UNIVERSITY of WISCONSIN-MADISON
Computer Sciences Department

CS 537
Introduction to Operating Systems

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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

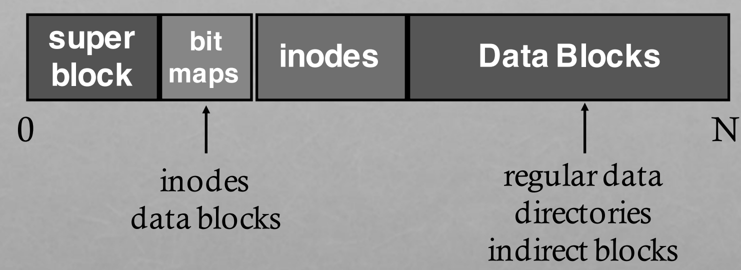
Local

- **FFS**: Fast File System
- **LFS**: Log-Structured File System

Network

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

Review: Basic Layout



What is stored as a data block?

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					

create /foo/bar

[populate inode]

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?

create /foo/bar

[add bar to /foo]

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			

append to /foo/bar

[write to block]

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

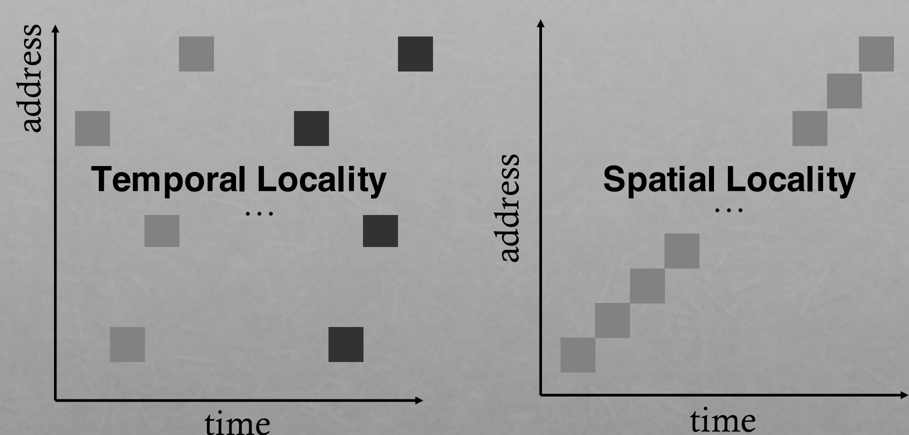
data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data
				read			
							read
				write			

close /foo/bar

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

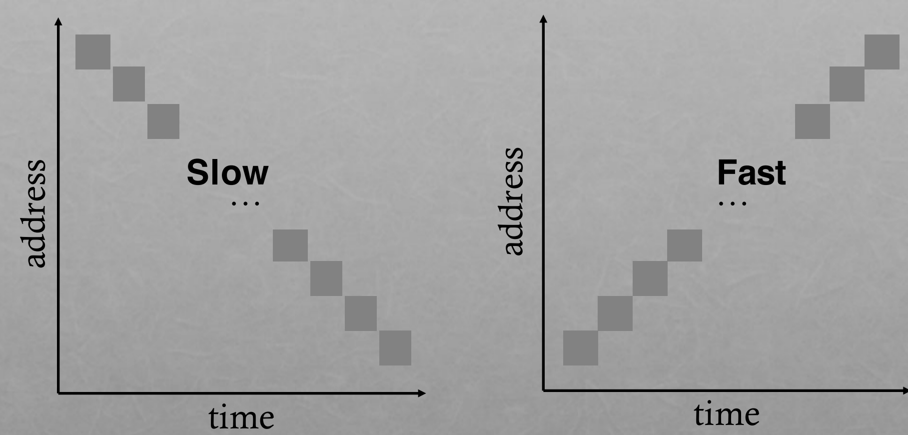
nothing to do on disk!

Review: Locality Types



Which type of locality is most interesting with a disk?

Order Matters

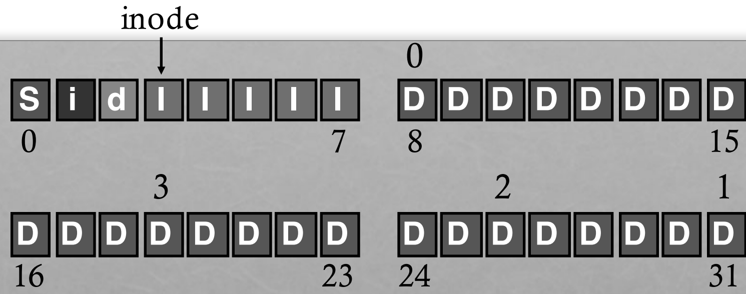


Implication for disk schedulers?

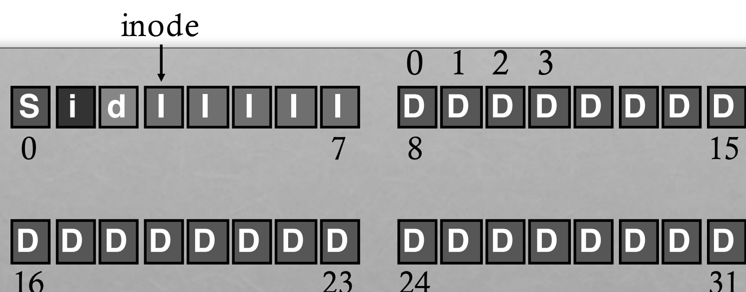
Policy: Choose Inode, Data Blocks

Assuming all free, which should be chosen?

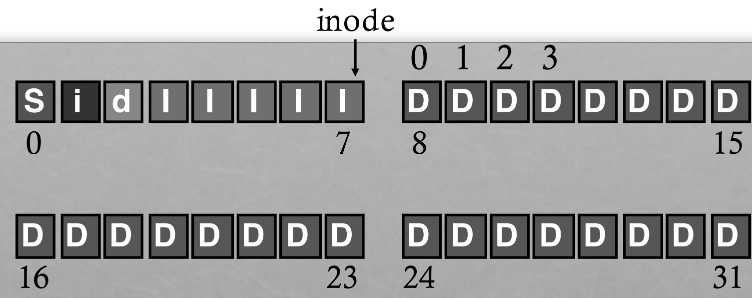
Bad File Layout



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!

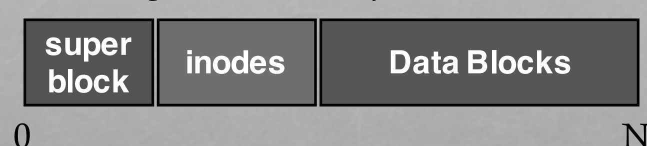
measure then build

Pro approach

1. identify existing state of the art
2. measure it, identify and understand problems
3. get idea (solutions often flow from deeply understanding 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?

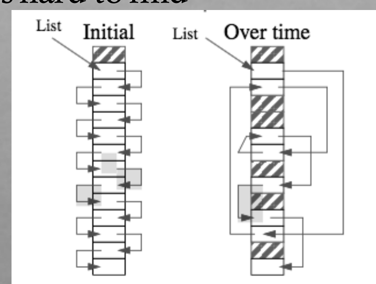
Measurement 1: Aging?

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 <u>block size</u> 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)

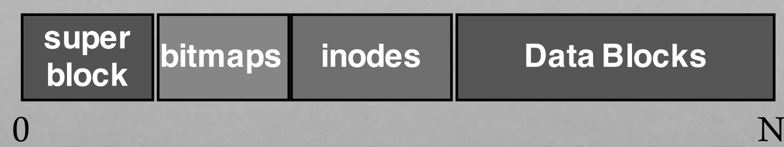
Problem: old FS treats disk like RAM!

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?

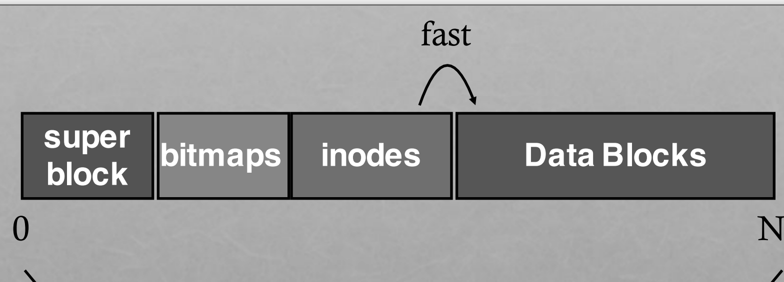
Placement Technique 1: Bitmaps



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

Faster to find contiguous free blocks

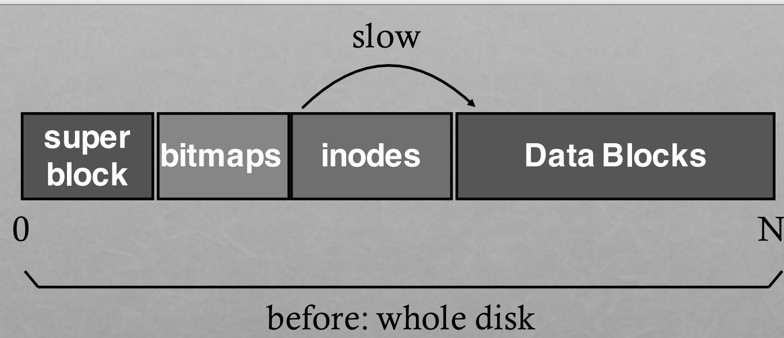
Placement Technique 2: Groups



before: whole disk

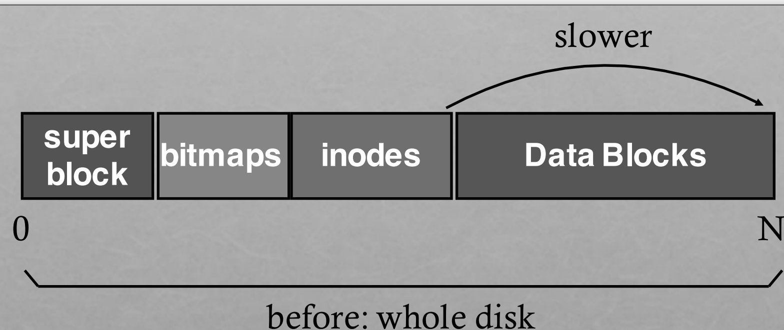
How to keep inode close to data?

Technique 2: Groups



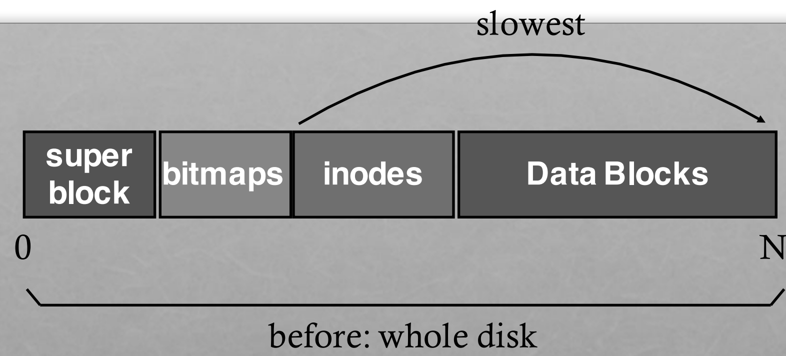
How to keep inode close to data?

Technique 2: Groups



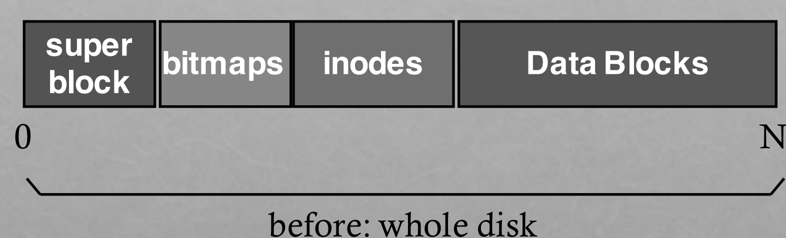
How to keep inode close to data?

Technique 2: Groups



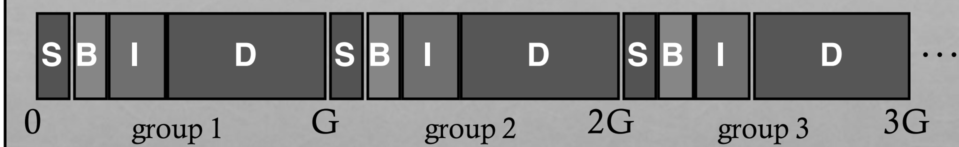
How to keep inode close to data?

Technique 2: Groups



How to keep inode close to data?

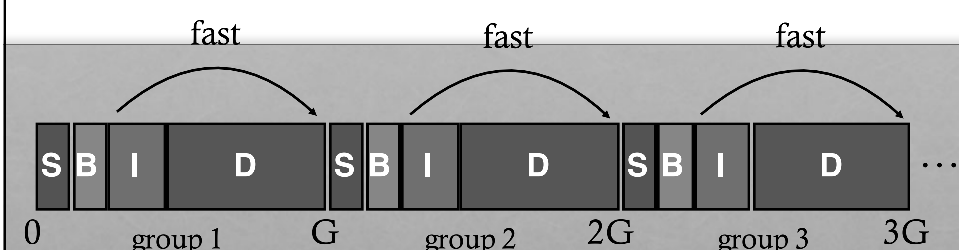
Technique 2: Groups



How to keep inode close to data?

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

Technique 2: Groups

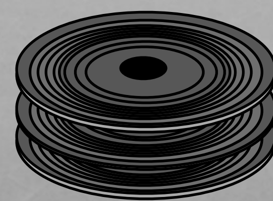


strategy: allocate inodes and data blocks in same group.

Groups

In FFS, groups were ranges of cylinders

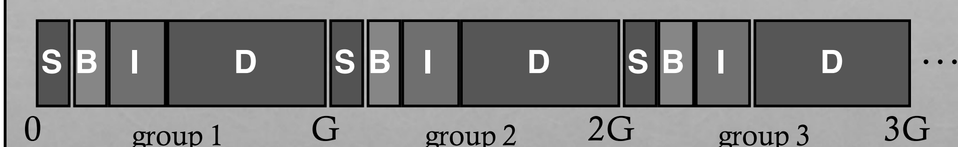
- called cylinder group



In ext2-4, groups are ranges of blocks

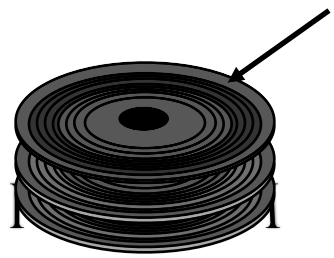
- called block group

Placement Technique 3: Super Rotation



Is it useful to have multiple super blocks?

Yes, if some (but not all) fail.



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

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.

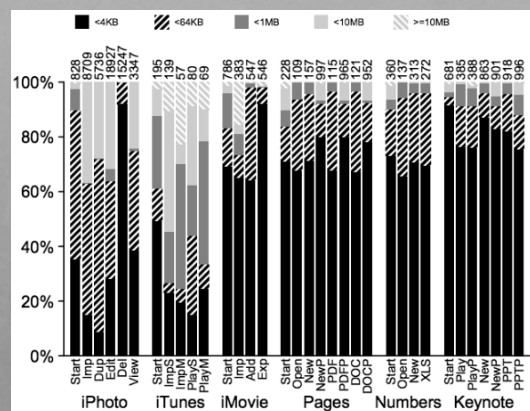
With 4KB block size, how large of a file can they support?

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

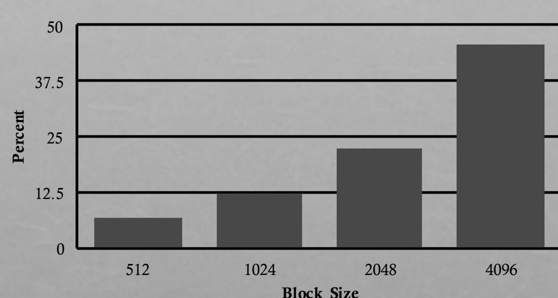
Technique: Larger Blocks

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

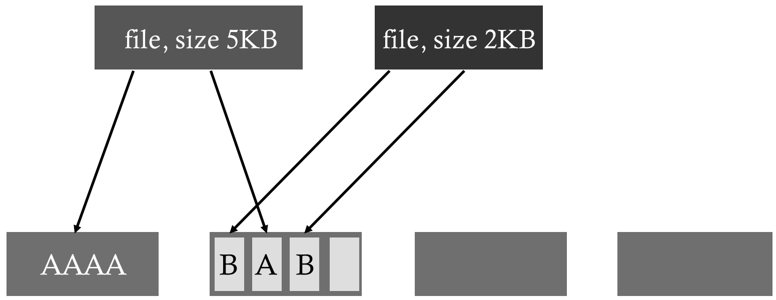
Fragment size = 1024

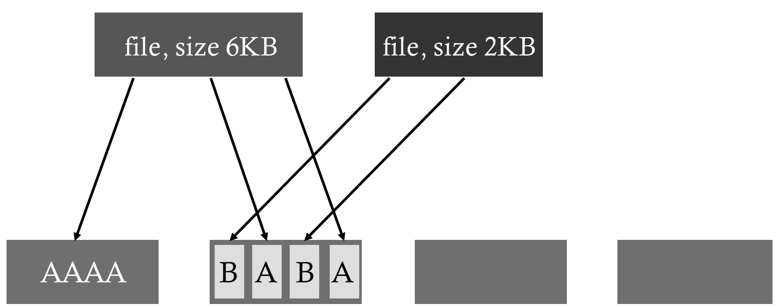
bits:	0000	0000	1111	0010
	blk1	blk2	blk3	blk4

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

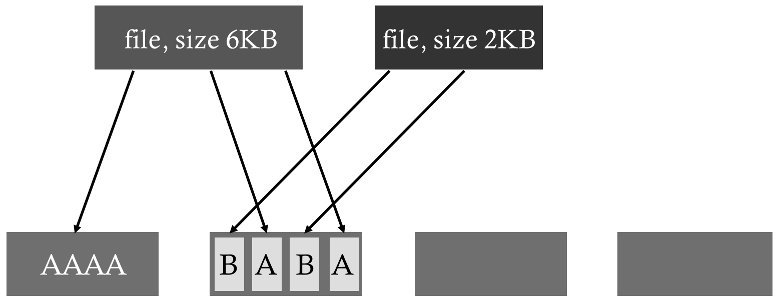
What about when files grow?

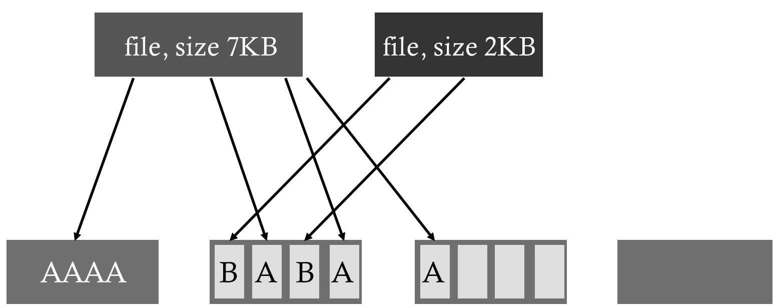
Must copy fragments to new block if no room to grow





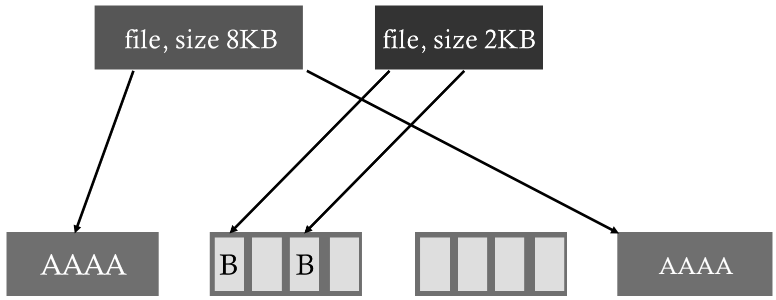
append A to first file





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

What to do instead?



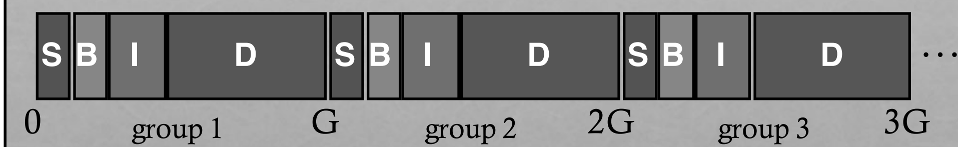
append A to first file,
copy to fragments to new block

Optimal Write Size

Writing less than a block is inefficient

Solution: new API exposes optimal write size

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!

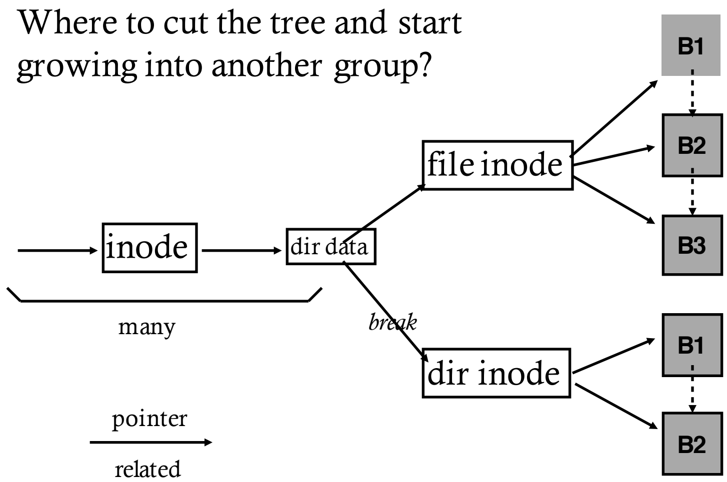
Revised Strategy

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

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 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

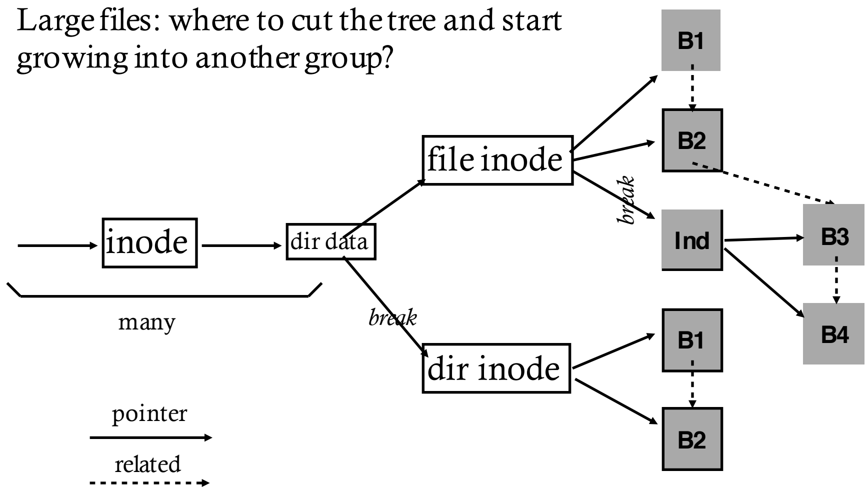
Problem: Large Files

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

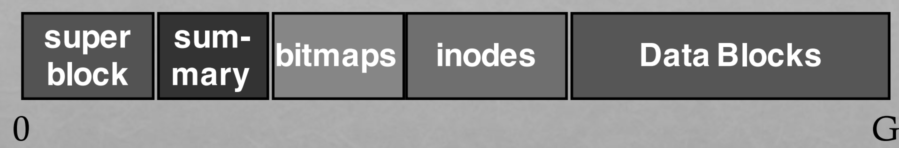
First data block: allocate near inode

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)

How does file system know which new group to pick?



Tracks number of free inodes and data blocks

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!