K22 – Operating Systems: Design Principles and Internals

Fall 2025 @dit

Vaggelis Atlidakis

Lecture 20

References: Similar OS courses @Columbia, @Stanford, @UC San Diego, @Brown, @di (previous years); and textbooks: Operating Systems: Three Easy Pieces, Operating Systems: Principles and Practice, Operating System Concepts, Linux Kernel Development, Understanding the Linux Kernel

Overview

- We'll start from hardware and follow a question-oriented approach
  - ~~Intro [Q: What is an OS?]~~
  - ~~Events [Q: When does the OS run?]~~
  - ~~Runtime [Q: How does a program look like in memory?]~~
  - ~~Processes [Q: What is a process?]~~
  - ~~IPC [Q: How do processes communicate?]~~
  - ~~Threads [Q: What is a thread?]~~
  - ~~Synchronization [Q: What goes wrong w/o synchronization?]~~
  - ~~Time Management [Q: What is scheduling?]~~
  - ~~Memory Management [Q: What is virtual memory?]~~
  - ~~Files [Q: What is a file descriptor?]~~
  - **Storage Management [Q: How do we allocate disk space to files?]**

* Basic (H/W & S/W)
* Abstractions
* Primitives
* Mechanisms

Overview

- **Storage**
  - **Q1**: Allocating storage space to files?
  - **Q2**: File system layout?
  - **Q3**: Files and directory names?
  - **Q4**: Path name resolution?
  - **Q5**: Linux file system data structures?
  - **Q6**: Achieving crash tolerance?
  - **Q7**: Achieving fault tolerance?

Allocating storage space to files

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- Be proactive => Prefetch data (leverage spatial locality)
- Hide latency => Do slow storage operations asynchronously

Calculating major vs minor page fault latency

```c
int main(int argc, char **argv) {
    // Assuming file already exists at path
    if ( (fd = open("/tmp/foo.txt", O_RDONLY, 0664)) < 0)
        return -1;
   char *buf = mmap(NULL, page_size, PROT_READ, MAP_PRIVATE, fd, 0);
   start_time = clock_gettime_ns();
   char a = buf[0];
   end_time = clock_gettime_ns();
   printf("time elapsed: %lu ns (1st read) \n", end_time -  start_time);
   start_time = clock_gettime_ns();
   char a = buf[0];
   end_time = clock_gettime_ns();
   printf("time elapsed: %lu ns (2nd read) \n", end_time -  start_time);
}
```

```
# 1 -> Drop in-kernel page caches
➜  git:(master) ✗  echo 1 | sudo tee /proc/sys/vm/drop_caches
1
➜  git:(master) ✗  ./demo
Time elapsed: 448,834 ns (1-st read) <-- Major page fault / Going to strorage
Time elapsed: 41 ns (2-nd read)
➜  git:(master) ✗  ./demo
Time elapsed: 11,041 ns (1-st read) <-- Minor page fault / Staying in main mem.
Time elapsed: 42 ns (2-nd read)
```

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- Allocation strategies

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- Linked allocation
- Indexed allocation
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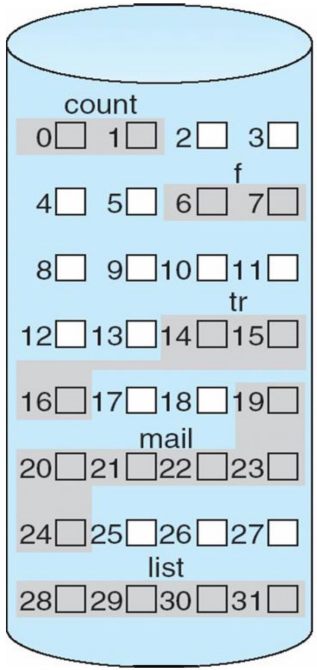

directory

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

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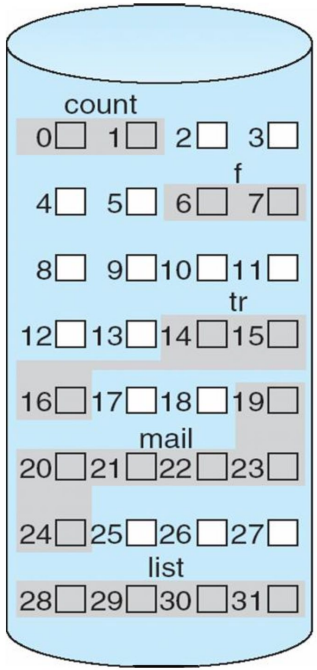
- Fast sequential access => Consecutive blocks
- Quick calculation of blocks for random accesses



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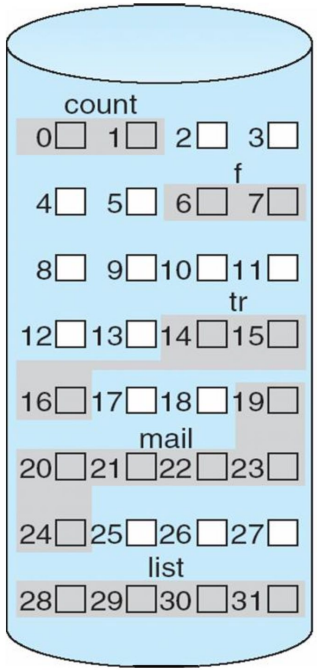
› Disadvantages

- Difficult to grow a file
- External fragmentation



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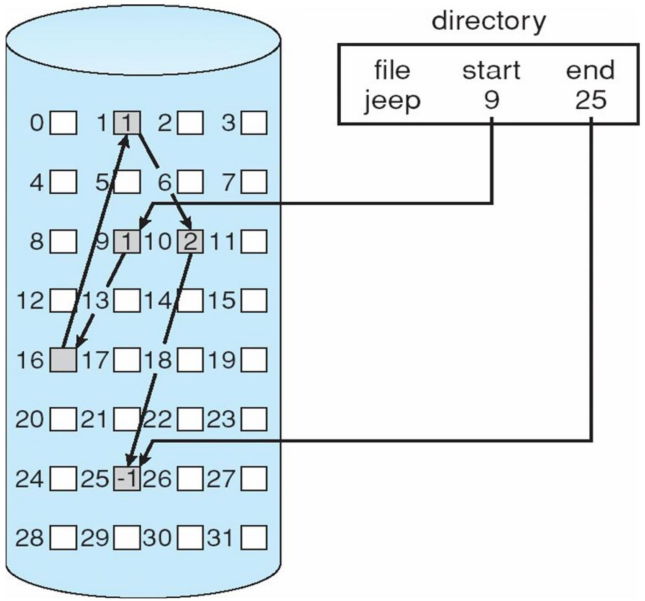

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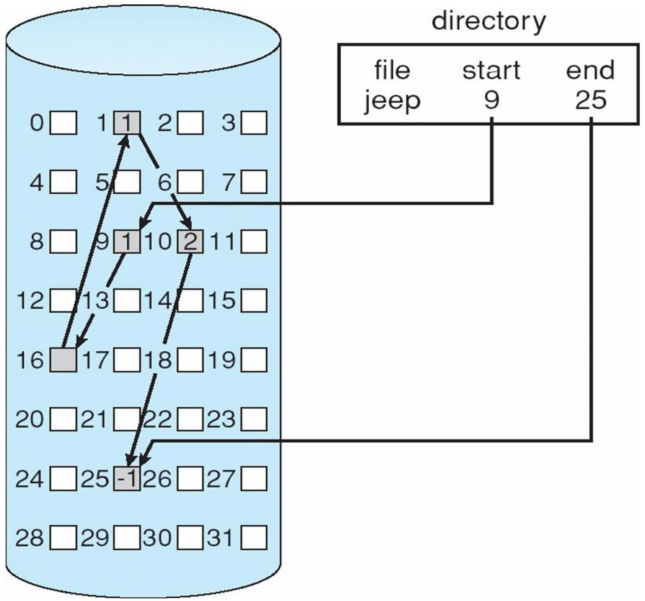

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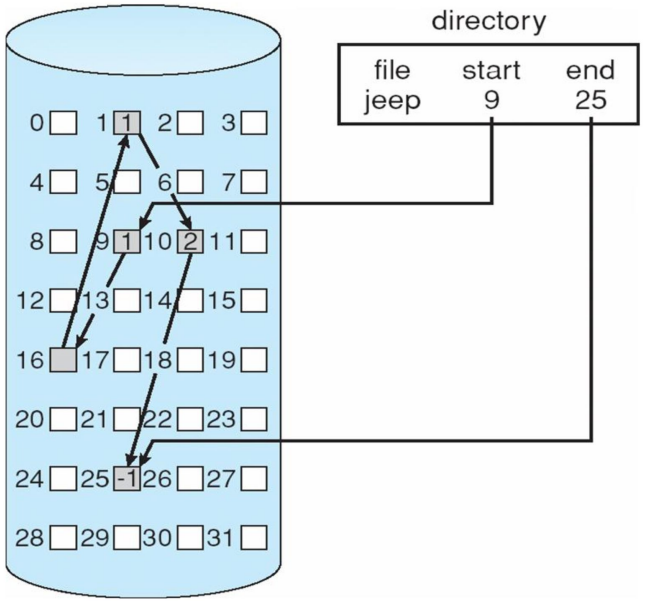

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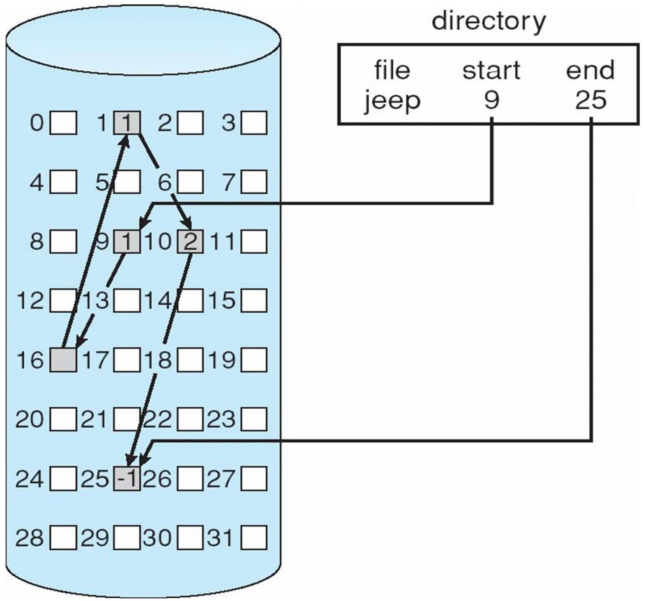

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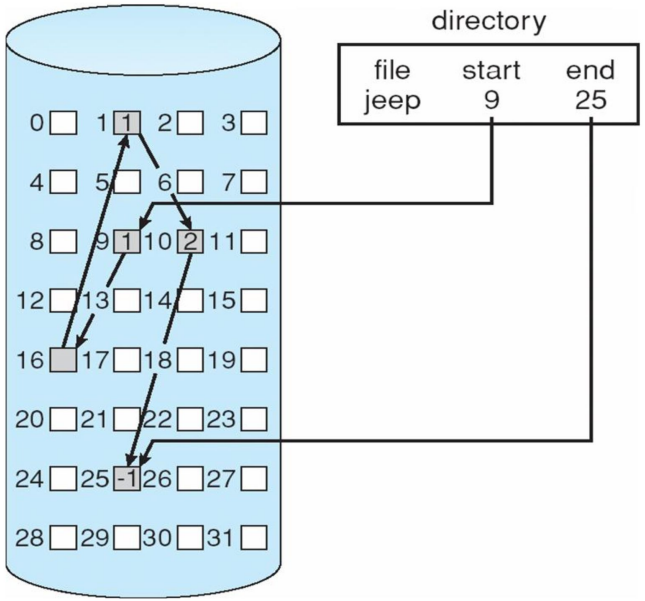

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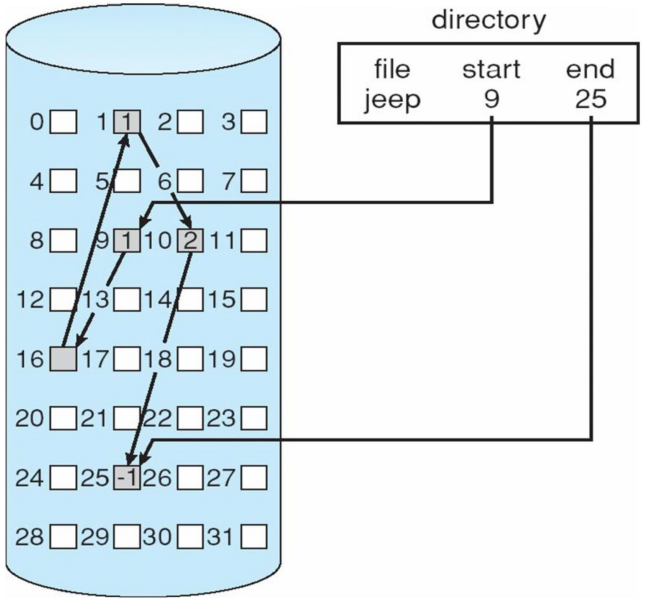
- **Unreliable:** Loose one block => loose everything



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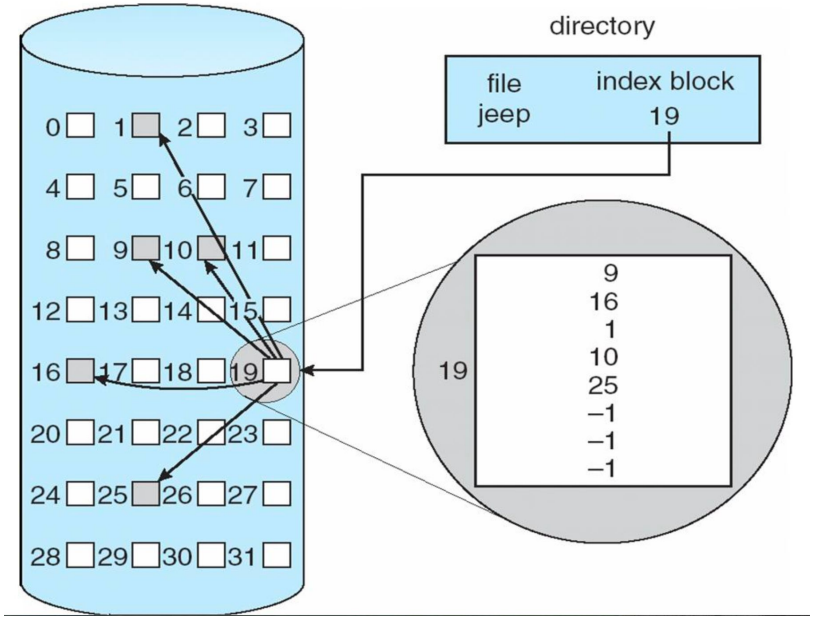

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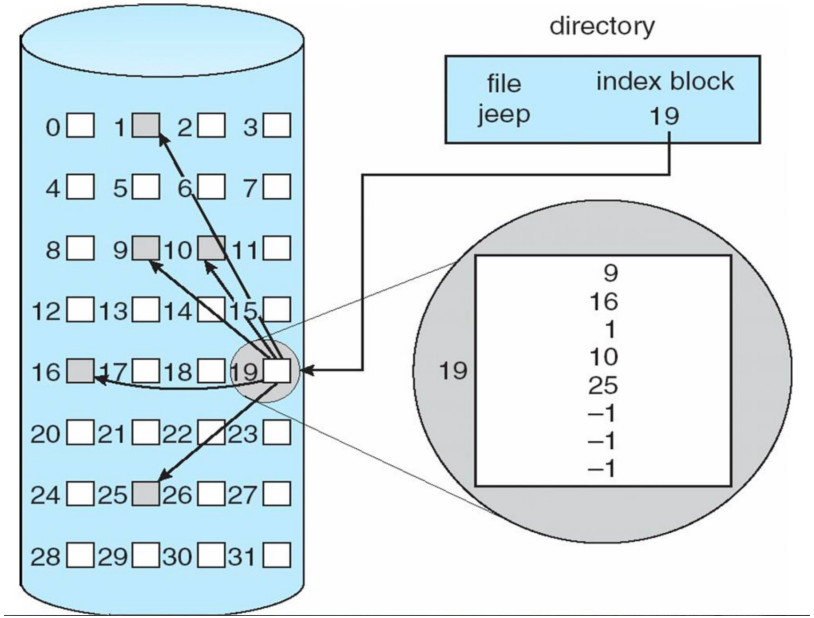

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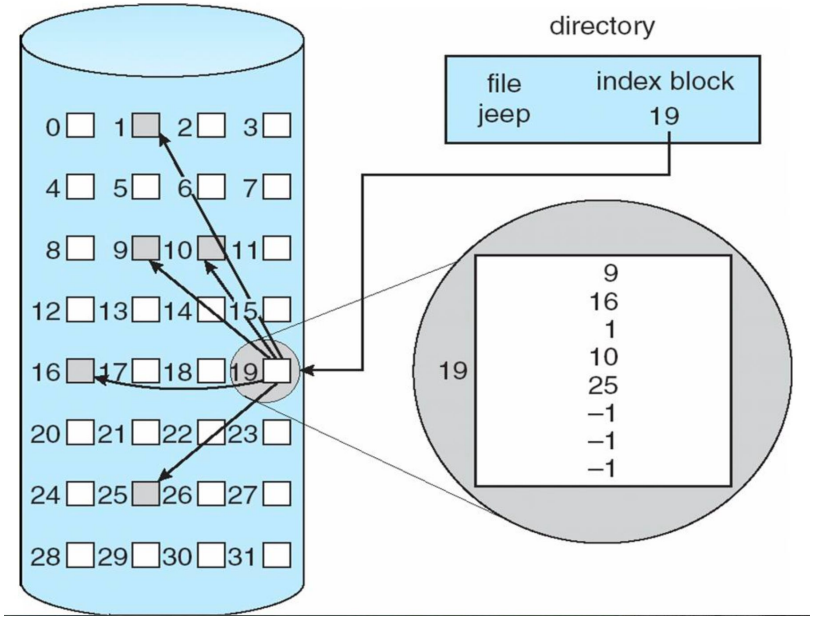

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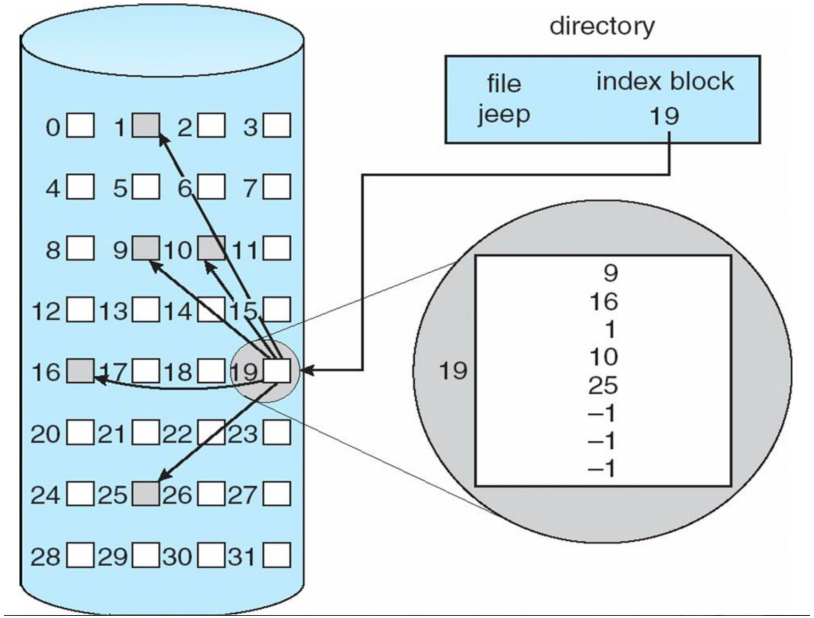

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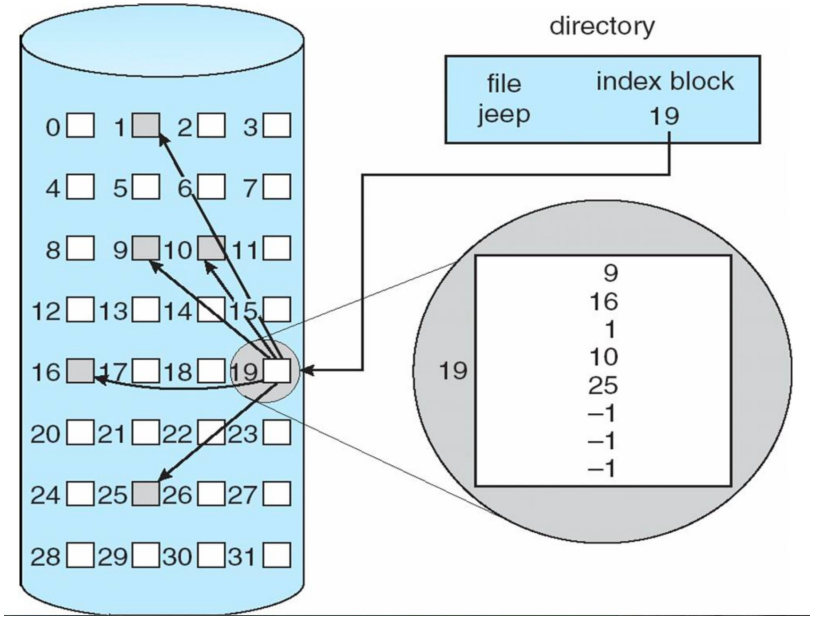

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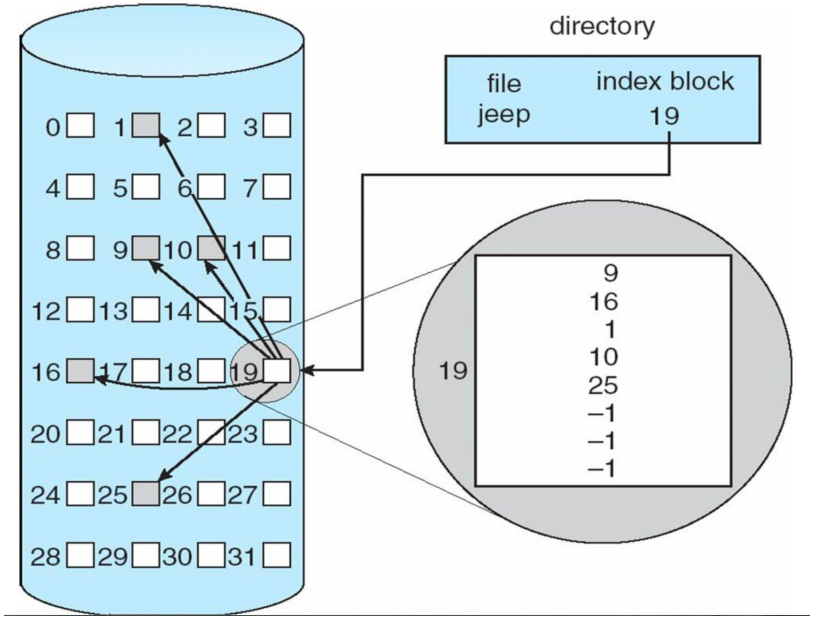
    …We've seen this story before!



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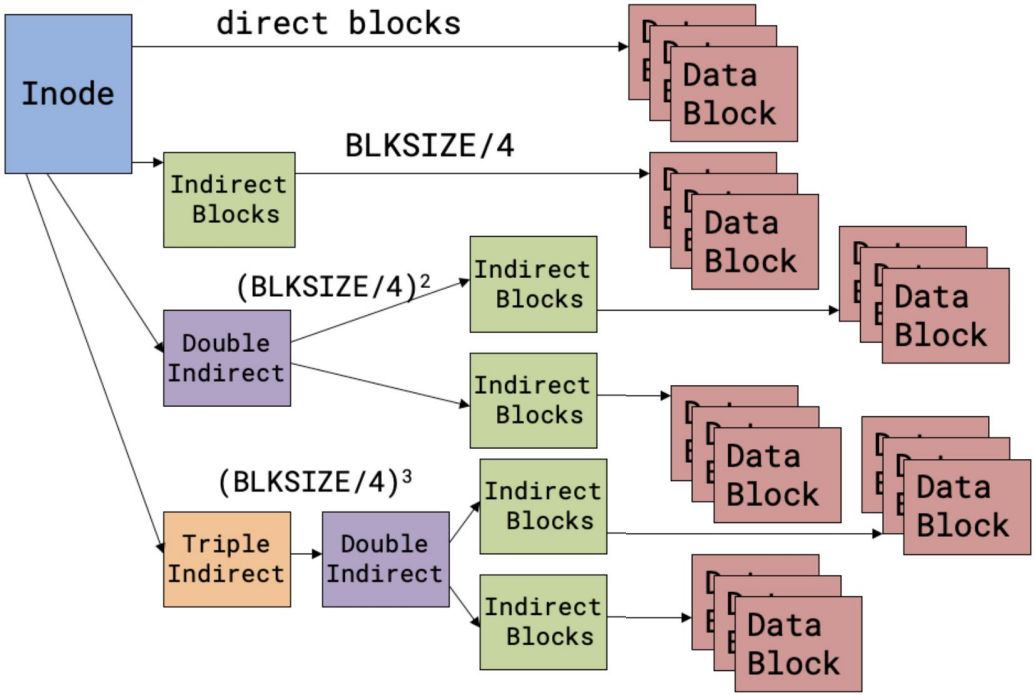

Image from: [COMS 4118, Operating Systems I]

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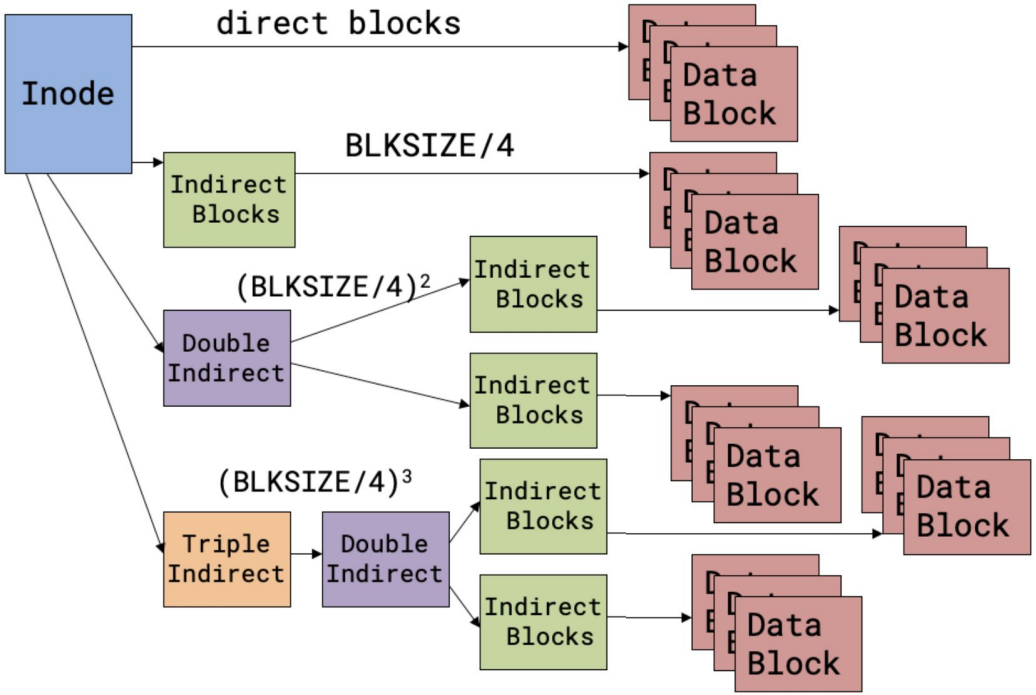

Assume 4KB blocks and 4 bytes ptrs

> **A typical 256 bytes inode has**

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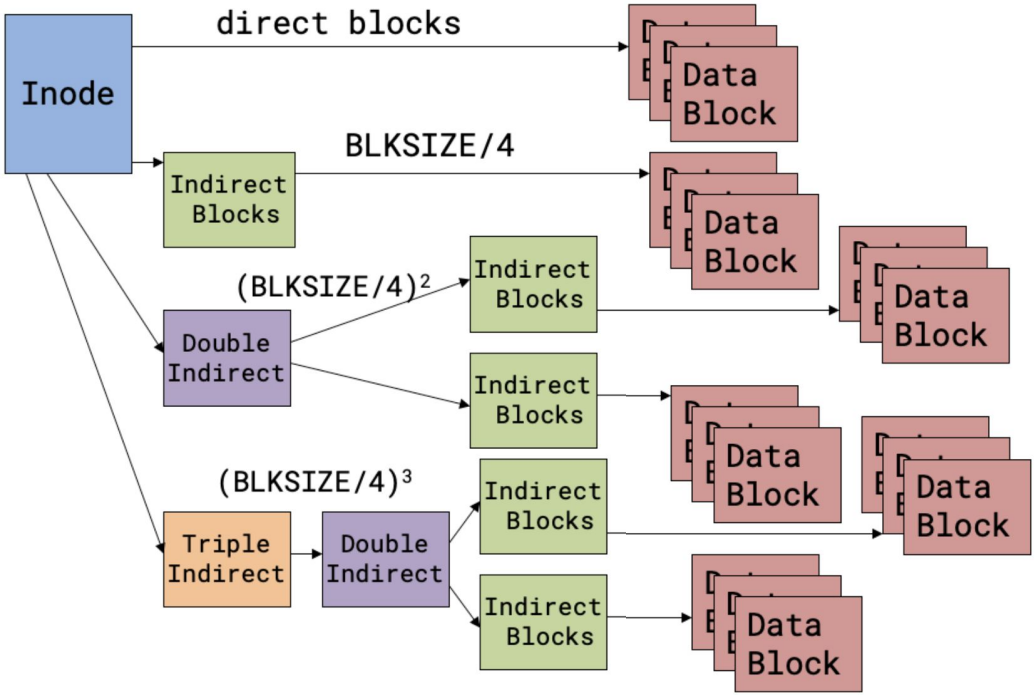

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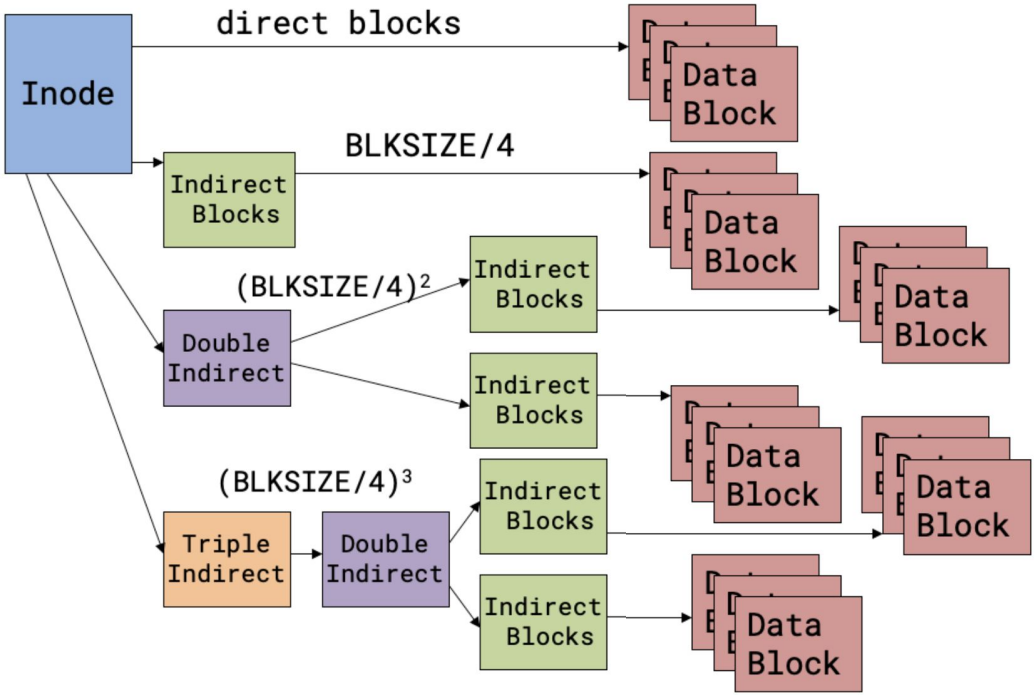

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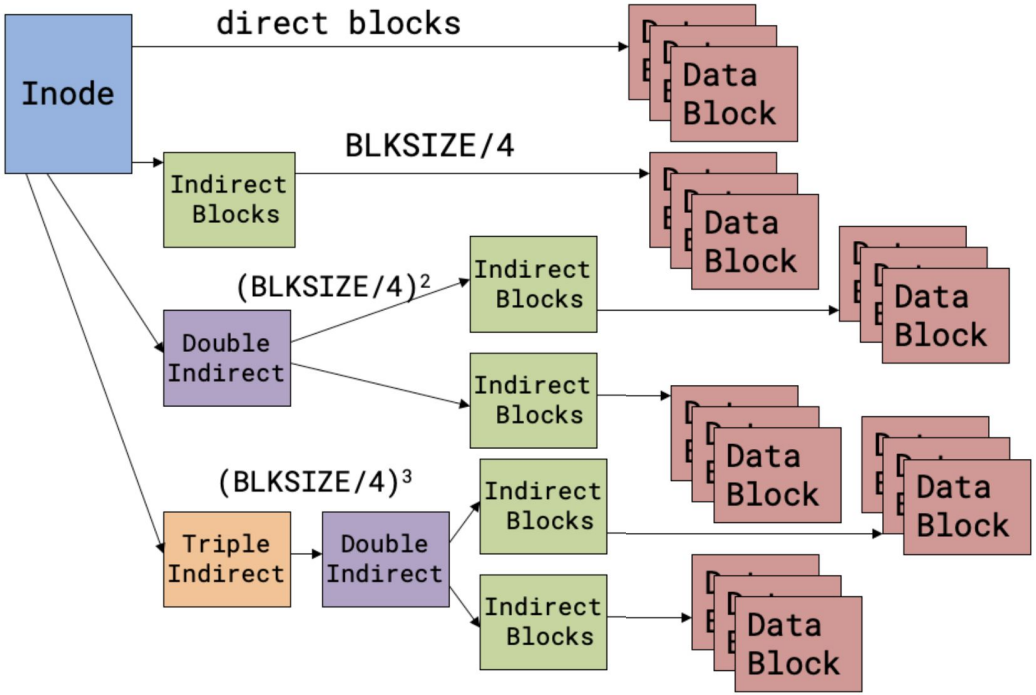

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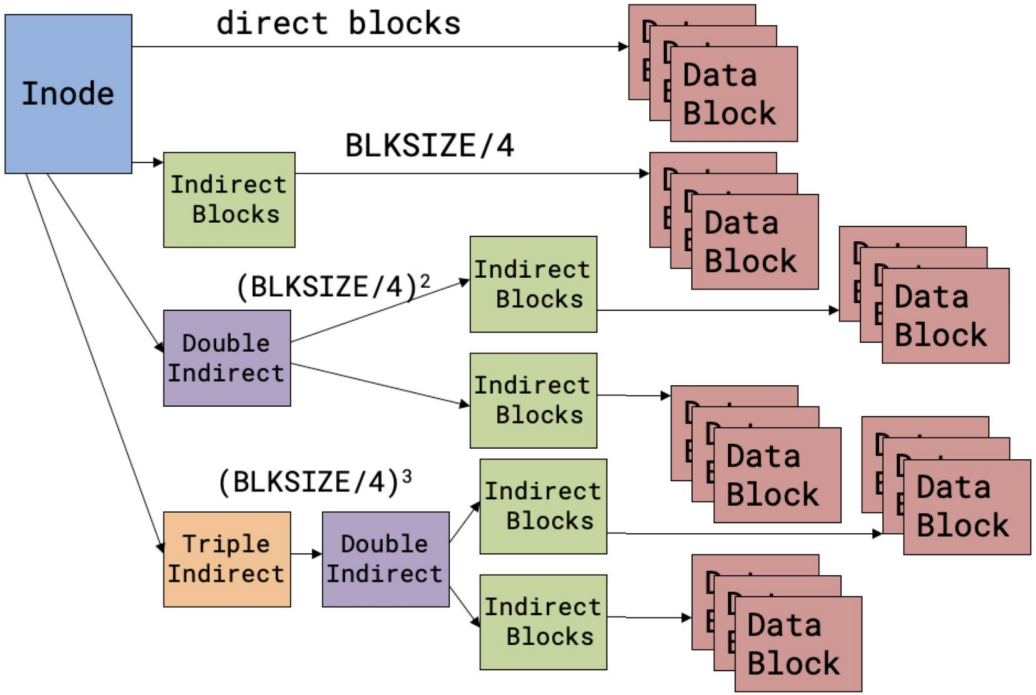

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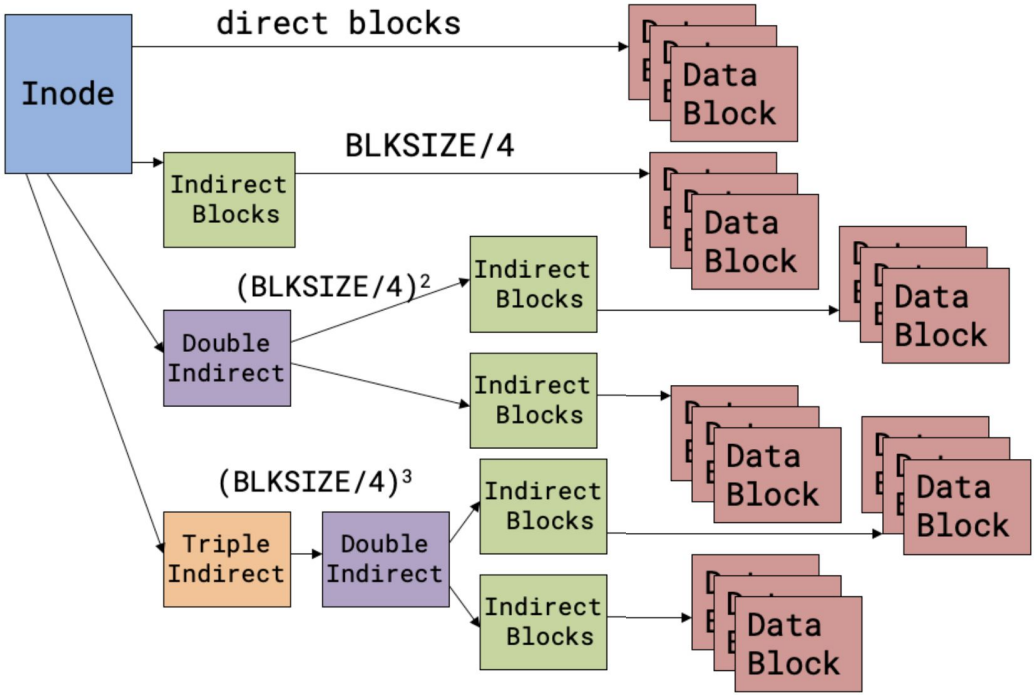

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Index grows dynamically, on demand...

Simplified Filesystem Layout (Linux ext2/3)

S	B	B	B	B	B	B	i	i	i	i	i	i	i	i
i	i	i	i	i	A			A	A	A	A			
A	A										A	A		A
A														
		A	A	A	A				A	A	A	A	A	

S — Superblock (holds pointer to the inode of root dir "/")

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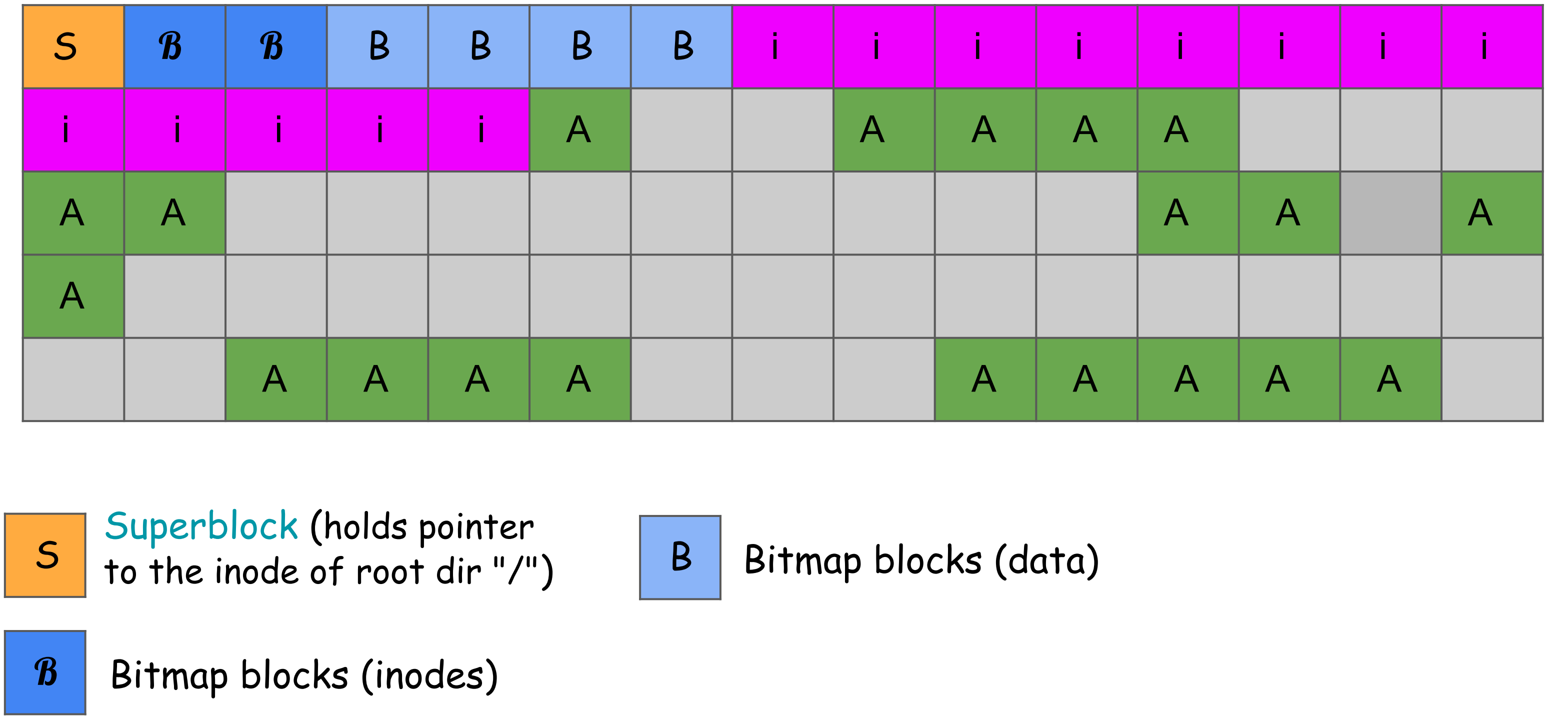

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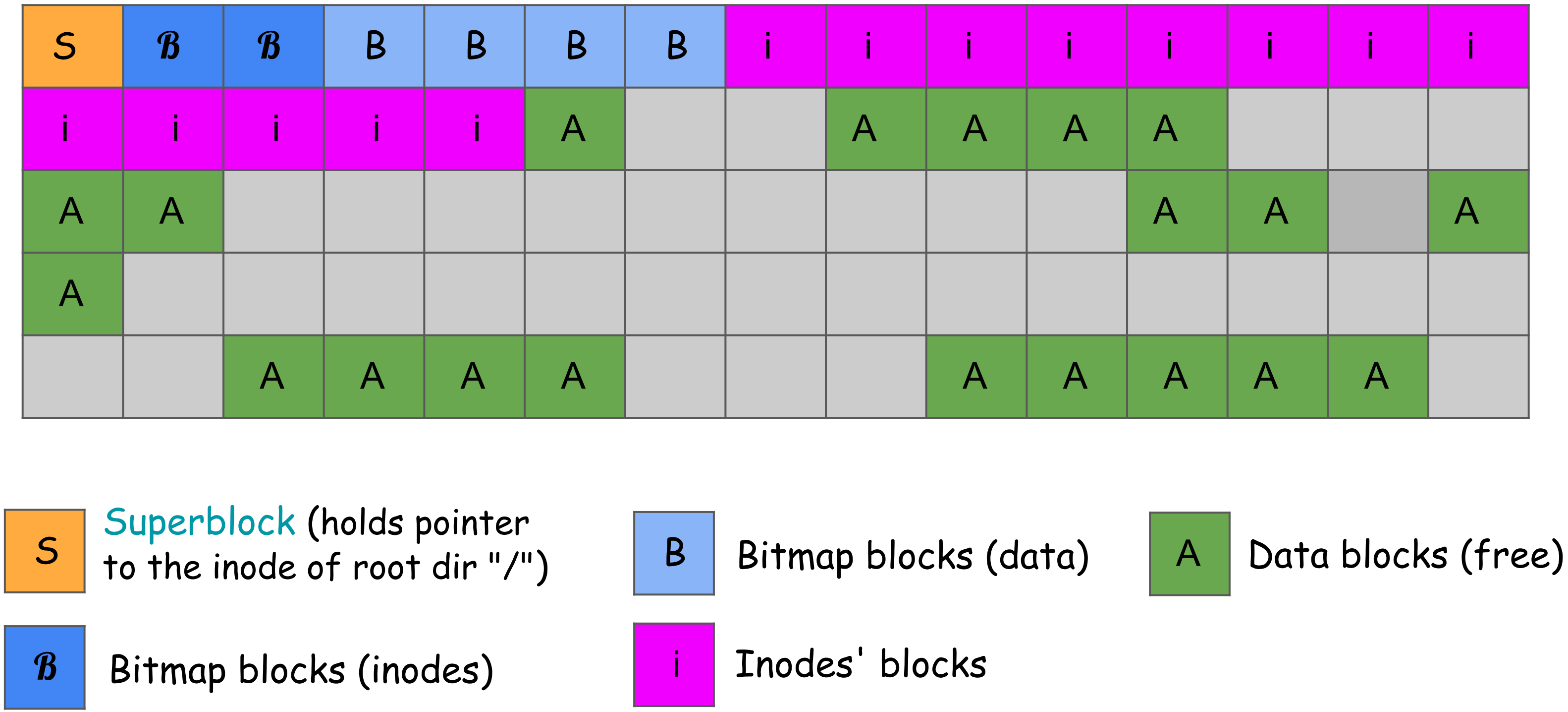

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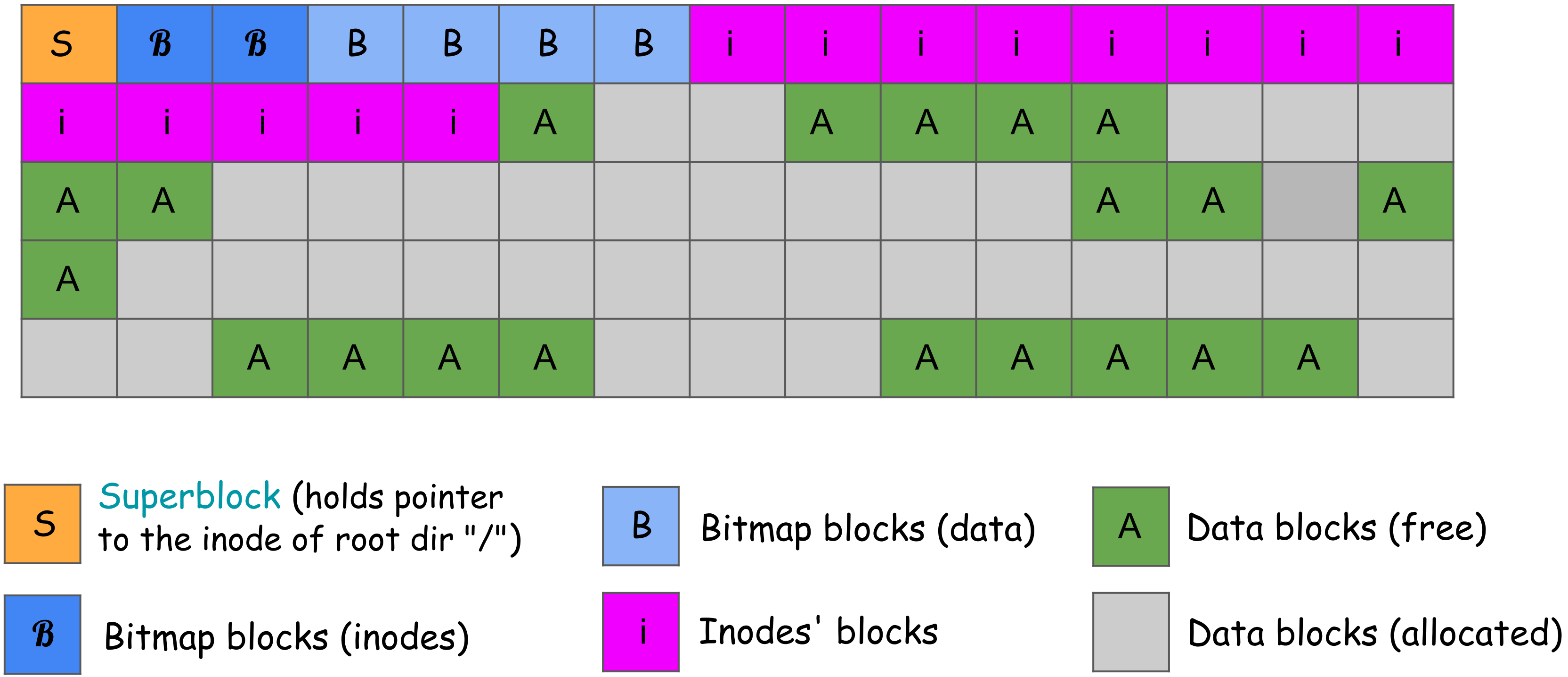

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> Soft link: Associates a name with an inode of a file containing paths to files

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Need to speed this translation disaster up

Linux File System Data Structures

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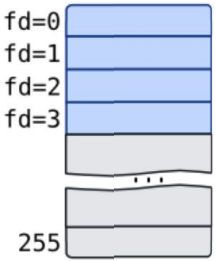
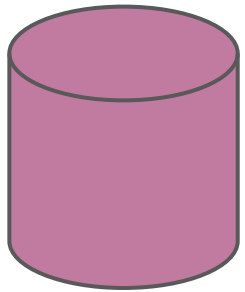
Per-process
fd table



Storage



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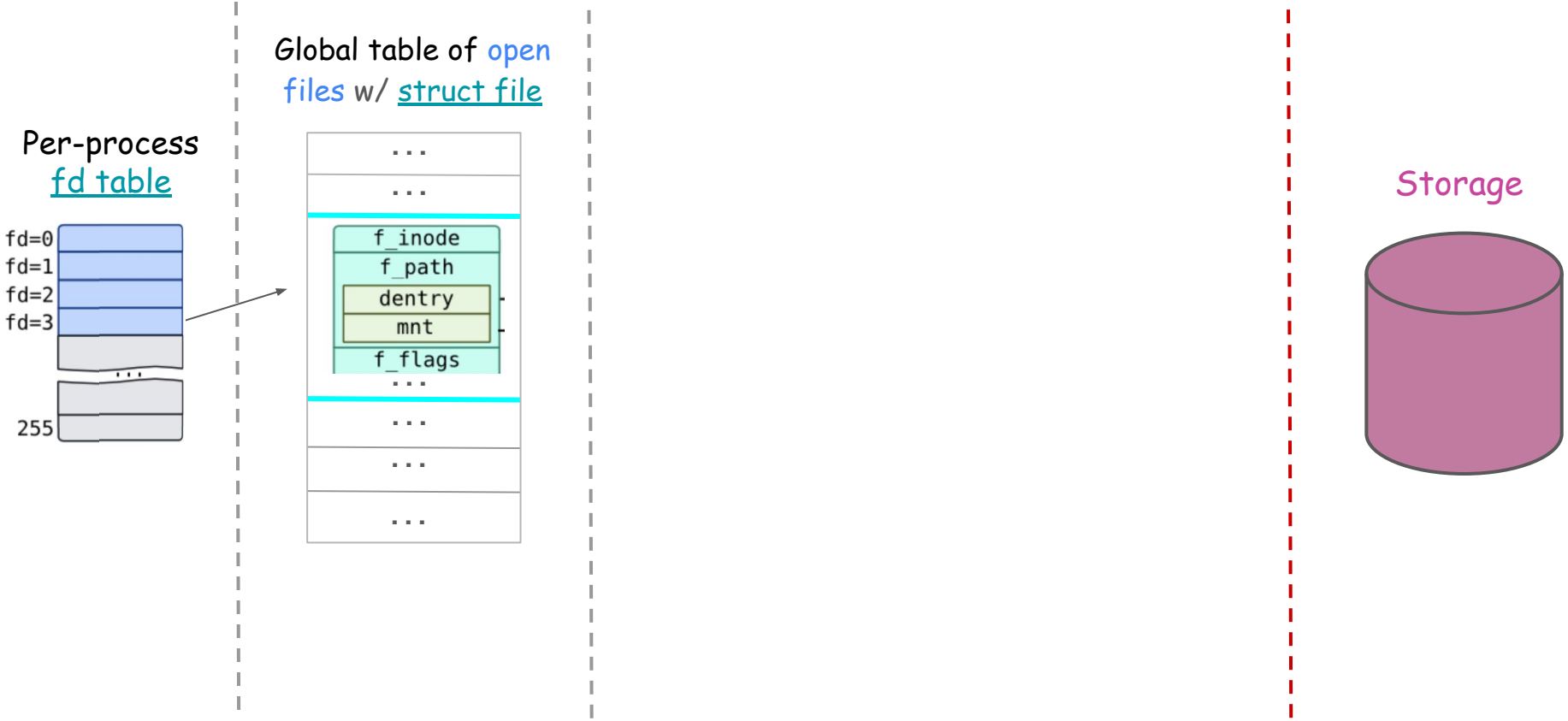

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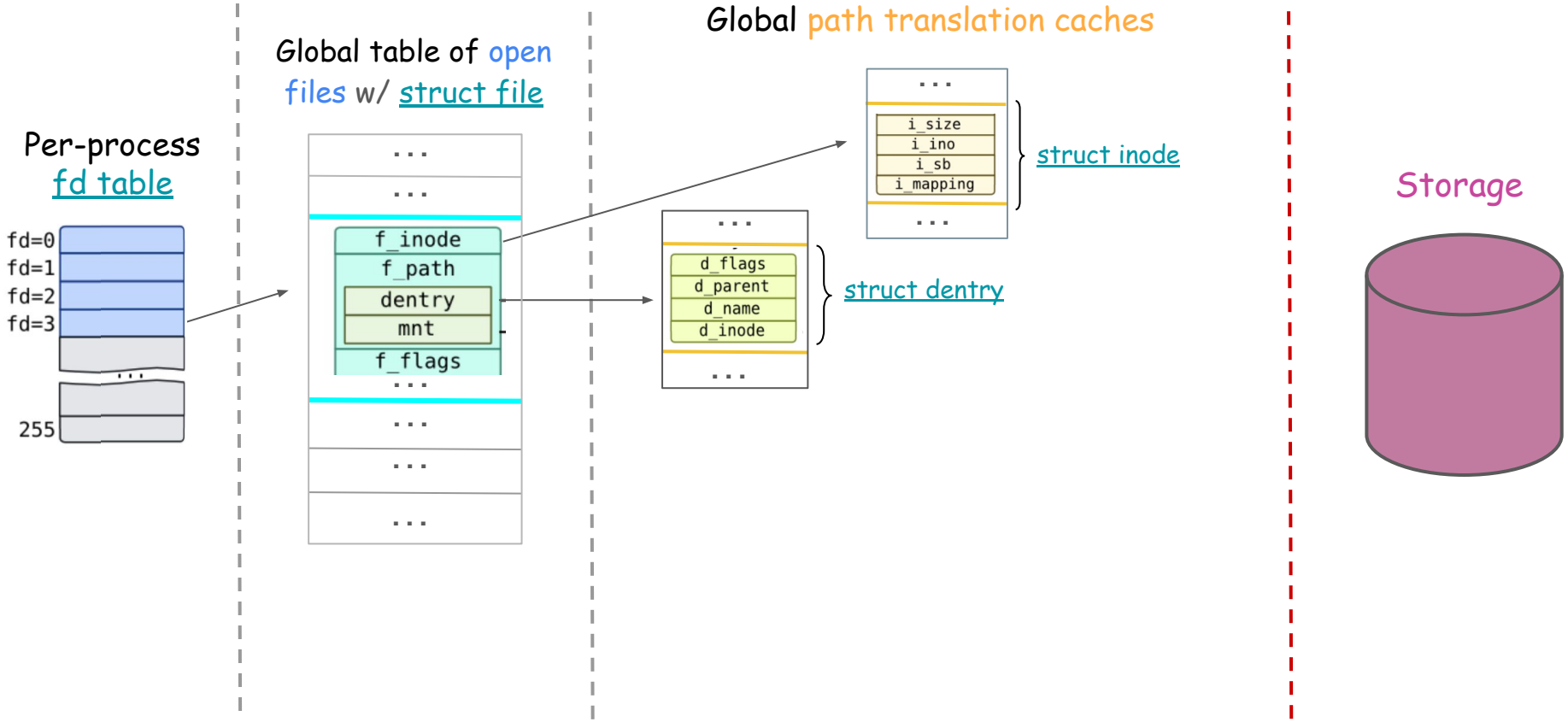

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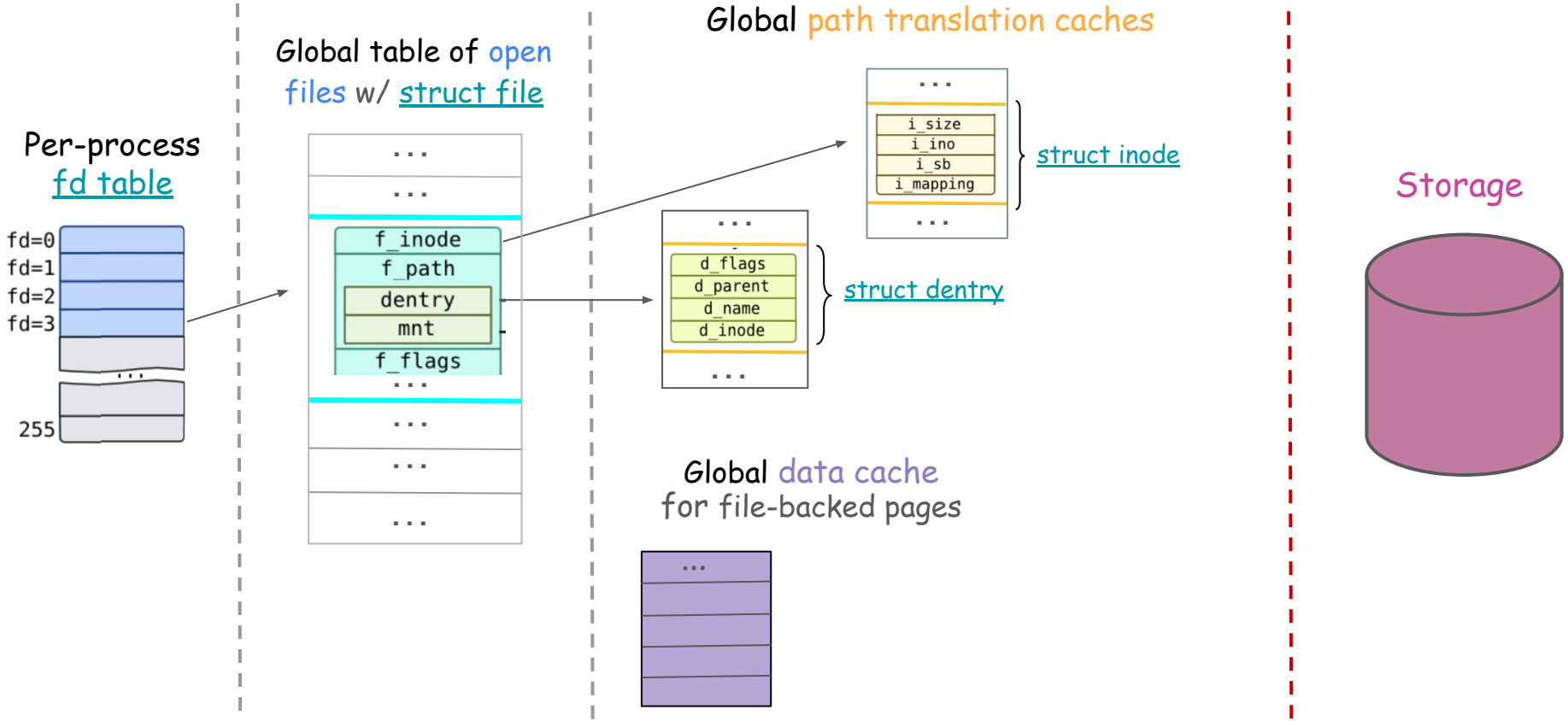

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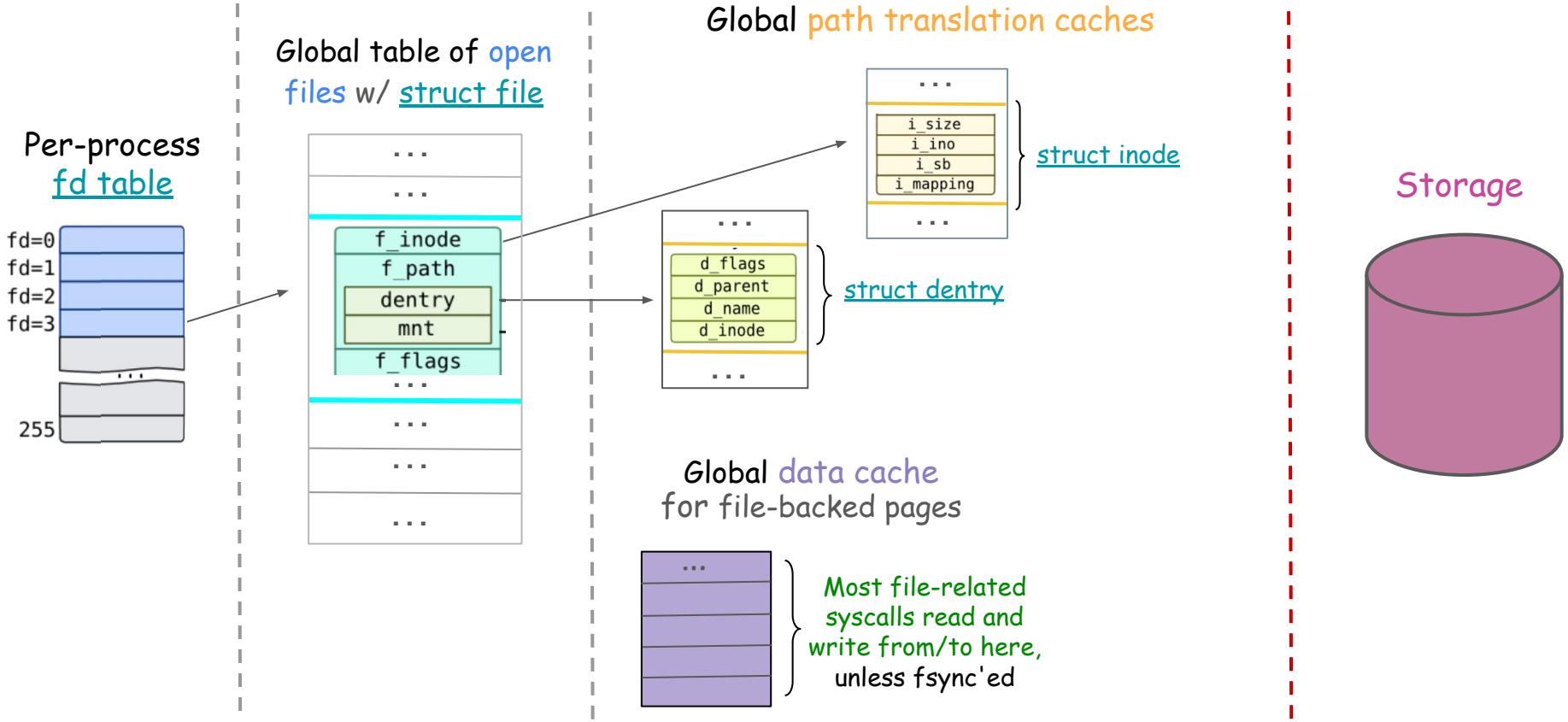

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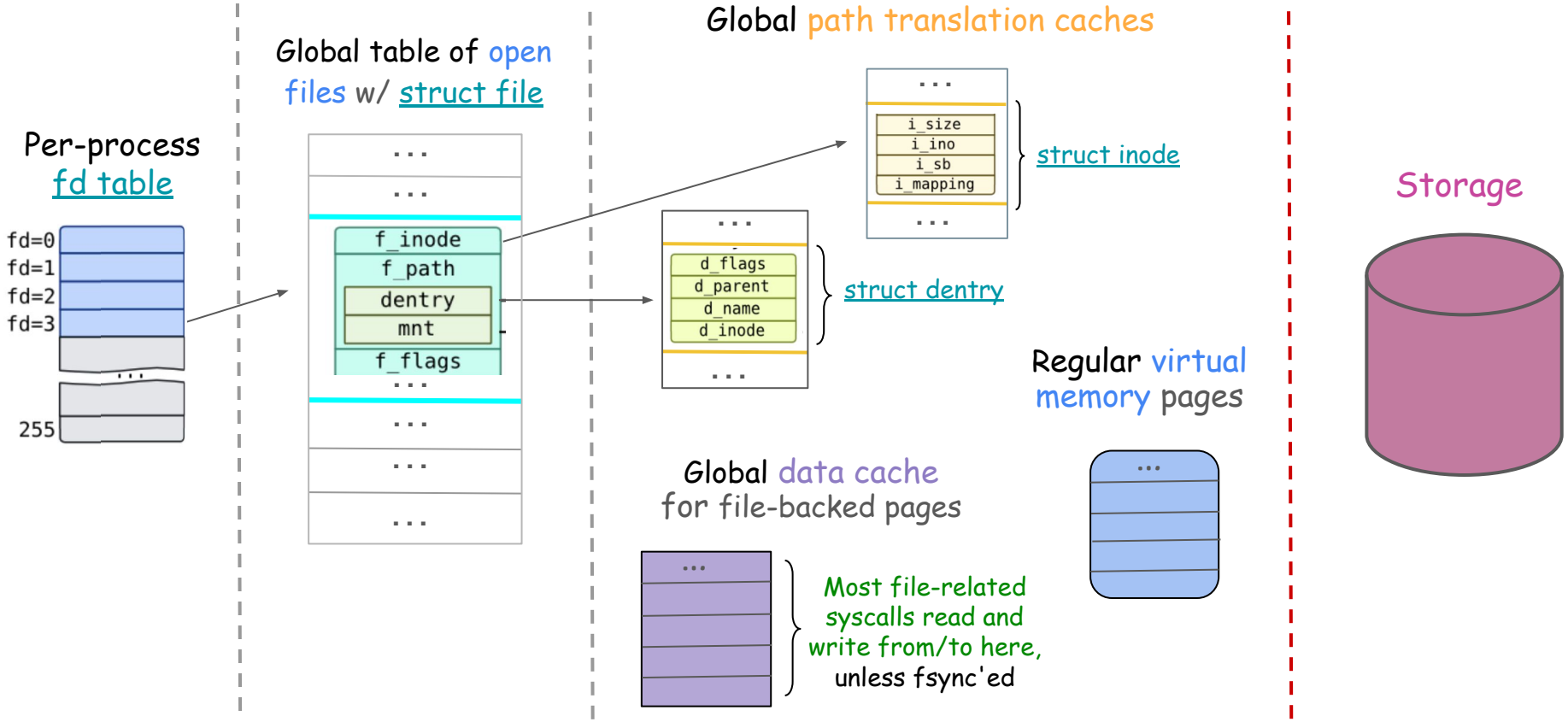

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} Could read garbage data—Example?

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- Cannot reorder writes and execute asynchronously <= Dealbreaker

Journaling (also called "write-ahead" logging)

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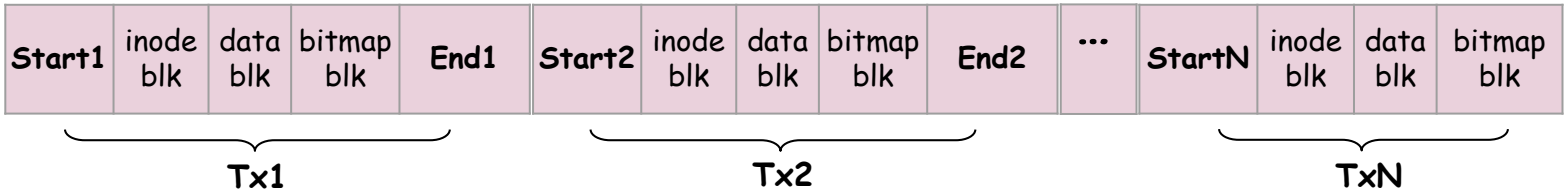

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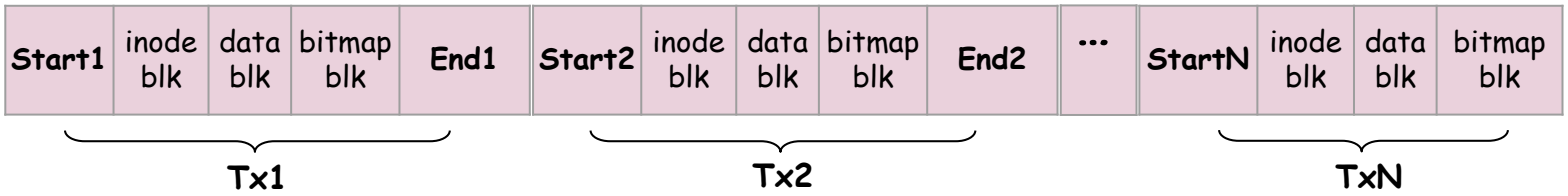

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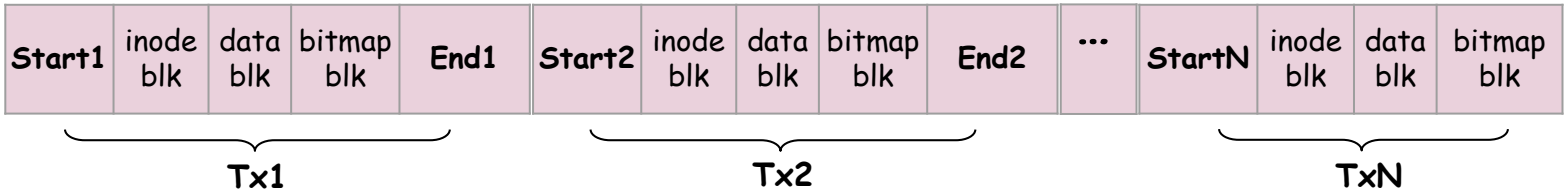

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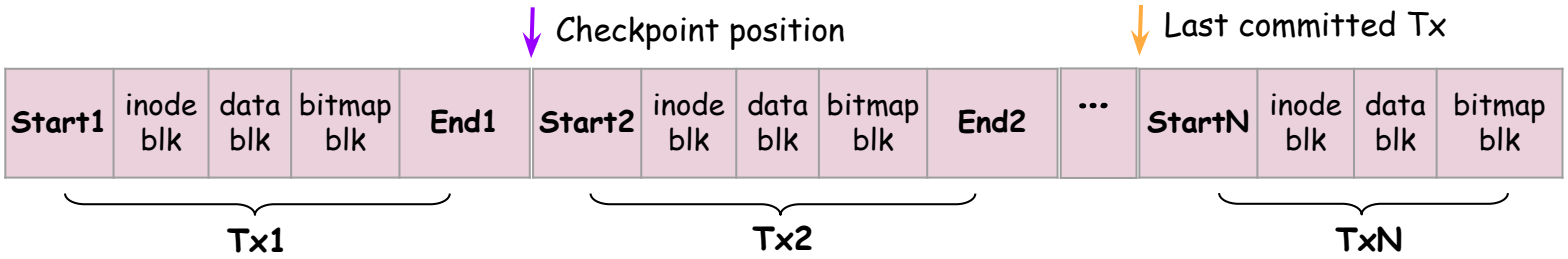

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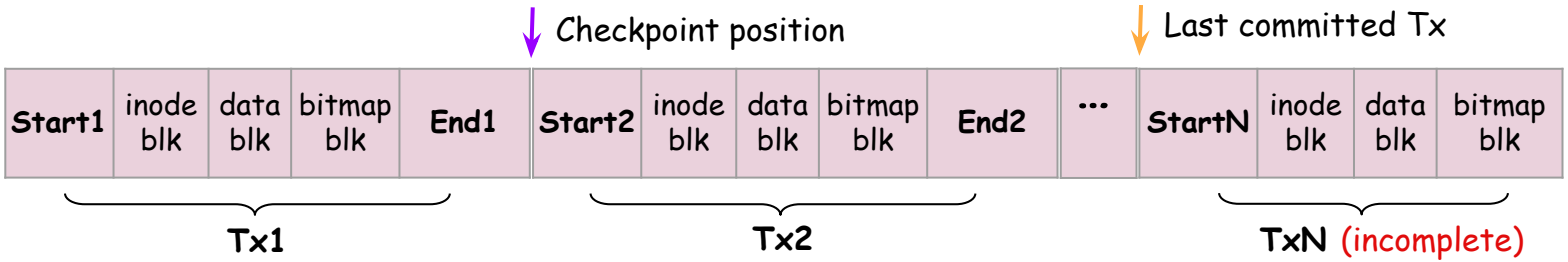
Crash occured? Replaying committed transactions after the last checkpoint will bring the fs to a consistent state (crash tolerance)



Fault Tolerance

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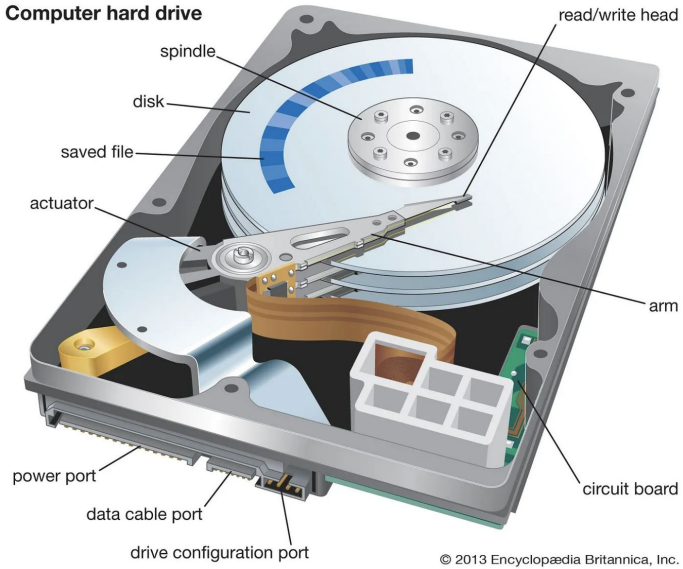

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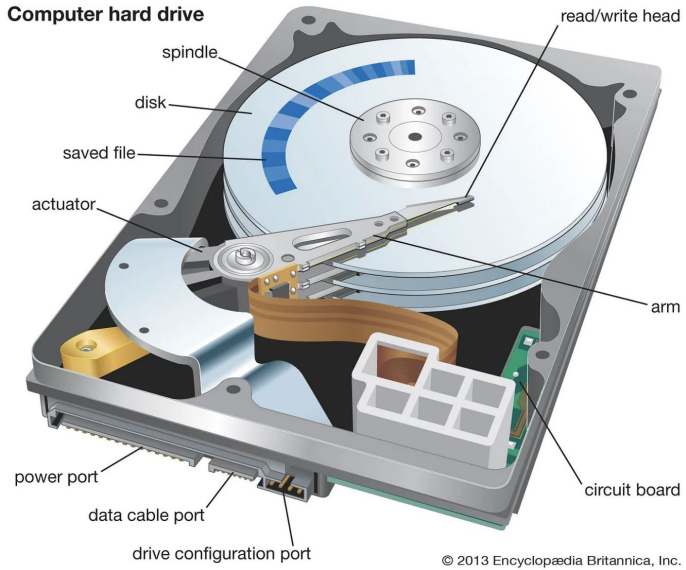

It is impressive that this piece of machinery carried us for so many decades...

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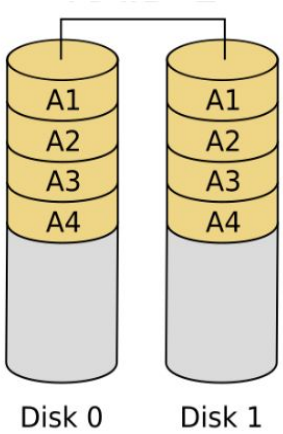
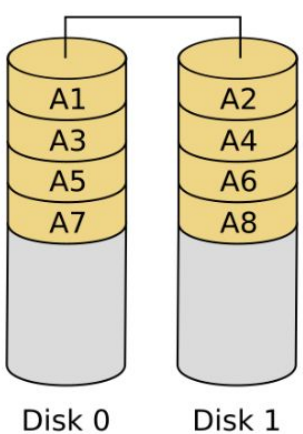
RAID-1 (disks >= 2)



RAID-0 (disks >= 2)



2x Throughput

No Fault tolerance

> Worse than single disk

Images from: Wikipedia

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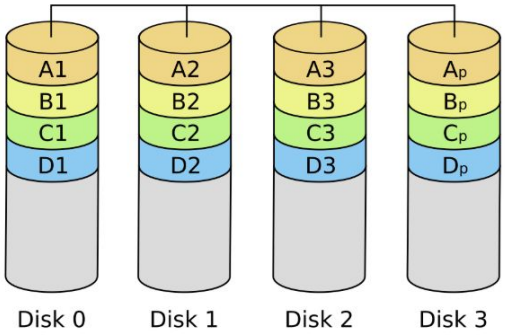

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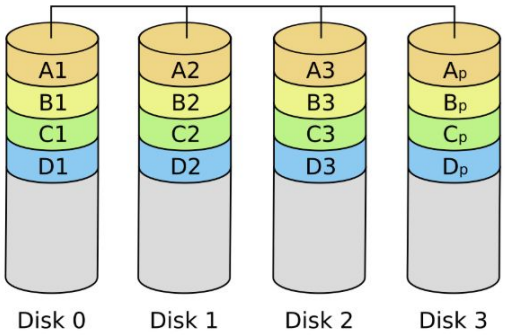
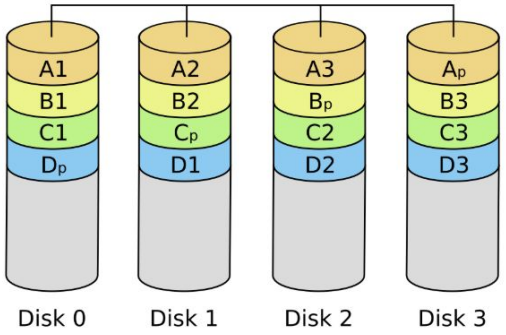


RAID-5 (disks >= 3)



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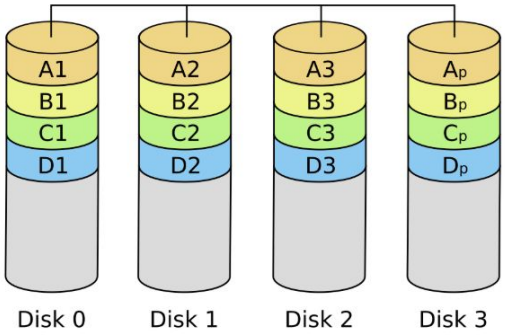

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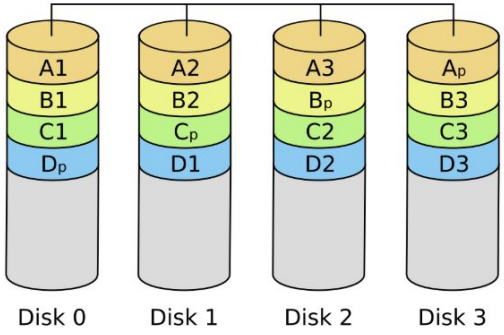
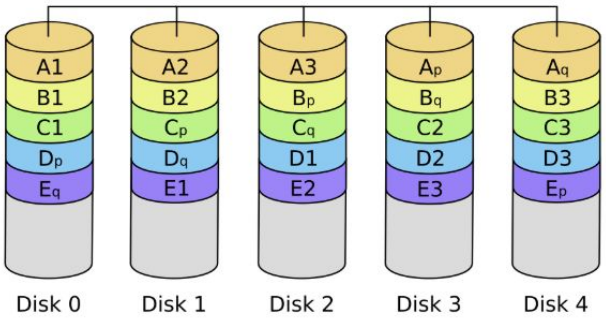


RAID-6 (disks >= 4)



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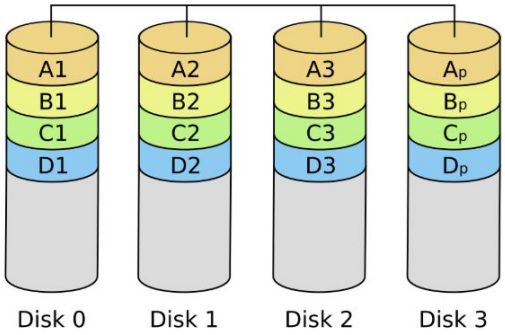

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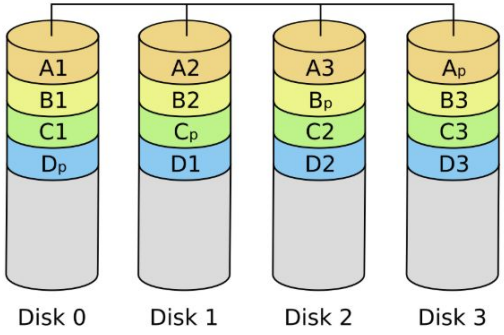

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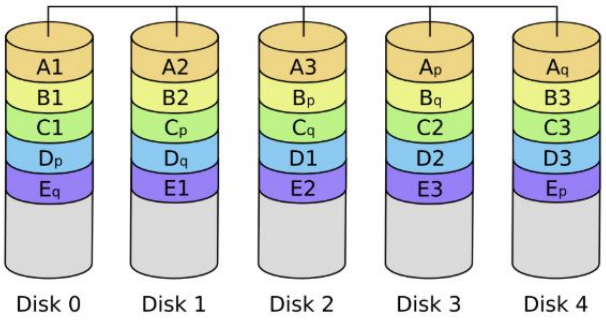

>> **Fault Tolerance:** RAID-0 < RAID-4 ≈ RAID-5 < RAID-6 < RAID-1

Images from: Wikipedia