Persistence

Abstractions
Resource management
(isolation; efficiency)

Virtualization (CPU, memory)
Concurrency

Interaction with Devices

Disks and Persistence

Store data users care about:
persist beyond reboots

Backing store for paging

Space multiplexing
(coexist)

Shared view of
storage!

Permissions

Intelligence in software, mostly

Motivation

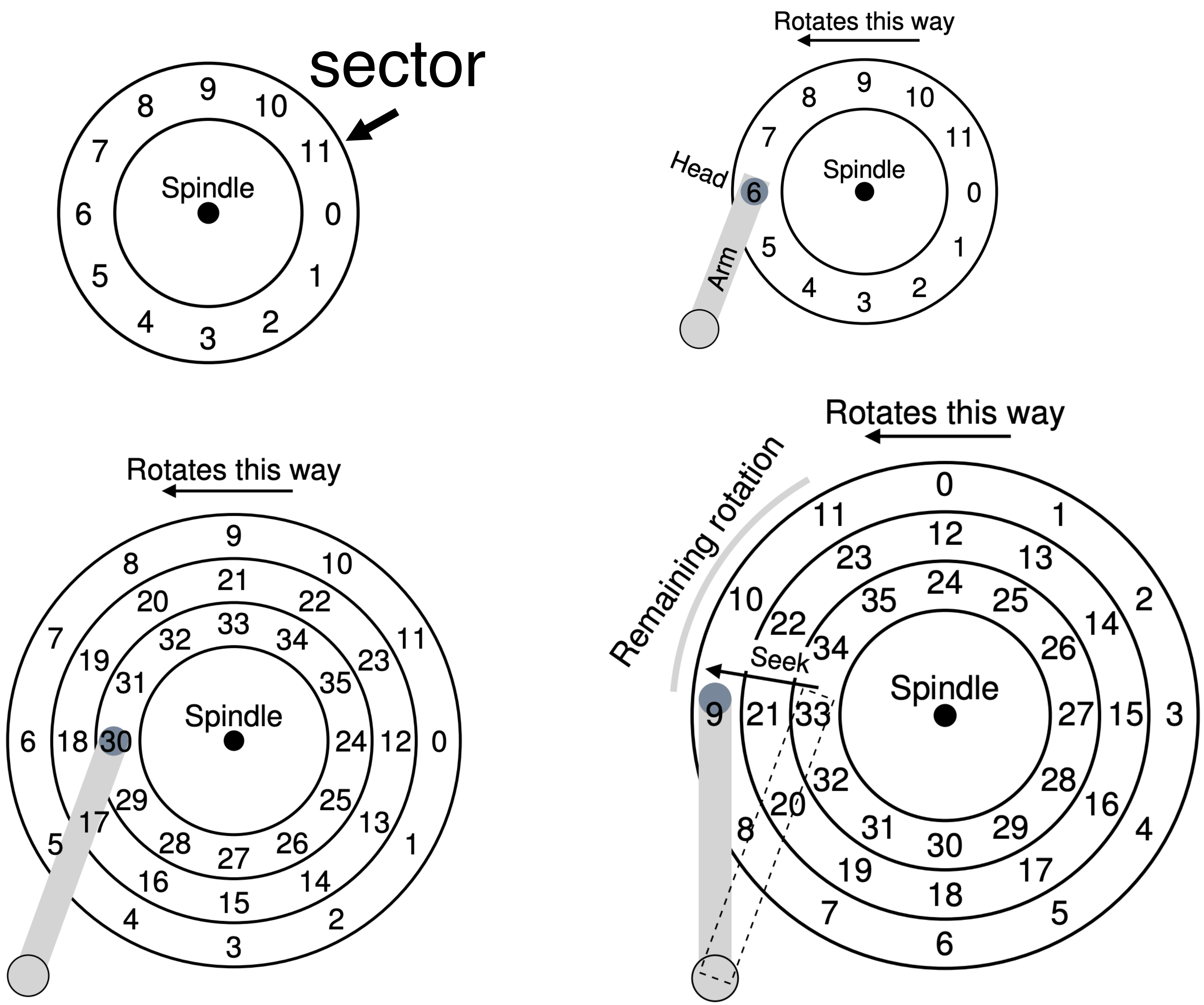
What good is a computer without any I/O devices?

- keyboard, display, disks

We want:

- **H/W** that will let us plug in different devices
- **OS** that can interact with different combinations

Disk



sector
Spindle
Rotates this way
Head
Arm
Spindle
Rotates this way
Spindle
Rotates this way
Remaining rotation
Seek
Spindle

Filesystems

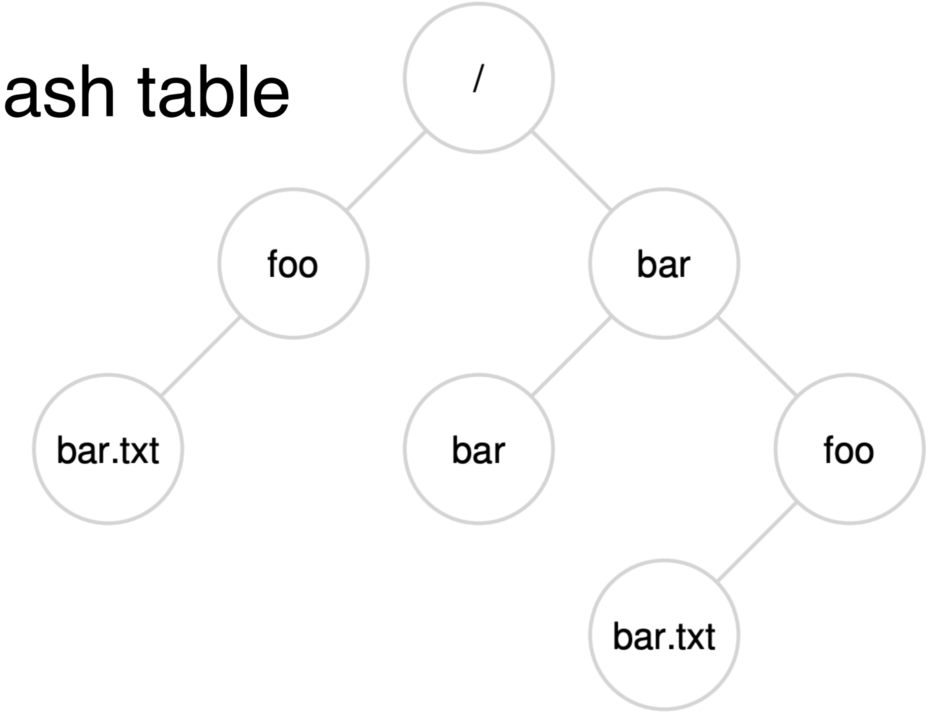
Abstractions over blocks of data

Flat mapping of name to blocks? E.g. hash table

Something a bit more flexible:

A hierarchy

```
   creat(), open(),
   read(), write(),
mkdir(), readdir(), …
   link(), unlink()
```



Filesystems

Why are file systems useful?

- Durability across restarts
- Naming and organization
- Sharing among programs and users

Why interesting?

- Crash recovery
- Performance
- API design for sharing
- Security for sharing
- Abstraction is useful: pipes, devices,
  - /proc, /afs, etc.

Filesystems

API example -- UNIX/Posix/Linux/xv6/&c:

- fd = open("x/y", -);
- write(fd, "abc", 3);
- link("x/y", "x/z");
- unlink("x/y");

- Plan 9 OS (Bell labs) - Attempts to structure entire OS as a filesystem

- http://plan9.bell-labs.com/plan9/

Questions for filesystems

- What **on-disk structures** to represent files and directories?
  - Contiguous, Extents, Linked, FAT, Indexed, Multi-level indexed
  - Which are good for different **metrics**?
- What disk **operations** are needed for:
- make directory
- open file
- write/read file
- close file

FS Implementation

1. On-disk structures

    - how does file system represent files, directories?

2. Access methods

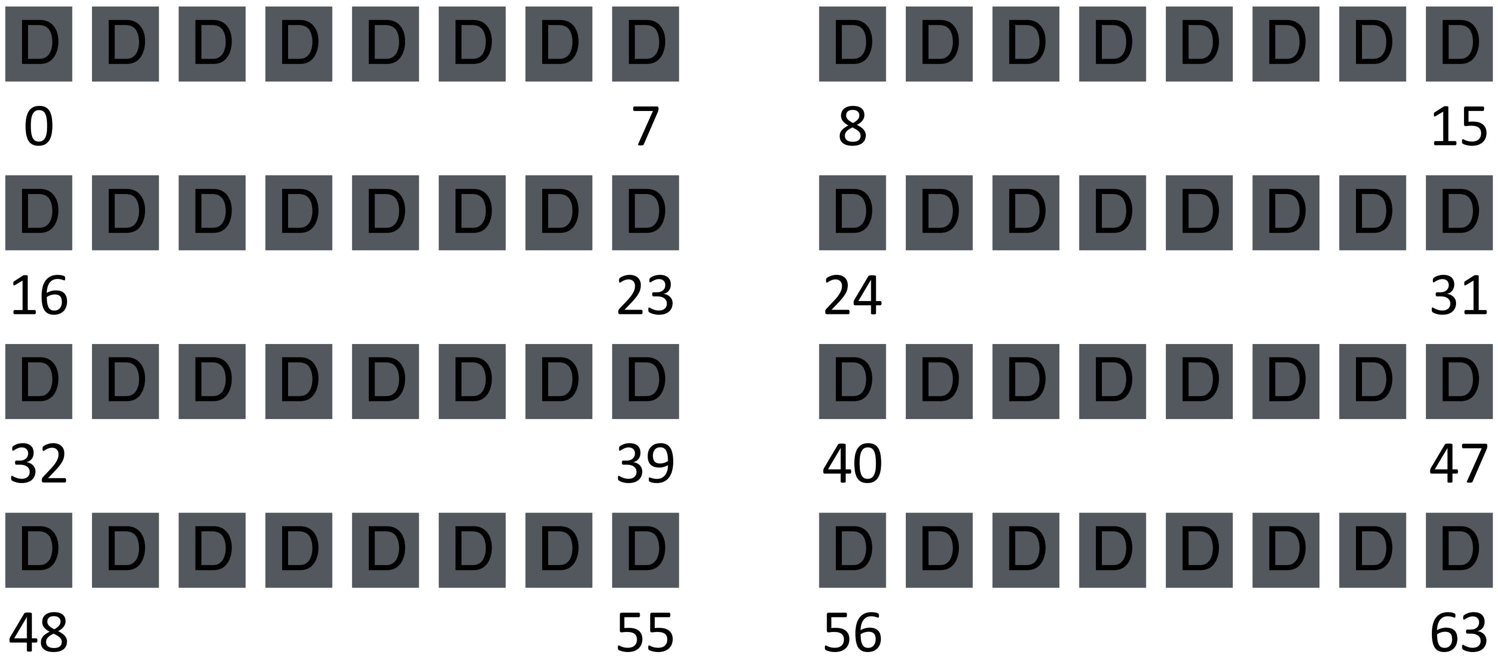
    - what steps must reads/writes take?

Part 1: Disk Structures

Persistent Store

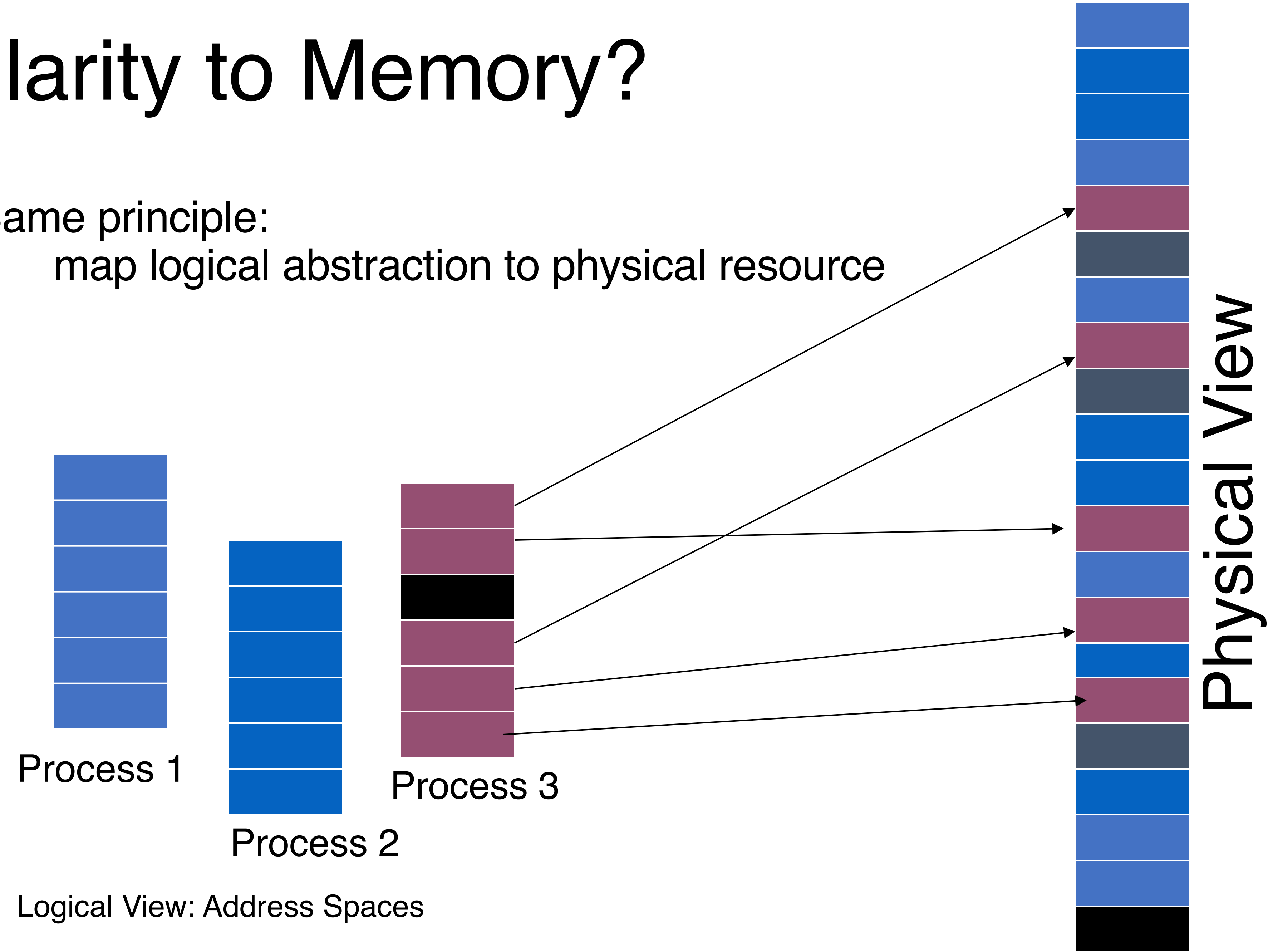
Given: large array of blocks on disk

Want: some structure to map files to disk blocks



Similarity to Memory?

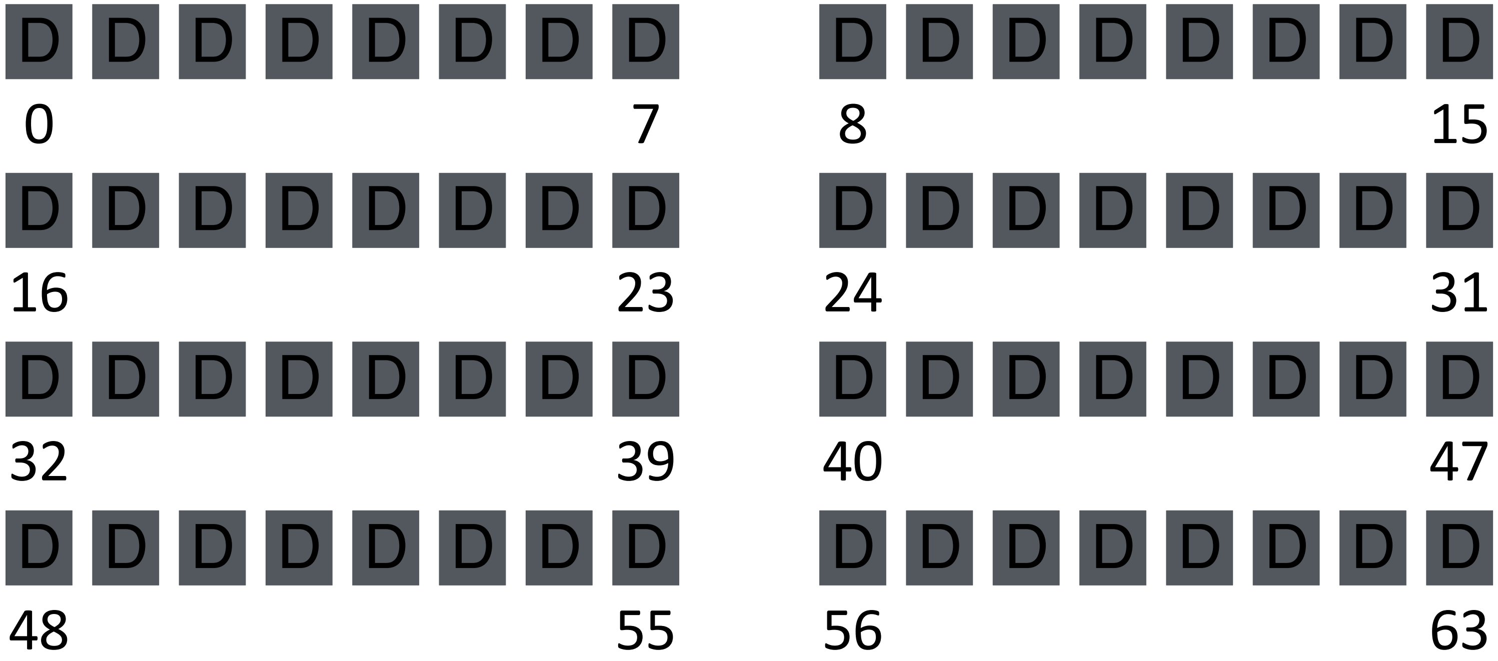
Same principle:
map logical abstraction to physical resource



On-Disk Structures

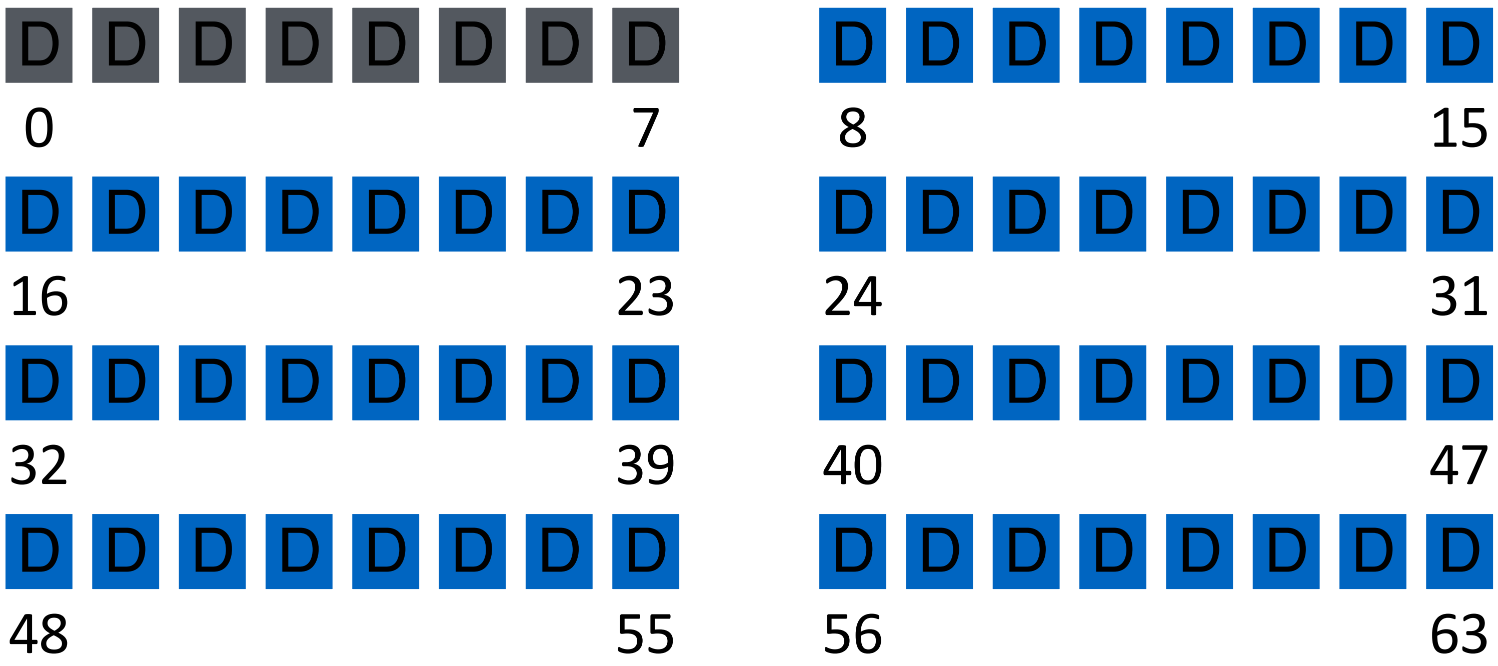
- data block
- inode table
- indirect block
- directories
- data bitmap
- inode bitmap
- superblock

FS Structs: Empty Disk



Assume each block is 4KB

Data Blocks


D D D D D D D D
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D D D D D D D D
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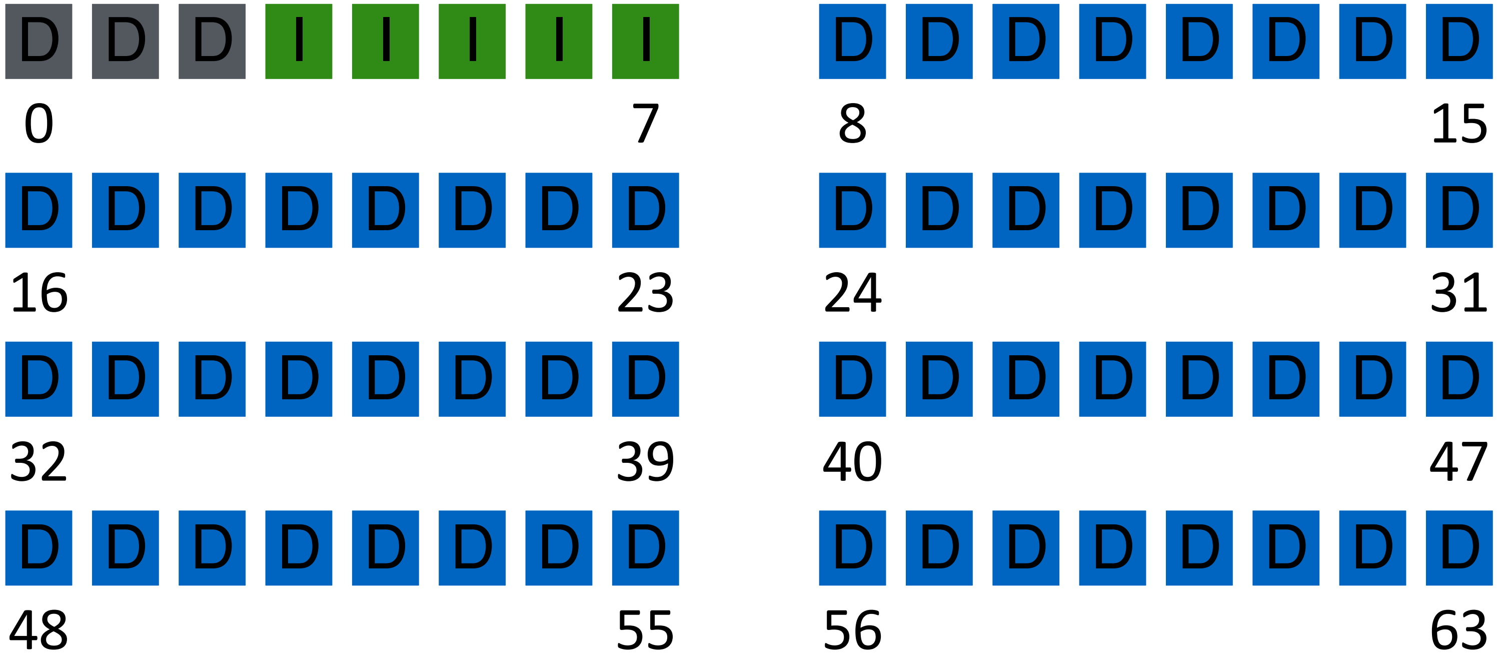
55
D D D D D D D D
56
63

Inodes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39
D D D D D D D D
40
47
D D D D D D D D
48
55
D D D D D D D D
56
63

One Inode Block

Each inode is typically 256 bytes (depends on the FS, maybe 128 bytes)

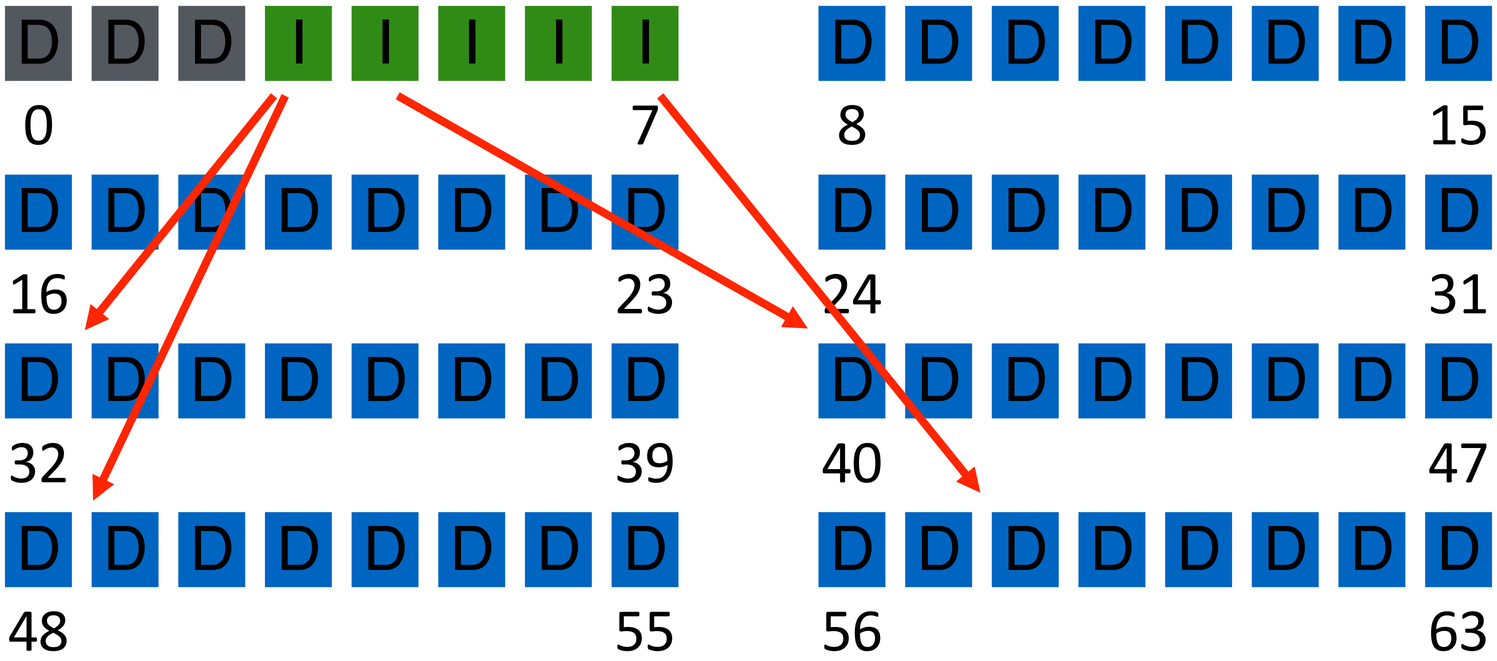
4KB disk block

16 inodes per inode block.

Inode

type (file or dir?)
uid (owner)
rwx (permissions)
size (in bytes)
Blocks
time (access)
ctime (create)
links_count (# paths)
addrs[N] (N data blocks)

Inodes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D D D D D D D D
32
39
D D D D D D D D
40
47
D D D D D D D D
48
55
D D D D D D D D
56
63

Inode

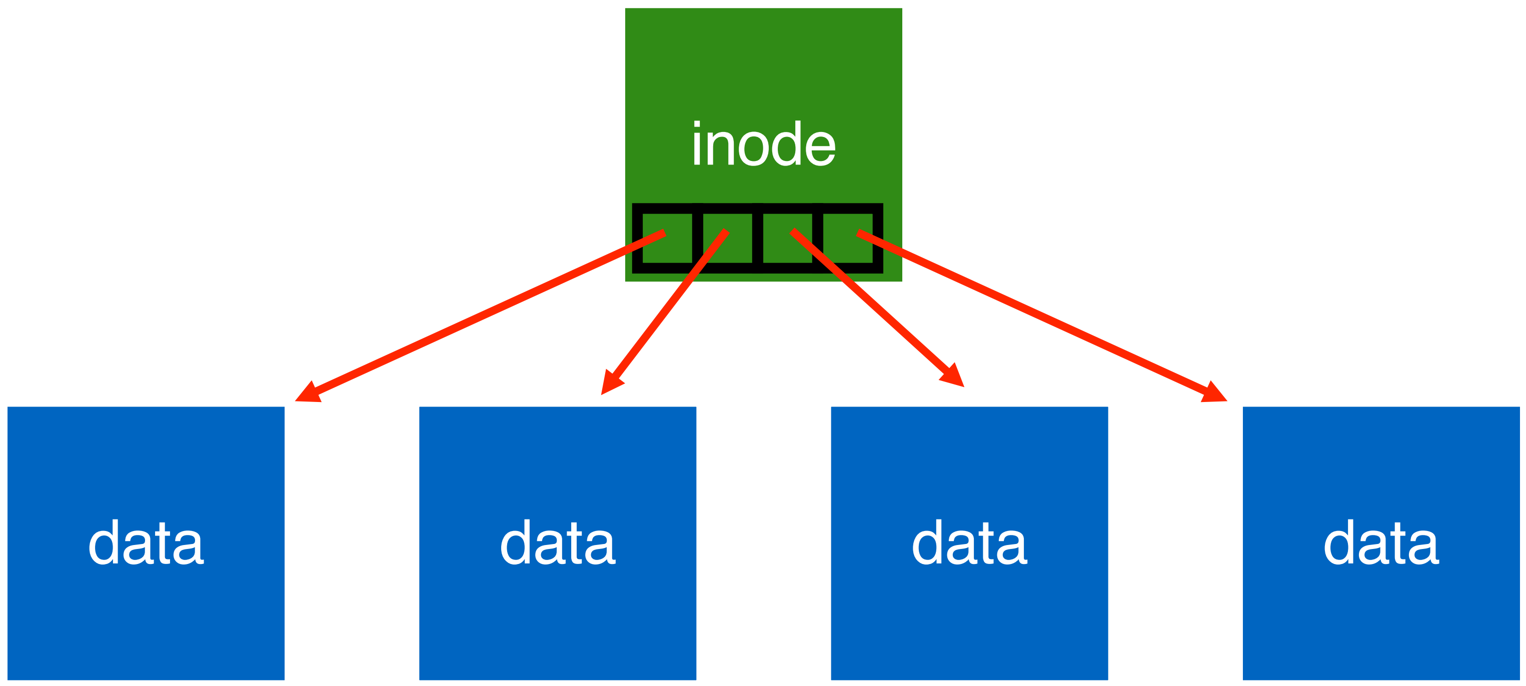
type
uid
rwx
size
blocks
time
ctime
links_count
addrs[N]

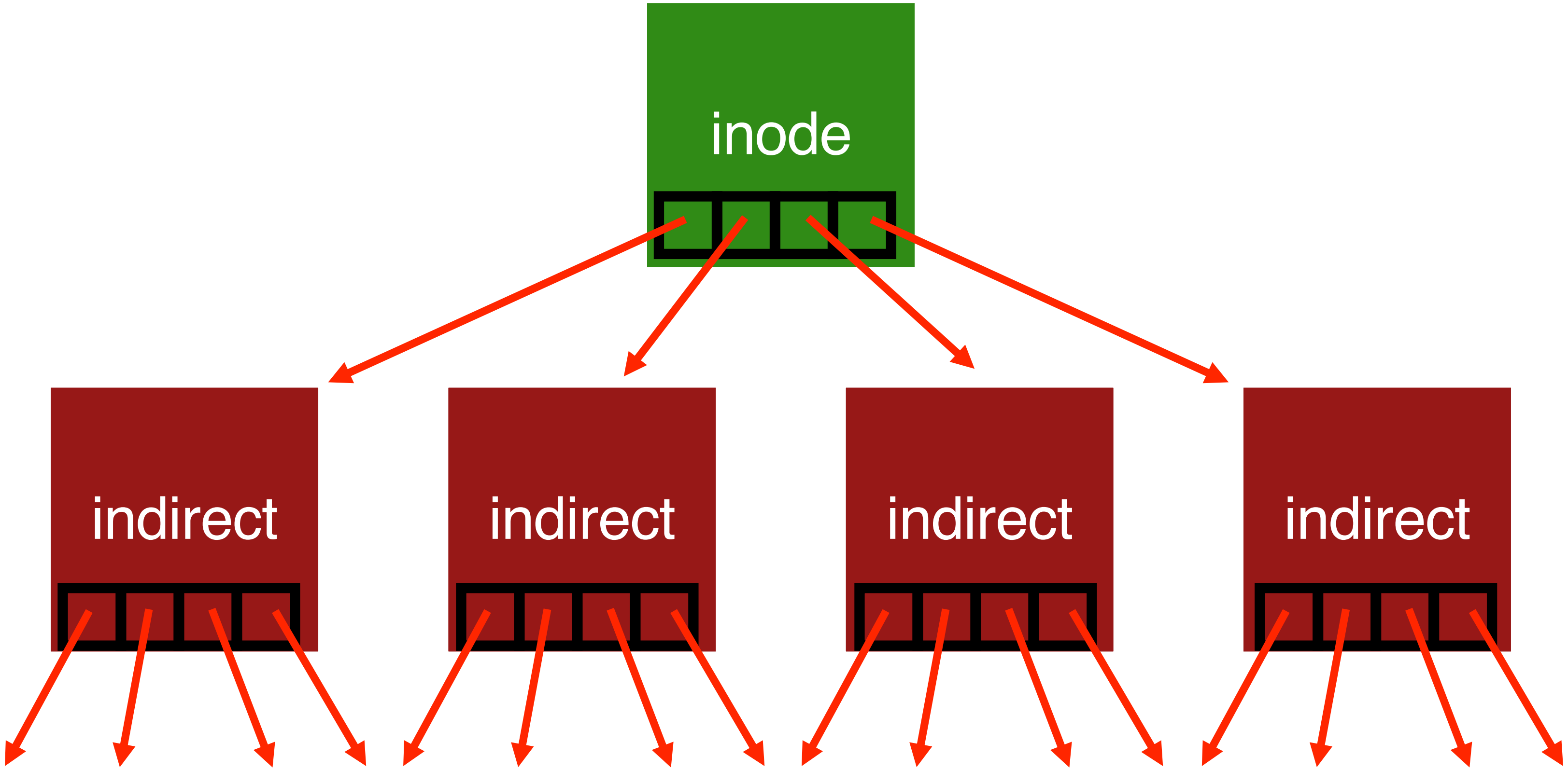
Assume single level (just pointers to data blocks)

What is max file size?
Assume 256-byte inodes (all can be used for pointers)
Assume 4-byte addrs

How to get larger files?

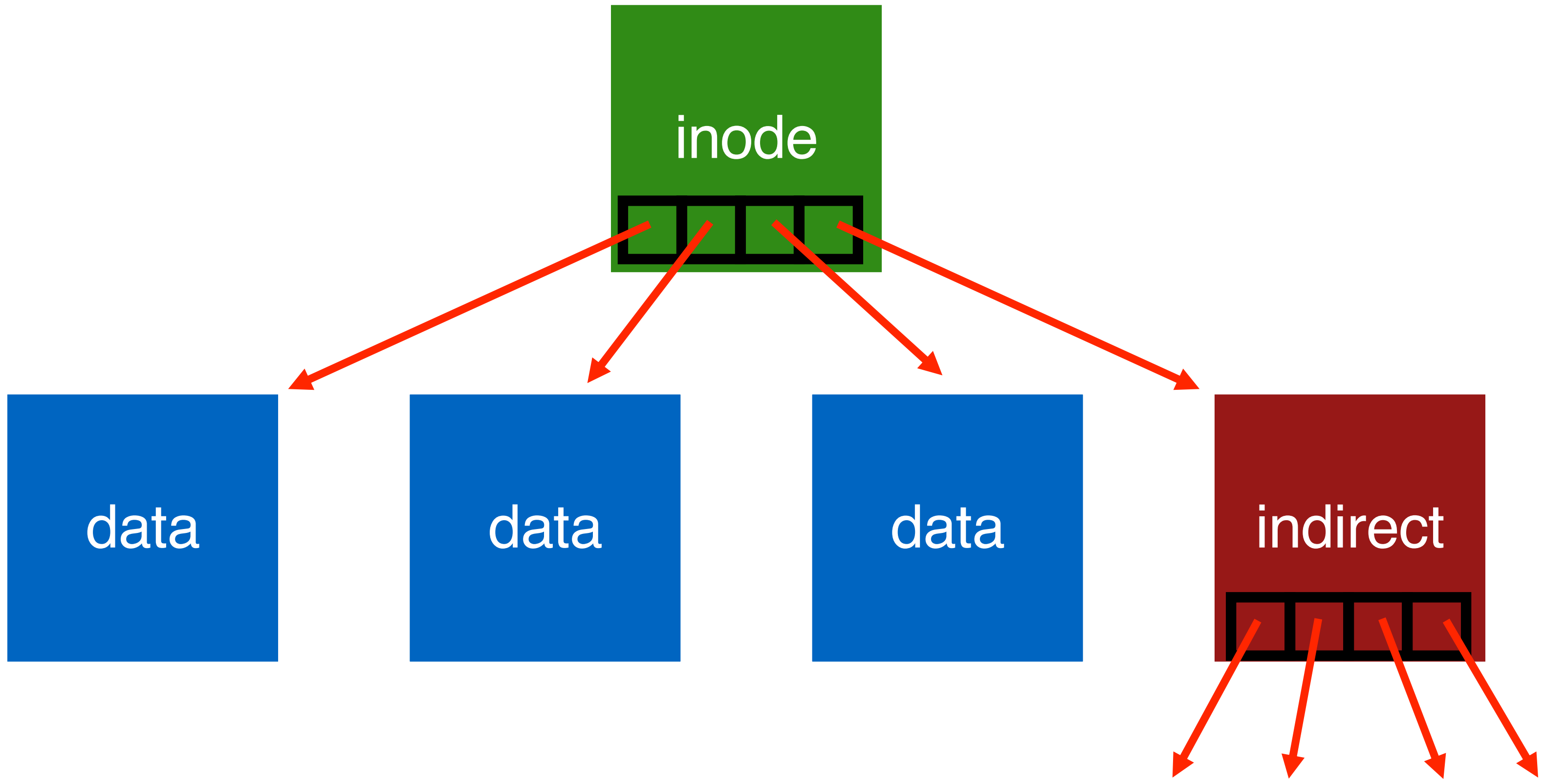
256 / 4 = 64
64 * 4K = 256 KB!


inode
data
data
data
data



Indirect blocks are stored in regular data blocks.

what if we want to optimize for small files?

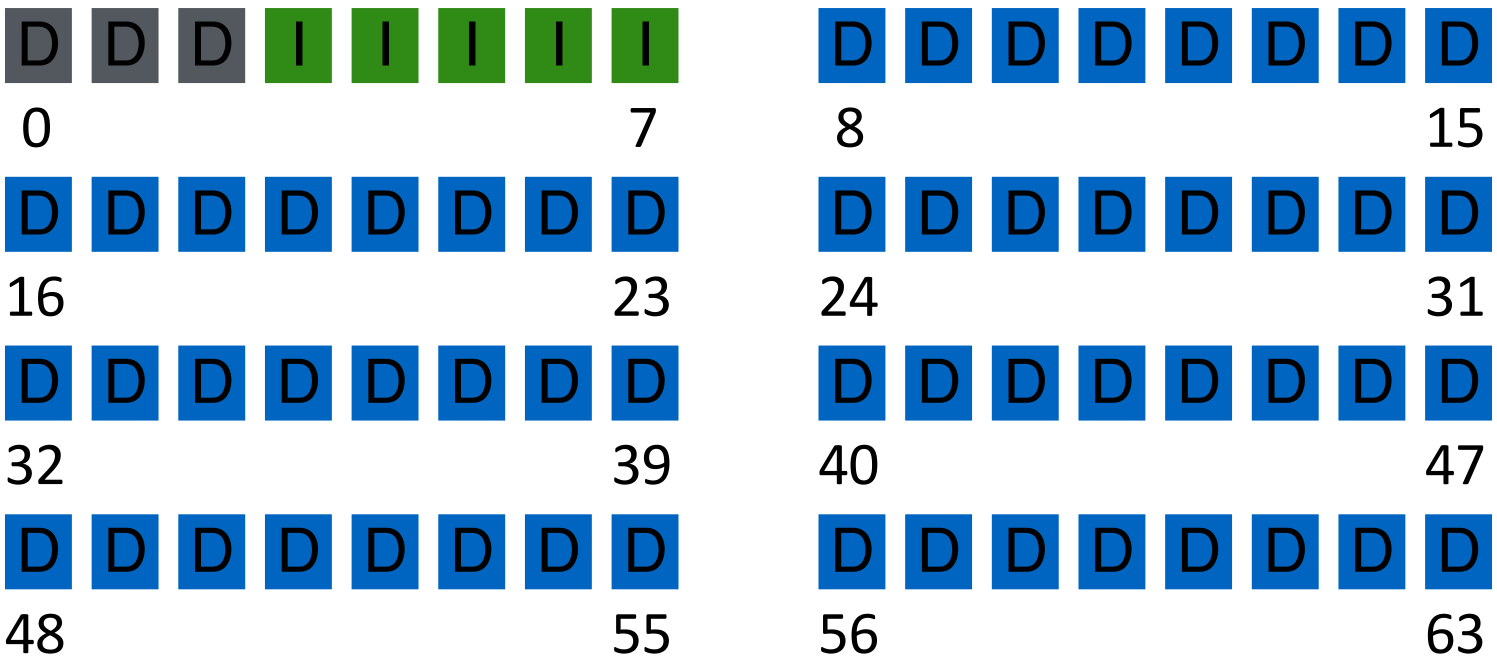


Better for small files

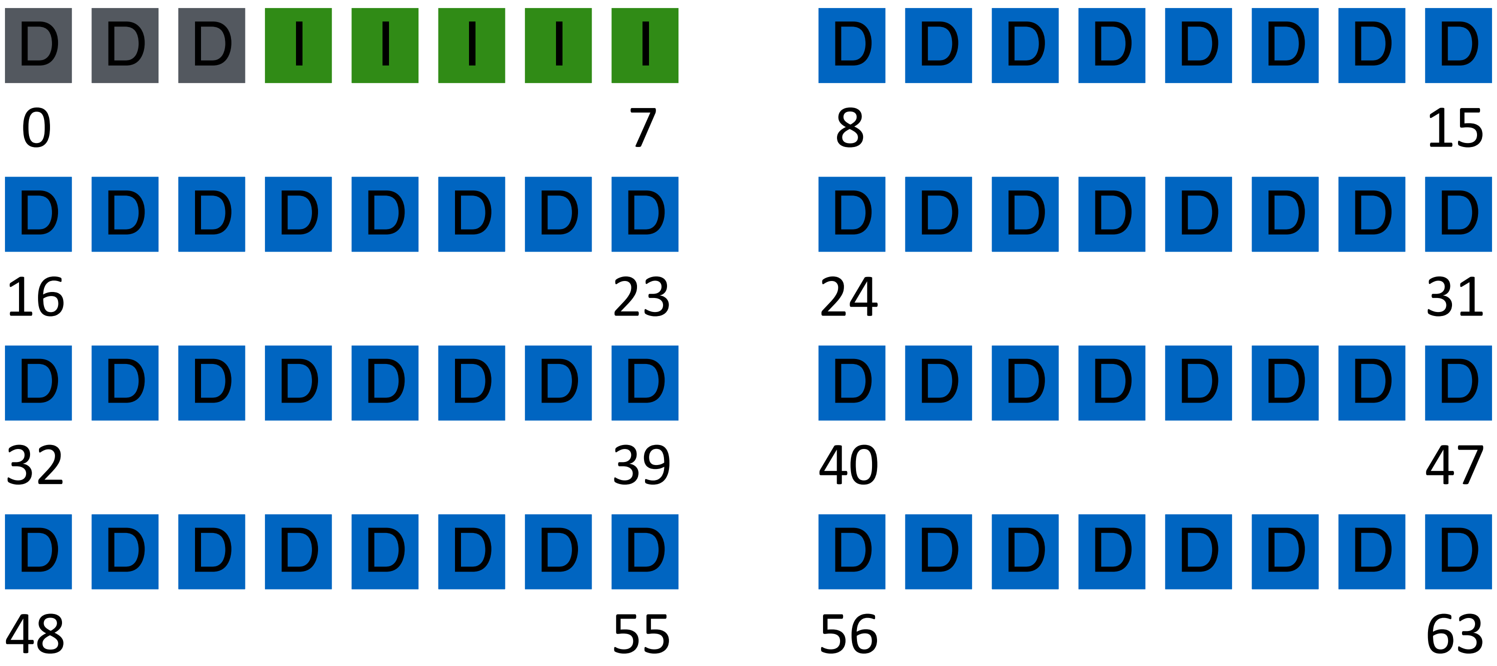
Inode

type
uid
rwx
size
Blocks (optional)
time
ctime
links_count
direct_ptr[N]
indirect_ptr[N+X]
//Some stat structure

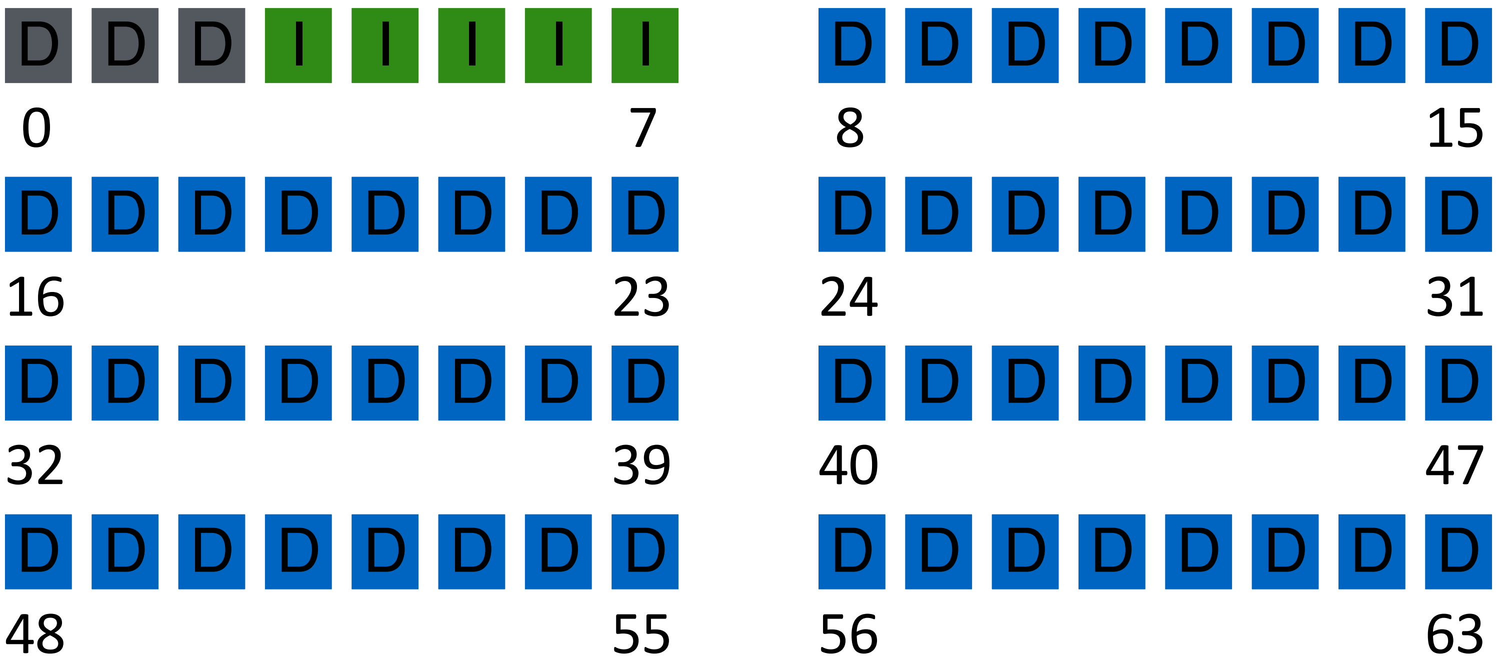
Assume 256 byte inodes (16 inodes/block).
What is offset for inode with number 0?



Assume 256 byte inodes (16 inodes/block).
What is offset for inode with number 4?

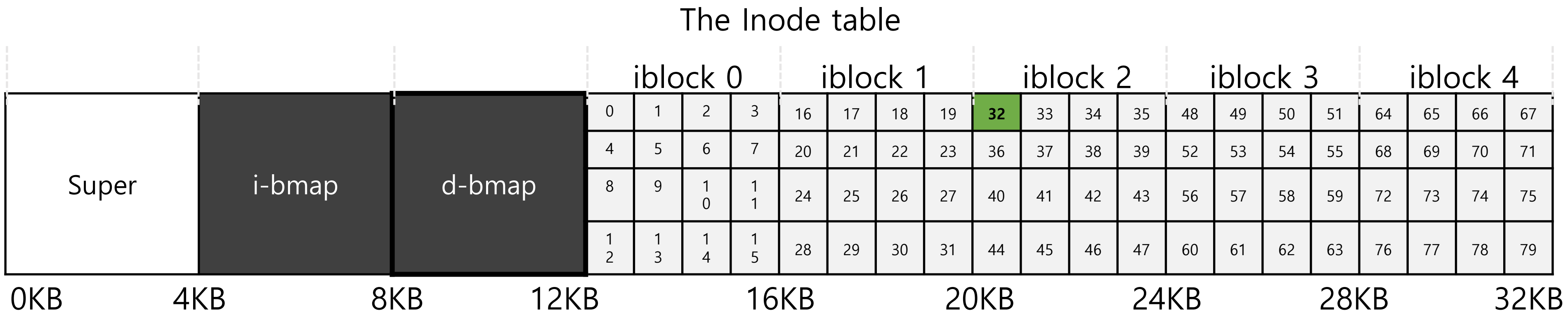


Assume 256 byte inodes (16 inodes/block).
What is offset for inode with number 40?



File Organization: The inode

- Each inode is referred to by inode number.
  - by inode number, File system calculate where the inode is on the disk.
  - Ex: inode number: 32
    - Calculate the offset into the inode region (32 x sizeof(inode) (256 bytes) = 8192
    - Add start address of the inode table(12 KB) + offset into inode region = 20 KB



Directories

File systems vary

Common design:
- Store directory entries in data blocks
- Large directories just use multiple data blocks
- Use bit in inode to distinguish directories from files

Various formats could be used

- lists
- b-trees

Simple Directory List Example

valid	name	inode
1	.	134
1	..	35
1	foo	80
1	bar	23

unlink(“foo”)

Hard links and Soft (symbolic) links

Hard Link :

- A hard link acts as a copy (mirrored) of the selected file. It accesses the data available in the original file.
- If earlier selected file is deleted, the hard link to the file will still contain the data of that file.

In /path/to/source /path/to/link

Soft Link :

- A soft link (also known as symbolic link) acts as a pointer or a reference to the file name. It does not access the data available
- in the original file. If the earlier file is deleted, the soft link will be pointing to a file that does not exist anymore

In -s /path/to/source /path/to/link

Allocation

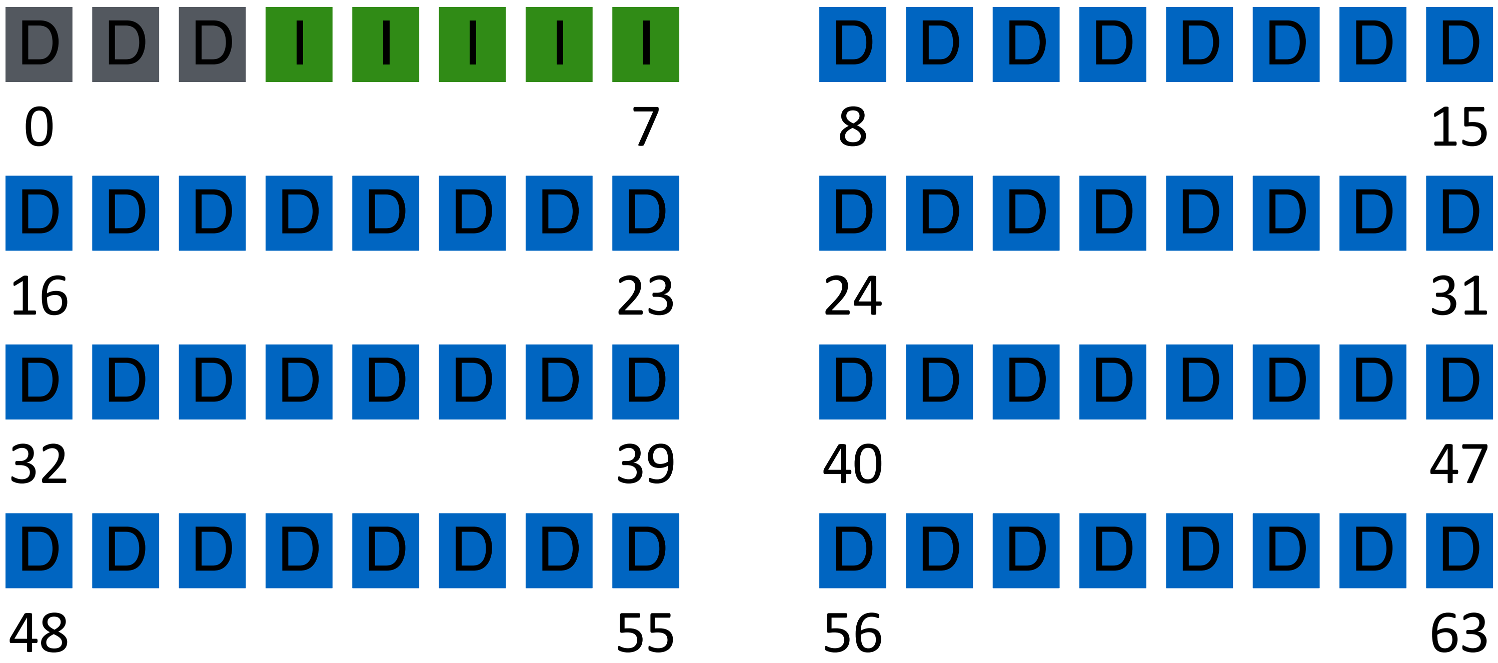
How do we find free data blocks or free inodes?

Free list

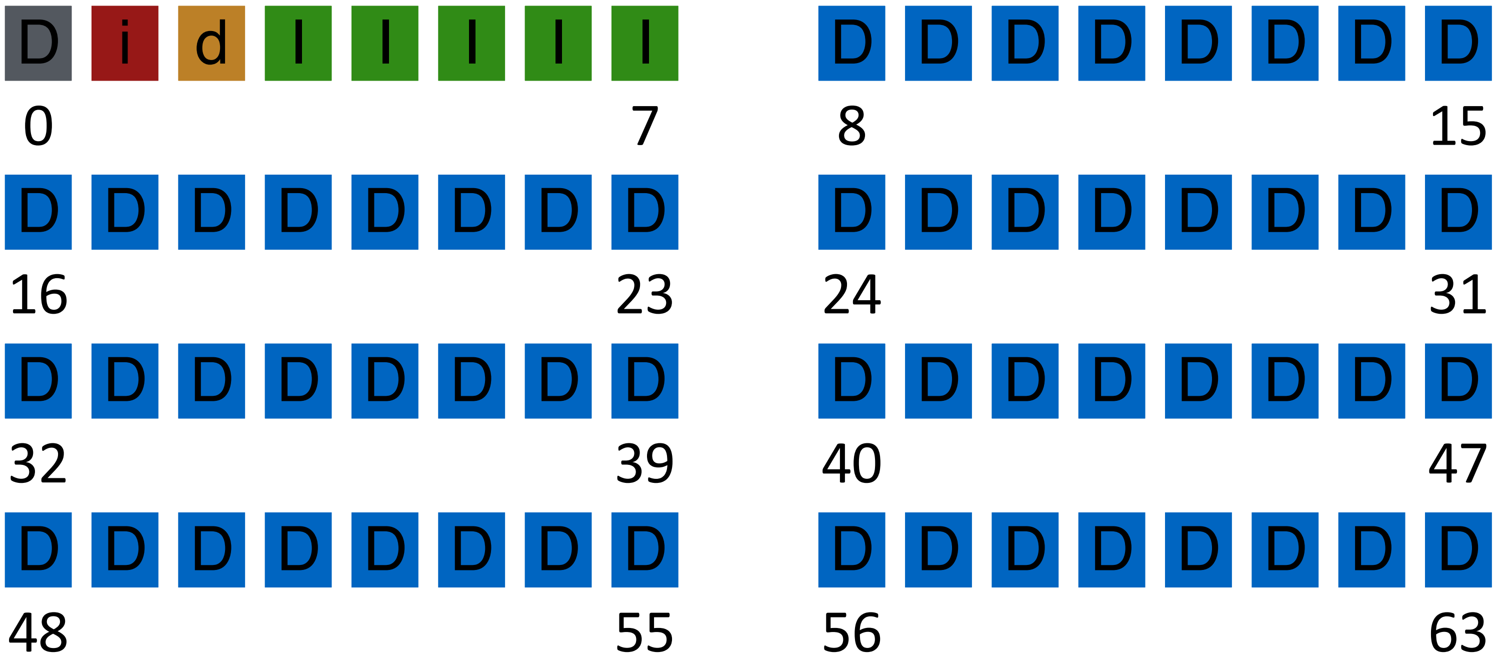
Bitmaps

Tradeoffs!

Bitmaps?


D D D I I I I I
0 7
D D D D D D D D
8 15
D D D D D D D D
16 23
D D D D D D D D
24 31
D D D D D D D D
32 39
D D D D D D D D
40 47
D D D D D D D D
48 55
D D D D D D D D
56 63

Opportunity for Inconsistency



(Need file system checking)

Superblock

Need to know basic FS configuration metadata, like:

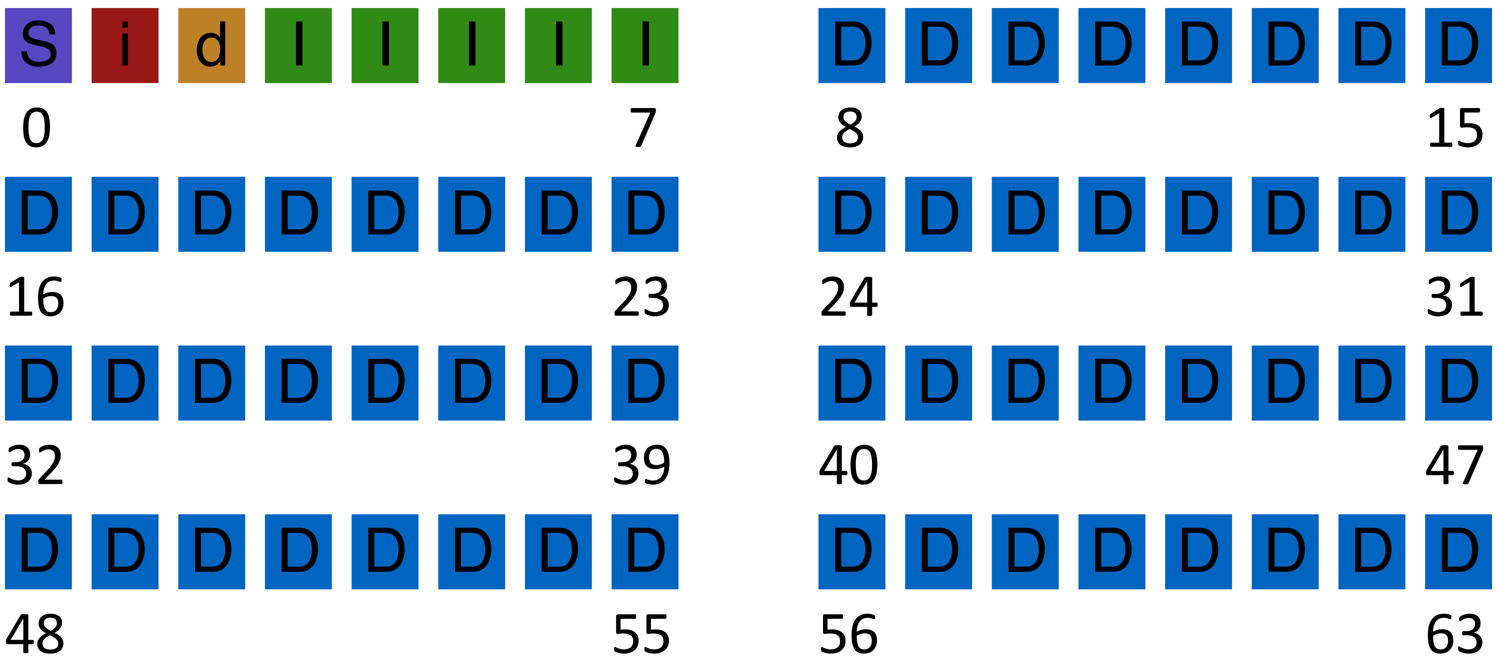
- block size
- # of inodes

Store this in superblock

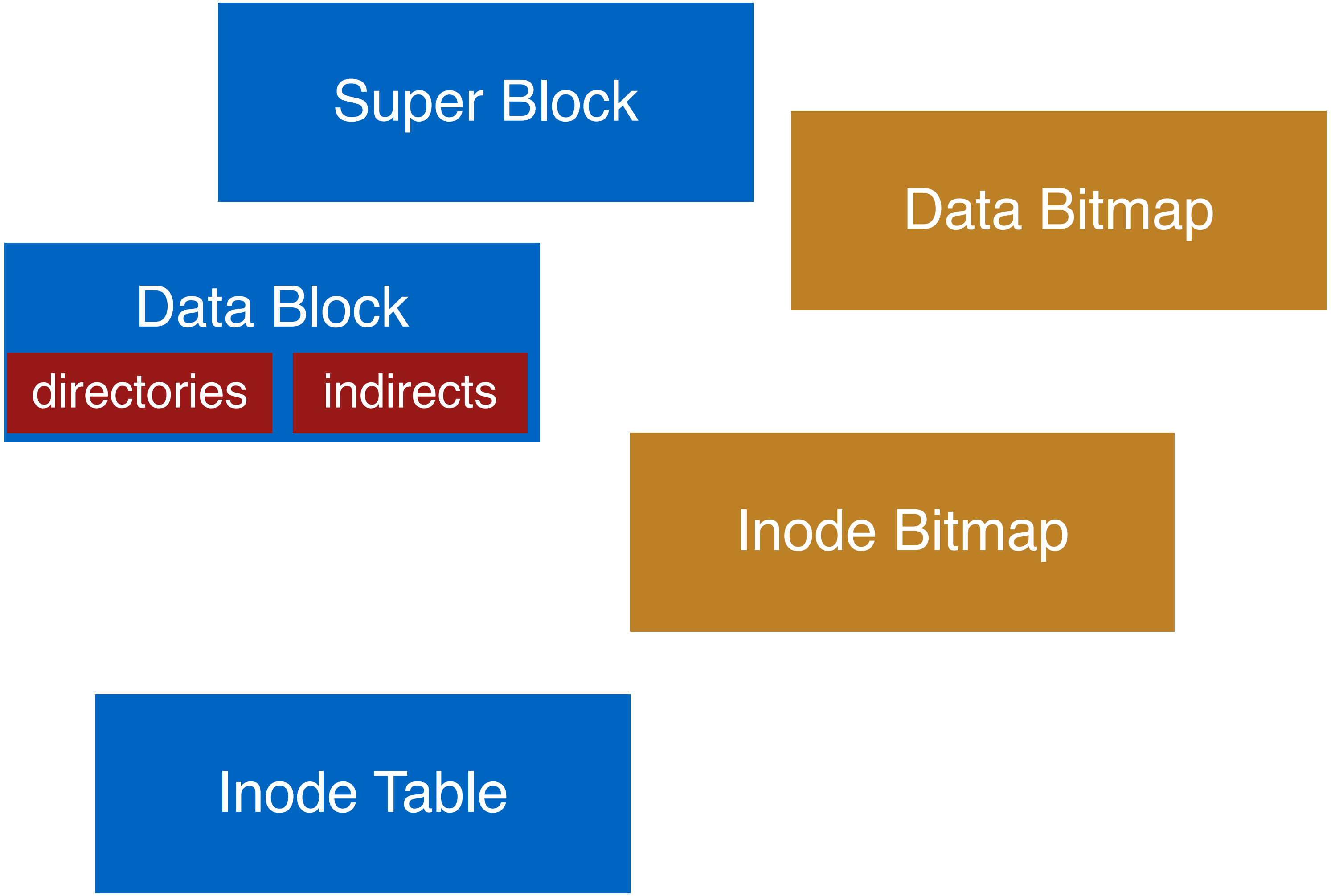
Superblock – Real FS (also FUSE)

```
Struct superblock{
    start address of inode bitmap
   start address of data block bitmap
   start address of inode region
   start address of data block region
   //Anything else that is required
}
```

Superblock



On-Disk Structures



Part 2 : Operations

- create file
- write
- open
- read
- close

How do they affect the data structures in the filesystem?

create /foo/bar

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

What needs to be read and written?

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			

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!

Efficiency

How can we avoid this excessive I/O for basic ops?

Cache for:

- reads
- write buffering

Write Buffering

Why does procrastination help?

Overwrites, deletes, scheduling

Shared structs (e.g., bitmaps+dirs) often overwritten.

We decide: how much to buffer, how long to buffer…
 - tradeoff durability vs. performance

How to allocate file data to disk blocks?

Allocation Strategies

Many different approaches

- Contiguous
- Extent-based
- Linked
- File-allocation Tables
- Indexed
- Multi-level Indexed

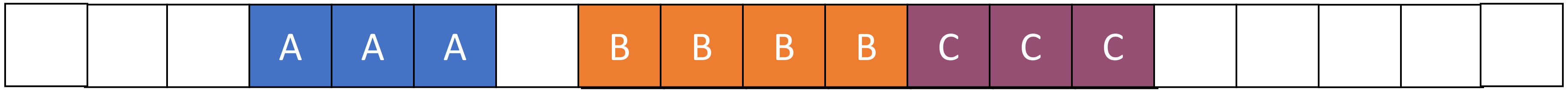
Questions

- Amount of fragmentation (internal and external)
  – freespace that can’t be used
- Ability to grow file over time?
- Performance of sequential accesses (contiguous layout)?
- Speed to find data blocks for random accesses?
- Wasted space for meta-data overhead (everything that isn’t data)?
  - Meta-data must be stored persistently too!

Contiguous Allocation

Allocate each file to contiguous sectors on disk

- Meta-data: Starting block and size of file
- OS allocates by finding sufficient free space
  - Must predict future size of file; Should space be reserved?
- Example: IBM OS/360



Fragmentation (internal and external)?

- Horrible external frag (needs periodic compaction)

Ability to grow file over time?

- May not be able to without moving

Seek cost for sequential accesses?

+ Excellent performance

Speed to calculate random accesses?

+ Simple calculation

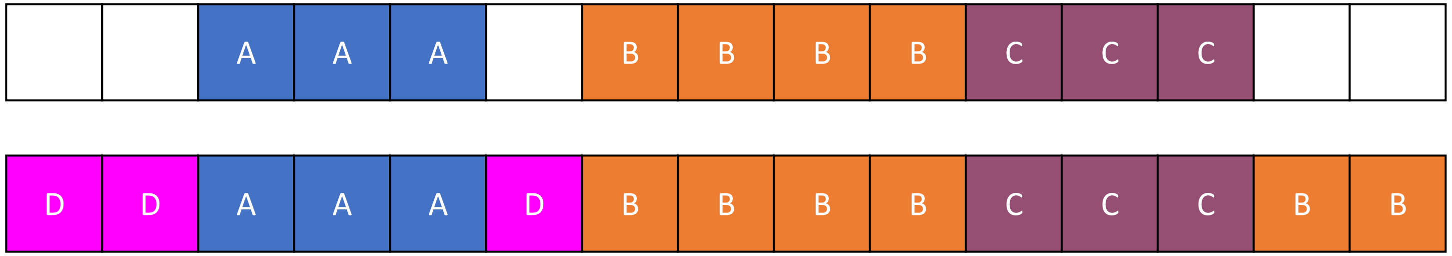
Wasted space for meta-data?

+ Little overhead for meta-data

Small # of Extents

Allocate multiple contiguous regions (extents) per file

- Meta-data: Small array (2-6) designating each extent
  Each entry: starting block and size



Fragmentation (internal and external)? - Helps external fragmentation

Ability to grow file over time? - Can grow (until run out of extents)

Seek cost for sequential accesses? + Still good performance

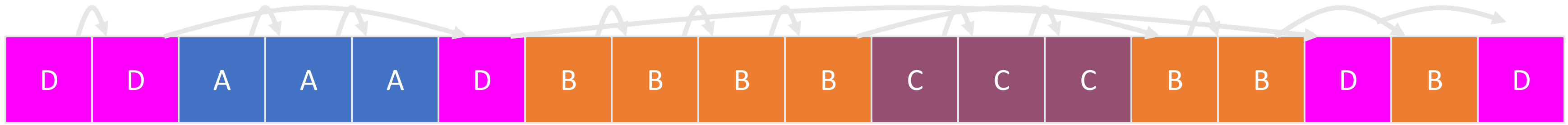
Speed to calculate random accesses? + Still simple calculation

Wasted space for meta-data? + Still small overhead for meta-data

Linked Allocation

Allocate linked-list of **fixed-sized** blocks (multiple sectors)

- Meta-data: Location of first block of file
  Each block also contains pointer to next block
- Examples: TOPS-10, Alto



Fragmentation (internal and external)? + No external frag (use any block); internal?

Ability to grow file over time? + Can grow easily

Seek cost for sequential accesses? +/- Depends on data layout

Speed to calculate random accesses? - Ridiculously poor

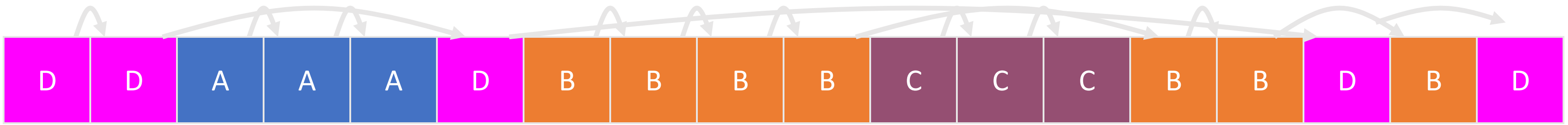
Wasted space for meta-data? - Waste pointer per block

Trade-off: Block size (does not need to equal sector size)

File-Allocation Table (FAT)

Variation of Linked allocation

- Keep linked-list information for all files in on-disk FAT table
- Meta-data: Location of first block of file
  - And, FAT table itself



Draw corresponding FAT Table?

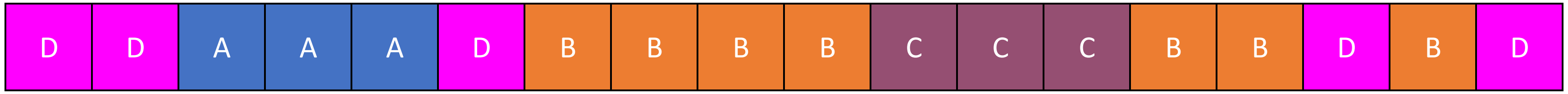
Comparison to Linked Allocation

- Same basic advantages and disadvantages
- Disadvantage: Read from two disk locations for every data read
- Optimization: Cache FAT in main memory
  - Advantage: Greatly improves random accesses
  - What portions should be cached? Scale with larger file systems?

Indexed Allocation

Allocate fixed-sized blocks for each file

- Meta-data: Fixed-sized array of block pointers
- Allocate space for ptrs at file creation time



Advantages

- No external fragmentation
- Files can be easily grown up to max file size
- Supports random access

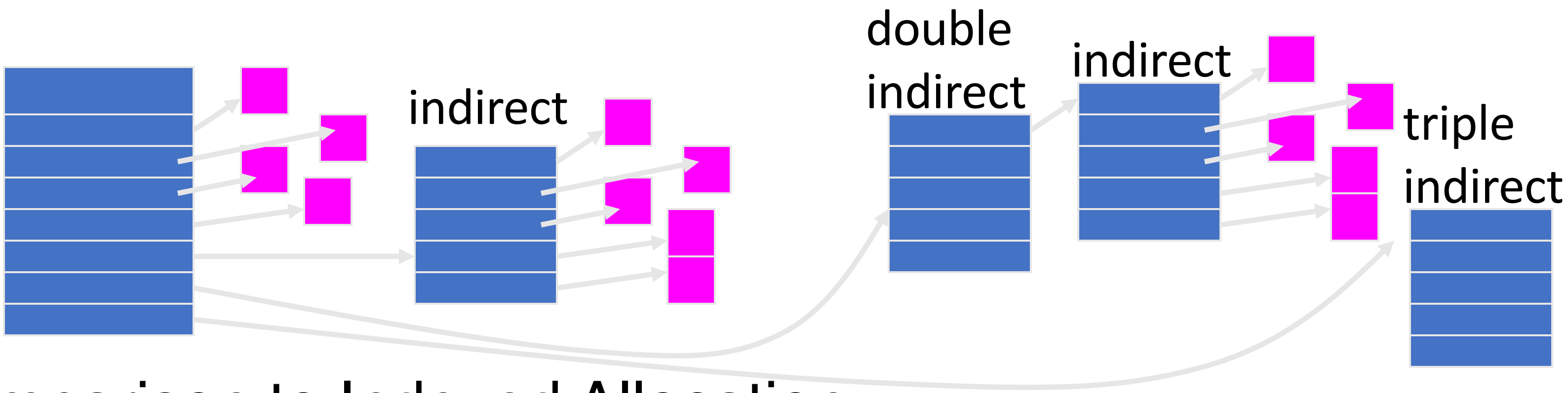
Disadvantages

- Large overhead for meta-data:
  - Wastes space for unneeded pointers (most files are small!)

Multi-Level Indexing

Variation of Indexed Allocation

- Dynamically allocate hierarchy of pointers to blocks as needed
- Meta-data: Small number of pointers allocated statically
    - Additional pointers to blocks of pointers
- Examples: UNIX FFS-based file systems, ext2, ext3



Comparison to Indexed Allocation

- Advantage: Does not waste space for unneeded pointers
    - Still fast access for small files
    - Can grow to what size??
- Disadvantage: Need to read indirect blocks of pointers to calculate addresses (extra disk read)
    - Keep indirect blocks cached in main memory

Flexible # of Extents

Modern file systems:

Dynamic multiple contiguous regions (extents) per file

- Organize extents into multi-level tree structure
  - Each leaf node: starting block and contiguous size
  - Minimizes meta-data overhead when have few extents
  - Allows growth beyond fixed number of extents

Fragmentation (internal and external)?	+ Both reasonable
Ability to grow file over time?	+ Can grow
Seek cost for sequential accesses?	+ Still good performance
Speed to calculate random accesses?	+/- Some calculations depending on size
Wasted space for meta-data?	+ Relatively small overhead

Assume Multi-Level Indexing

- Simple approach
- More complex file systems build from these basic data structures

Summary/Future

We’ve described a very simple FS.

- basic on-disk structures
- the basic ops

Future questions:

- how to handle **crashes**?

Summary

Using multiple types of name provides

- convenience
- efficiency

Mount and link features provide flexibility.

Special calls (fsync, rename) let developers communicate special requirements to file system