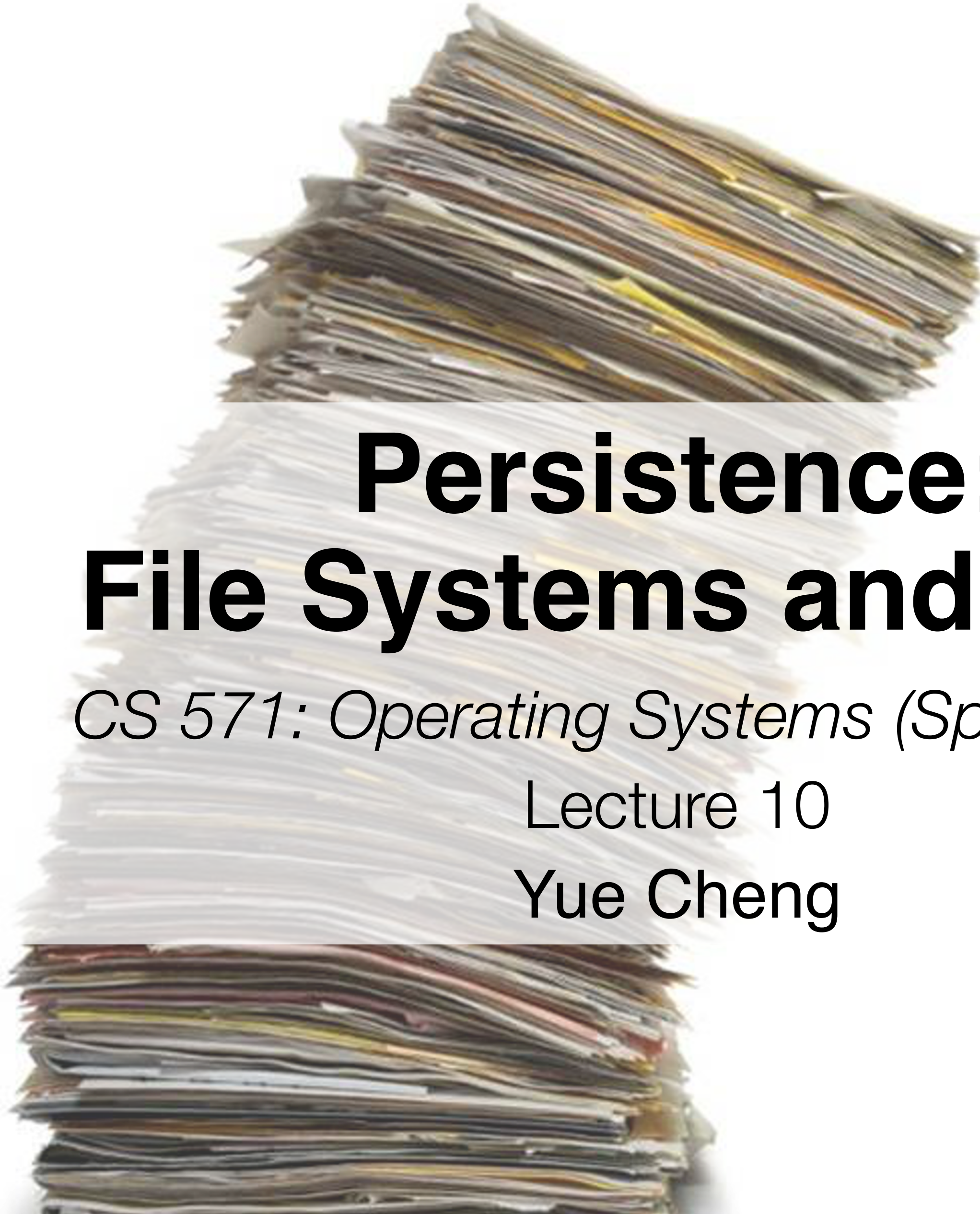

Persistence: File Systems and RAID

CS 571: Operating Systems (Spring 2021)

Lecture 10

Yue Cheng

File System Abstraction

What is a File?

- File: Array of bytes
  - Ranges of bytes can be read/written
- File system (FS) consists of many files
- Files need names so programs can choose the right one

File Names

- Three types of names (abstractions)
  - inode (low-level names)
  - path (human readable)
  - file descriptor (runtime state)

Inodes

- Each file has exactly one inode number
- Inodes are unique (at a given time) within a FS
- Numbers may be recycled after deletes

Inodes

- Each file has exactly one inode number

- Inodes are unique (at a given time) within a FS

- Numbers may be recycled after deletes

- Show inodes via `stat`
  - `$ stat <file or dir>`

'stat' Example

```
PROMPT>: stat test.dat
File: 'test.dat'  Size: 5     Blocks: 8     IO Block: 4096   regular
file
Device: 803h/2051d        Inode: 119341128   Links: 1
Access: (0664/-rw-rw-r--)  Uid: ( 1001/     yue)   Gid: ( 1001/     yue)
Context: unconfined_u:object_r:user_home_t:s0
Access: 2015-12-17 04:12:47.935716294 -0500
Modify: 2014-12-12 19:25:32.669625220 -0500
Change: 2014-12-12 19:25:32.669625220 -0500
Birth: -
```

Path (multiple directories)

- A directory is a file
  - Associated with an inode

- Contains a list of <user-readable name, low-level name> pairs

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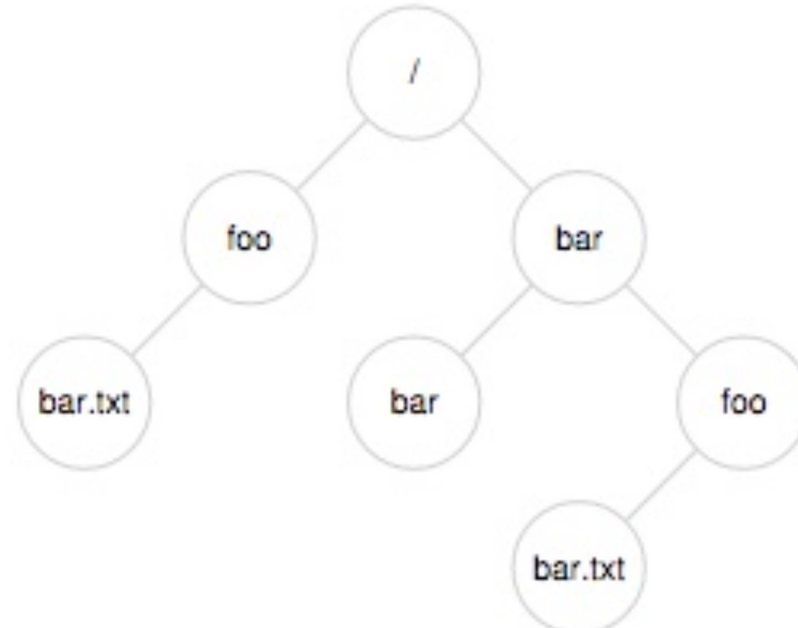

Path (multiple directories)

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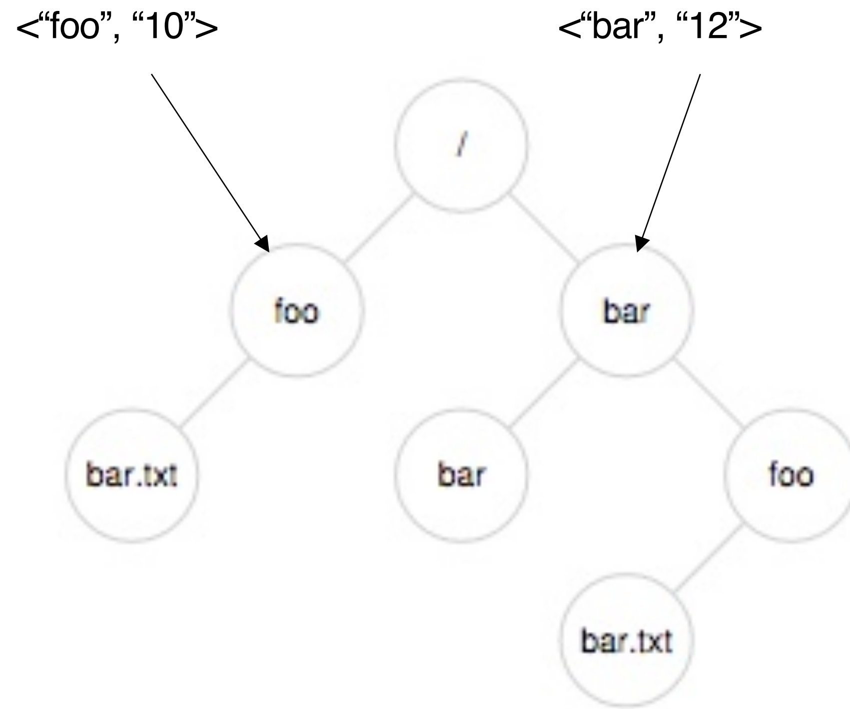
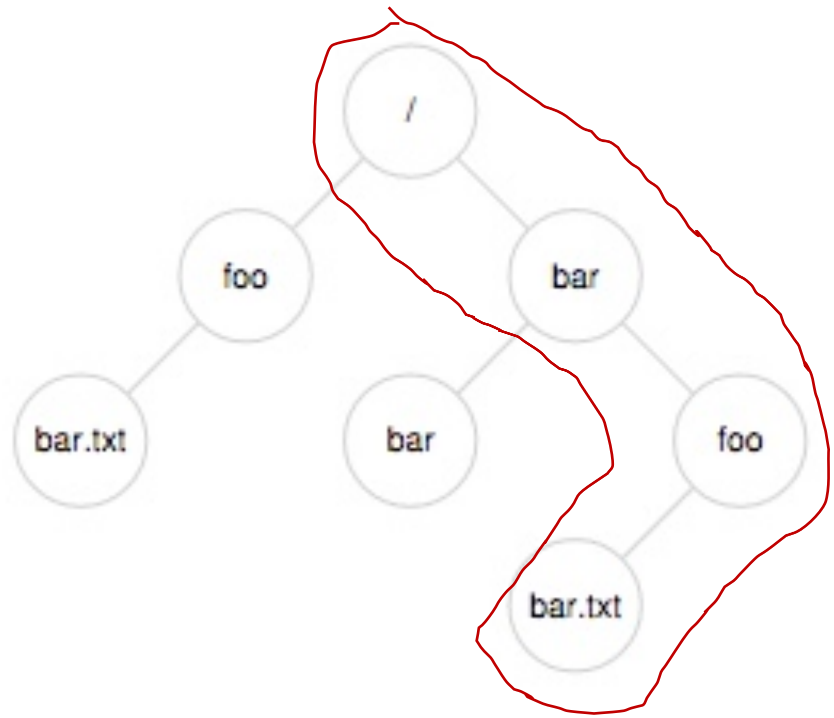


Path (multiple directories)

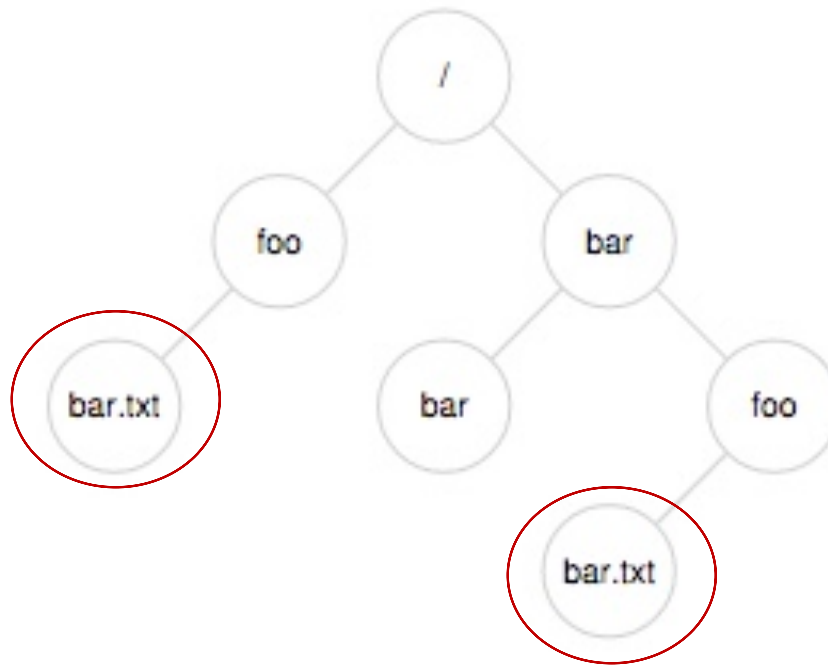
- A directory is a file
  - Associated with an inode
- Contains a list of <user-readable name, low-level name> pairs
- Directory tree: reads for getting final inode called traversal



[traverse /bar/foo/bar.txt]

File Naming

- Directories and files can have the same name as long as they are in different locations of the file-system tree



- .txt, .c, etc.
  - Naming convention
  - In UNIX-like OS, no enforcement for extension name

Special Directory Entries

```
prompt> ls -al
total 216
drwxr-xr-x   19 yue   staff    646 Nov 23 16:28 .
drwxr-xr-x+  40 yue   staff   1360 Nov 15 01:41 ..
-rw-r--r--@   1 yue   staff   1064 Aug 29 21:48 common.h
-rwxr-xr-x    1 yue   staff   9356 Aug 30 14:03 cpu
-rw-r--r--@   1 yue   staff    258 Aug 29 21:48 cpu.c
-rwxr-xr-x    1 yue   staff   9348 Sep  6 12:12 cpu_bound
-rw-r--r--    1 yue   staff    245 Sep  5 13:10 cpu_bound.c
...
```

File System Interfaces

Creating Files

- UNIX system call: open( )

```
int fd = open(char *path, int flag, mode_t mode);

-OR-

int fd = open(char *path, int flag);
```

File Descriptor (`fd`)

- `open()` returns a file descriptor (`fd`)
  - A `fd` is an integer
  - Private per process

- An opaque handle that gives caller the power to perform certain operations

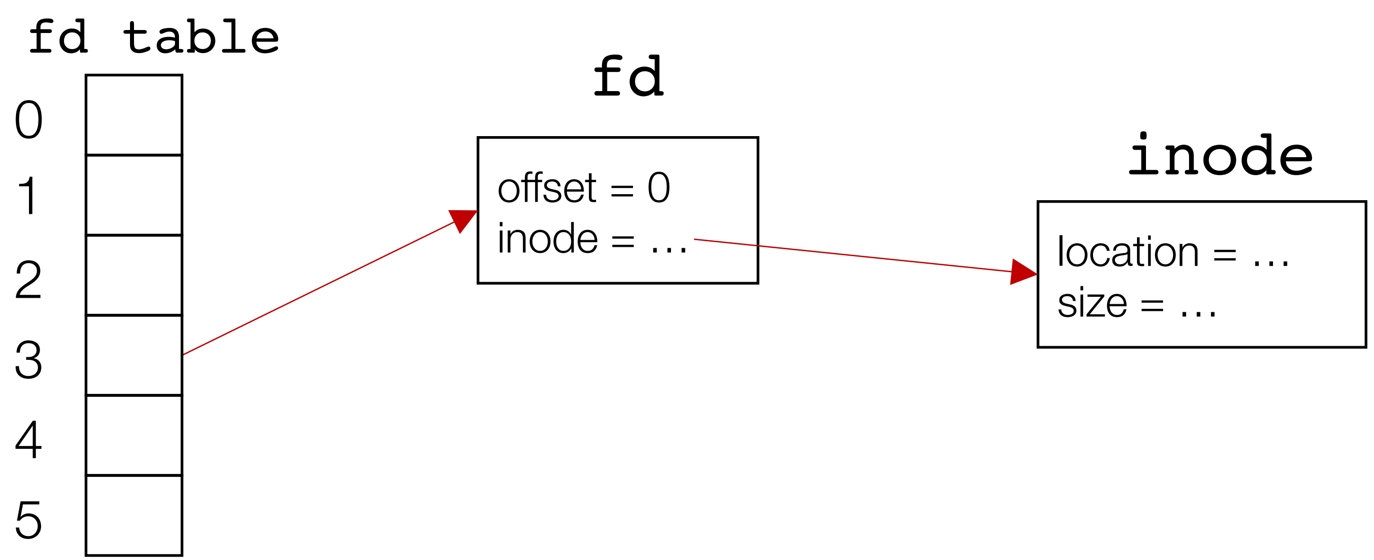
- Think of a `fd` as a pointer to an object of the file
  - By owning such an object, you can call other “methods” to access the file

open() Example

```
int fd1 = open("file.txt", O_CREAT);  // return 3
read(fd1, buf, 8);
int fd2 = open("file.txt", O_WRONLY); // return 4
int fd3 = dup(fd2);                   // return 5
```

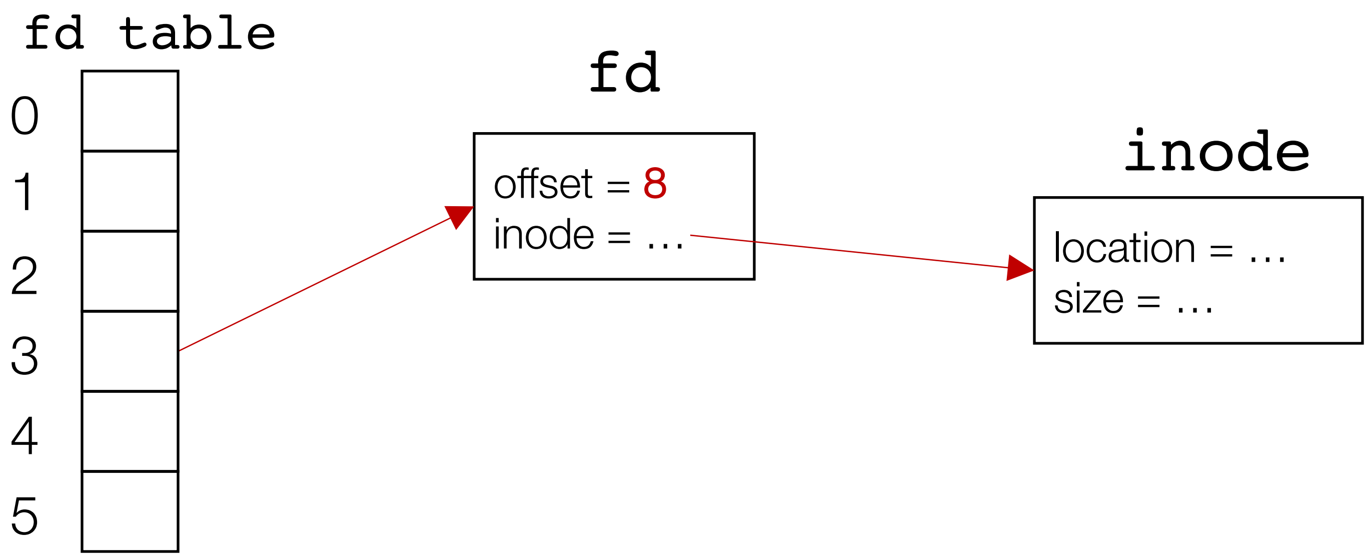
open( ) Example

```
int fd1 = open("file.txt", O_CREAT);  // return 3
```



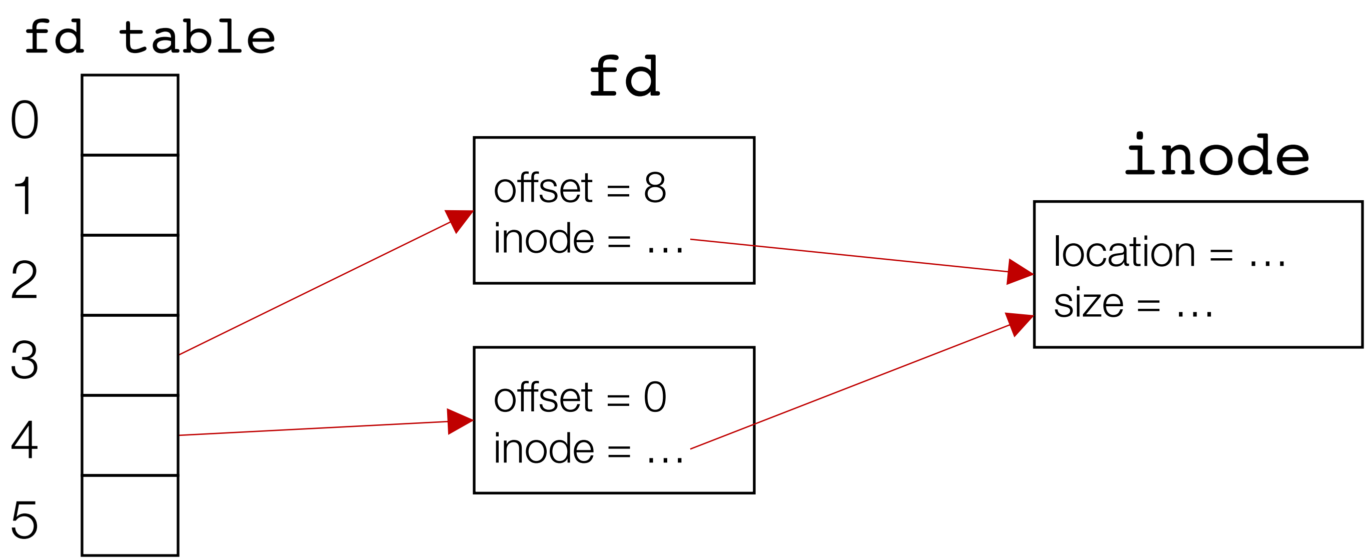
open() Example

```
int fd1 = open("file.txt", O_CREAT);  // return 3
read(fd1, buf, 8);
```



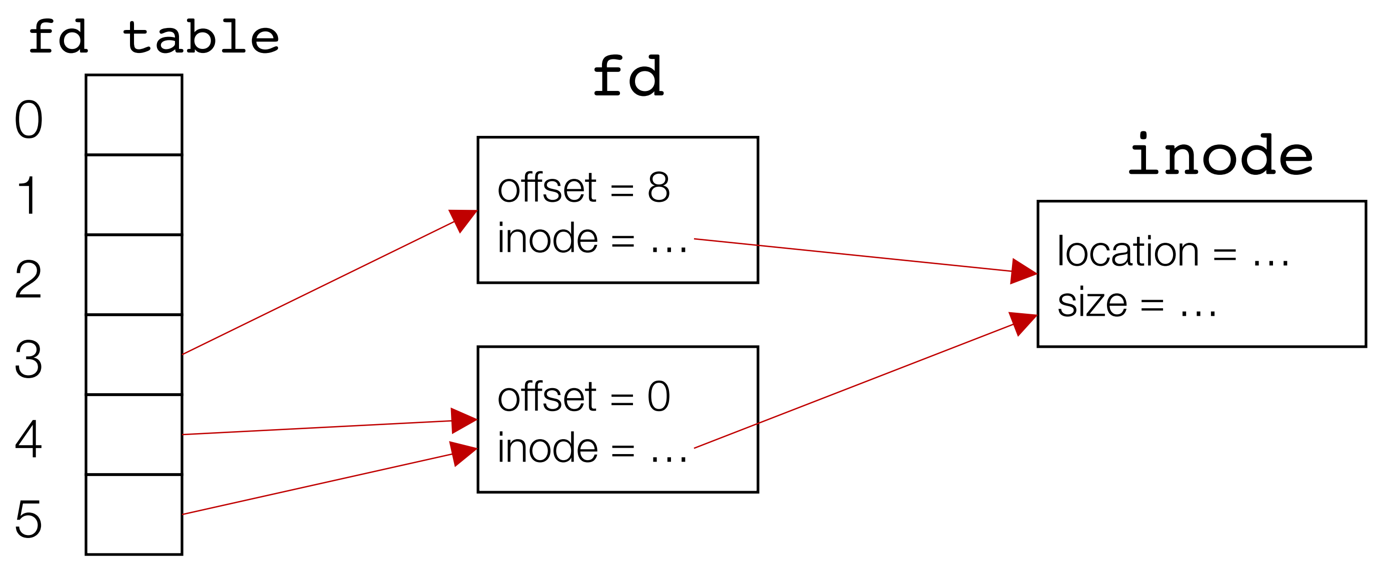
open( ) Example

```
int fd1 = open(“file.txt”, O_CREAT);  // return 3
read(fd1, buf, 8);
int fd2 = open(“file.txt”, O WRONLY); // return 4
```



open( ) Example

```
int fd1 = open("file.txt", O_CREAT);   // return 3
read(fd1, buf, 8);
int fd2 = open("file.txt", O_WRONLY); // return 4
int fd3 = dup(fd2);                    // return 5
```



UNIX File Read and Write APIs

```
int fd = open(char *path, int flag, mode_t mode);
-OR-
int fd = open(char *path, int flag);

ssize_t sz = read(int fd, void *buf, size_t count);

ssize_t sz = write(int fd, void *buf, size_t count);

int ret = close(int fd);
```

Reading and Writing Files

```
prompt> echo hello > file.txt
prompt> cat file.txt
hello
prompt>
```

Reading and Writing Files

```
prompt> strace cat file.txt
...
open("file.txt", O_RDONLY)              = 3
read(3, "hello\n", 65536)               = 6
write(1, "hello\n", 6)                  = 6
read(3, "", 65536)                      = 0
close(3)                                = 0
...
prompt>
```

Reading and Writing Files

Open the file with read only mode

```
prompt> strace cat file.txt
...
open("file.txt", O_RDONLY)          = 3
read(3, "hello\n", 65536)           = 6
write(1, "hello\n", 6)              = 6
read(3, "", 65536)                  = 0
close(3)                            = 0
...
prompt>
```

Reading and Writing Files

Open the file with read only mode

Read content from file

```
prompt> strace cat file.txt
...
open("file.txt", O_RDONLY)              = 3
read(3, "hello\n", 65536)               = 6
write(1, "hello\n", 6)                  = 6
read(3, "", 65536)                      = 0
close(3)                                = 0
...
prompt>
```

Reading and Writing Files

Open the file with read only mode

Read content from file

Write string to std output `fd` 1

```
prompt> strace cat file.txt
...
open("file.txt", O_RDONLY)            = 3
read(3, "hello\n", 65536)             = 6
write(1, "hello\n", 6)                = 6
read(3, "", 65536)                    = 0
close(3)                              = 0
...
prompt>
```

Reading and Writing Files

Open the file with read only mode

Read content from file

Write string to std output `fd` 1

`cat` tries to read more but reaches EOF

```
prompt> strace cat file.txt
...
open("file.txt", O_RDONLY)              = 3
read(3, "hello\n", 65536)               = 6
write(1, "hello\n", 6)                  = 6
read(3, "", 65536)                      = 0
close(3)                                = 0
...
prompt>
```

Reading and Writing Files

Open the file with read only mode

Read content from file

Write string to std output `fd` 1

`cat` tries to read more but reaches EOF

`cat` done with file ops and closes the file

```
prompt> strace cat file.txt
...
open("file.txt", O_RDONLY)          = 3
read(3, "hello\n", 65536)           = 6
write(1, "hello\n", 6)              = 6
read(3, "", 65536)                  = 0
close(3)                            = 0
...
prompt>
```

Non-Sequential File Operations

```
off_t offset = lseek(int fd, off_t offset, int whence);
```

Non-Sequential File Operations

```
off_t offset = lseek(int fd, off_t offset, int whence);
```

whence:

- If `whence` is `SEEK_SET`, the offset is set to `offset` bytes
- If `whence` is `SEEK_CUR`, the offset is set to its current location plus `offset` bytes
- If `whence` is `SEEK_END`, the offset is set to the size of the file plus `offset` bytes

Non-Sequential File Operations

```
off_t offset = lseek(int fd, off_t offset, int whence);
```

whence:

- If `whence` is `SEEK_SET`, the offset is set to `offset` bytes
- If `whence` is `SEEK_CUR`, the offset is set to its current location plus `offset` bytes
- If `whence` is `SEEK_END`, the offset is set to the size of the file plus `offset` bytes

Note: Calling `lseek()` does not perform a disk seek!

Writing Immediately with `fsync()`

```
int fd = fsync(int fd);
```

- `fsync(fd)` forces buffers to flush to disk, and (usually) tells the disk to flush its write cache too
  - To make the data durable and persistent
- Write buffering improves performance

Renaming Files

```
prompt> mv file.txt new_name.txt
```

Renaming Files

```
prompt> strace mv file.txt new_name.txt
...
rename("file.txt", "new_name.txt")   = 0
...
prompt>
```

Renaming Files

System call `rename()` atomically renames a file

```
prompt> strace mv file.txt new_name.txt
...
rename("file.txt", "new_name.txt")   = 0
...
prompt>
```

File Renaming Example

```
prompt> vim file.txt
```

```
int fd = open(".file.txt.swp",O_WRONLY|O_CREAT|O_TRUNC,S_IRUSR|S_IWUSR);
```

Using `vim` to edit a file and then save it

File Renaming Example

```
prompt> vim file.txt
… vim editing session …
```

```
int fd = open(".file.txt.swp",O_WRONLY|O_CREAT|O_TRUNC,S_IRUSR|S_IWUSR);
write(fd, buffer, size); // write out new version of file (editing…)
```

Using `vim` to edit a file and then save it

File Renaming Example

```
prompt> vim file.txt
… vim editing session …
prompt>
```

:wq

```
int fd = open(".file.txt.swp",O_WRONLY|O_CREAT|O_TRUNC,S_IRUSR|S_IWUSR);
write(fd, buffer, size); // write out new version of file
fsync(fd);               // make data durable
close(fd);               // close tmp file
rename(".file.txt.swp", "file.txt");// change name and replacing old file
```

Using `vim` to edit a file and then save it

Deleting Files

```
prompt> rm file.txt
```

Deleting Files

```
prompt> strace rm file.txt
...
unlink("file.txt")              = 0
...
prompt>
```

Deleting Files

System call `unlink()` is called to delete a file

```
prompt> strace rm file.txt
...
unlink("file.txt")                = 0
...
prompt>
```

Deleting Files

System call `unlink()` is called to delete a file

```
prompt> strace rm file.txt
...
unlink("file.txt")                = 0
...
prompt>
```

Directories are deleted when `unlink()` is called

Q: File descriptors are deleted when ???

Demo: Hard Links vs. Symbolic Links

File System Implementation

File System Implementation

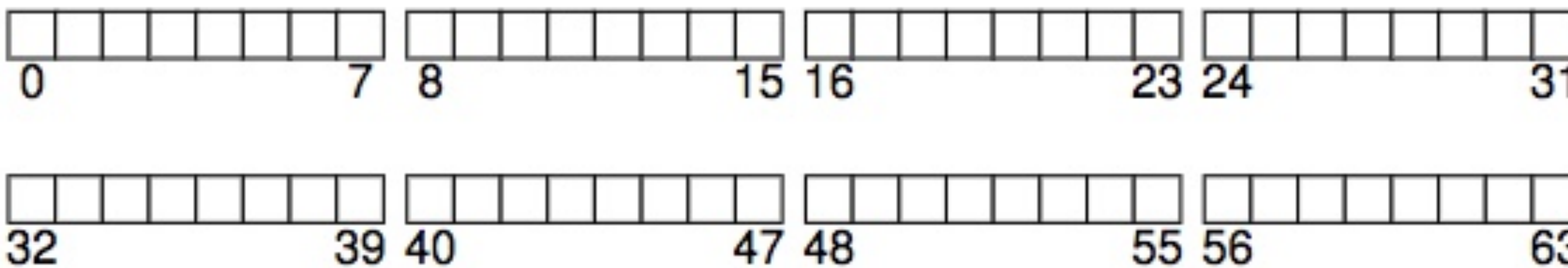
- On-disk structures
  - How do we represent files and directories?
- File system operations (internally)
  - How on-disk structures get touched when performing FS operations
- File system locality & data layout policies
  - How data layout impacts locality for on-disk FS?

On-Disk Structures

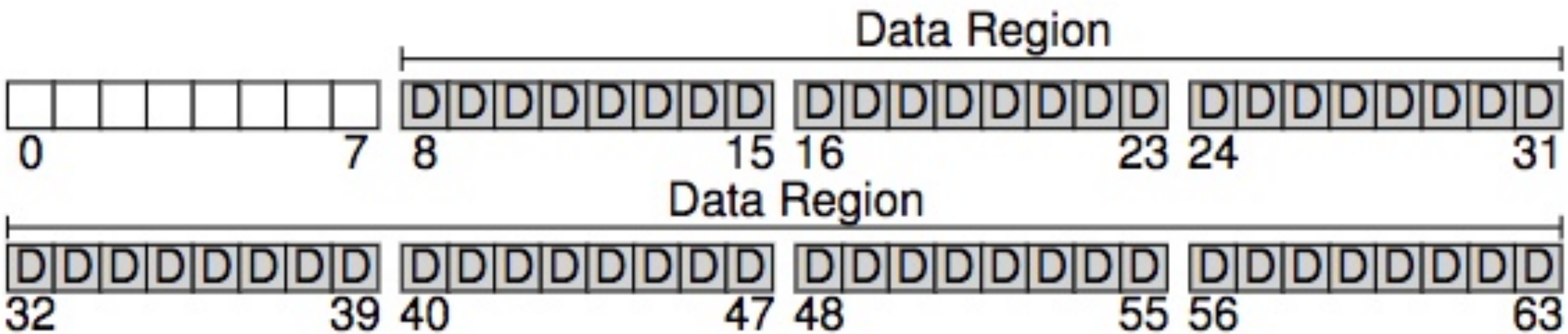
On-Disk Structures

- Common file system structures
  - Data block
  - inode table
  - Directories
  - Data bitmap
  - inode bitmap
  - Superblock

On-Disk Structure: Empty Disk



On-Disk Structure: Data Blocks



On-Disk Structures

- Common file system structures
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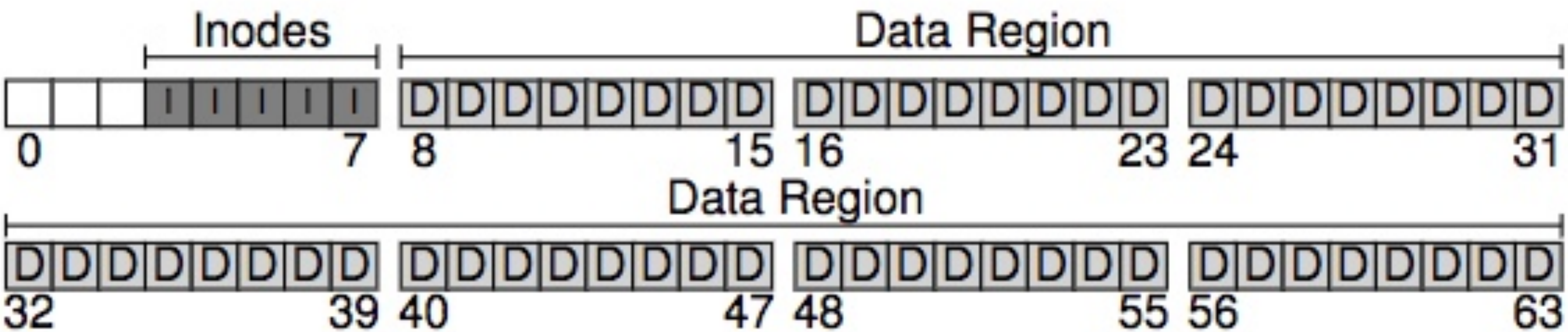
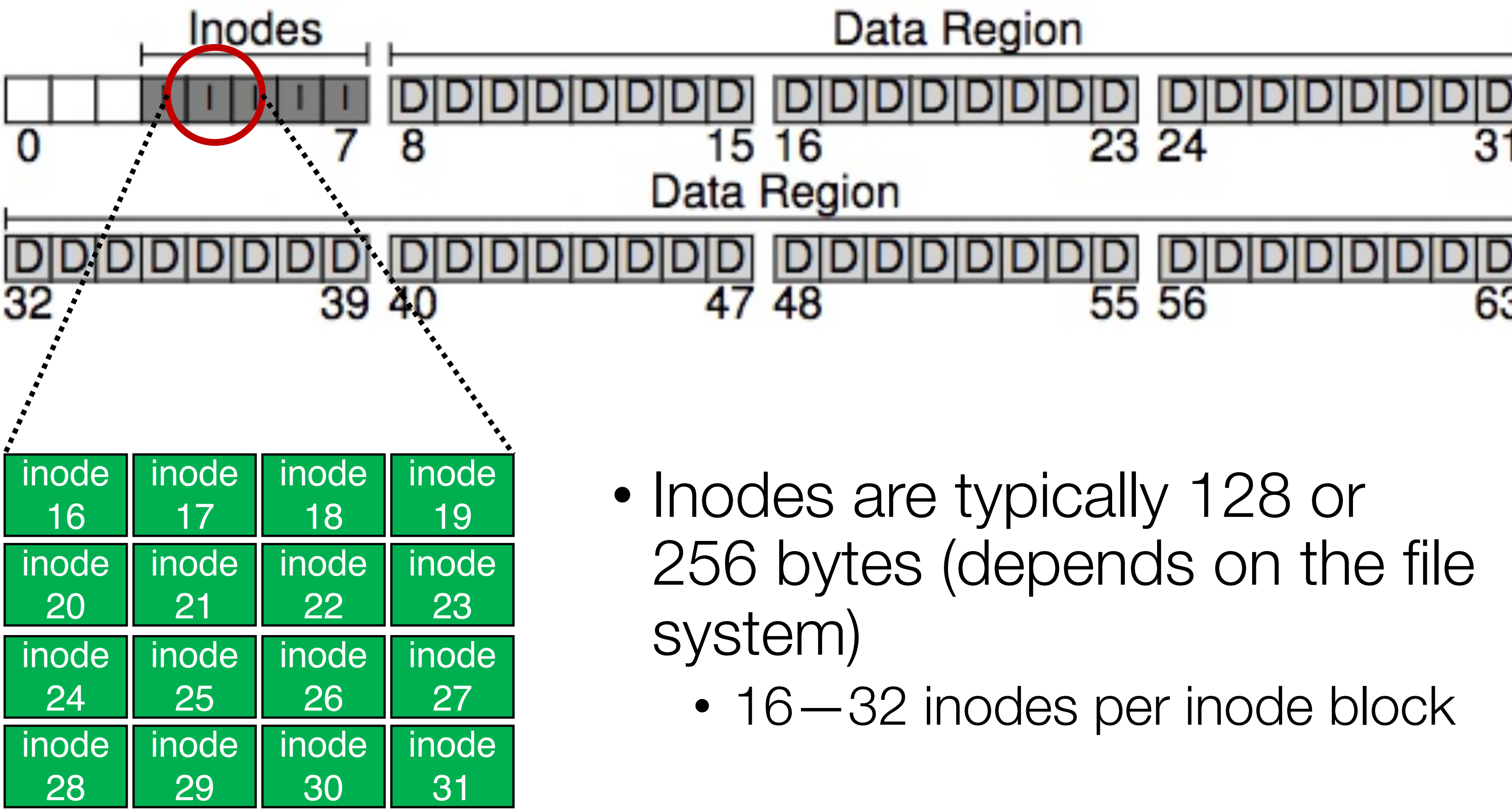
On-Disk Structure: Inodes



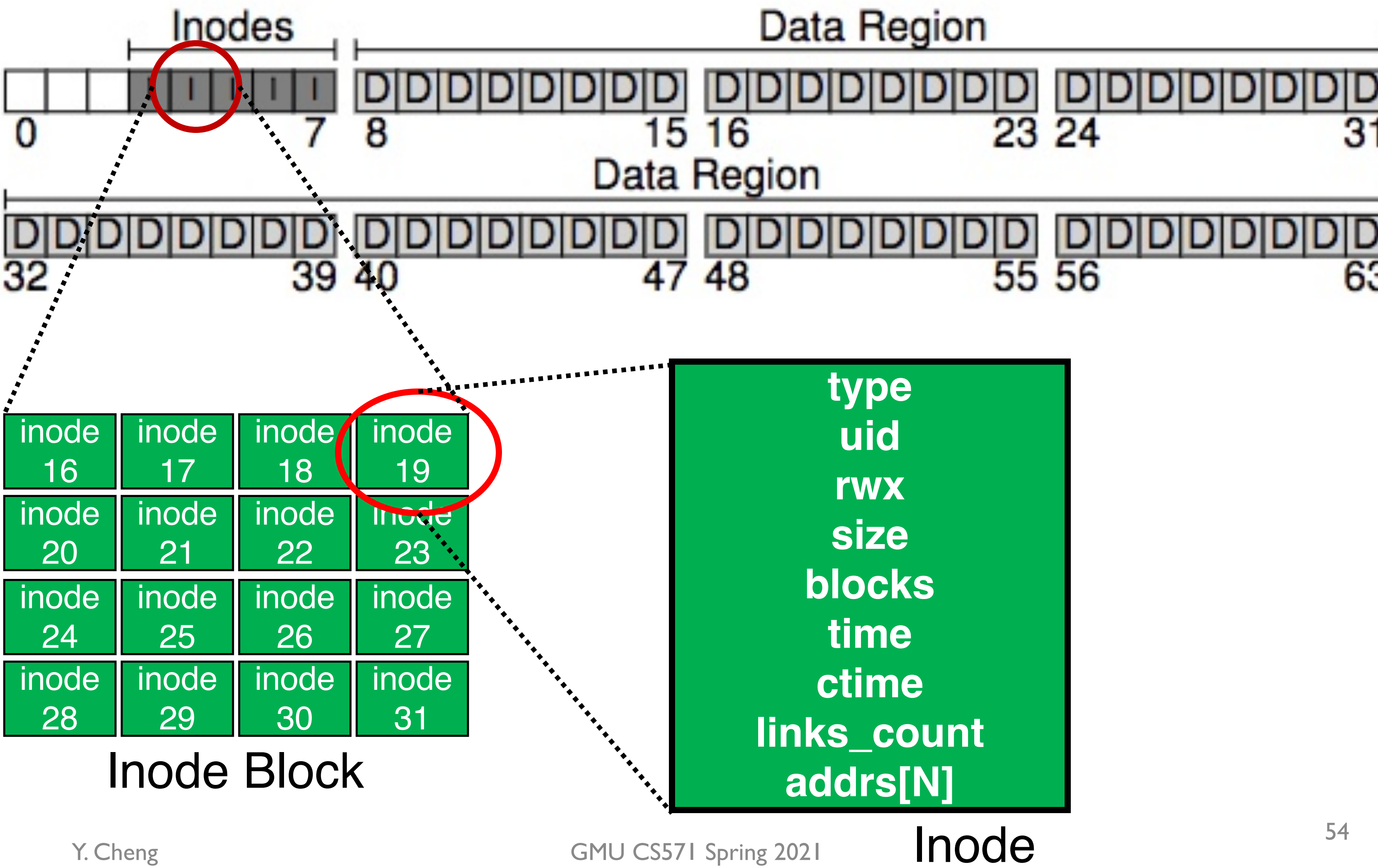
On-Disk Structure: Inodes



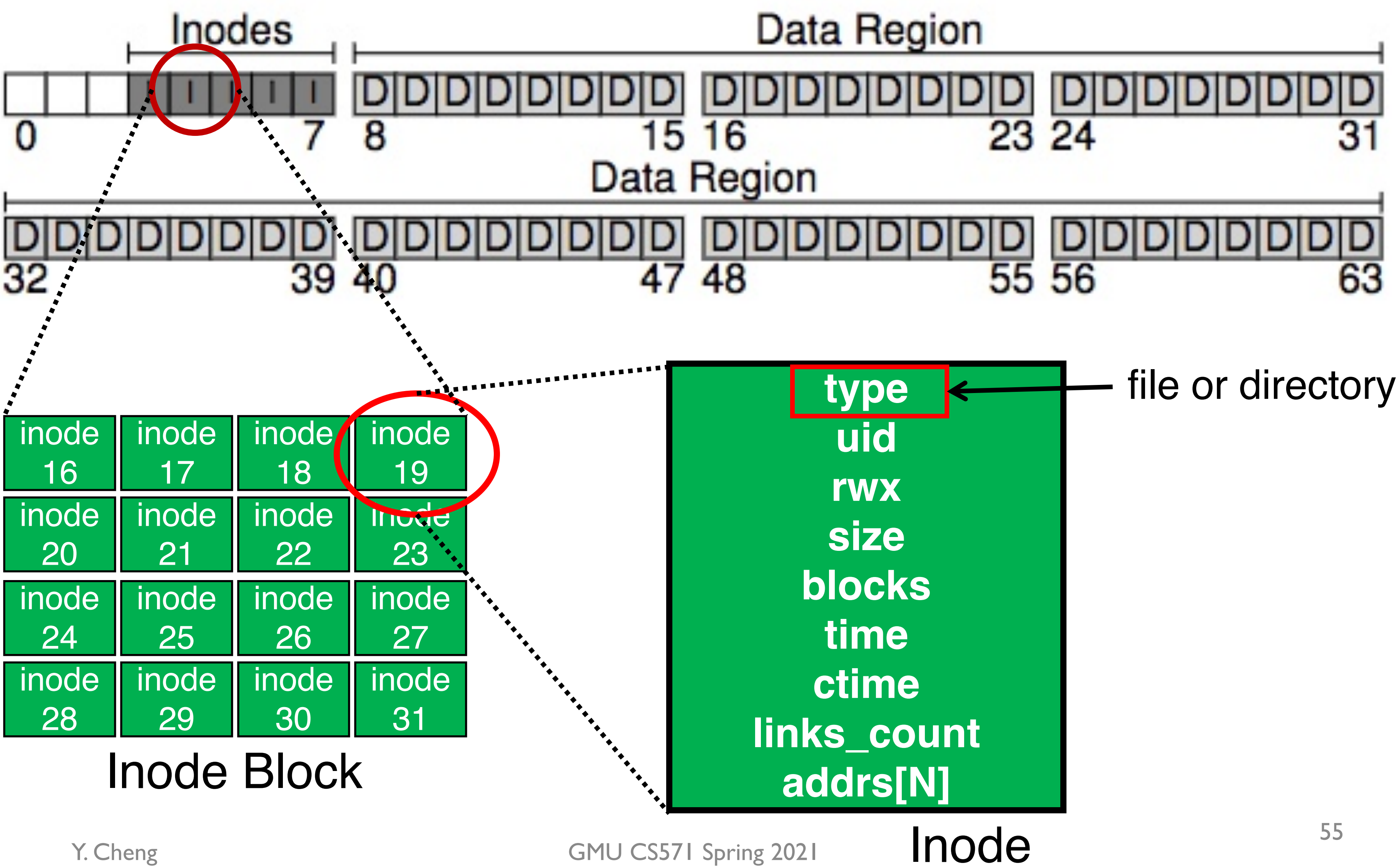
Inode Block

- Inodes are typically 128 or 256 bytes (depends on the file system)
  - 16—32 inodes per inode block

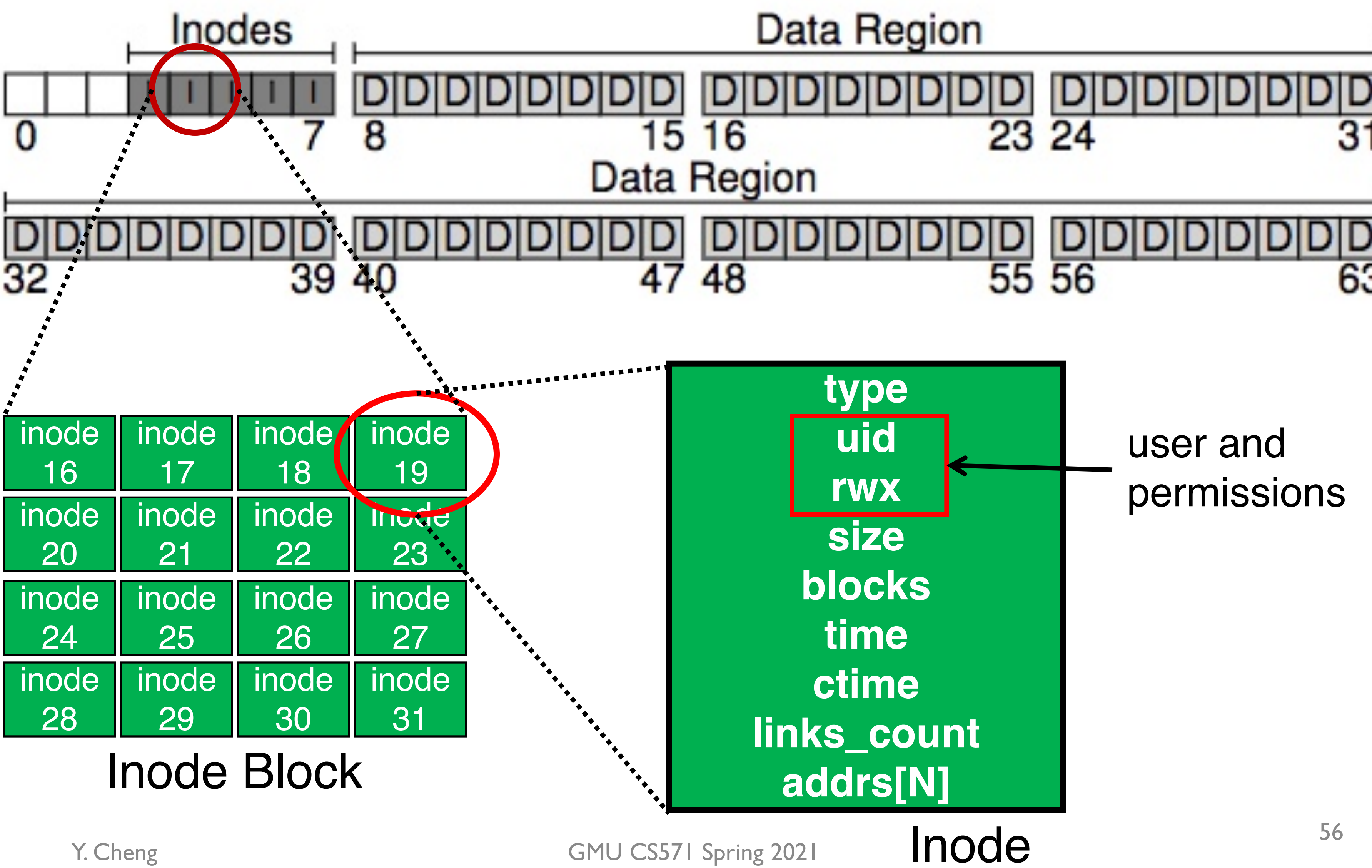
On-Disk Structure: Inodes



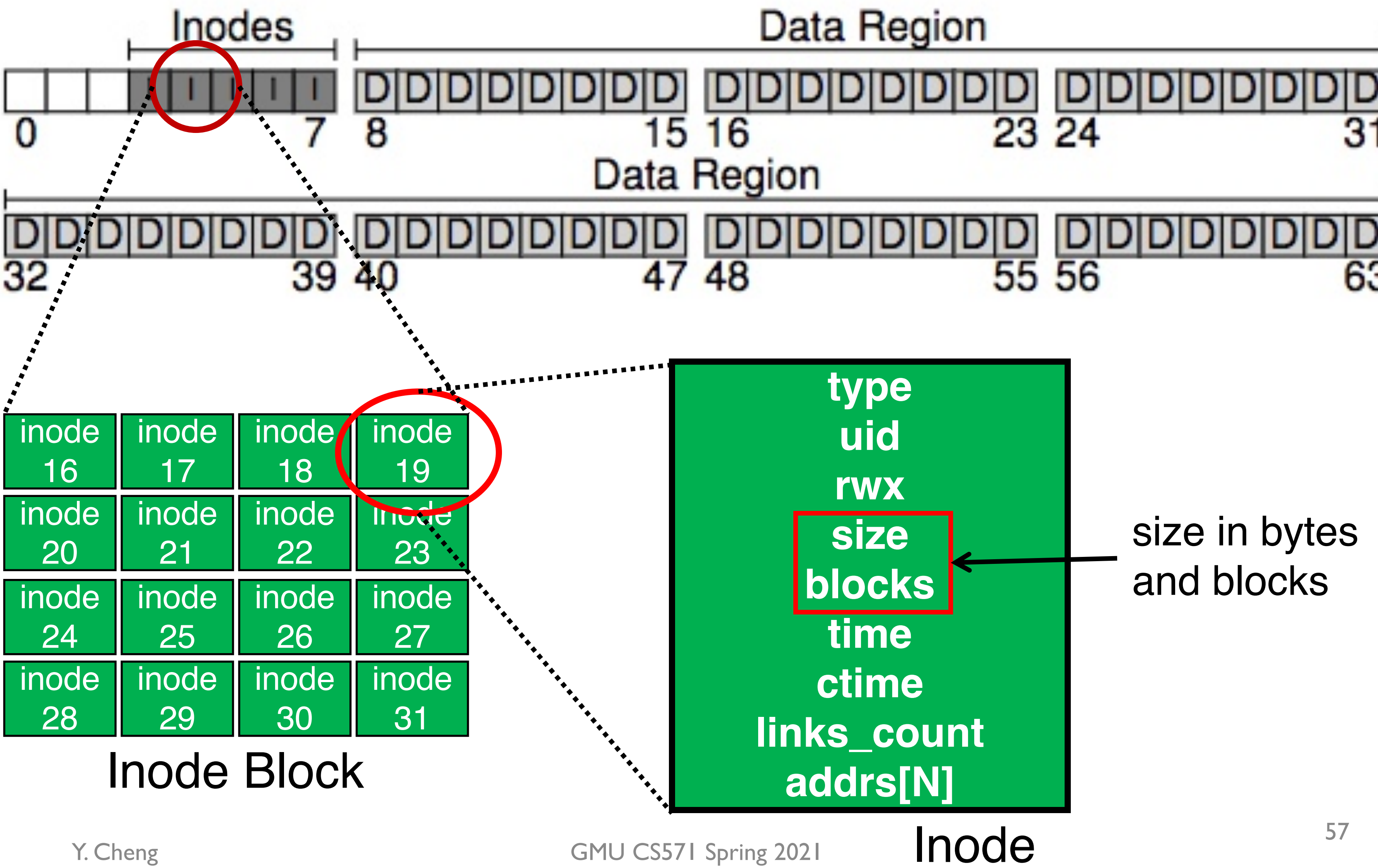
On-Disk Structure: Inodes



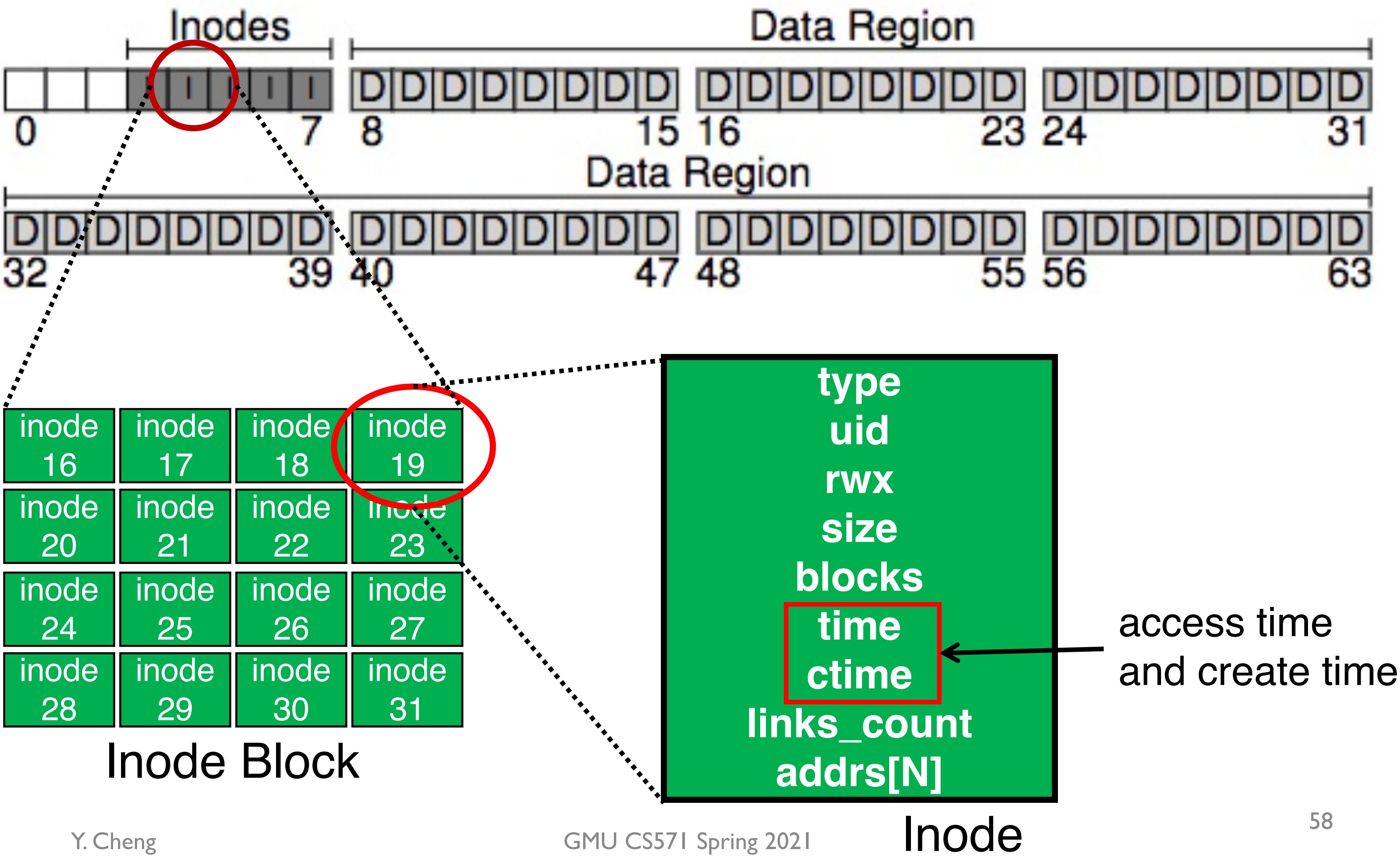
On-Disk Structure: Inodes



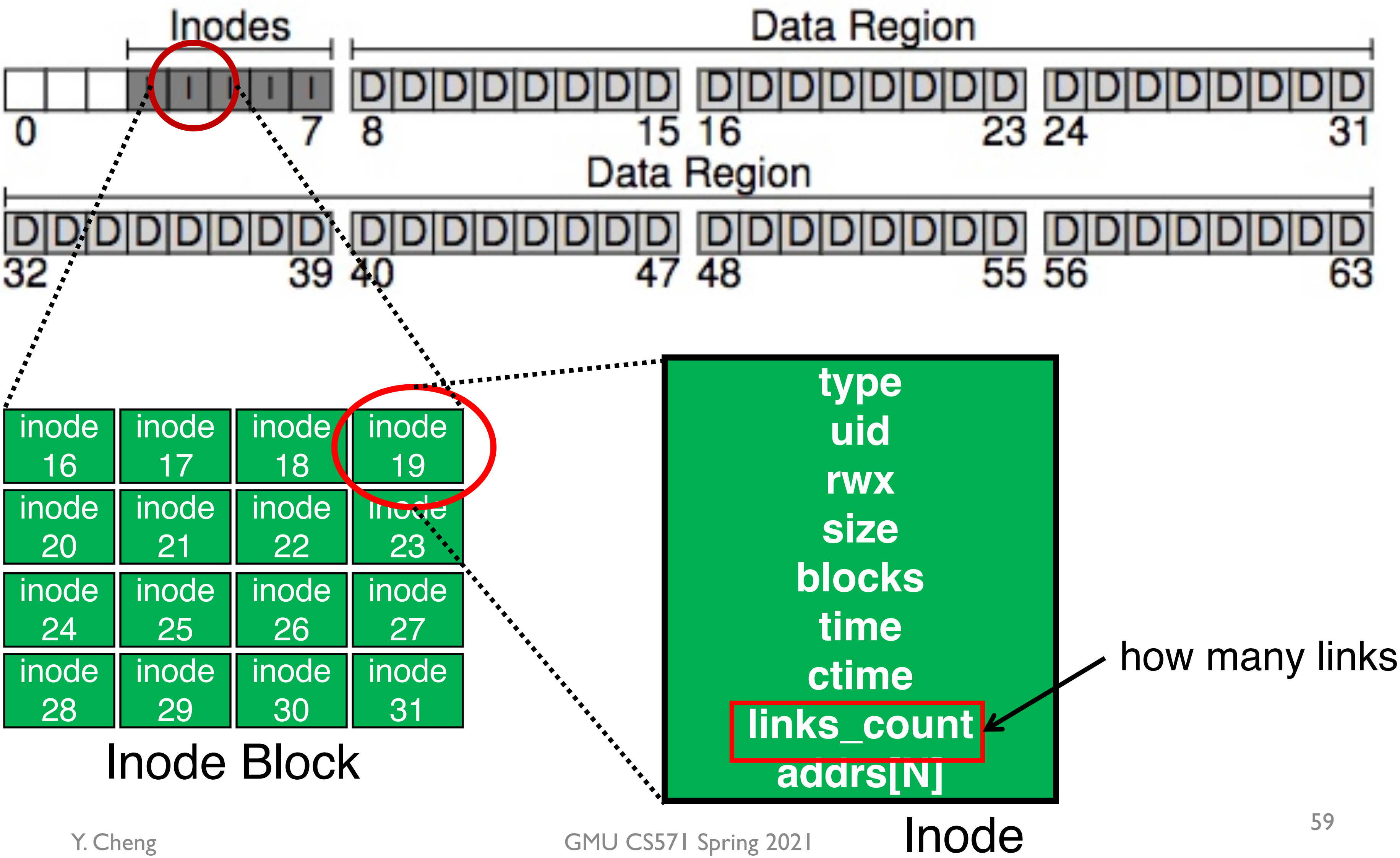
On-Disk Structure: Inodes



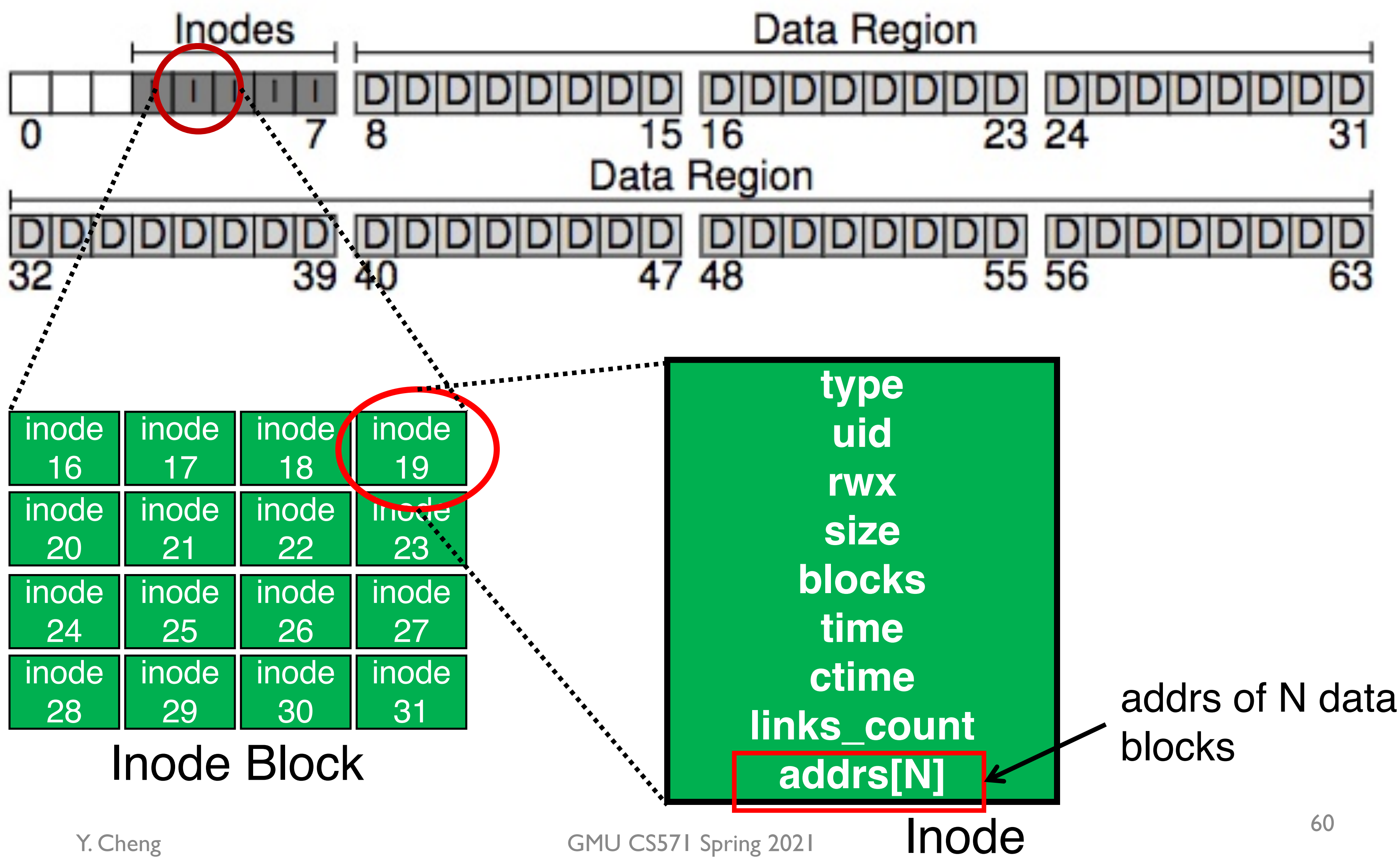
On-Disk Structure: Inodes



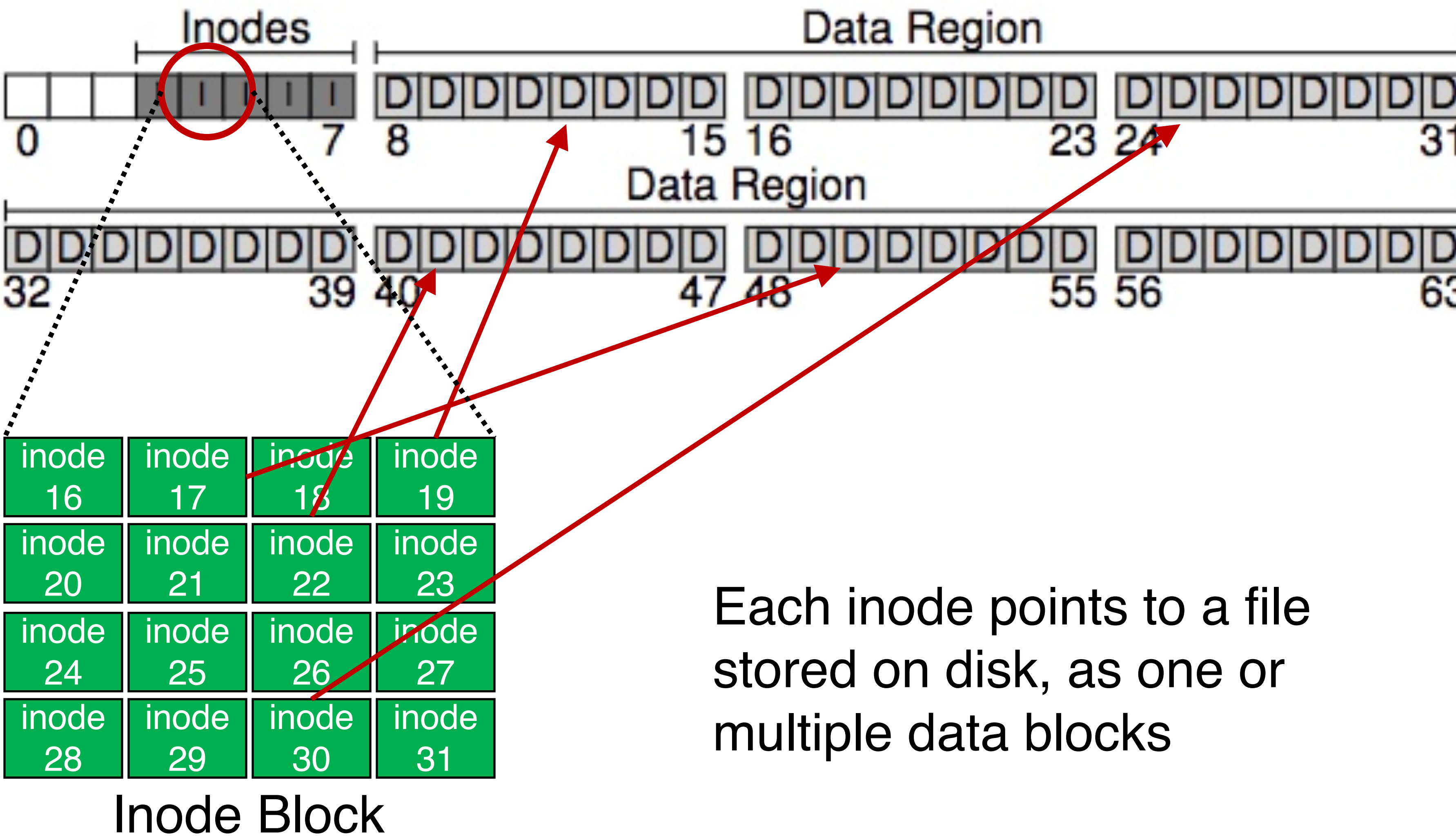
On-Disk Structure: Inodes



On-Disk Structure: Inodes



On-Disk Structure: Inodes



Each inode points to a file stored on disk, as one or multiple data blocks

On-Disk Structures

- Common file system structures
  - Data block
  - Inode table
  - Directories
  - Data bitmap
  - Inode bitmap
  - Superblock

On-Disk Structure: Directories

- Common directory design: just store directory entries in files
  - Different file systems vary

- Various data structures (formats) could be used
  - Lists
  - B-trees

On-Disk Structures

- Common file system structures
  - Data block
  - inode table
  - Directories
  - Data bitmap
  - inode bitmap
  - Superblock

Allocation

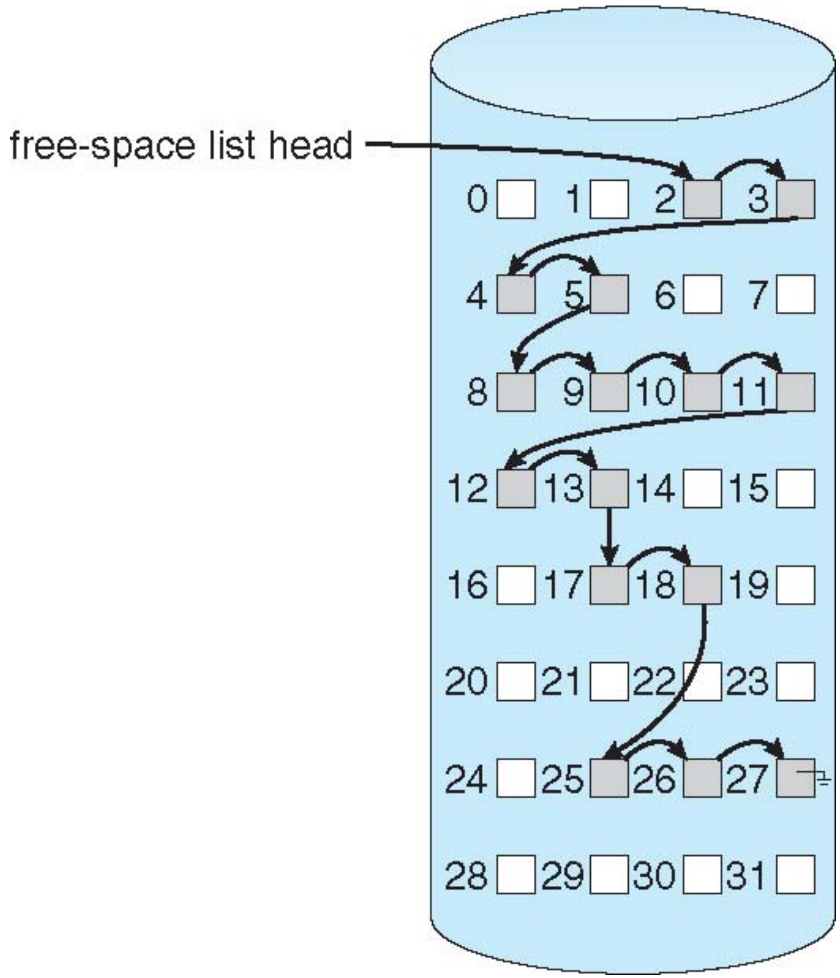
- How does file system find free data blocks or free inodes?

Allocation

- How does file system find free data blocks or free inodes?
  - Free list
  - Bitmaps

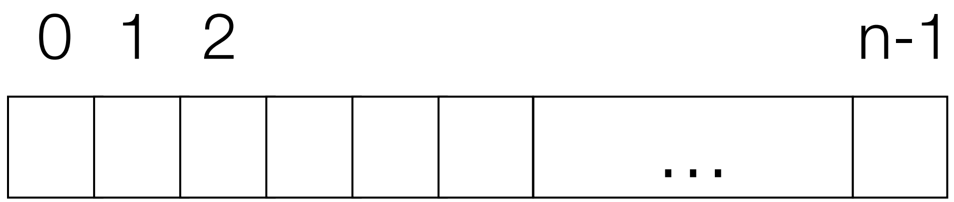
- What are the tradeoffs?

Free List


free-space list head
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31

Bitmap

Each bit of the bitmap is used to indicate whether the corresponding object/block is free (0) or in-use (1)



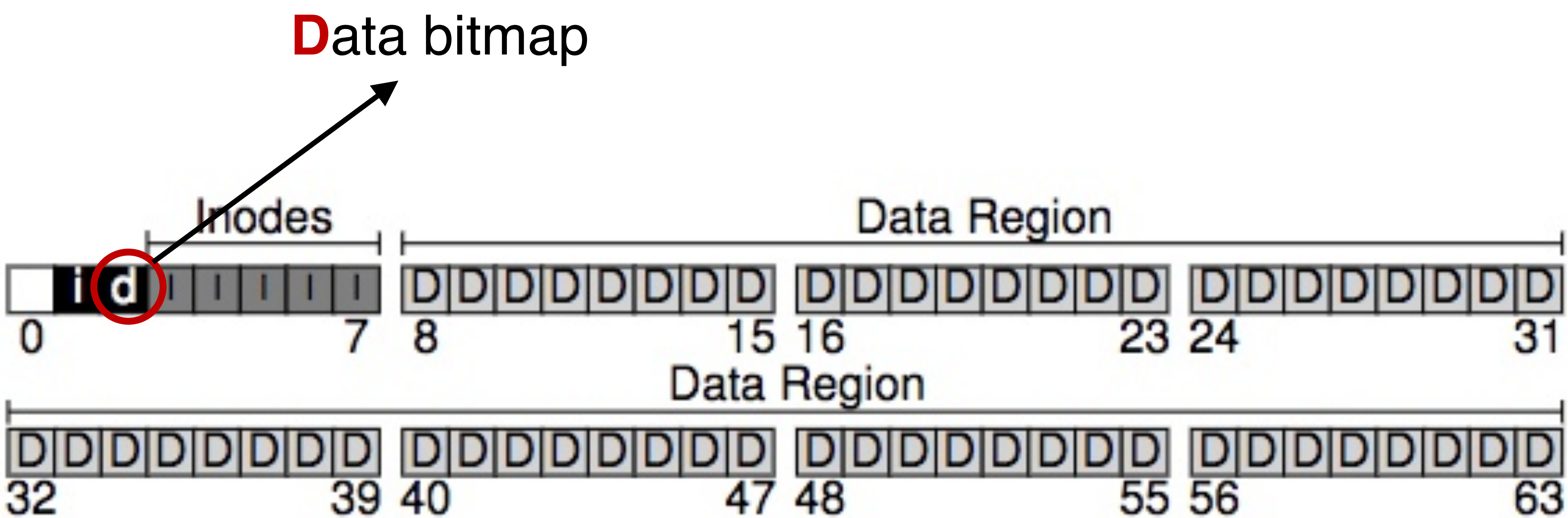
$$\text{bit}[i] = \begin{cases} 1 \Rightarrow \text{object}[i] \text{ in use} \\ 0 \Rightarrow \text{object}[i] \text{ free} \end{cases}$$

Allocation

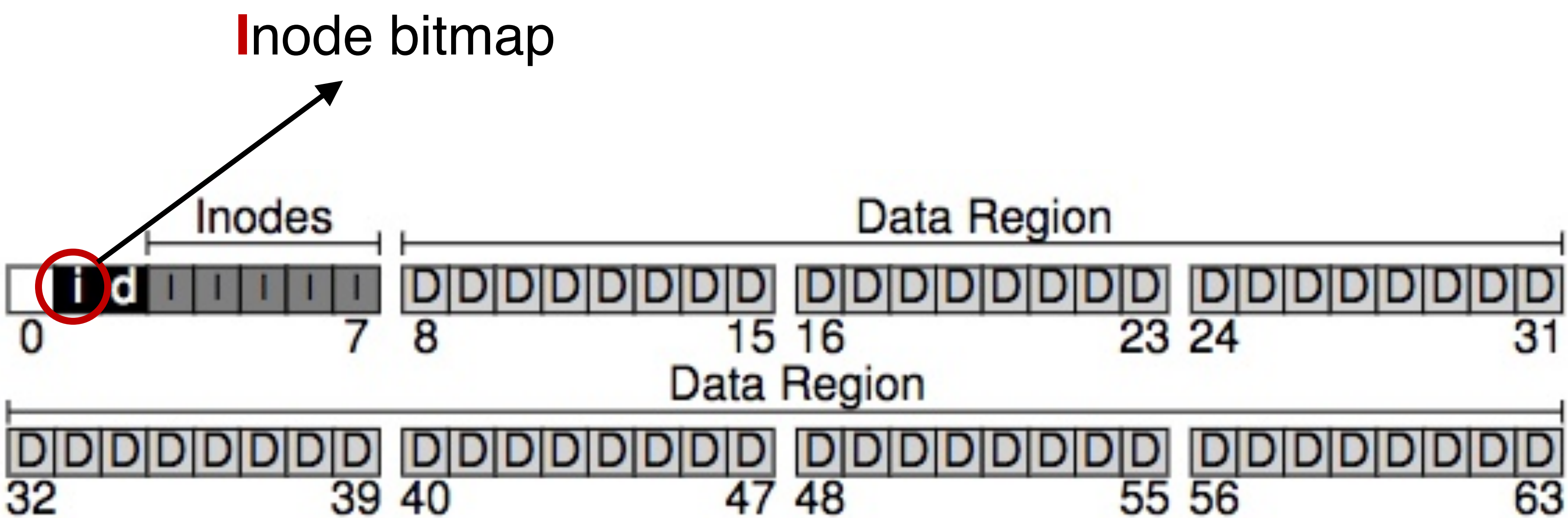
- How does file system find free data blocks or free inodes?
  - Free list
  - Bitmaps

- What are the tradeoffs?
  - Free list: Cannot get contiguous space easily
  - Bitmap: Easy to allocate contiguous space for files

On-Disk Structure: Data Bitmaps



On-Disk Structure: Inode Bitmaps



On-Disk Structures

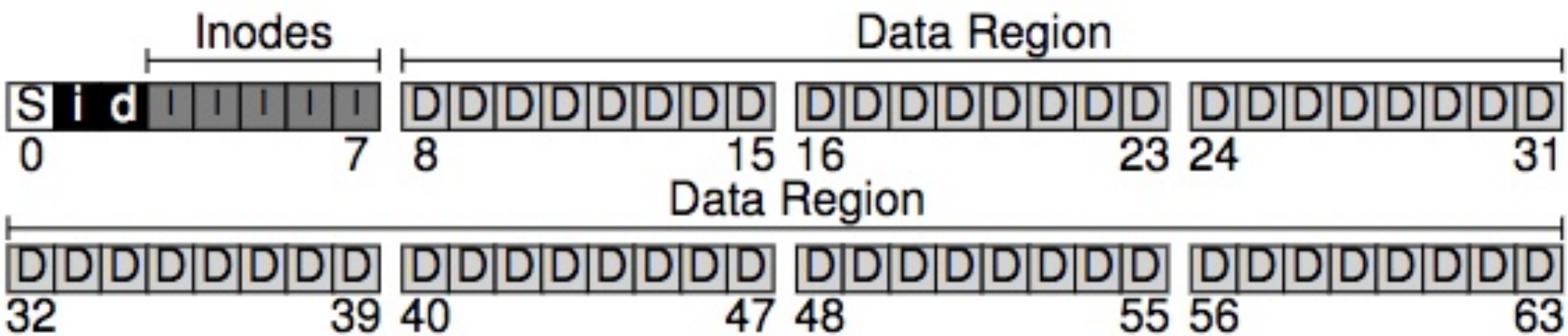
- Common file system structures
  - Data block
  - Inode table
  - Directories
  - Data bitmap
  - Inode bitmap
  - Superblock

On-Disk Structure: Superblock

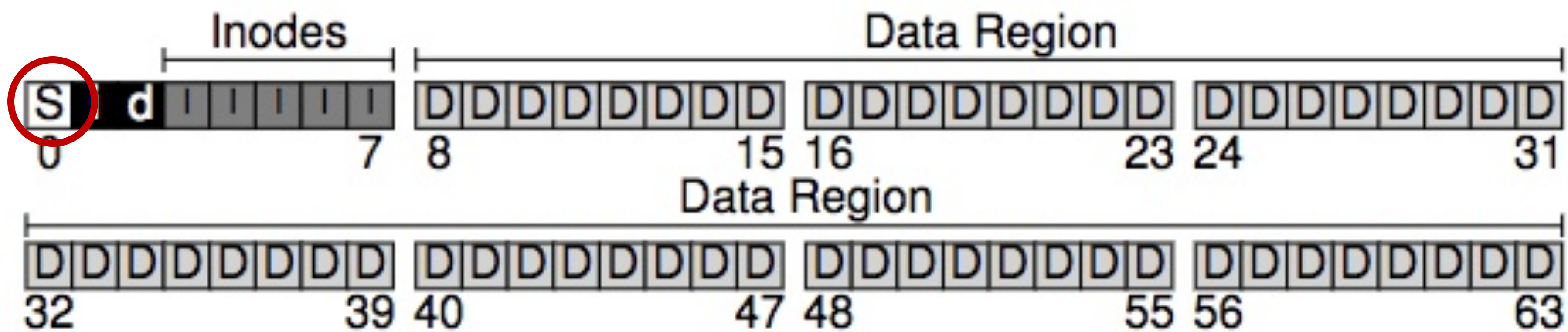
- Need to know basic file system configuration and runtime status, such as:
  - Block size
  - How many inodes are there
  - How much free space

- Store all these metadata info in a superblock

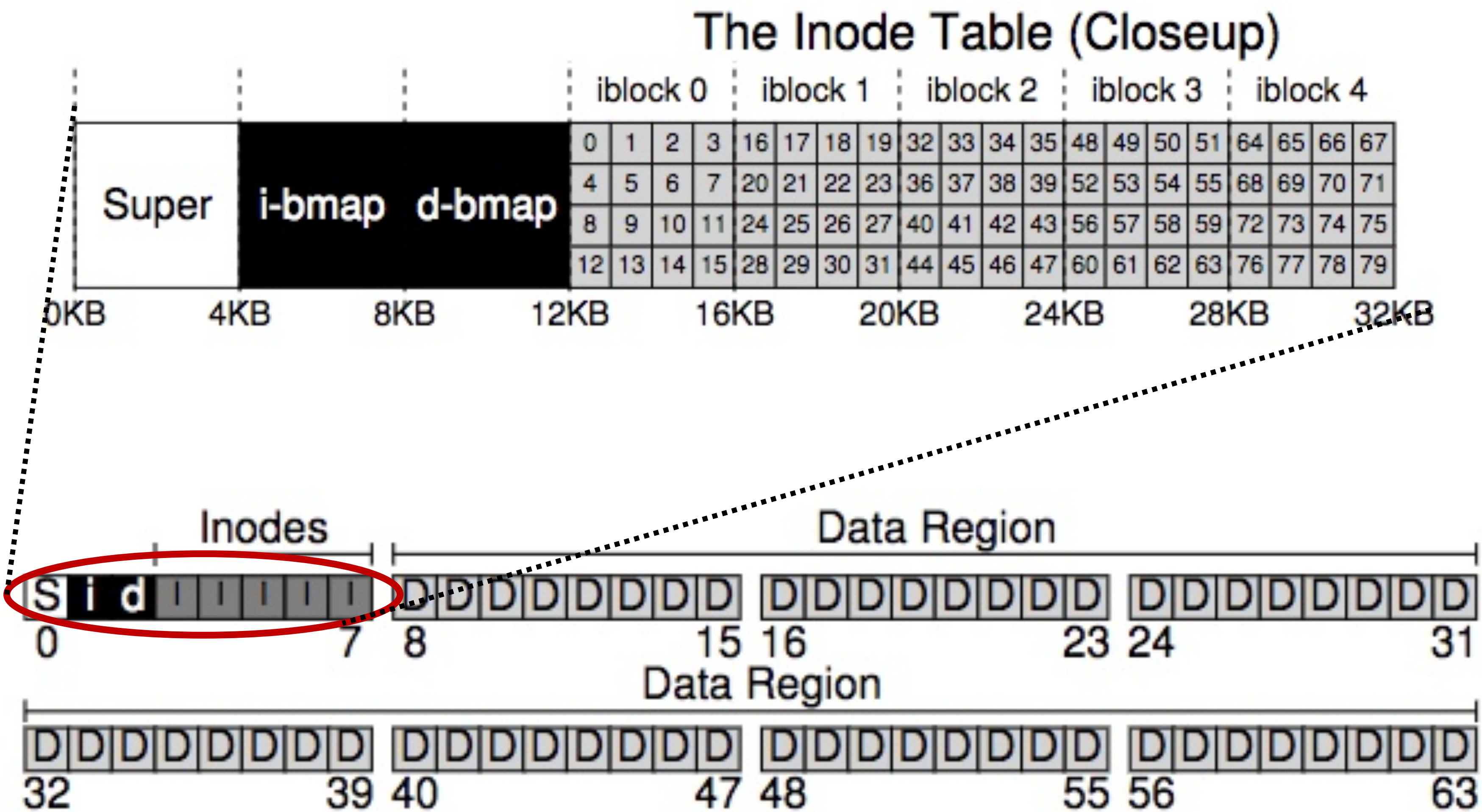
On-Disk Structure: Superblock



On-Disk Structure: Superblock



On-Disk Structure Overview



File System Operations

Basic File System Operations

create /foo/bar

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

Basic File System Operations

create /foo/bar [traverse]

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

Basic File System Operations

create /foo/bar [traverse]

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

Basic File System Operations

create /foo/bar [traverse]

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

foo inode: we have permission
foo data: bar doesn't exist

Basic File System Operations

create /foo/bar

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

Basic File System Operations

create /foo/bar [allocate inode]

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

Basic File System Operations

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		

Basic File System Operations

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

Basic File System Operations

write to /foo/bar

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

Basic File System Operations

write to /foo/bar [block full? yes]

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

Basic File System Operations

write to /foo/bar [allocate block]

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

Basic File System Operations

write 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			

Basic File System Operations

write 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

Basic File System Operations

write to /foo/bar

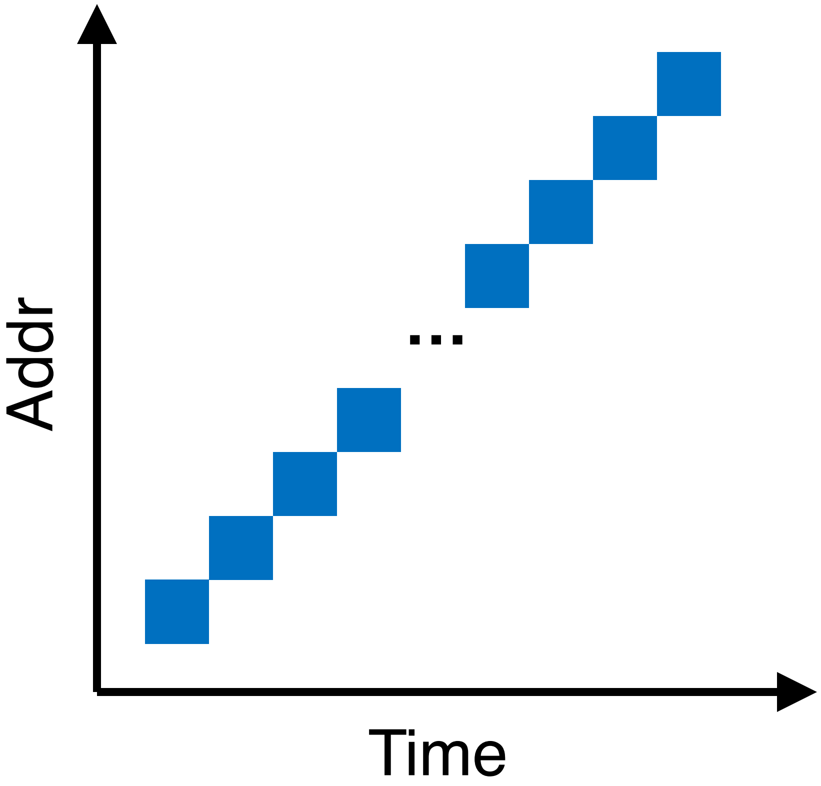
[point to block]

data bitmap	inode bitmap	root inode	foo inode	bar inode	root data (dir blocks)	foo data (dir blocks)	bar data (file)
				read			
read write							
				write			
							write

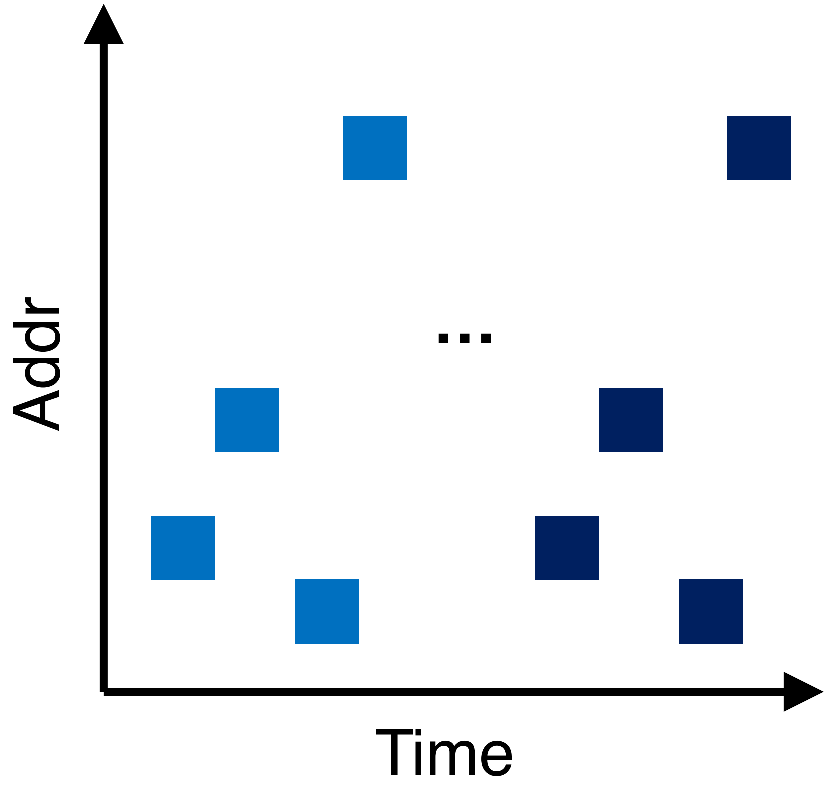
Locality & Data Layout

Review: Locality Types

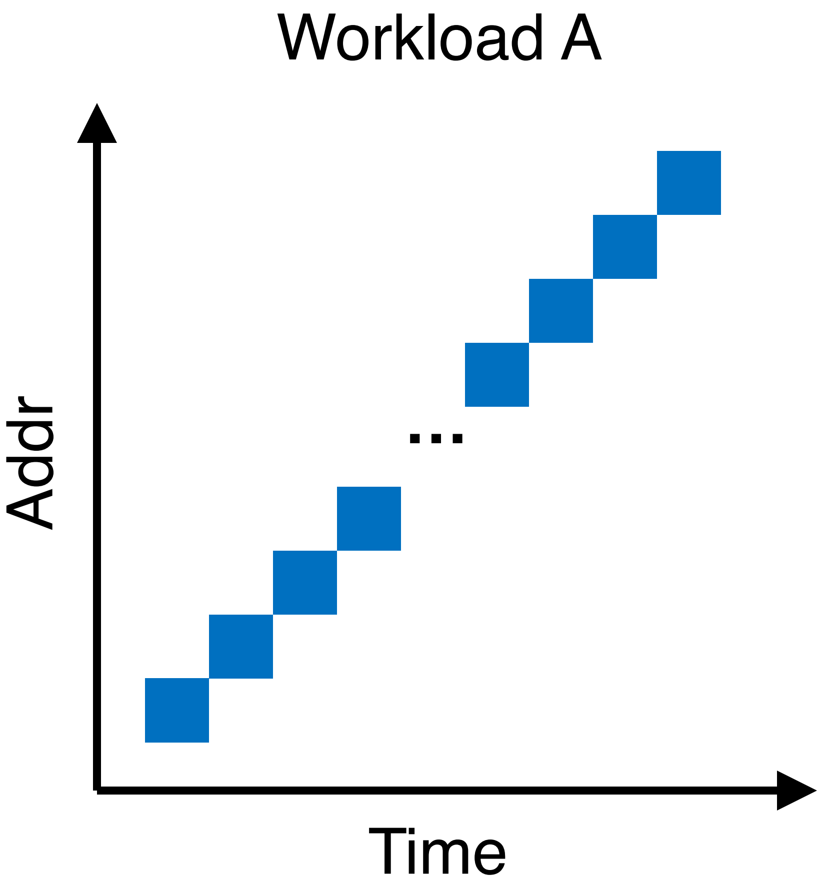
Workload A



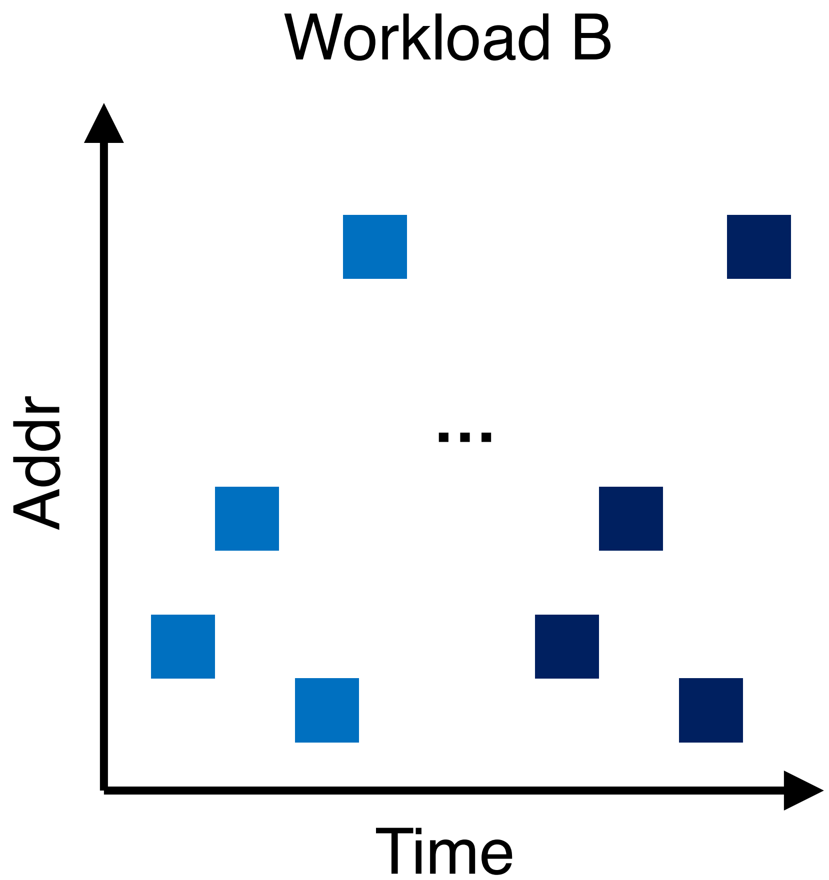
Workload B



Review: Locality Types



Spatial Locality



Temporal Locality

Locality Usefulness in the Context of Disk-based File Systems

- What types of locality are useful for a cache?

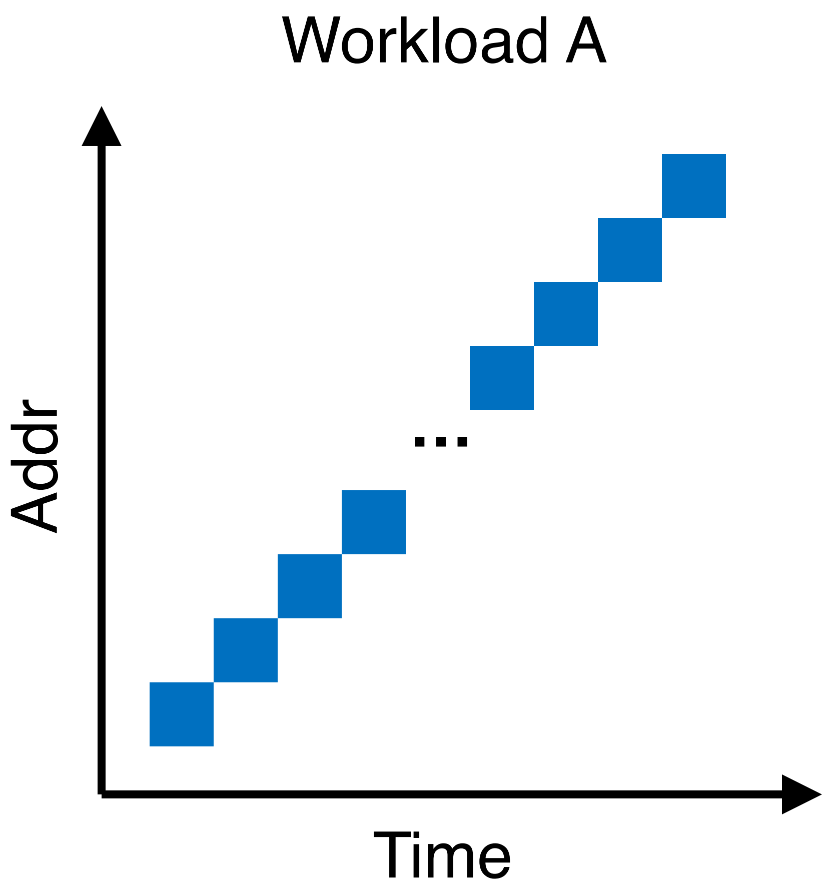
- What types of locality are useful for a disk?

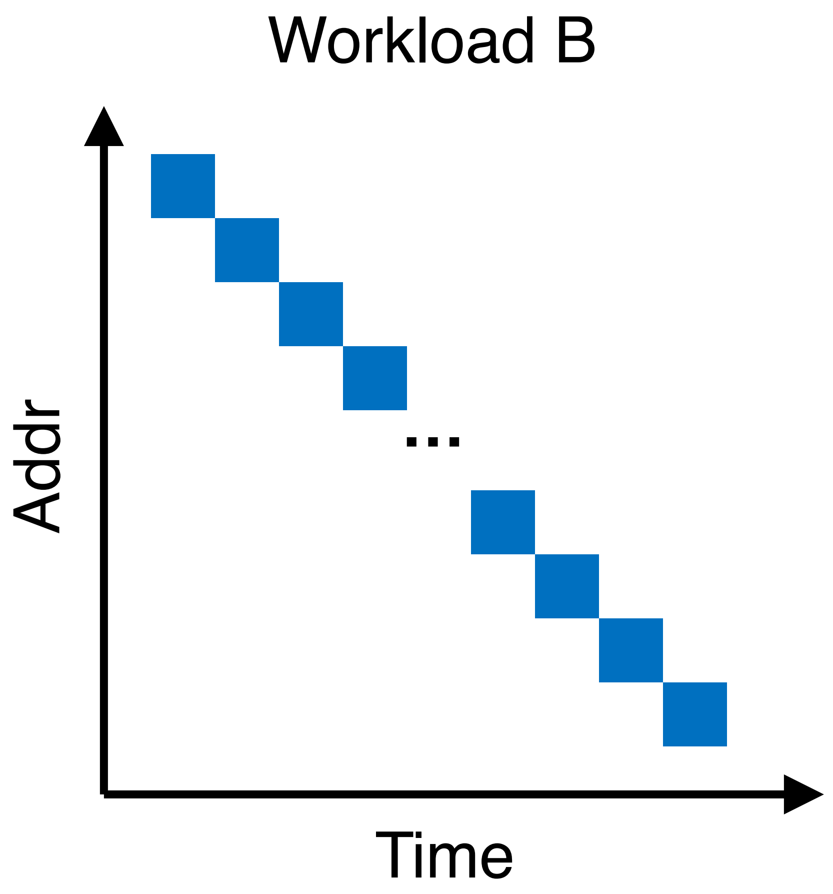
Locality Usefulness in the Context of Disk-based File Systems

- What types of locality are useful for a cache?
  - Possibly, both spatial & temporal locality

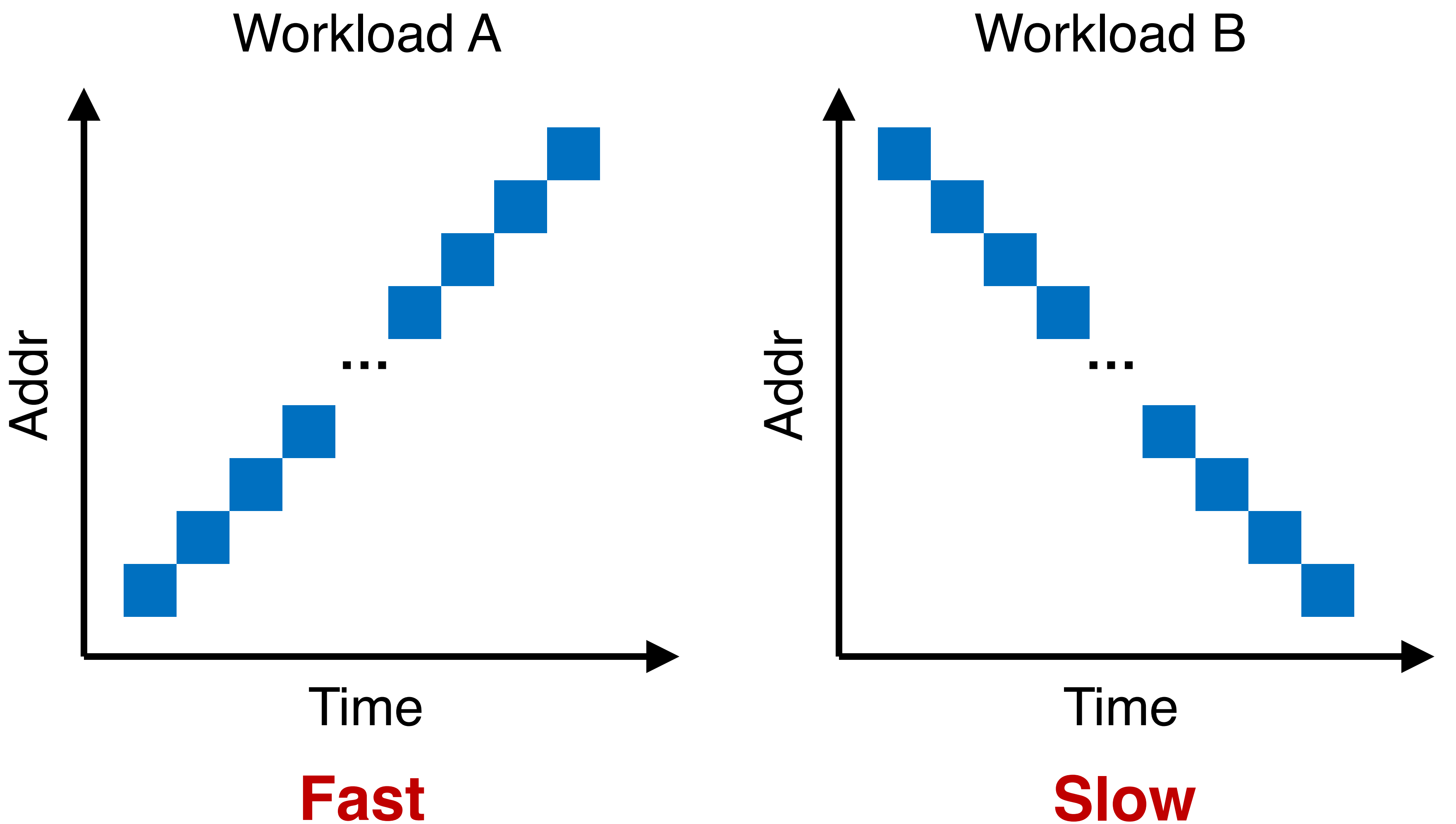
- What types of locality are useful for a disk?
  - Spatial locality, since a disk sucks in random I/Os but can provide reasonably good sequential performance

Order Matters Now for FS on Disk

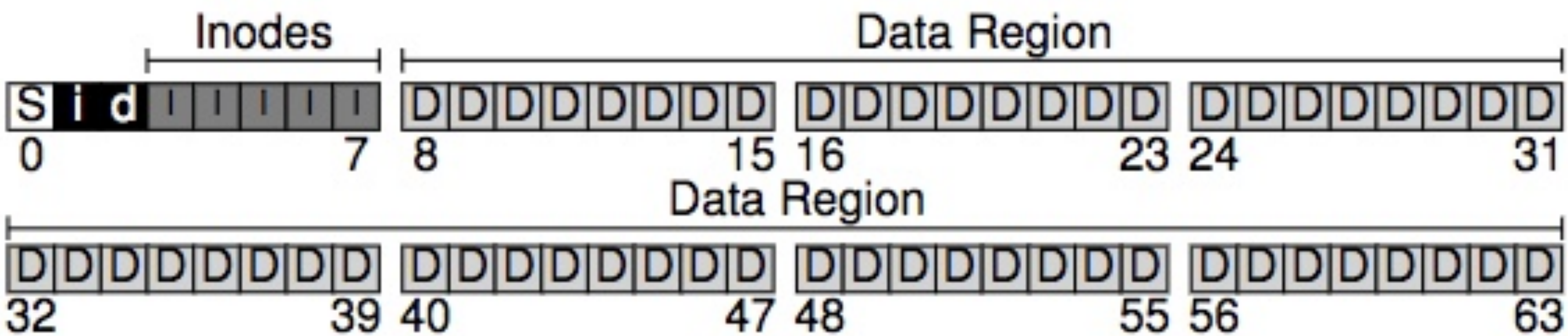




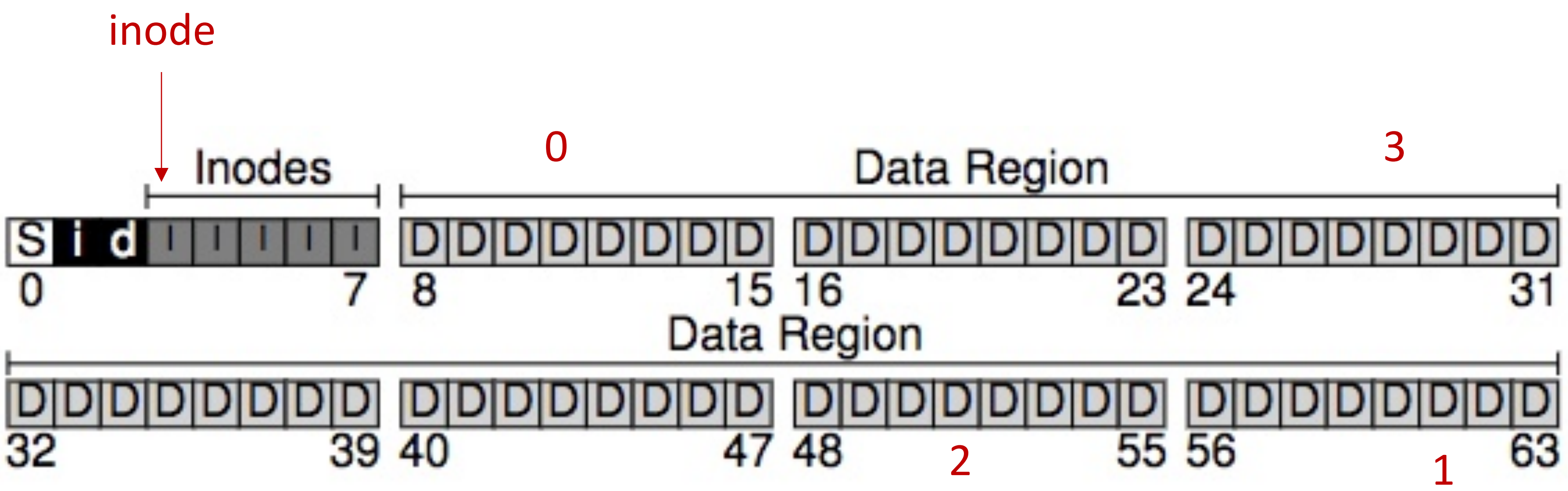
Order Matters Now for FS on Disk



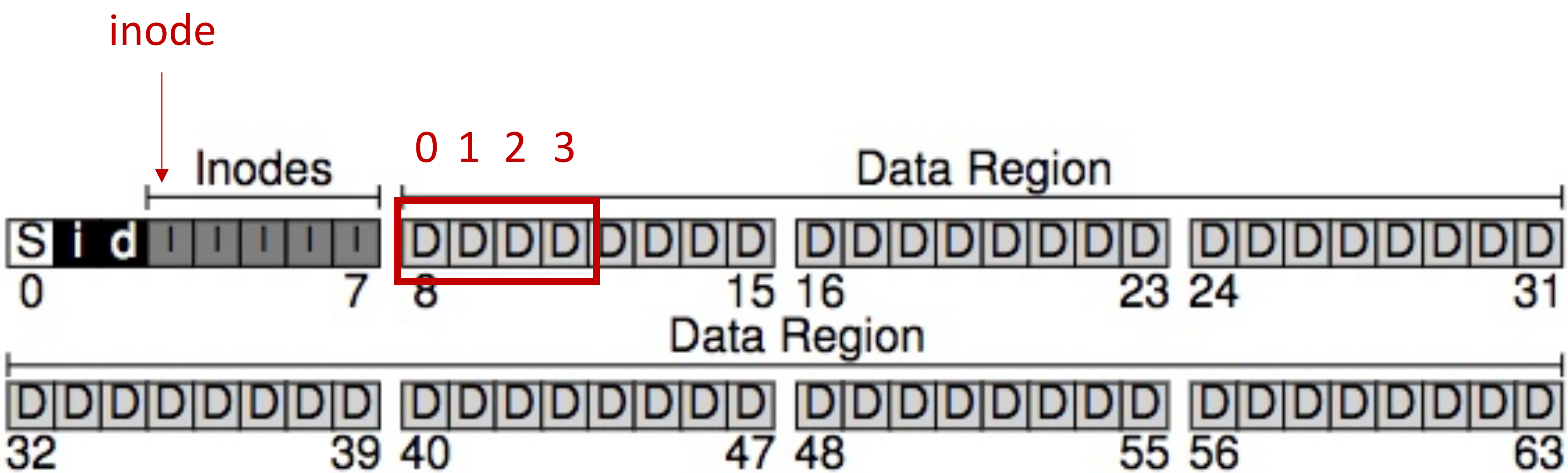
Policy: Choose Inode, Data Blocks



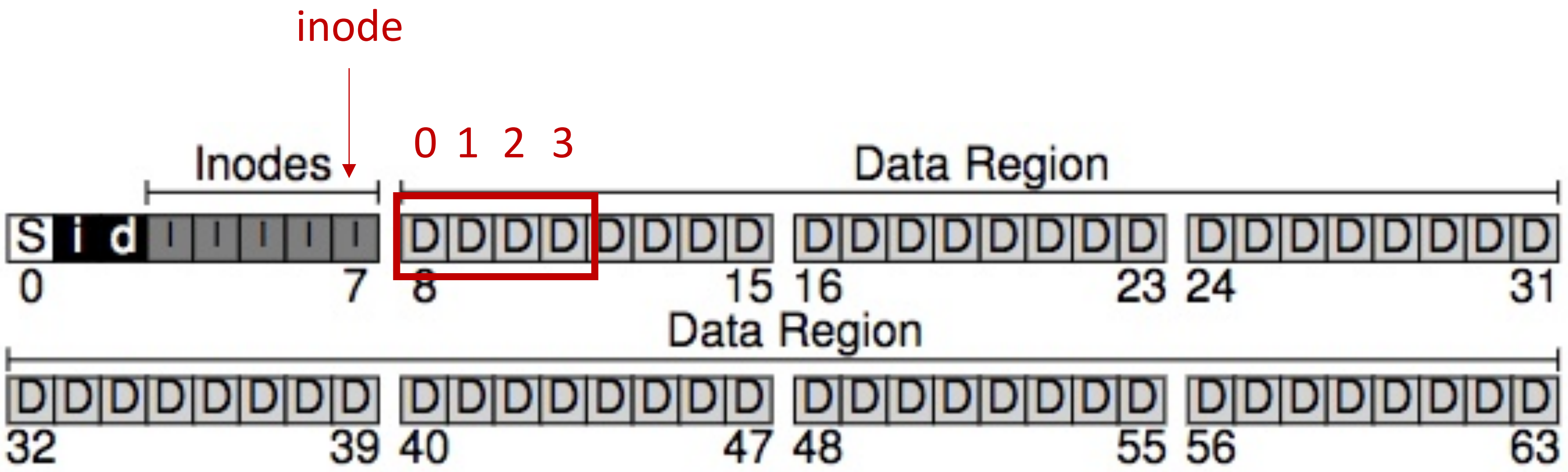
Bad File Layout



Better File Layout



Best File Layout



Recap on Disks

Properties of A Single Disk

- A single disk is slow
  - Kind of Okay sequential I/O performance
  - Really bad for random I/O

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Properties of A Single Disk

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  - Kind of Okay sequential I/O performance
  - Really bad for random I/O
- The storage capacity of a single disk is limited
- A single disk is not reliable

RAID: Redundant Array of Inexpensive Disks

Wish List for a Disk

- Wish it to be faster
  - I/O is always the performance bottleneck

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Wish List for a Disk

- Wish it to be faster
  - I/O is always the performance bottleneck
- Wish it to be larger
  - More and more data needs to be stored
- Wish it to be more reliable
  - We don’t want our valuable data to be gone

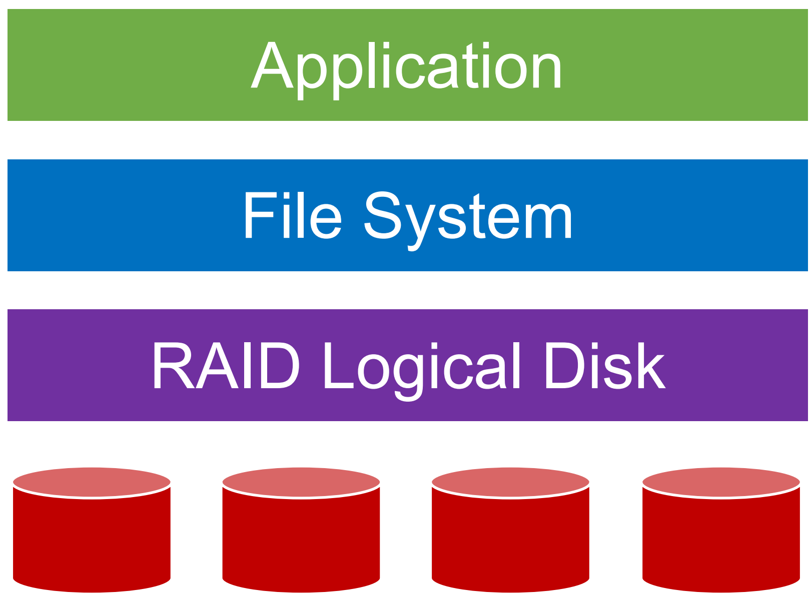
Only One Disk?

- Sometimes we want many disks
  - For higher performance
  - For larger capacity
  - For better reliability

- Challenge: Most file systems work on only one disk

Solution: RAID

RAID: Redundant Array of Inexpensive Disks

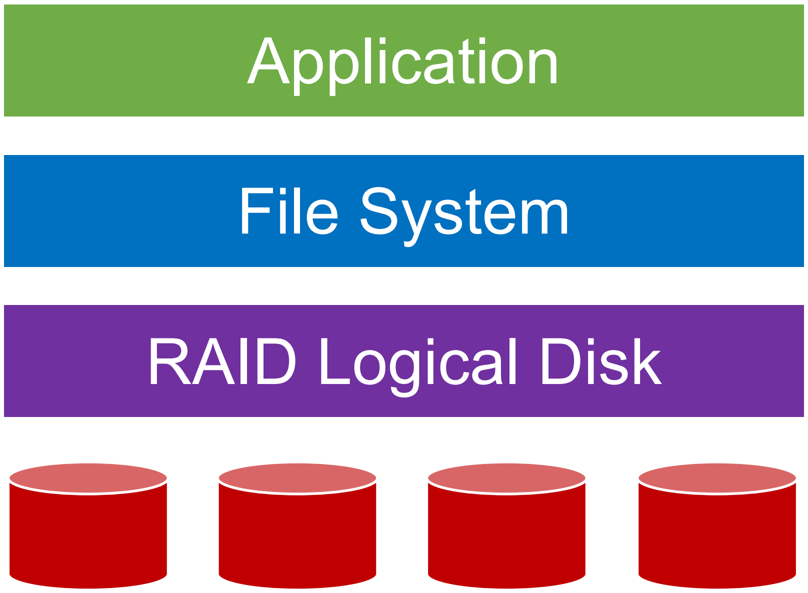


Build a logical disk from many physical disks

Solution: RAID

RAID: Redundant Array of Inexpensive Disks

RAID is
- Transparent
- Deployable



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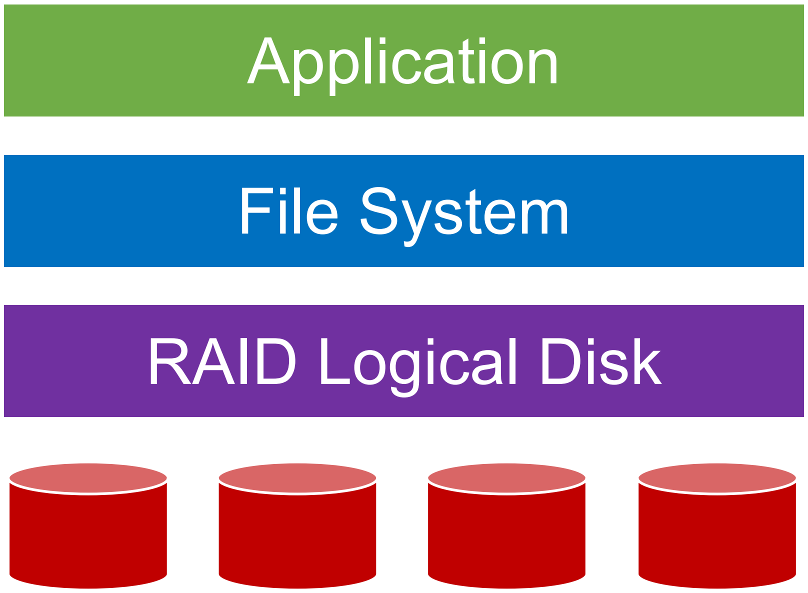

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- Performance
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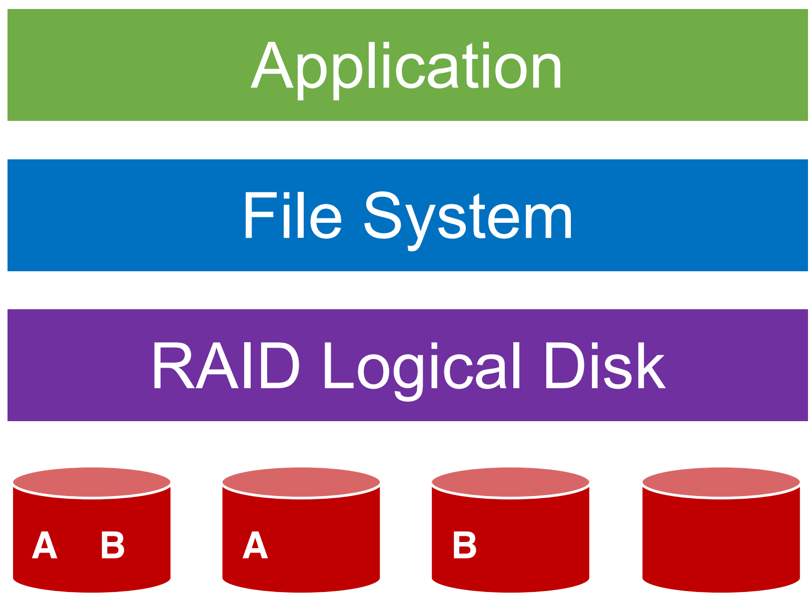

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- Performance
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Why Inexpensive Disks?

- Economies of scale! Cheap disks are popular

- You can often get many commodity hardware components for the same price as a few expensive components

Why Inexpensive Disks?

- Economies of scale! Cheap disks are popular

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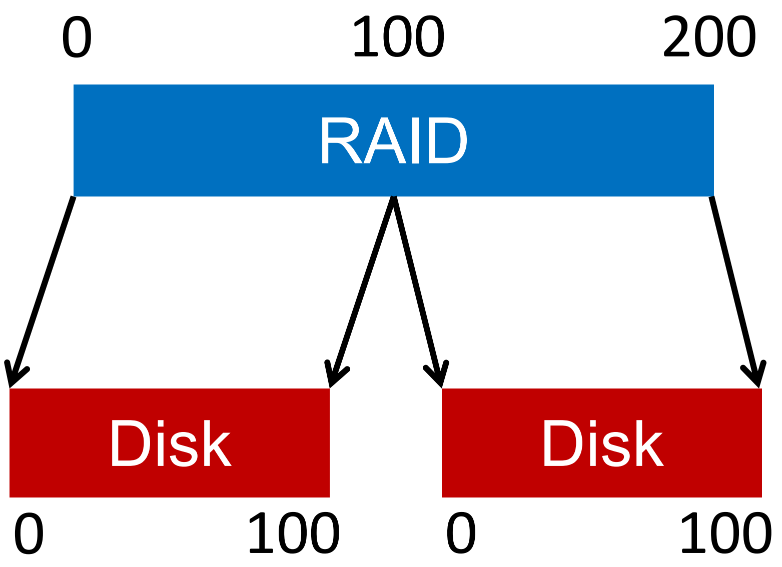
- Strategy: Write software to build high-quality logical devices from many cheap devices
  - Tradeoff: To compensate poor properties of cheap devices

General Strategy

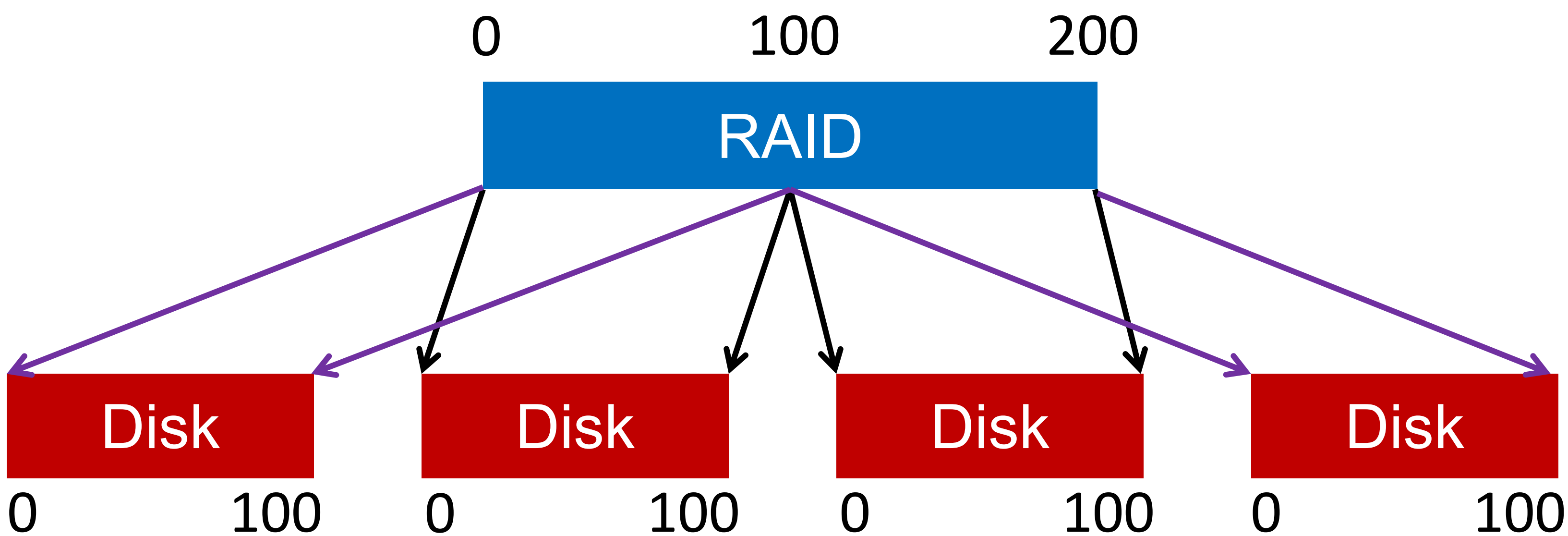
Build fast and large disks from smaller ones



General Strategy

Build fast and large disks from smaller ones

Add more disks for reliability++!



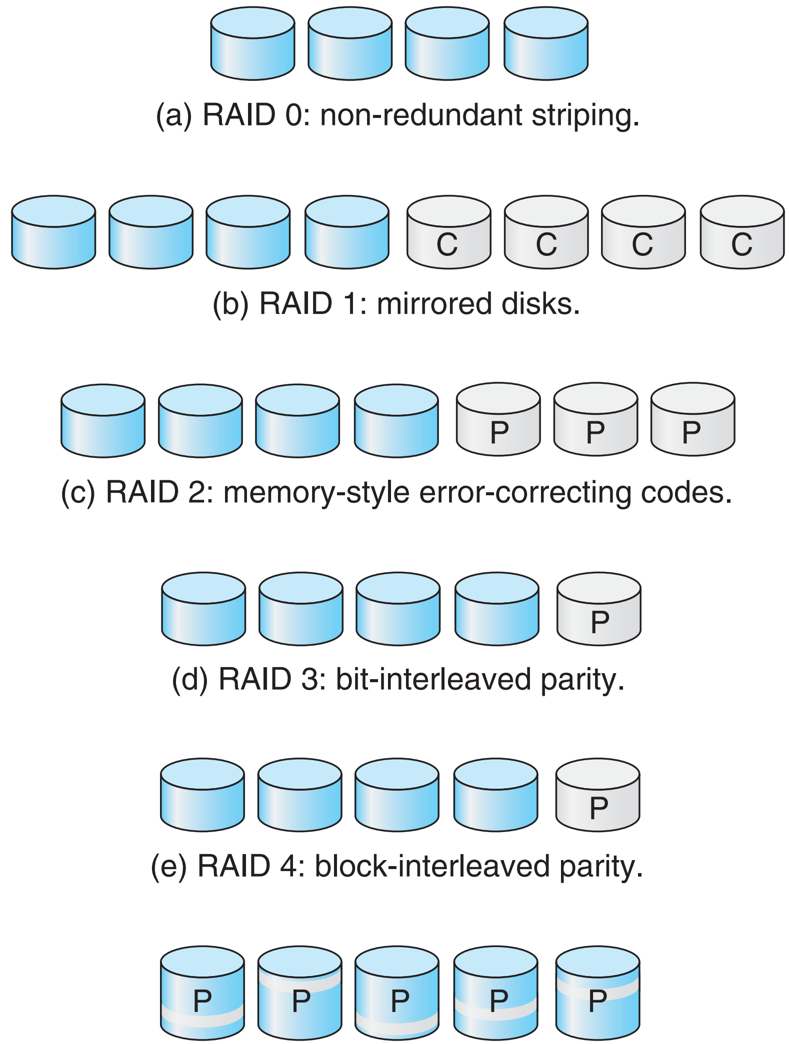
RAID Metrics

- Performance
  - How long does each workload take?
- Capacity
  - How much space can apps use?
- Reliability
  - How many disks can we safely lose?

RAID Metrics

- Performance
  - How long does each workload take?
- Capacity
  - How much space can apps use?
- Reliability
  - How many disks can we safely lose?
  - Assume fail-stop model!

RAID Levels



(a) RAID 0: non-redundant striping.

(b) RAID 1: mirrored disks.

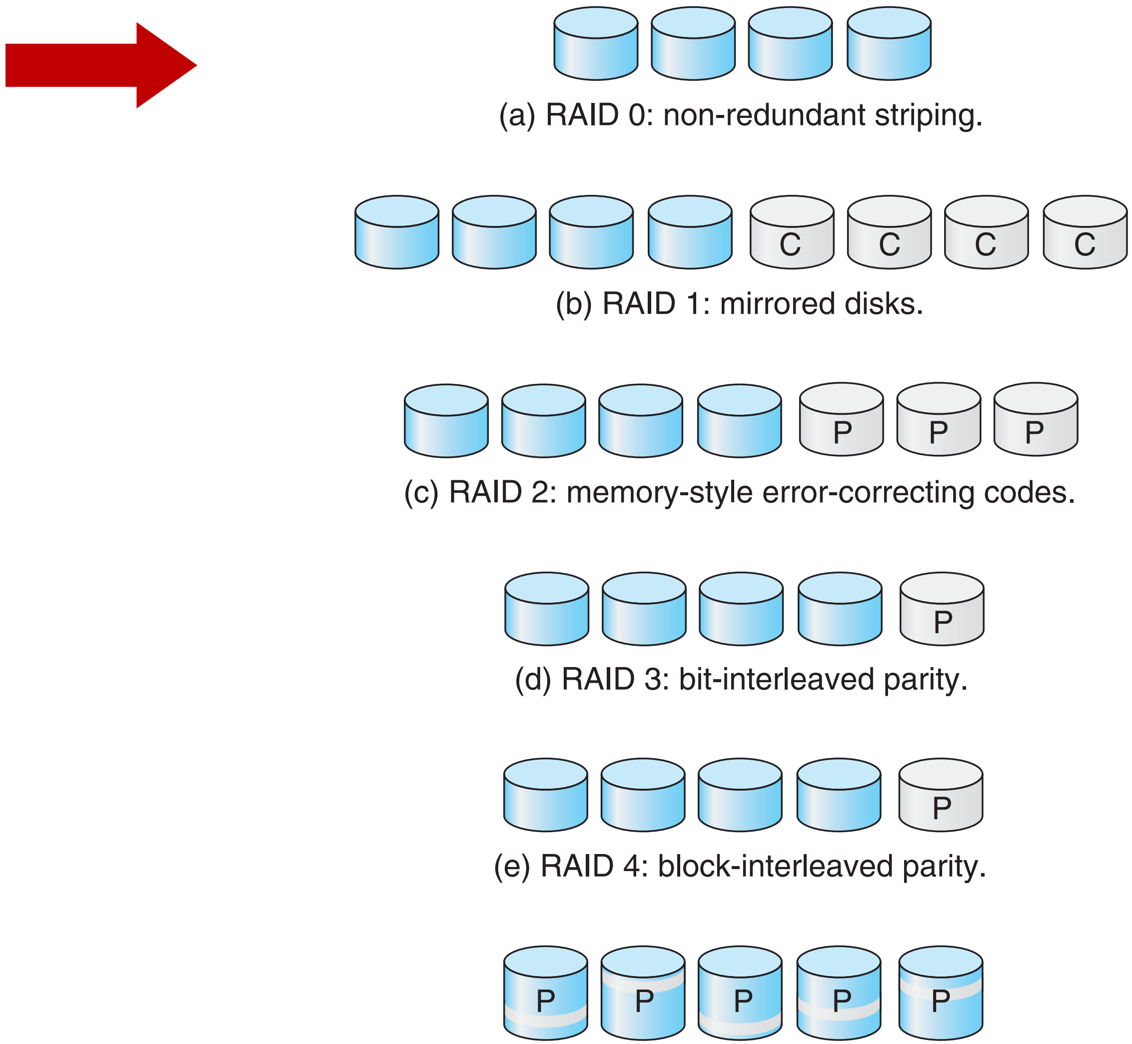
(c) RAID 2: memory-style error-correcting codes.

(d) RAID 3: bit-interleaved parity.

(e) RAID 4: block-interleaved parity.

(f) RAID 5: block-interleaved distributed parity.

RAID Level 0



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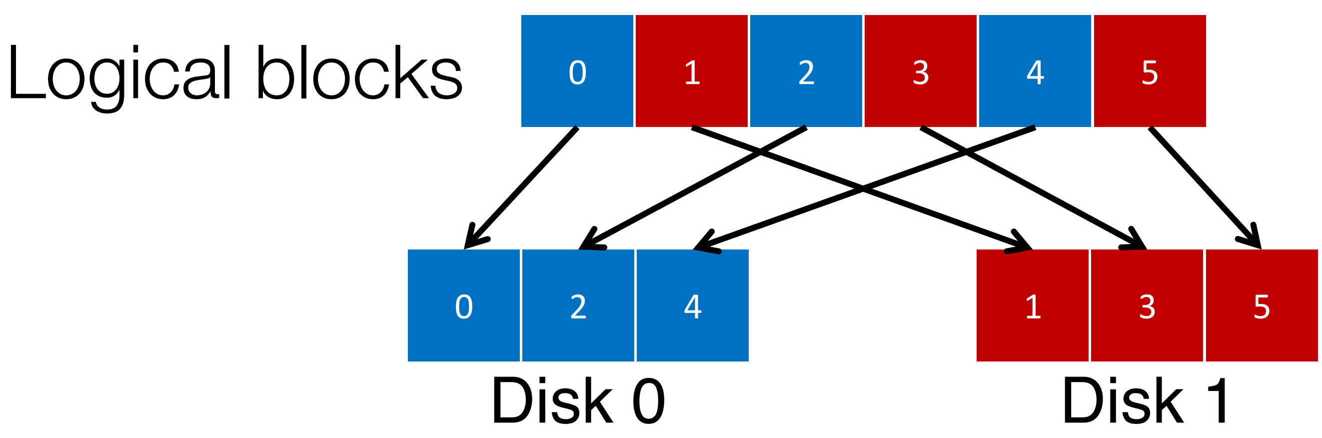
RAID-0: Striping

- No redundancy

- Serves as upper bound for
  - Performance
  - Capacity



4 Disks

Disk 0	Disk 1	Disk 2	Disk 3
0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

4 Disks

	Disk 0	Disk 1	Disk 2	Disk 3
	0	1	2	3
stripe:	4	5	6	7
	8	9	10	11
	12	13	14	15

How to Map?

- Given logical address A:
  - Disk = …
  - Offset = …

Disk 0	Disk 1	Disk 2	Disk 3
0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

How to Map?

- Given logical address A:
  - Disk = `A % disk_count`
  - Offset = `A / disk_count`

Disk 0	Disk 1	Disk 2	Disk 3
0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

Mapping Example: Find Block 13

- Given logical address 13:
  - Disk = `13 % 4 = 1`
  - Offset = `13 / 4 = 3`

Offset	Disk 0	Disk 1	Disk 2	Disk 3
0	0	1	2	3
1	4	5	6	7
2	8	9	10	11
3	12	13	14	15

Chunk Size = 1

Disk 0	Disk 1	Disk 2	Disk 3
0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

Chunk Size = 1

Disk 0	Disk 1	Disk 2	Disk 3
0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

Chunk Size = 2

Disk 0	Disk 1	Disk 2	Disk 3	
0	2	4	6	chunk size:
1	3	5	7	2 blocks
8	10	12	14	
9	11	13	15	

Chunk Size = 1

Disk 0	Disk 1	Disk 2	Disk 3
0	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

In all following examples, we assume chunk size of 1

Chunk Size = 2

Disk 0	Disk 1	Disk 2	Disk 3	
0	2	4	6	chunk size:
1	3	5	7	2 blocks
8	10	12	14	
9	11	13	15	

RAID-0 Analysis

1. What is capacity?

2. How many disks can fail?

3. Throughput?

4. Latency?

RAID-0 Analysis

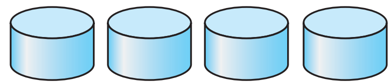
1. What is capacity? N * C

2. How many disks can fail? 0

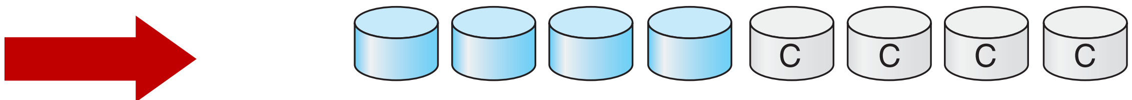
3. Throughput? N * S and N * R

4. Latency? D

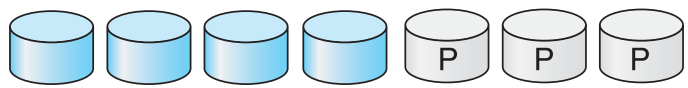
RAID Level 1



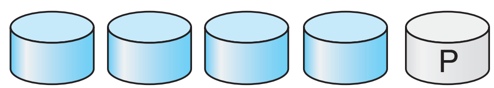
(a) RAID 0: non-redundant striping.



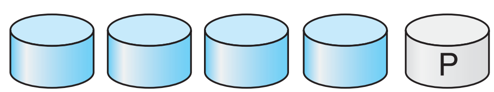
(b) RAID 1: mirrored disks.



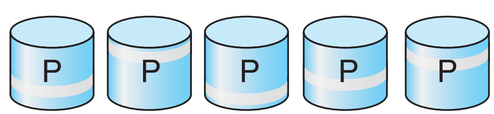
(c) RAID 2: memory-style error-correcting codes.



(d) RAID 3: bit-interleaved parity.



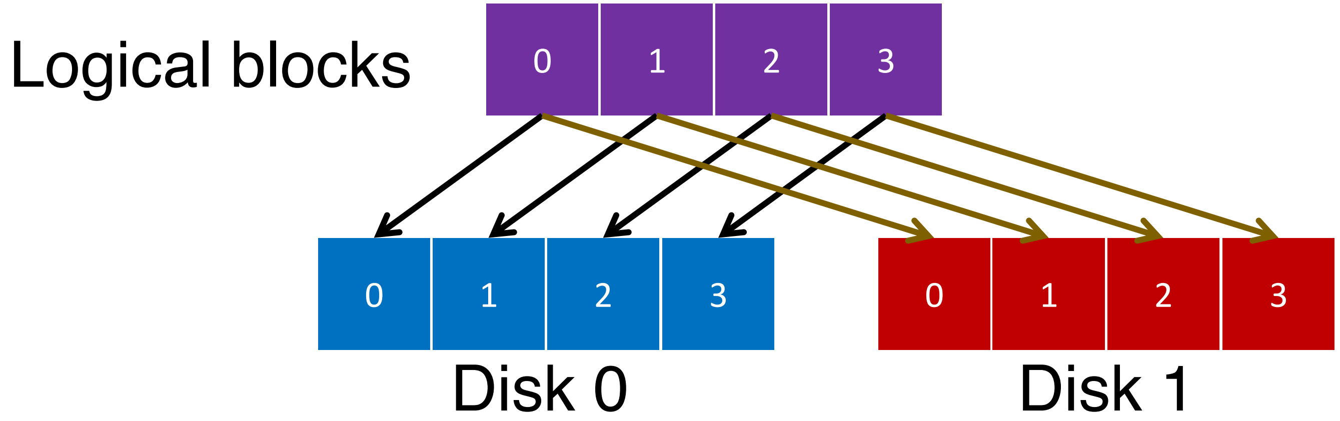
(e) RAID 4: block-interleaved parity.



(f) RAID 5: block-interleaved distributed parity.

RAID-1: Mirroring

- RAID-1 keeps two copies of each block



Assumption

- Assume disks are fail-stop
  - Two states
    - They work or they don't
  - We know when they don't work

4 Disks

Disk 0	Disk 1	Disk 2	Disk 3
0	0	1	1
2	2	3	3
4	4	5	5
6	6	7	7

4 Disks

4 × R

Disk 0	Disk 1	Disk 2	Disk 3
0	0	1	1
2	2	3	3
4	4	5	5
6	6	7	7

How many disks can fail?

RAID-1 Analysis

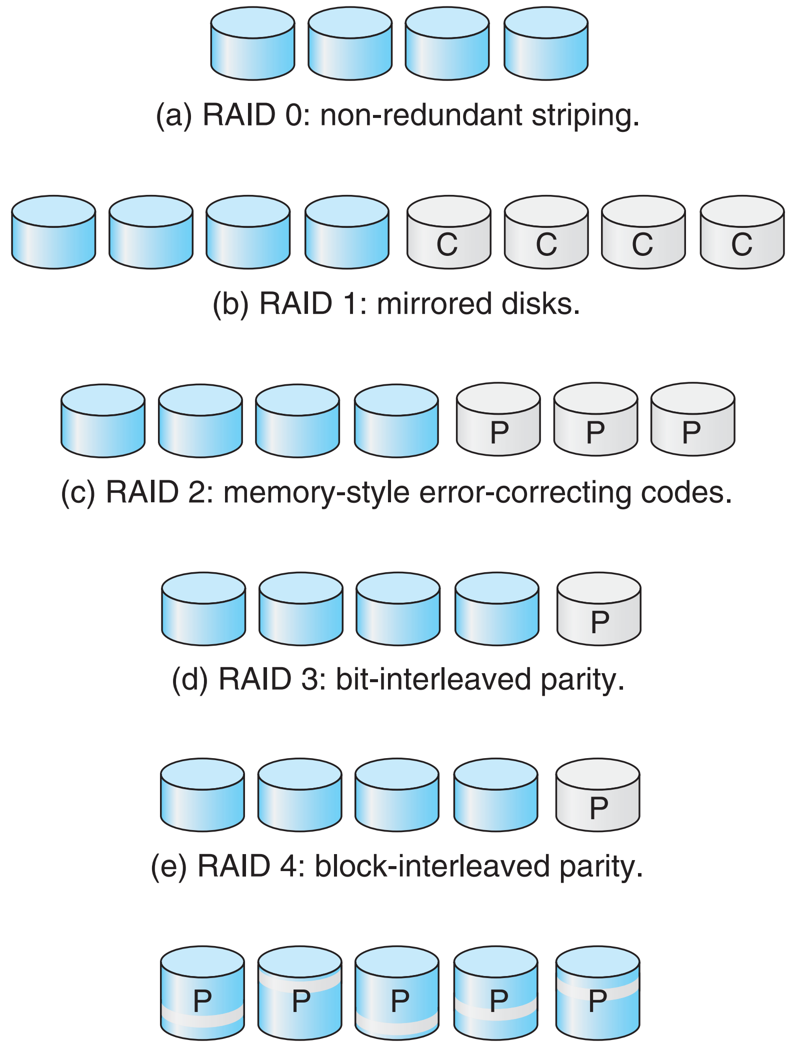
1. What is capacity? N/2 * C

2. How many disks can fail? 1 or maybe N / 2

3. Throughput?
   - Seq read: N/2 * S
   - Seq write: N/2 * S
   - Rand read: N * R
   - Rand write: N/2 * R

4. Latency? D

RAID Level 4



(a) RAID 0: non-redundant striping.

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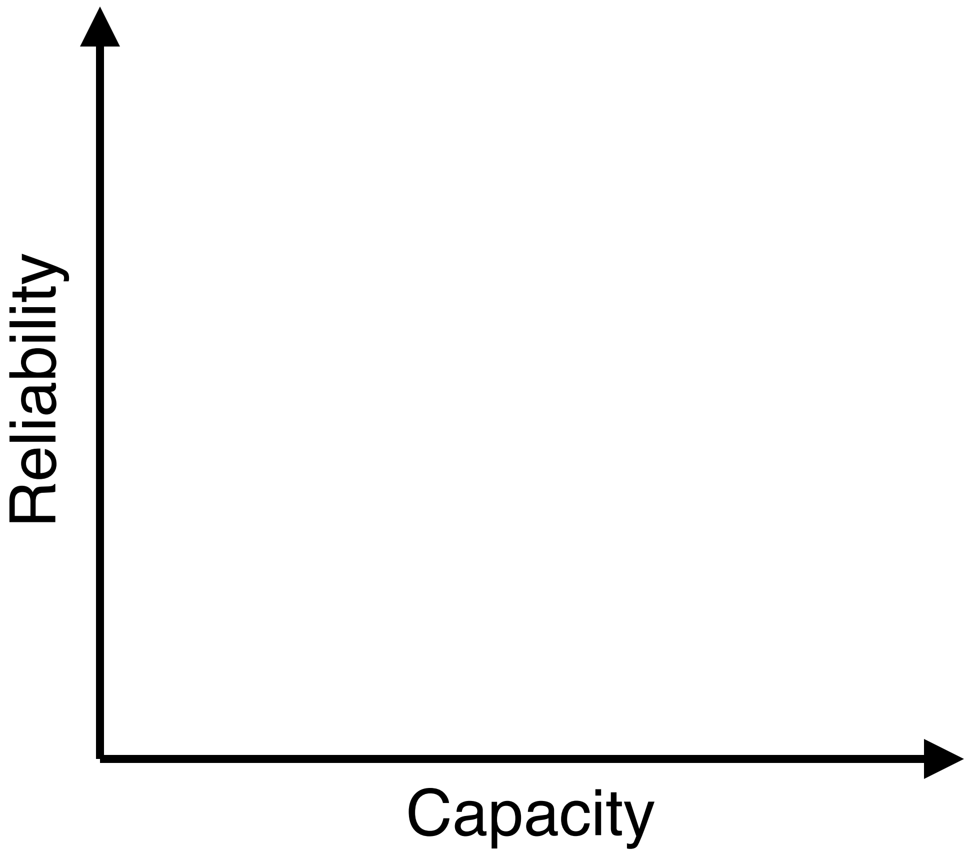
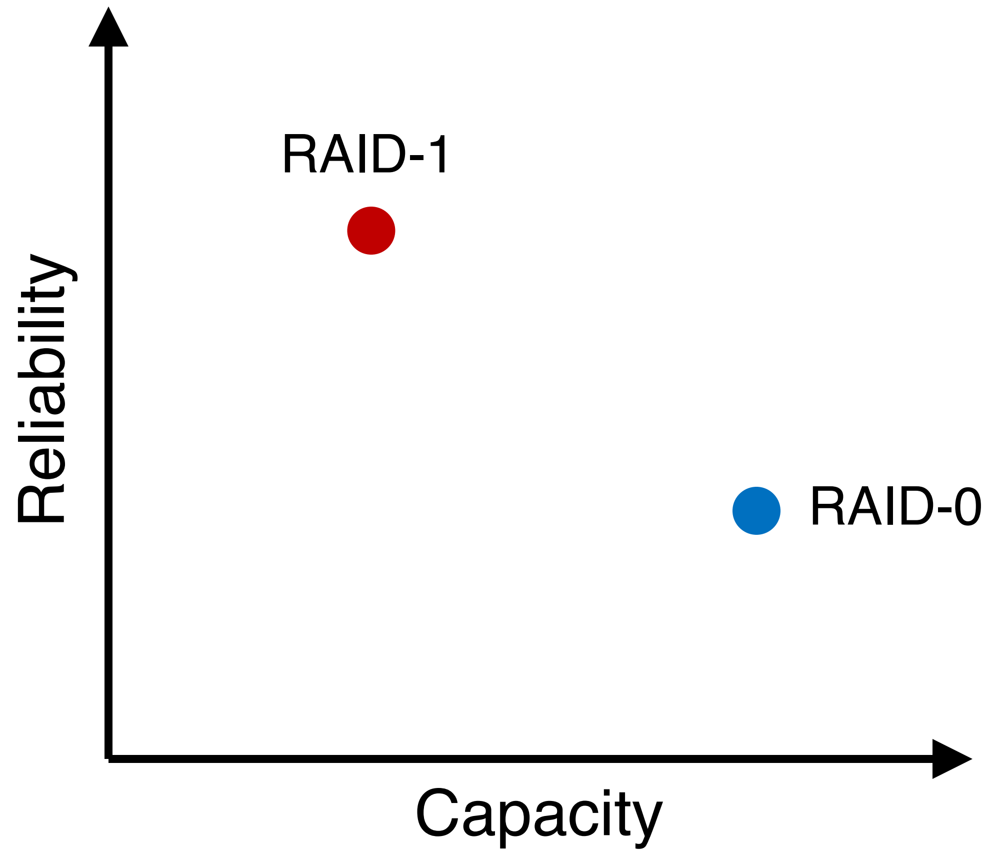
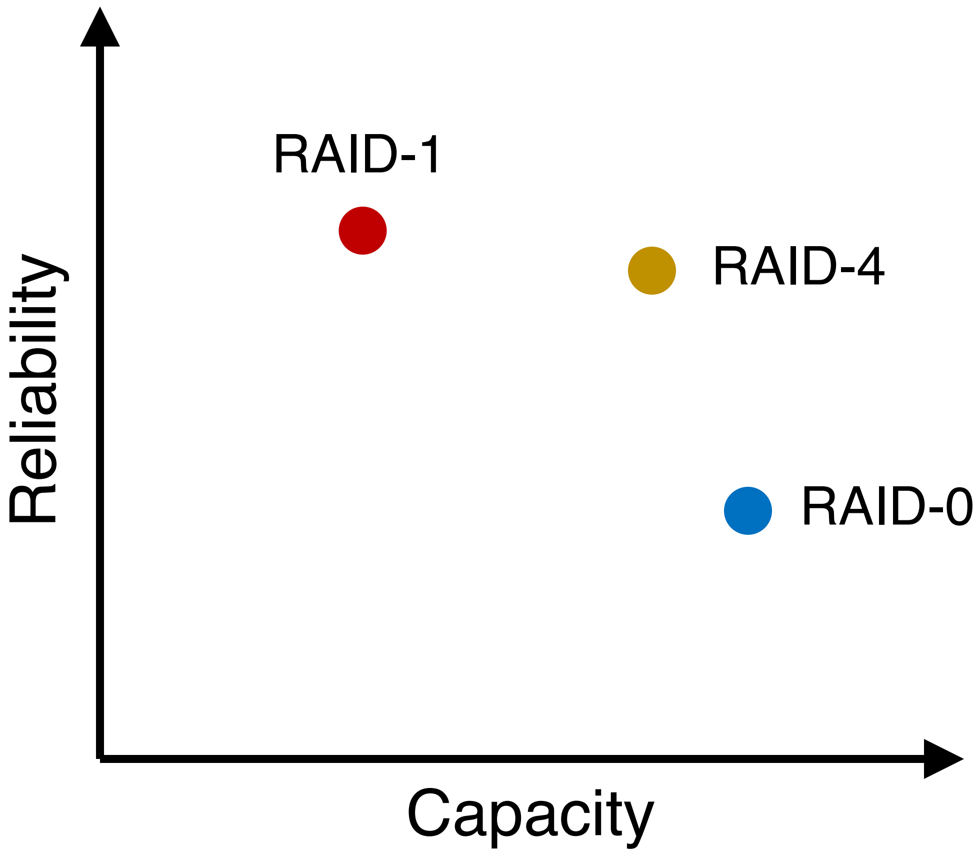
RAID-4



RAID-4



RAID-4



RAID-4: Strategy

- Use parity disk

- In algebra, if an equation has N variables, and N-1 are known, you can also solve for the unknown

- Treat the sectors/blocks across disks in a stripe as an equation

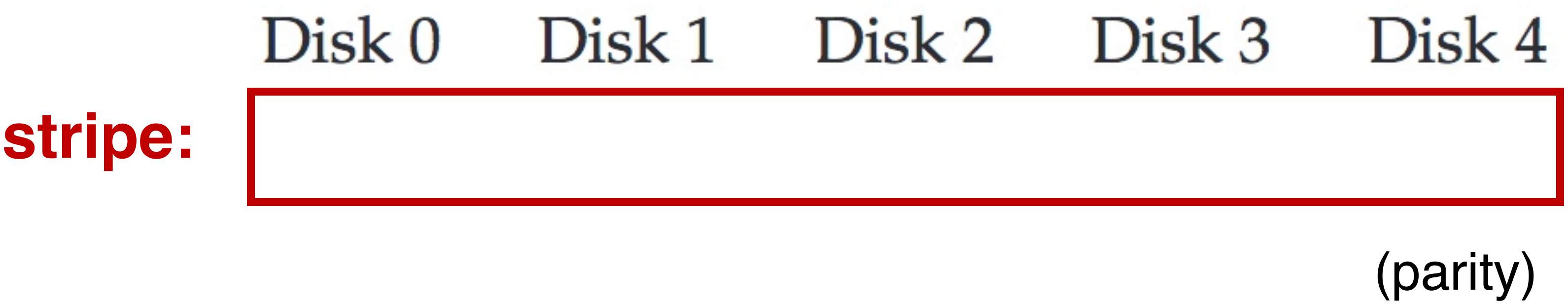
RAID-4: Strategy

- Use parity disk
- In algebra, if an equation has N variables, and N-1 are known, you can also solve for the unknown
- Treat the sectors/blocks across disks in a stripe as an equation
- A failed disk is like an unknown in that equation

5 Disks

Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	1	2	3	P0
4	5	6	7	P1
8	9	10	11	P2
12	13	14	15	P3

Example



Example

	Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
stripe:	4	3	0	2	
					(parity)

Example

	Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
stripe:	4	3	0	2	9
					(parity)

Example

	Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
stripe:	X	3	0	2	9
					(parity)

Example

	Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
stripe:	**4**	3	0	2	9
					(parity)

Parity Function: XOR Example

C0	C1	C2	C3	P
0	0	1	1	XOR(0,0,1,1) = 0
0	1	0	0	XOR(0,1,0,0) = 1

Parity Function: XOR Example

C0	C1	C2	C3	P
0	0	1	1	XOR(0,0,1,1) = 0
0	1	0	0	XOR(0,1,0,0) = 1

XOR function:

- P = 0: The number of 1 in a stripe must be an even number
- P = 1: The number of 1 in a stripe must be an odd number

Parity Function: XOR Example

	Block0	Block1	Block2	Block3	Parity
stripe:	00	10	11	10	11
	10	01	00	01	10

XOR function:

- P = 0: The number of 1 in a stripe must be an even number
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Parity Function: XOR Example

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Parity Function: XOR Example

	Block0	Block1	Block2	Block3	Parity
stripe:	X	10	11	10	11
	10	01	00	01	10

Block0 = XOR(10,11,10,11) = 00

XOR function:

- P = 0: The number of 1 in a stripe must be an even number
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Parity Function: XOR Example

	Block0	Block1	Block2	Block3	Parity
stripe:	00	10	11	10	11
	10	01	00	01	10

Block0 = XOR(10,11,10,11) = **00**

XOR function:

- P = 0: The number of 1 in a stripe must be an even number
- P = 1: The number of 1 in a stripe must be an odd number

RAID-4 Analysis

1. What is capacity? (N-1) * C

2. How many disks can fail? 1

3. Throughput?
   - Seq read: (N-1) * S
   - Seq write: (N-1) * S
   - Rand read: (N-1) * R
   - Rand write: R/2

4. Latency? D, 2D

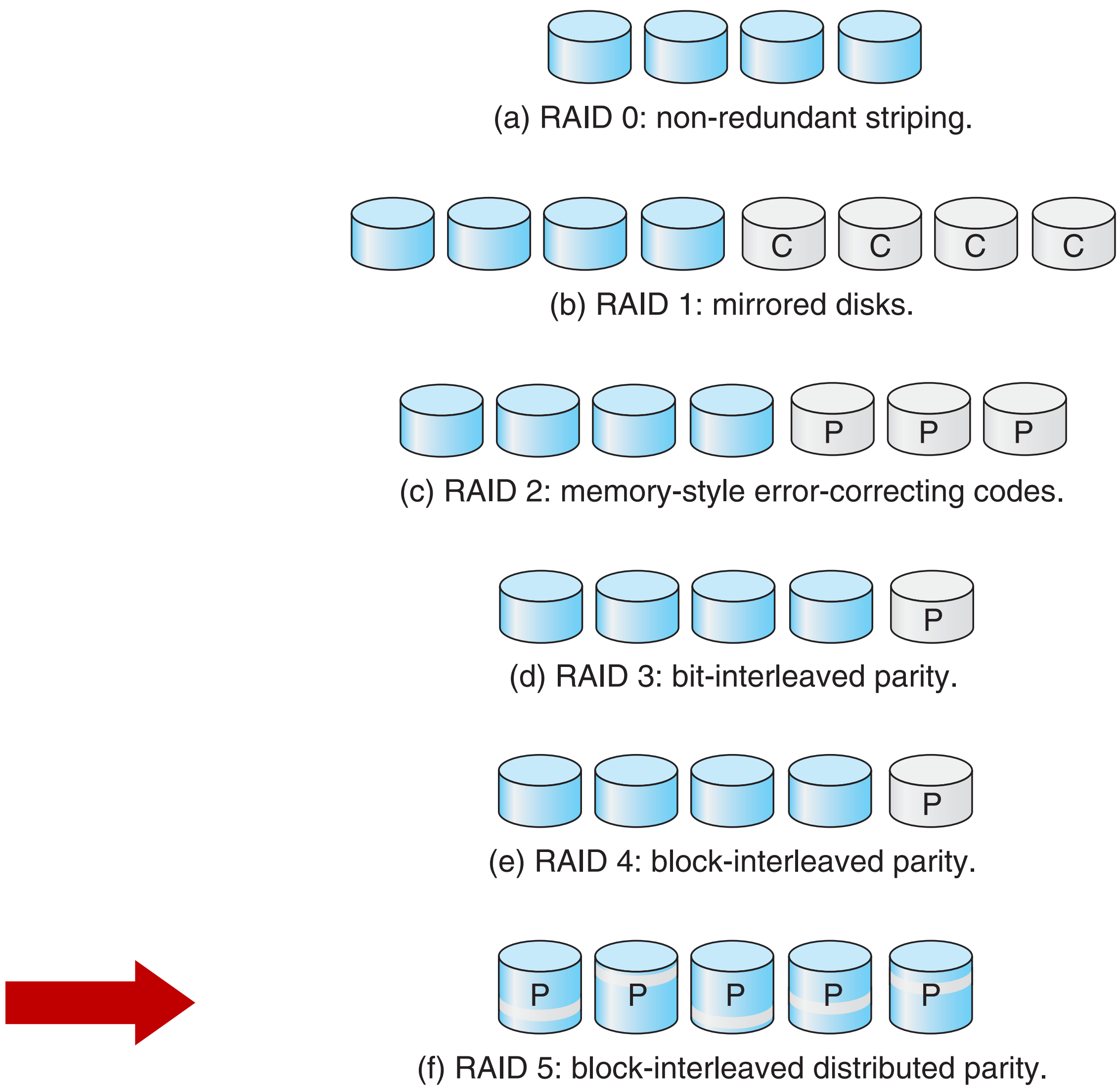
RAID-4 Analysis: Random Write

Random write to 4, 13, and respective parity blocks

Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	1	2	3	P0
*4	5	6	7	+P1
8	9	10	11	P2
12	*13	14	15	+P3

Small write problem (for parity-based RAIDs):
Parity disk serializes all random writes; each **logical** I/O generates two **physical** I/Os (**one read and one write for parity P1**)

RAID Level 5


(a) RAID 0: non-redundant striping.
C
C
C
C
(b) RAID 1: mirrored disks.
P
P
P
(c) RAID 2: memory-style error-correcting codes.
P
(d) RAID 3: bit-interleaved parity.
P
(e) RAID 4: block-interleaved parity.
P
P
P
P
P
(f) RAID 5: block-interleaved distributed parity.

RAID-5: Rotating Parity

Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	1	2	3	P0
5	6	7	P1	4
10	11	P2	8	9
15	P3	12	13	14
P4	16	17	18	19

RAID-5 works almost identically to RAID-4, except that it rotates the parity block across drives

RAID-5 Analysis

1. What is capacity? (N-1) * C

2. How many disks can fail? 1

3. Throughput?
   - Seq read: (N-1) * S
   - Seq write: (N-1) * S
   - Rand read: N * R
   - Rand write: ???

4. Latency? D, 2D

RAID-5: Random Write

Write

Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	1	2	3	P0
5	6	7	P1	4
10	11	P2	8	9
15	P3	12	13	14
P4	16	17	18	19

Random write to Block 10 on Disk 0

RAID-5: Random Write

1. Read

Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	1	2	3	P0
5	6	7	P1	4
10	11	P2	8	9
15	P3	12	13	14
P4	16	17	18	19

Random write to Block 10 on Disk 0

1. Read Block 10

RAID-5: Random Write

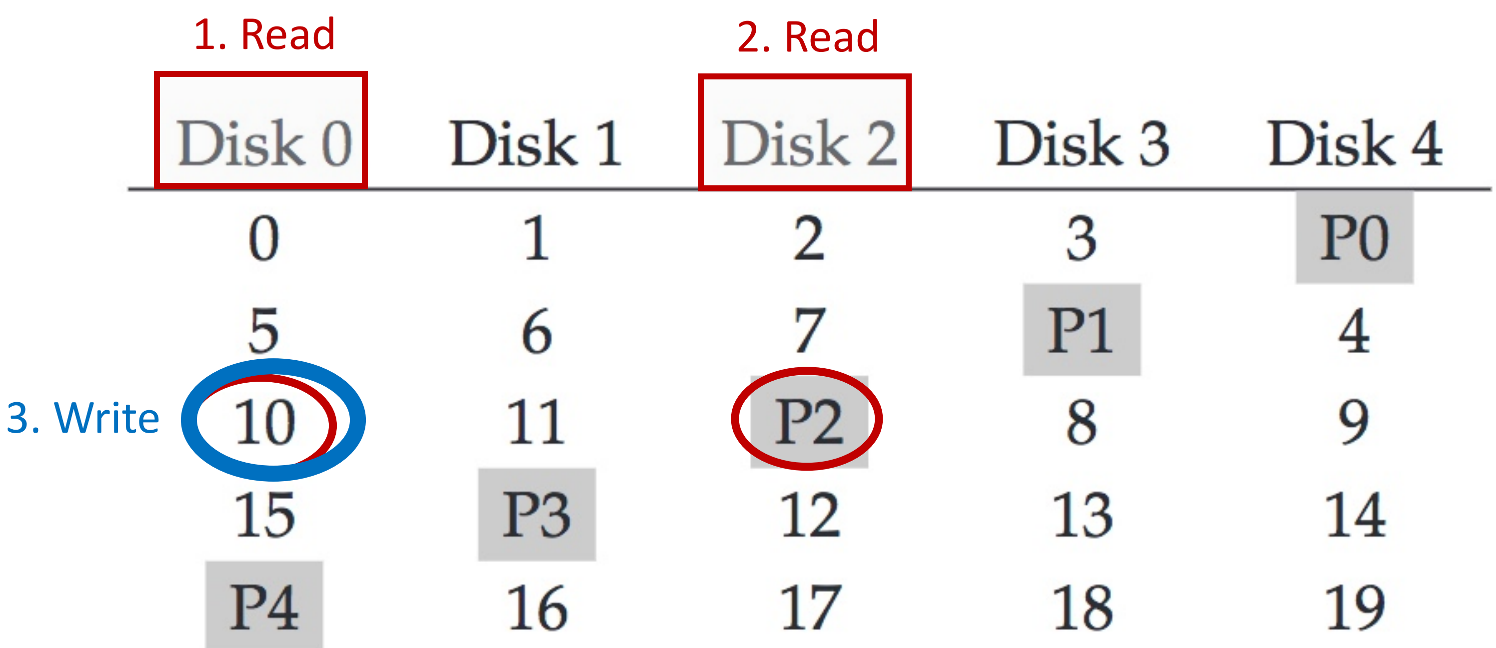
1. Read (Disk 0) 2. Read (Disk 2)

Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	1	2	3	P0
5	6	7	P1	4
10	11	P2	8	9
15	P3	12	13	14
P4	16	17	18	19

Random write to Block 10 on Disk 0

1. Read Block 10
2. Read the Parity P2

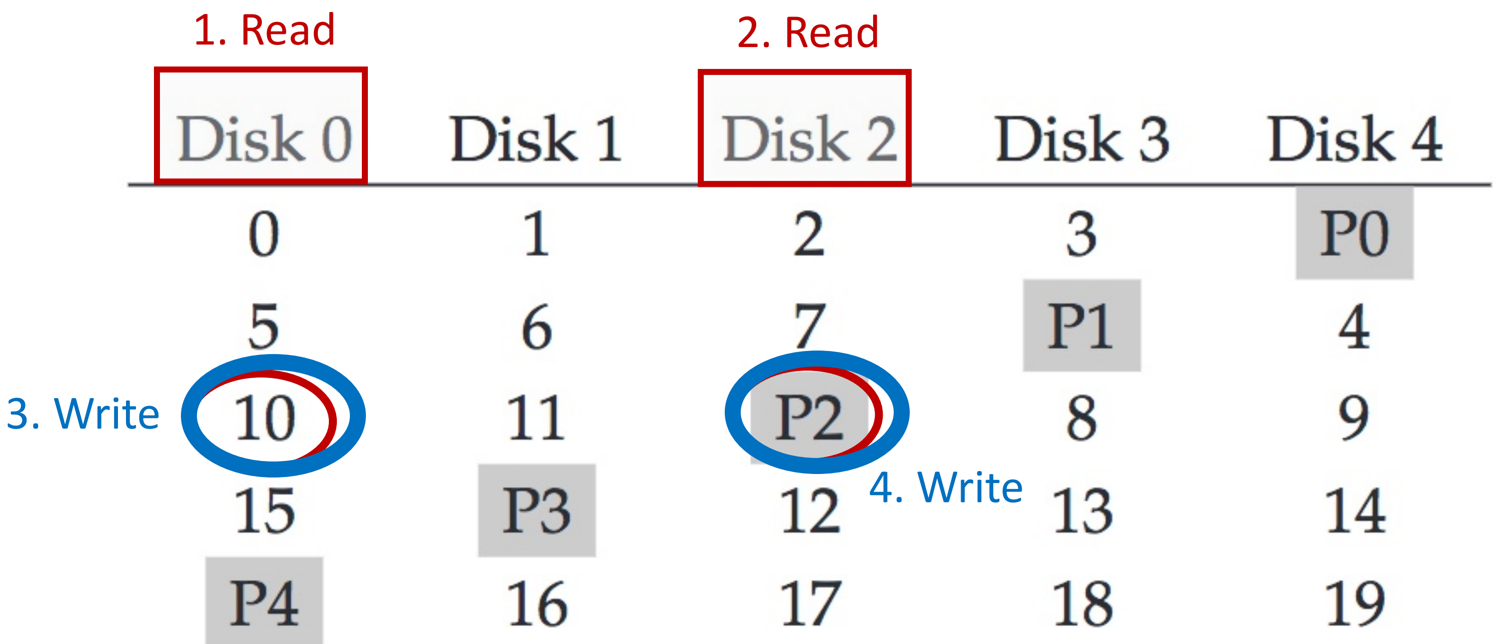
RAID-5: Random Write



Random write to Block 10 on Disk 0

1. Read Block 10
2. Read the Parity P2
3. Write new data in Block 10

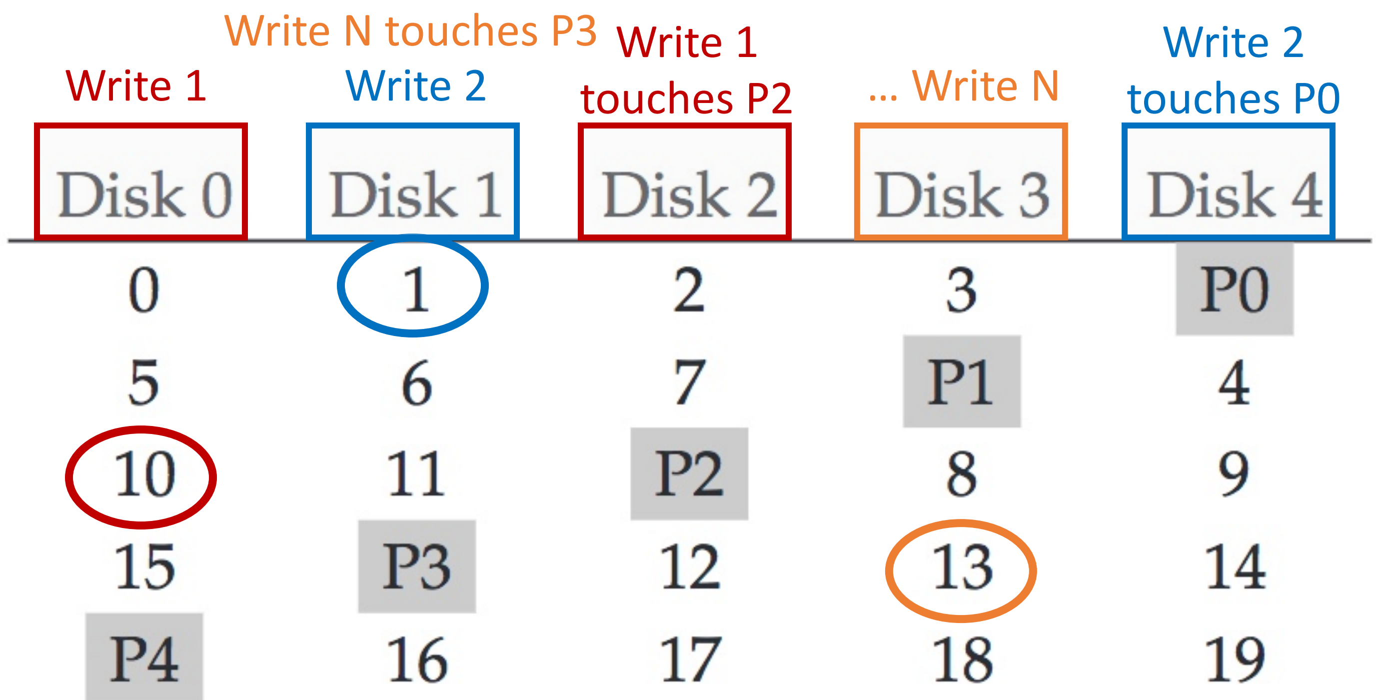
RAID-5: Random Write



Random write to Block 10 on Disk 0

1. Read Block 10
2. Read the Parity P2
3. Write new data in Block 10
4. Write new parity P2

RAID-5: Random Write



Performance reasoning

Generally, for a large number of random read/write requests, RAID-5 will be able to keep all disks busy: thus **N * R**

Each random (RAID-5) writes generates 4 physical I/O operations: thus **N * R / 4**

RAID-5 Analysis

1. What is capacity? (N-1) * C

2. How many disks can fail? 1

3. Throughput?
   - Seq read: (N-1) * S
   - Seq write: (N-1) * S
   - Rand read: N * R
   - Rand write: N * R/4

4. Latency? D, 2D

Summary: All RAID's

	Reliability	Capacity
RAID-0	0	C * N
RAID-1	1 or N/2	C * N/2
RAID-4	1	C * (N-1)
RAID-5	1	C * (N-1)

Summary: All RAID's

	Seq Read	Seq Write	Rand Read	Rand Write
RAID-0	N * S	N * S	N * R	N * R
RAID-1	N/2 * S	N/2 * S	N * R	N/2 * R
RAID-4	(N-1) * S	(N-1) * S	(N-1) * R	R/2
RAID-5	(N-1) * S	(N-1) * S	N * R	N/4 * R

Please Read the Textbook!

Please do read the textbook chapter “RAID” to gain a deeper understanding of the various analyses covered in lecture.