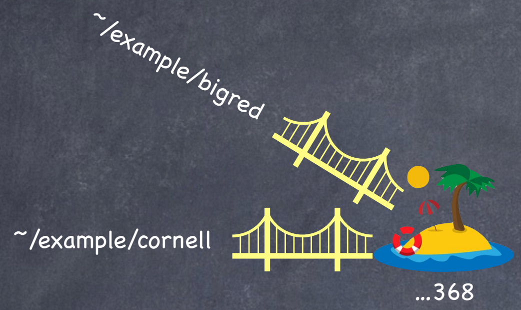
The Directory

- The directory holds mappings between human-friendly names (HFNs) and inode numbers
- It stores two types of mappings:
  - Hard links
    - map a file's HFN (its local path) to the file's inode number
  - Symbolic (soft) links
    - Logically, map a file's HFN (its local path) to the HFN of a different file
    - Implementation: maps a file's HFN to the number of an inode that contains the HFN of a different file

Hard links

- Creating file foo adds a hard link for file foo in the file's directory
- Command ln oldpath newpath
  - adds to the directory a hard link mapping HFN newpath to the inode number of the file with HFN oldpath
  - Now two HFNs are mapping to the same inode!
  - calls int link(const char *oldpath, const char *newpath)
- Removing a file through the rm [file] command invokes a call to int unlink(const char *pathname)
  - removes from directory the hard link between pathname and corresponding inode number
- File's inode stores the number of hard links to it
  - inode reclaimed (file deleted) only when link count = 0; if file opened, wait to reclaim until file is closed




```
la13@en-cs-cisugcl10:~$ cd example
la13@en-cs-cisugcl10:~/example$ ls
la13@en-cs-cisugcl10:~/example$ ls -ai
392852366 .  391230414 ..
la13@en-cs-cisugcl10:~/example$ echo ezra > cornell
la13@en-cs-cisugcl10:~/example$ cat cornell
ezra
la13@en-cs-cisugcl10:~/example$ ls -ai
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la13@en-cs-cisugcl10:~/example$ ln cornell bigred
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ezra
la13@en-cs-cisugcl10:~/example$ ls -i
392852368 bigred  392852368 cornell
```

Example

Example

inode of the
parent directory

inode of the
current directory

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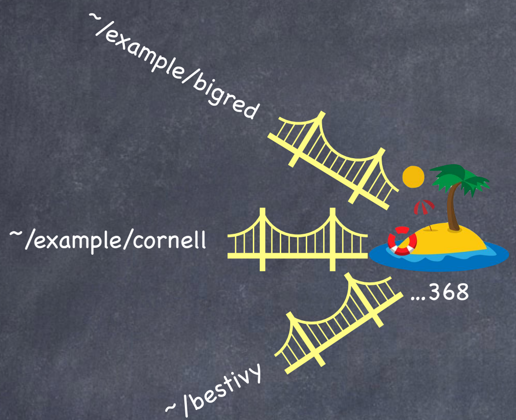
Example



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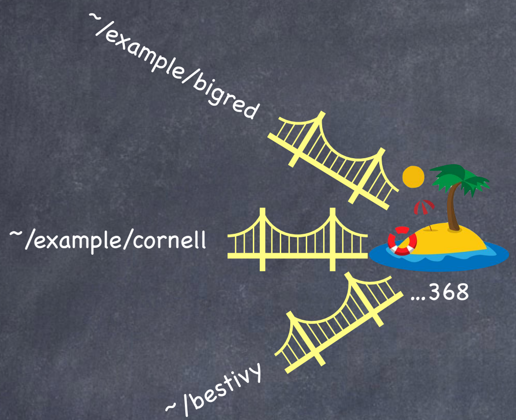

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la13@en-cs-cisugcl10:~/example$ cd ..
```

Example

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392852368 bestivy  398842589 CS4410-2020sp-A4  392852366 example
la13@en-cs-cisugcl10:~$ 
```

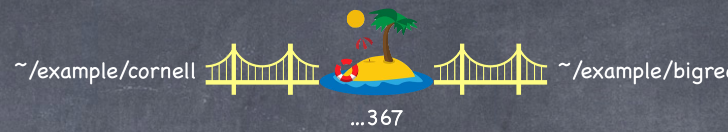
Symbolic (Soft) links

- More flexible than hard links
  - can link to a directory
  - can link to files in another volume
- A map between pathnames
  - to link newpathname to existingpathname for file inode1:
    - create a hard link between newpathname and new file inode2
    - store in inode2 the existingpathname for inode1
  - so, a symbolic link is really a file (inode2 in our example) of a third type
    - neither a regular file nor a directory
- Created using ln, but with the -s flag

Example


```
la13@en-cs-cisugcl05:~$ cd example
la13@en-cs-cisugcl05:~/example$ echo ezra > cornell
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 cornell
```

Example




```
la13@en-cs-cisugcl05:~$ cd example
la13@en-cs-cisugcl05:~/example$ echo ezra > cornell
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 cornell
la13@en-cs-cisugcl05:~/example$ ln cornell bigred
la13@en-cs-cisugcl05:~/example$ ls -i
392852367 bigred  392852367 cornell
```

Example


```
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la13@en-cs-cisugcl05:~/example$ cd ..
la13@en-cs-cisugcl05:~$ ln example/cornell bestivy
la13@en-cs-cisugcl05:~$ ln -s example/cornell highabove
la13@en-cs-cisugcl05:~$ ls -i
392852367 bestivy  398842589 CS4410-2020sp-A4  392852366 example  392971138 highabove
```

Example


```
la13@en-cs-cisugcl05:~$ cd example
la13@en-cs-cisugcl05:~/example$ echo ezra > cornell
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la13@en-cs-cisugcl05:~$ ls -i
392852367 bestivy  398842589 CS4410-2020sp-A4  392852366 example  392971138 highabove
la13@en-cs-cisugcl05:~$ ls -l
total 8
-rw-r--r-- 3 la13 pug-la13    5 Apr 28 23:03 bestivy
drwxr-sr-x 4 la13 pug-la13 4096 Apr 27 11:55 CS4410-2020sp-A4
drwxr-sr-x 2 la13 pug-la13 4096 Apr 28 23:03 example
lrwxrwxrwx 1 la13 pug-la13   15 Apr 28 23:04 highabove -> example/cornell
```

Example


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la13@en-cs-cisugcl05:~$ rm example/cornell
```

Example


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la13@en-cs-cisugcl05:~$ cat bestivy
ezra
la13@en-cs-cisugcl05:~$ cat highabove
cat: highabove: No such file or directory
la13@en-cs-cisugcl05:~$
```

Permission Bits

```
la13@en-cs-cisugcl05:~$ ls -l
total 8
-rw-r--r-- 3 la13 pug-la13    5 Apr 28 23:03 bestivy
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```
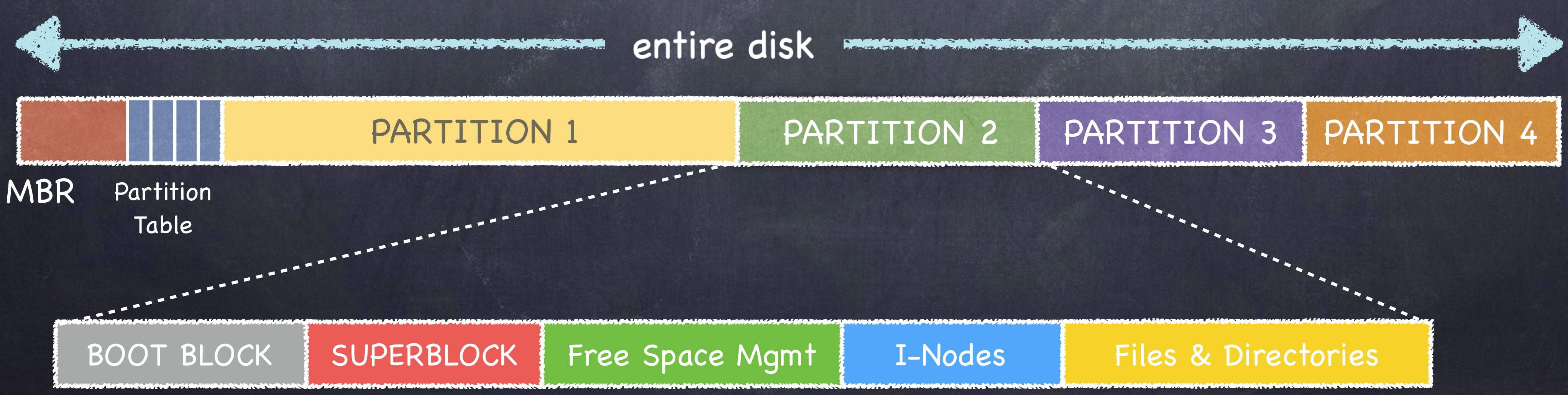

- File bestivy
  - leading - says bestivy is a regular file
    - d is for directory; l is for soft link
  - Next nine characters are permission bits
    - rwx for owner, group, everyone
      - owner can read and write; group and others can just read
      - x set in a regular file means means file can be executed
      - x set in a directory that user/group/everybody is allow to cd to that directory
    - can be set using chmod

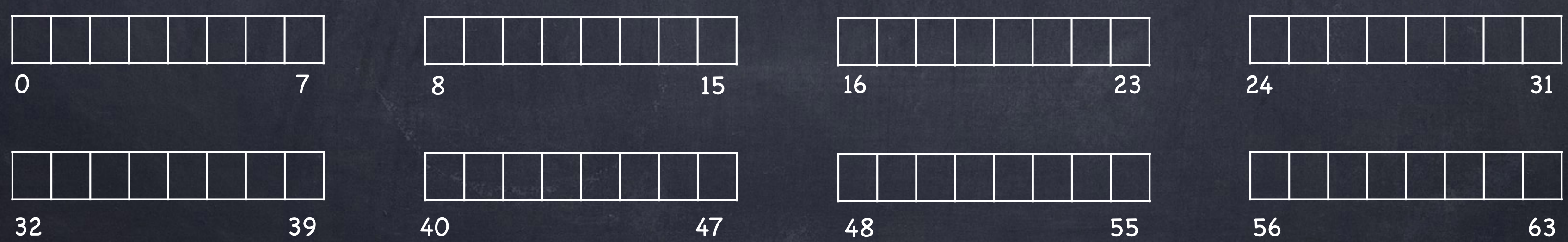
File System Layout

- File System is stored on disks
  - disk can be divided into one or more partitions
  - Sector 0 of disk: Master Boot Record (MBR). It contains:
    - bootstrap code (loaded and executed by firmware)
    - partition table (addresses of where partitions start & end)
  - First block of each partition has boot block
    - loaded by executing code in MBR and executed on boot



Peeking Inside

- Persistent storage modeled as a sequence of N blocks
  - from 0 to N-1
    - in this example, 64 blocks, each 4KB
  - some blocks store data



Peeking Inside

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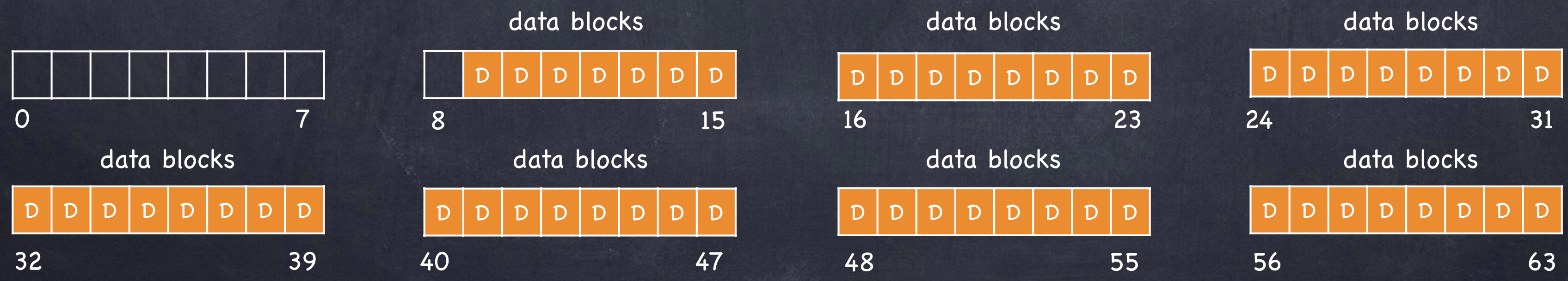
    - in this example, 64 blocks, each 4KB
  - some blocks store data
  - other blocks store metadata
    - an array of inodes
      - if an inode is 256 bytes, then 16 inodes per block.
        With 5 blocks for inodes, file system can have up to 80 files



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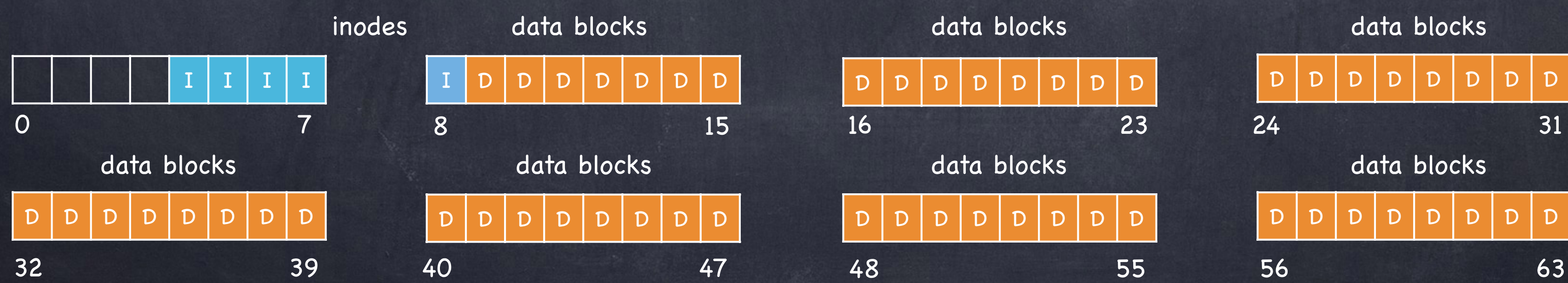

Peeking Inside

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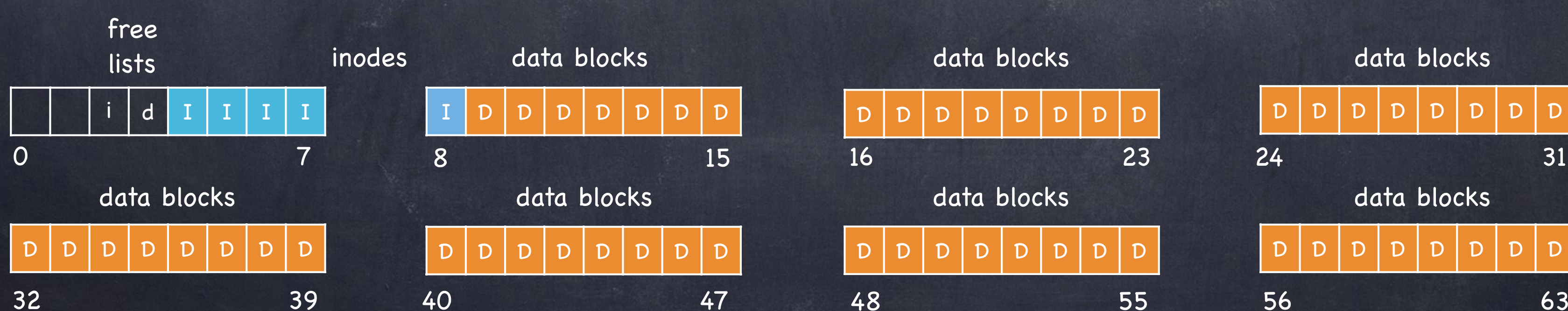
      - if an inode is 256 bytes, then 16 inodes per block.
        With 5 blocks for inodes, file system can have up to 80 files
    - bitmaps tracking free inodes and data blocks;



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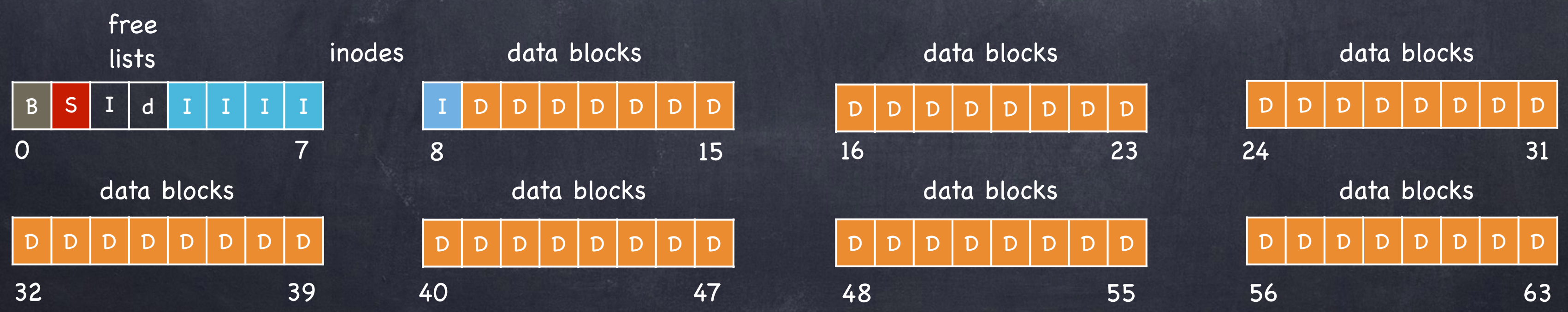
    - an array of inodes
      - if an inode is 256 bytes, then 16 inodes per block.
        With 5 blocks for inodes, file system can have up to 80 files
    - bitmaps tracking free inodes and data blocks; Superblock; Boot block



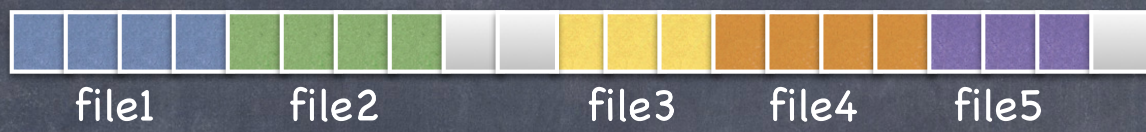
The Superblock

- One logical superblock per file system
  - at a well-known location
  - contains metadata about the file system, including
    - how many inodes
    - how many data blocks
    - where the inode table begins
    - may contain info to manage free inodes/data blocks
  - read first when mounting a file system

Storing Files

- Files can be allocated in different ways
  - Contiguous allocation
    - all bytes together, in order
  - Linked Structure
    - Each points to the next block
  - Indexed Structure
    - Index block, pointing to many other blocks
- Which is best?
  - For sequential access? Random access?
  - Large files? Small files? Mixed?

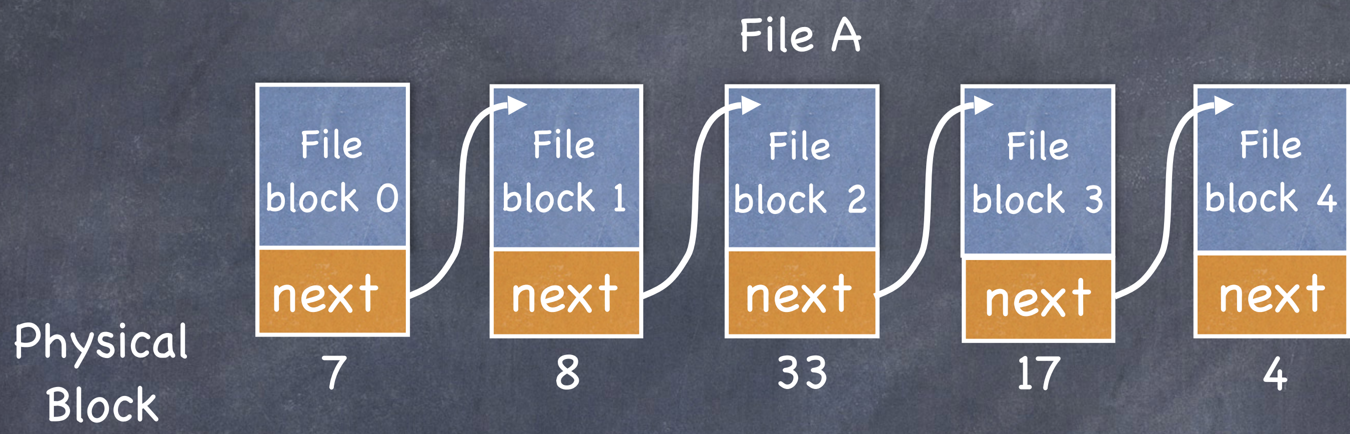
Contiguous Allocation



- All bytes together, in order
  - Simple: only need start block and size
  - Efficient: one seek to read entire file
  - Fragmentation: external, and can be serious
  - Usability: User need to know file's size at time of creation

Used in CD-ROm, DVDs

Linked List Allocation

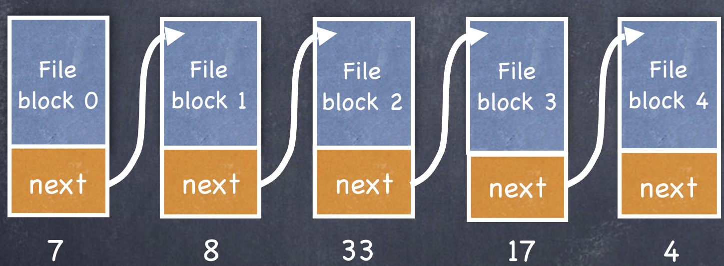


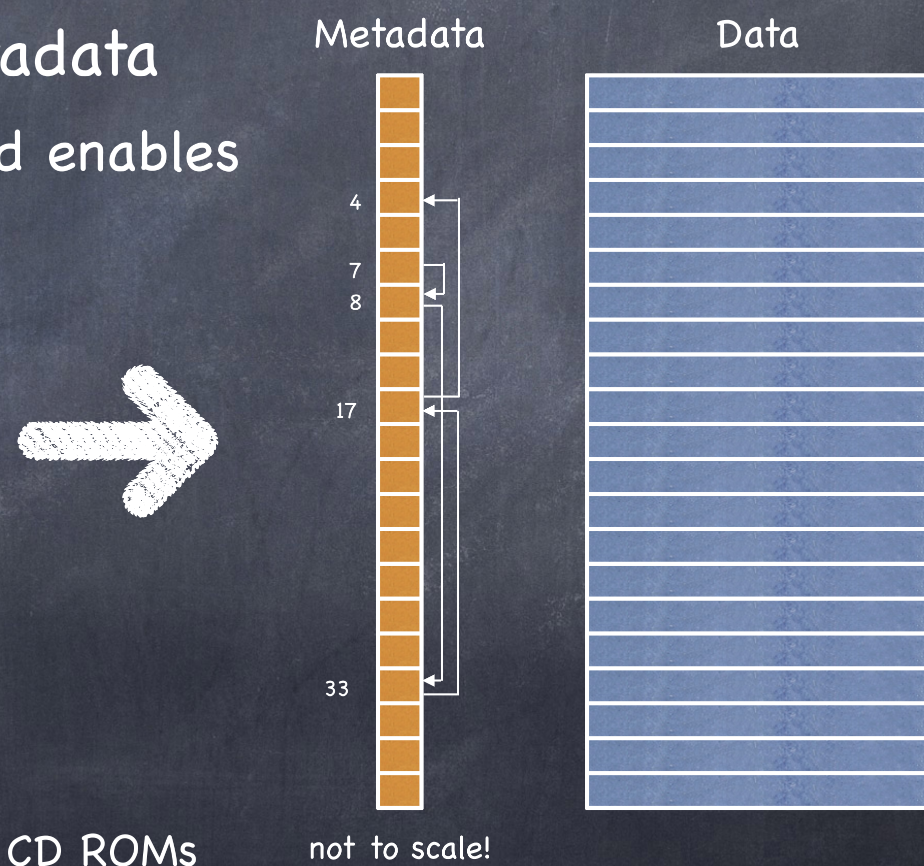
- Each file is stored as a linked list of blocks
  - first word of each block points to next block
  - the rest of the block is data

- Space utilization: no external fragmentation
- Simplicity: only need to find first block of each file
- Performance: random access is slow
- Implementation: blocks mix data and metadata

File Allocation Table (FAT) FS

- Decouple data and metadata
  - reduces disk seeks (and enables caching!)





Microsoft, late 70s

- still widely used today
  - thumb drives, camera cards, CD ROMs

FAT File system

Index Structures

File Allocation Table (FAT)

- array of 32-bit entries
- one entry per block
- file represented as a linked list of FAT entries
- file # = index of first FAT entry

Free space map

- If data block i is free, then FAT[i] = 0
- find free blocks by scanning FAT

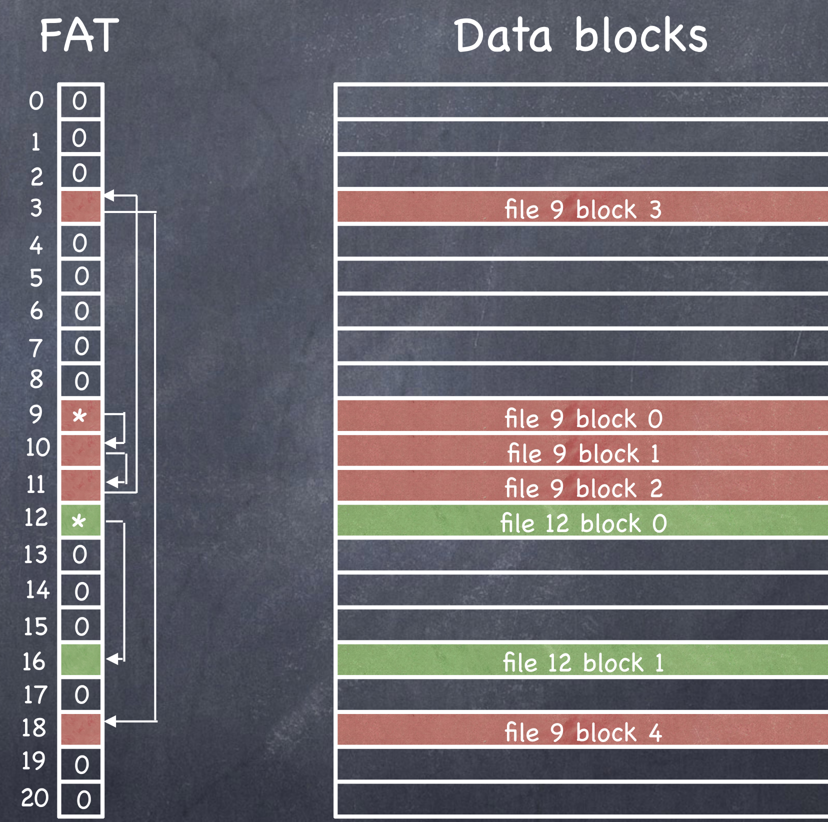
Locality heuristics

- As simple as next fit:
  - scan sequentially from last allocated entry and return next free entry
- Can be improved through defragmentation

Directory

- Maps file name to FAT index

Directory	
jack.txt	12
jill.txt	9



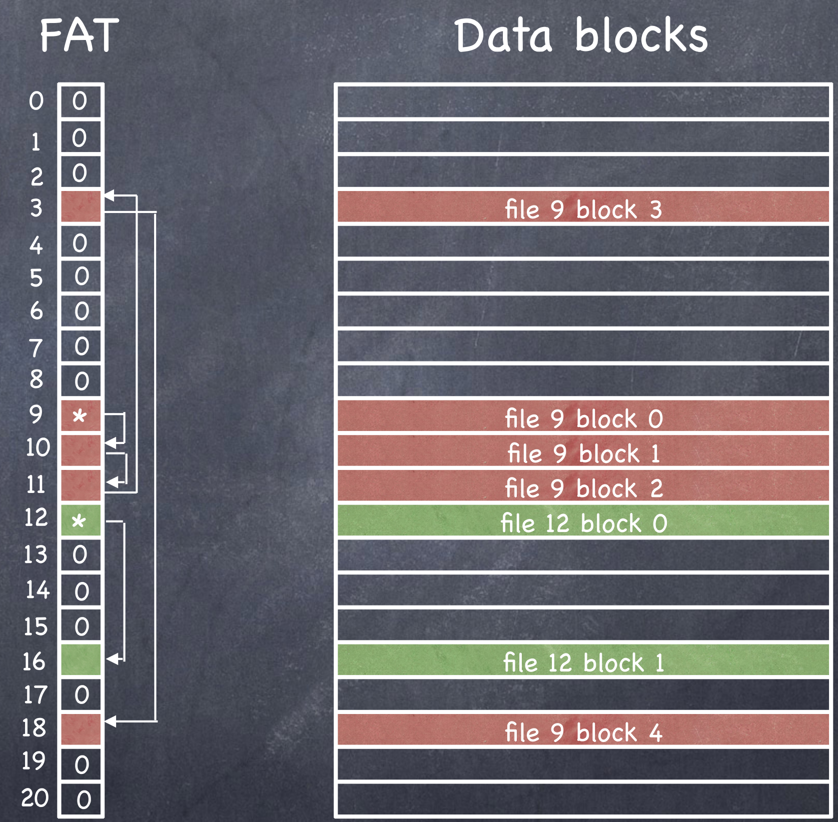
FAT File system

Advantages

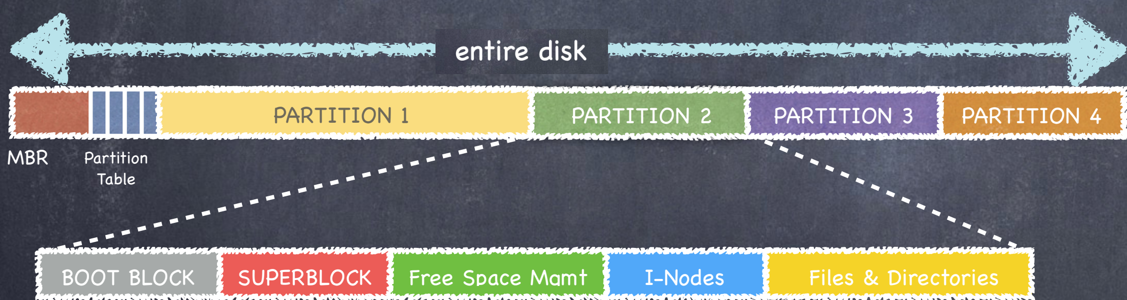
- simple!
  - per file, needs only start block
- widely supported
- no external fragmentation
- no conflating data and metadata in the same block

Disadvantages

- Poor locality
  - many file seeks unless entire FAT in memory
  - 1 TB (2^{40} bytes) disk, 4kb (2^{12} bytes block, 2^{28} FAT entries; at 4B/entry, 1 GB (!)
- Poor random access
  - needs sequential traversal
- Limited access control
  - no file owner or group ID
  - any user can read/write any file
- No support for hard links
- Volume and file size are limited
  - FAT entry is 32 bits, but top 4 are reserved
  - no more than 2^{28} blocks
  - with 4kB blocks, at most 1TB FS
  - file no bigger than 4GB
- No support for advanced reliability techniques

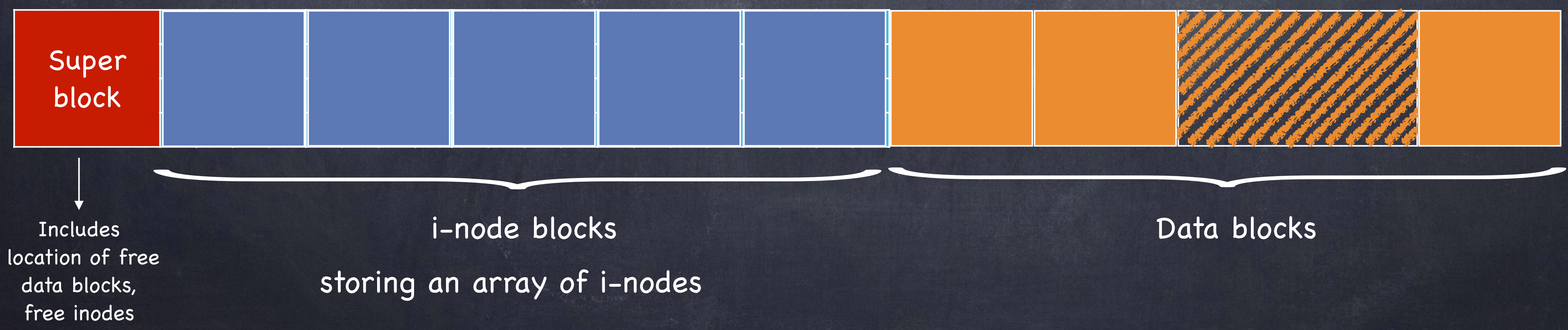


File System Layout



Tree-based Multi-level Index

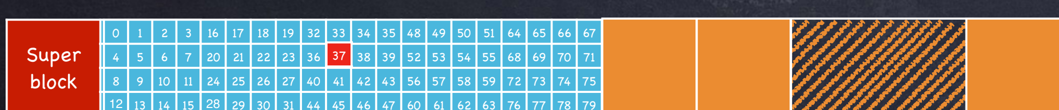
- UFS (Unix File System) (Ken Thompson, 1969)
- 4.2 BSD FFS (Fast File System) (McKusick, Joy, Leffler, Fabry, 1983)



Multilevel index

Inode Array

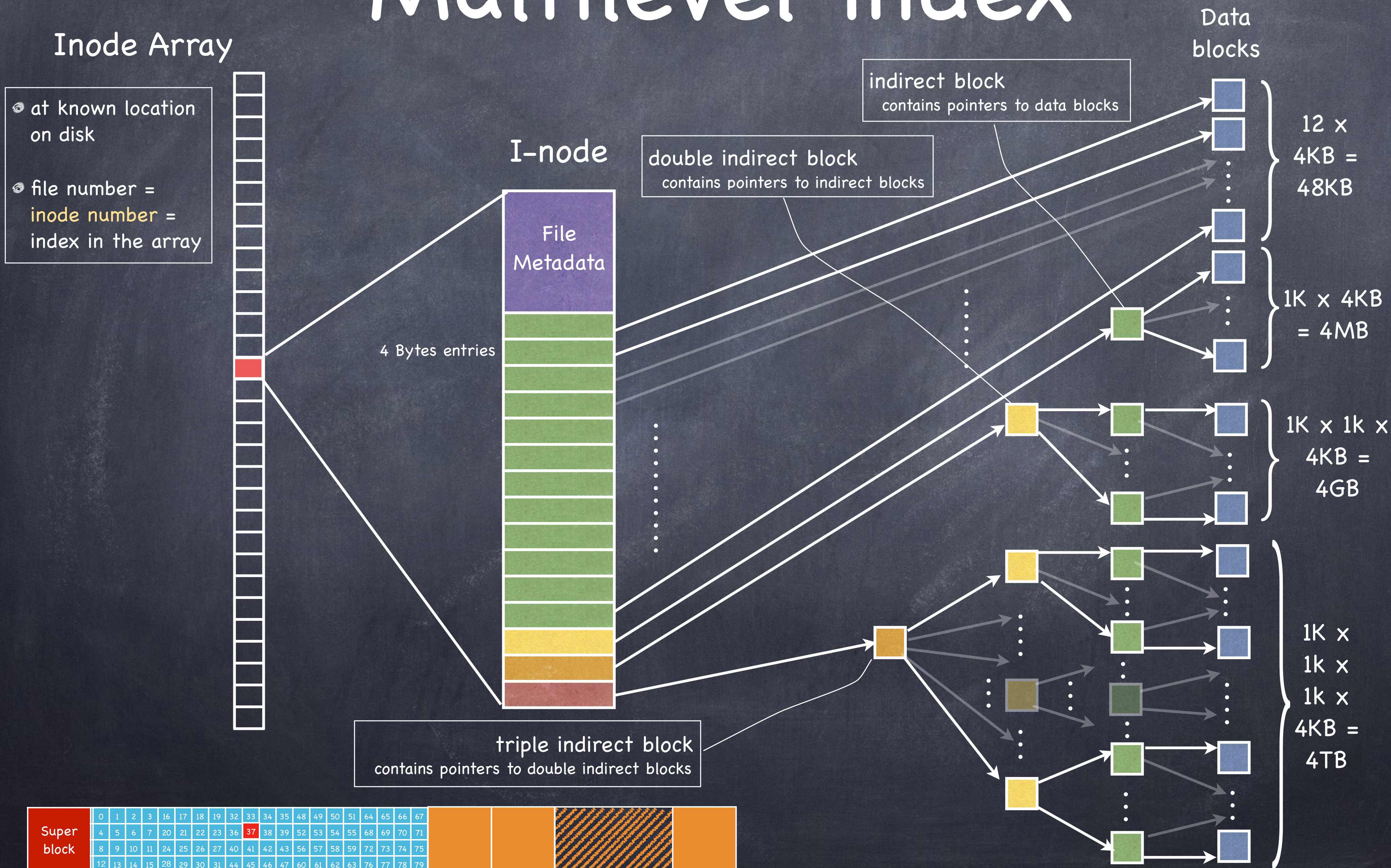
- at known location on disk
- file number = inode number = index in the array



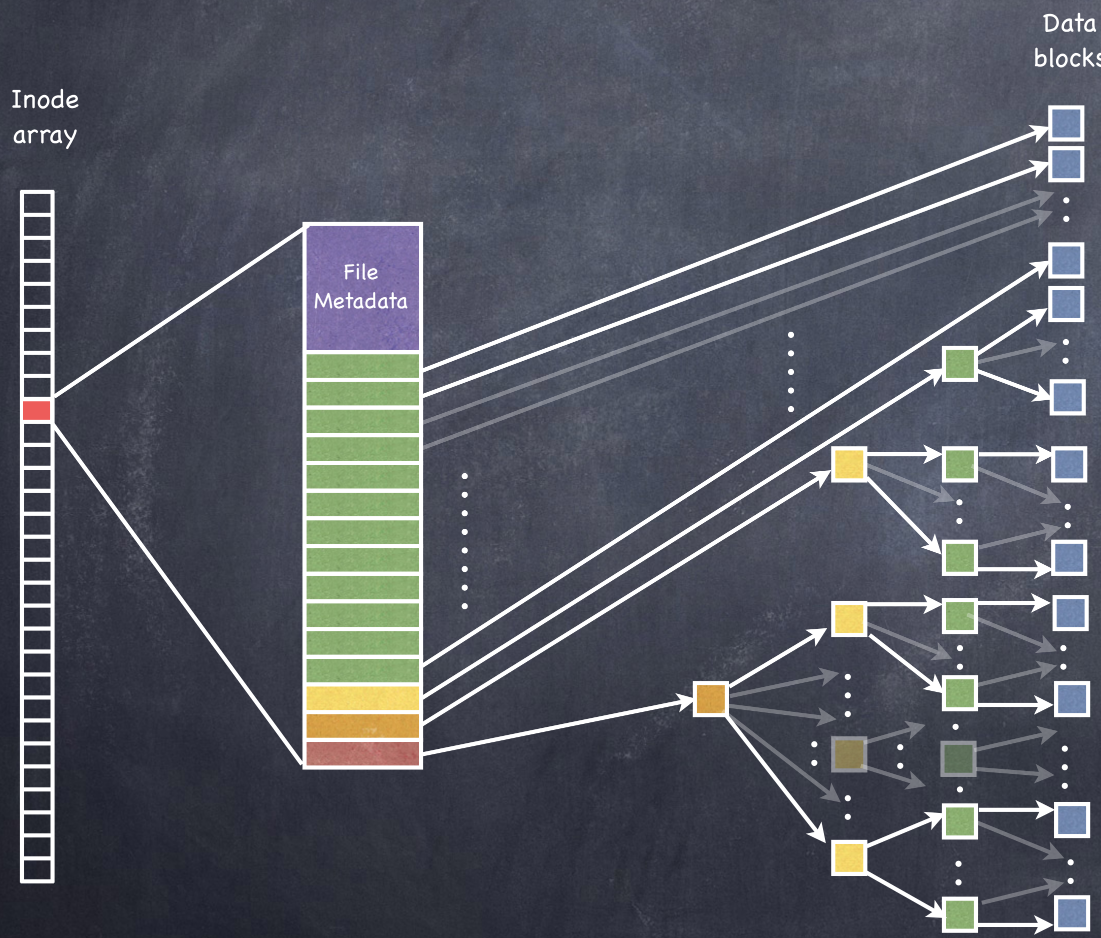
File structure

- Each file is a fixed, asymmetric tree, with fixed size data blocks (e.g. 4KB) as its leaves
- The root of the tree is the file's inode, containing
  - metadata (more about it later)
  - a set of 15 pointers
    - first 12 point to data blocks
    - last three point to intermediate blocks, themselves containing pointers…
      - #13: pointer to a block containing pointers to data blocks
      - #14: double indirect pointer
      - #15: triple indirect pointer (!)

Multilevel index

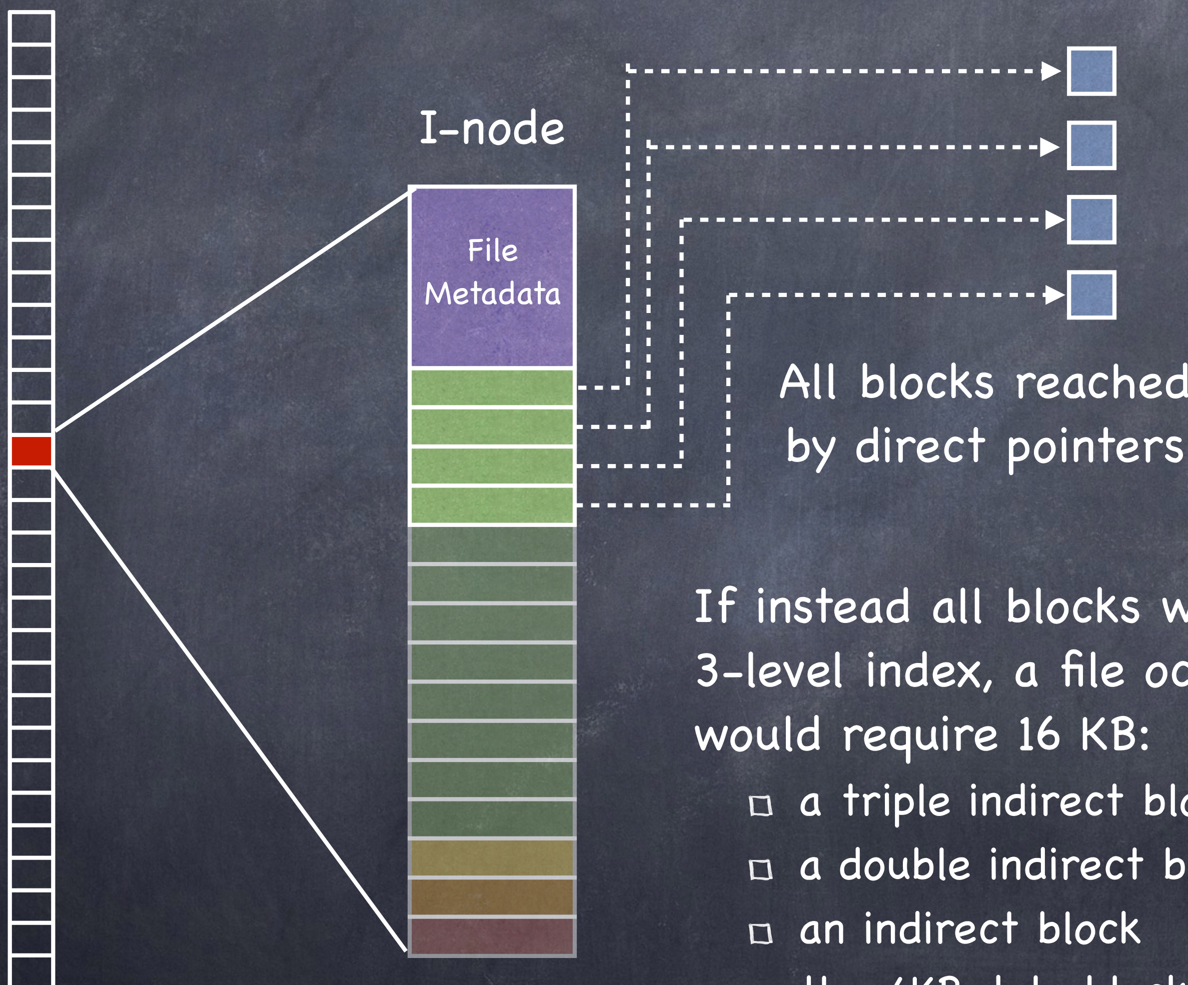


Multilevel index: key ideas



- Tree structure
  - efficient in finding blocks
- High degree
  - efficient in sequential reads
    - once an indirect block is read, can read 100s of data block
- Fixed structure
  - simple to implement
- Asymmetric
  - supports large files
  - small files don't pay large overheads

Good for small files...

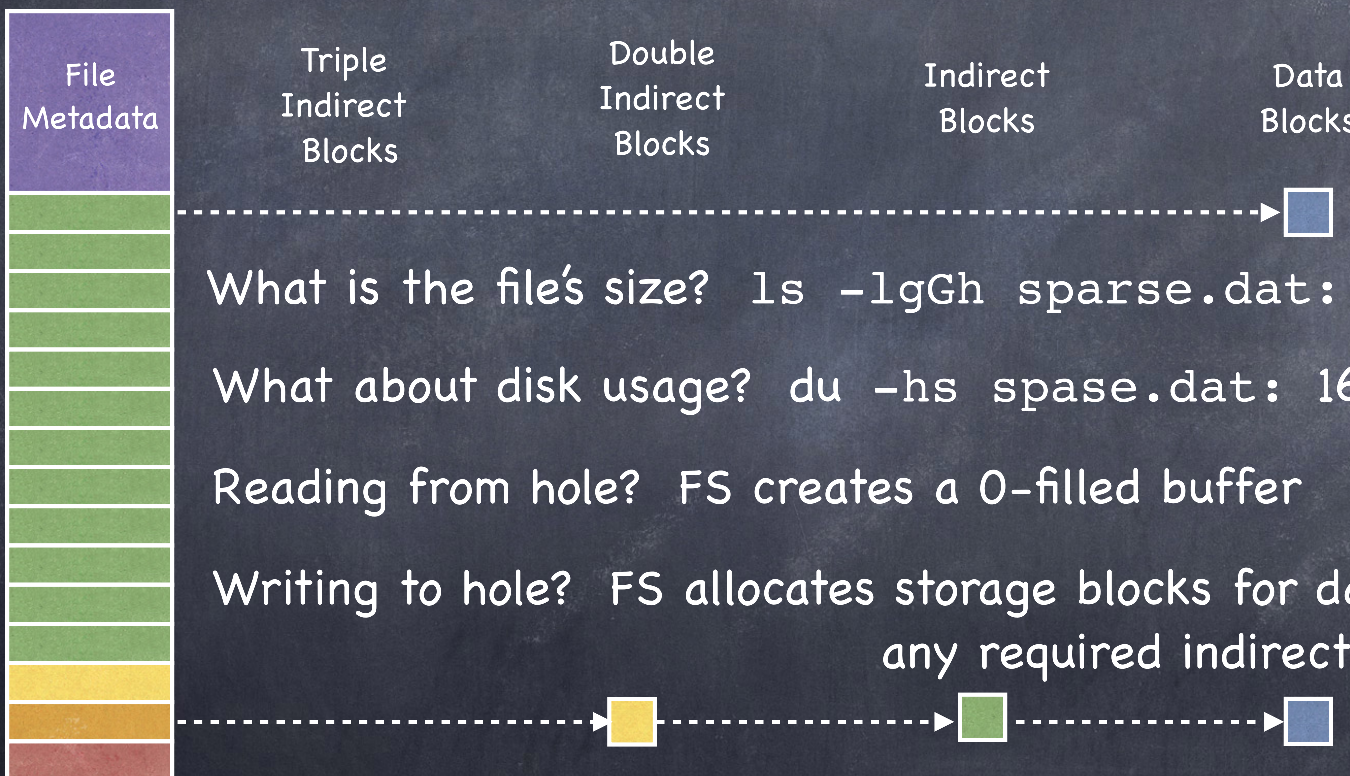


If instead all blocks were accessed through a 3-level index, a file occupying a single 4KB block would require 16 KB:

- a triple indirect block
- a double indirect block
- an indirect block
- the 4KB data block
- reading would require reading 5 blocks to traverse the tree

...and for sparse files

Consider file `sparse.dat` with two 4K blocks: one at offset 0;
the other at offset 2^{30}



What is the file's size? `ls -lgGh sparse.dat:` 1.1.GB

What about disk usage? `du -hs spase.dat:` 16KB (!)

Reading from hole? FS creates a 0-filled buffer

Writing to hole? FS allocates storage blocks for data + any required indirect block

What else is in an i-node?

- Type
  - ordinary file
  - directory
  - symbolic link
  - special device
- Size of the file (in bytes)
- No. of links to the i-node
- Owner (user id & group id)
- Protection bits
- Times: creation, last accessed, last modified

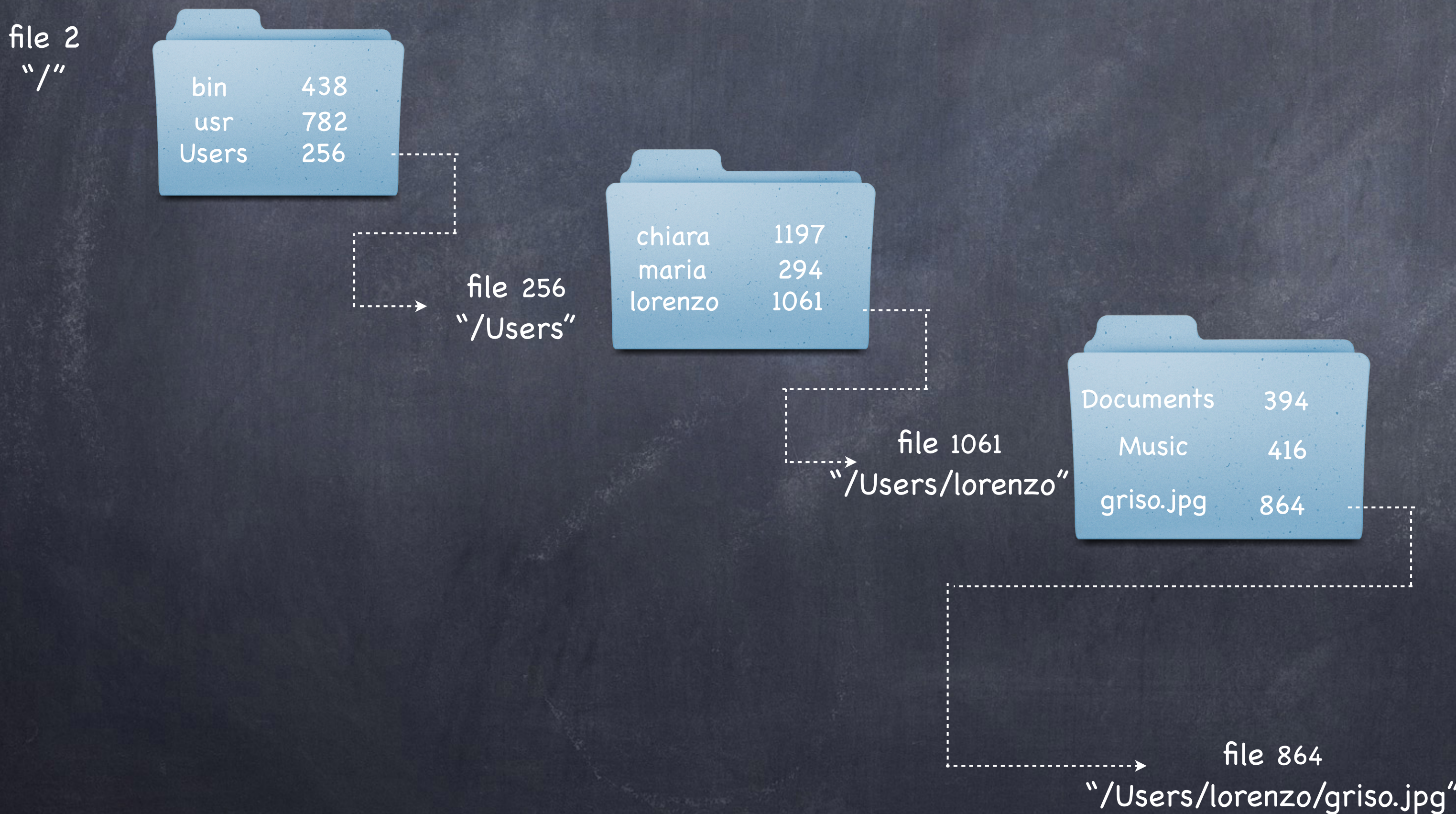
Directory

- A file that contains a collection of mapping from file name to file inode

- To look up a file, find the directory that contains the mapping to the file's inode
- To find that directory, find the parent directory that contains the mapping to that directory's inode..
- Good news: root directory has well-known number (2)

Looking up a file

- Find file /Users/lorenzo/griso.jpg



Directory Layout

- Directory stored as a file
  - Linear search to find filename (small directories)

File 1061
/Users/lorenzo

- Larger directories use B trees
  - searched by hash of file name

Reading a File

- First, must open the file
  - open("/CS4410/roster", O_RDONLY)
  - Follow the directory tree, until we get to the inode for "roster"
  - Read that inode
    - do a permission check
    - return a file descriptor fd
- Then, for each read() that is issued:
  - read inode
  - read appropriate data block (depending on offset)
  - update last access time in inode
  - update file offset in in-memory open file table for fd

Read first 3 data blocks from /CS4410/roster

	data bitmap	inode bitmap	root inode	CS4410 inode	roster inode	root data	CS4410 data	roster data[0]	roster data[1]	roster data[2]
open(CS4410)			read()							
						read()				
				read()						
							read()			
					read()					
read()					read()					
								read()		
					write()					
read()					read()					
									read()	
					write()					
read()					read()					
										read()
					write()					

Writing a File

- Must open the file, like before
- But now may have to allocate a new data block
  - each logical write can generate up to five I/O ops
    - reading the free data block bitmap
    - writing the free data block bitmap
    - reading the file's inode
    - writing the file's inode to include pointer to the new block
    - writing the new data block
- Creating a file is even worse!
    - read and write free inode bitmap
    - write inode
    - (read) and write directory data
    - write directory inode

and if directory block is full, must allocate another block

Create /CS4410/roster & Write first 3 Data Blocks

	data bitmap	inode bitmap	root inode	CS4410 inode	roster inode	root data	CS4410 data	roster data[0]	roster data[1]	roster data[2]
			read()							
						read()				
				read()						
							read()			
create		read()								
(/CS4410/roster)		write()								
							write()			
					read()					
					write()					
				write()						
					read()					
	read()									
write()	write()									
								write()		
					write()					
					read()					
	read()									
write()	write()									
									write()	
					write()					
					read()					
	read()									
write()	write()									
										write()
					write()					

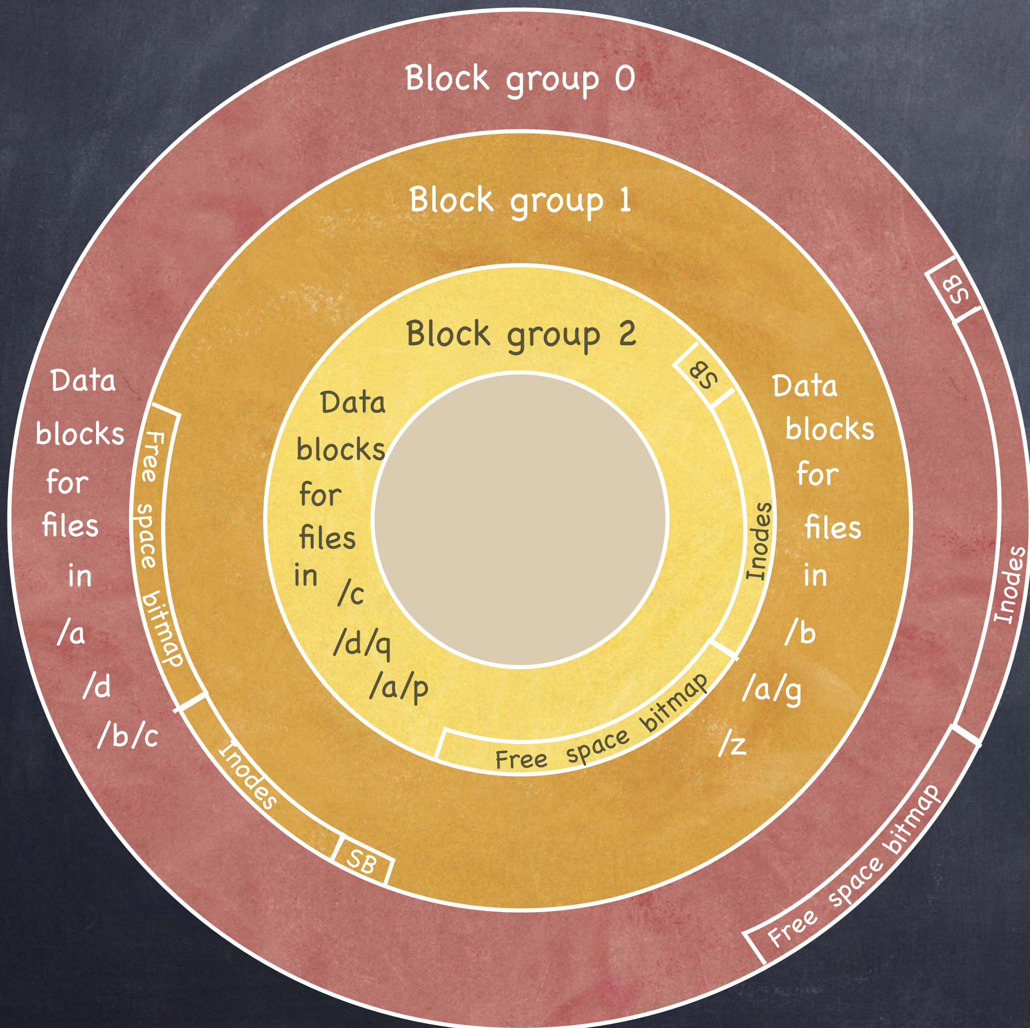
Caching

- Reading a long path can cause a lot of I/O ops!
- Cache aggressively!
  - early days: fixed sized cache for popular blocks
    - static partitioning can be wasteful
  - current: dynamic partitioning via unified page cache
    - virtual memory pages and file system blocks in a single cache
- Caching can significantly reduce disk I/O for reads
- Buffering can reduce cost of writes
  - some blocks may be overwritten
  - batching helps with scheduling disk accesses

BSD FFS: Fast File System

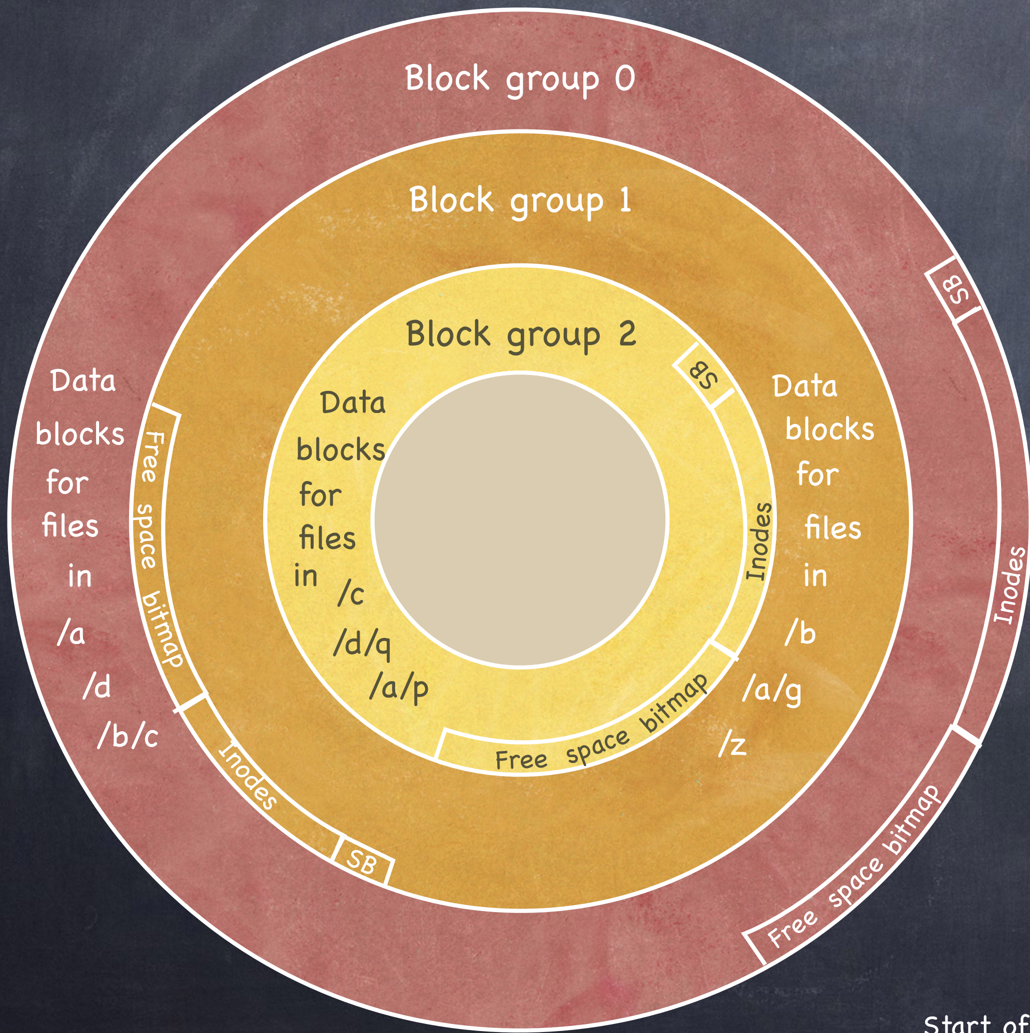
- UFS treats disks as if they were RAM
  - files grab first free data block: seeks and fragmentation
- FFS optimizes file system layout for how disks work
- Smart locality heuristics
  - block group placement
    - optimizes placement for when a file data and metadata, and other files within same directory, are accessed together
  - reserved space
    - gives up about 10% of storage to allow flexibility needed to achieve locality

Locality heuristics: block group placement



- Divide disk in block groups
  - sets of nearby tracks
- Distribute metadata
  - old design: free space bitmap and inode map in a single contiguous region
    - lots of seeks when going from reading metadata to reading data
  - FFS: distribute free space bitmap and inode array among block groups. Keep a superblock copy in each block group
- File Placement
  - when a new regular file is created, FFS looks for inodes in the same block as the file's directory
  - when a new directory is created, FFS places it in a different block from the parent's directory
- Data Placement
  - first free heuristics
  - trade short term for long term locality

Locality heuristics: block group placement



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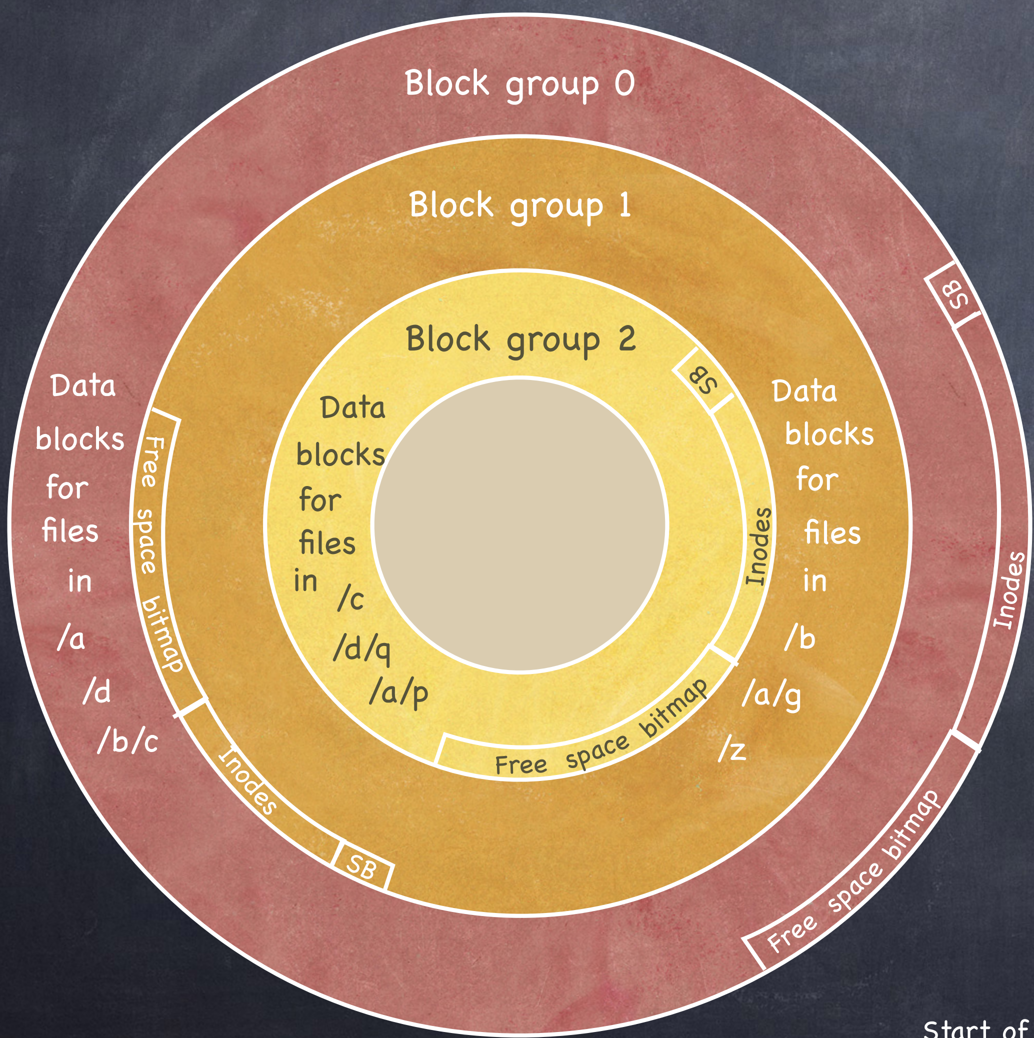

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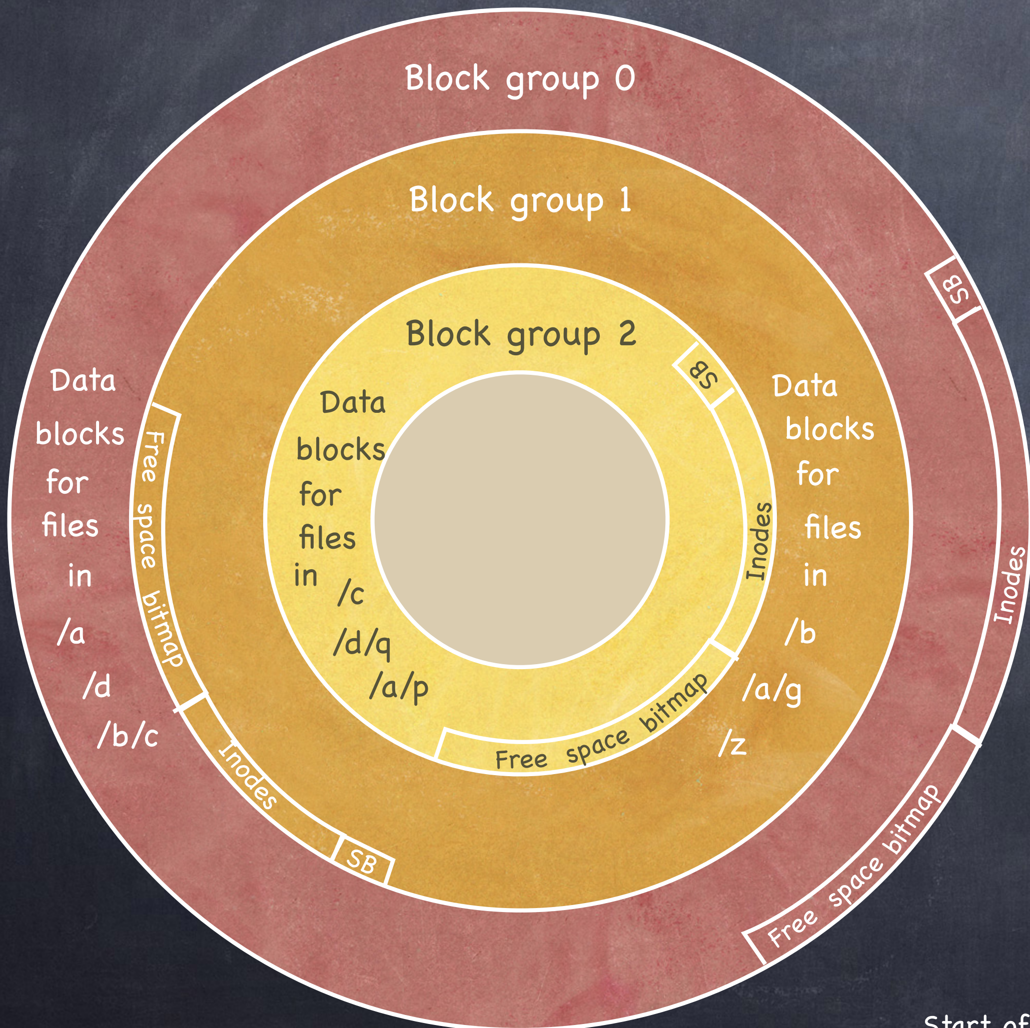

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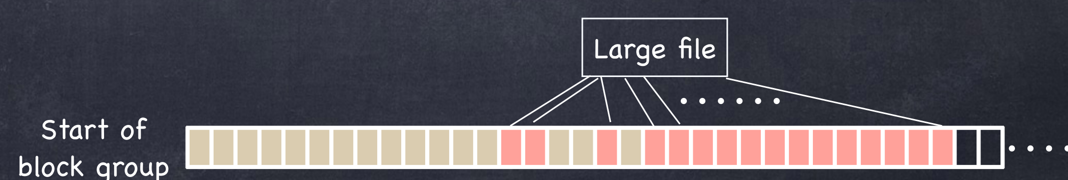
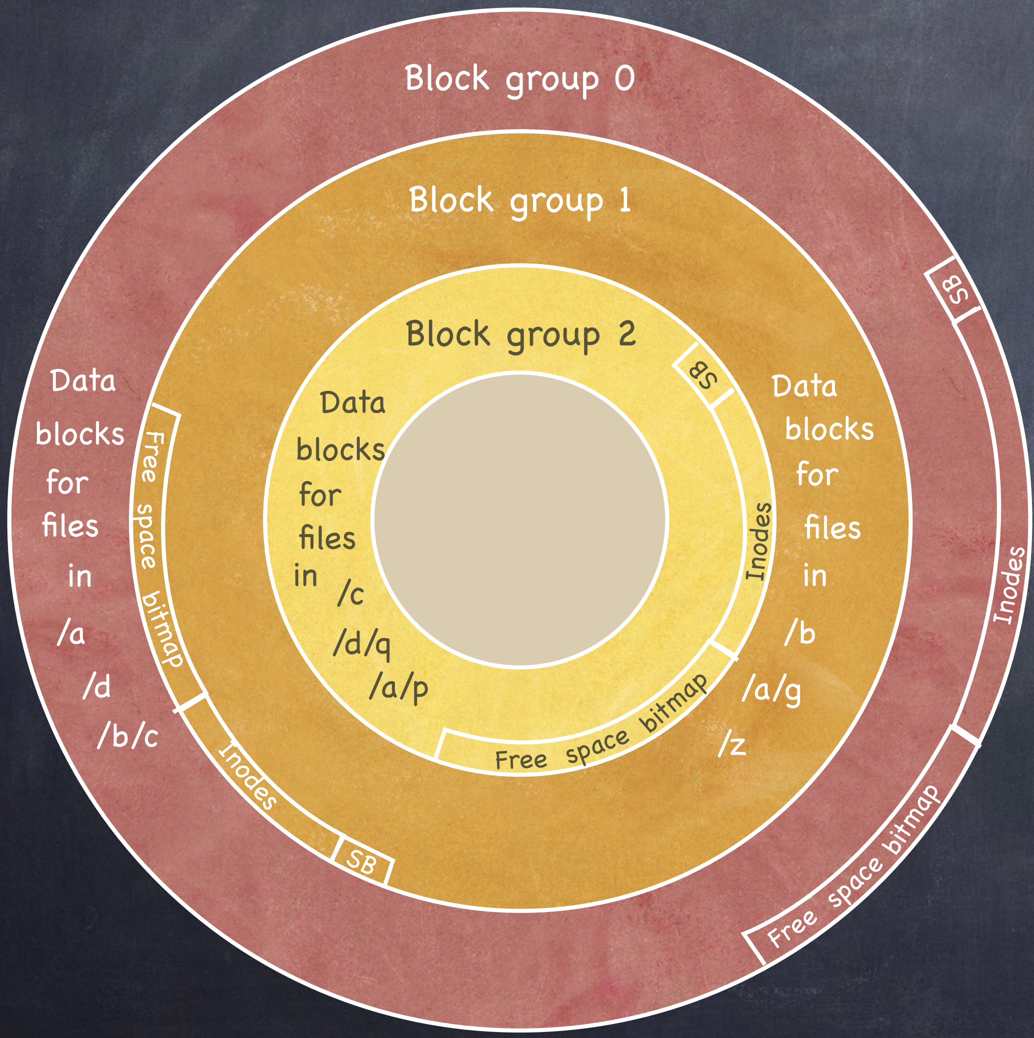


Locality heuristics: reserved space



- When a disk is full, hard to optimize locality
  - file may end up scattered through disk
- FFS presents applications with a smaller disk
  - about 10%-20% smaller
  - user's write that encroaches on reserved space fails
  - super user still able to allocate inodes to clean things up

Long File Exception

- Blocks of a huge file not all in the same block group
  - or they will eat up all the blocks in the group!
  - Instead, 12 blocks in a group (direct index)
  - others divided in "chunks"
- Locality lost when moving between chunks
  - choose chunk size to amortize cost of seeks

Say we want 90% of peak transfer, and transfer rate is 40MB/s

- if positioning time (seek+rotation) is 10ms, we need a chunk large enough that transfer takes 90ms

$$\text{chunk size} = \frac{40\text{MB}}{\text{s}} \times \frac{1\text{s}}{1000\text{ms}} \times 90\text{ms} = 3.6\text{ MB}$$

- In practice, FFS uses 4 MB chunks

Caching and Consistency

- File systems maintain many data structures
  - Bitmap of free blocks and inodes
  - Directories
  - Inodes
  - Data blocks
- Data structures cached for performance
  - works great for read operations...
  - ...but what about writes?

Caching and Consistency

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  - Directories
  - Inodes
  - Data blocks
- Data structures cached for performance
  - works great for read operations...
  - ...but what about writes?
- Write-back caches
  - delay writes: higher performance at the cost of potential inconsistencies
- Write-through caches
  - write synchronously but poor performance (fsync)
    - do we get consistency at least?