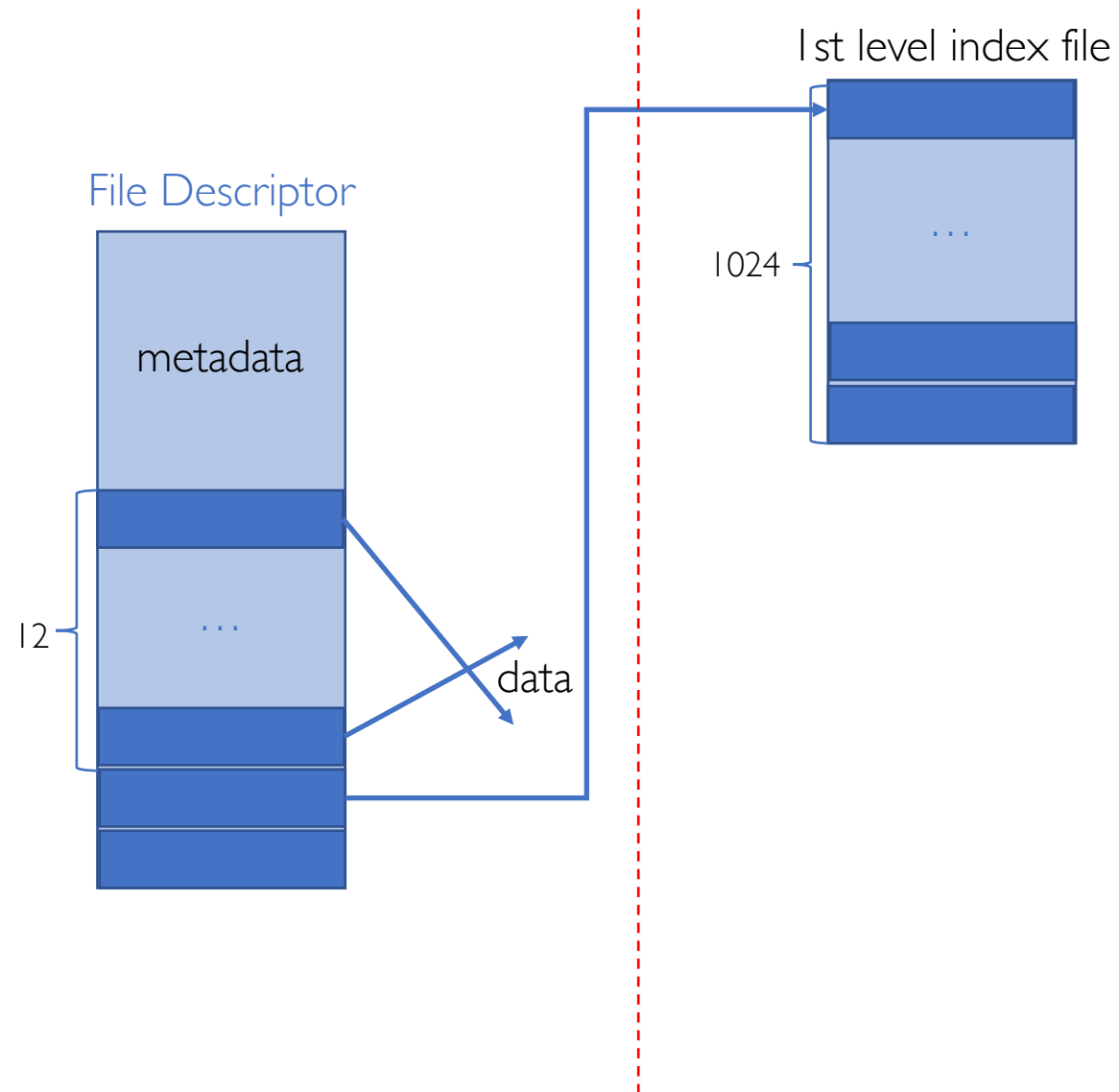
Option 4: Multi-Level Indexed Files

- 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

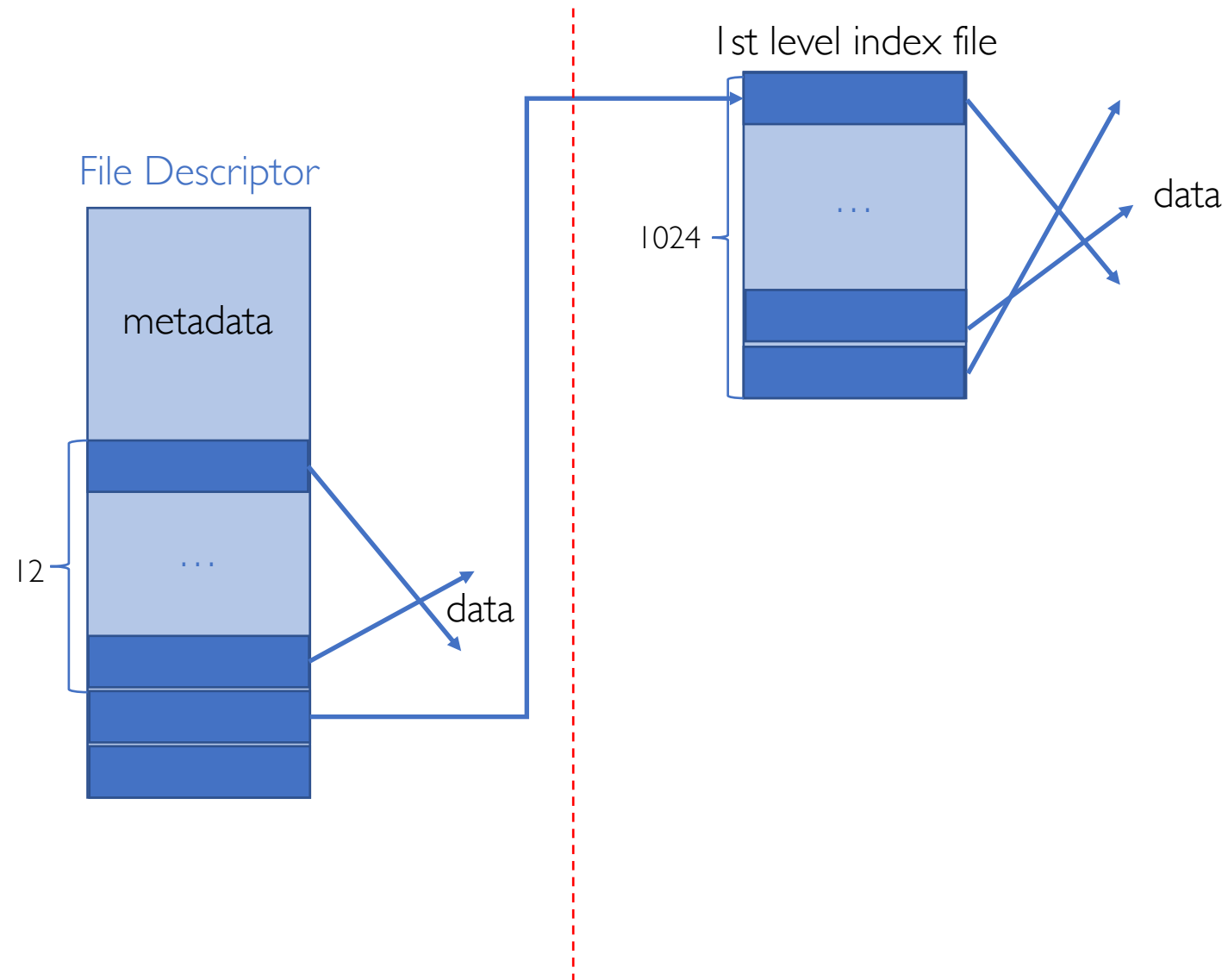
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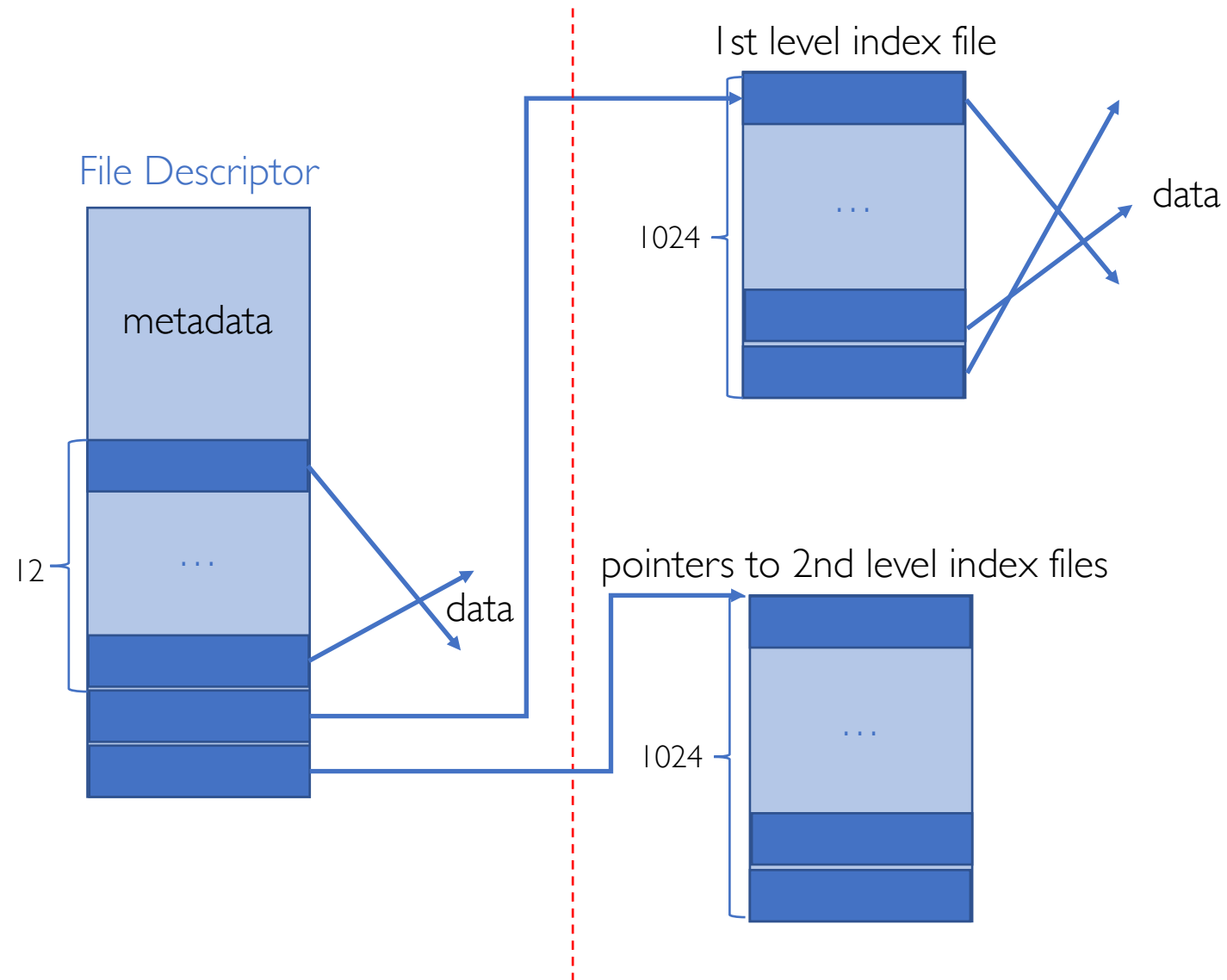
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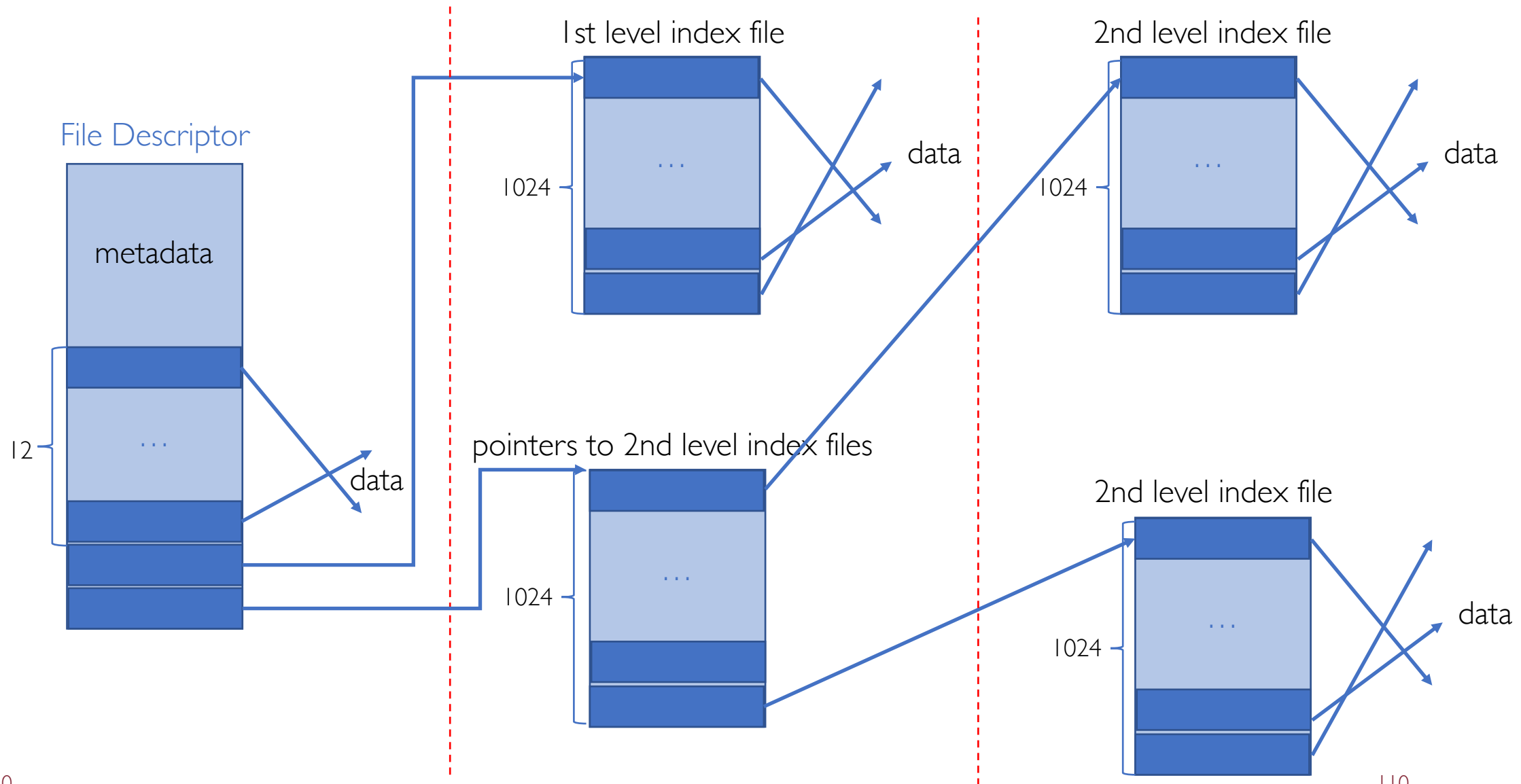
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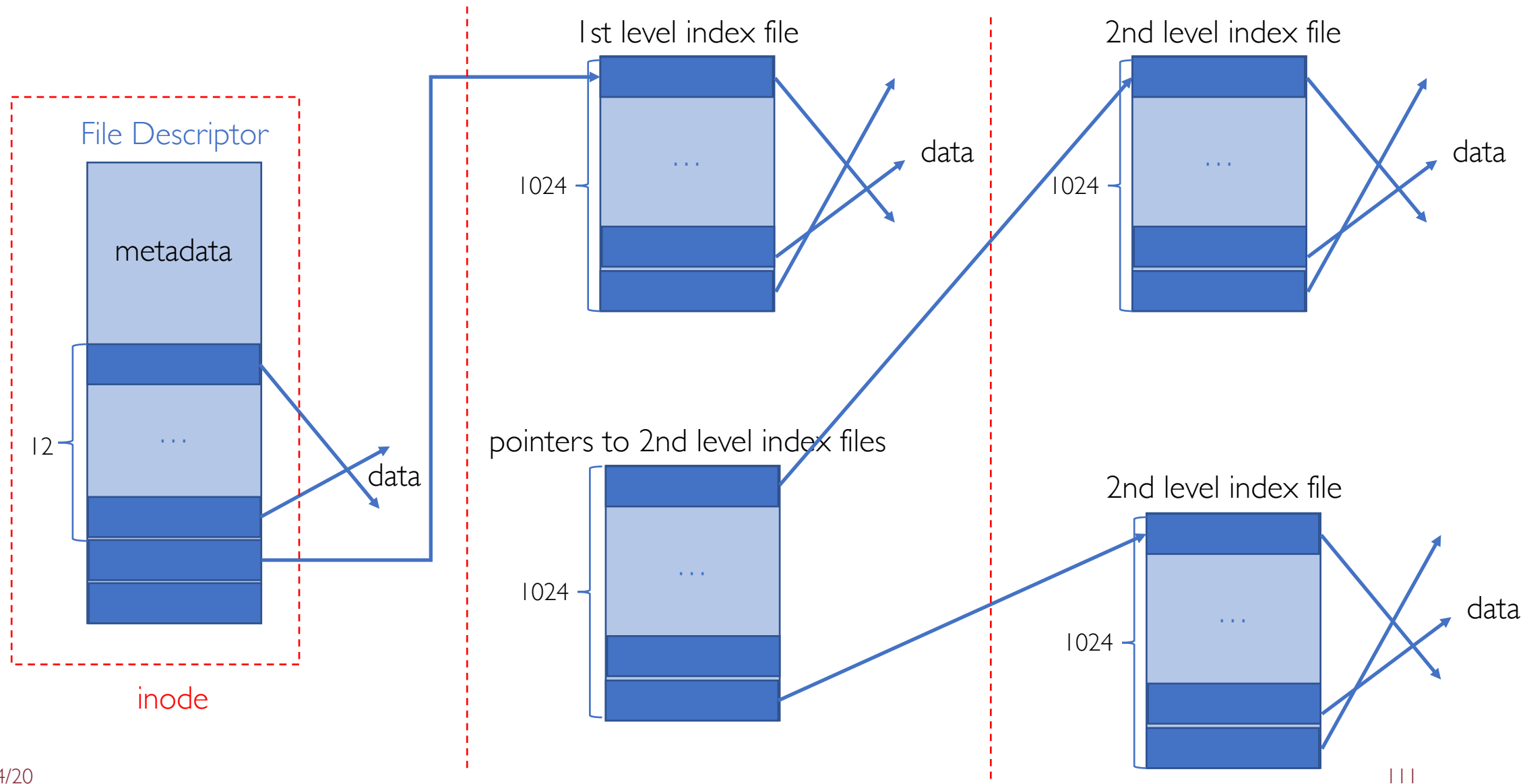
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In general, $\sim k^l$ if k = n. of block pointers and l = n. of levels

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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 blocks 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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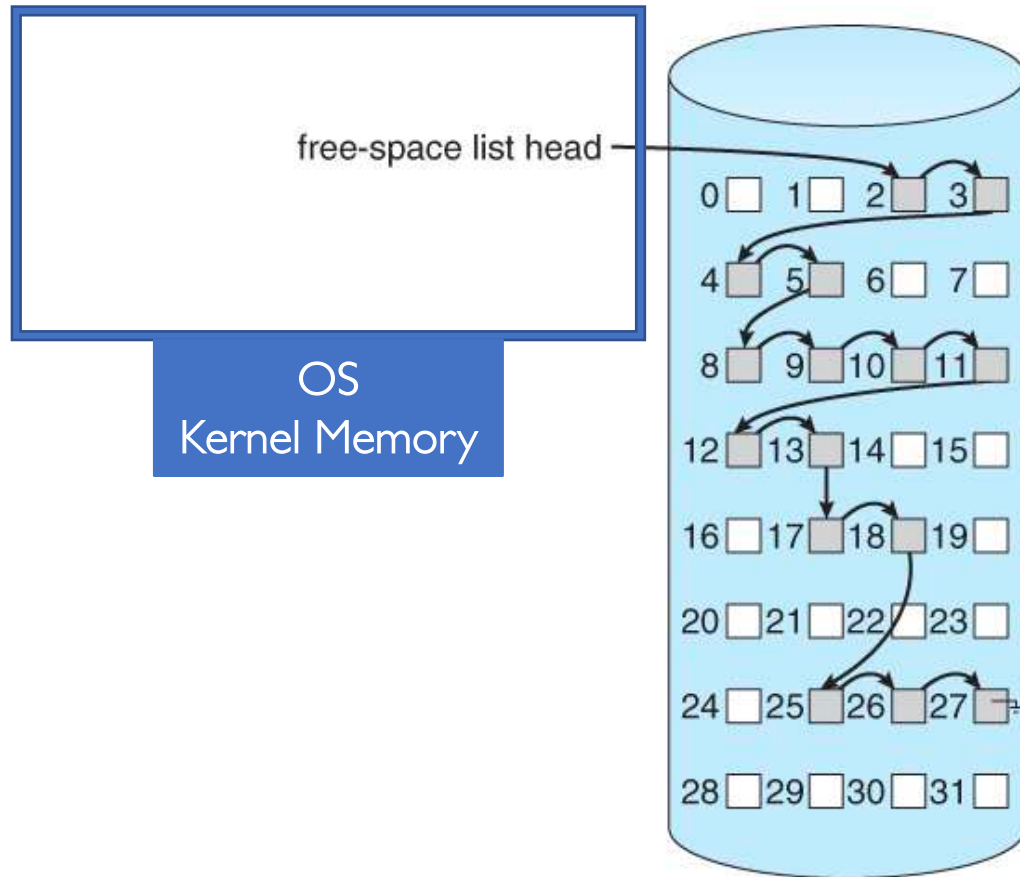


$\sim 4,000,000,000$ bitmap entries = 500,000,000 bytes = 500MB

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

Free Space Management: Linked List



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- 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