OSTEP
Persistence:
FAST FILE SYSTEM (FFS)

Questions answered in this lecture:

How to improve performance of complex system?

Why do file systems obtain worse performance over time?

How to choose the right block size? How to avoid internal fragmentation?

How to place related blocks close to one another on disk?

File-System Case Studies

Local

- **FFS**: Fast File System [today]
- **LFS**: Log-Structured File System

Network

- **NFS**: Network File System
- **AFS**: Andrew File System

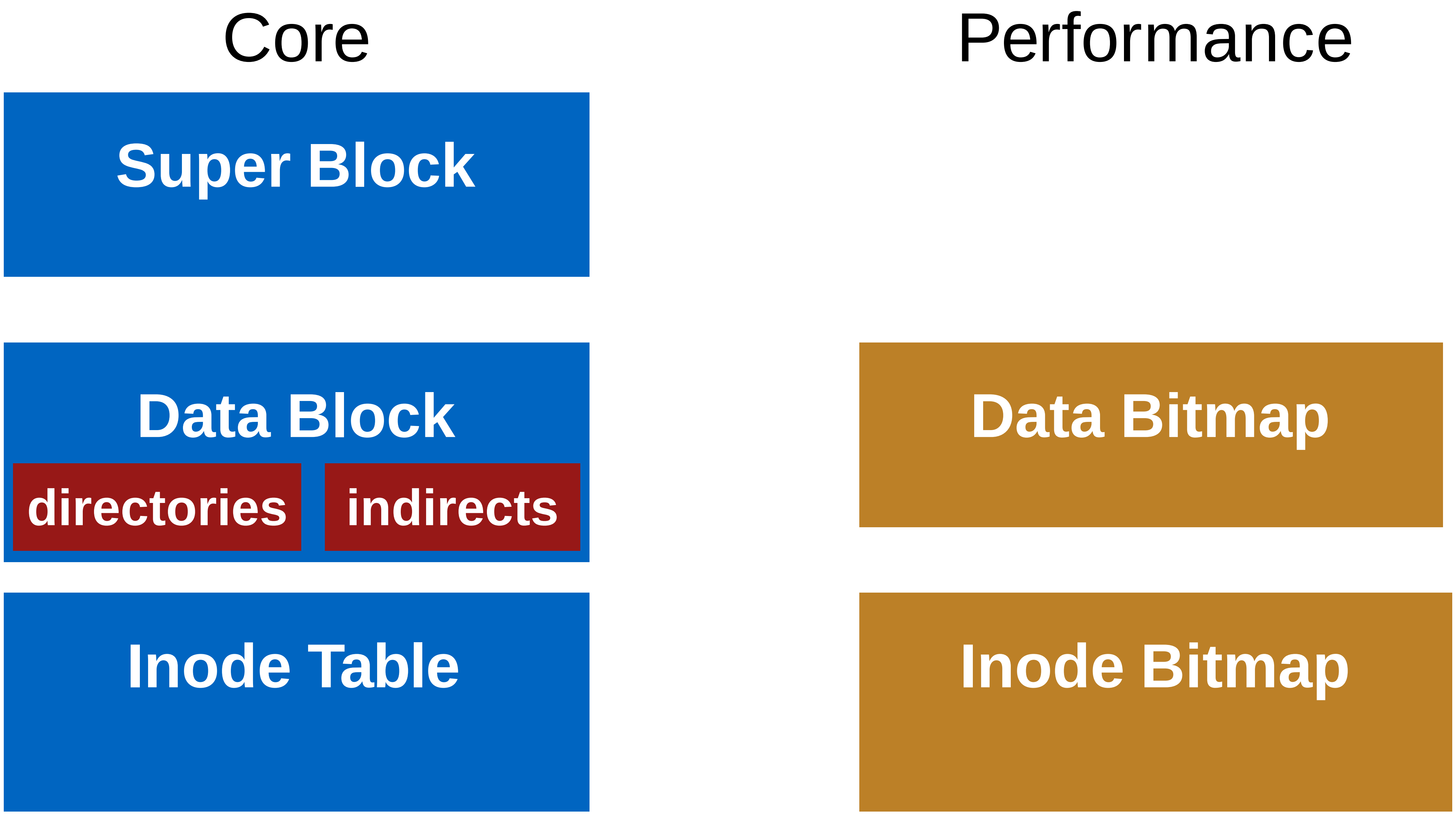
REVIEW basic fs

Basic fs

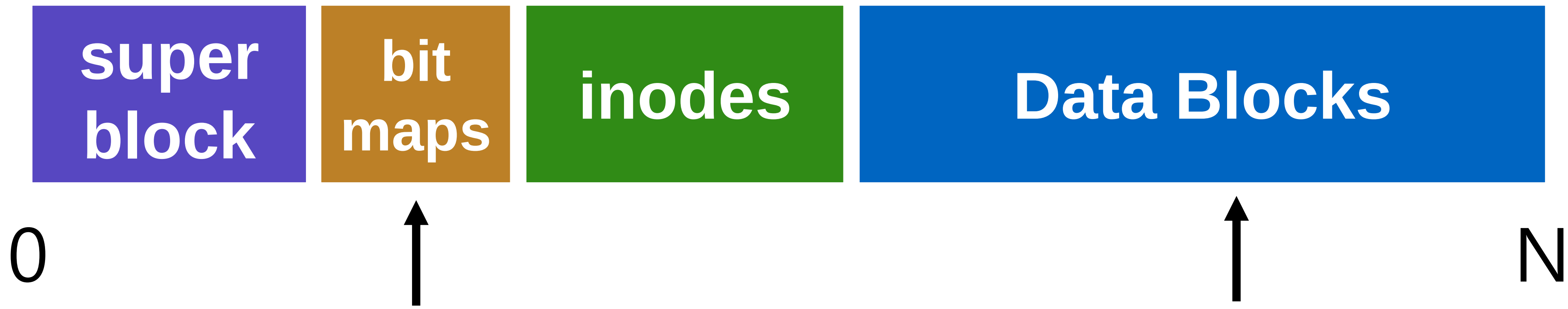
Structures (on disk)

Operations

Structure Overview



Basic Layout



inodes
data blocks

regular data
directories
indirect blocks

What is stored as a data block?

Basic fs

Structures (on disk)

Operations

REVIEW: create /foo/bar

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data

[traverse]

create /foo/bar

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data
		read				
					read	
			read			
						read

Verify that bar does not already exist

[allocate inode]

create /foo/bar

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data
		read				
					read	
			read			
						read
	read					
	write					

[populate inode]

create /foo/bar

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data
		read				
					read	
			read			
						read
	read write					
				read write		

Why must **read** bar inode?
How to initialize inode?

[add bar to /foo]

create /foo/bar

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data
		read				
					read	
			read			
						read
	read					
	write					
				read		
				write		
			write			
						write

Update inode (e.g., size) and data for directory

open /foo/bar

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data
		read					
					read		
			read				
						read	
				read			

write to /foo/bar (assume file exists and has been opened)

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data
				read			
read							
write							
							write
				write			

append to /foo/bar

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data

append to /foo/bar (opened already)

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data
				read			

append to /foo/bar

[allocate block]

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data
				read			
read							
write							

append to /foo/bar

[point to block]

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data
				read			
read							
write							
				write			

[write to block]

append to /foo/bar

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data
				read			
read							
write							
				write			
							write

read /foo/bar – assume opened

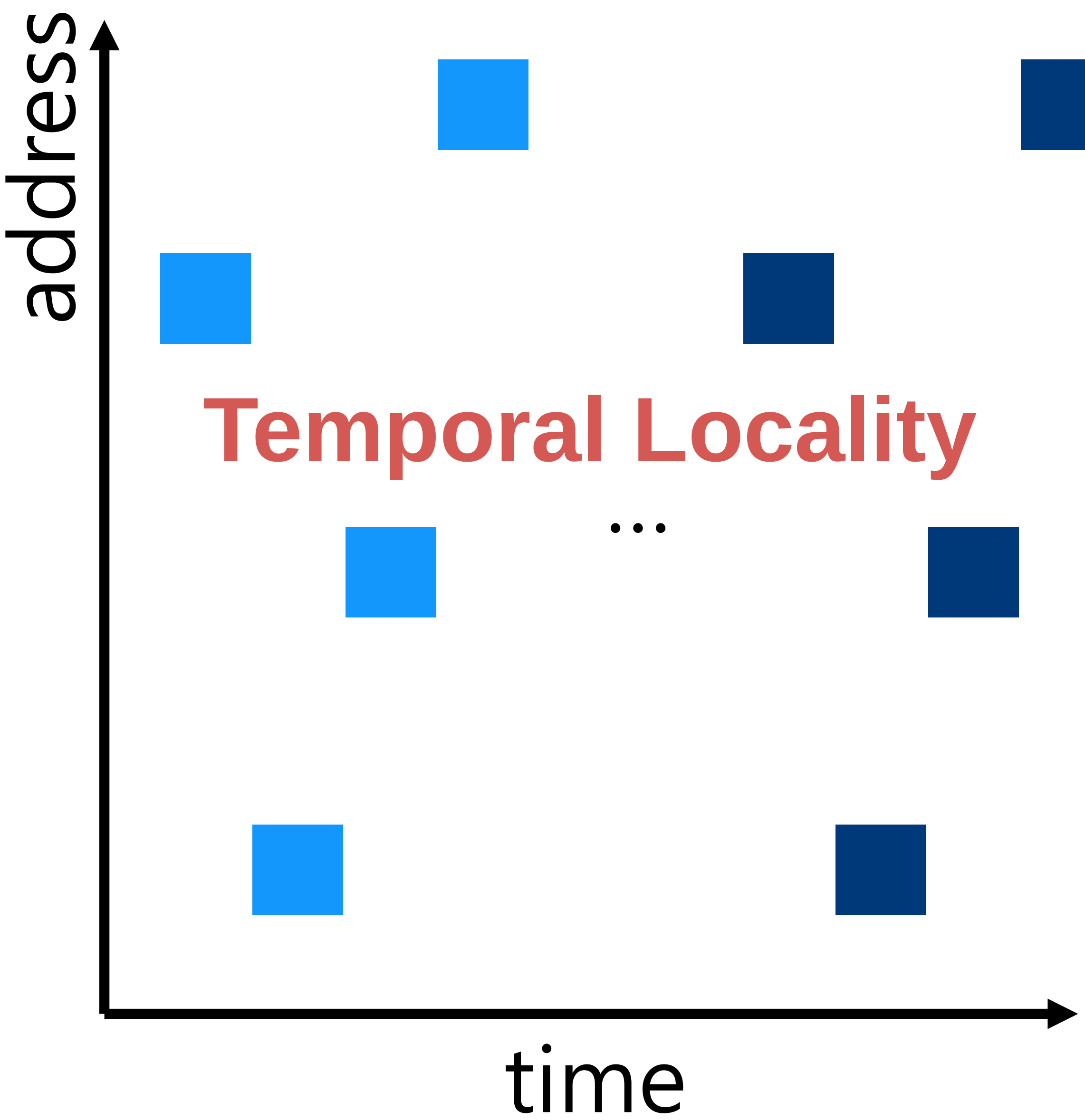
data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data
				read			
							read
				write			

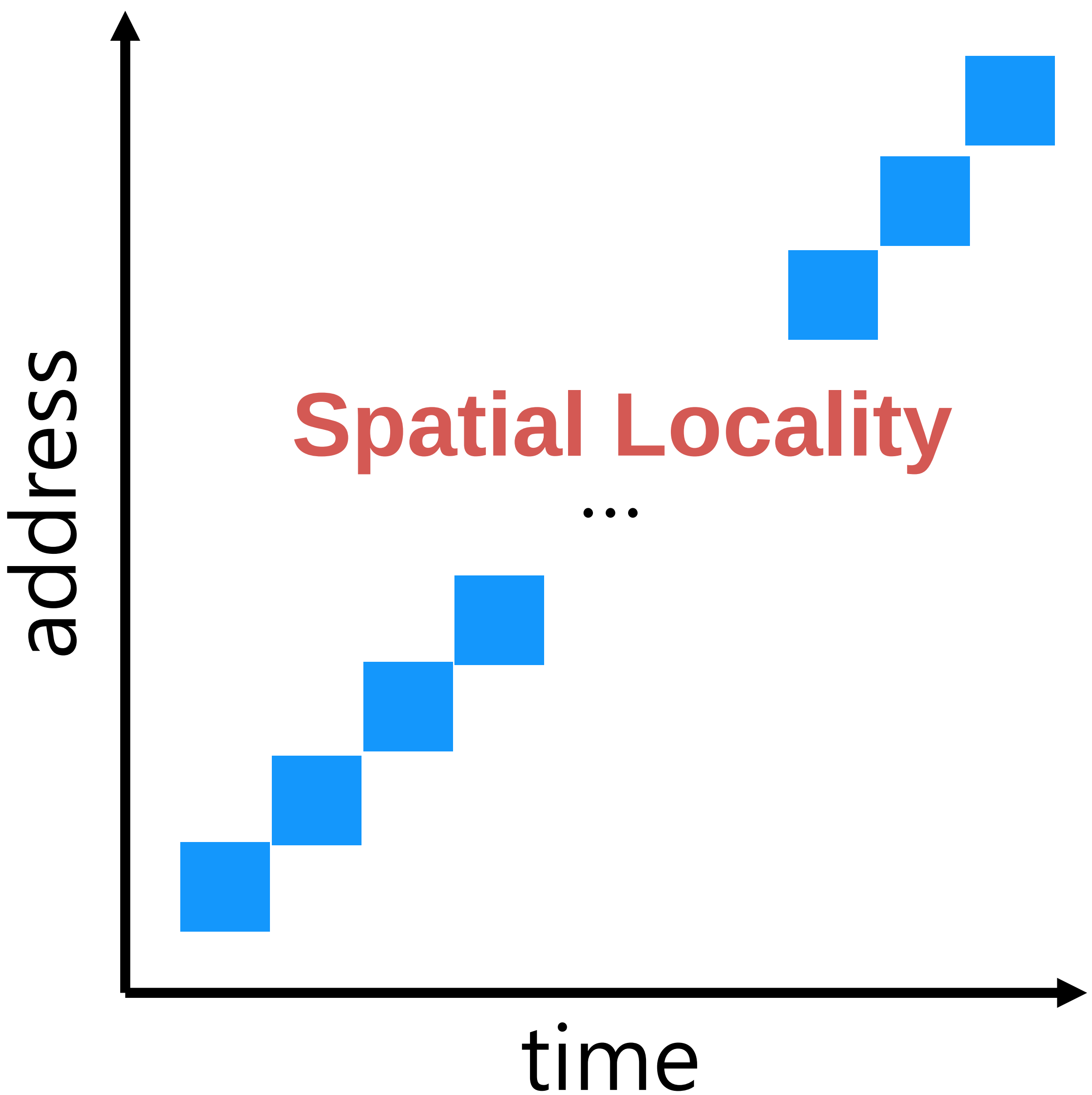
close /foo/bar

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data

nothing to do on disk!

Review: Locality Types





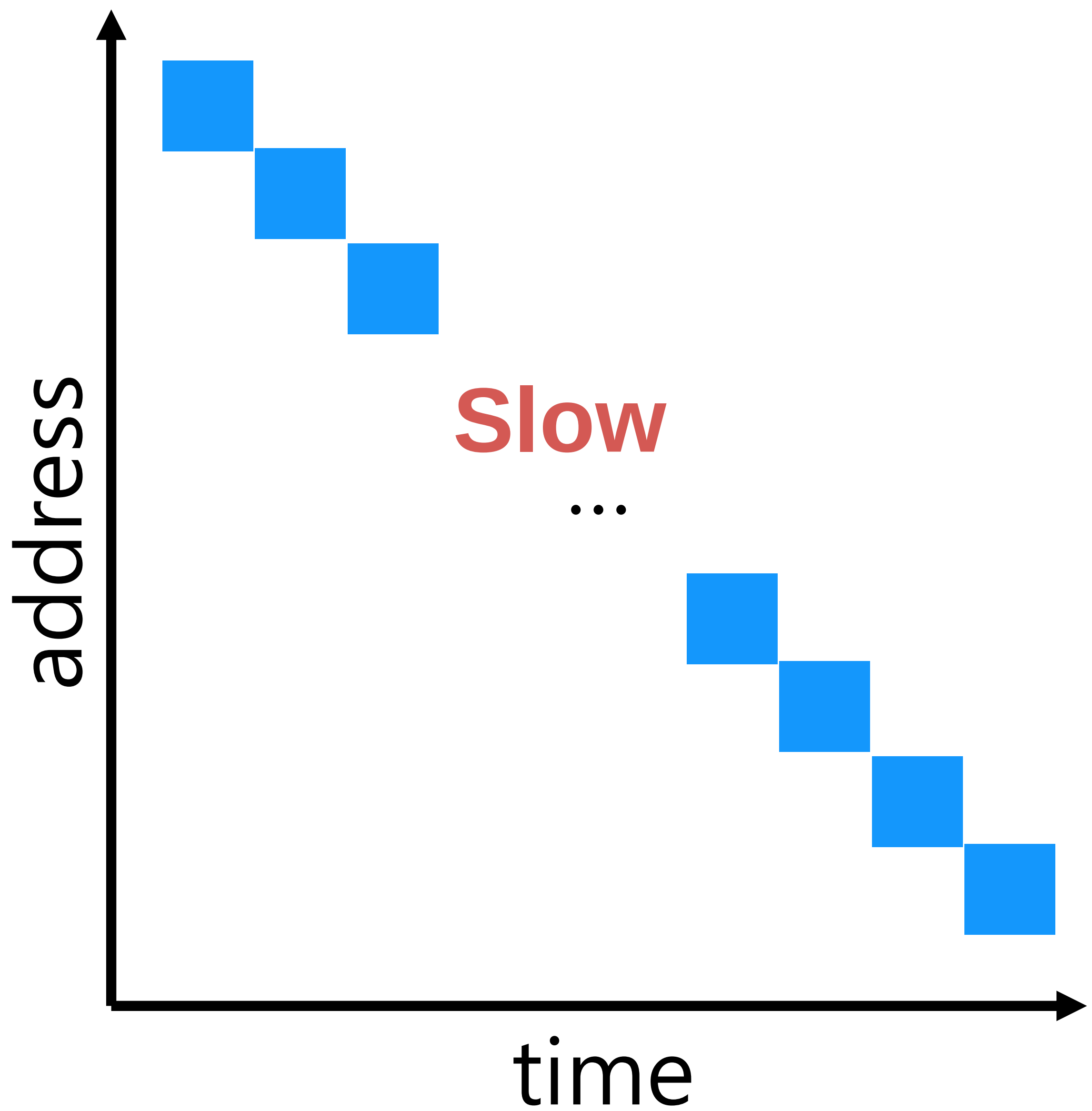
Which type of locality is most interesting with a disk?

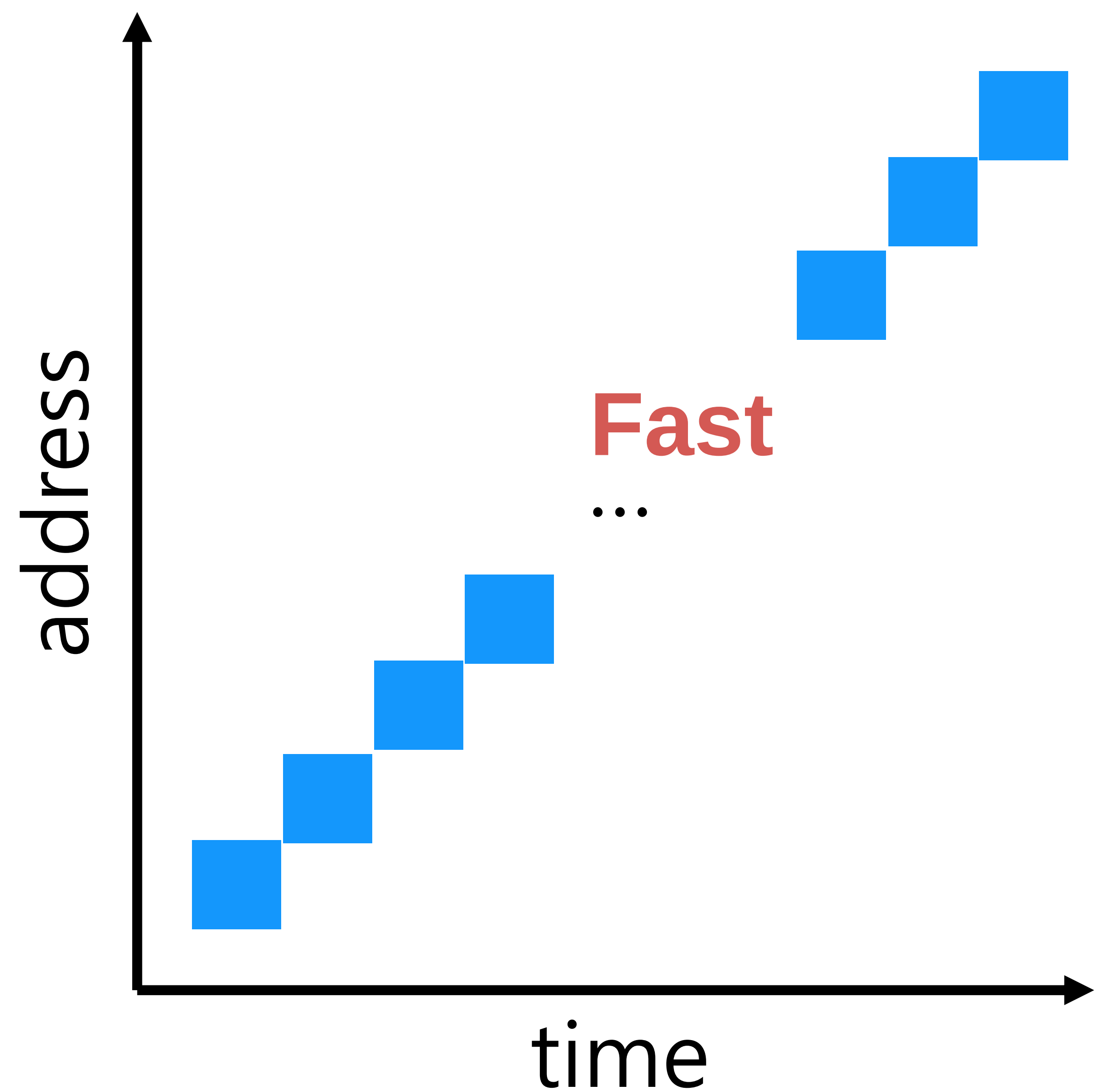
Locality Usefulness

What types of locality are useful for a cache?

What types of locality are useful for a disk?

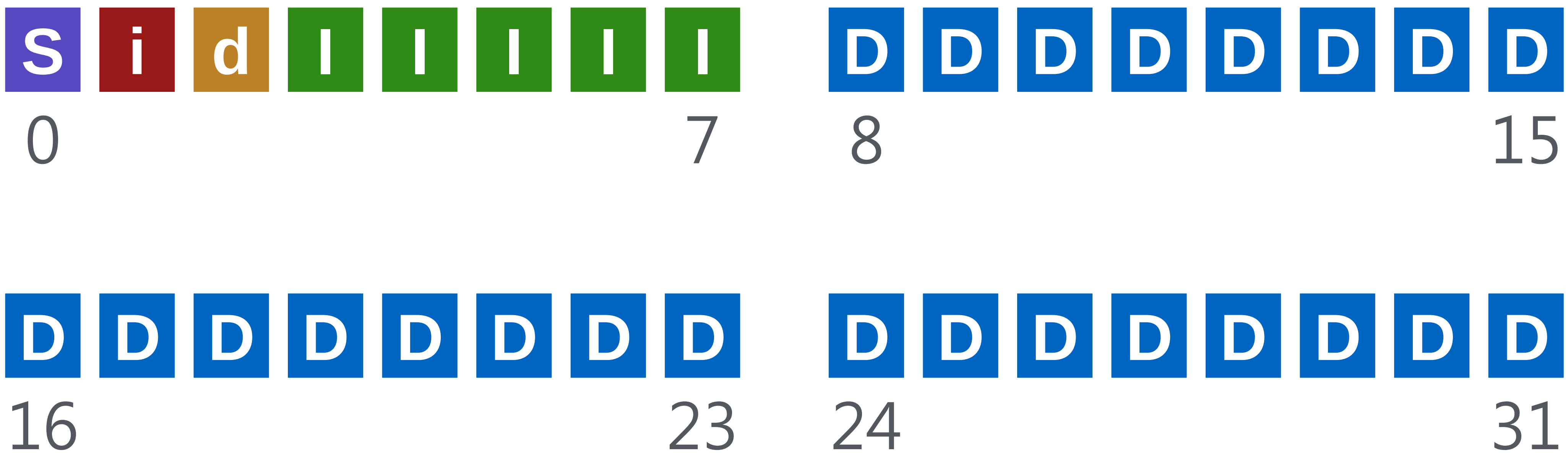
Order Matters





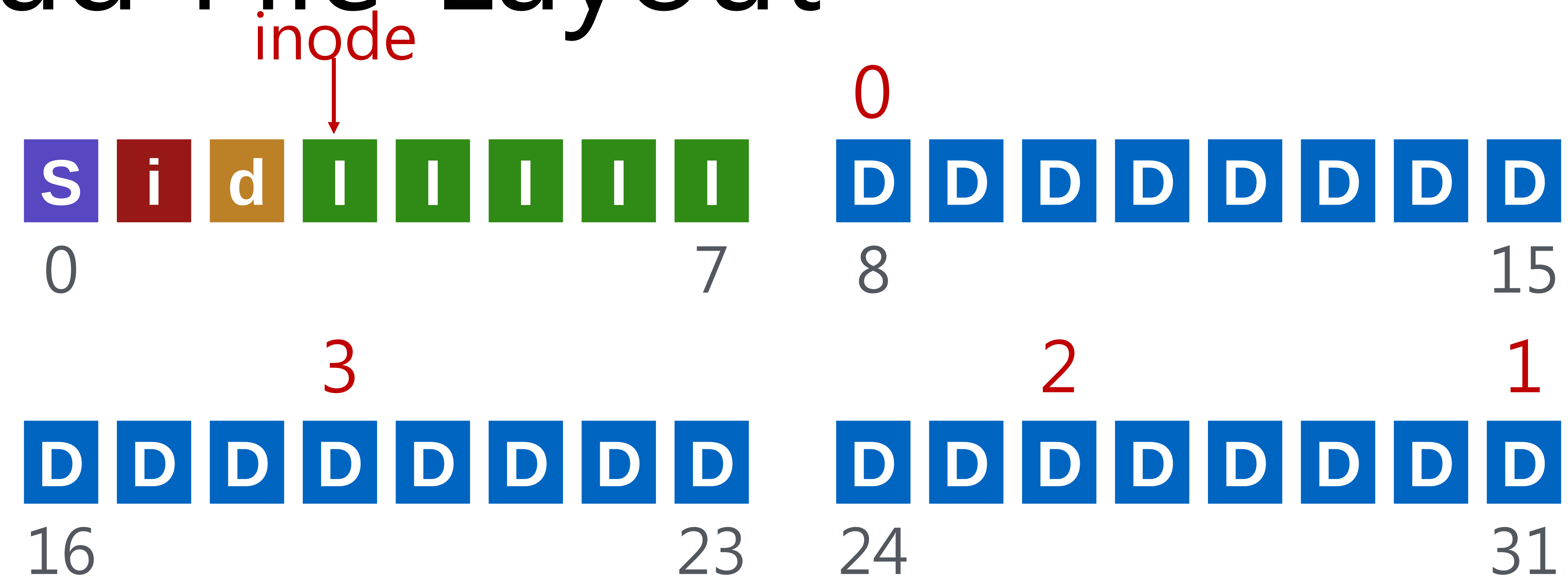
Implication for disk schedulers?

Policy: Choose Inode, Data Blocks

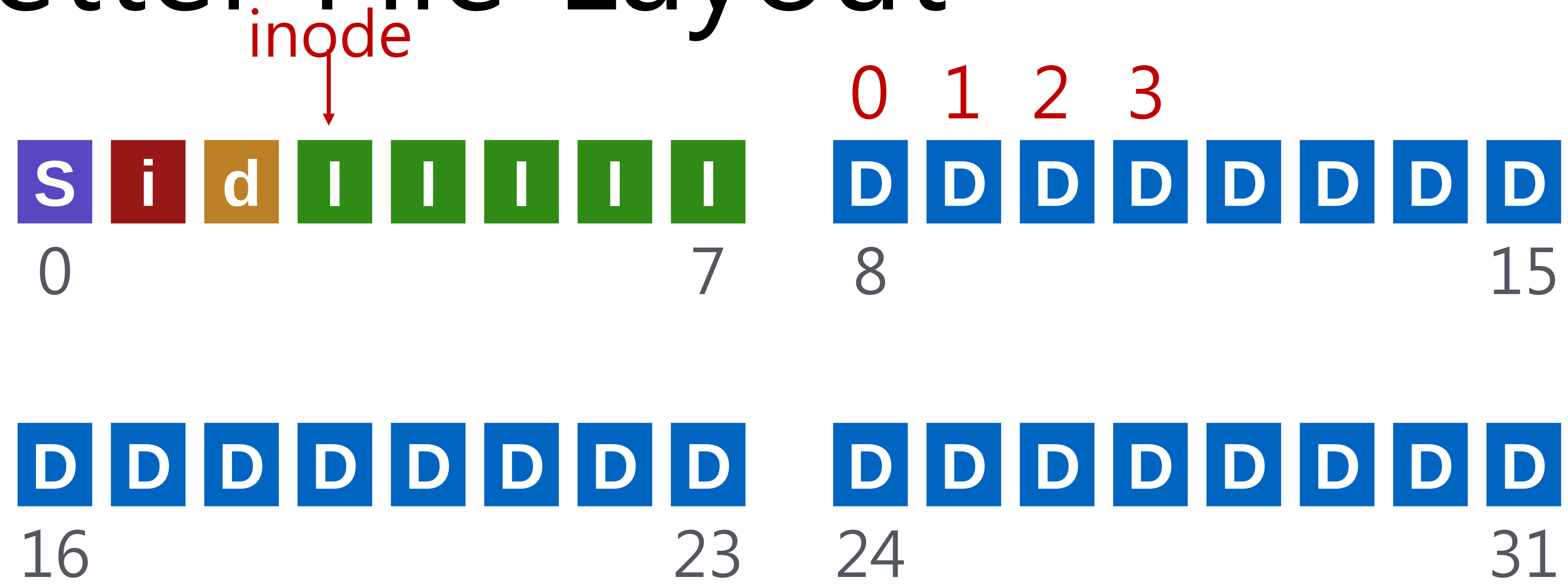


Assuming all free, which should be chosen?

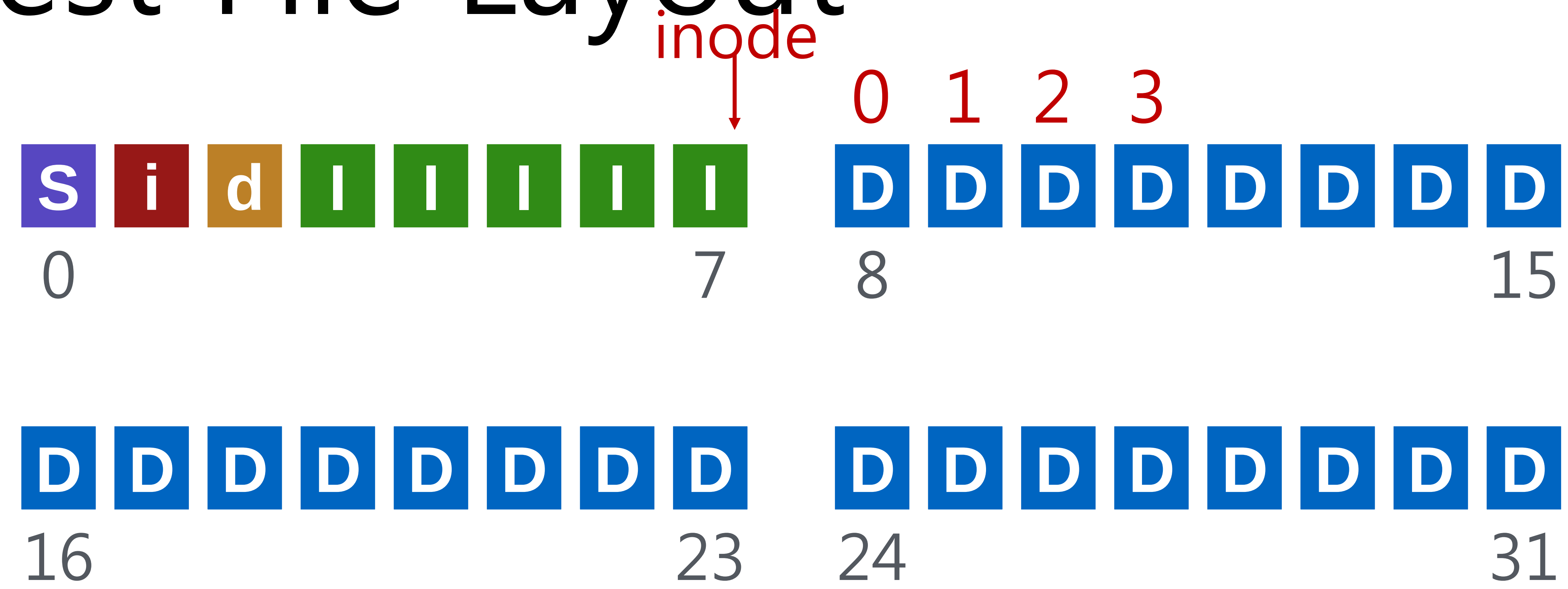
Bad File Layout



Better File Layout



Best File Layout



Can’t do this for all files ☹

Fast File System: FFS(1980’s)

System Building

Beginner's approach

1. get idea
2. build it!

Pro approach

1. identify existing state of the art
2. measure it, identify and understand problems
3. get idea (solutions often flow from deeply unders tanding problem)
4. build it!

System Building

Beginner's approach

1. get idea
2. build it!

measure then build

Pro approach

1. identify existing state of the art
2. measure it, identify and understand problems
3. get idea (solutions often flow from deeply und erstanding problem)
4. build it!

Measure Old FS

State of the art: original UNIX file system

Free lists are embedded in inodes, data blocks

Data blocks are 512 bytes

Measure throughput for whole sequential file reads/writes

Compare to theoretical max, which is… disk bandwidth

Old UNIX file system: achieved only **2%** of potential. Why?

Measurement 1: Aging?

What is performance before/after **aging**?

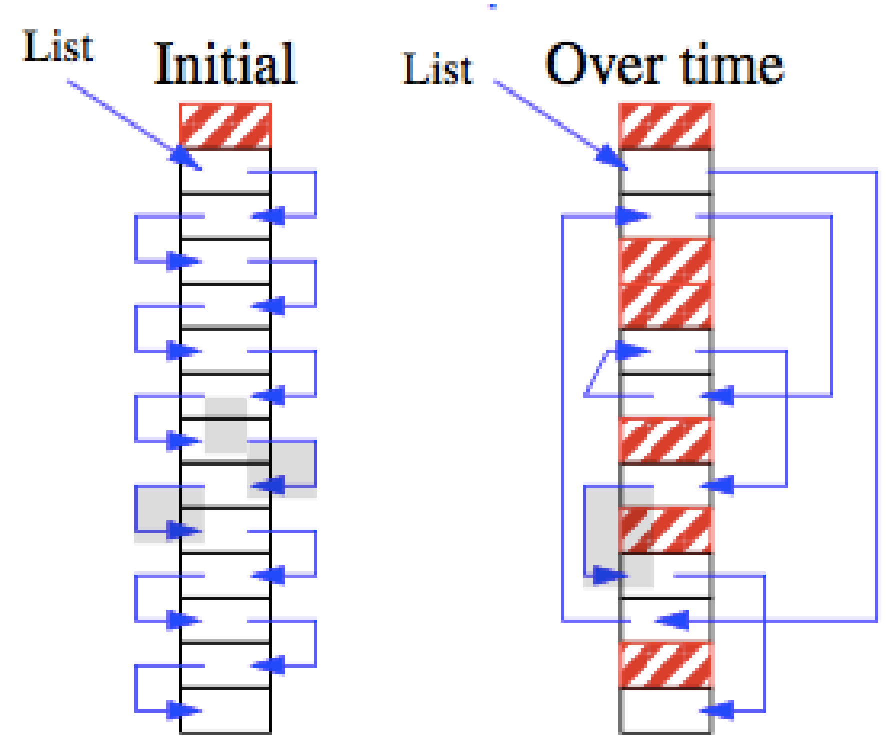
- New FS: **17.5%** of disk bandwidth
- Few weeks old: **3%** of disk bandwidth

Problem: FS is becomes fragmented over time

- Free list makes contiguous chunks hard to find

Hacky Solutions:

- Occassional defrag of disk
- Keep freelist sorted



Measurement 2: Block SIZE?

How does block size affect performance?
Try doubling it!

Result: Performance **more** than doubled

Why double the performance?
- Logically adjacent blocks not physically adjacent
- Only half as many seeks+rotations now required

Why **more** than double the performance?
- Smaller blocks require more indirect blocks

Old FS Summary

Free list becomes scrambled → random allocations

Small blocks (512 bytes)

Blocks laid out poorly

- long distance between inodes/data
- related inodes not close to one another
  - Which inodes related?

Inodes in same directory (ls –l)

Result: **2%** of potential performance! (and worse over time)

Problem: old FS treats disk like RAM!

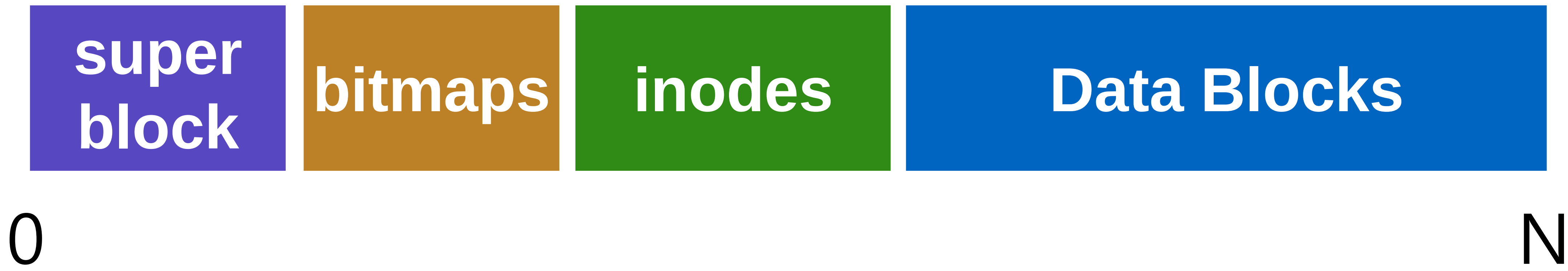
Solution: a disk-aware

Primary File System Design Questions:

- Where to place meta-data and data on disk?

- How to use big blocks without wasting space?

Placement Technique 1: Bitmaps



Use bitmaps instead of free list
Provides better speed, with more global view

Faster to find contiguous free blocks

Techniques

Bitmaps

Organizing Structure: The Cylinder Group

- FFS divides the disk into a bunch of groups. **(Cylinder Group)**
  - Modern file system call cylinder group as block group.

G0	**G1**	**G2**	**G3**	**G4**	**G5**	**G6**	**G7**	**G8**	**G9**

- These groups are used to improve seek performance.
  - By placing two files within the same group.
  - Accessing one after the other **will not be long seeks** across the disk.
  - FFS needs to allocate files and directories within each of these groups.

Organizing Structure: The Cylinder Group (Cont.)

- Data structure for each cylinder group.
  - A copy of the **super block(S)** for reliability reason.
  - **inode bitmap(ib)** and **data bitmap(db)** to track free inode and data block.
  - **inodes** and **data block** are same to the previous very-simple file system(VSFS).

How To Allocate Files and Directories?

- Policy is "**keep related stuff together**"
- The placement of directories
  - Find the cylinder group with a low number of allocated directories and a high number of free inodes.
  - Put the directory data and inode in that group.

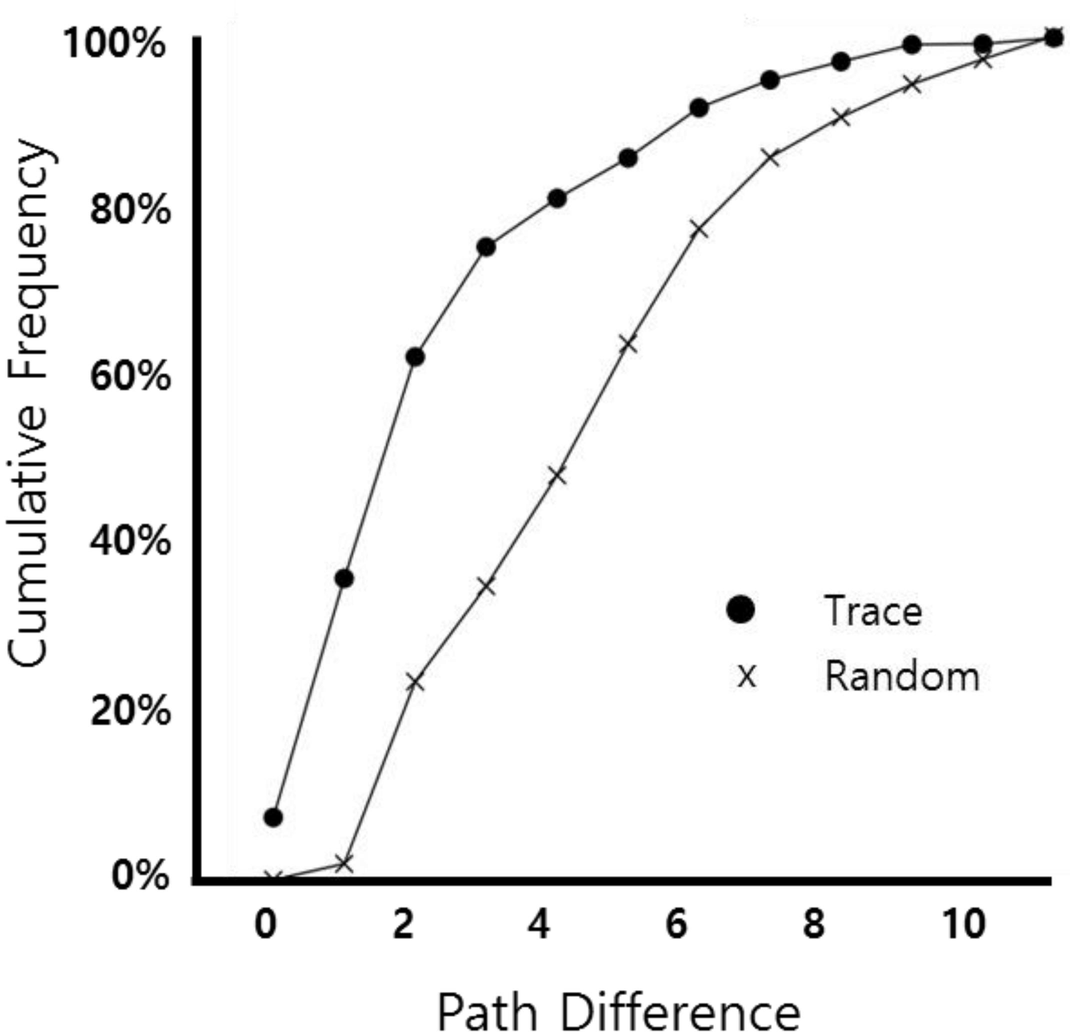
- The placement of files.
  - Allocate data blocks of a file in the same group as its inode
  - It places all files in the same group as their directory

FFS Locality for SEER Traces.

- How "**far away**" file accesses were from one another in the directory tree.

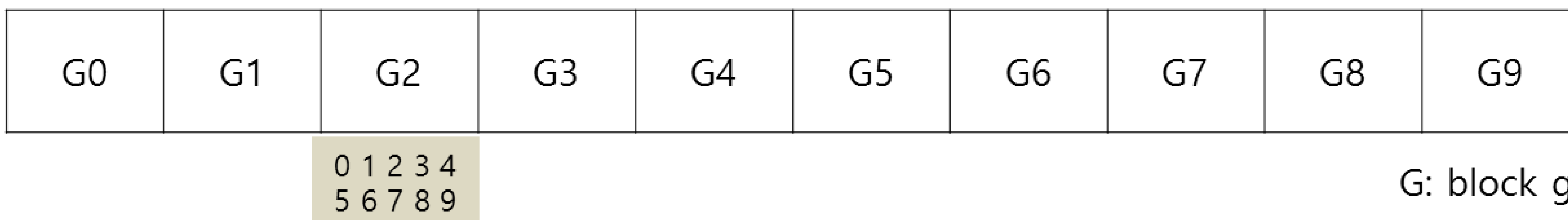
```
              proc/src/foo.c
              proc/src/bar.c
the distance of two file access is 1

              proc/src/foo.c
              proc/obj/foo.o
the distance of two file access is 2
```

  - 7% of file accesses to the same file
  - Nearly 40% of file accesses in the same directory
  - 25% of file accesses were two distances



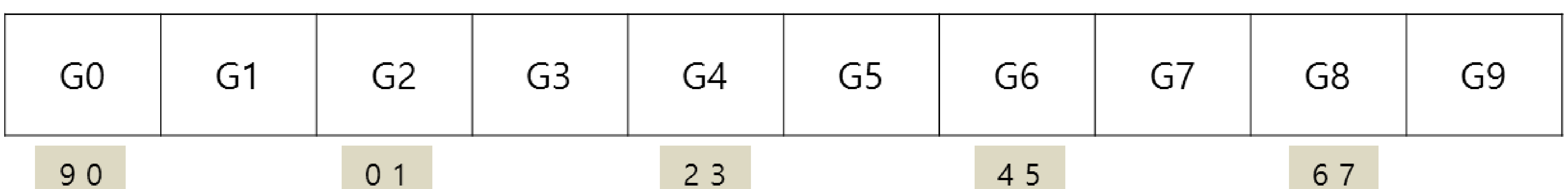
The Large-File Exception

- General policy of file placement
  - Entierly fill the block group it is first place within
  - Hurt file-access locality from "related" file being placed

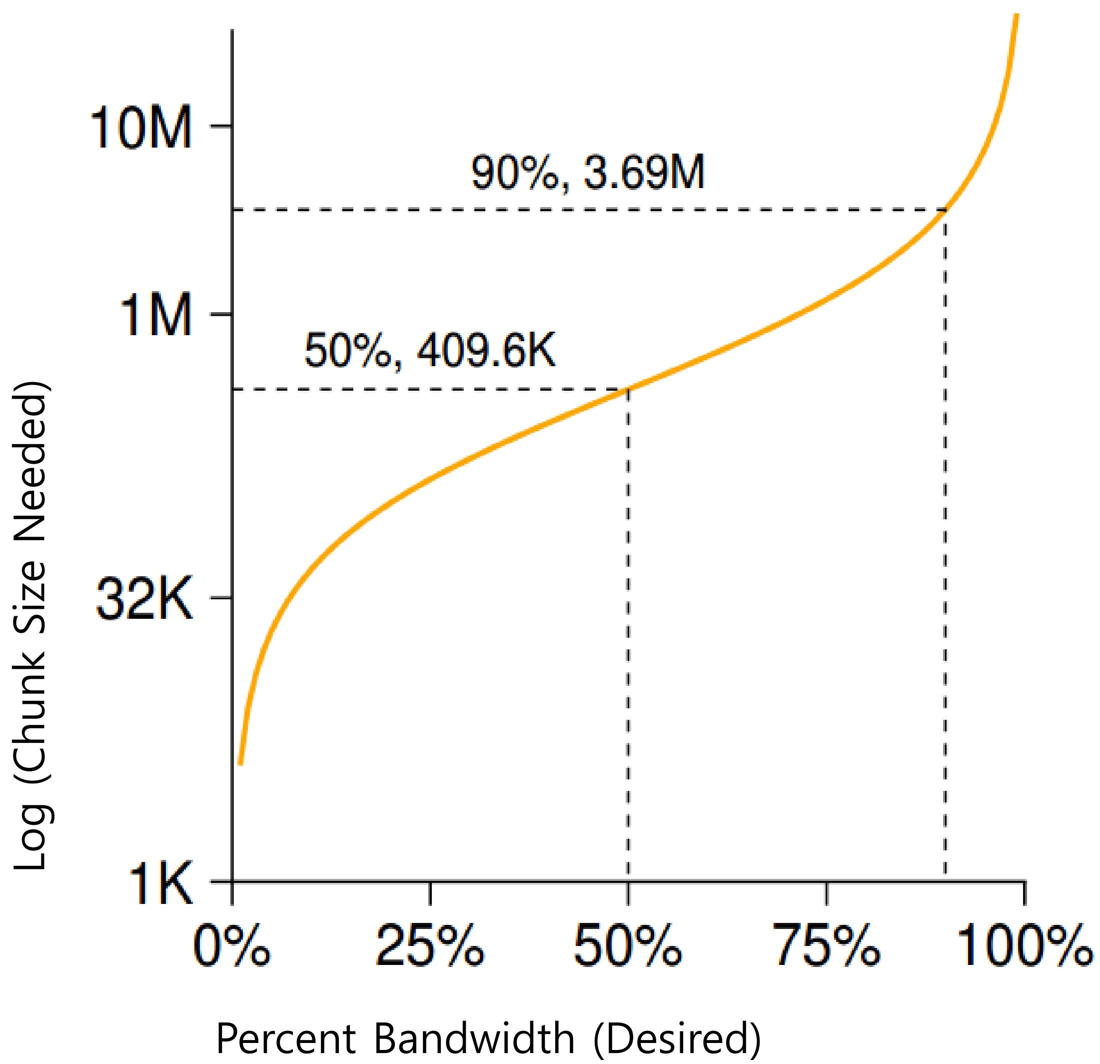


G: block group

- For large files, chunks are spread across the disk
  - Hurt performance, but it can be addressed by choosing chunk size
  - **Amortization**: reducing overhead by doing more work



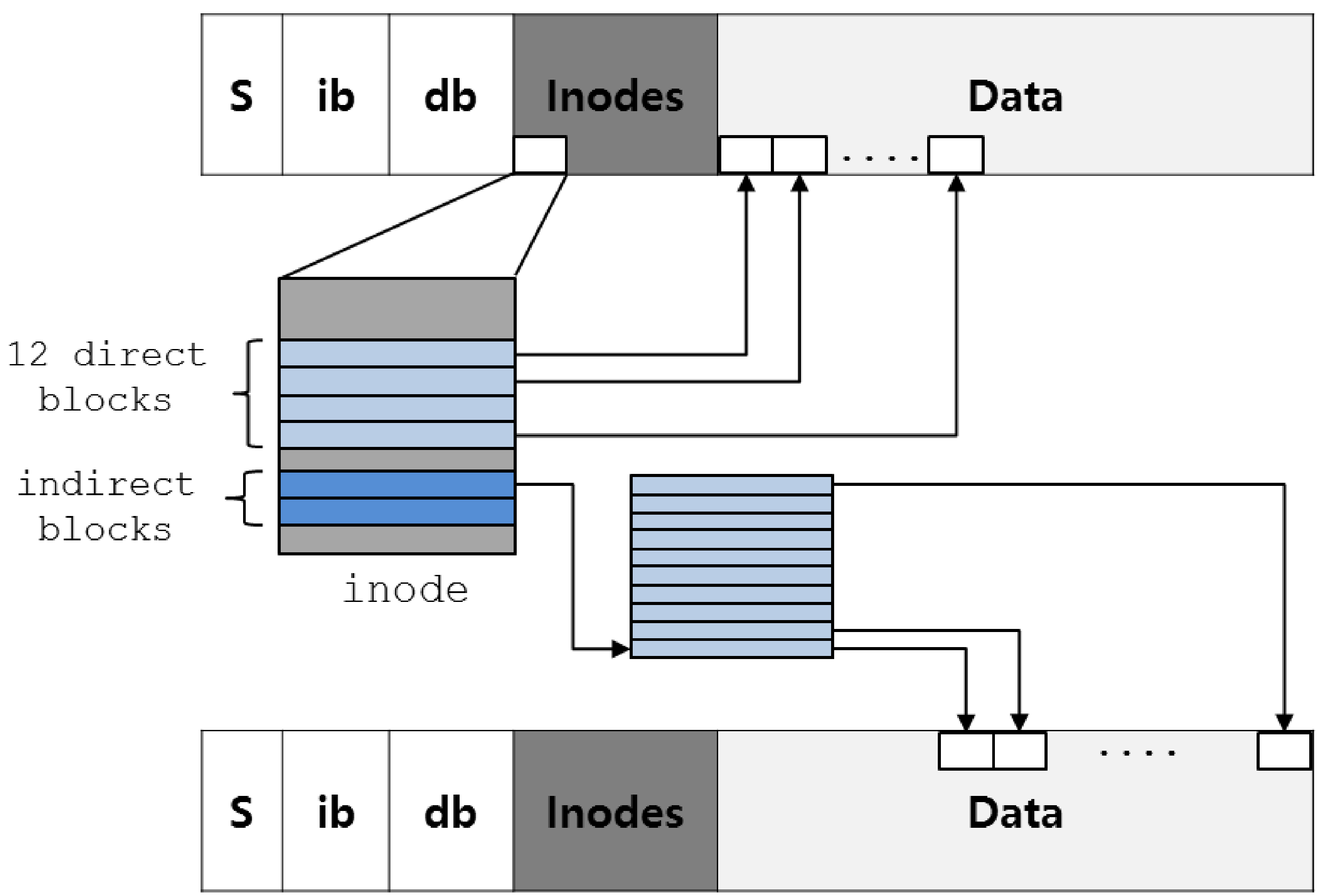
Amortization: How Big Do Chunks Have To Be?



- Computation of the size of chunk
  - Desire 50% of peak disk performance
    - half of time seeking and
      half of time trasferring
  - Disk bandwidth: 40 MB/s
  - Positioning time: 10ms
  - $\frac{40\ \cancel{MB}}{\cancel{sec}} \cdot \frac{1024\ KB}{1\ \cancel{MB}} \cdot \frac{1\ \cancel{sec}}{1000\ \cancel{ms}} \cdot 10\ \cancel{ms} = 409.6\ KB$
    - Transfer only 409.6 KB every time seeking
  - 99% of peak performance on 3.69MB chunk size

The Large-File Exception in FSS

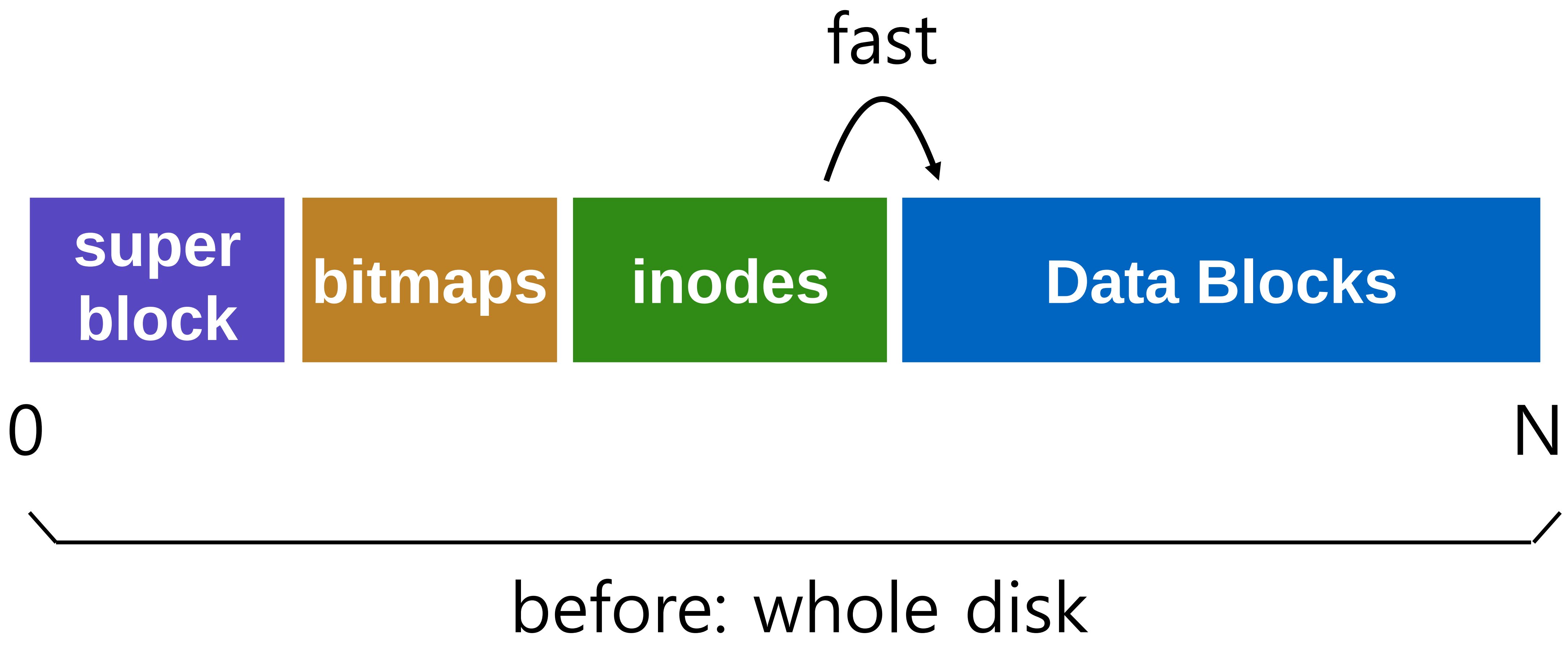
- A simple approach based on the structure of inode
  - Each subsequent **indirect blocks**, and all the **blocks it pointed to**, placed in **a different block group.**
  - Every **1024 blocks (4MB)** of the **file in a separate group**



A few other Things about FFS

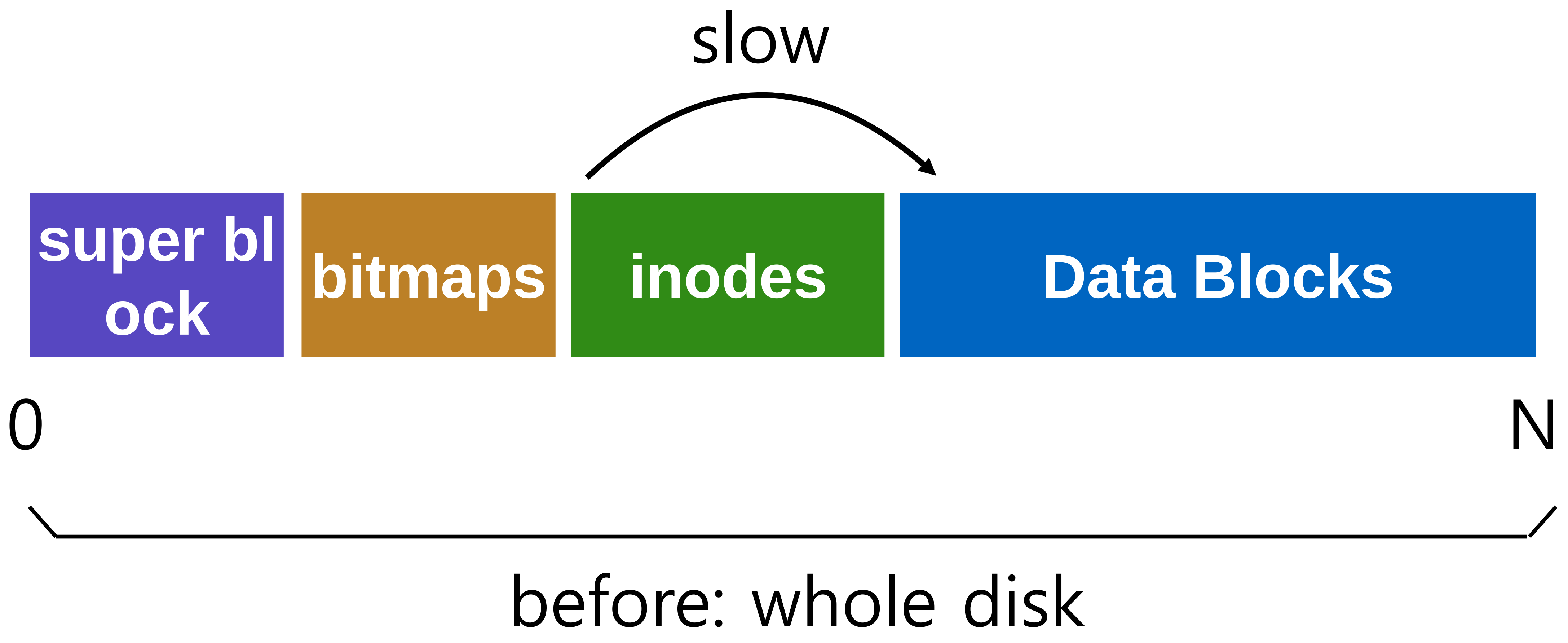
- Internal fragmentation
- Sub-blocks
  - Ex) Create a file with 1 KB : use two sub-blocks, not an entire 4-KB blocks
- Parameterization
- Track buffer
- Long file names
  - Enabling more expressive names in the file system
- Symbolic link

Placement Technique 2: Groups



How to keep inode close to data?

Technique 2: Groups



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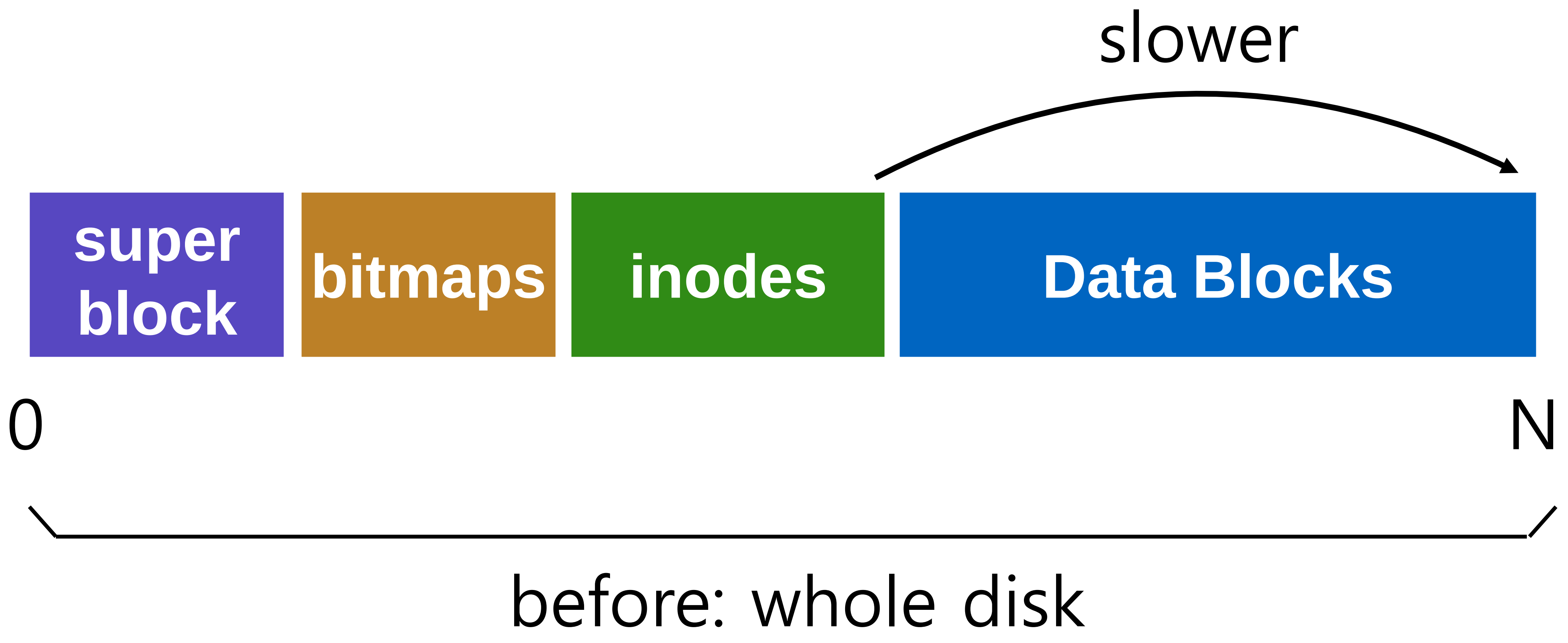
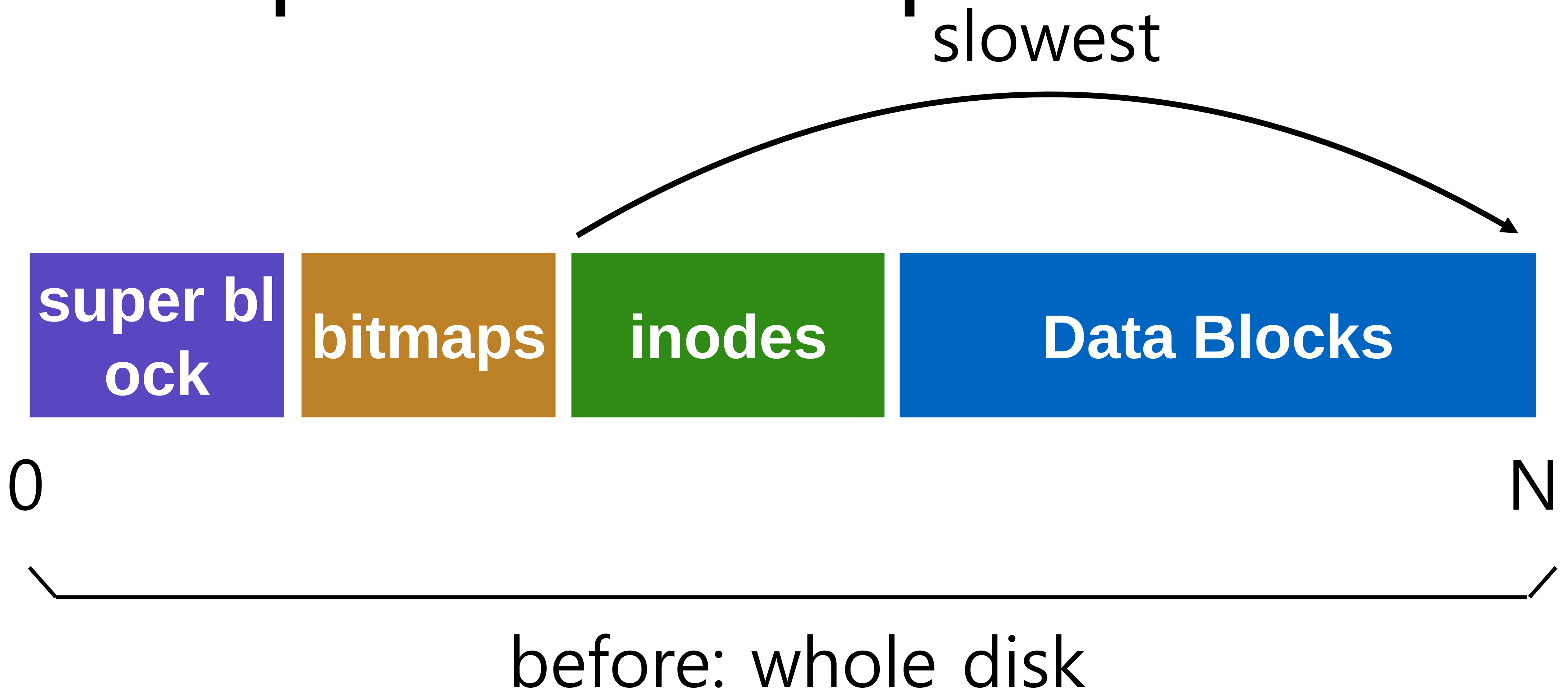
Technique 2: Groups



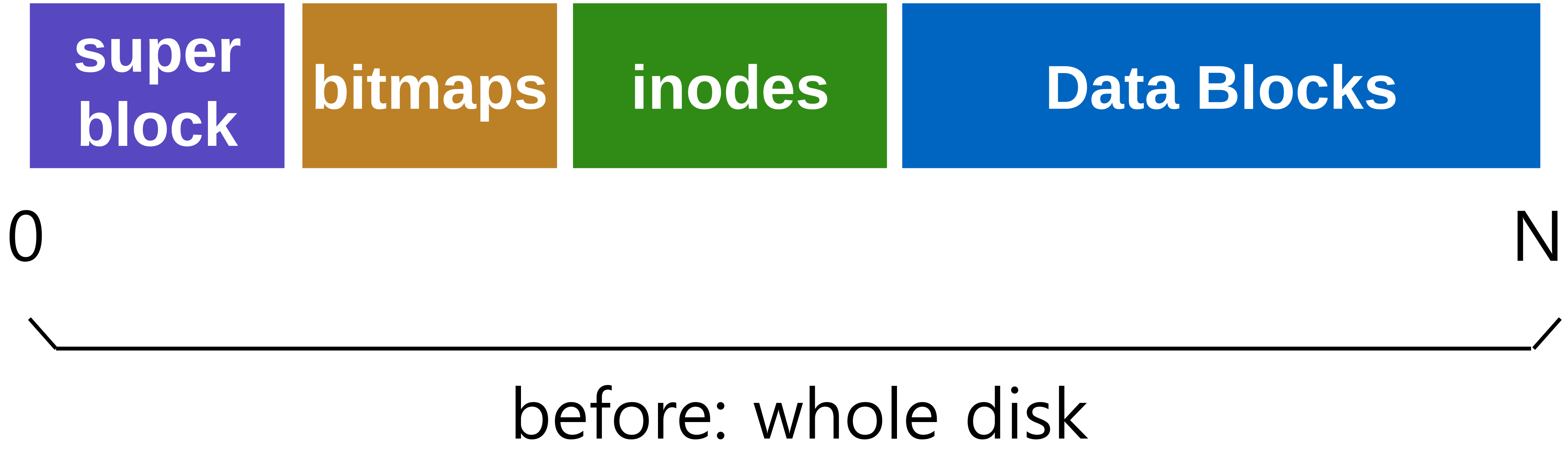
How to keep inode close to data?

Technique 2: Groups



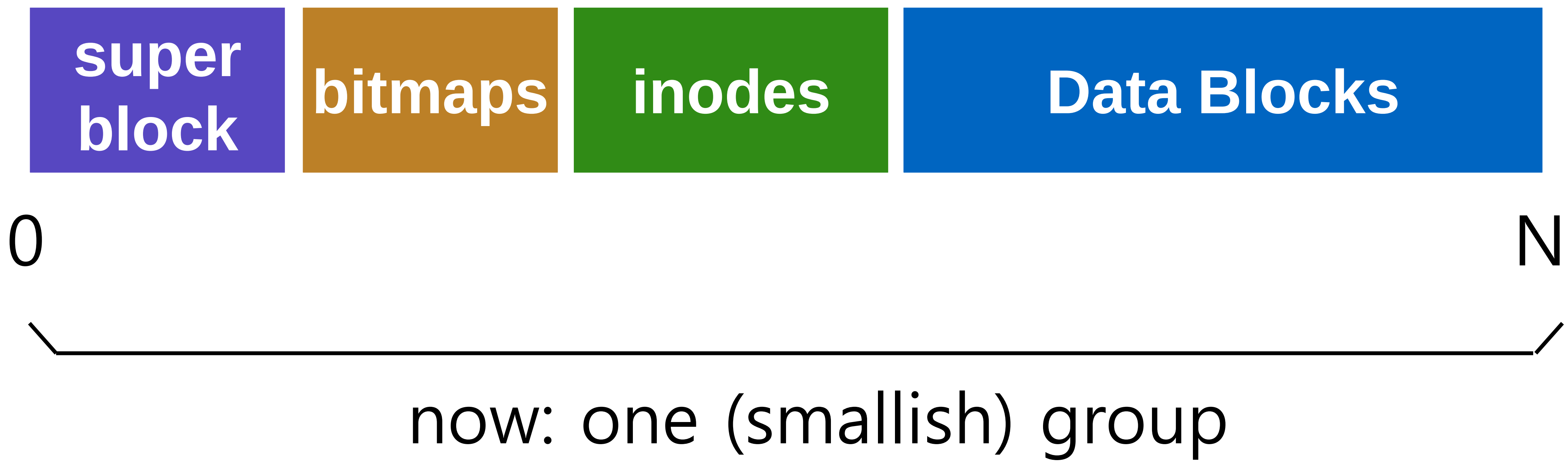
How to keep inode close to data?

Technique 2: Groups



How to keep inode close to data?

Technique 2: Groups



How to keep inode close to data?

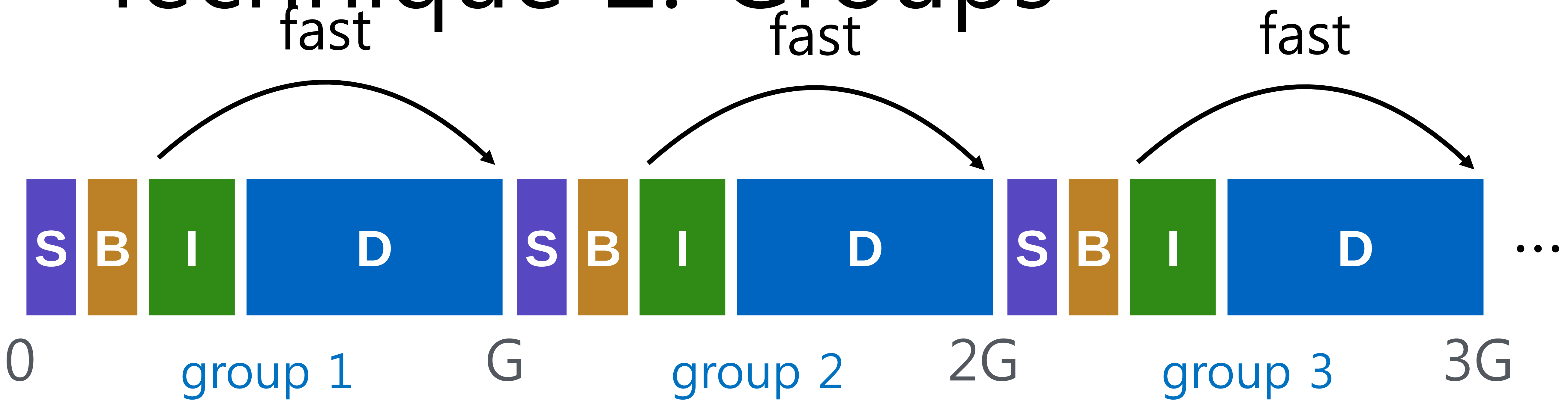
Technique 2: Groups

zoom out

How to keep inode close to data?

Answer: Use groups across disks;
Try to place inode and data in same group

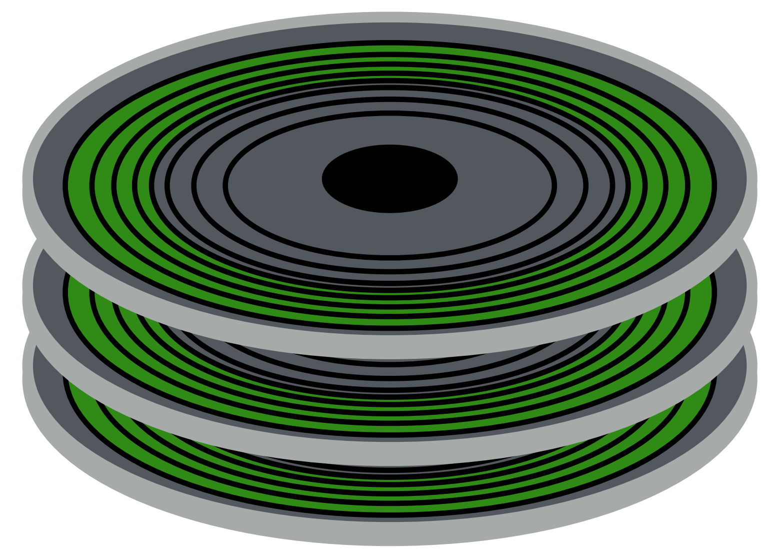
Technique 2: Groups



strategy: allocate inodes and data blocks in same group.

Groups

In FFS, groups were ranges of cylinders
 - called <u>cylinder group</u>



In ext2-4, groups are ranges of blocks
 - called <u>block group</u>

Techniques

Bitmaps

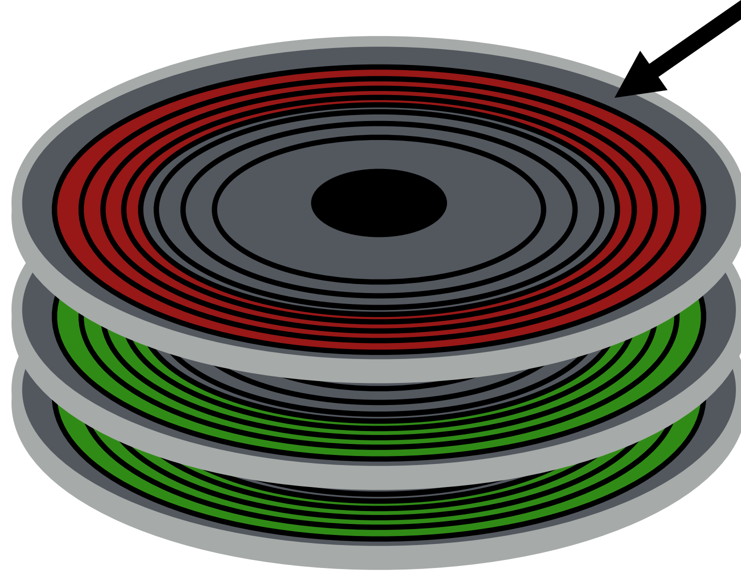
Locality groups

Placement Technique 3: Super Rotation

Is it useful to have multiple super blocks?

Yes, if some (but not all) fail.

Problem



Old FS: All super-block copies are on the top platter. Correlated failures! What if top platter dies?

solution: for each group, store super-block at different offset

Techniques

Bitmaps
Locality groups
Rotated super

Technique 4: Block Size

Observation: Doubling the block size for the old FS over doubled performance.

Strategy: choose block size so never read more than two indirect blocks (i.e., double indirect) to reach data block.

With 4KB block size, how large of a file can they support?

(Blocksize / 4 bytes) * (Blocksize / 4bytes) * Blocksize = 4 GB
Blocksize^3 = 256 MB

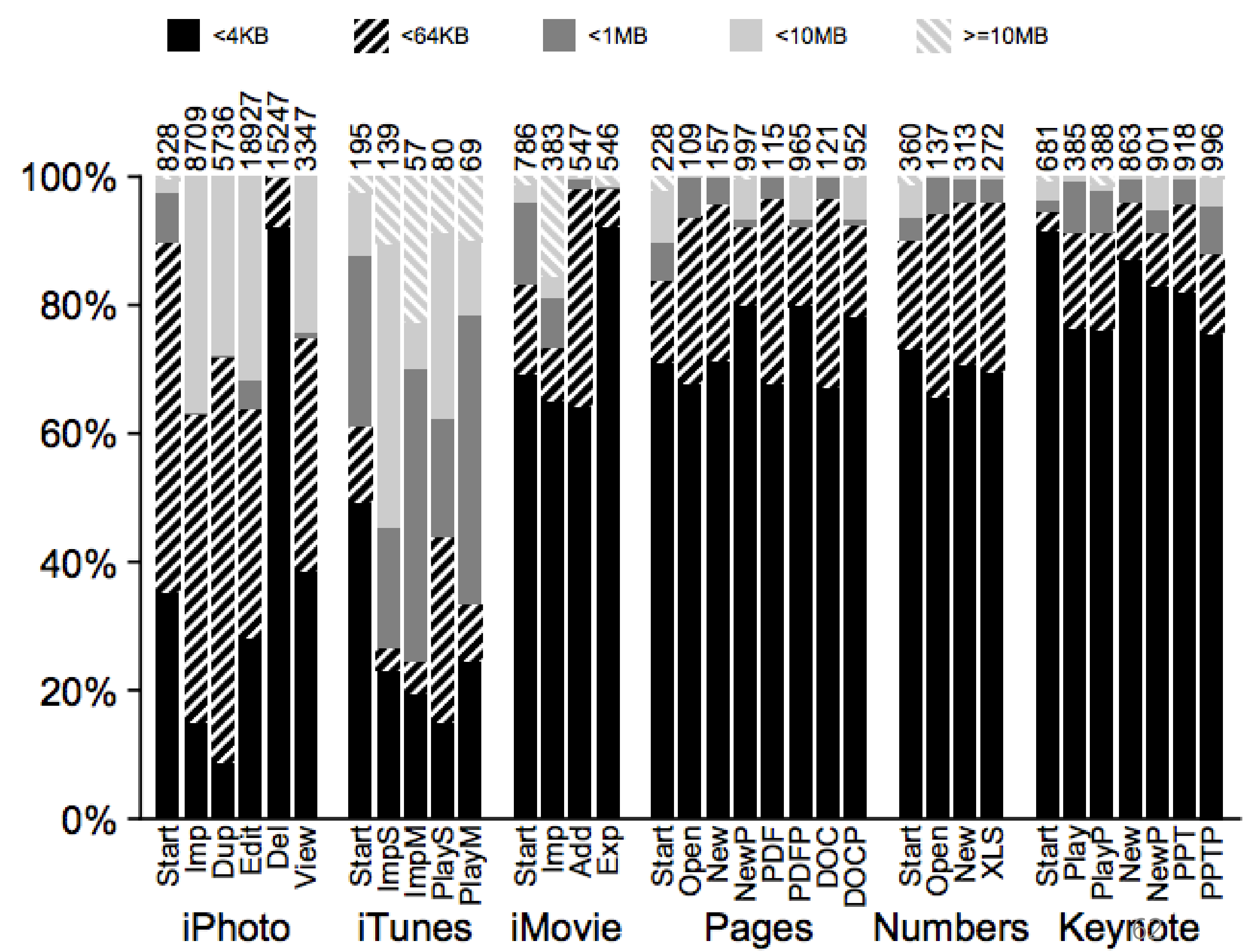
Techniques

Bitmaps
Locality groups
Rotated super
Large blocks

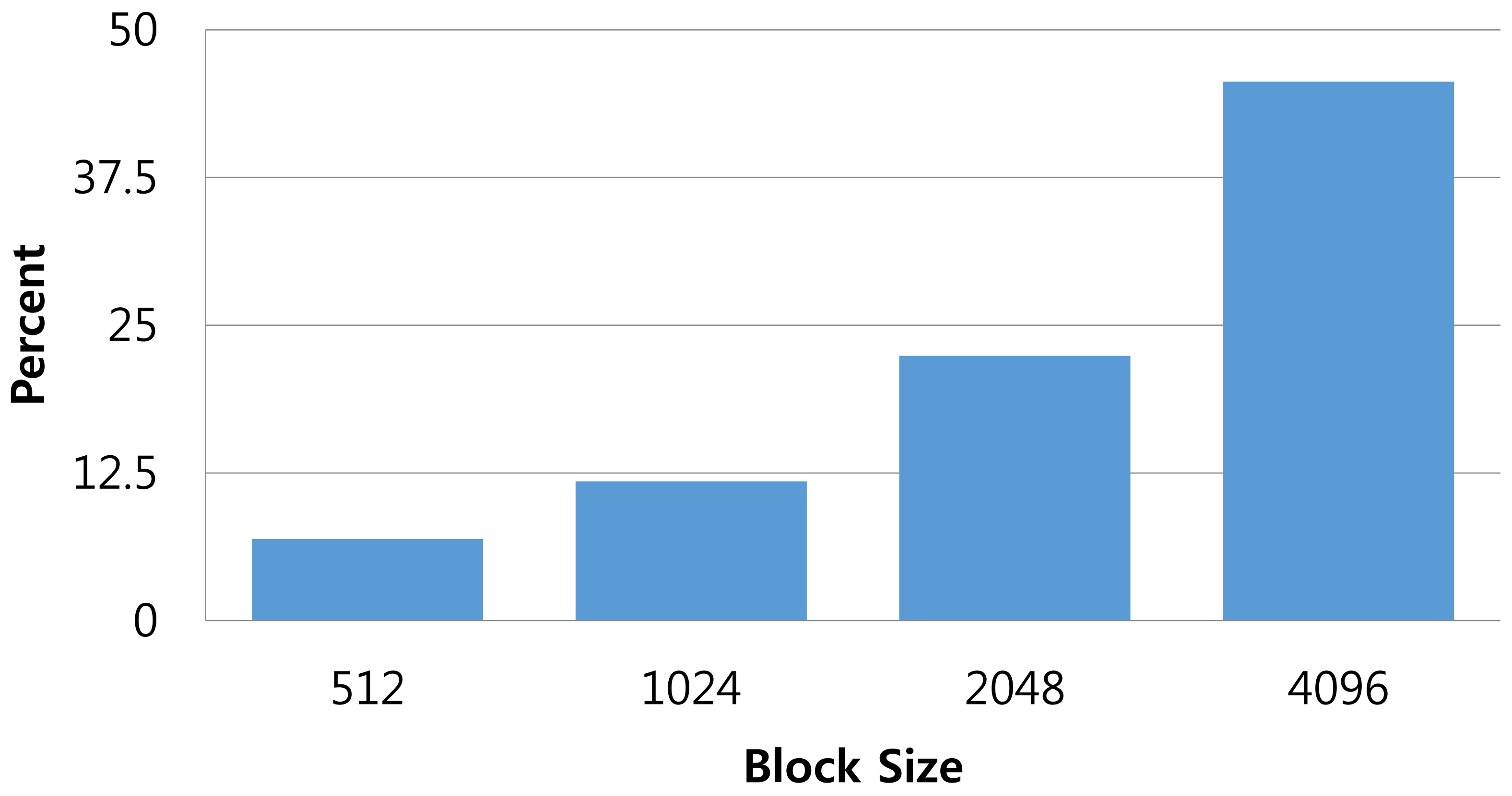
Technique: Larger Blocks

Observation: Doubling block size for old FS over doubled performance
Why not make blocks huge?

Most file are very small, even today!



LargeR Blocks



Lots of waste due to internal fragment in most blocks

Time vs. Space tradeoffs…

Solution: Fragments

Hybrid – combine best of large blocks and best of small blocks

Use large block when file is large enough

Introduce “fragment” for files that use parts of blocks

- Only tail of file uses fragments

Fragment Example

Block size = 4096

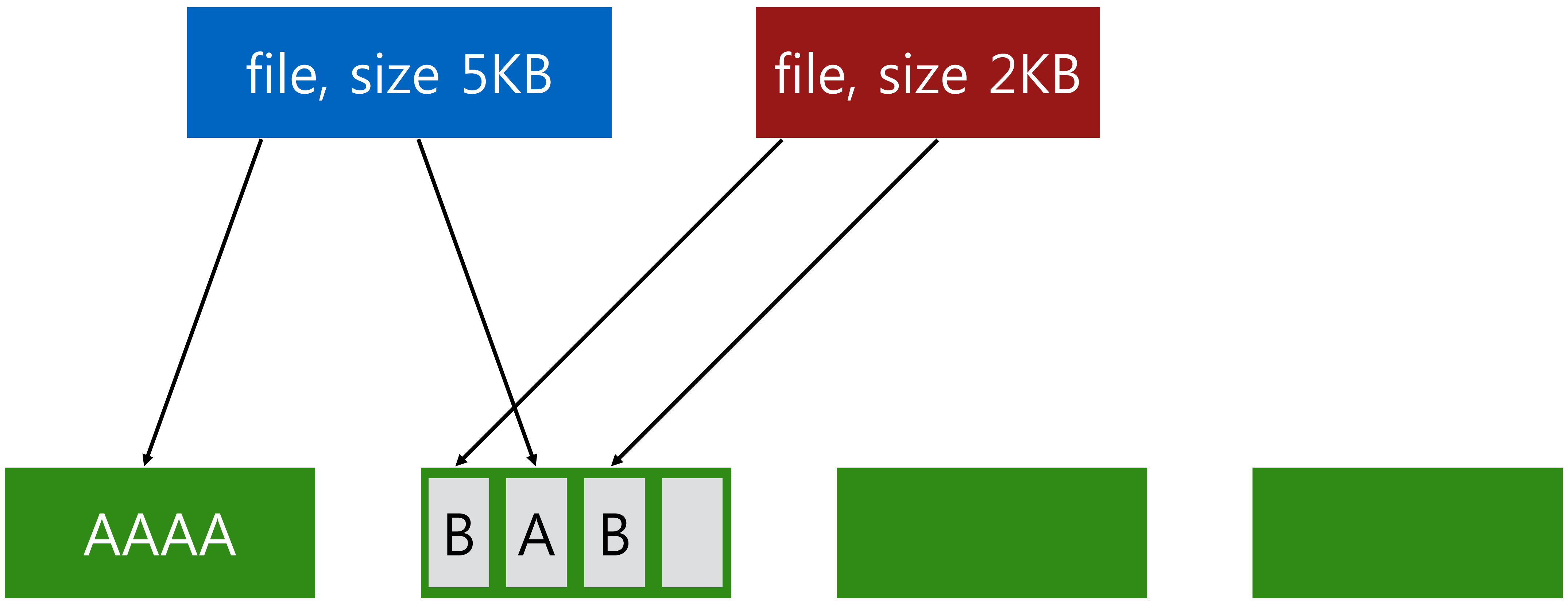
Fragment size = 1024

bits: 0000	0000	1111	0010
blk1	blk2	blk3	blk4

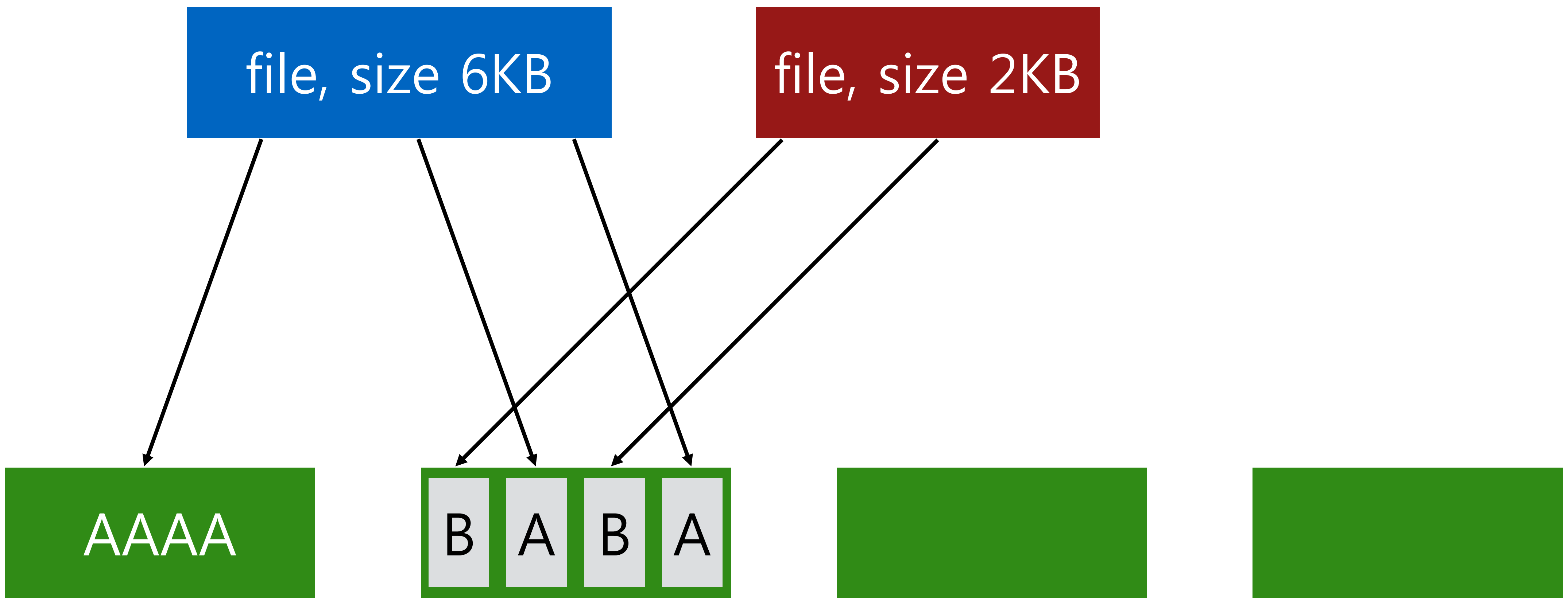
Whether addr refers to block or fragment is inferred by file offset

What about when files grow?

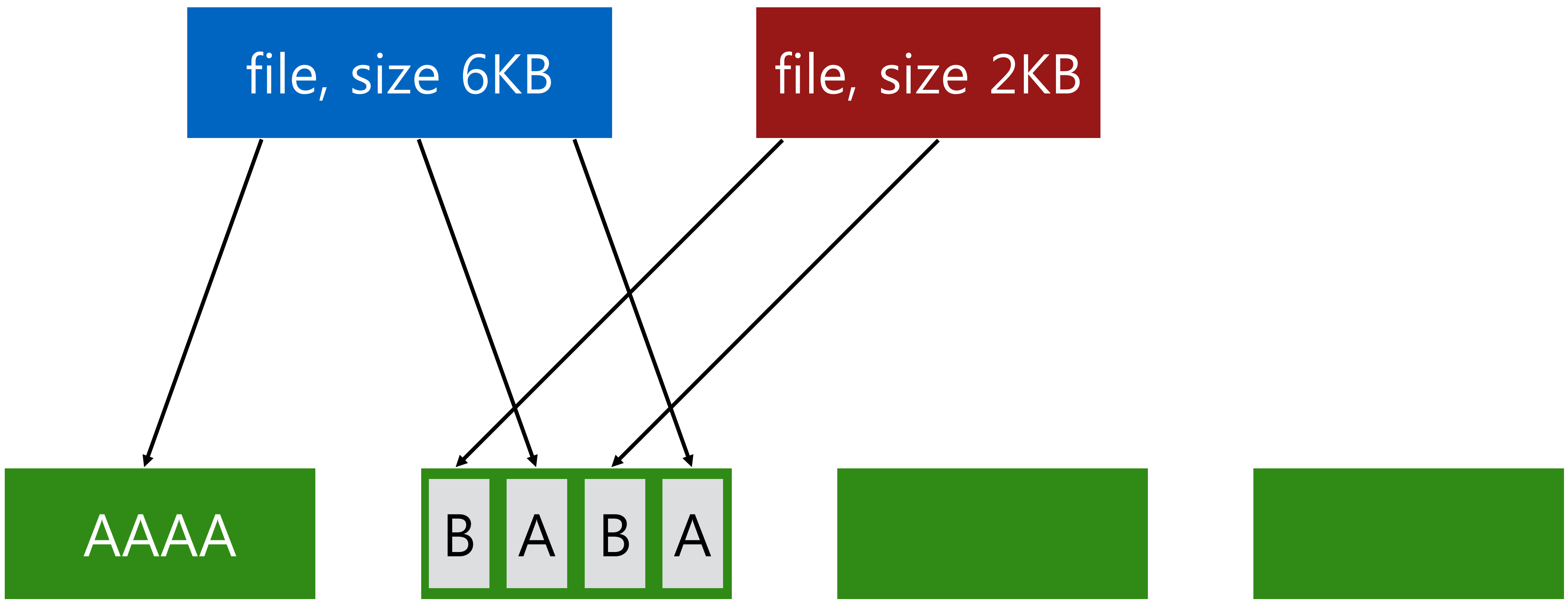
Must copy fragments to new block if no room to grow

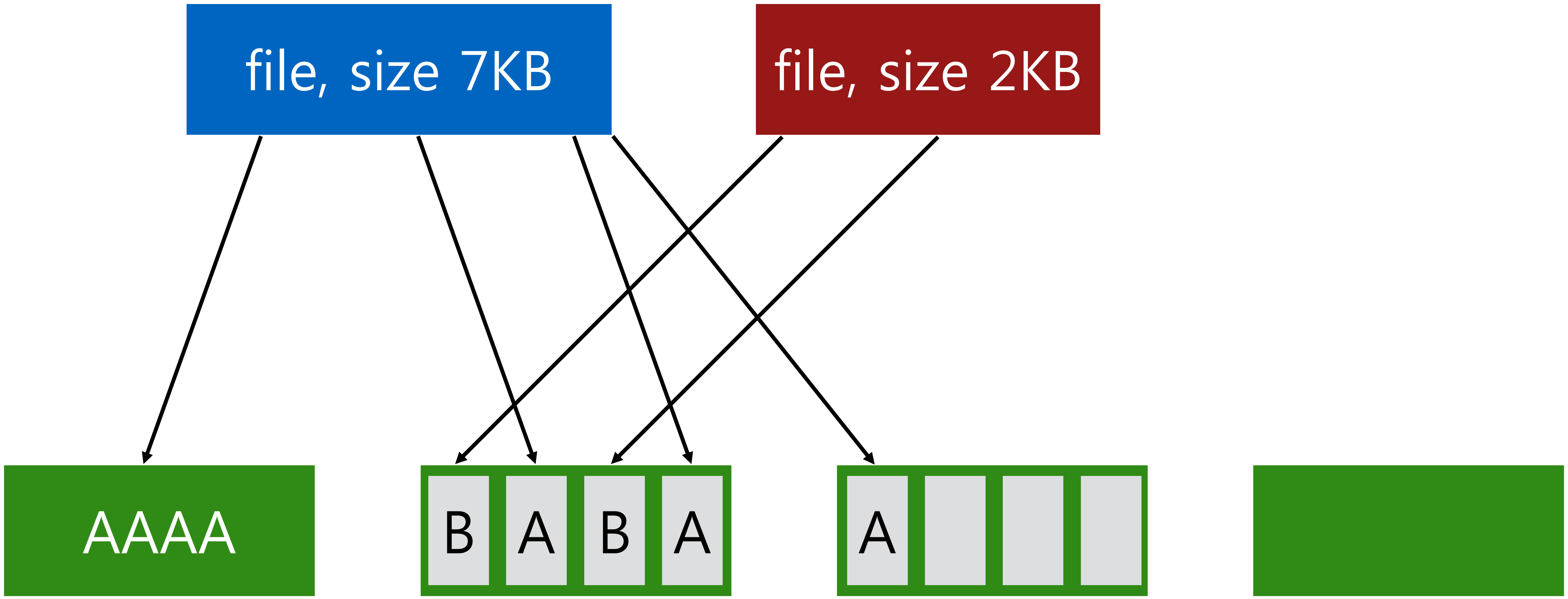


file, size 5KB
file, size 2KB
AAAA
B
A
B



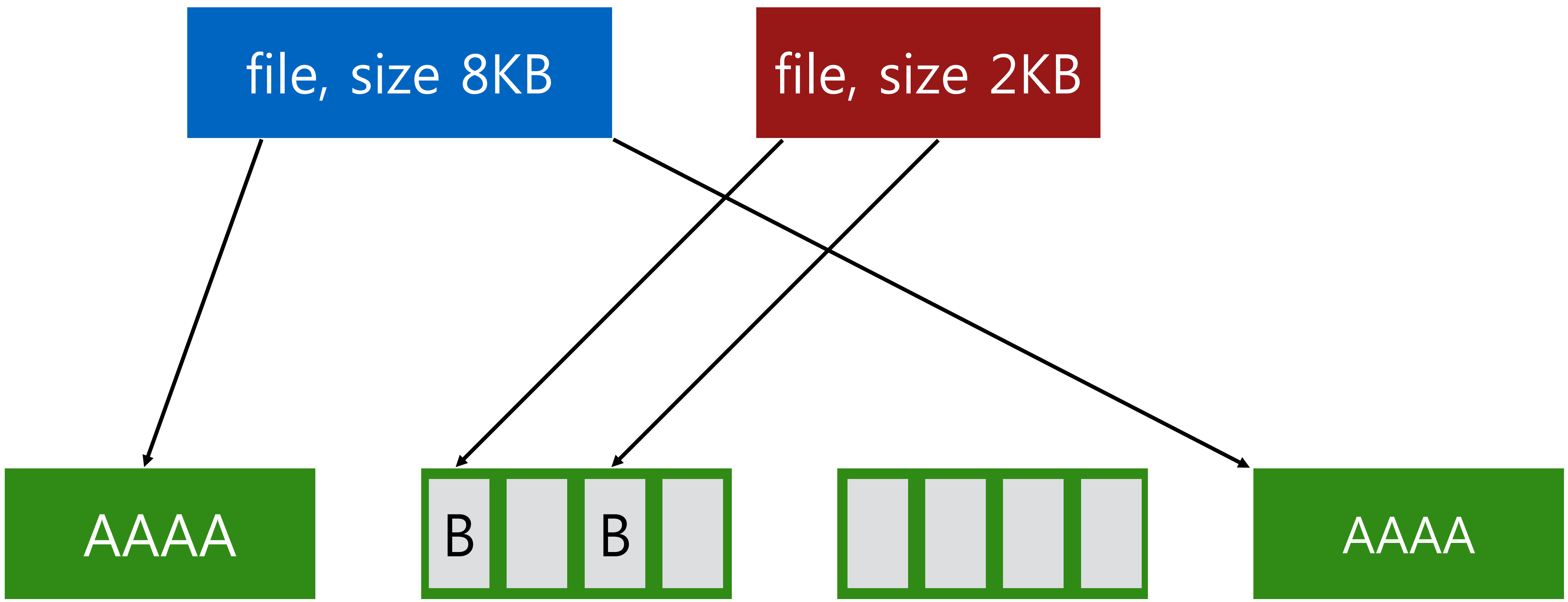
append A to first file


file, size 6KB
file, size 2KB
AAAA
B
A
B
A



append A to first file
Not allowed to use fragments across multiple blocks!

What to do instead?



append A to first file,
copy to fragments to new block

Optimal Write Size

Writing less than a block is inefficient

Solution: new API exposes optimal write size

For pipes and sockets, the new call returns the buffer size.

The stdio library uses this call.

Techniques

Bitmaps

Locality groups

Rotated super

Large blocks

Fragment

Smart Policy

Where should new inodes and data blocks go?

Strategy

Put related pieces of data near each other.

Rules:

1. Put directory entries near directory inodes.
2. Put inodes near directory entries.
3. Put data blocks near inodes.

Sound good?

Problem: File system is one big tree

- All directories and files have a common root.
- All data in same FS is related in some way

Trying to put everything near everything else doesn't make any choices!

Revised Strategy

Put more-related pieces of data near each other

Put less-related pieces of data **far** from each other

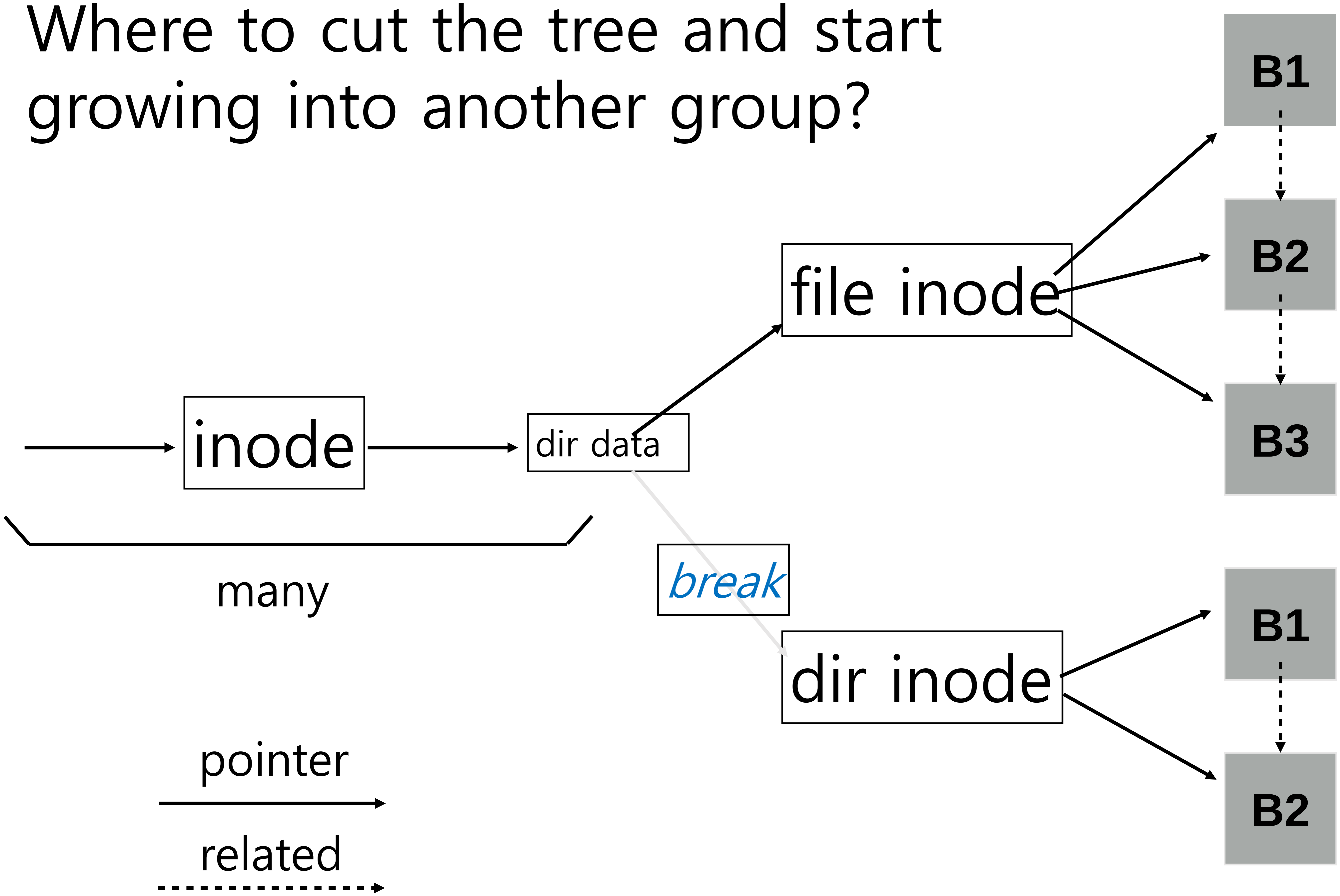
FFS developers used their best judgement

FFS: Two-Level Allocator

Level 1: decide which group

Level 2: decide where in group

Where to cut the tree and start growing into another group?



FFS puts dir inodes in a new group

"ls" is fast on directories with many files.

Preferences

File inodes: allocate in <u>same</u> group with dir

Dir inodes: allocate in <u>new</u> group with fewer used inodes than average group

First data block: allocate near inode

Other data blocks: allocate near previous block

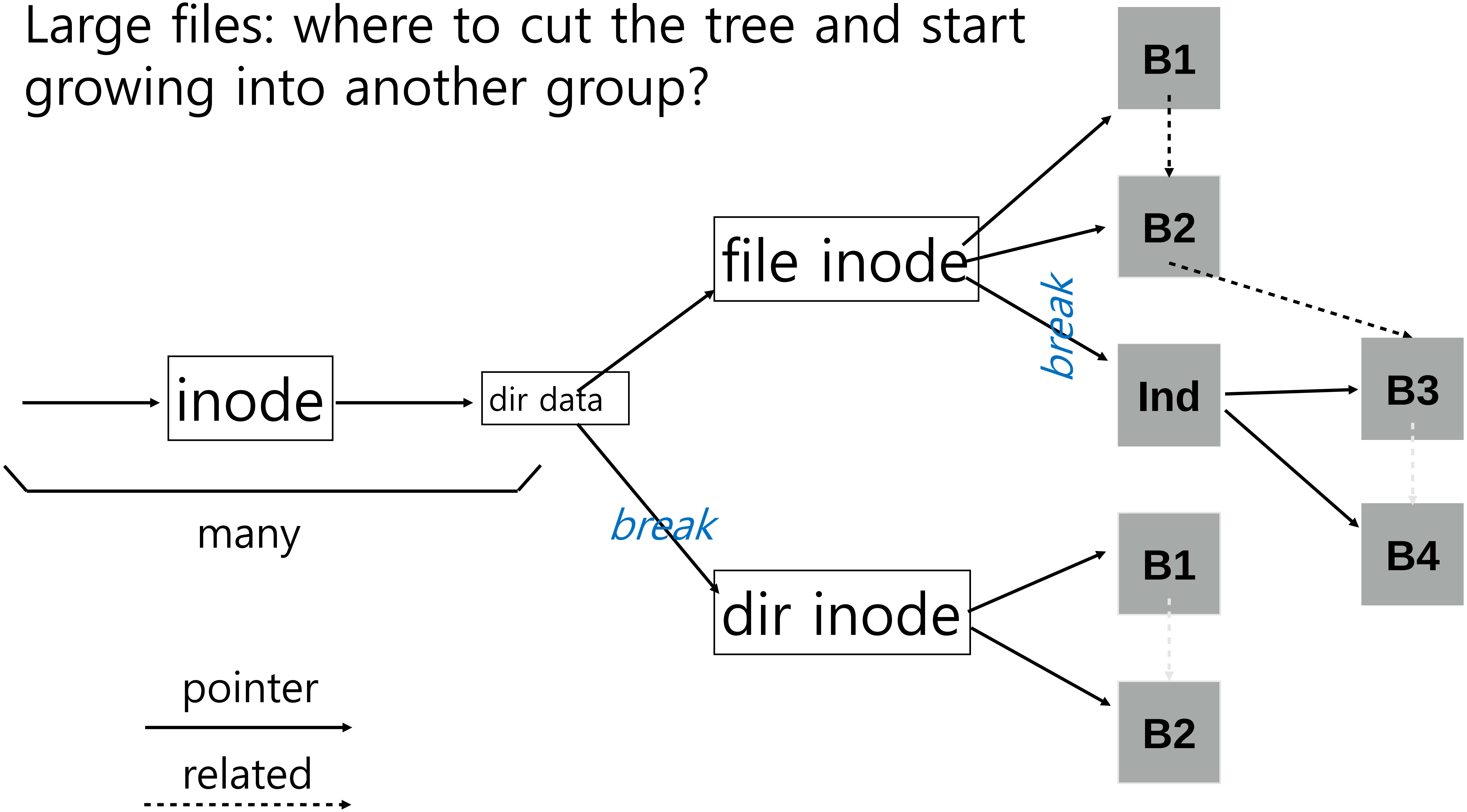
Problem: Large Files

Single large file can fill nearly all of a group

Displaces data for many small files

Better to do one seek for large file than one seek for each of many small files

Large files: where to cut the tree and start growing into another group?



Define "large" as requiring an indirect block

Starting at indirect (e.g., after 48 KB) put blocks in a new block group.

Preferences

File inodes: allocate in same group with dir

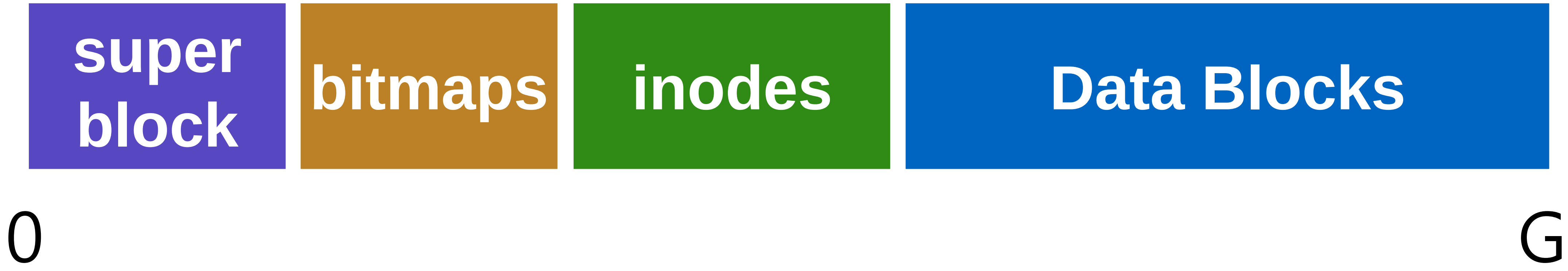
Dir inodes: allocate in new group with fewer used inodes than average group

First data block: allocate near inode

Other data blocks: allocate near previous block

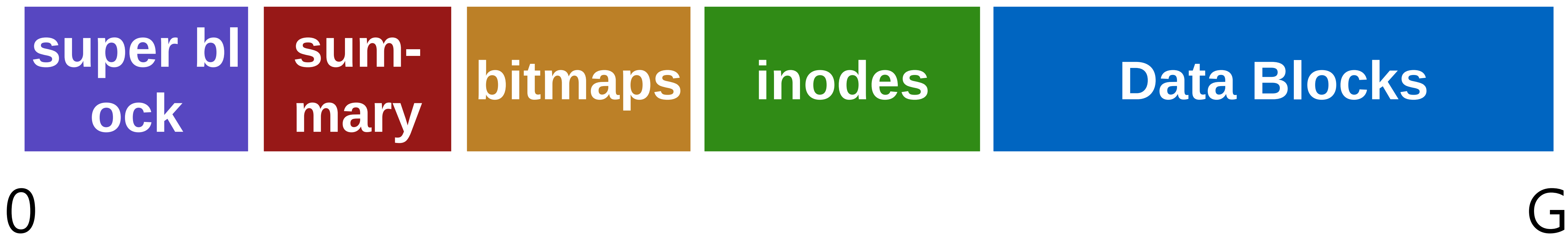
Large file data blocks: after 48KB, go to new group. Move to another group (w/ fewer than avg blocks) every subsequent 1MB.

Group Descriptor (aka Summary Block)



Group Descriptor (aka Summary Block)

How does file system know which new group to pick?



Tracks number of free inodes and data blocks

Techniques

Bitmaps
Locality groups
Rotated super
Large blocks
Fragment
Smart allocation

Conclusion

First disk-aware file system

- Bitmaps
- Locality groups
- Rotated superblocks
- Large blocks
- Fragments
- Smart allocation policy

FFS inspired modern files systems, including ext2 and ext3

FFS also introduced several new features:

- long file names
- atomic rename
- symbolic links

Advice

All hardware is unique

Treat disk like disk!

Treat flash like flash!

Treat random-access memory like random-access memory!
(actually don't – the name is a lie)