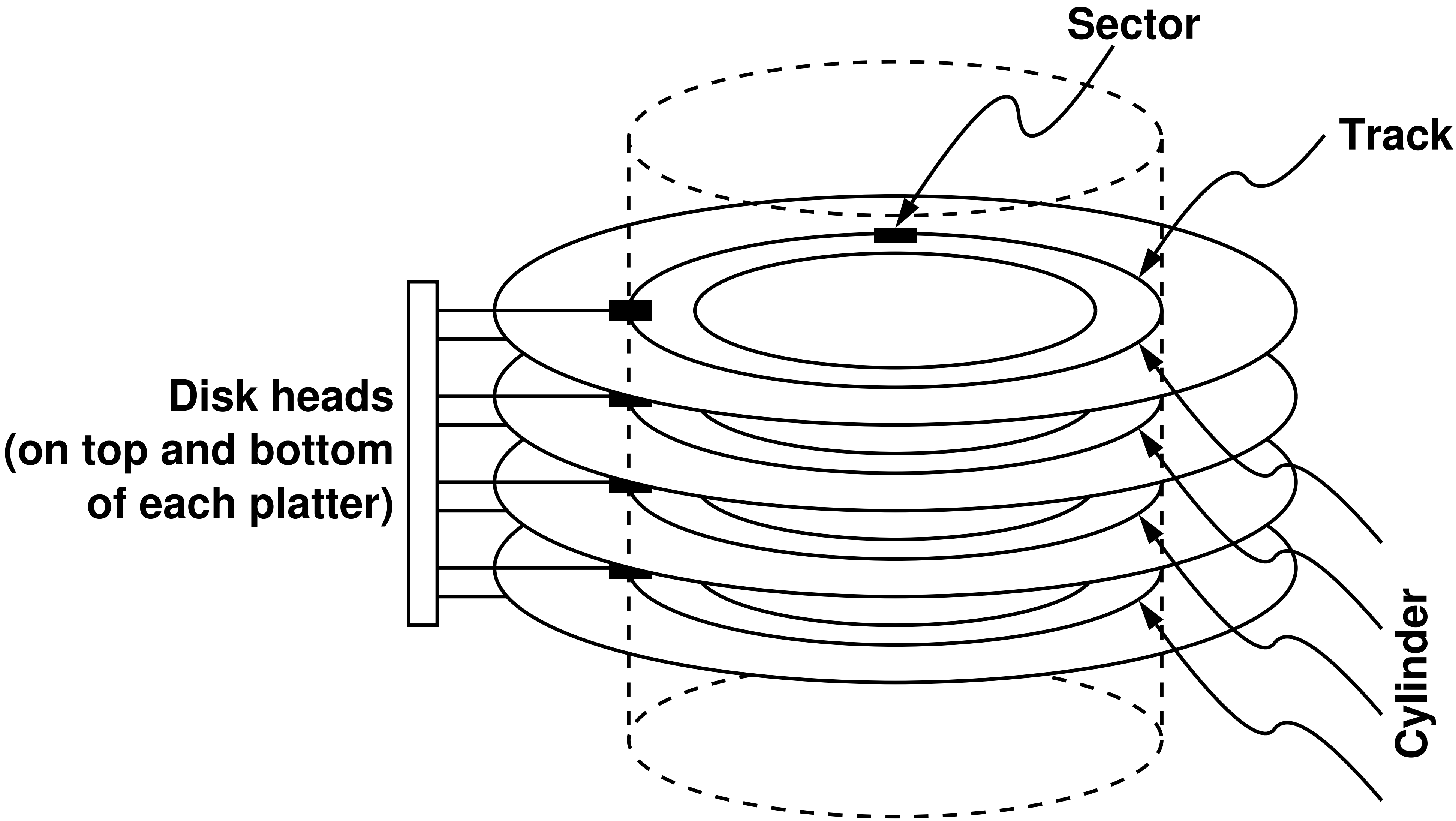
6.1 The Basics of File Systems

- UNIX’s S5FS
- Disk Architecture
- *Problems with S5FS*
- Improving Performance

Disk Architecture



- Smallest addressable unit is a *sector*
  - disk address = (*head/surface#*, *cylinder/track#*, *sector#*)

Rhinopias Disk Drive

Rotation speed	10,000 RPM
Number of surfaces	8
Sector size	512 bytes
Sectors/track	500-1000; 750 average
Tracks/surface	100,000
Storage capacity	307.2 billion bytes
Average seek time	4 milliseconds
One-track seek time	.2 milliseconds
Maximum seek time	10 milliseconds

S5FS on Rhinopias (A Marketing Disaster ...)

- **Rhinopias's maximum transfer speed?**
  - **63.9 MB/sec**
- **S5FS's average speed on Rhinopias?**
  - **average seek time:**
    - **< 4 milliseconds (say 2)**
  - **average rotational latency:**
    - **~3 milliseconds**
  - **per-sector transfer time:**
    - **negligible**
  - **time/sector: 5 milliseconds**
  - **effective transfer speed: 102.4 KB/sec (.16% of maximum)**
- **In general, we have:**
  - ***access time = seek time + rotational latency + data transfer time***
    - **some people would use the term "response time" to mean "access time"**

6.1 The Basics of File Systems

- UNIX’s S5FS
- Disk Architecture
- Problems with S5FS
- *Improving Performance*

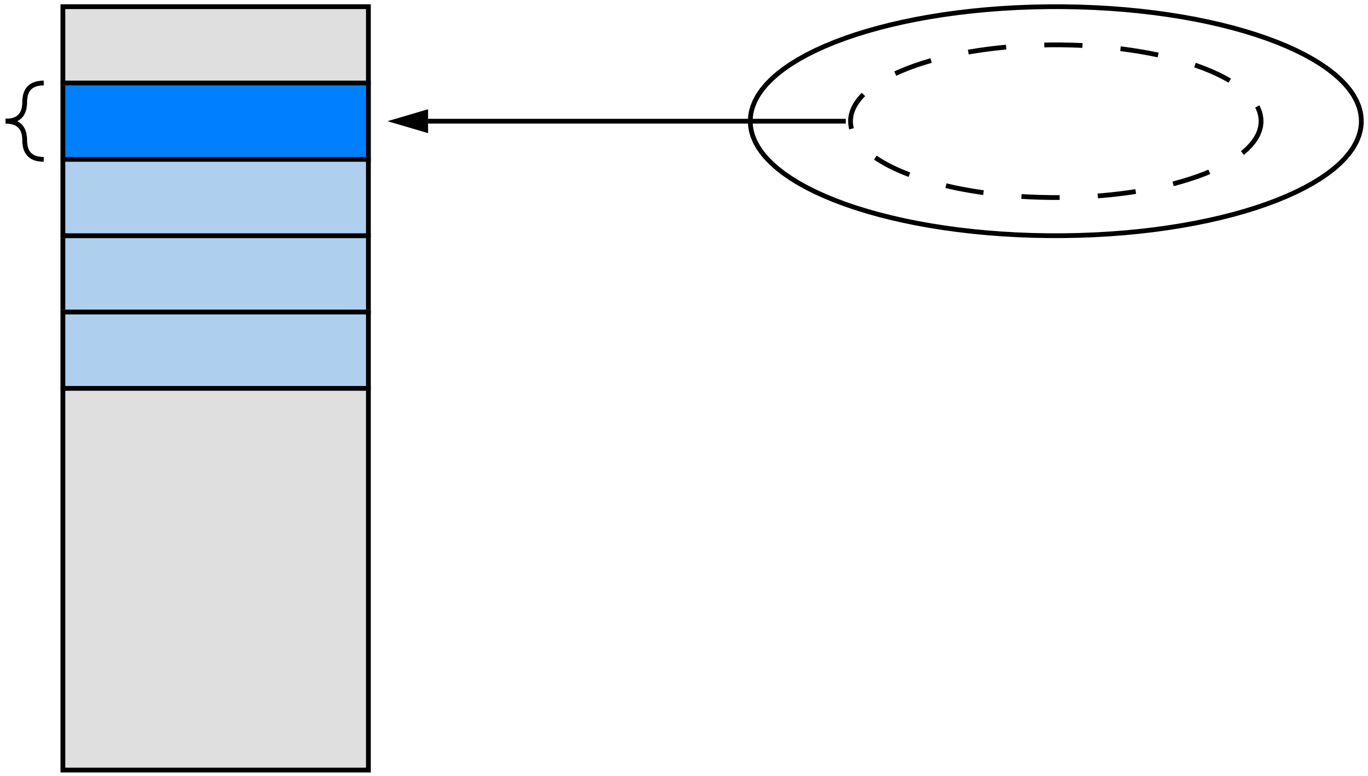
What to Do About It?

- Hardware
  - employ pre-fetch buffer
    - filled by hardware with what's underneath head
    - helps reads a bit; doesn't help writes
- Software
  - better on-disk data structures
    - increase block size
    - minimize seek time
    - reduce rotational latency

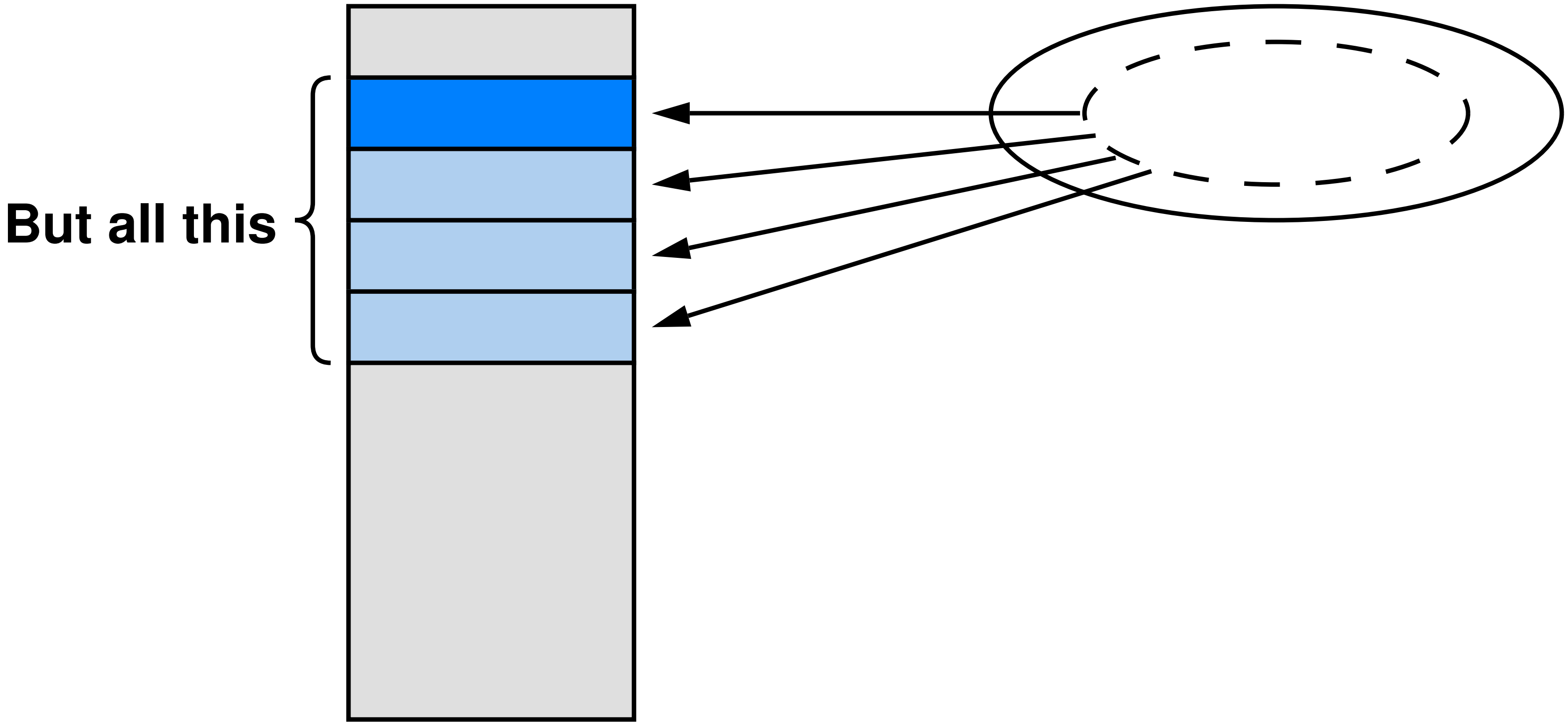
FFS

- Better on-disk organization
- Longer component names in directories
- Retains disk map of S5FS

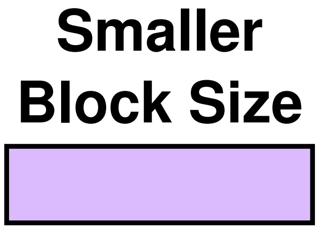
Larger Block Size



Larger Block Size



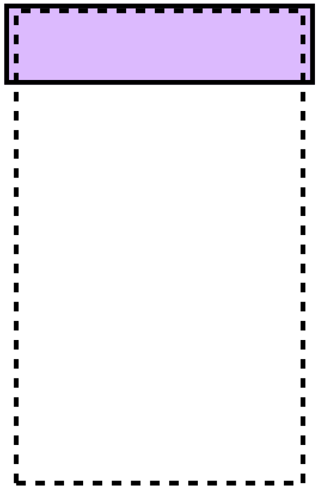
The Down Side ...



Smaller Block Size

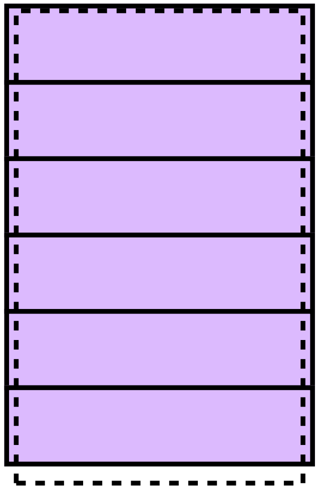
The Down Side ...

Smaller
Block Size

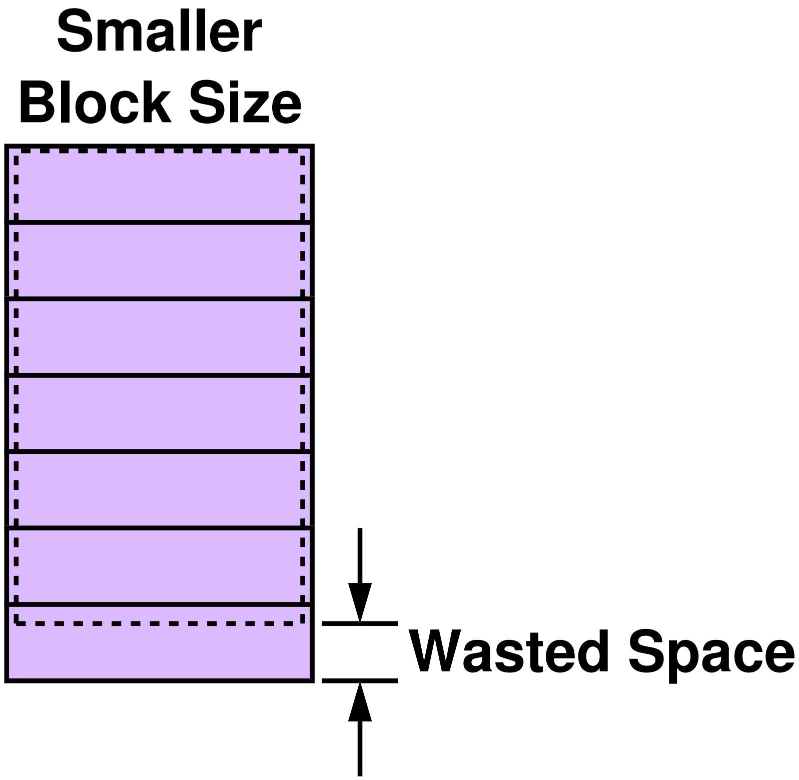


The Down Side ...

Smaller
Block Size

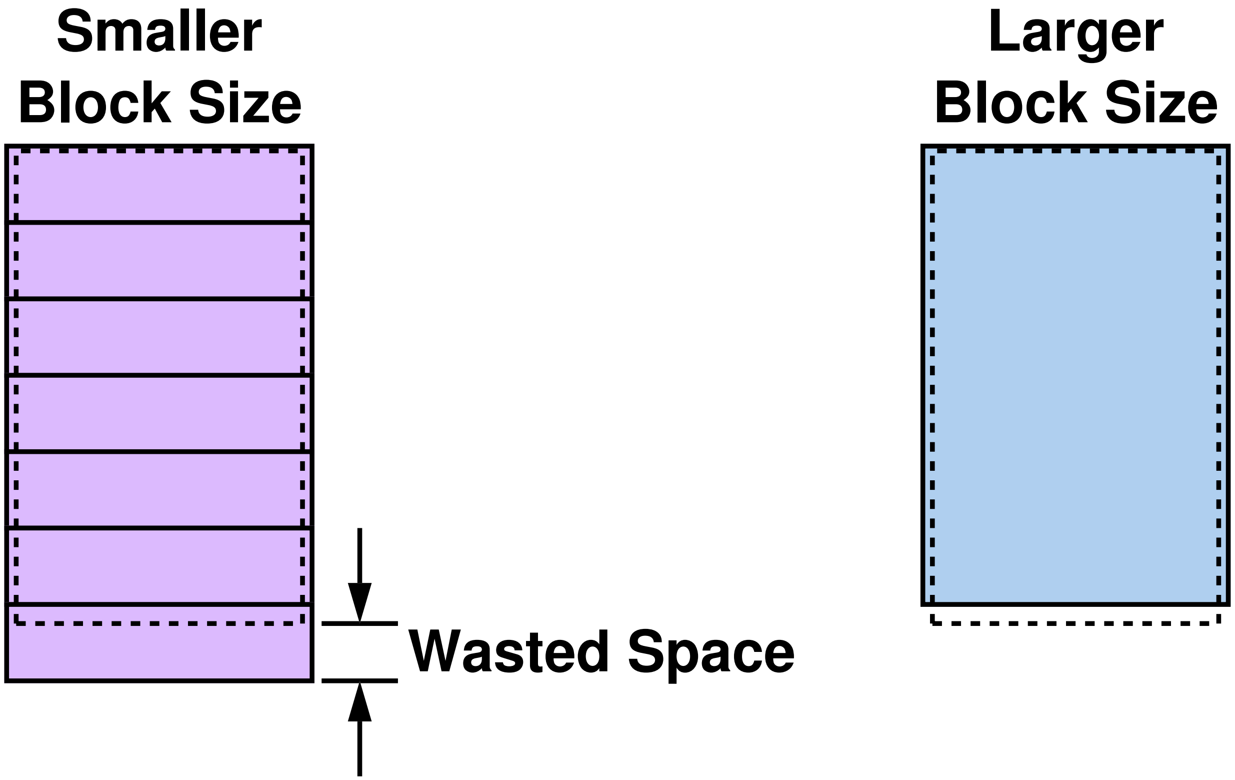


The Down Side ...

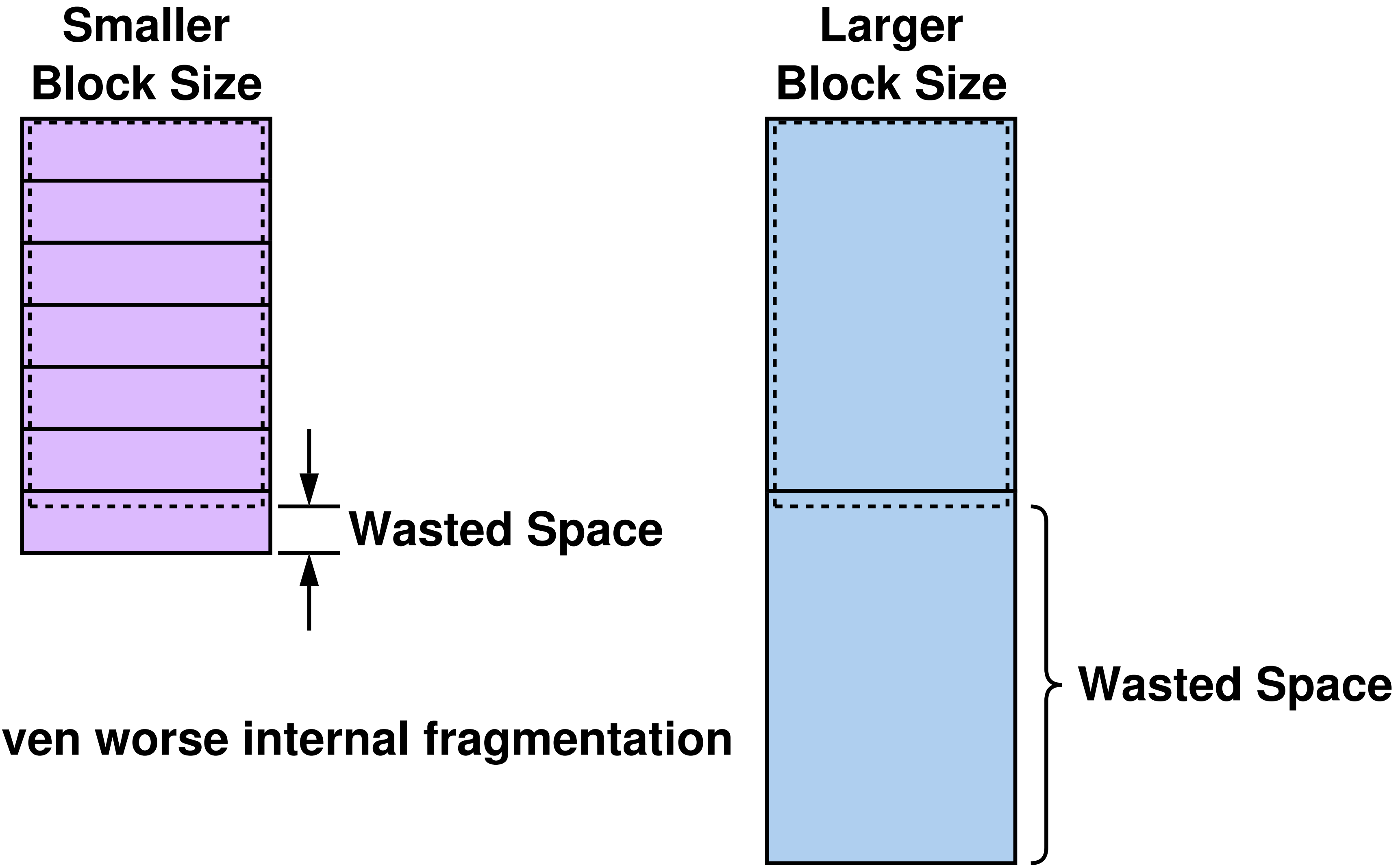


- internal fragmentation

The Down Side ...

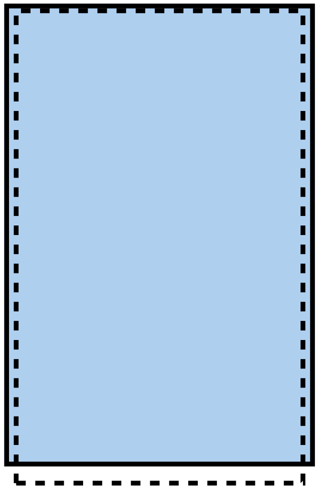


The Down Side ...

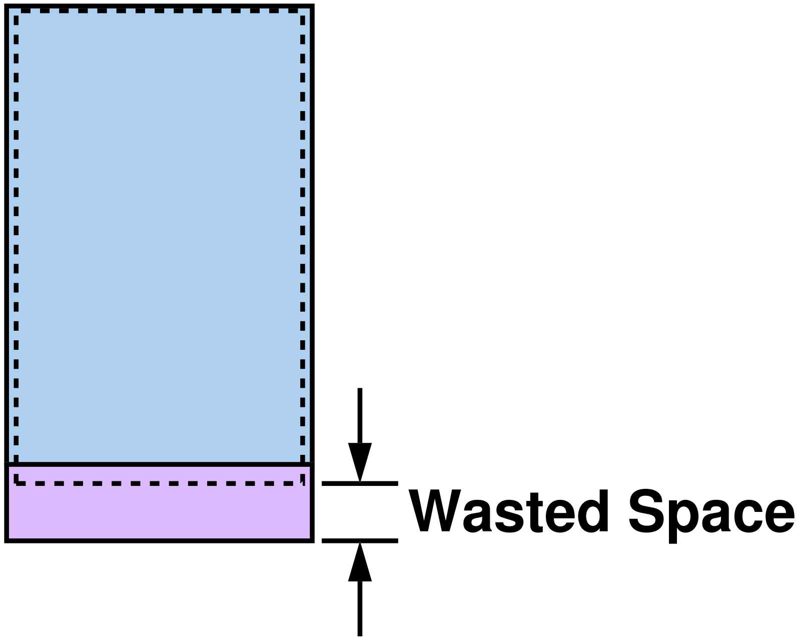


- even worse internal fragmentation

Two Block Sizes ...



Two Block Sizes ...

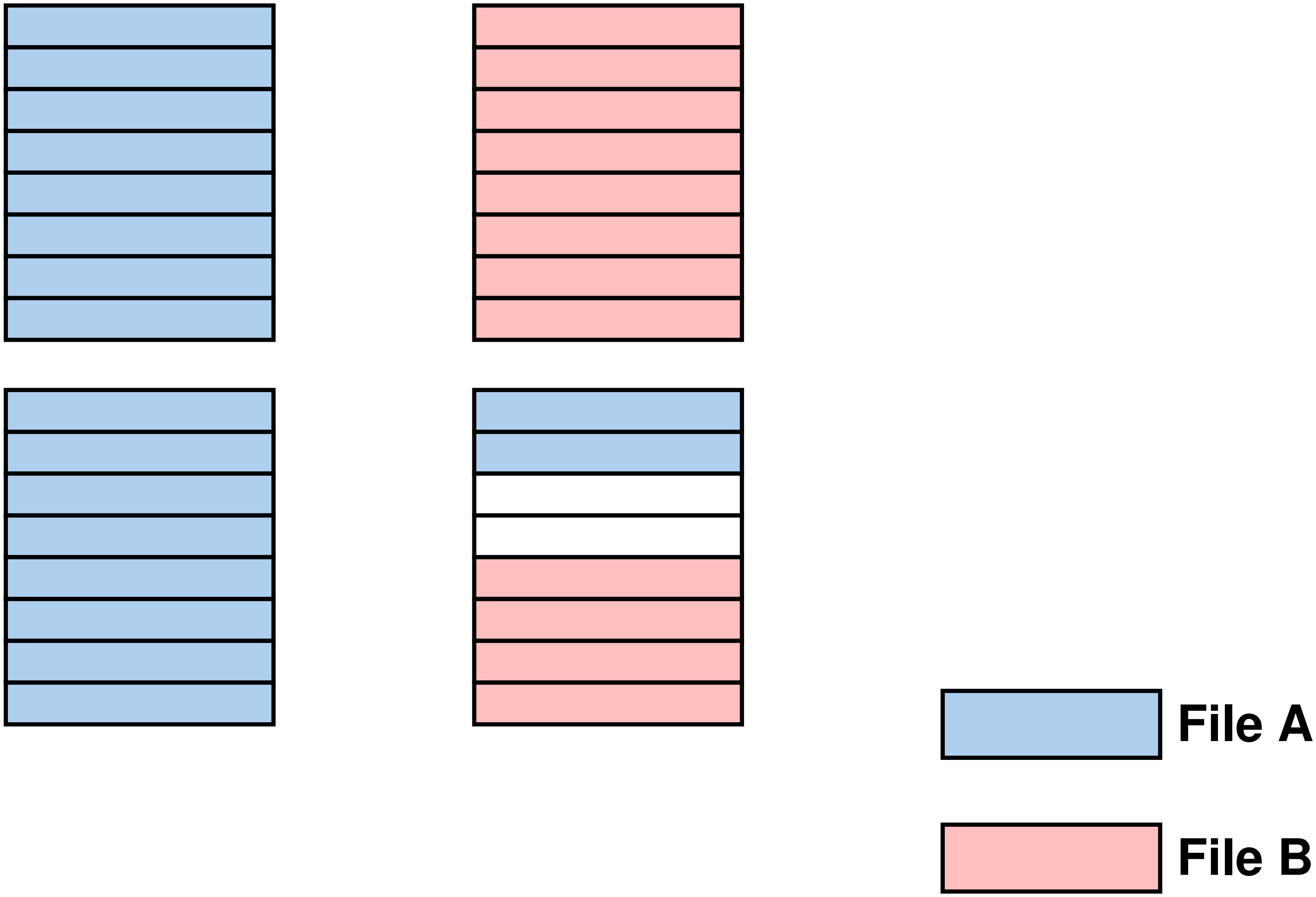


- e.g., 16KB blocks and 1KB fragments
- best of both worlds

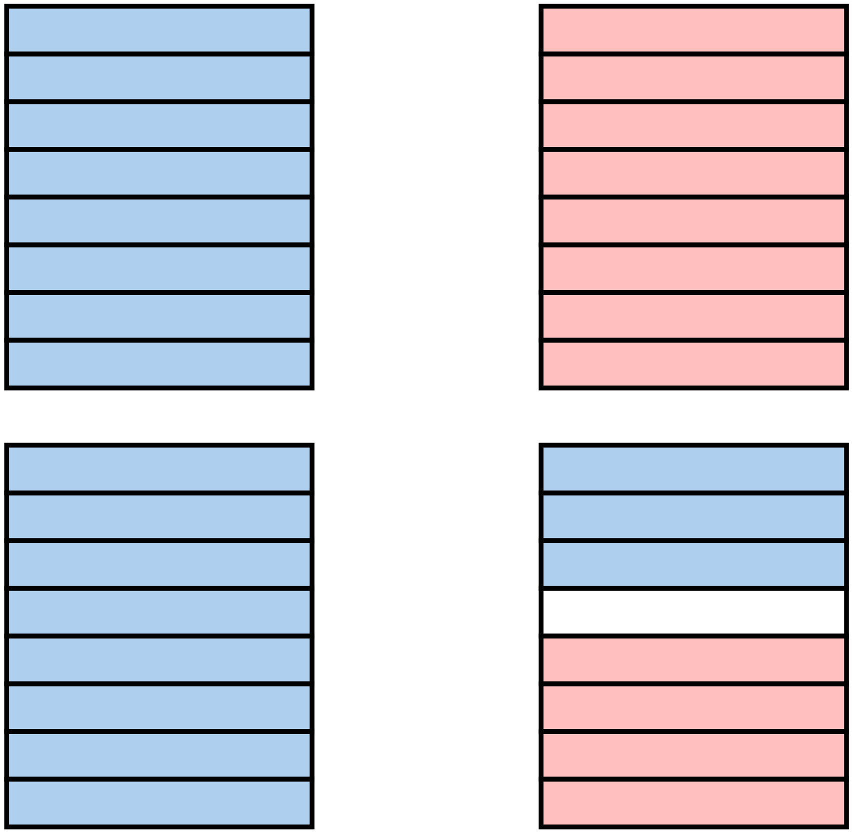
Rules

- File-system blocks may be split into fragments that can be independently assigned to files
  - fragments assigned to a file must be contiguous and in order
- The number of fragments per block (1, 2, 4, or 8) is fixed for each file system
- Allocation in fragments may only be done on what would be the last block of a file, and only for small files

Use of Fragments (1)



Use of Fragments (2)

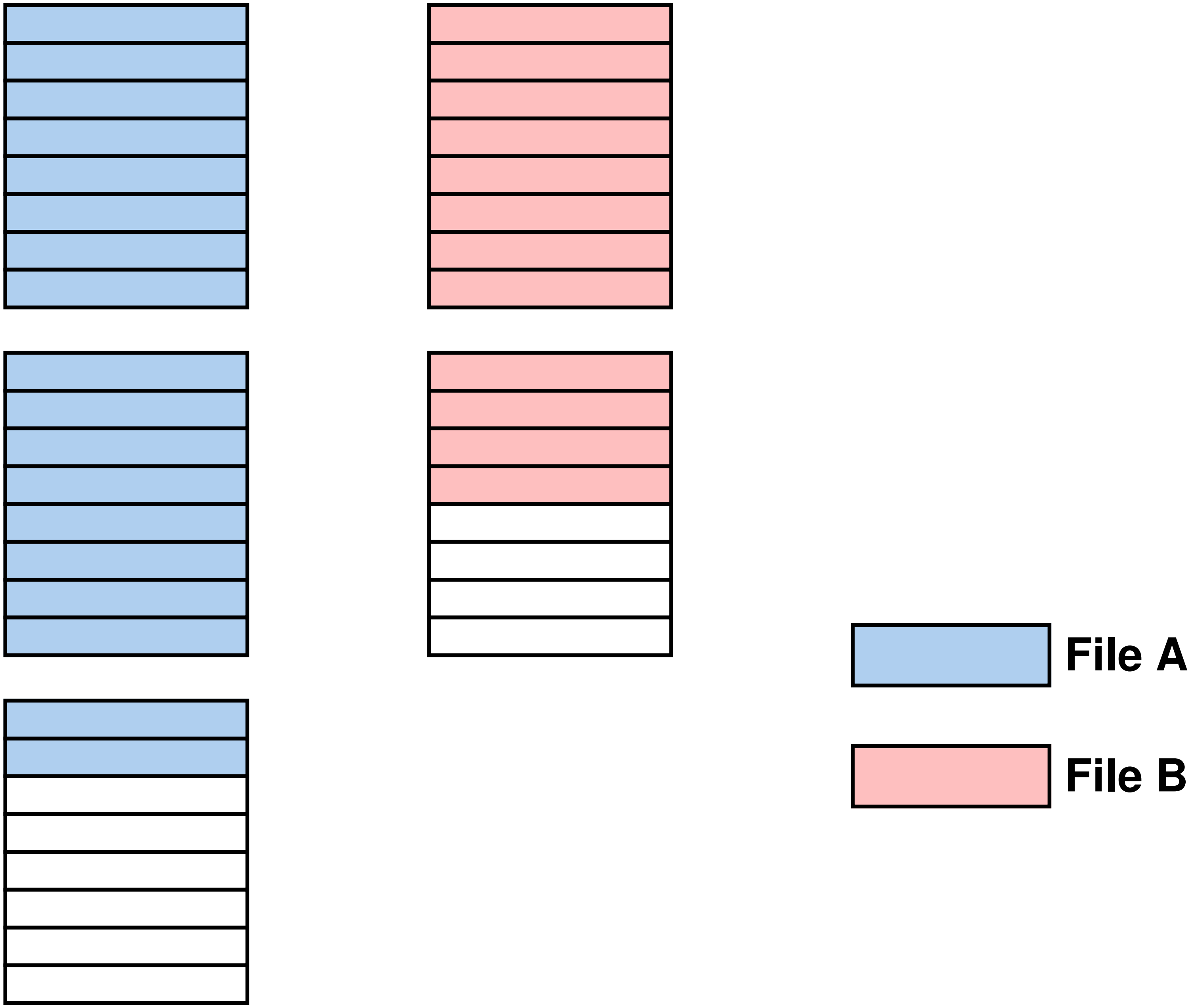


🟦 File A

🟥 File B

- A can grow by 2 segments

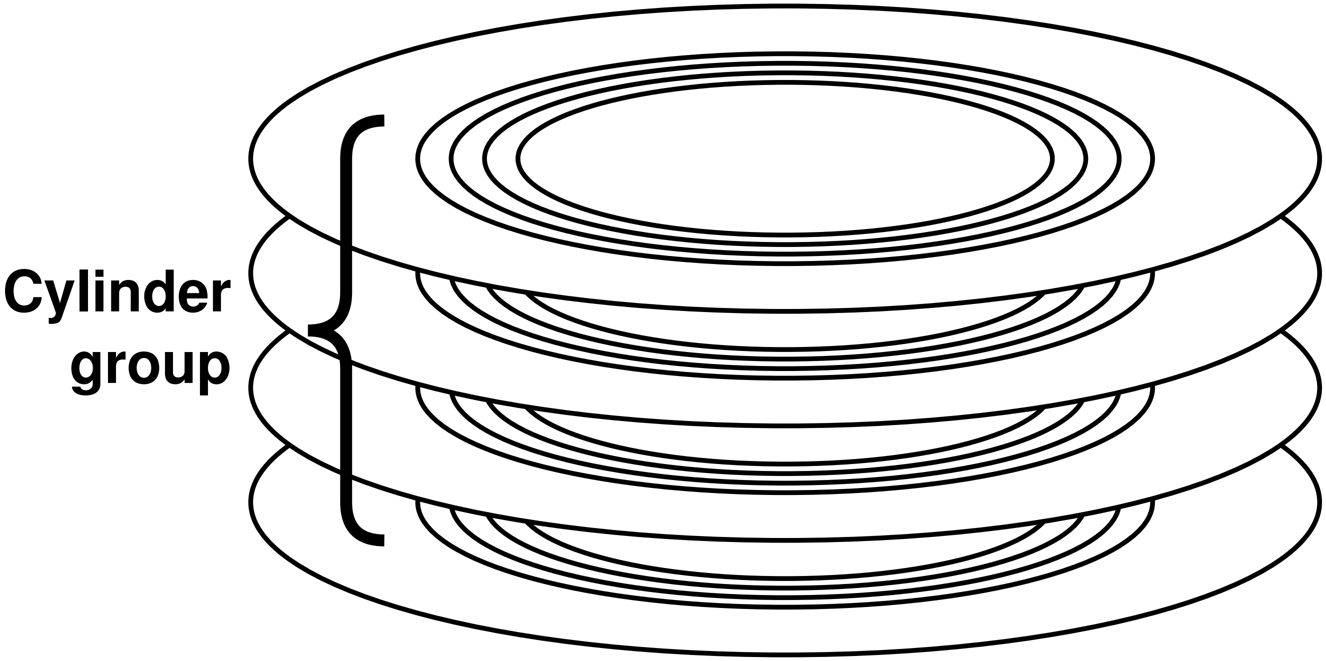
Use of Fragments (3)



Minimizing Seek Time

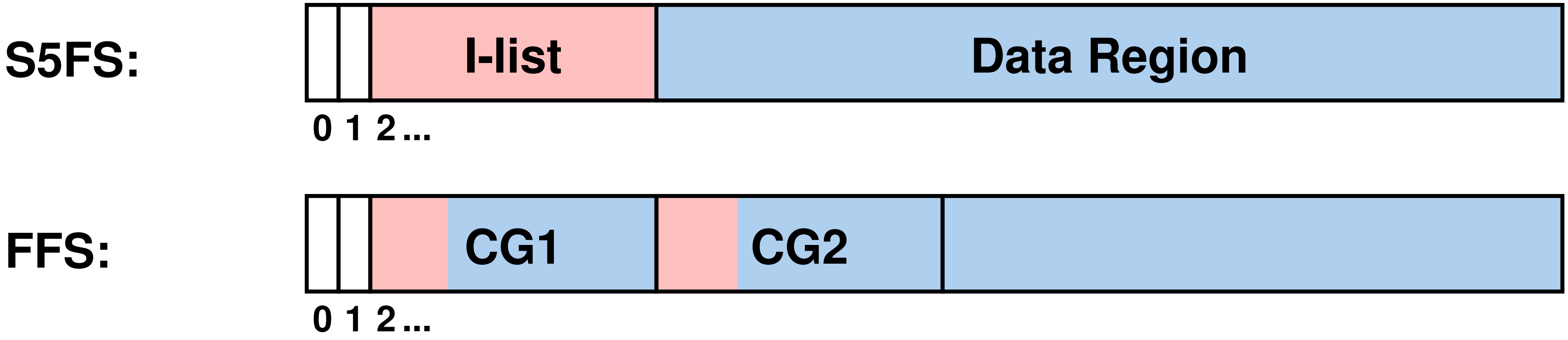
- Keep related things close to one another
- Separate unrelated things

Cylinder Groups



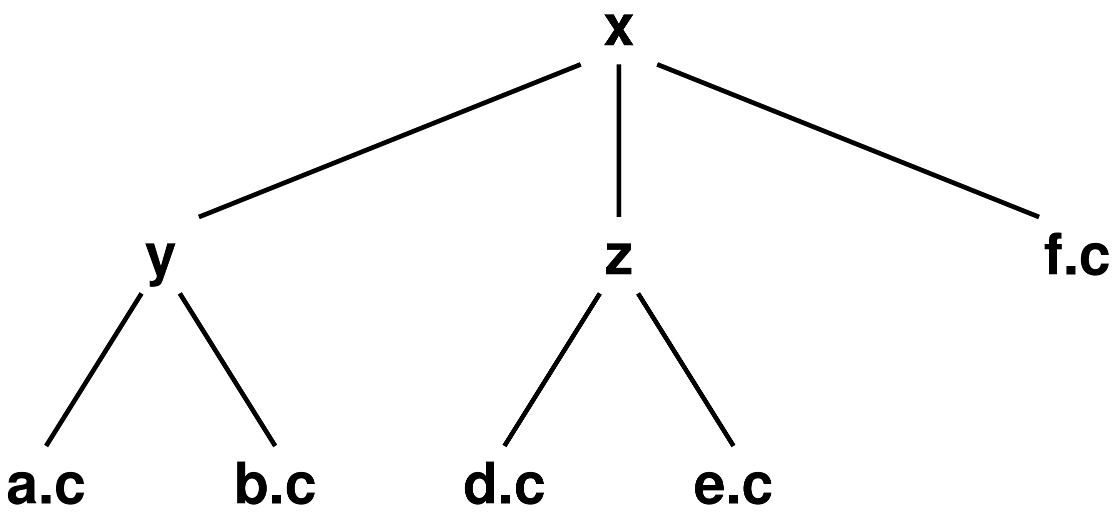
- recall that *seeking* to the *next cyliner/track* is much *faster*

Minimizing Seek Time



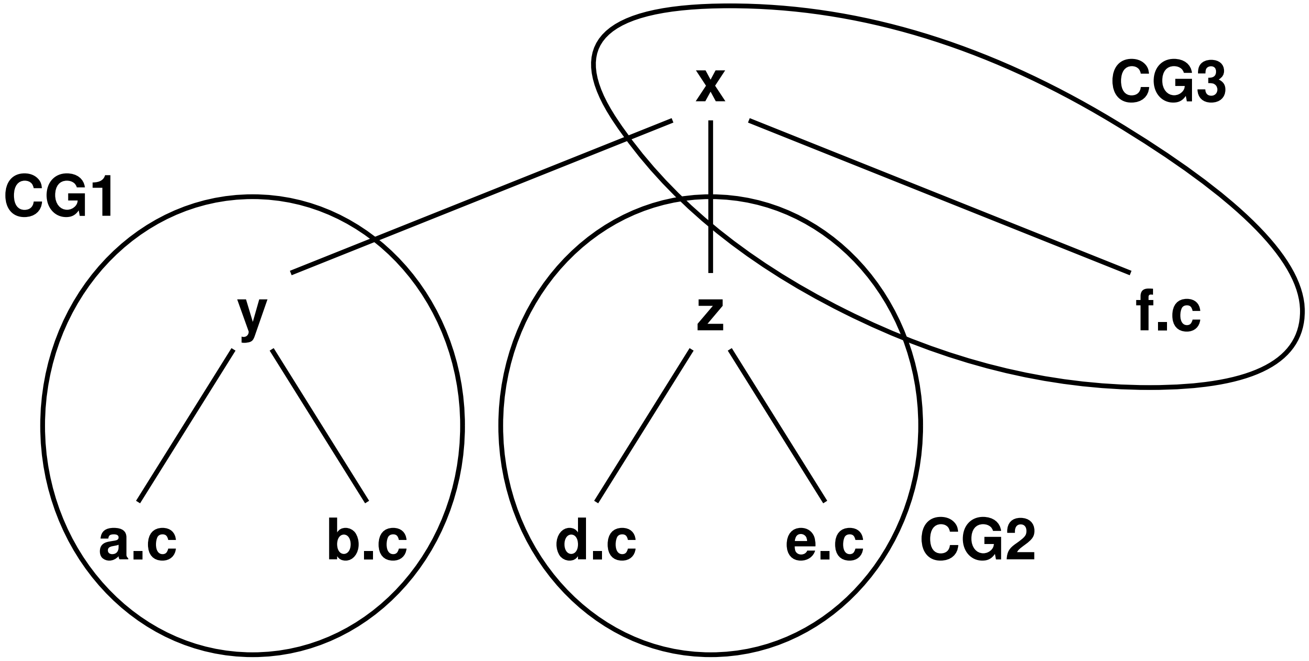
- The practice (heuristics):
  - attempt to put new inodes in the same cylinder group as their directories
  - put inodes for new directories in cylinder groups with "lots" of free space
  - put the beginning of a file (first 10KB, i.e., direct blocks) in the inode’s cylinder group
  - put additional portions of the file (each 2MB) in cylinder groups with "lots" of free space

Locality Of File Access



- if access "d.c", likely to access "e.c"

Locality Of File Access

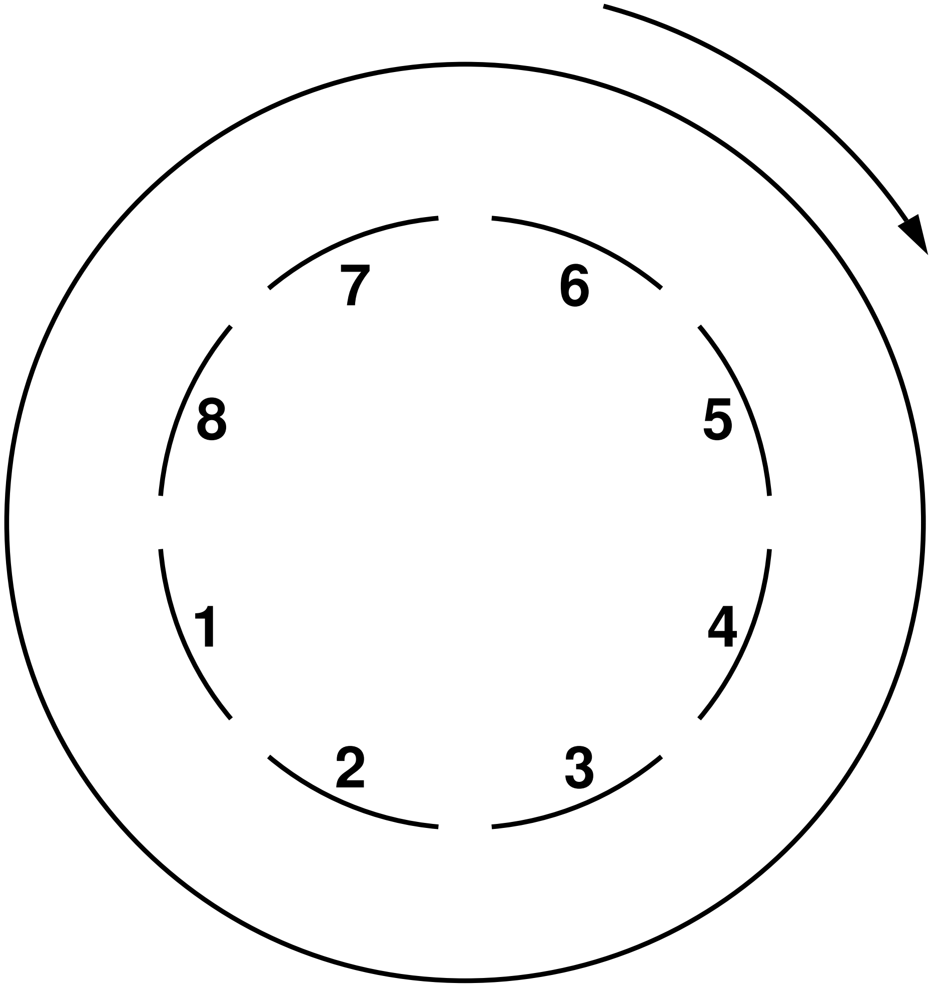


- if access "d.c", likely to access "e.c"

How Are We Doing? (Part 1)

- Configure Rhinopias with 20 cylinders per group
  - 2-MB file fits entirely within one cylinder group
  - average seek time within cylinder group is ~.3 milliseconds
  - average rotational delay still 3 milliseconds
  - .12 milliseconds required for disk head to pass over 8KB block
  - 3.42 milliseconds for each block
  - 2.4 million bytes/second average effective transfer speed
  - *factor of 20 improvement*
  - 3.7% of maximum possible

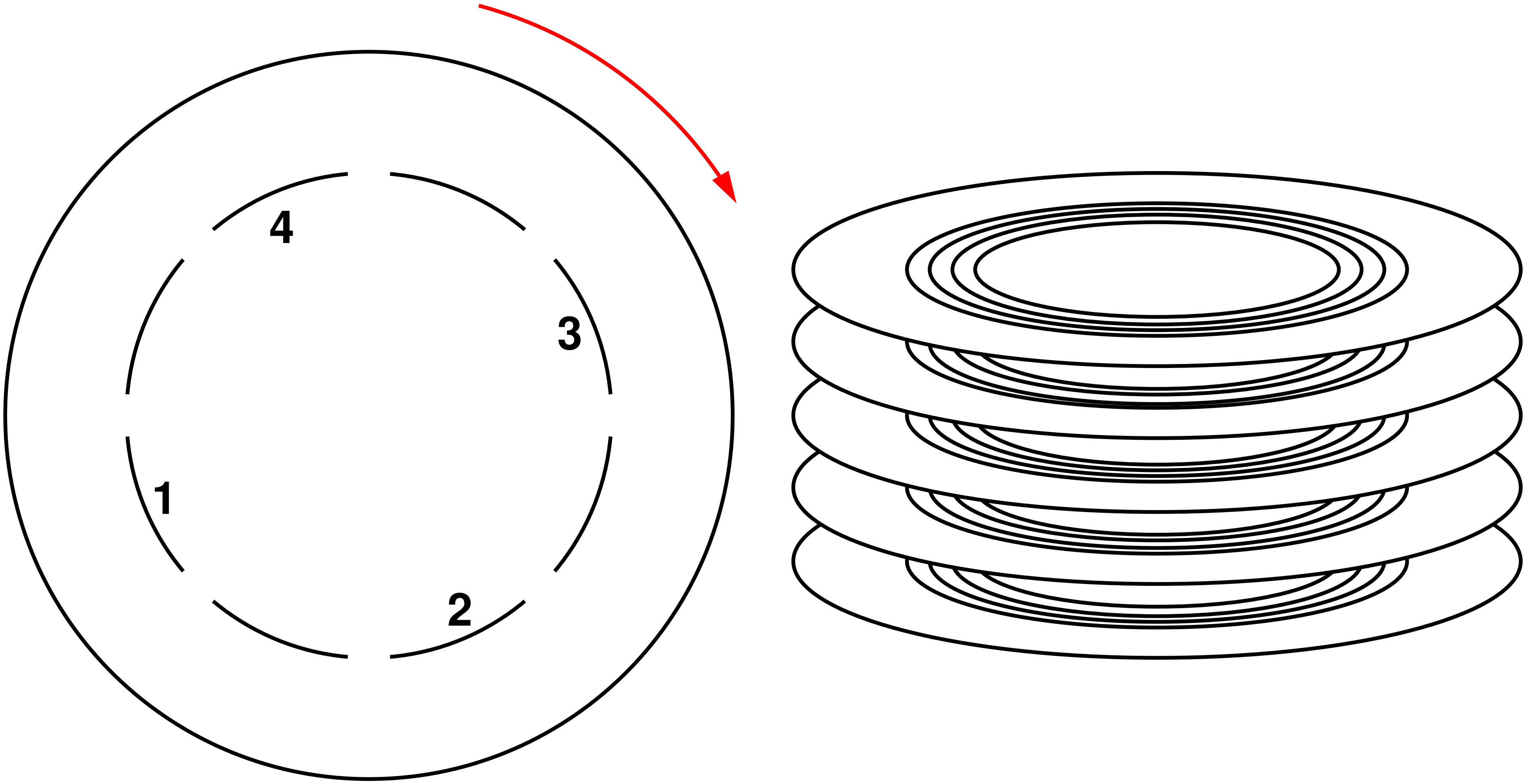
Minimizing Latency



Numbers

- Rhinopias spins at 10,000 RPM
  - 6 milliseconds/revolution
- 100 microseconds required to service disk-completion interrupt and start next operation
  - typical of early 1980s
- Each block takes 120 microseconds to traverse disk head
- Reading successive blocks is expensive!

Minimizing Latency



- **Block interleaving**

How’re We Doing Now? (Part 2)

- Time to read successive blocks (two-way interleaving):
  - after request for second block is issued, must wait 20 microseconds for the beginning of the block to rotate under disk head
  - *factor of 15 improvement*
    - together with other improvements, overall, a factor of 300 improvement

How’re We Doing Now? (Altogether)

- Same setup as before
  - 2-MB file within one cylinder group
  - actually fits in one cylinder
  - block interleaving employed: every other block is skipped
  - .3-millisecond seek to that cylinder
  - 3-millisecond rotational delay for first block
  - 50 blocks/track, but 25 read in each revolution
  - 10.24 revolutions required to read all of file
  - 32.4 MB/second (50% of maximum possible)

Further Improvements?

- S5FS: 0.16% of capacity
- FFS without block interleaving
  - factor of 20 improvement
  - reached 3.8% of capacity
- FFS with block interleaving
  - another factor of 15 improvement
  - reached 50% of capacity
- What next?

Larger Transfer Units

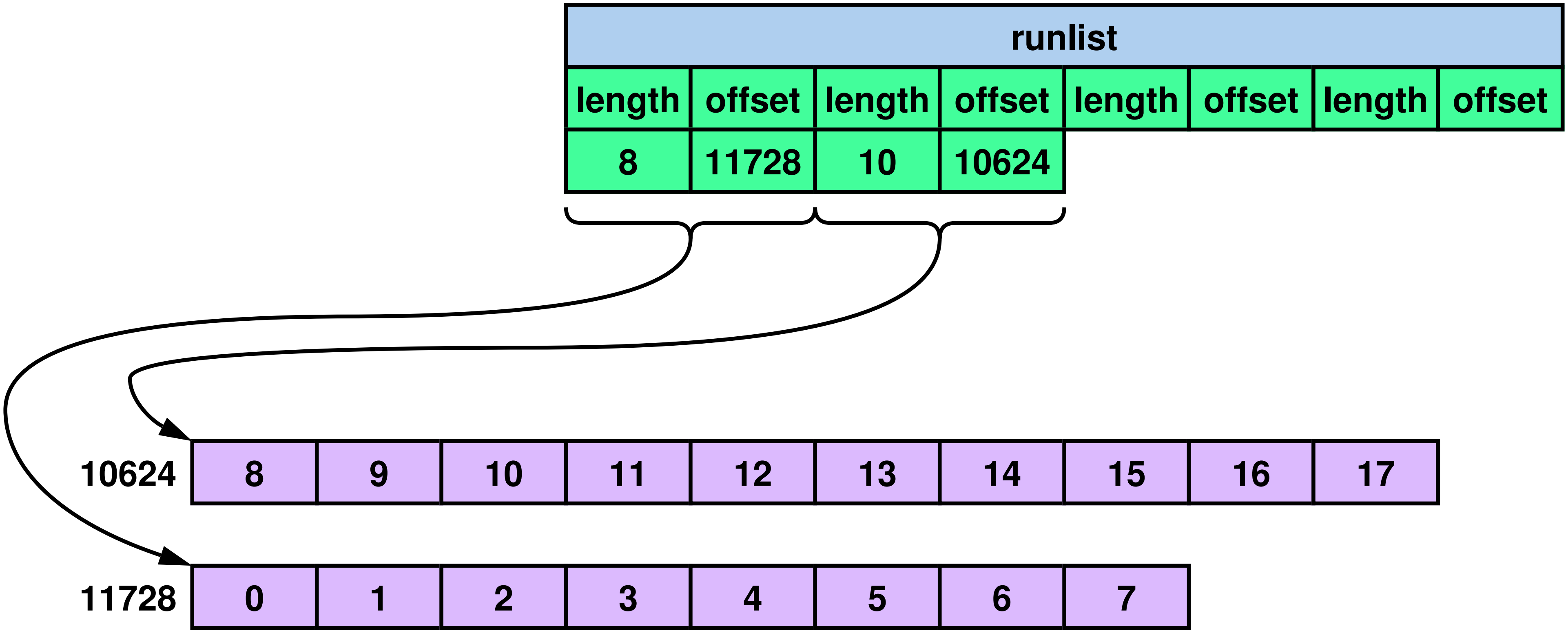
- Allocate in whole tracks or cylinders
  - too much wasted space
- Allocate in blocks, but group them together
  - transfer many at once

Block Clustering

- Allocate space in blocks, eight at a time
- Linux's Ext2 (an FFS clone):
  - allocate eight blocks at a time
  - extra space is available to other files if there is a shortage of space
- FFS on Solaris (~1990)
  - delay disk-space allocation until:
    - 8 blocks are ready to be written
    - or the file is closed

Extents

- Windows



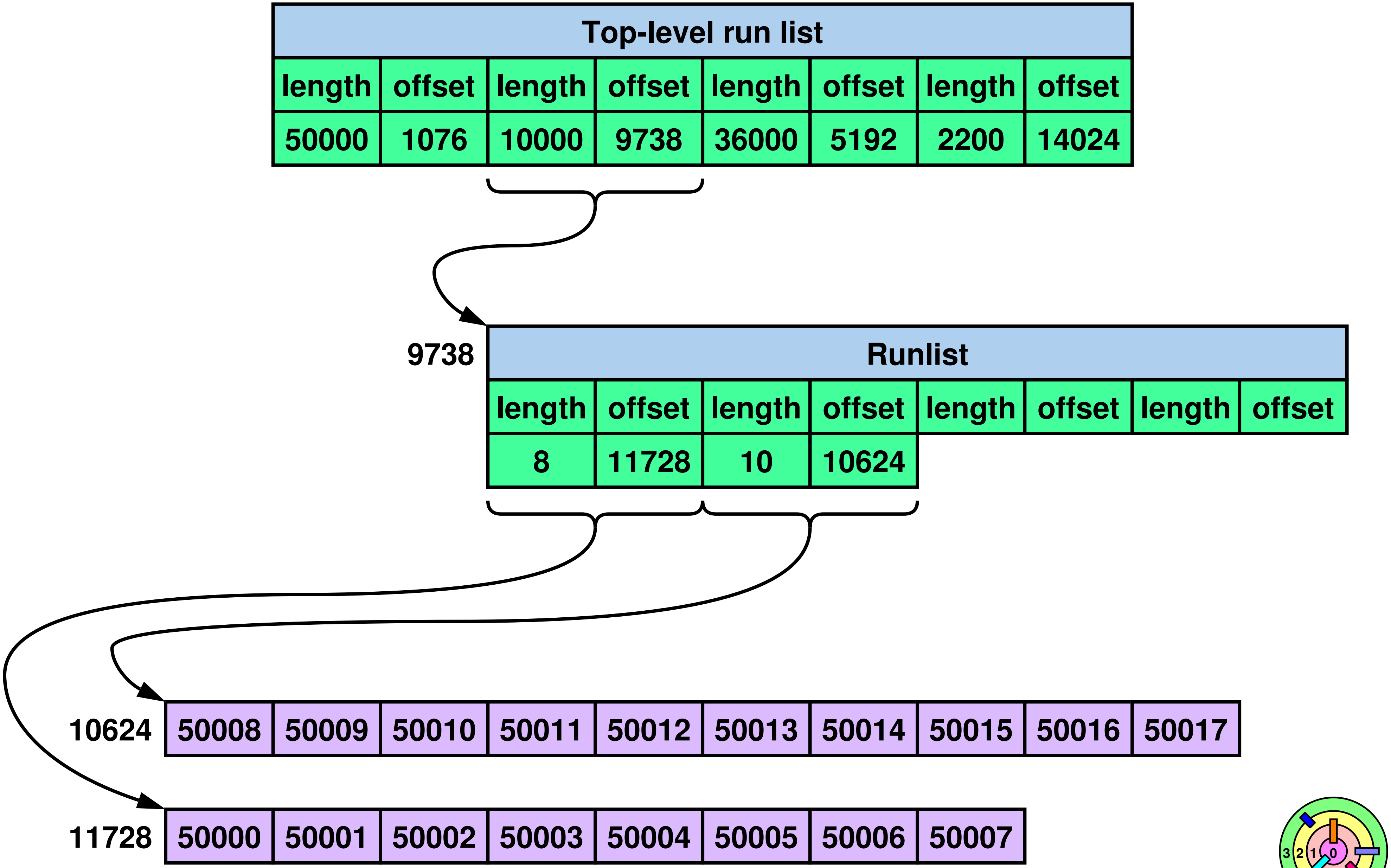
runlist							
length	offset	length	offset	length	offset	length	offset
8	11728	10	10624				

10624	8	9	10	11	12	13	14	15	16	17
11728	0	1	2	3	4	5	6	7		

Problems with Extents

- Could result in highly fragmented disk space
  - lots of small areas of free space
    - external fragmentation
  - solution: use a *defragmenter* to *coalesce* free space
- Random access
  - *linear search* through a long list of extents
  - solution: *multiple levels*
    - usually two levels

Extents in NTFS



Top-level run list

length	offset	length	offset	length	offset	length	offset
50000	1076	10000	9738	36000	5192	2200	14024

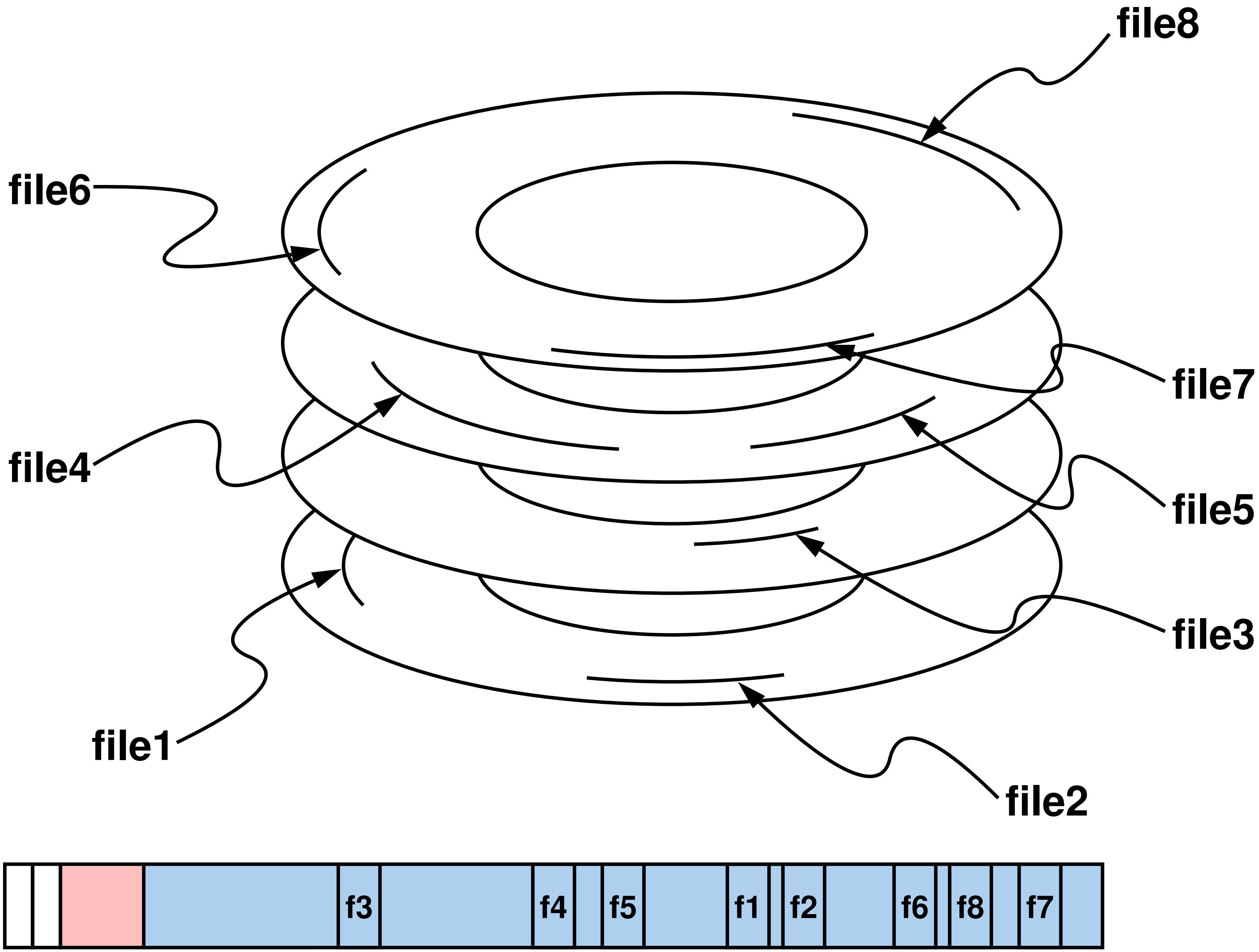
9738

Runlist

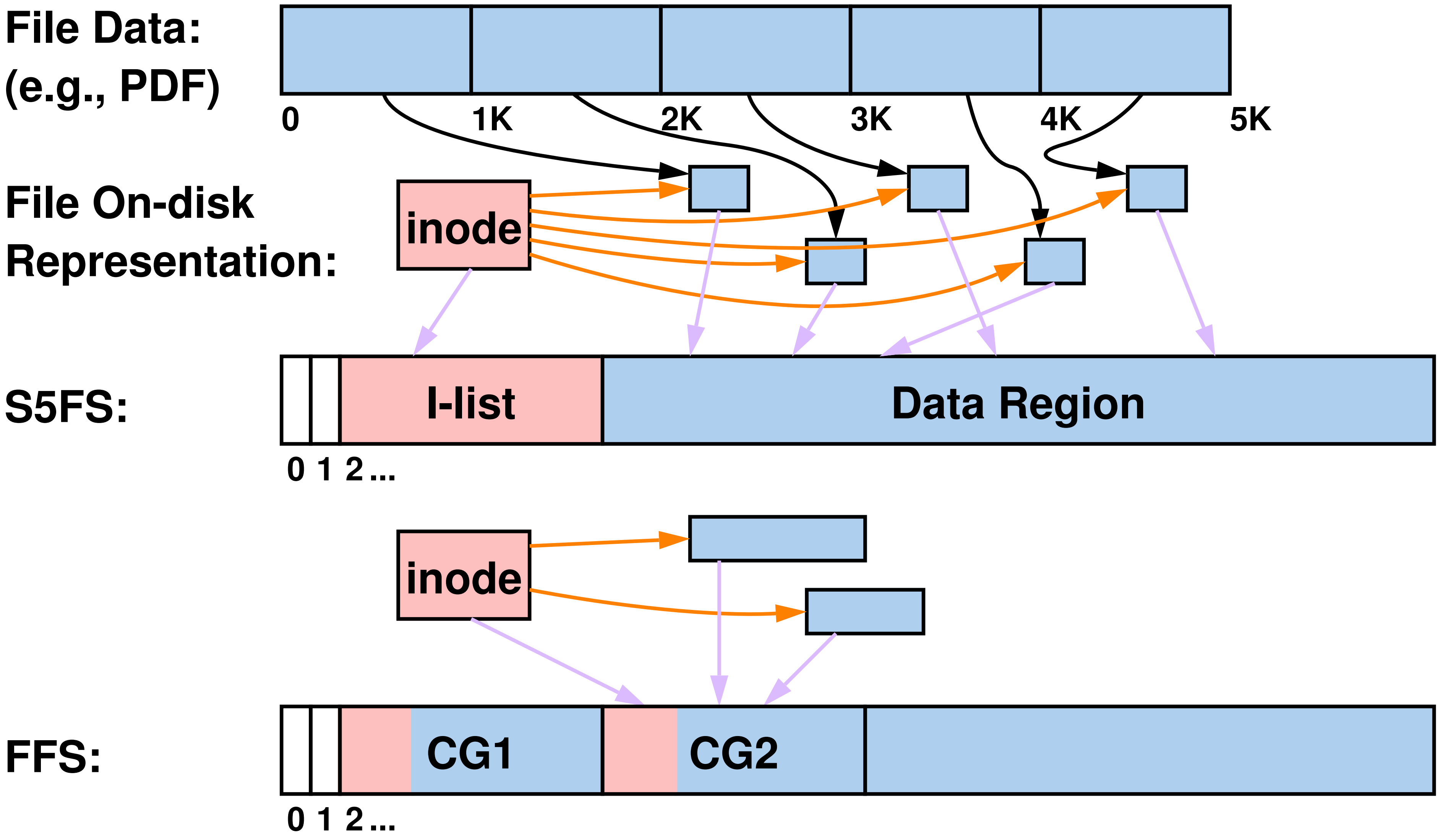
length	offset	length	offset	length	offset	length	offset
8	11728	10	10624				

10624	50008	50009	50010	50011	50012	50013	50014	50015	50016	50017
11728	50000	50001	50002	50003	50004	50005	50006	50007		

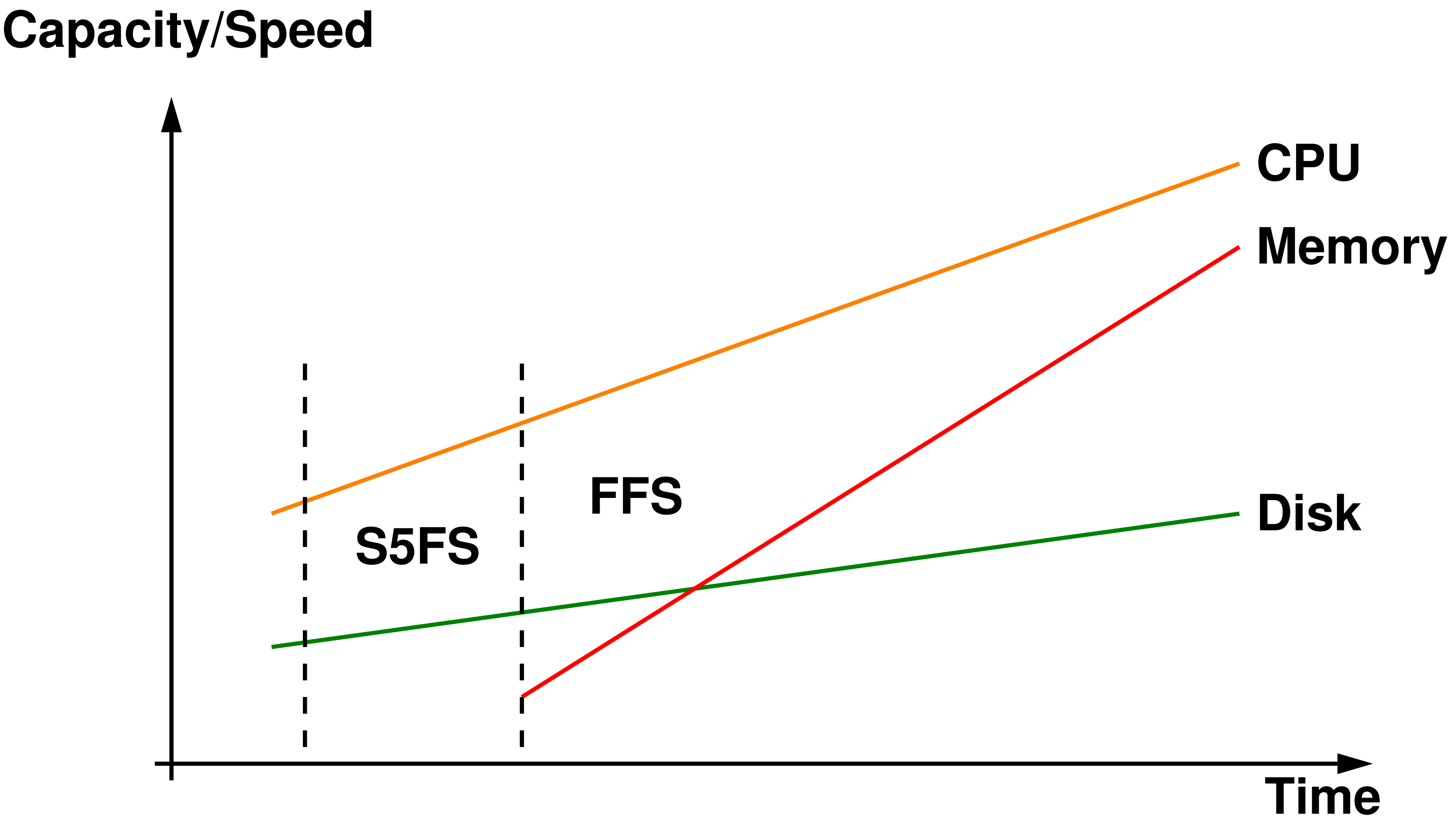
Are We There Yet?



Recall What A File Look Like in S5FS & FFS



CPU, Memory, Disk Speeds Over Time



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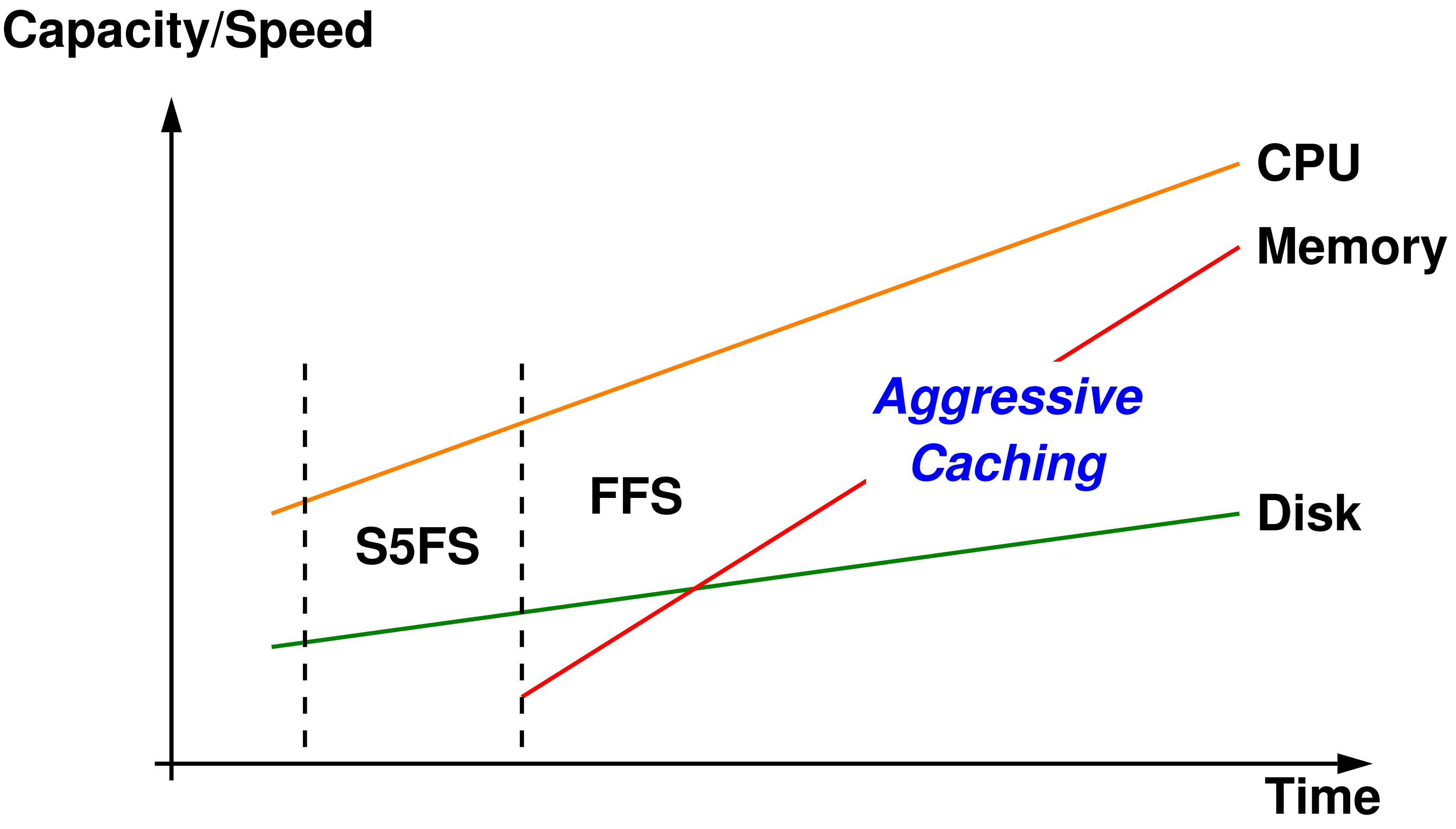
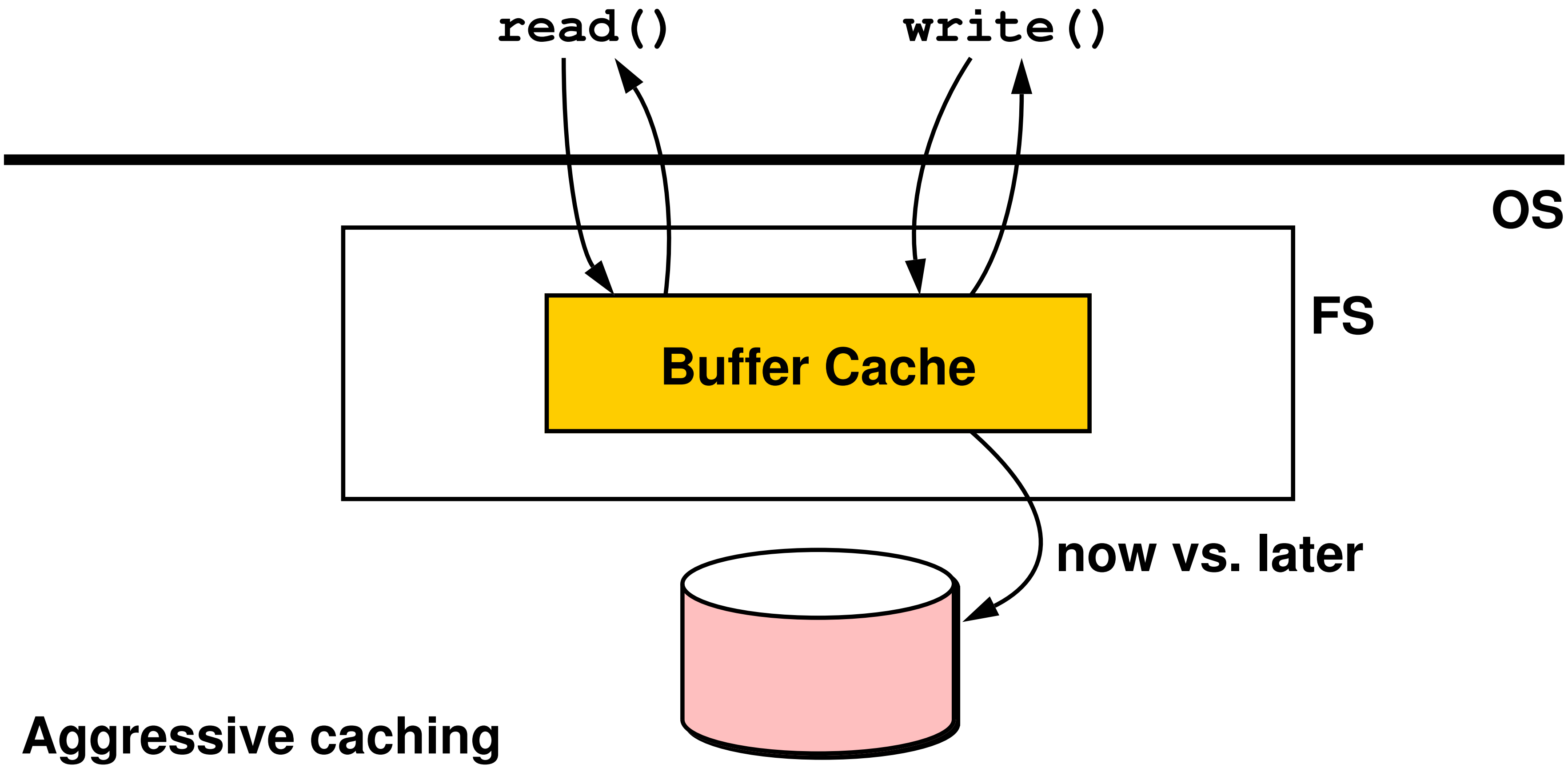


A Different Approach

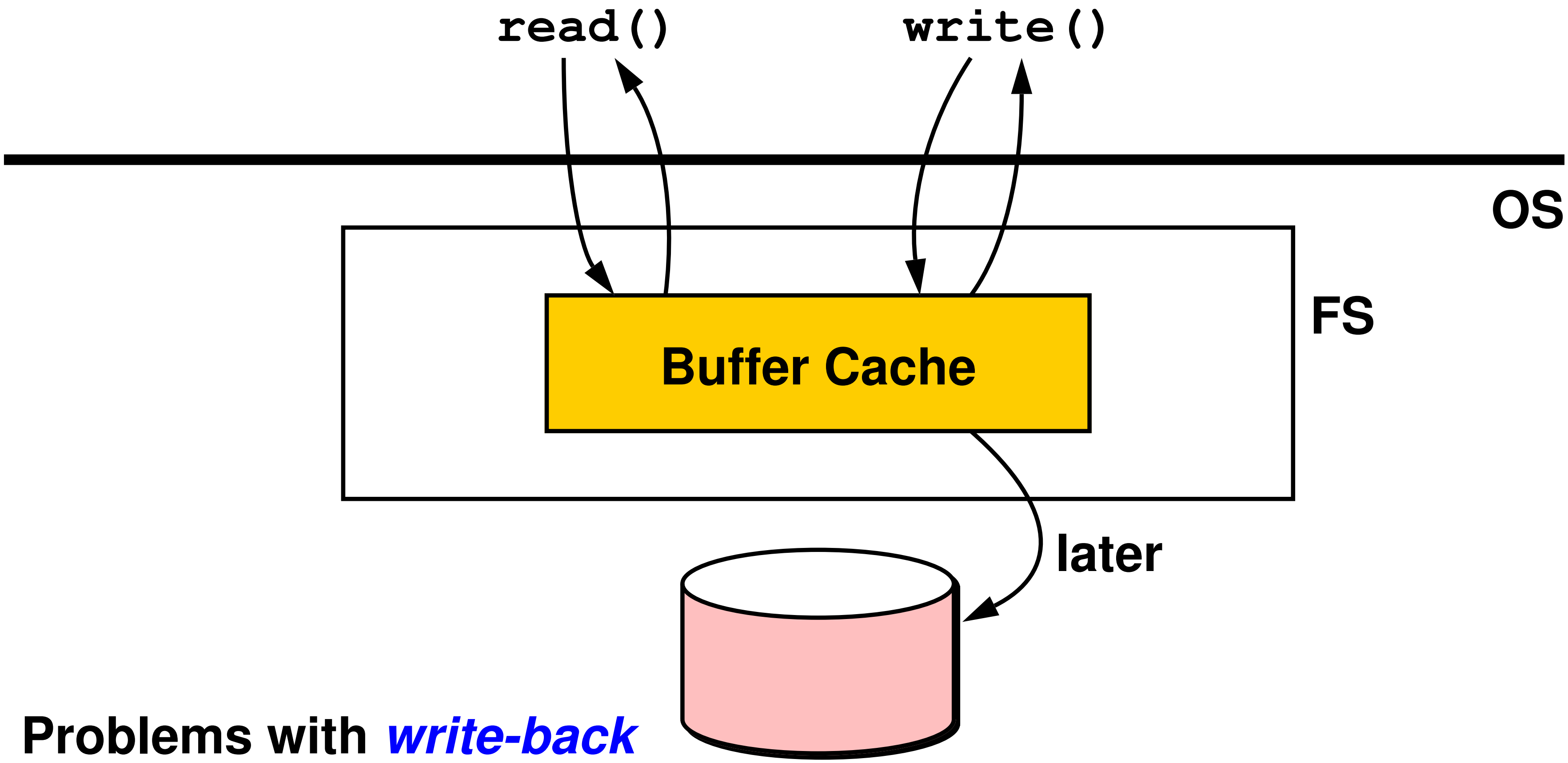
- We have lots of primary memory
  - enough to cache all commonly used files
- Read time from disk doesn’t matter
- Time for writes does matter

The Buffer Cache



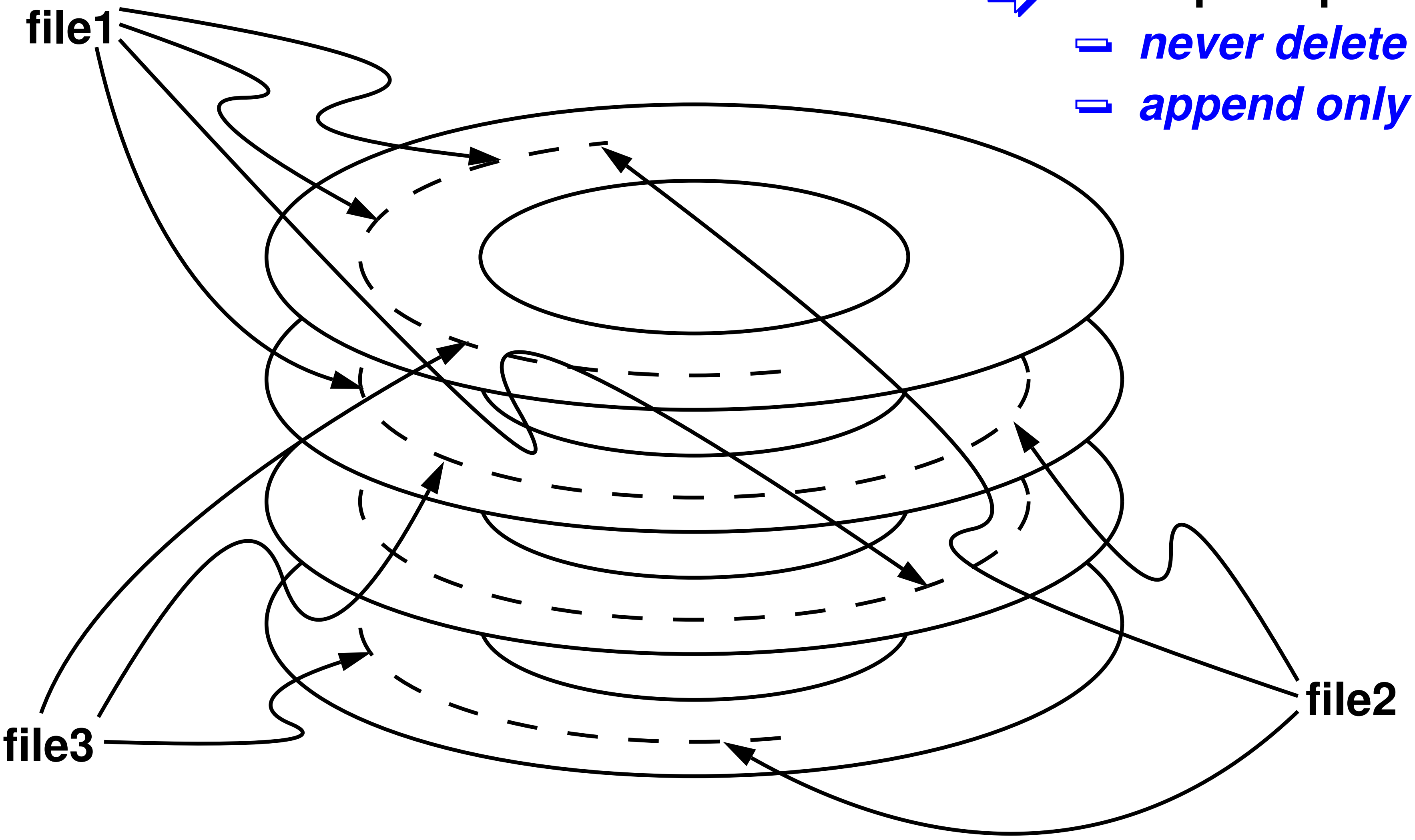
- Aggressive caching
  - most read and write will have a *cache hit*
  - for writes, need to update the disk
    - *write through* vs. *write back*

The Buffer Cache

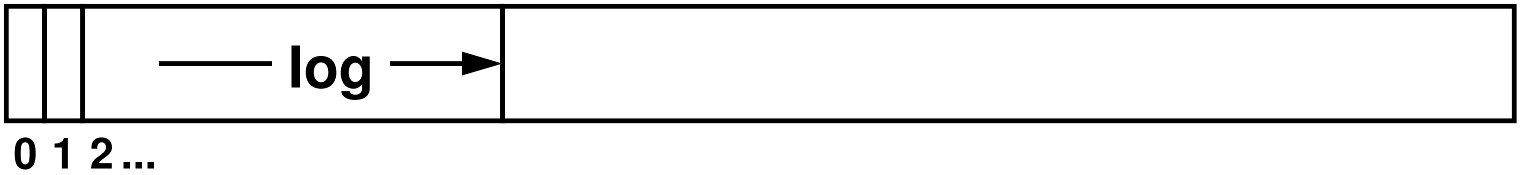


- Problems with ***write-back***
  - writes to the disk can wait, may be for quite a while
    - longer the wait, higher the ***risk***
- Need a file system optimized for ***writing!***
  - how?
    - you organize the disk as a very long ***log***

Log-Structured File Systems



- **Main principles**
  - ***never delete***
  - ***append only***



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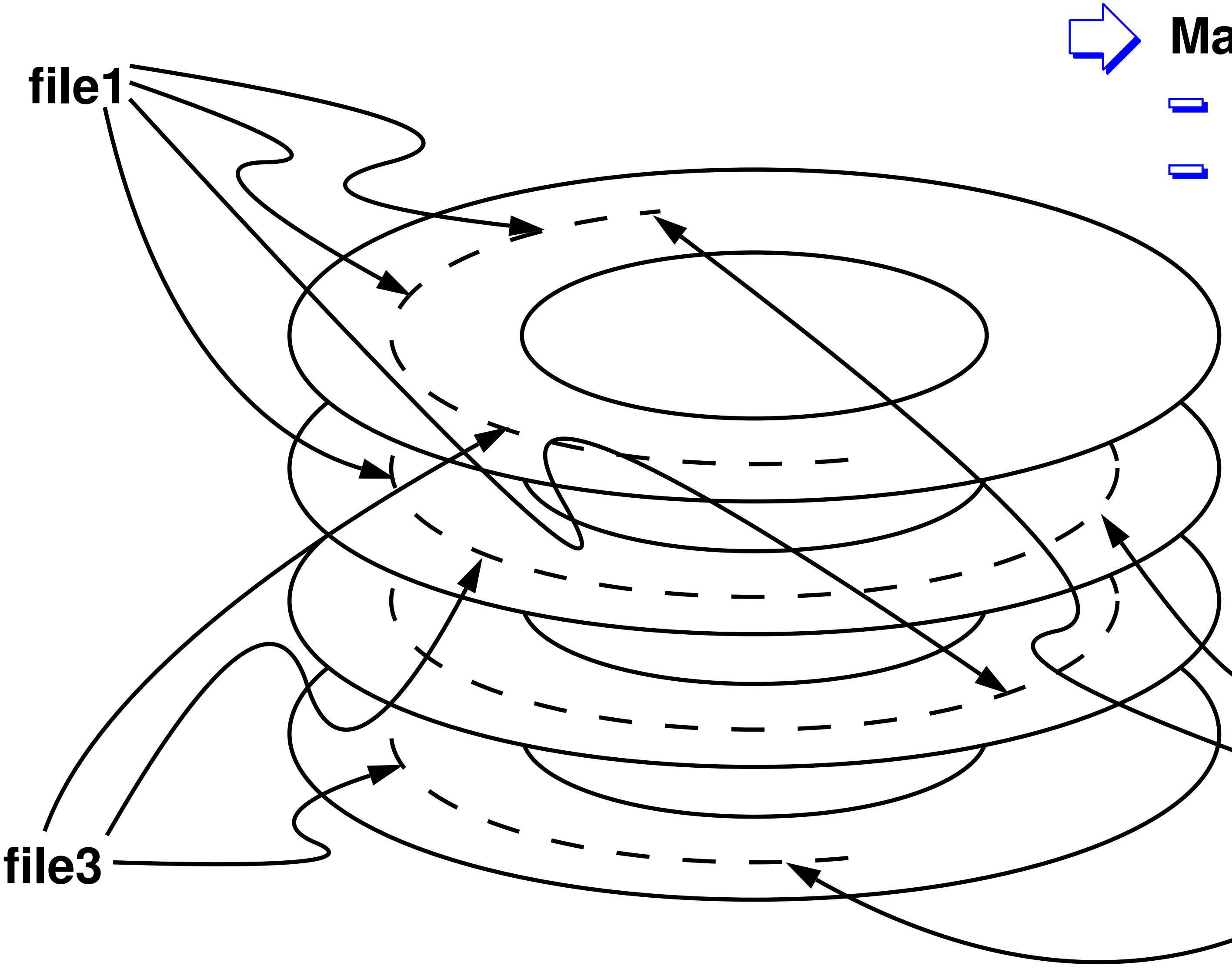

- Main principles
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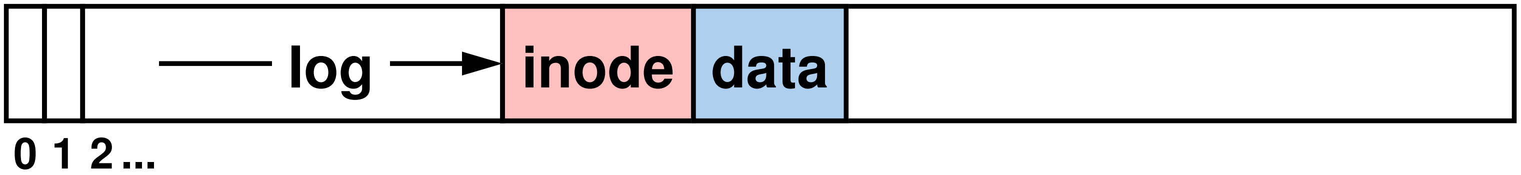


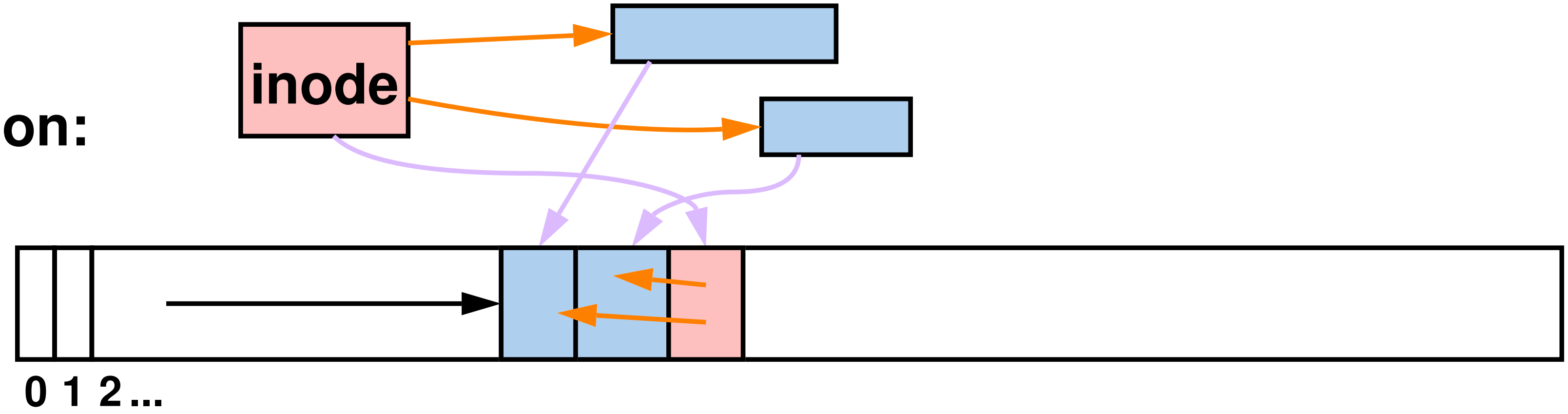
Log-Structured File Systems

- How does "never delete" and "always append" help with performance?
  - minimize seek latency
  - minimize rotational latency
    - write a cylinder at a time
- *Sprite FS* (a log-structured file system)
  - through batching, a single, long write can write out everything

LFS Data Placement Example

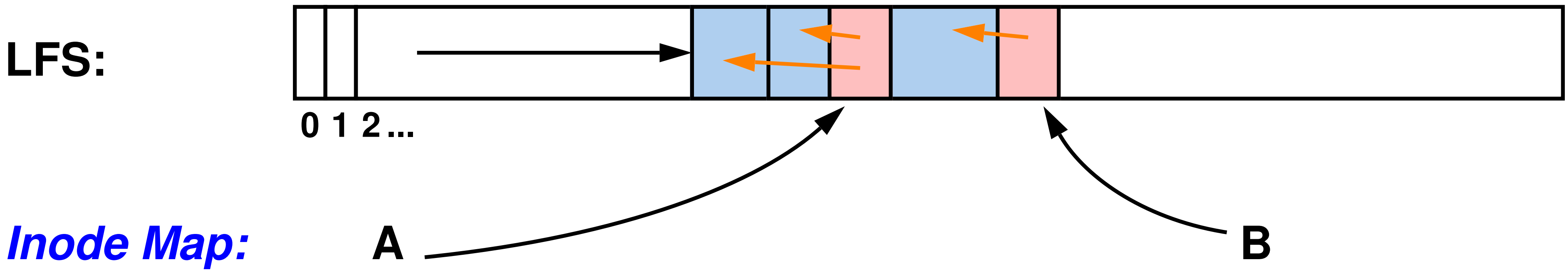
File On-disk Representation:

LFS:



LFS Data Placement Example

- What happens if you want to modify the file?
  - how does "append-only" really work?
- Ex: you create file A and then file B



  - you modify file A, e.g., append to the last block of file A
  - the new file will be referred as A’

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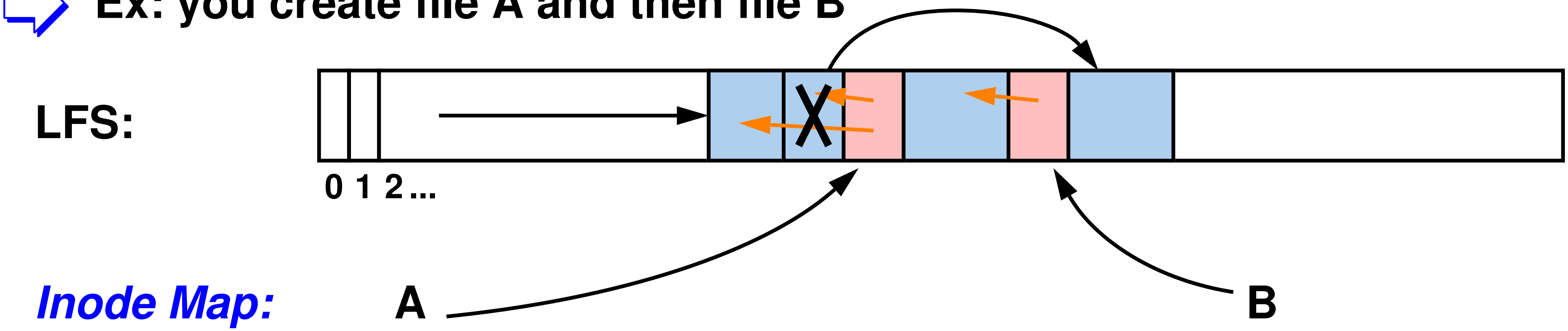

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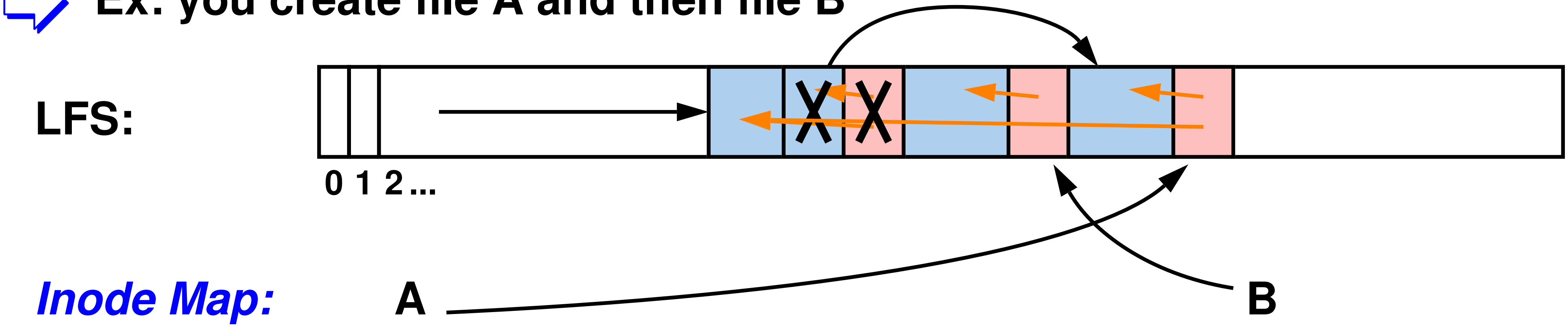

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  - the updated file is still file A
    - but the inode has changed

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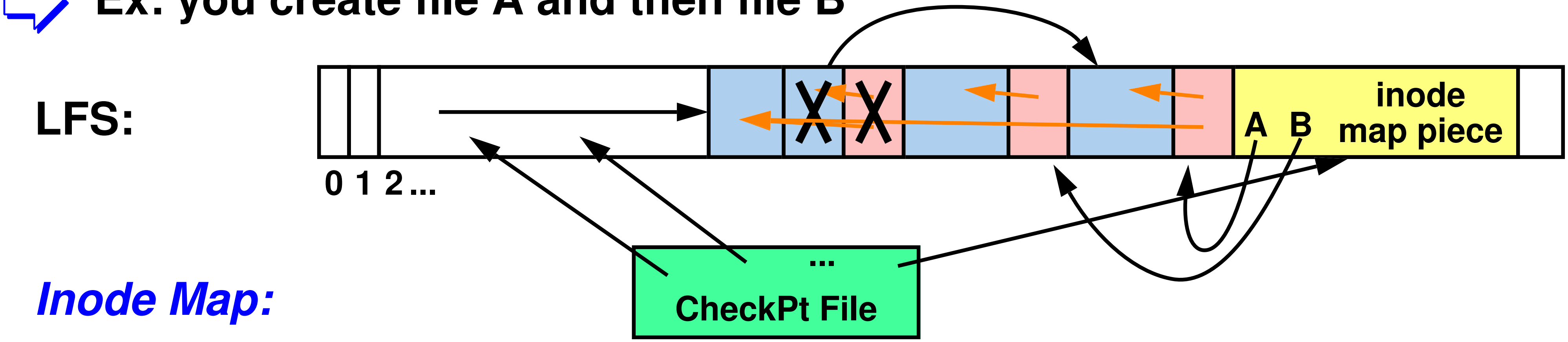
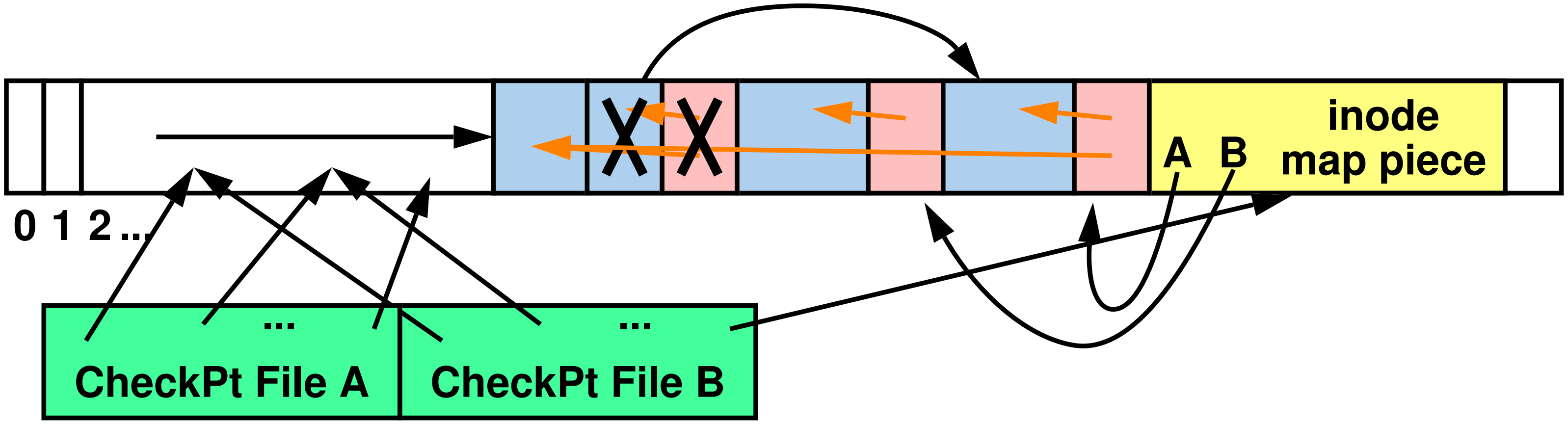


Inode Map:

- you modify file A, e.g., append to the last block of file A
- the updated file is still file A
  - but the inode has changed
- a ***piece*** of the ***inode map*** is appended to the log
  - fixed regions (previous version and current version) on the disk keeps track of ***all*** the ***inode map pieces***
    - known as ***checkpoint file***

More On Inode Map

- *Inode Map* cached in primary memory
  - indexed by inode number
  - points to inode on disk
  - written out to disk in pieces as updated
  - *checkpoint file* contains locations of pieces
    - written to disk occasionally
    - two copies: current and previous
    - outside of the "log" part of the LFS



- Commonly/Recently used inodes and other disk blocks cached in primary memory

LFS Summary

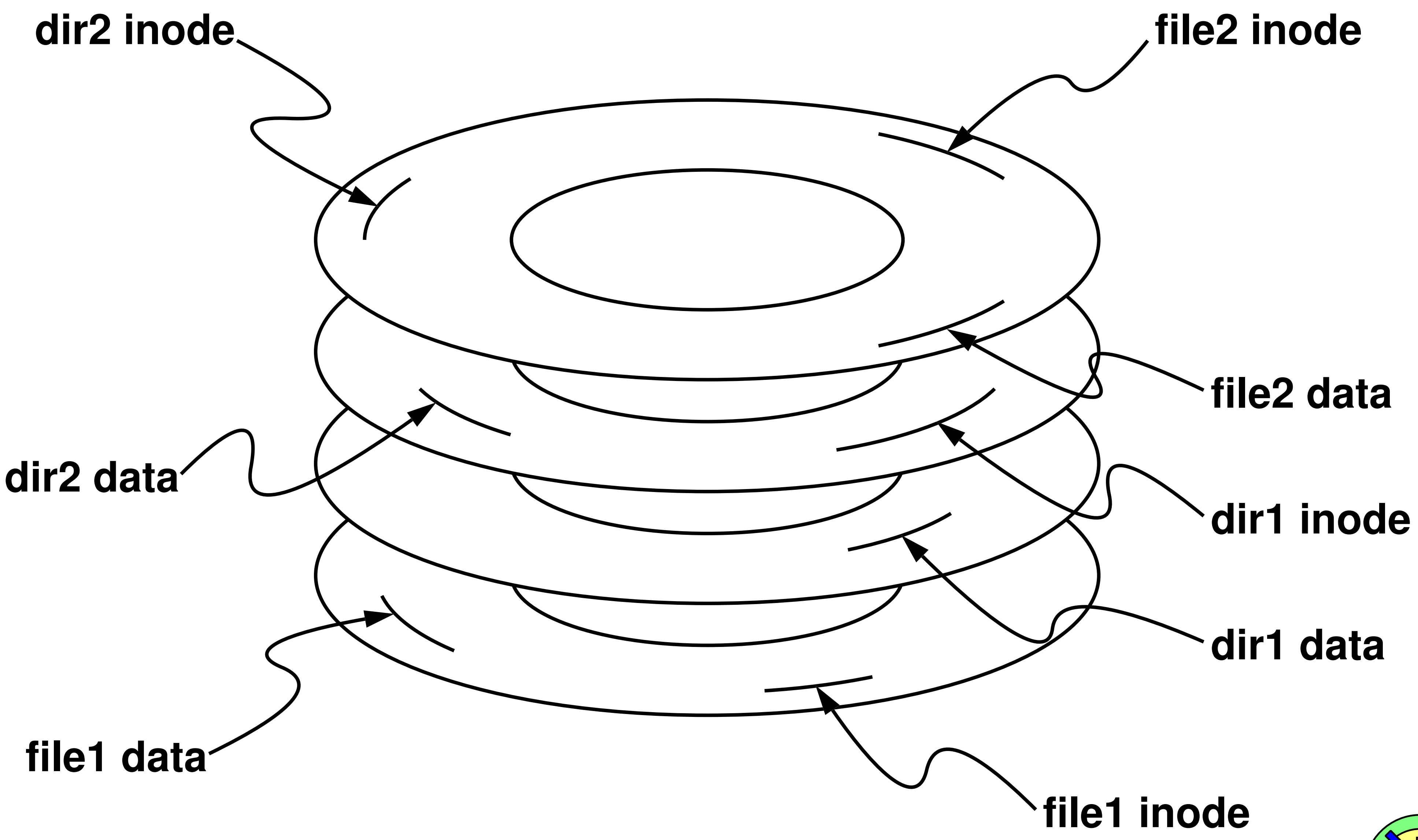
- Advantages
  - good performance for writes
  - can recover from crashes easily through the use of checkpoint files
- Disadvantages
  - can waste a lot of disk space

Extra Slides

Example

- We create two single-block files
  - dir1/file1
  - dir2/file2
- FFS
  - allocate and initialize inode for file1 and write it to disk
  - update dir1 to refer to it (and update dir1 inode)
  - write data to file1
    - allocate disk block
    - fill it with data and write to disk
    - update inode
  - six writes, plus six more for the other file
    - seek and rotational delays

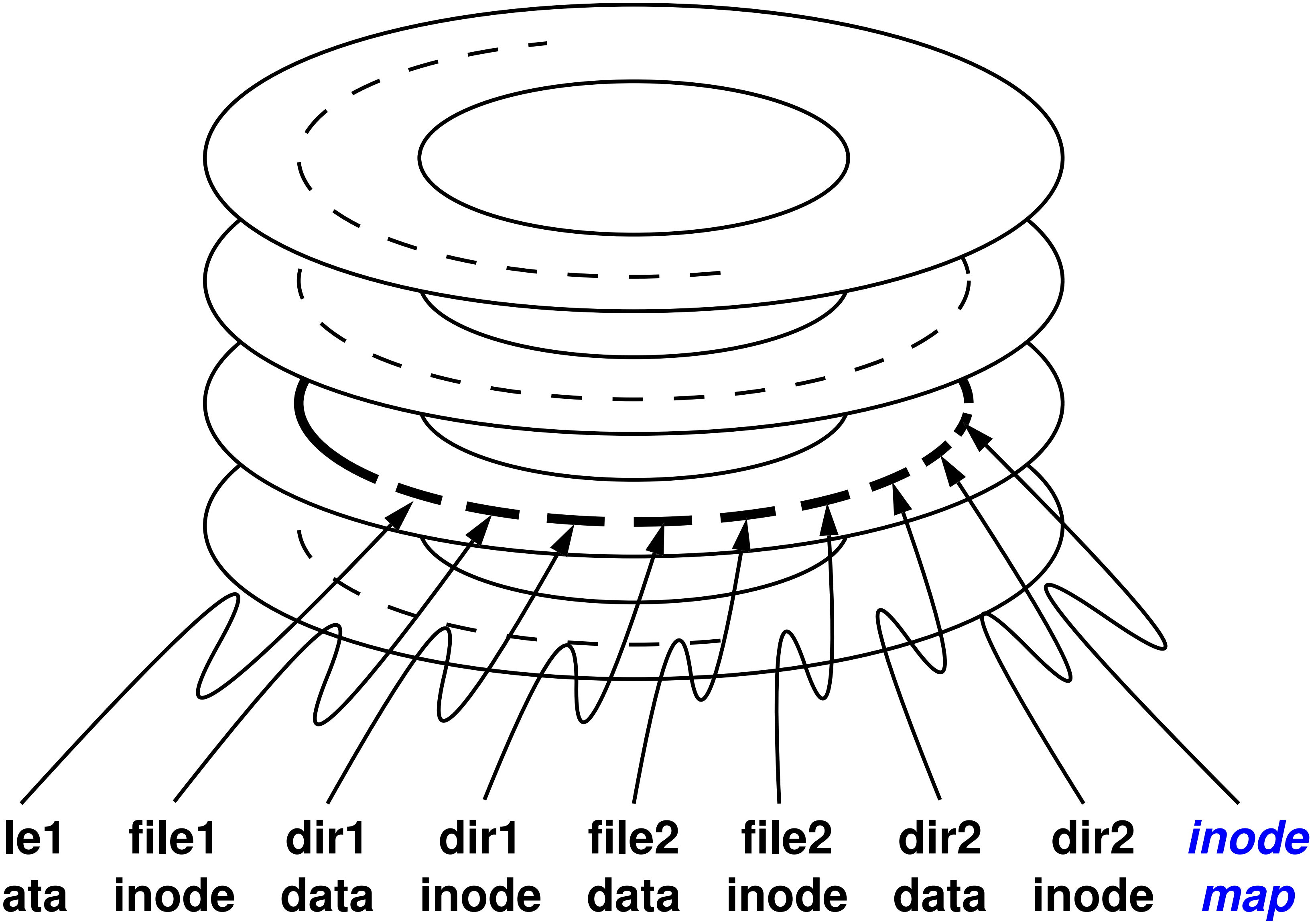
FFS Picture


dir2 inode
file2 inode
file2 data
dir2 data
dir1 inode
dir1 data
file1 data
file1 inode

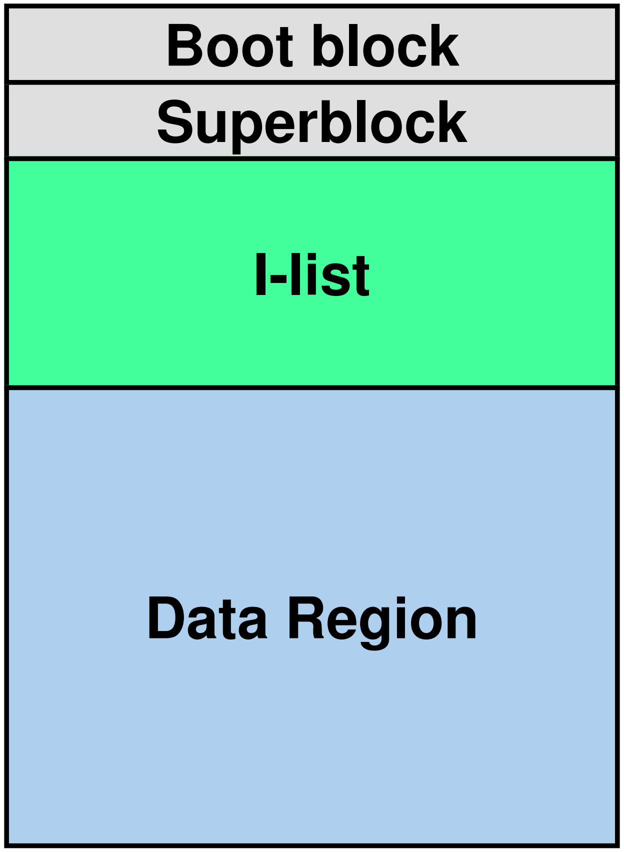
Example (Continued)

- Sprite (a log-structured file system)
  - one single, long write does everything

Sprite Picture



S5FS Layouts



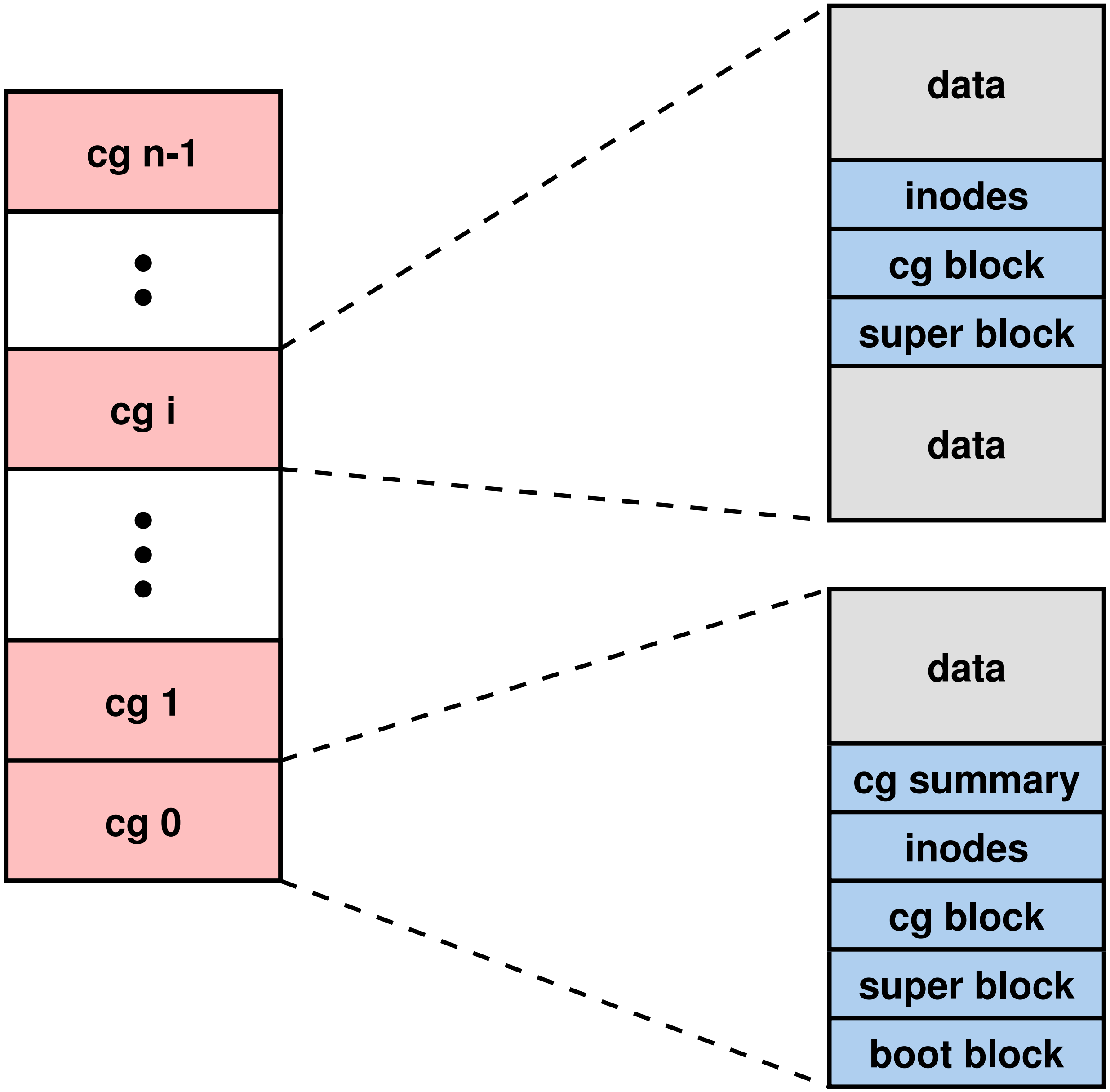
Boot block

Superblock

I-list

Data Region

FFS Layout


cg n-1
cg i
cg 1
cg 0
data
inodes
cg block
super block
data
data
cg summary
inodes
cg block
super block
boot block

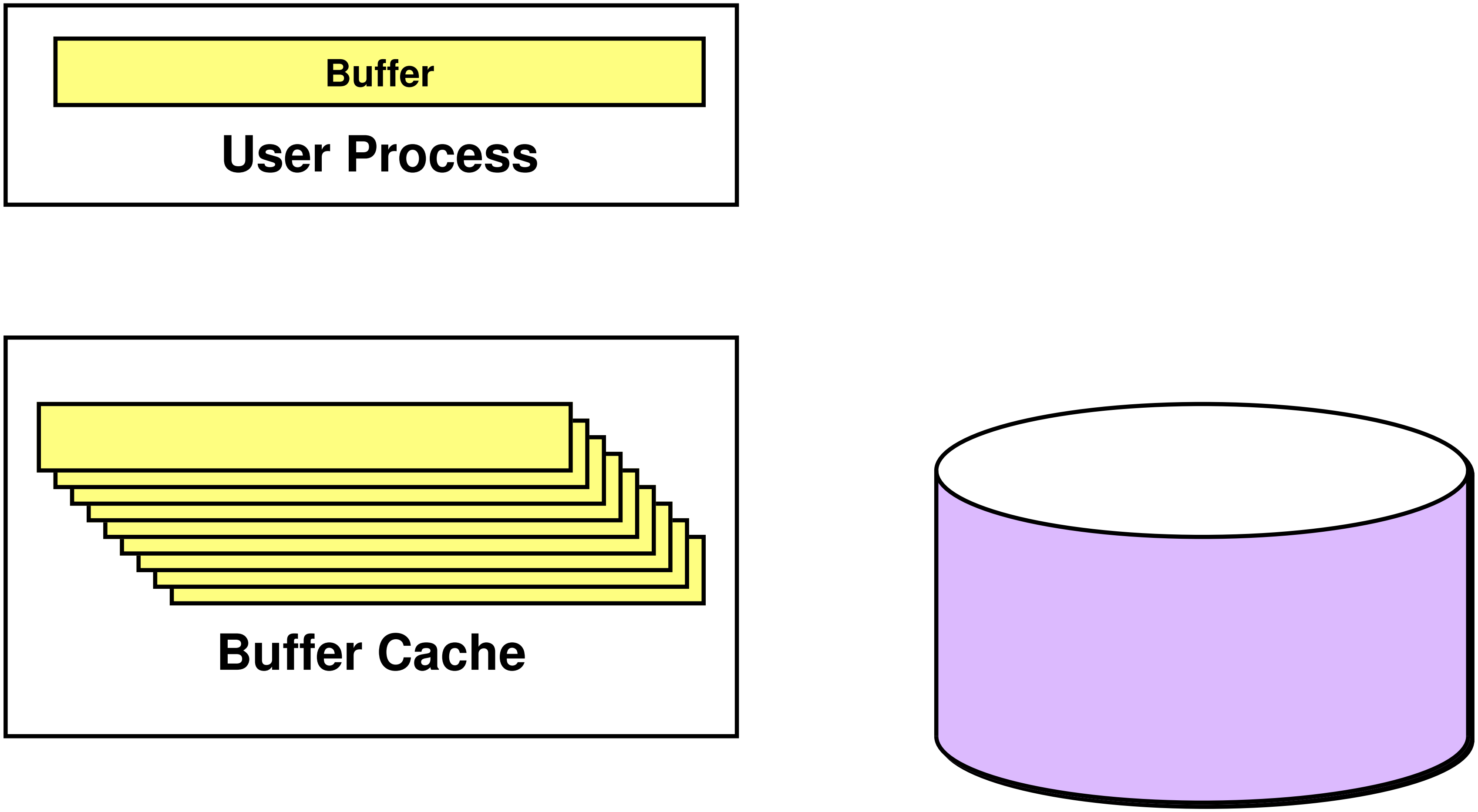
6.1 The Basics of File Systems

- UNIX’s S5FS
- Disk Architecture
- Problems with S5FS
- Improving Performance
- *Dynamic Inodes*

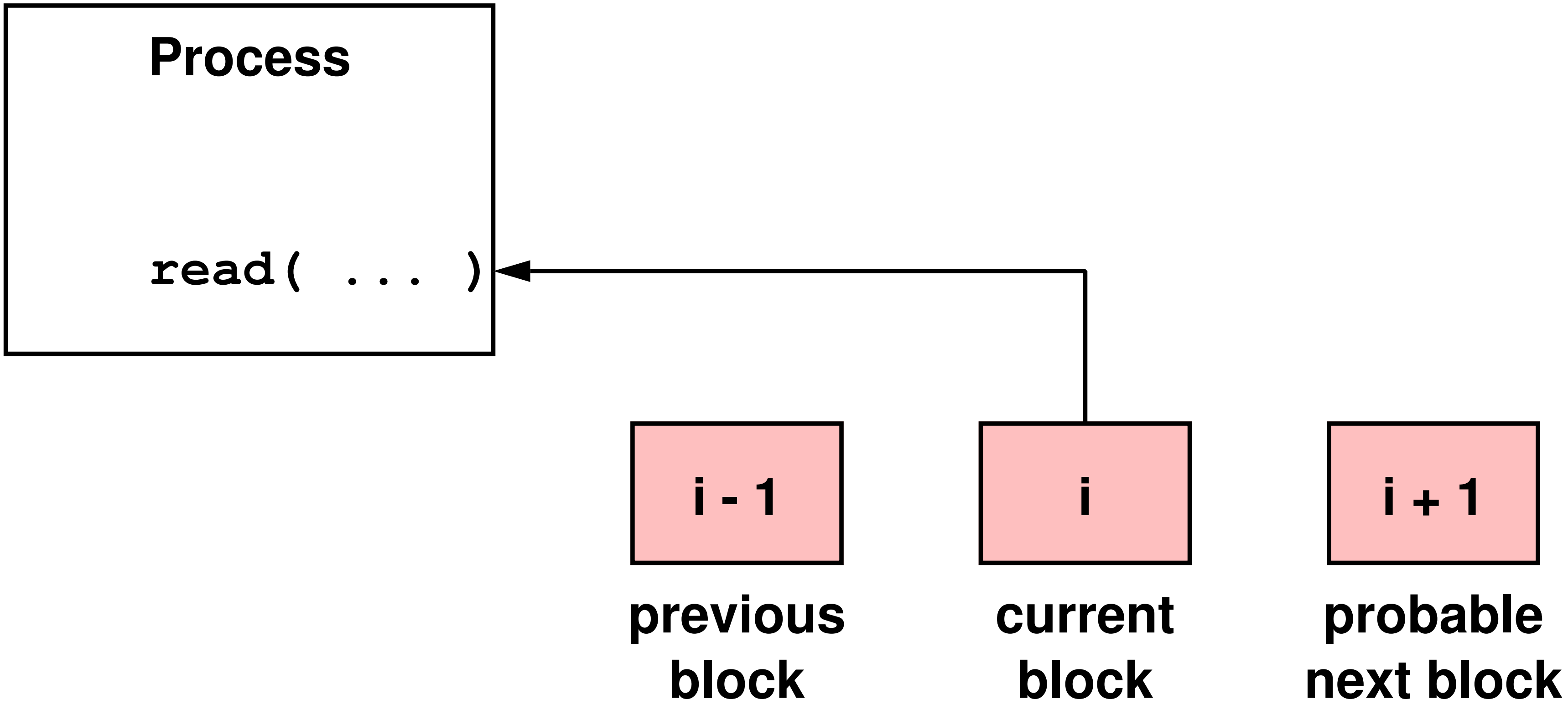
NTFS Master File Table

MFT
MFT Mirror
Log
Volume Info
Attribute Definitions
Root Directory
Free-Space Bitmap
Boot File
Bad-Cluster File
Quota Info
Expansion entries
User File 0
User File 1

The Buffer Cache



Multi-Buffered I/O



Process

`read( ... )`

i - 1

previous block

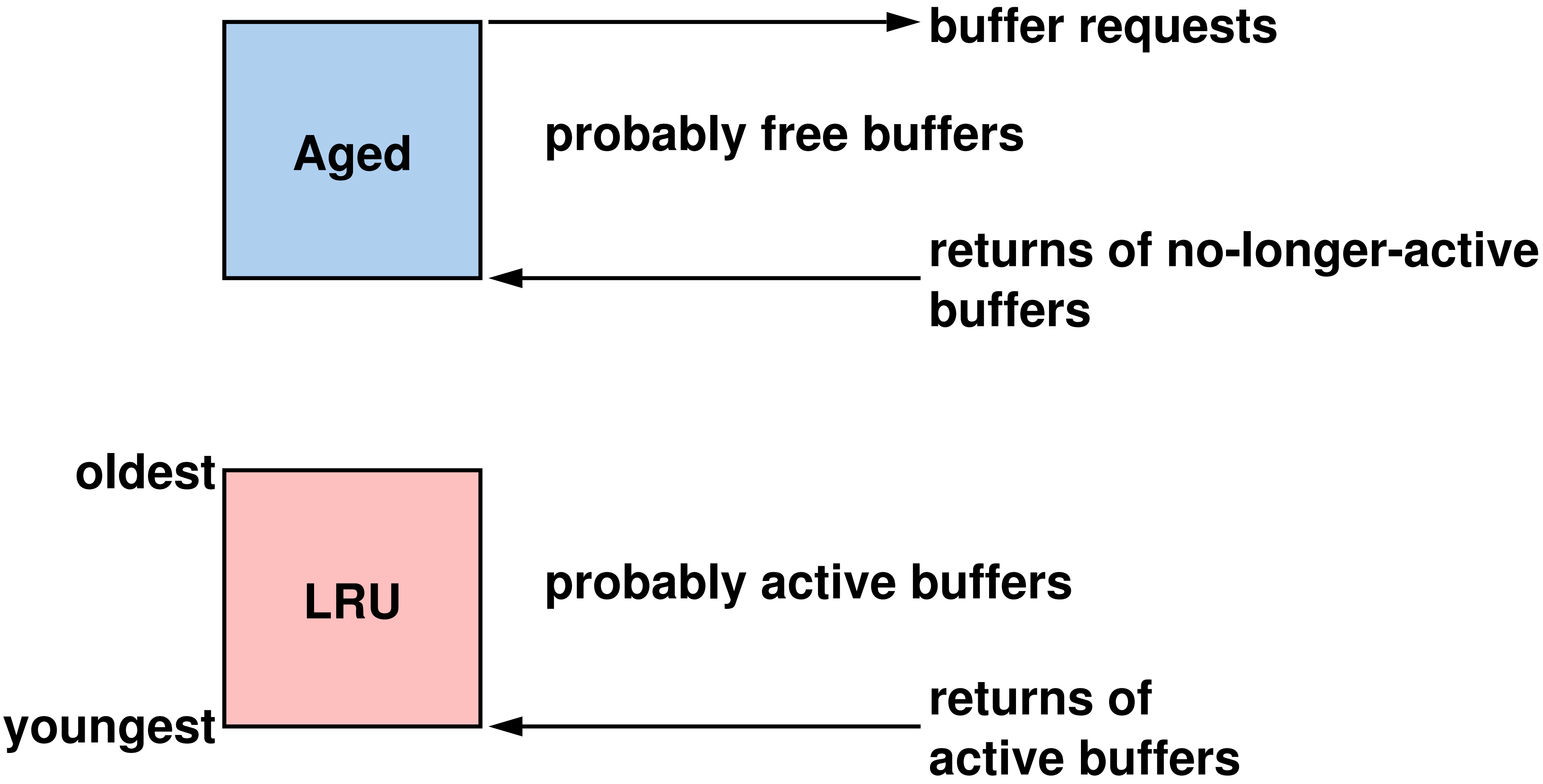
i

current block

i + 1

probable next block

Maintaining the Cache



Aged

buffer requests

probably free buffers

returns of no-longer-active buffers

oldest

LRU

youngest

probably active buffers

returns of active buffers