Persistence II: File System Implementation, RAID, and InfiniCache

CS 571: Operating Systems (Spring 2022)

Lecture 9

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Some material taken/derived from:

- Wisconsin CS-537 materials by Remzi Arpaci-Dusseau.

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

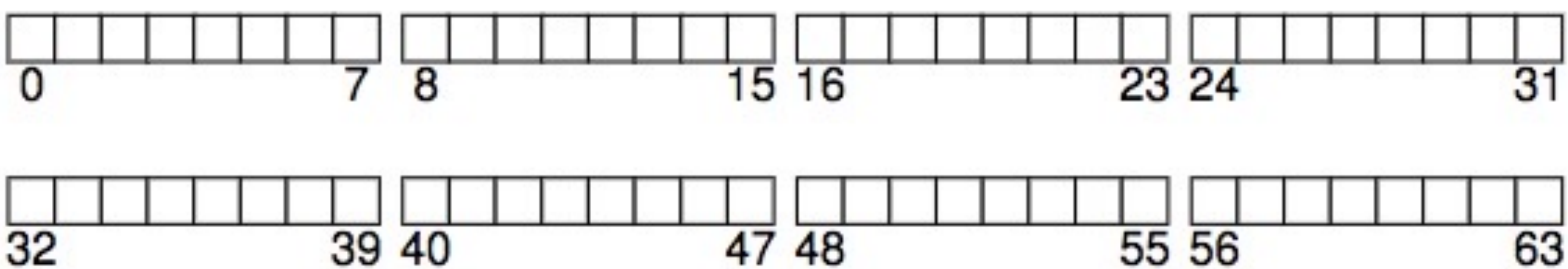
- File system locality & data layout policies
  - How data layout impacts locality for on-disk FS?

On-Disk Structures

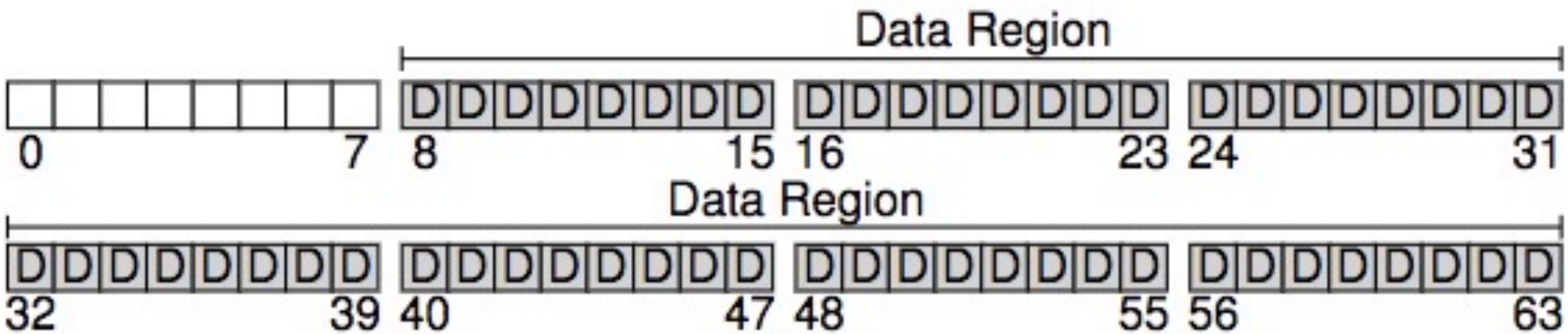
On-Disk Structures

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

On-Disk Structure: Empty Disk



On-Disk Structure: Data Blocks



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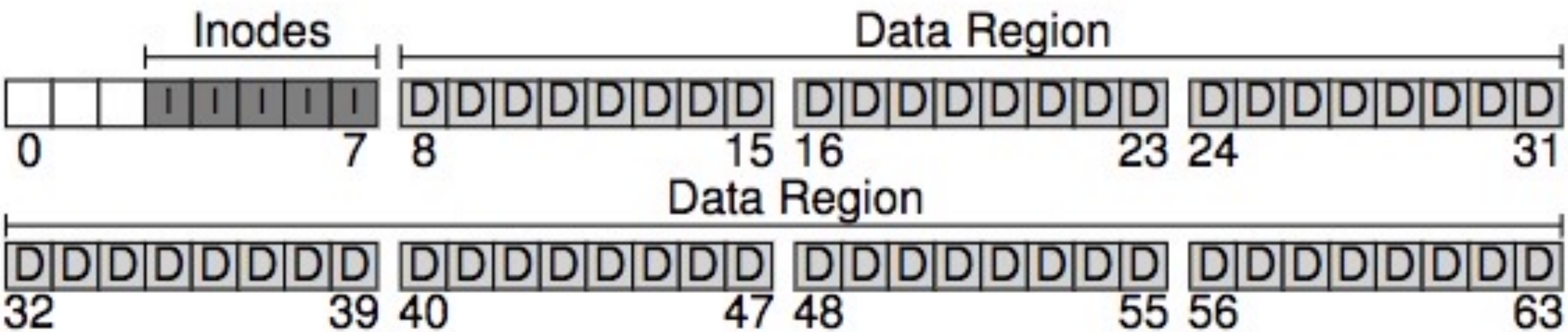
On-Disk Structure: Inodes



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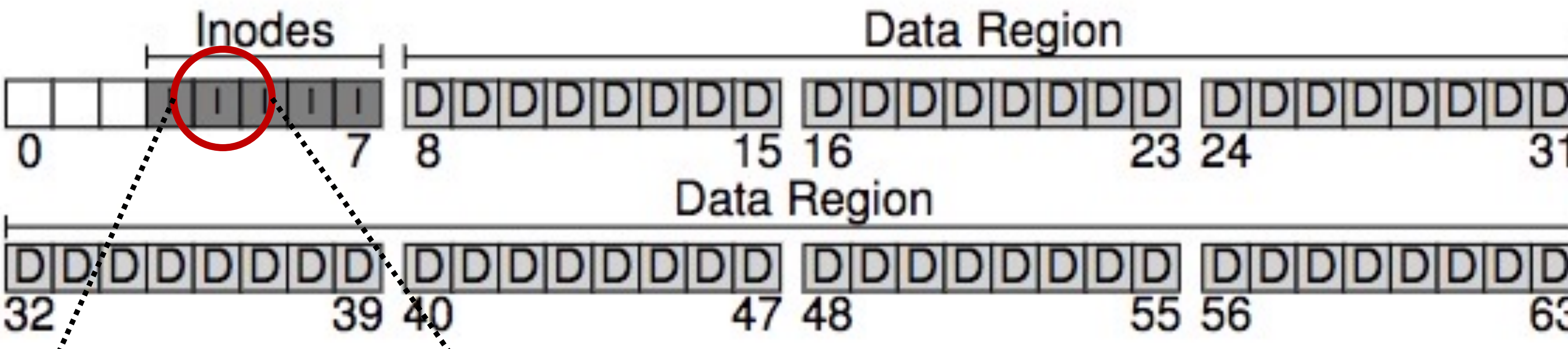
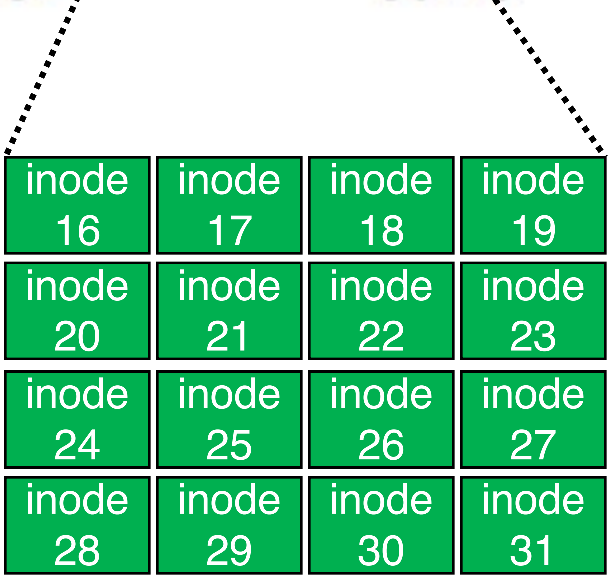
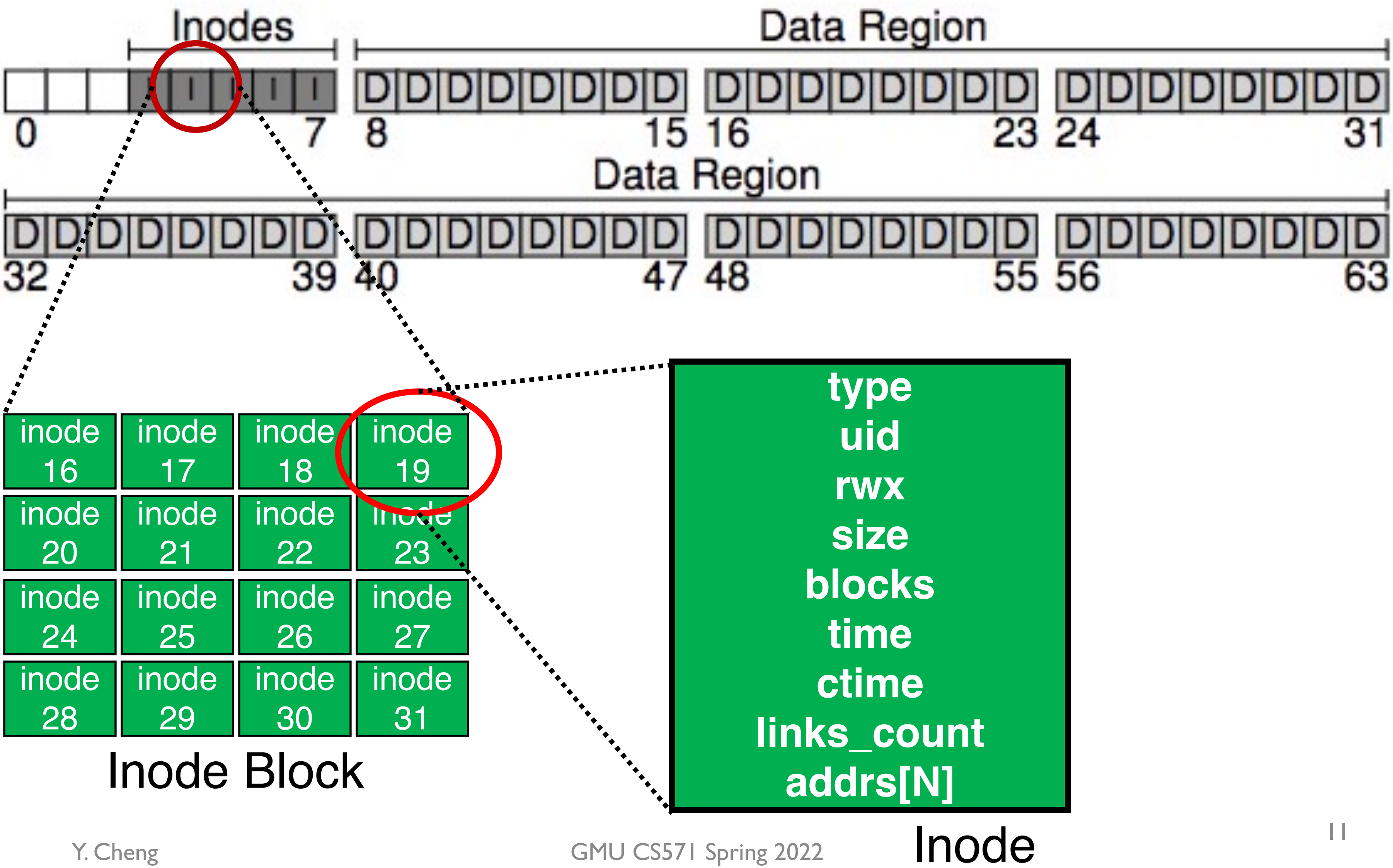




Inode Block

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

On-Disk Structure: Inodes



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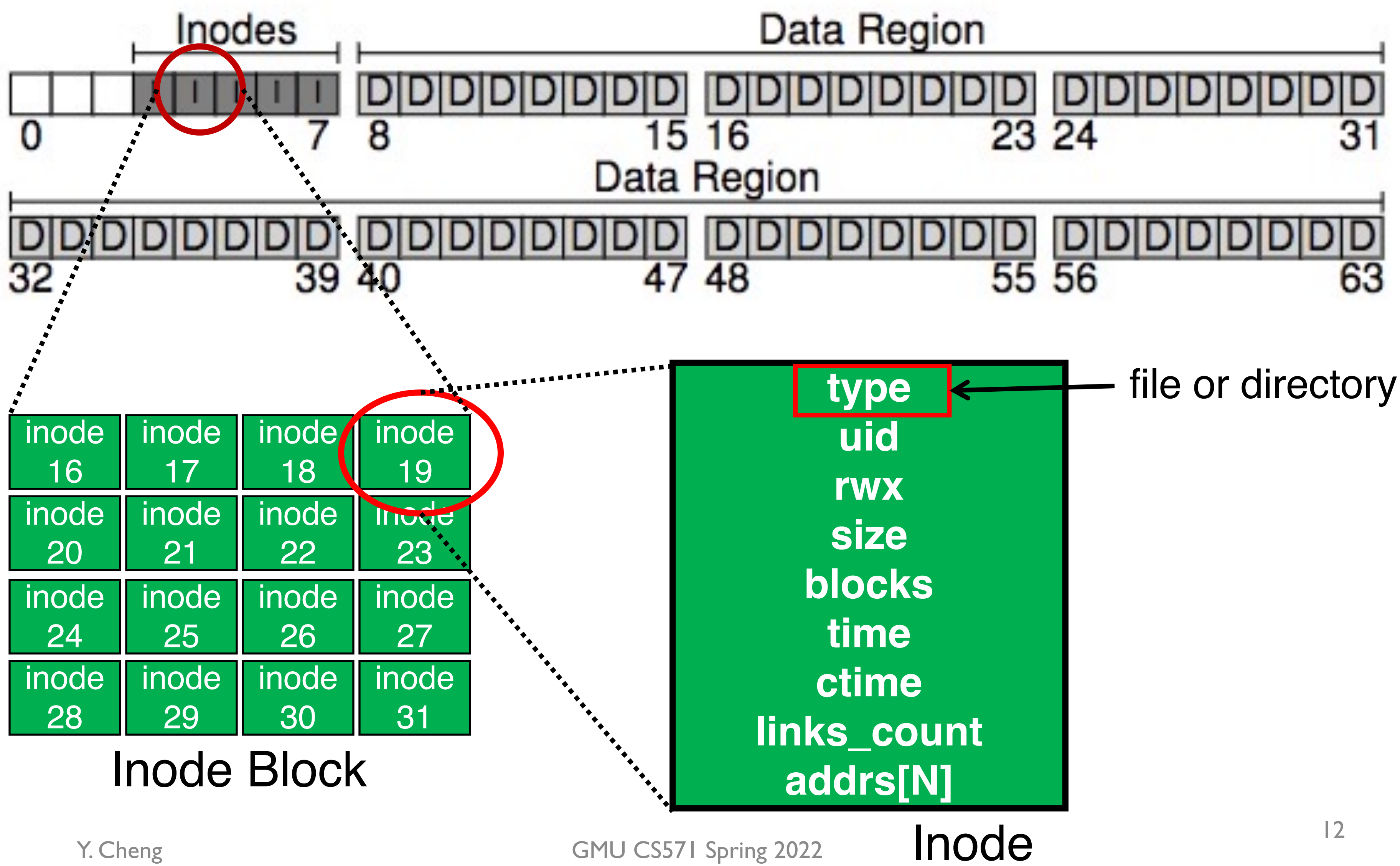

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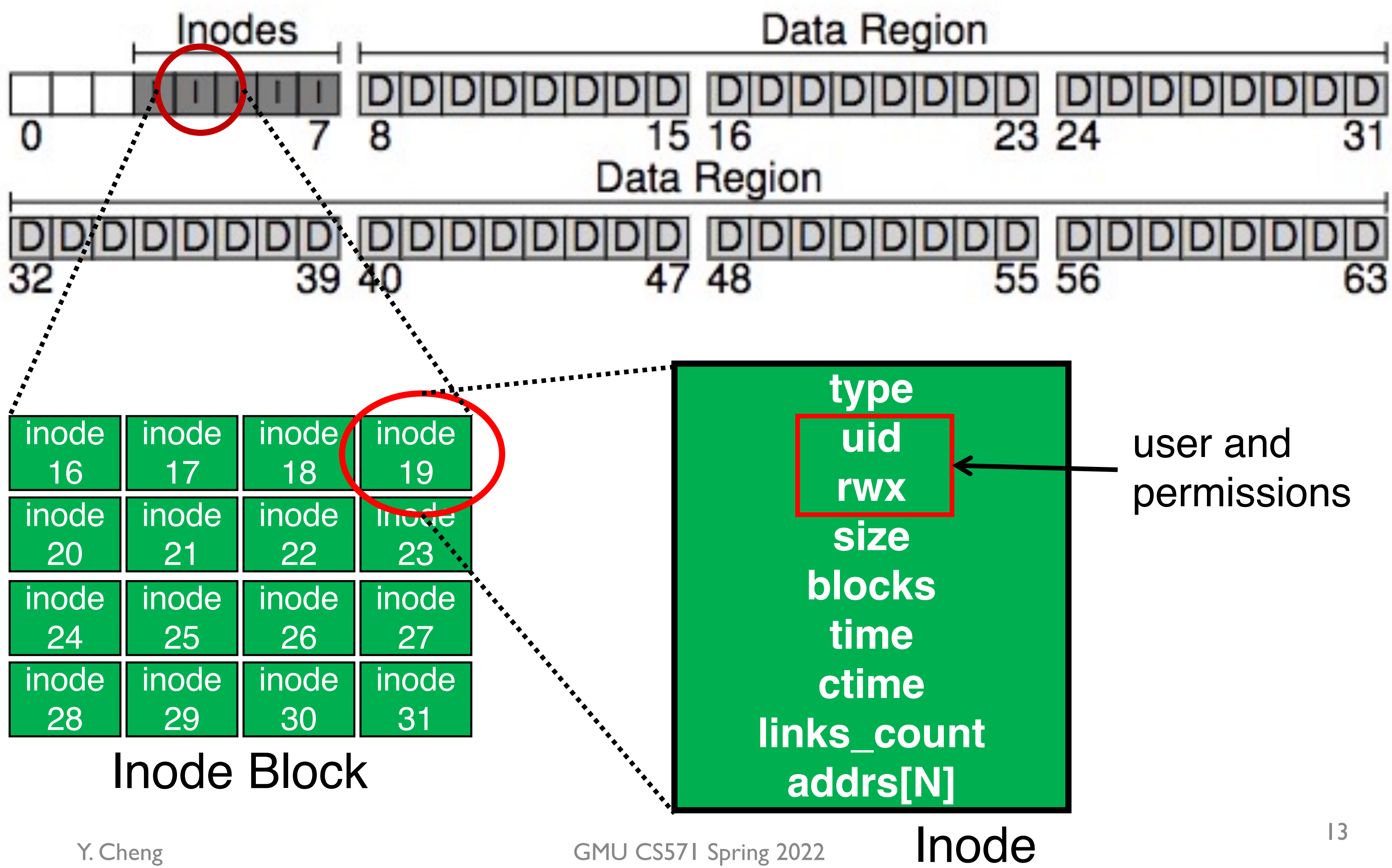

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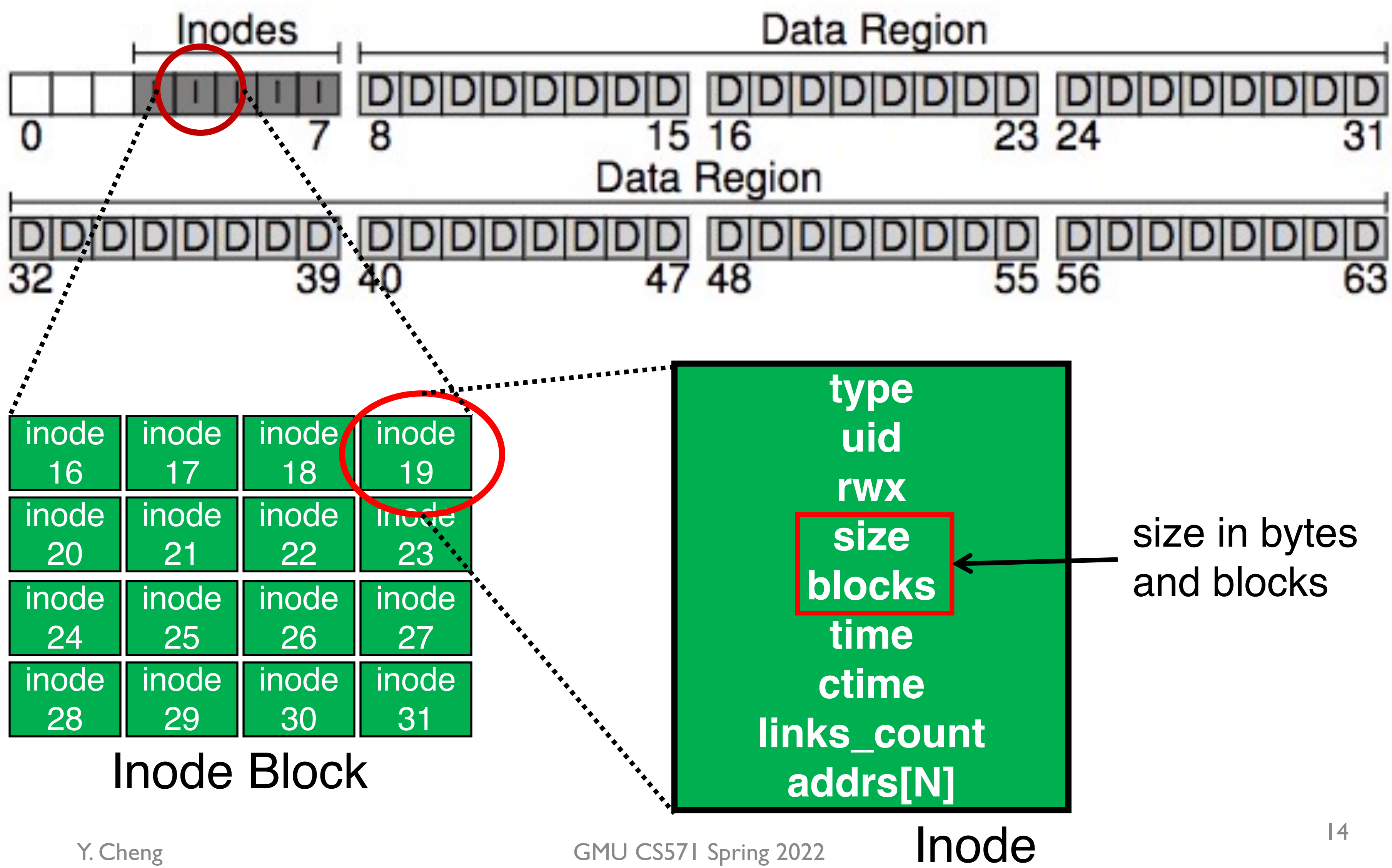
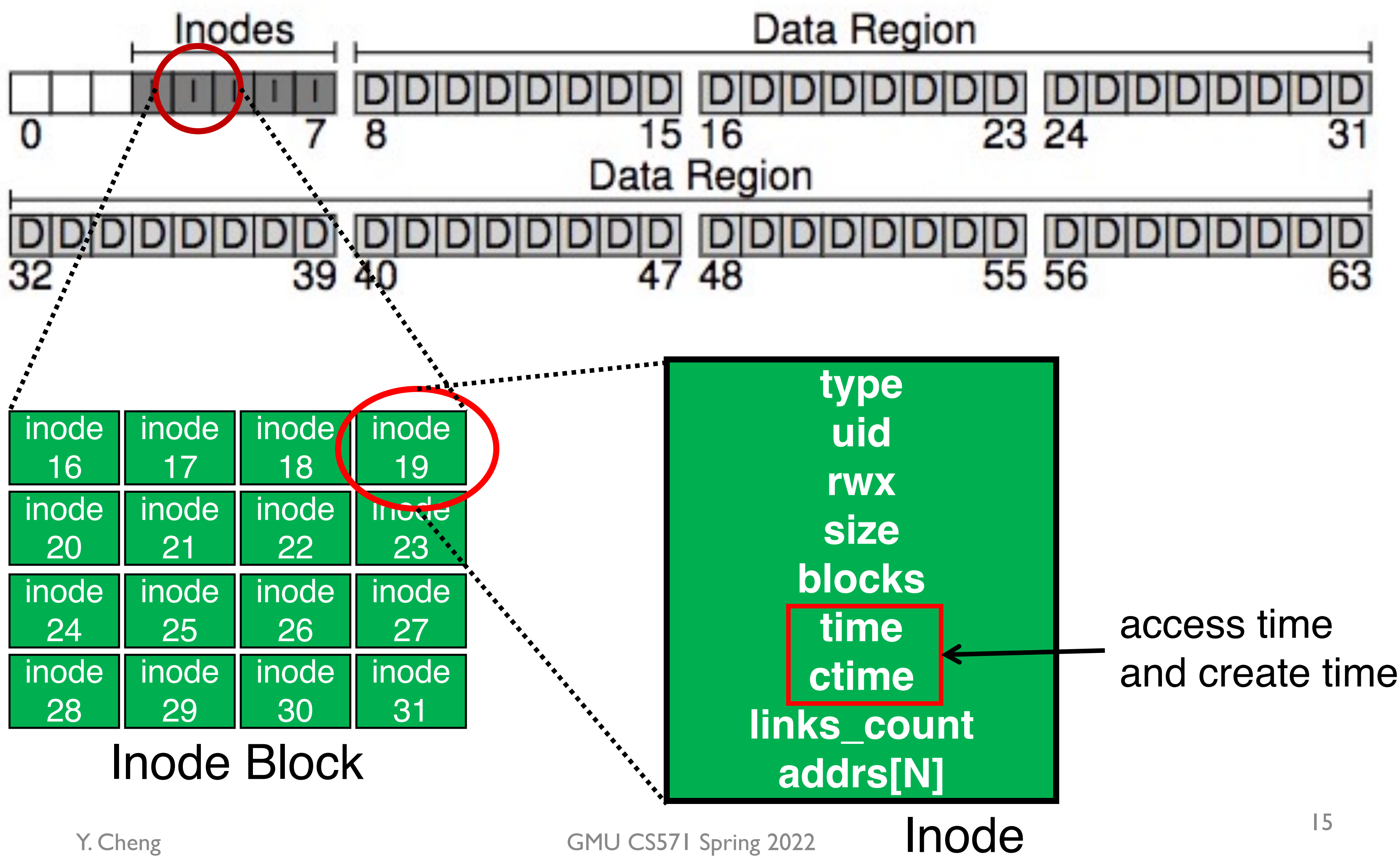
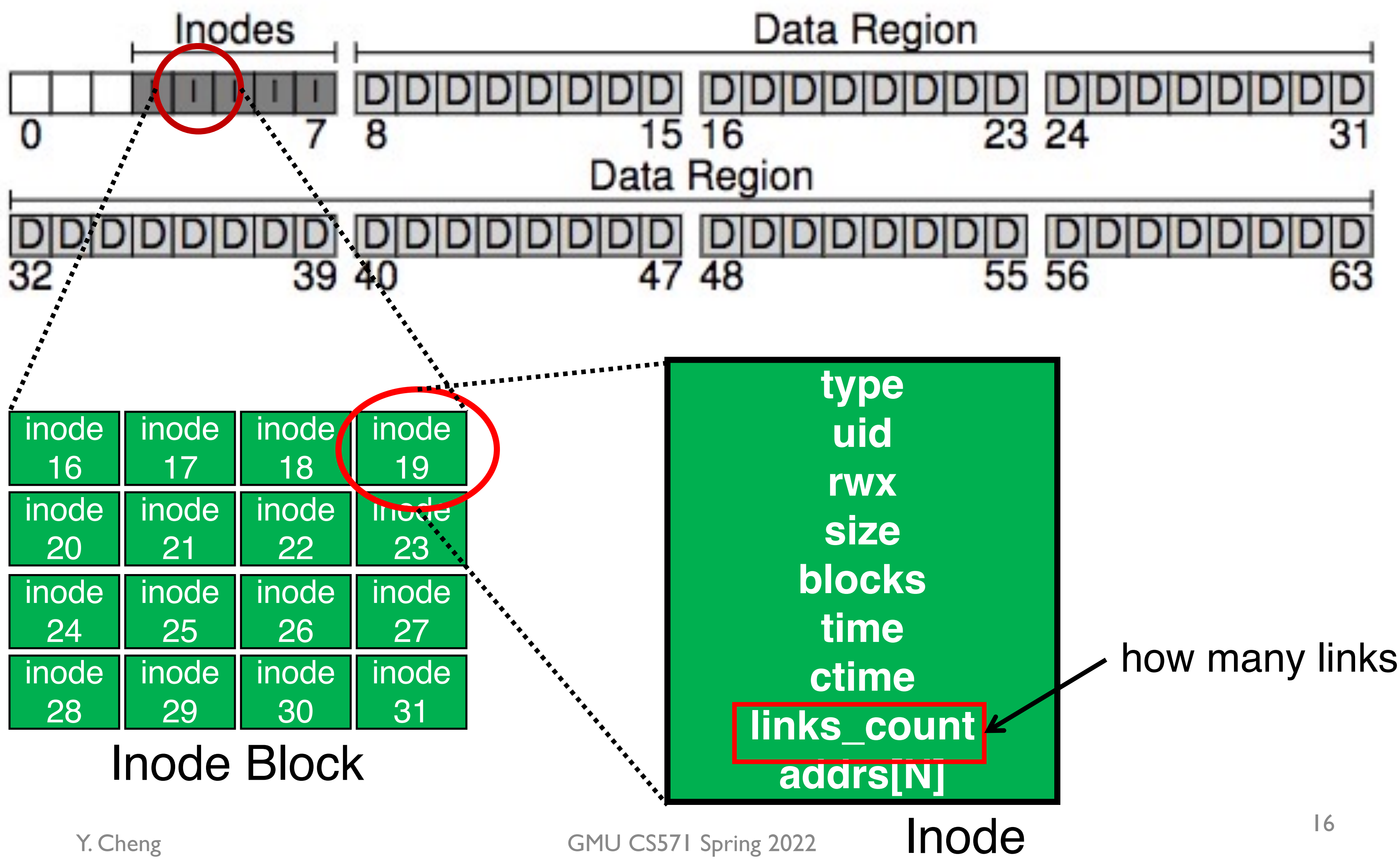


On-Disk Structure: Inodes



On-Disk Structure: Inodes



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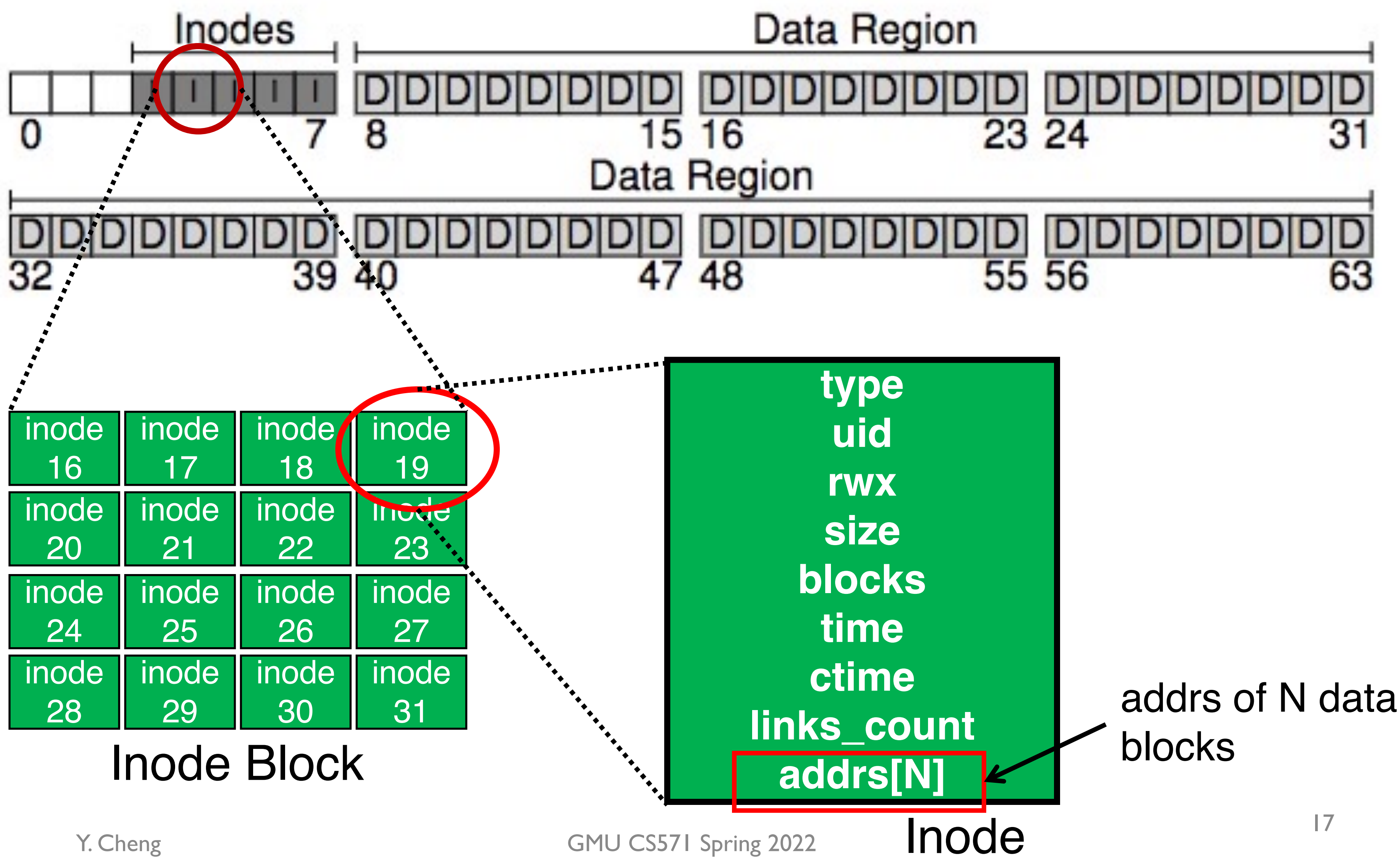

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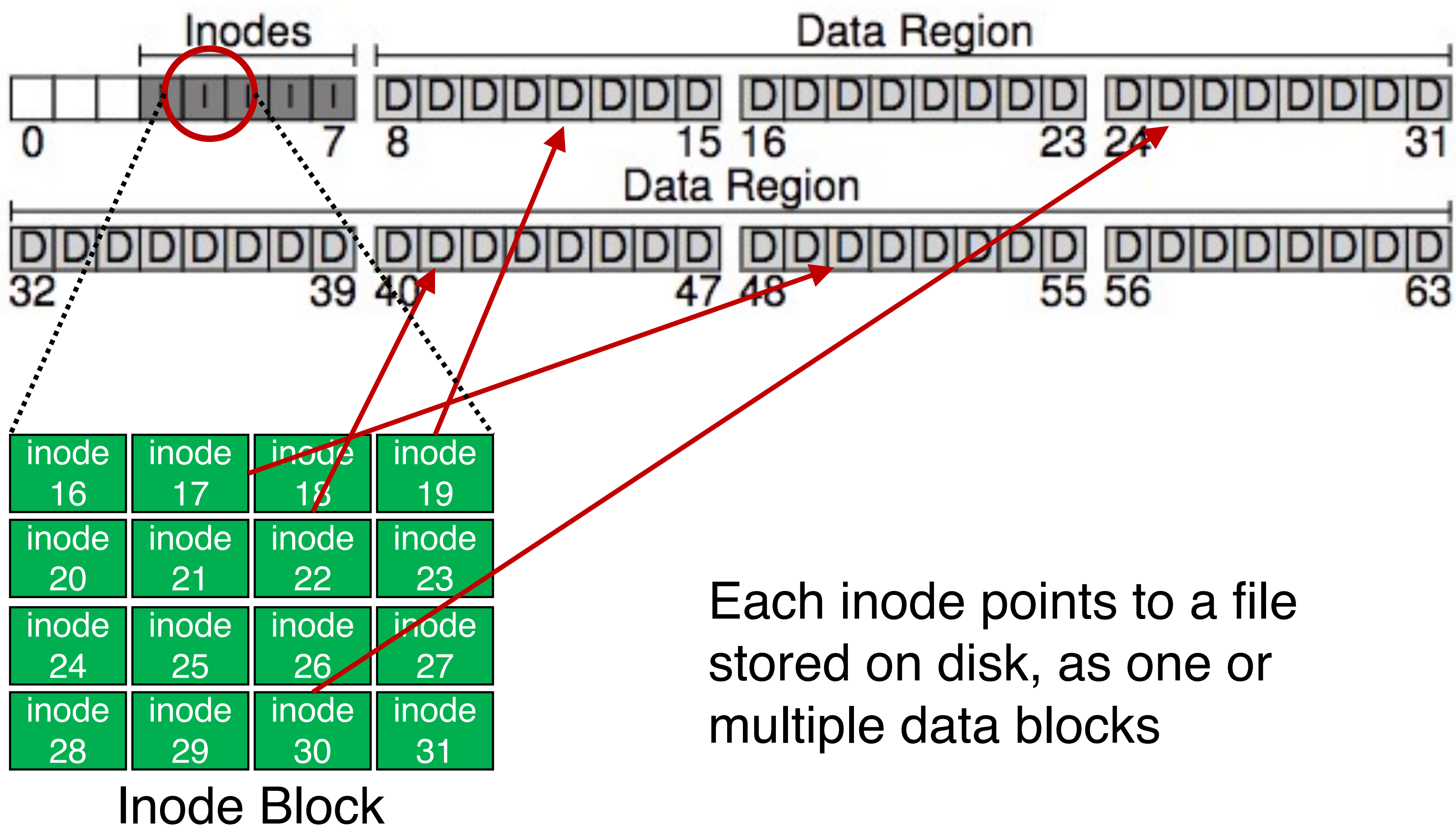

Each inode points to a file stored on disk, as one or multiple data blocks

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
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  - inode table
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  - inode bitmap
  - Superblock

Allocation

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

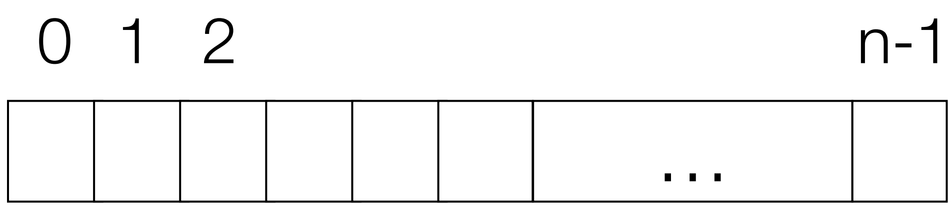
Allocation

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

- What are the tradeoffs?

Bitmap

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



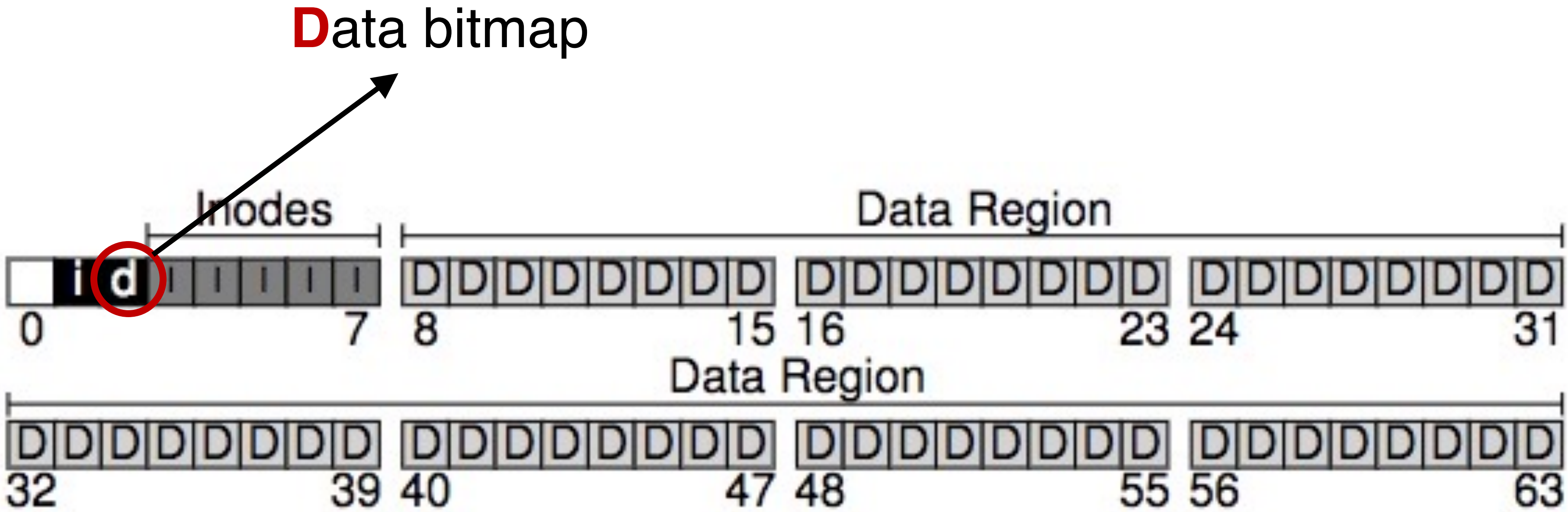
$$\text{bit}[i] = \begin{cases} 1 \Rightarrow \text{object}[i] \text{ in use} \\ 0 \Rightarrow \text{object}[i] \text{ free} \end{cases}$$

Allocation

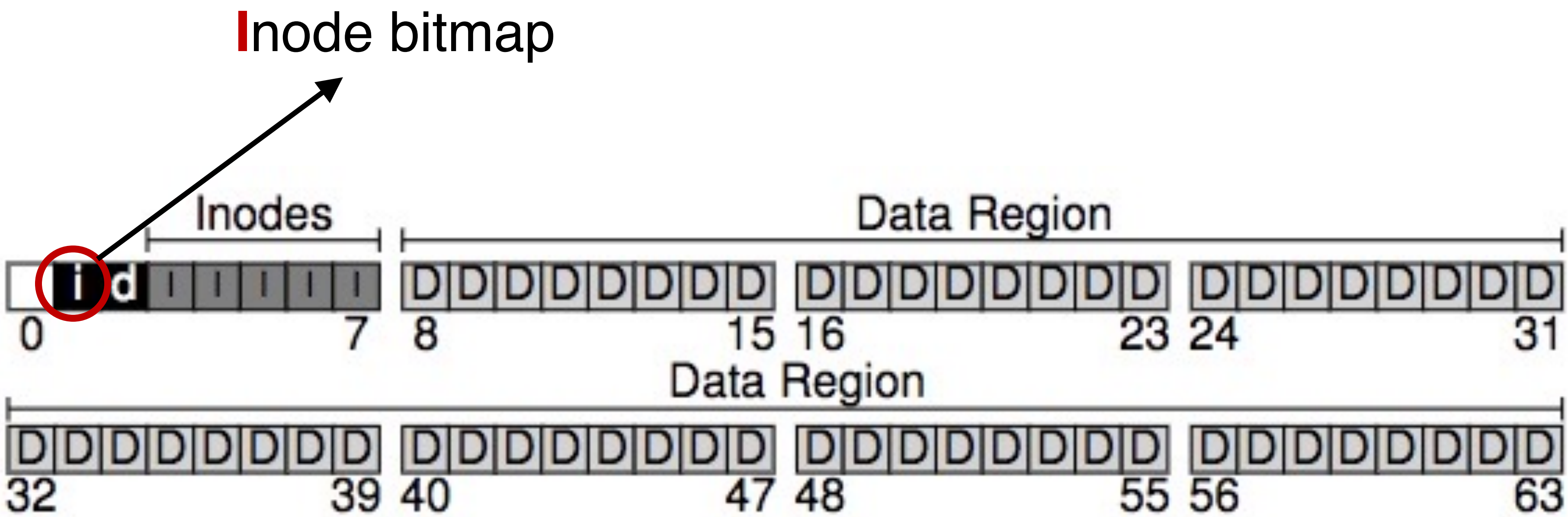
- How does file system find free data blocks or free inodes?
  - Free list
  - Bitmaps

- 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

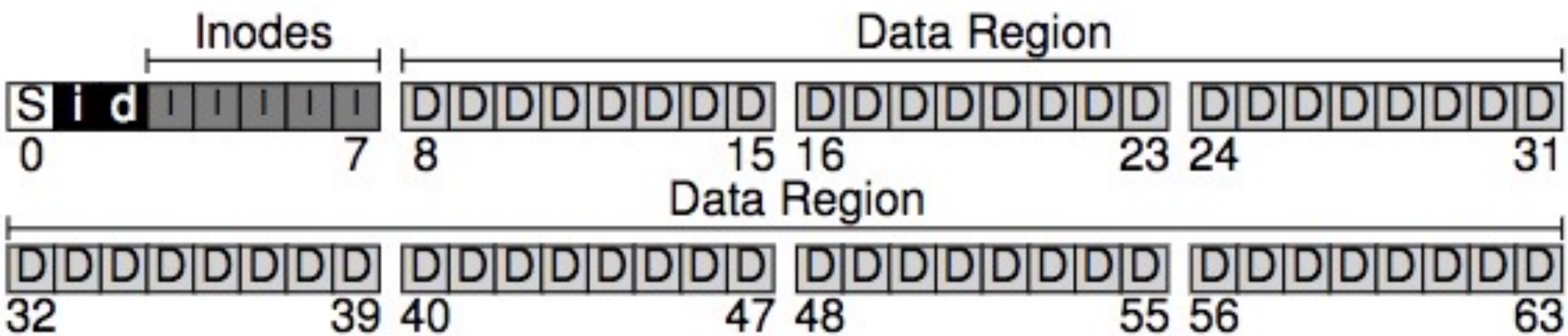
- Common file system structures
  - Data block
  - Inode table
  - Directories
  - Data bitmap
  - Inode bitmap
  - Superblock

On-Disk Structure: Superblock

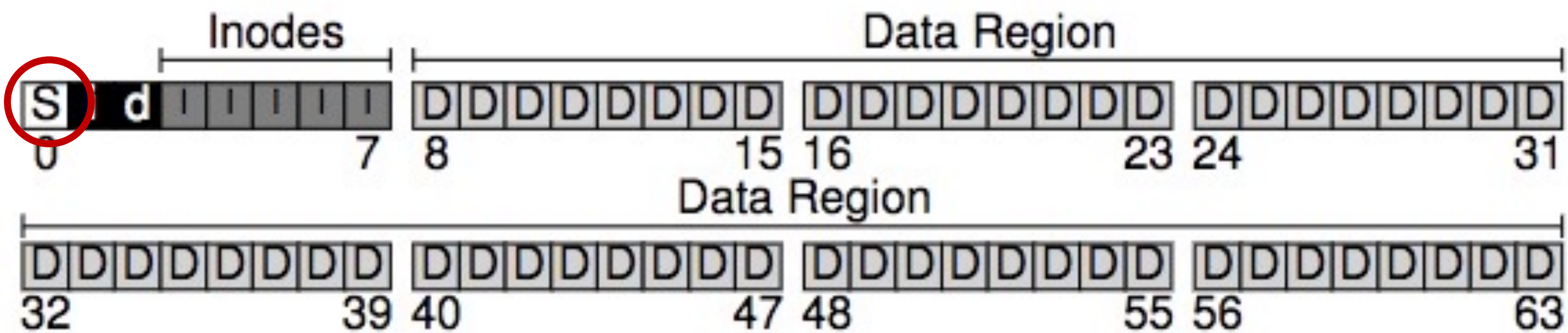
- Need to know basic file system configuration and runtime status, such as:
  - Block size
  - How many inodes are there
  - How much free space

- Store all these metadata info in a superblock

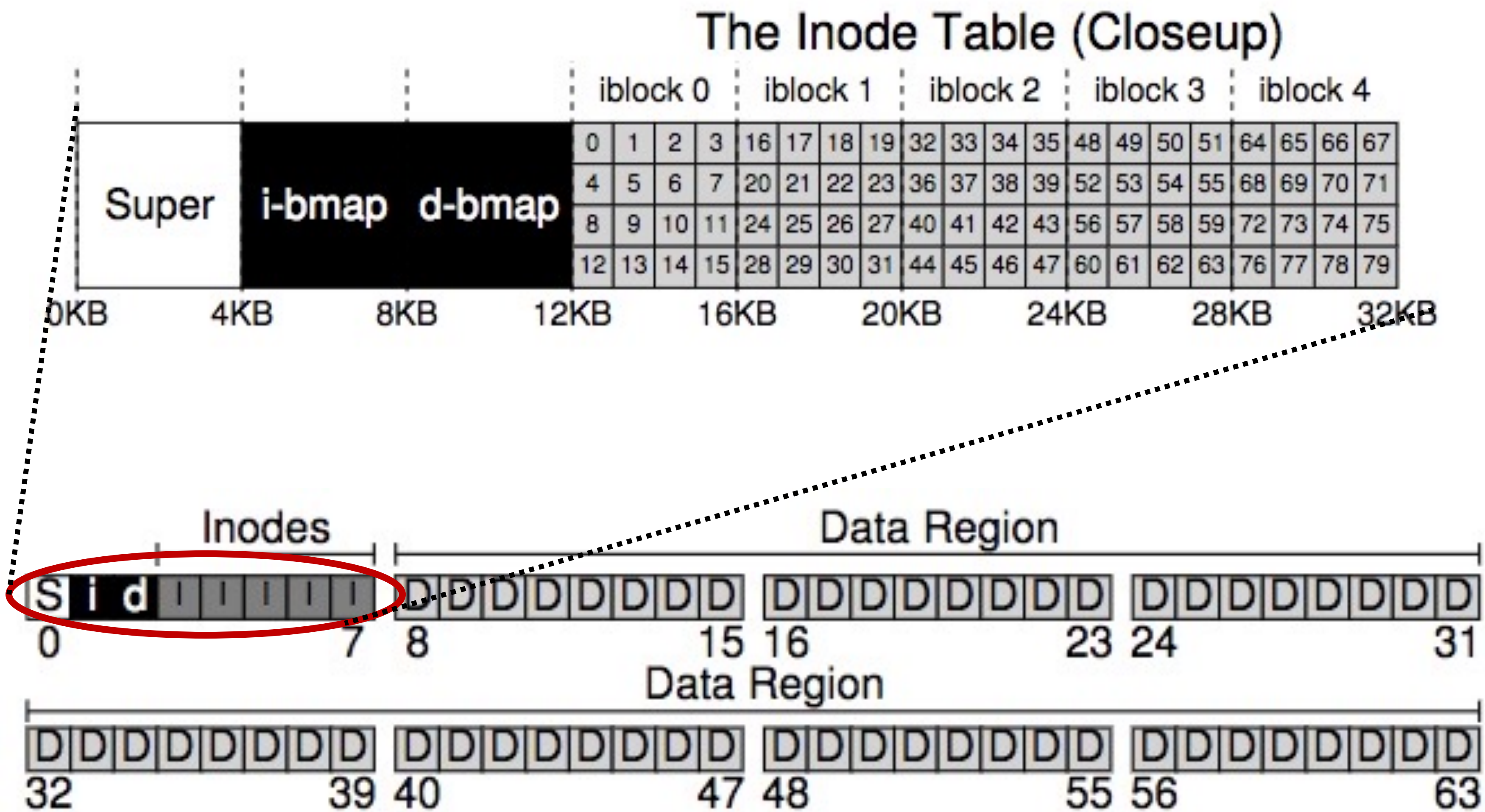
On-Disk Structure: Superblock



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

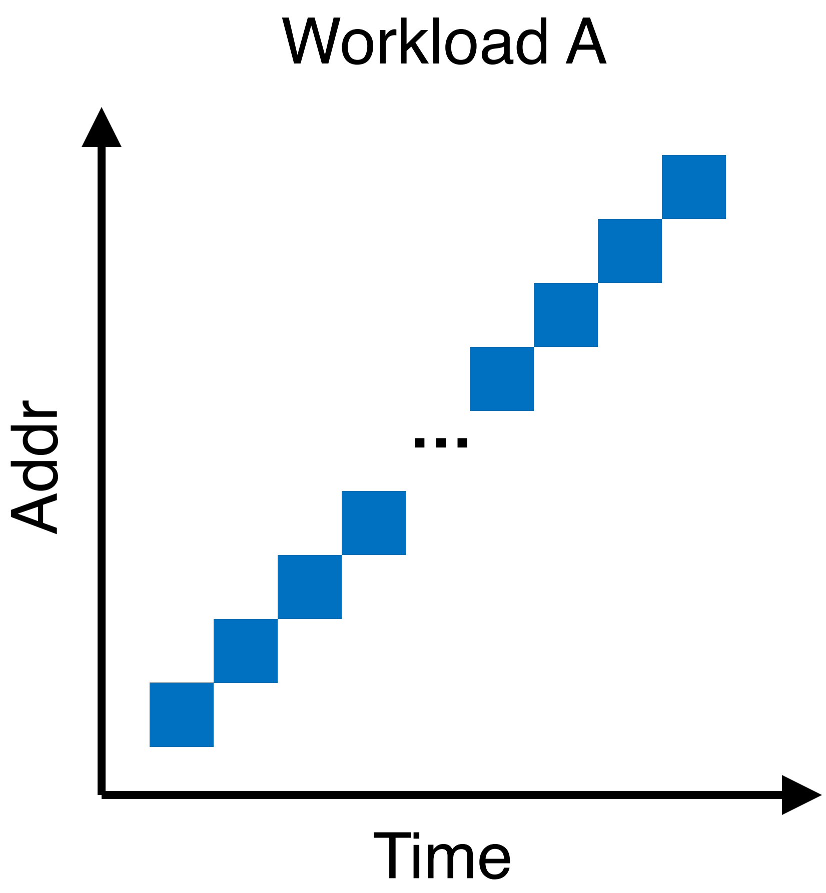
write to /foo/bar

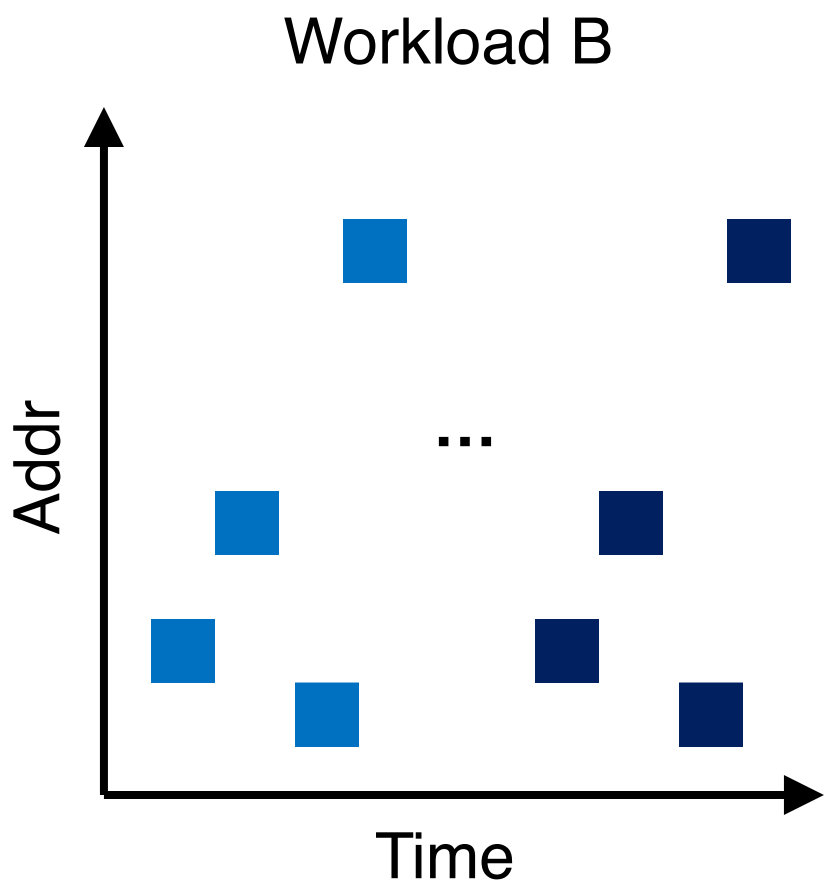
[point to block]

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

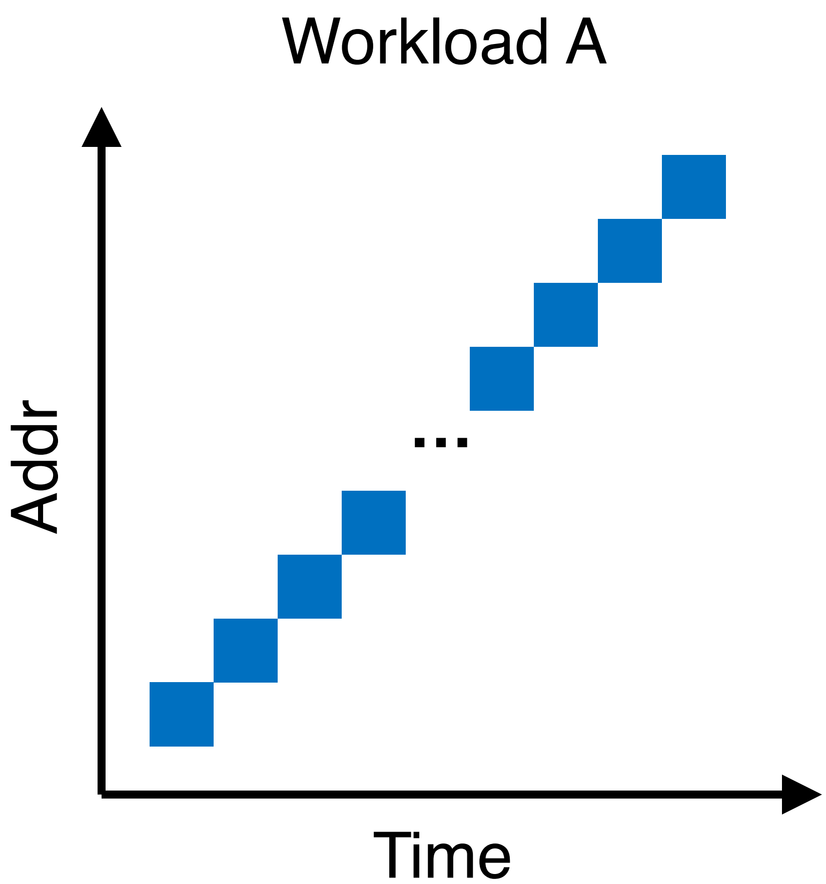
Locality & Data Layout

Locality Types

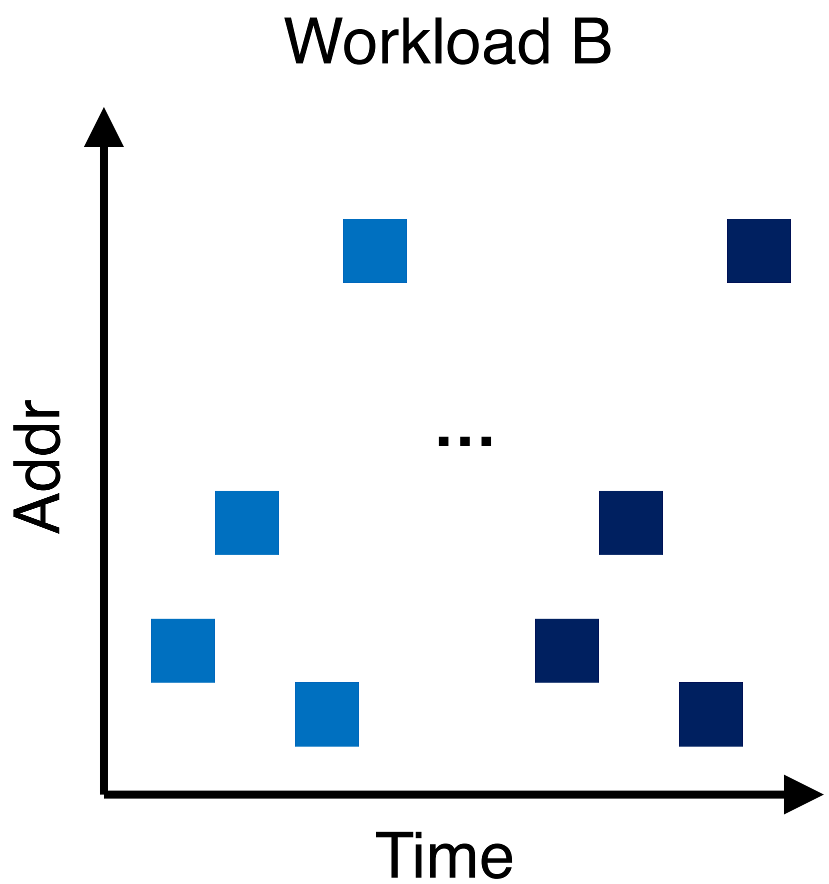




Locality Types



Spatial Locality



Temporal Locality

Locality Usefulness in the Context of Disk-based File Systems

- What types of locality are useful for a cache?

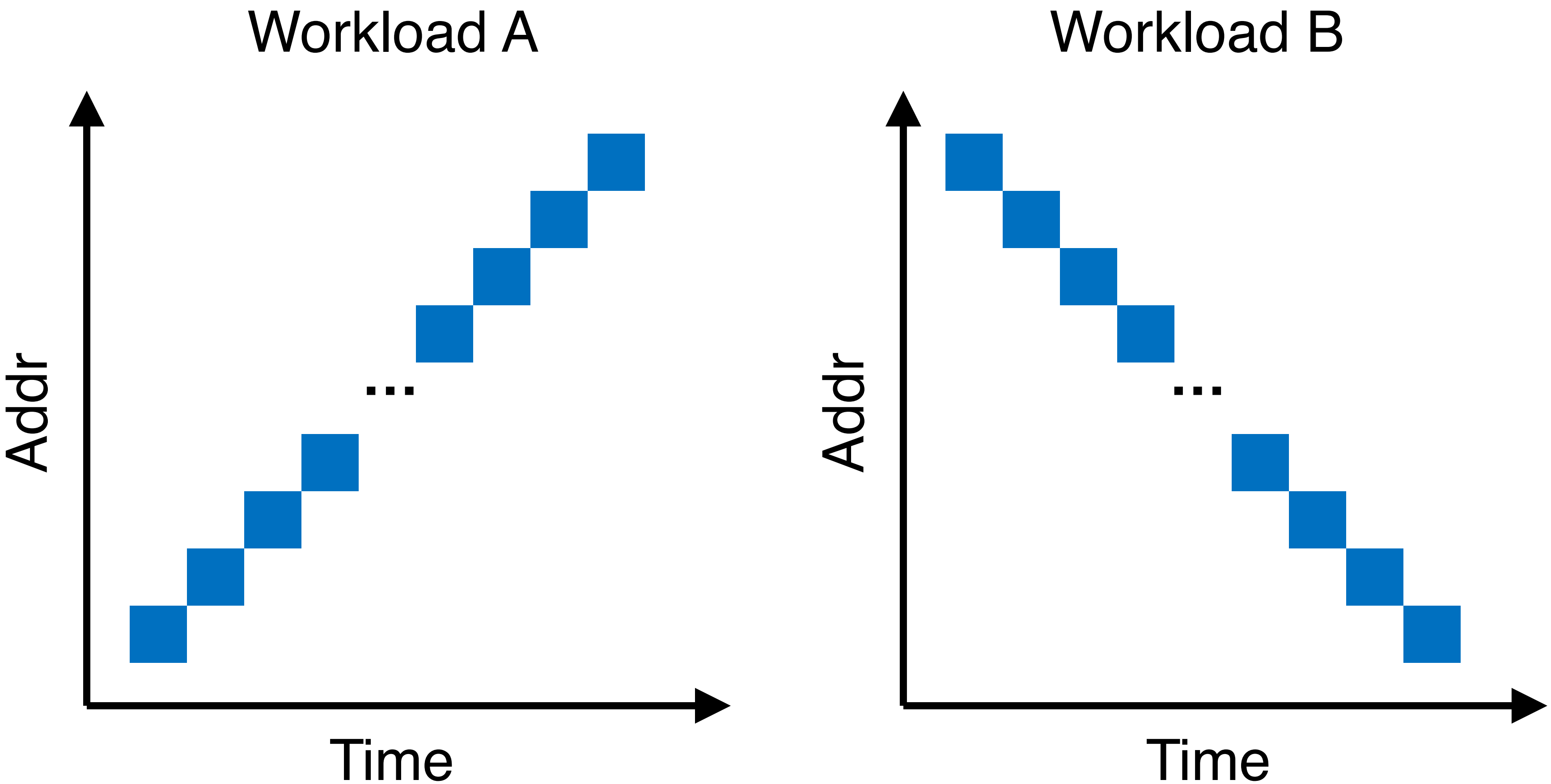
- What types of locality are useful for a disk?

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



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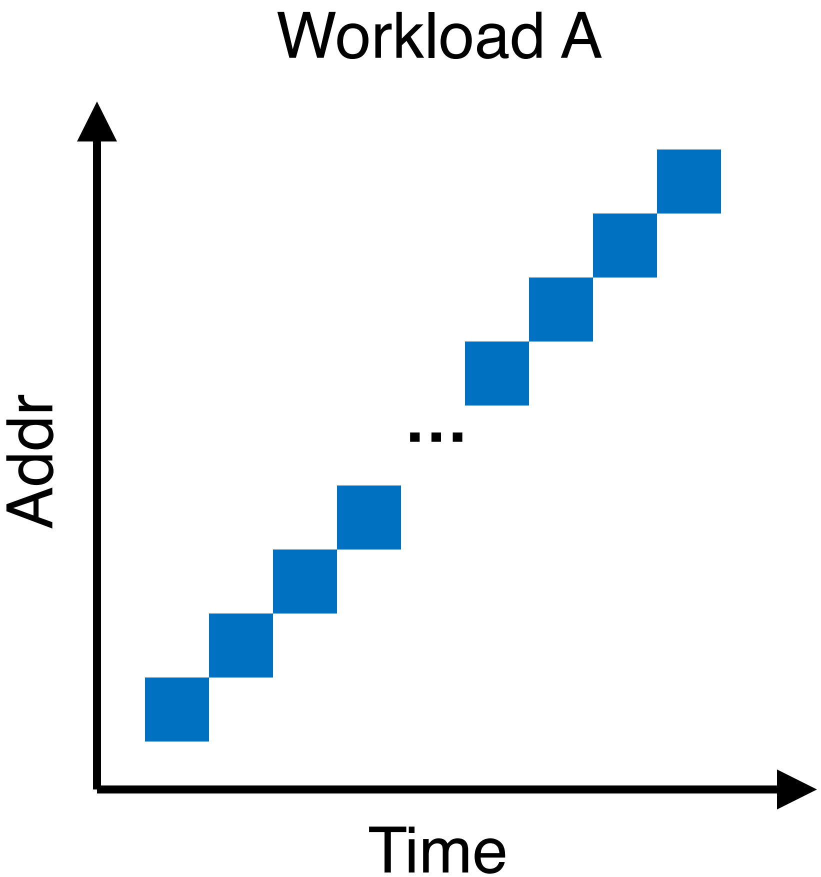
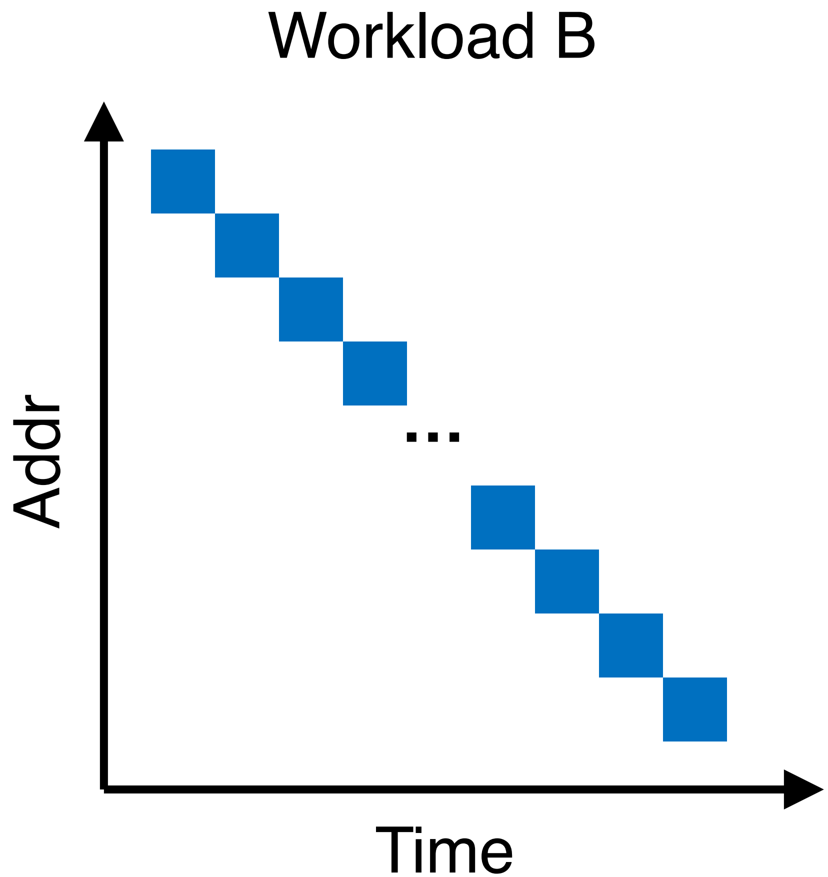
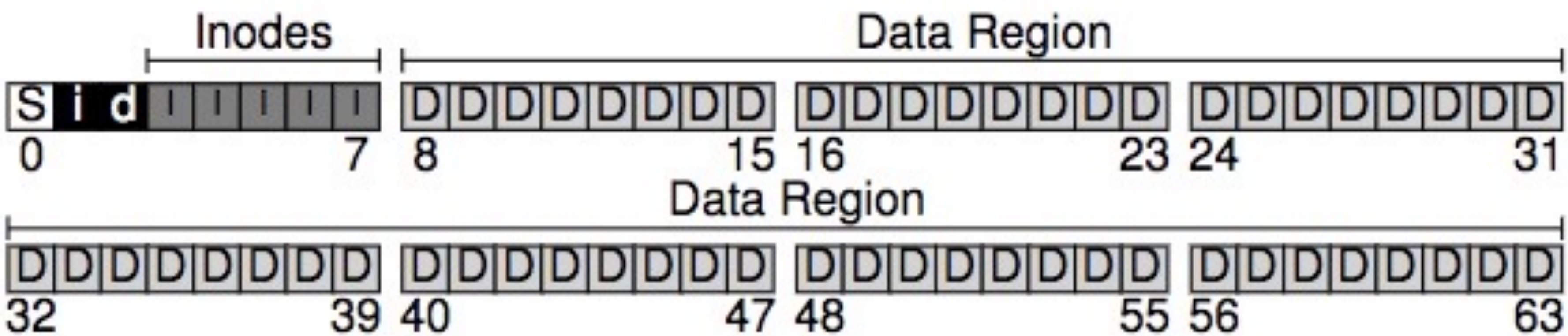


Fast

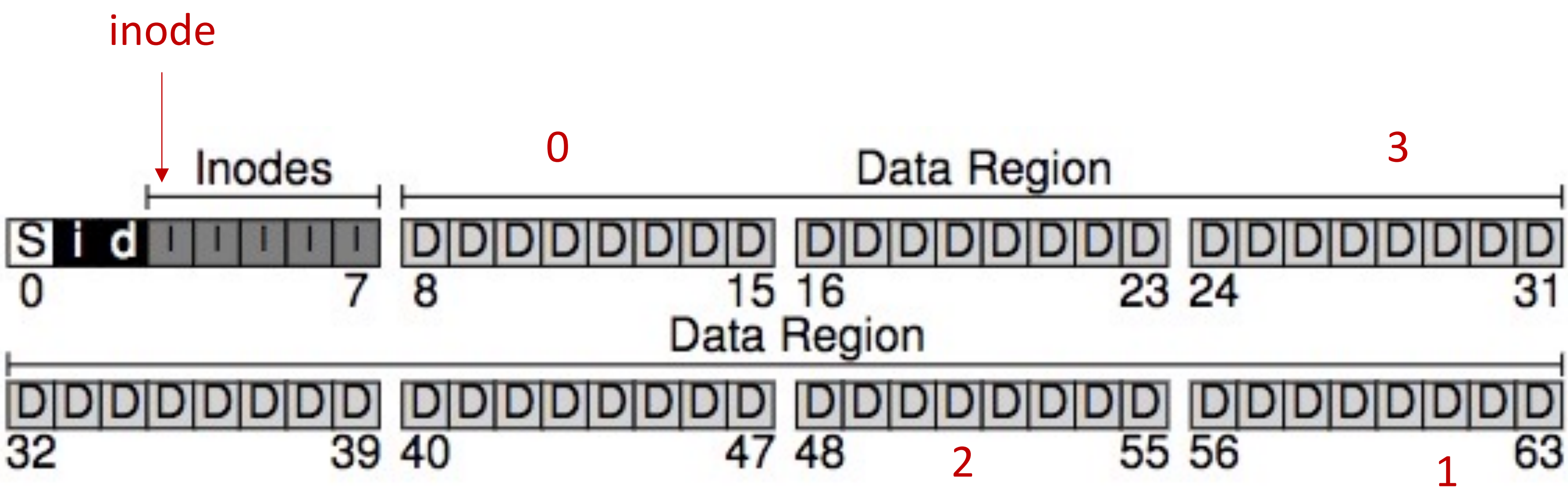


Slow

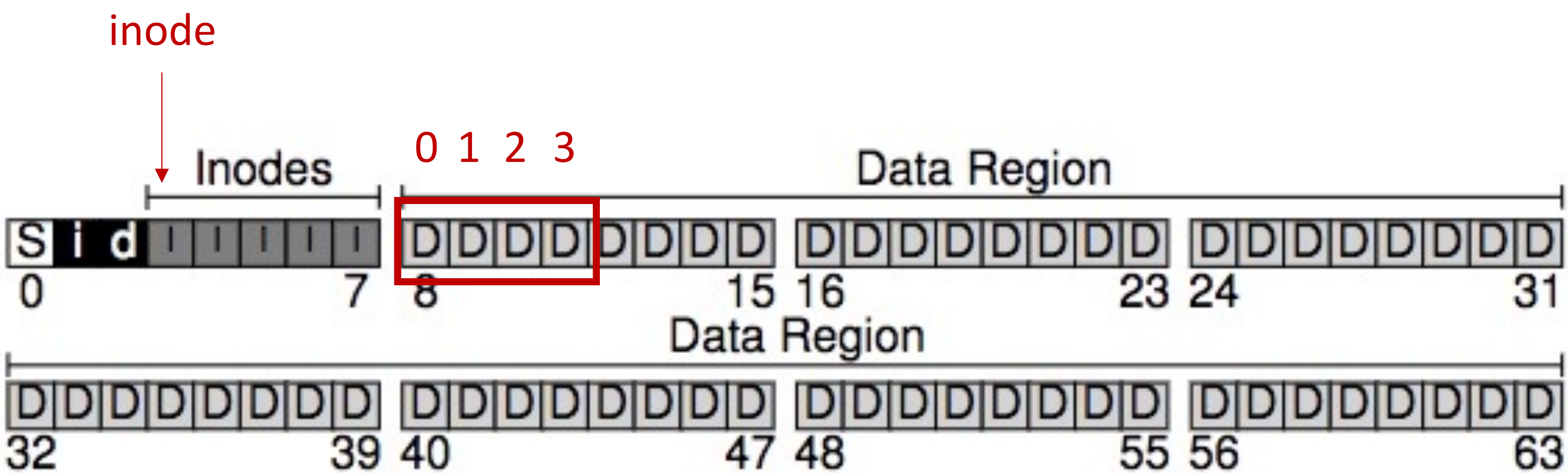
Policy: Choose Inode, Data Blocks



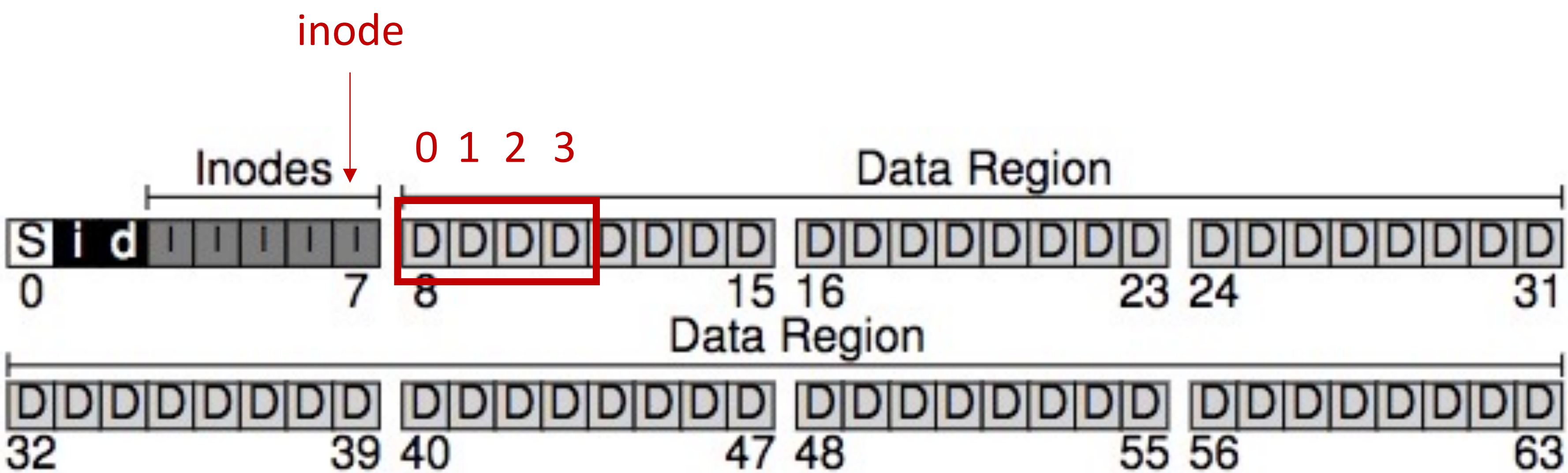
Bad File Layout



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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- 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 it to be faster
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- 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

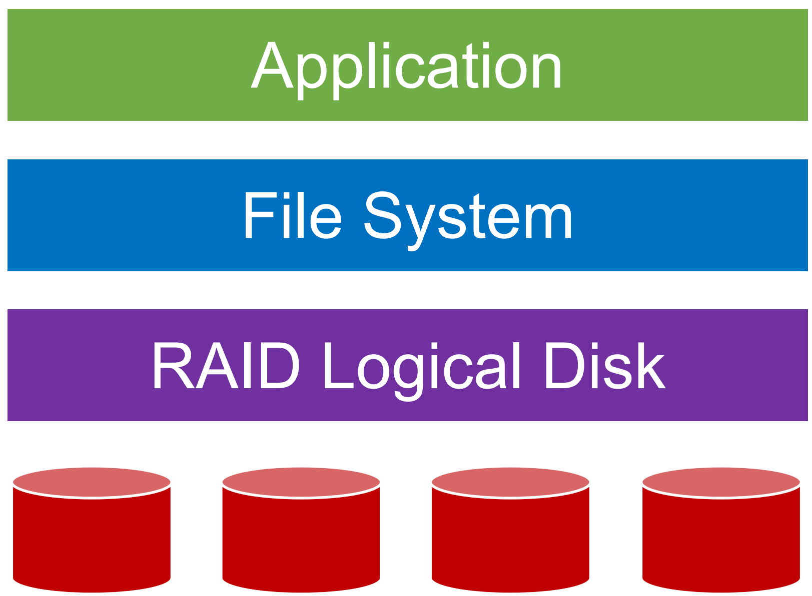
Only One Disk?

- 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

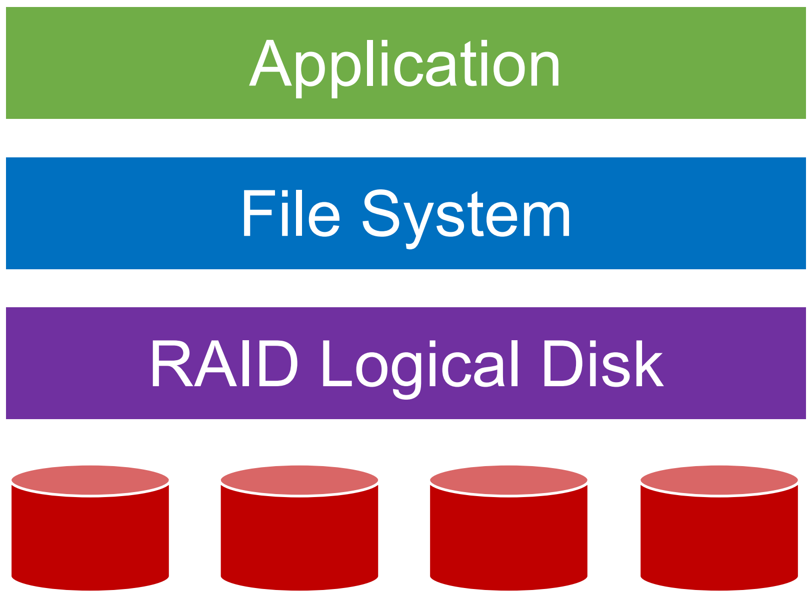


Build a logical disk from many physical disks

Solution: RAID

RAID: Redundant Array of Inexpensive Disks

RAID is
- Transparent
- Deployable



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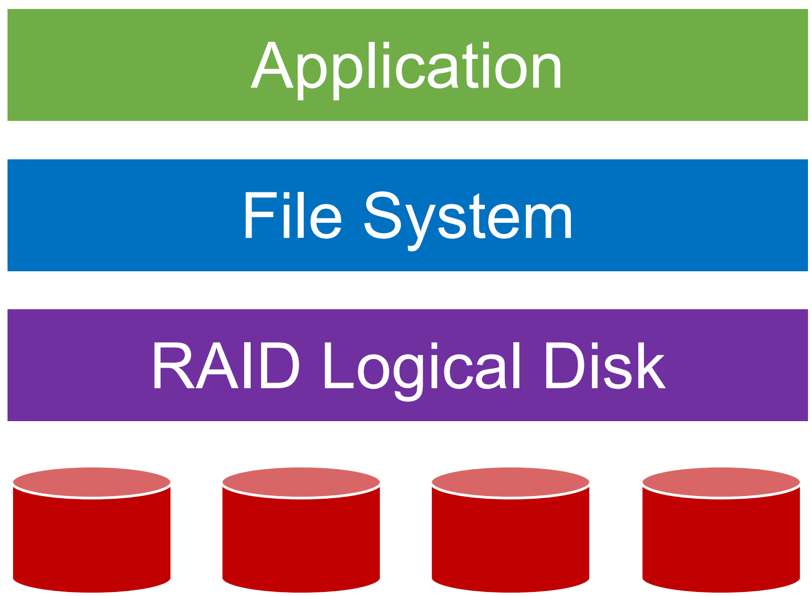

Logical disks gives
- Performance
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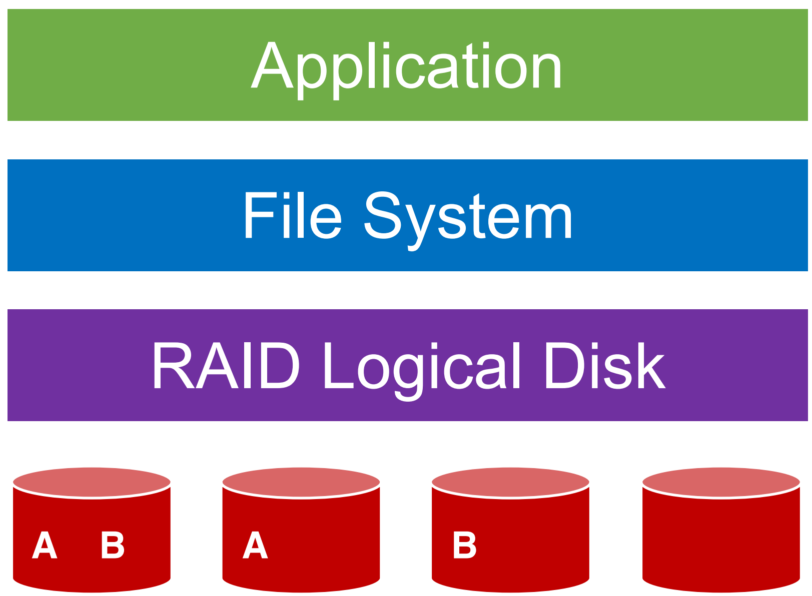

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Why Inexpensive Disks?

- Economies of scale! Cheap disks are popular

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

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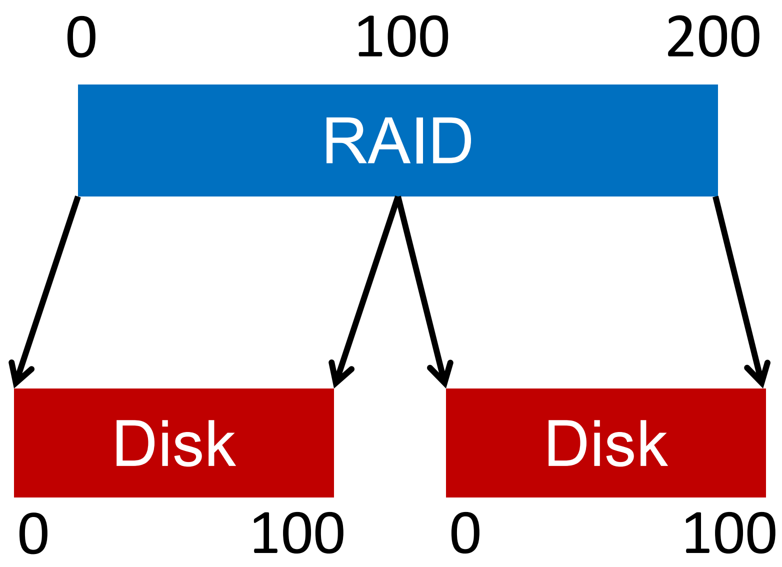
- Strategy: Write software to build high-quality logical devices from many cheap devices
  - Tradeoff: To compensate poor properties of cheap devices

General Strategy

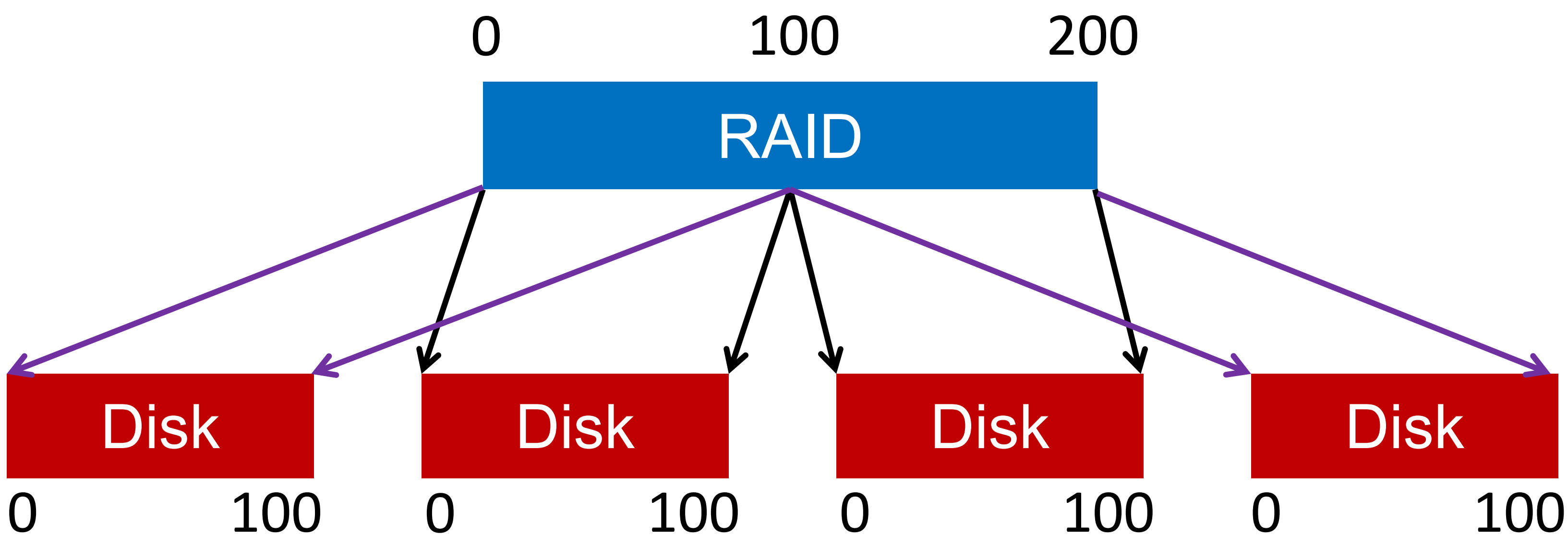
Build fast and large disks from smaller ones



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?
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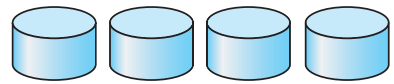
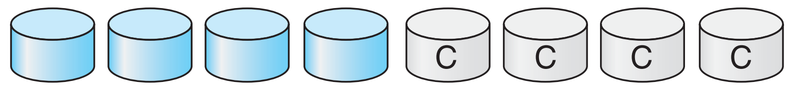
  - How much space can apps use?
- Reliability
  - How many disks can we safely lose?
  - Assume fail-stop model!

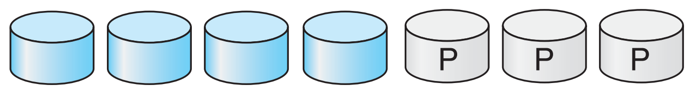
RAID Levels



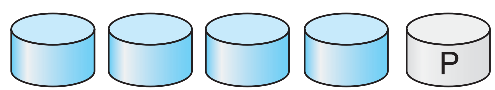
(a) RAID 0: non-redundant striping.



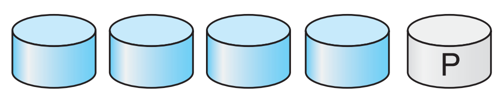
(b) RAID 1: mirrored disks.



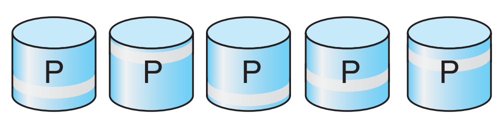
(c) RAID 2: memory-style error-correcting codes.



(d) RAID 3: bit-interleaved parity.

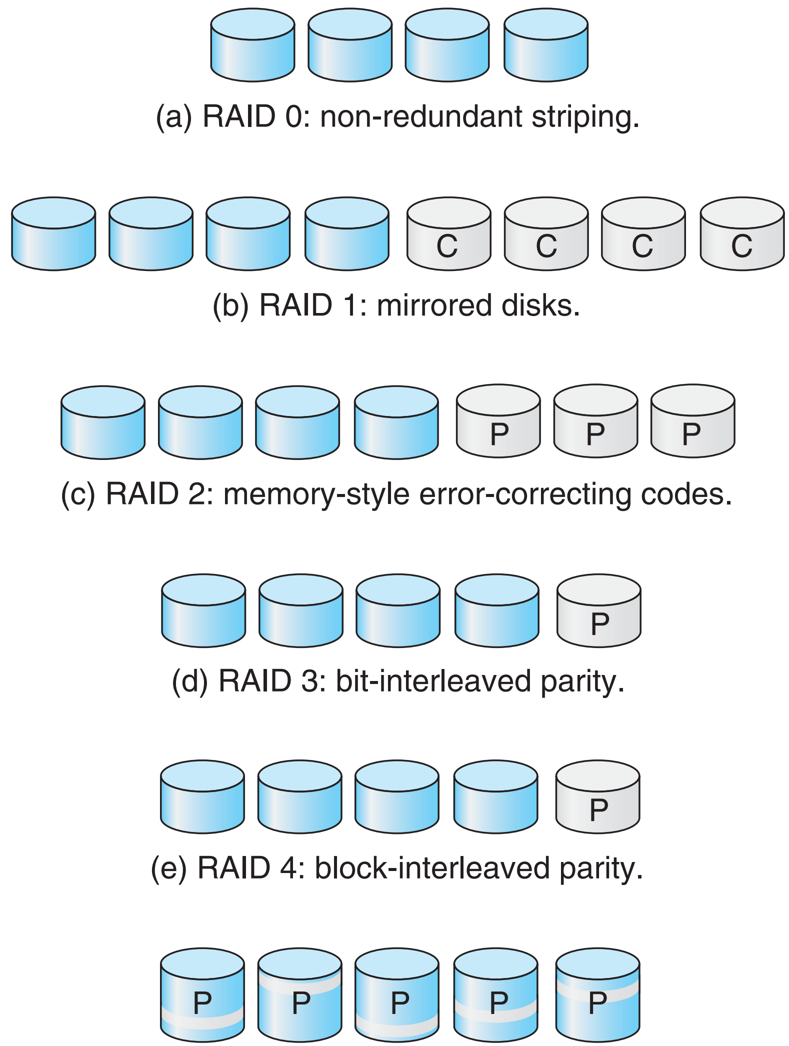


(e) RAID 4: block-interleaved parity.



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

RAID Level 0



(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.

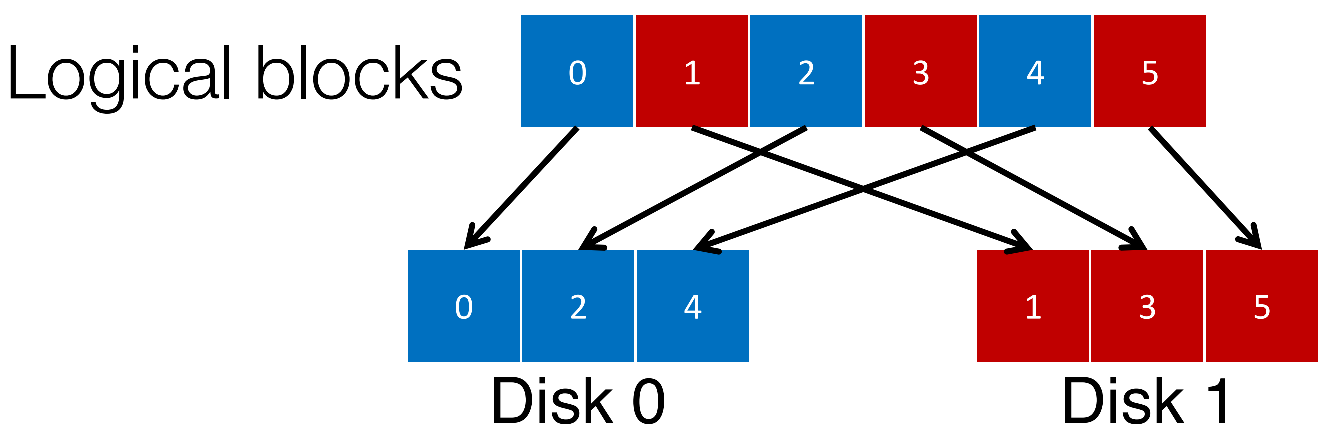
(e) RAID 4: block-interleaved parity.

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

RAID-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:	$\boxed{4}$	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?

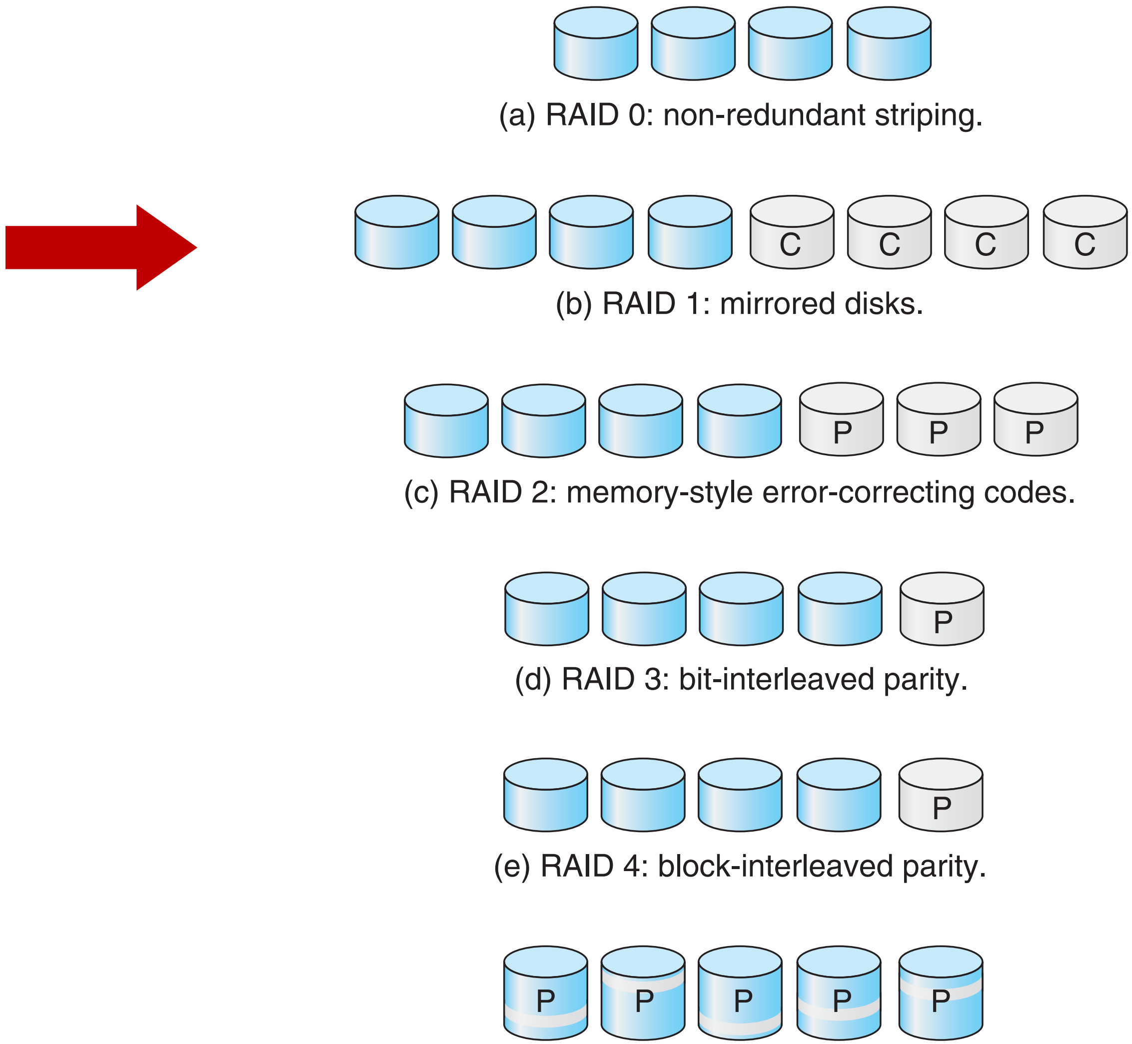
3. Throughput?

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.

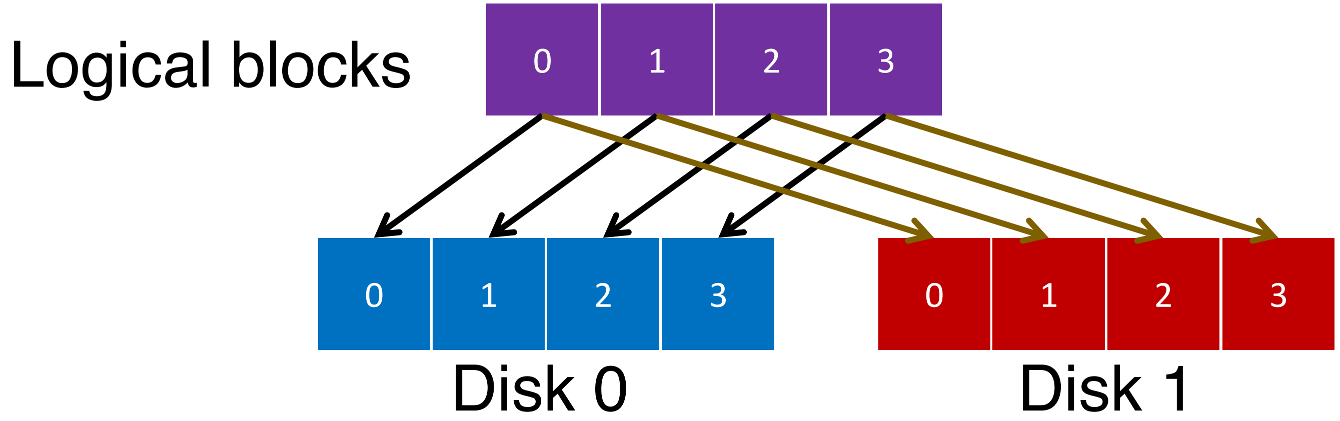
(d) RAID 3: bit-interleaved parity.

(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

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

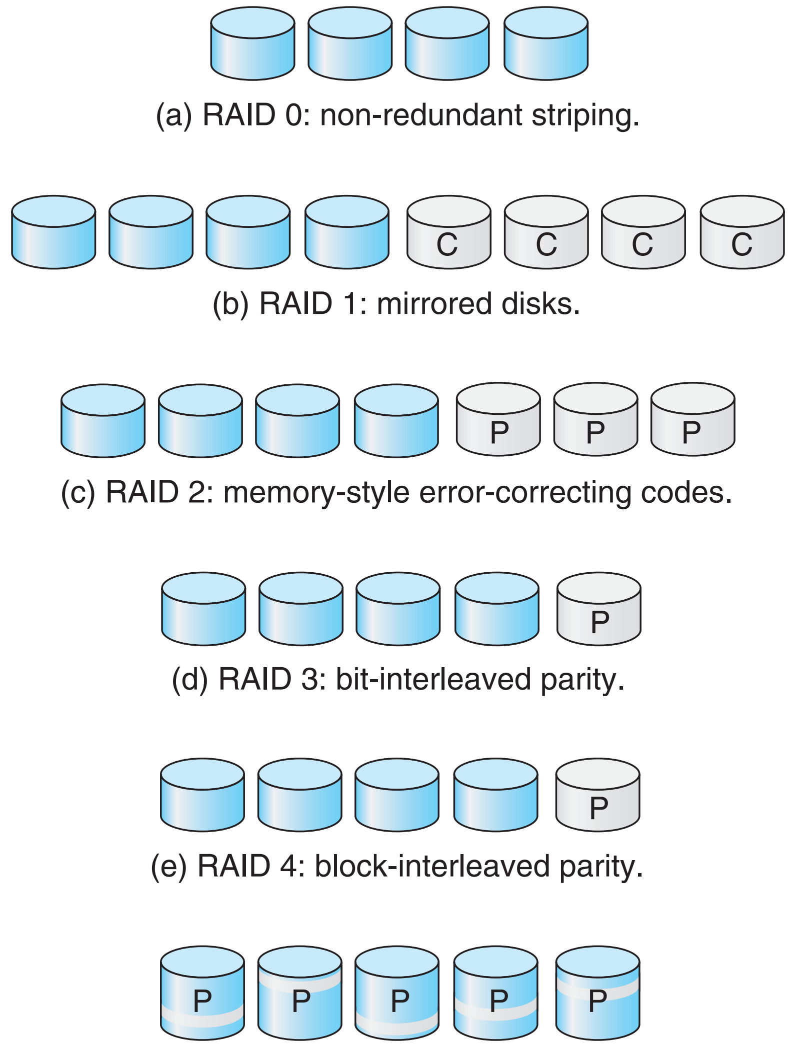
1. What is capacity? N/2 * C

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.

(b) RAID 1: mirrored disks.

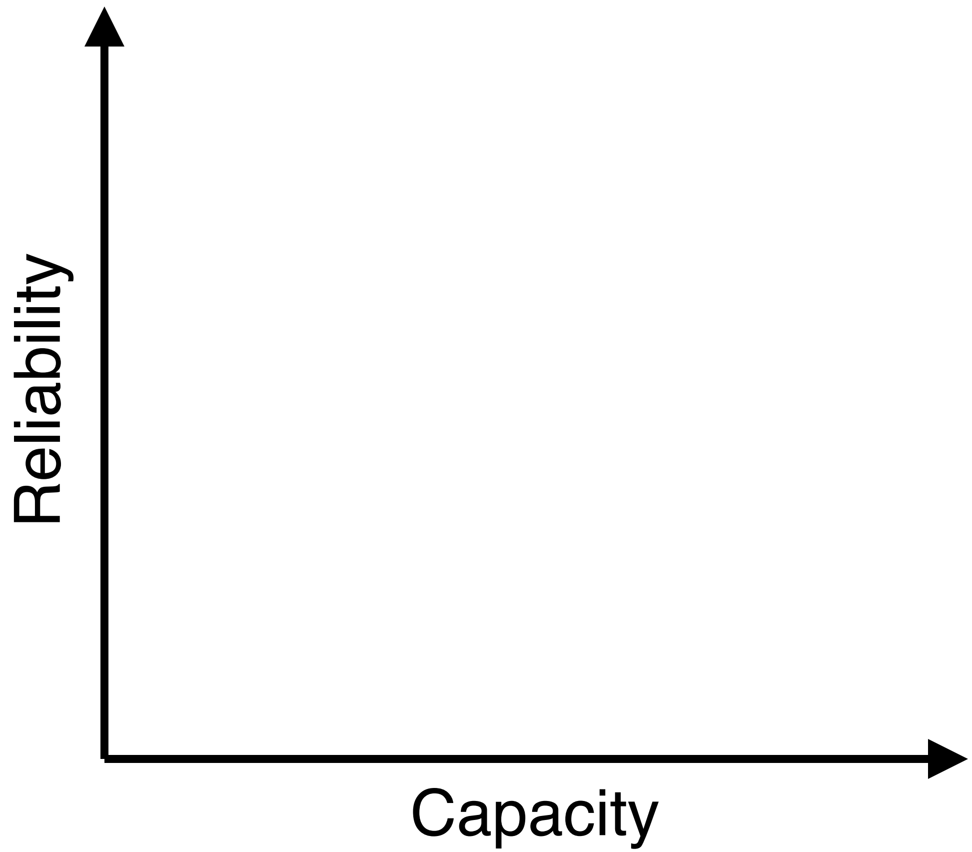
(c) RAID 2: memory-style error-correcting codes.

(d) RAID 3: bit-interleaved parity.

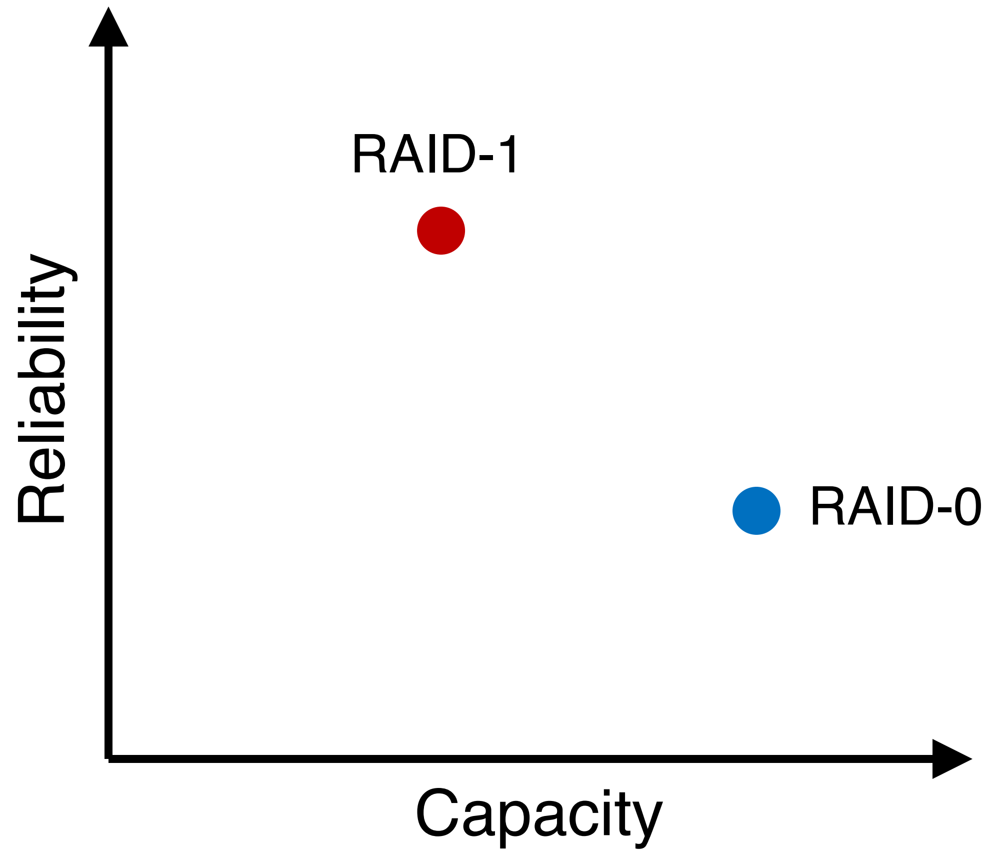
(e) RAID 4: block-interleaved parity.

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

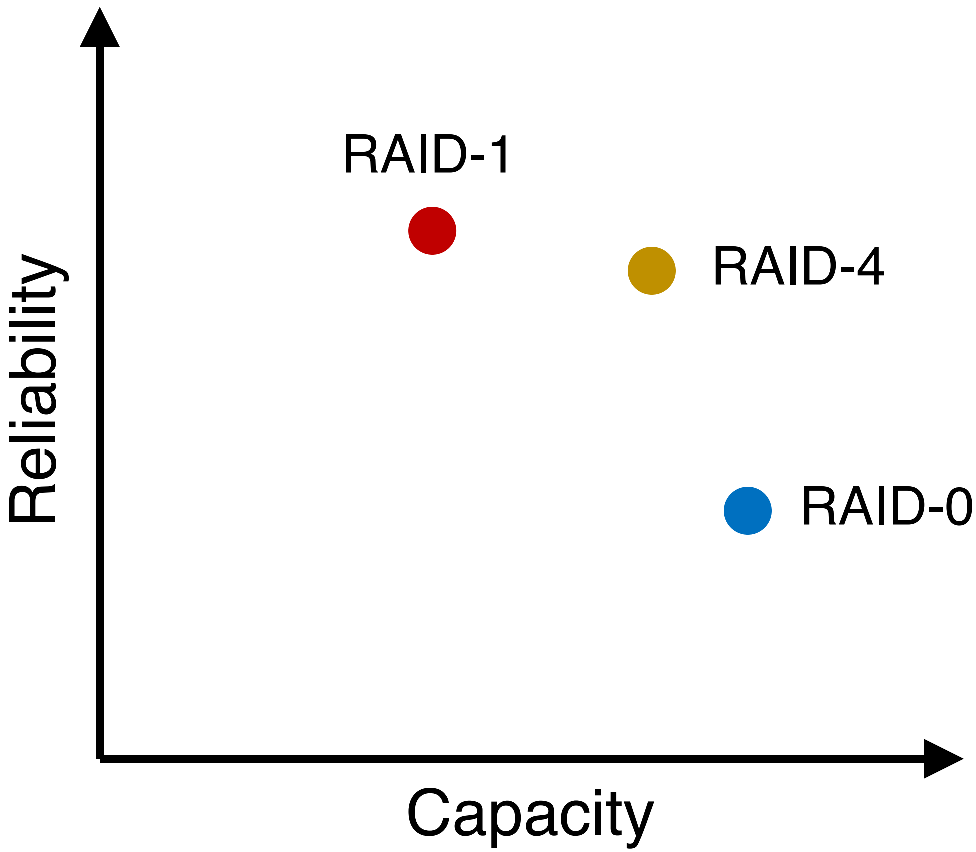
RAID-4



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

stripe:

(parity)

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

Parity Function: XOR Example

	Block0	Block1	Block2	Block3	Parity
stripe:	X	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
- P = 1: The number of 1 in a stripe must be an odd number

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
- 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

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

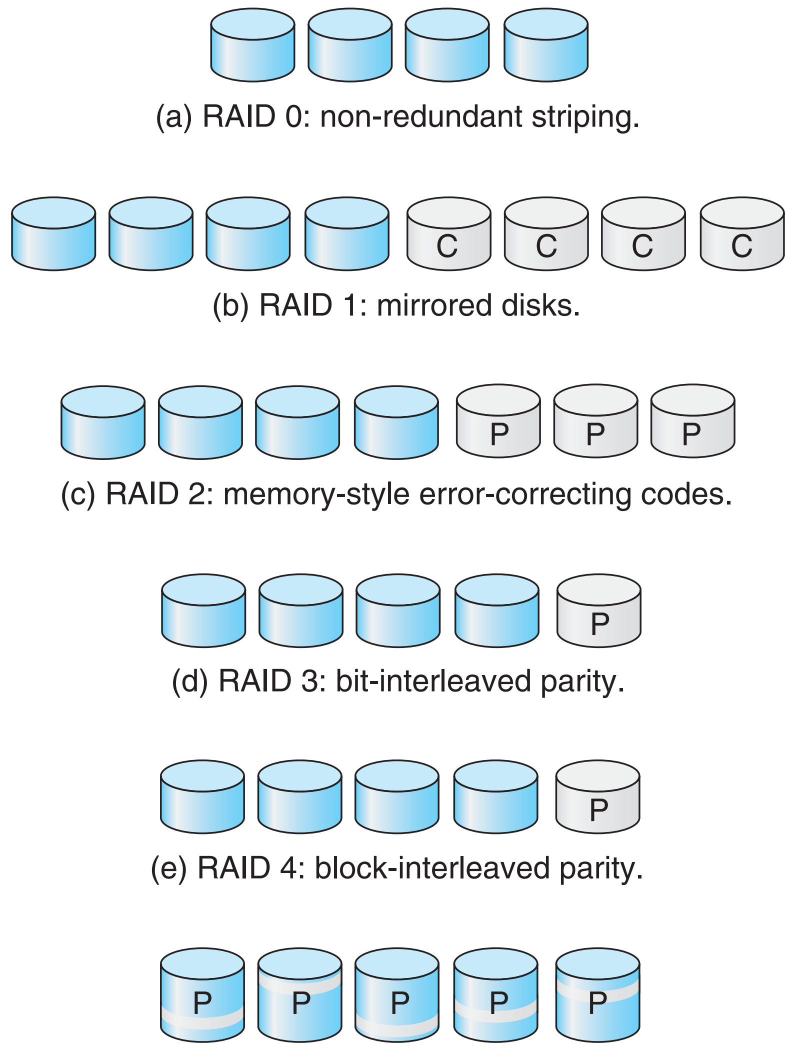
RAID-4 Analysis: Random Write

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.

(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-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

1. Read — Disk 0

2. Read — Disk 2

3. Write — 10

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
3. Write new data in Block 10

RAID-5: Random Write

1. Read 2. 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

3. Write 4. 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

Write 1	Write N touches P3 Write 2	Write 1 touches P2	... Write N	Write 2 touches P0
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

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!

Do read the text chapter “RAID”: it has in-depth discussion of the various performance analyses covered in lecture.