CS 471 Operating Systems

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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

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

RAID

Wish List for A Disk

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  – 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

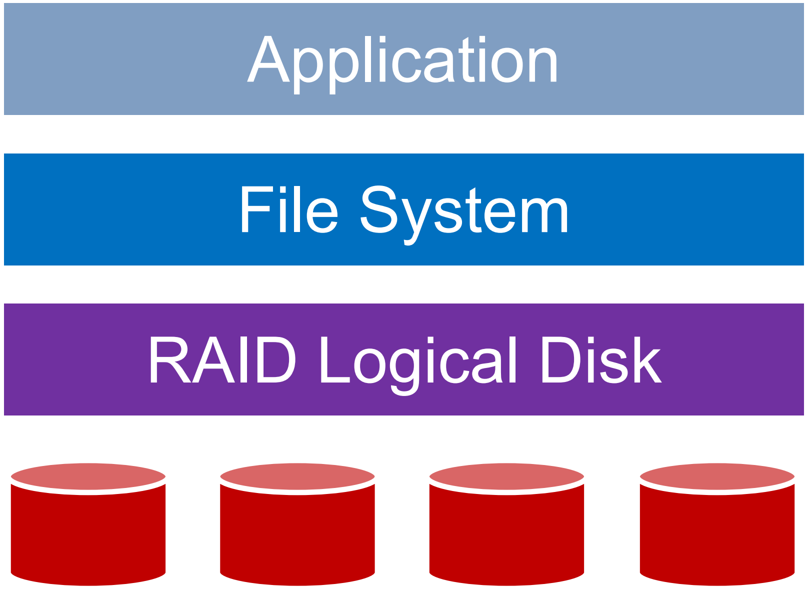
Only One Disk?

- 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: **R**edundant **A**rray of **I**nexpensive **D**isks



Build a logical disk from many physical disks

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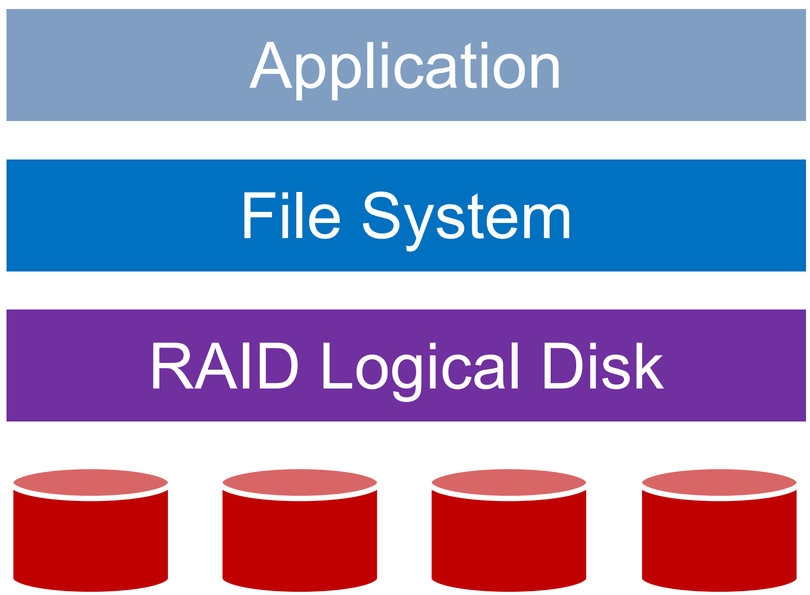
RAID is
- Transparent
- Deployable



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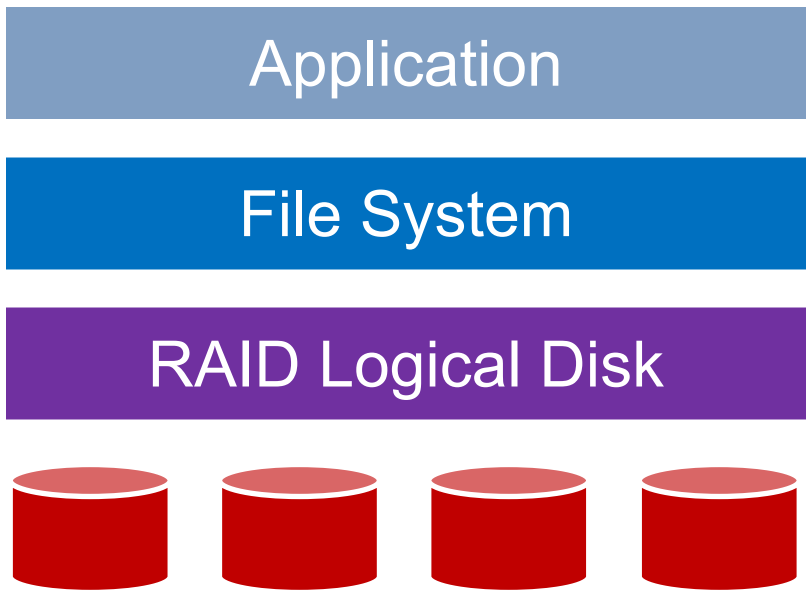

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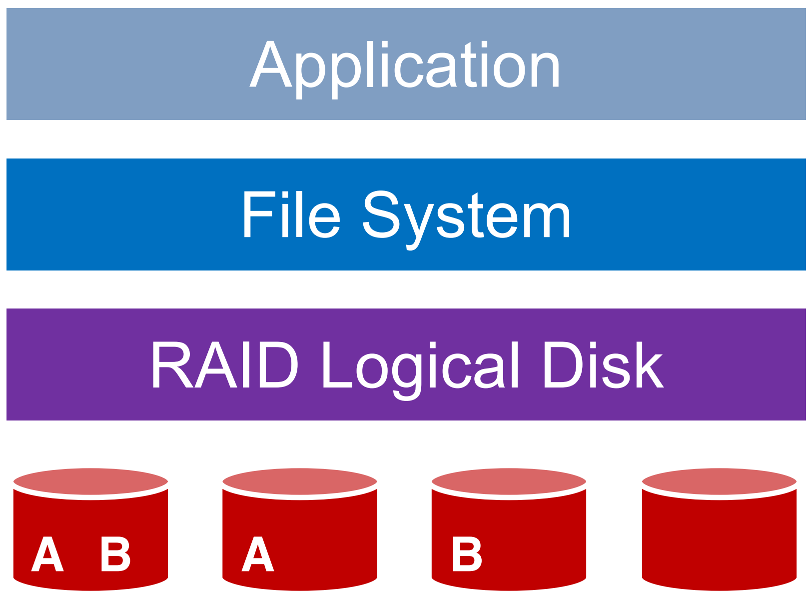

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- Economies of scale! Cheap disks are popular.

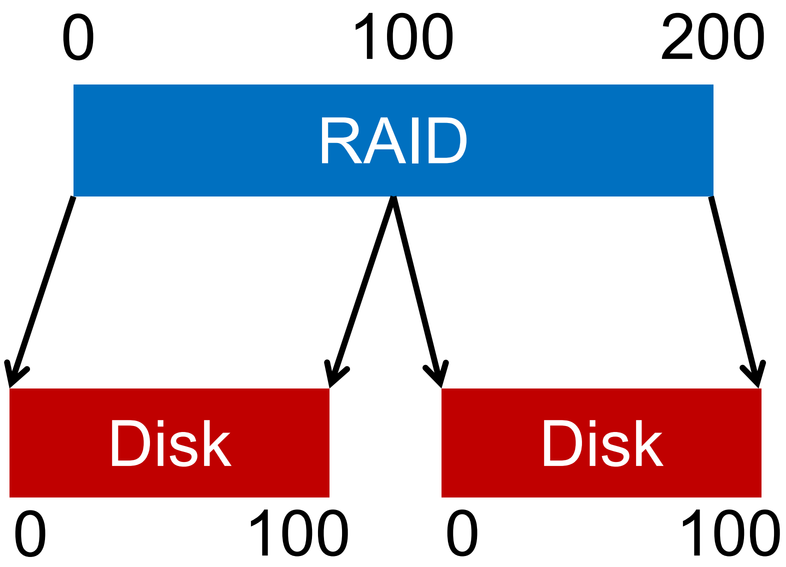
- You can often get many commodity hardware components for the same price as a few expensive components

Why Inexpensive Disks?

- Economies of scale! Cheap disks are popular.
- You can often get many commodity hardware components for the same price as a few expensive components
- Strategy: Write software to **build high-quality logical devices from many cheap devices**
  - Tradeoff: To compensate poor properties of cheap devices

General Strategy

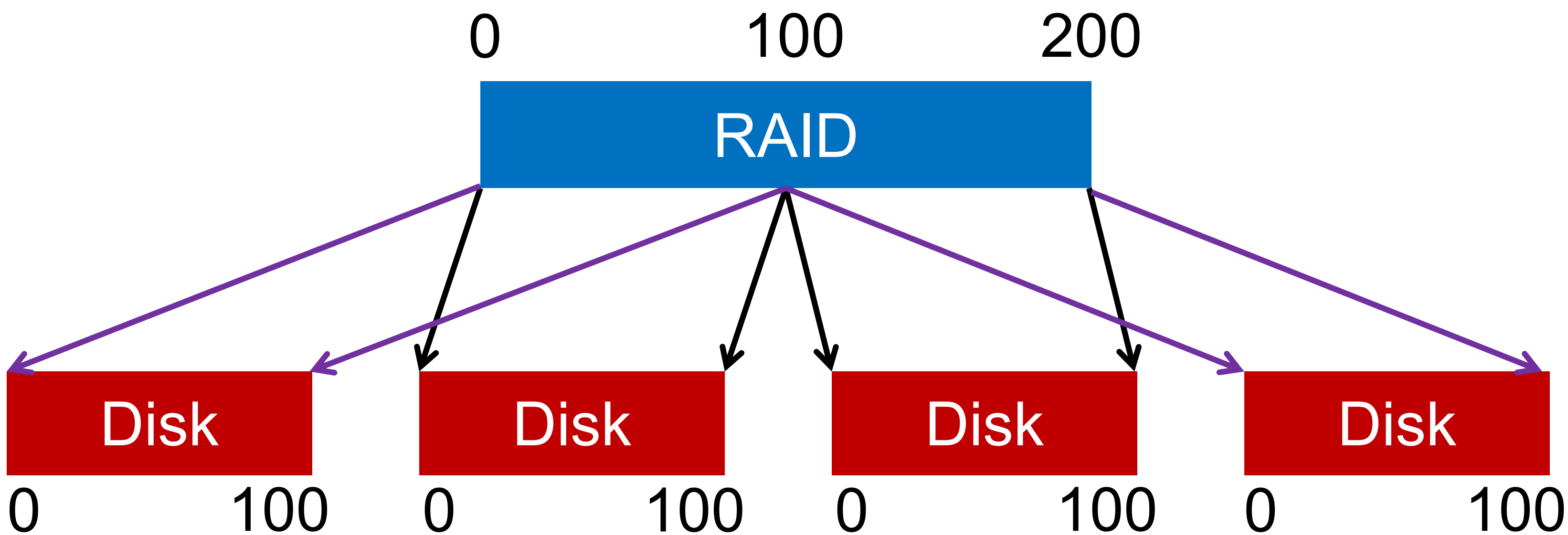
Build fast and large disks from smaller ones



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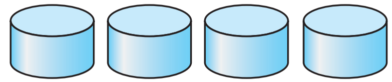
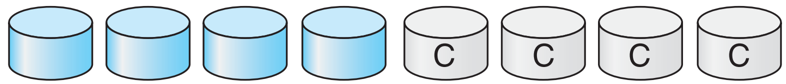
  - How much space can apps use?
- Reliability
  - How many disks can we safely lose?
  - Assume **fail-stop** model!

RAID Levels



(a) RAID 0: non-redundant striping.



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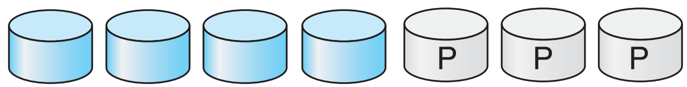

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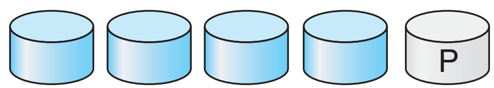

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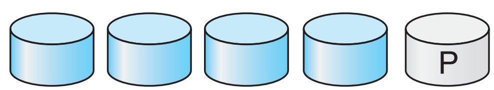

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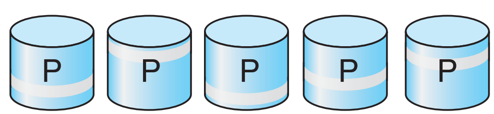
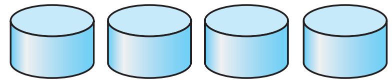


(f) RAID 5: block-interleaved distributed parity.

RAID Level 0



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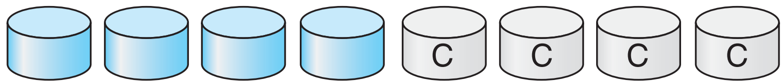

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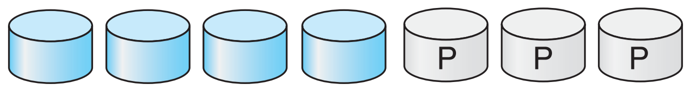

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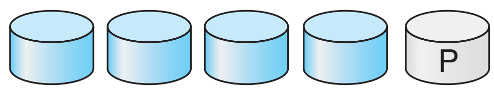

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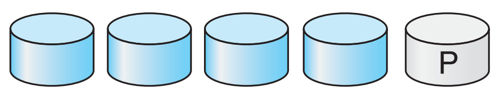

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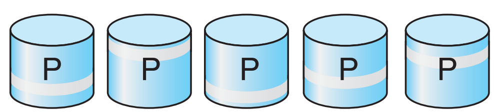
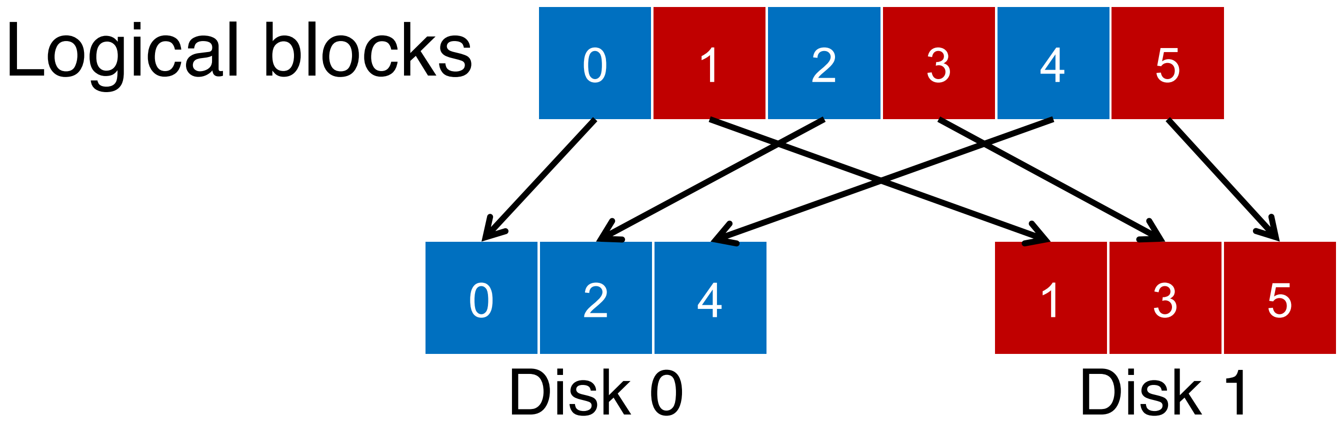


(f) RAID 5: block-interleaved distributed parity.

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:	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 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?

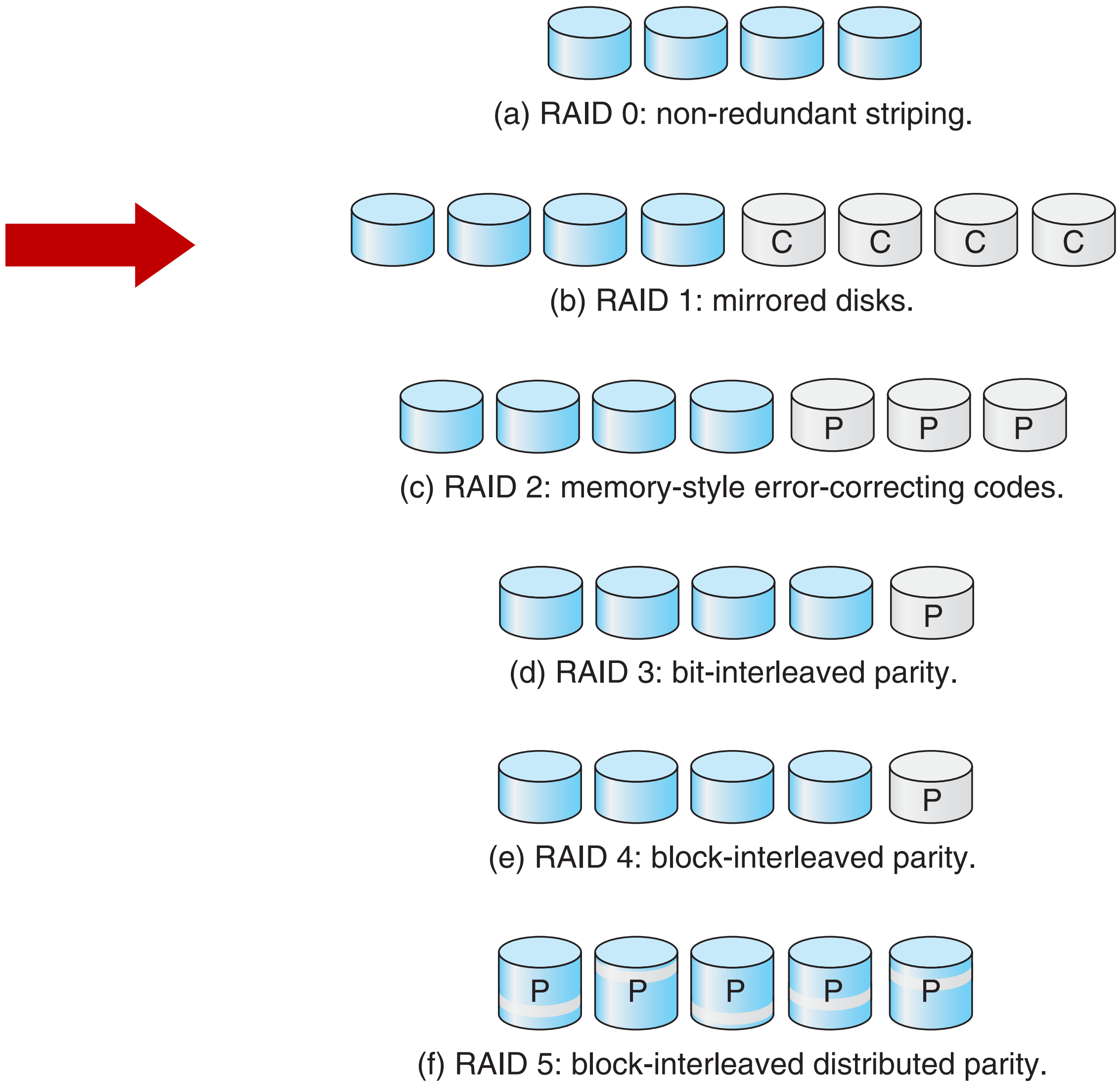
3. Throughput?

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**

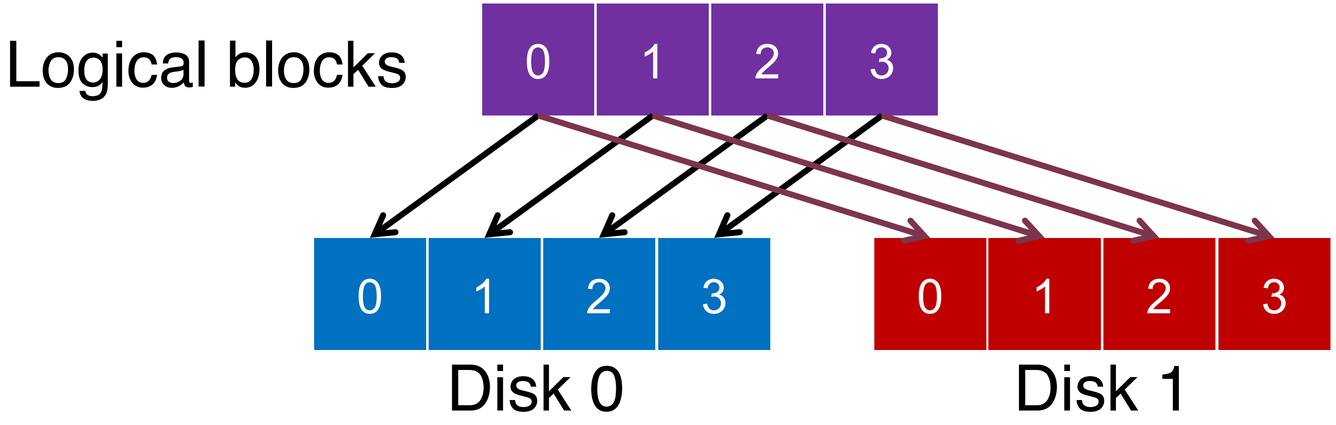
RAID Level 1



(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

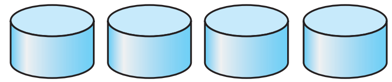
1. What is capacity? **N/2 * C**

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



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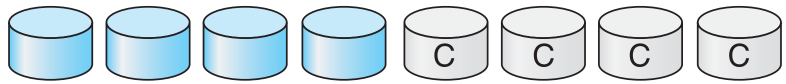

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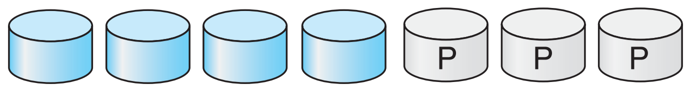

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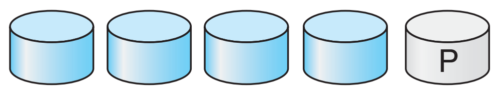

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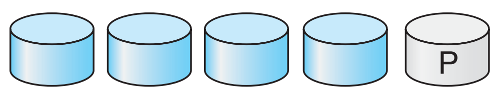

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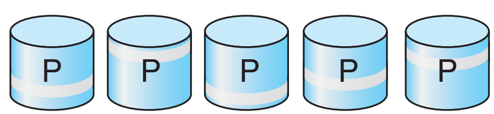
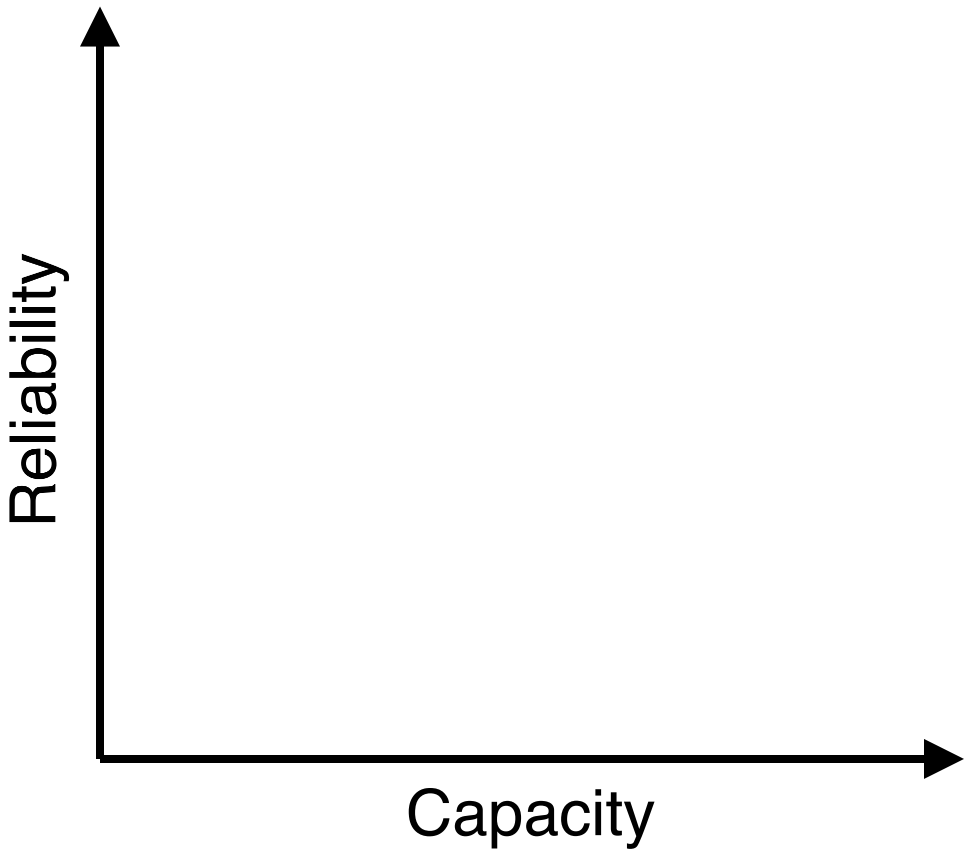


(f) RAID 5: block-interleaved distributed parity.

RAID-4



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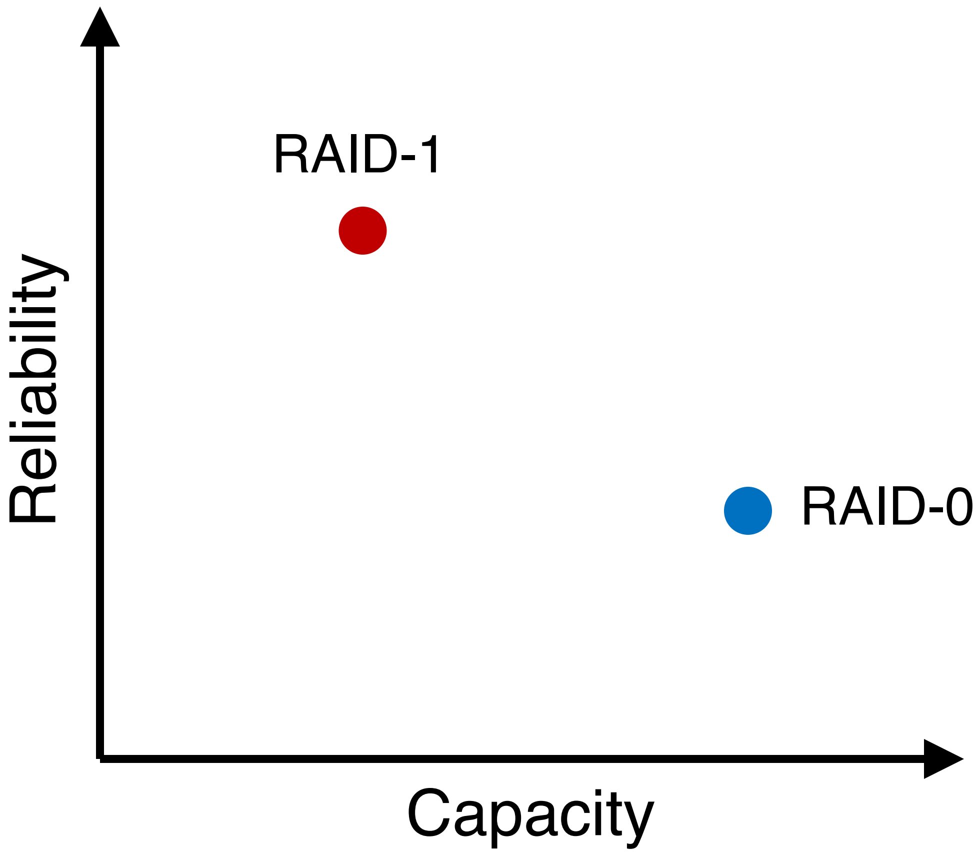

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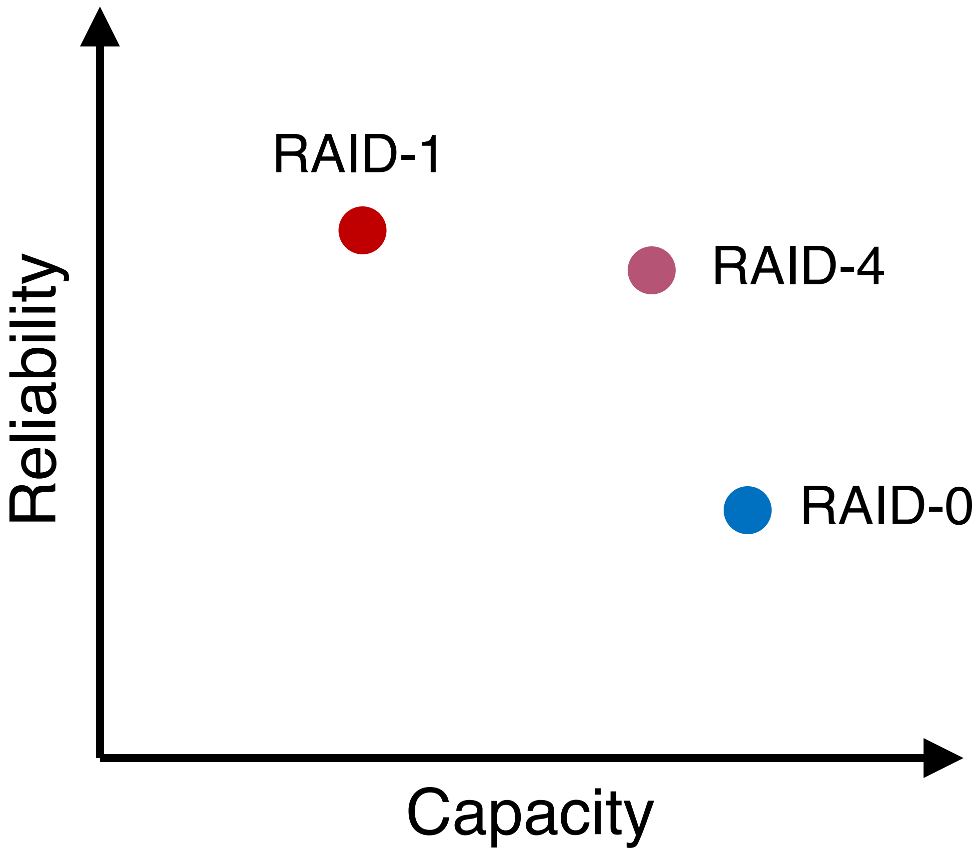


RAID-4: Strategy

- 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

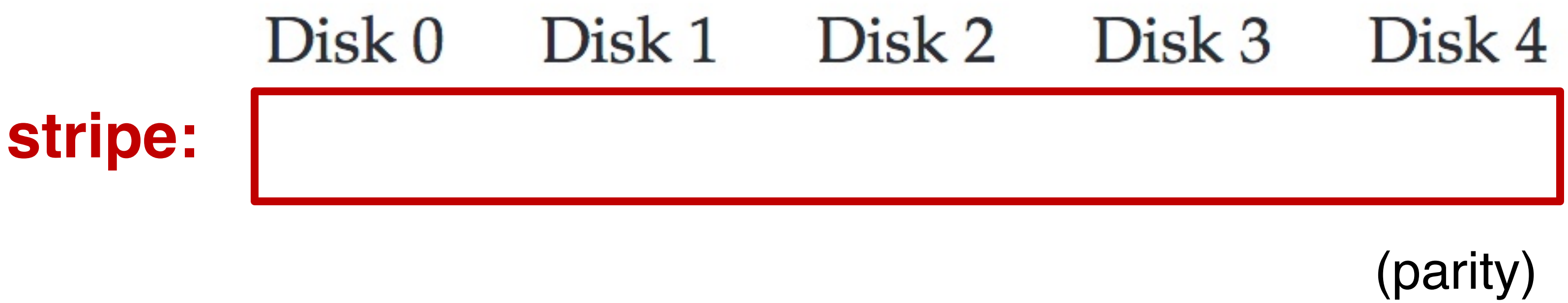
RAID-4: Strategy

- 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
- 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

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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
- 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**

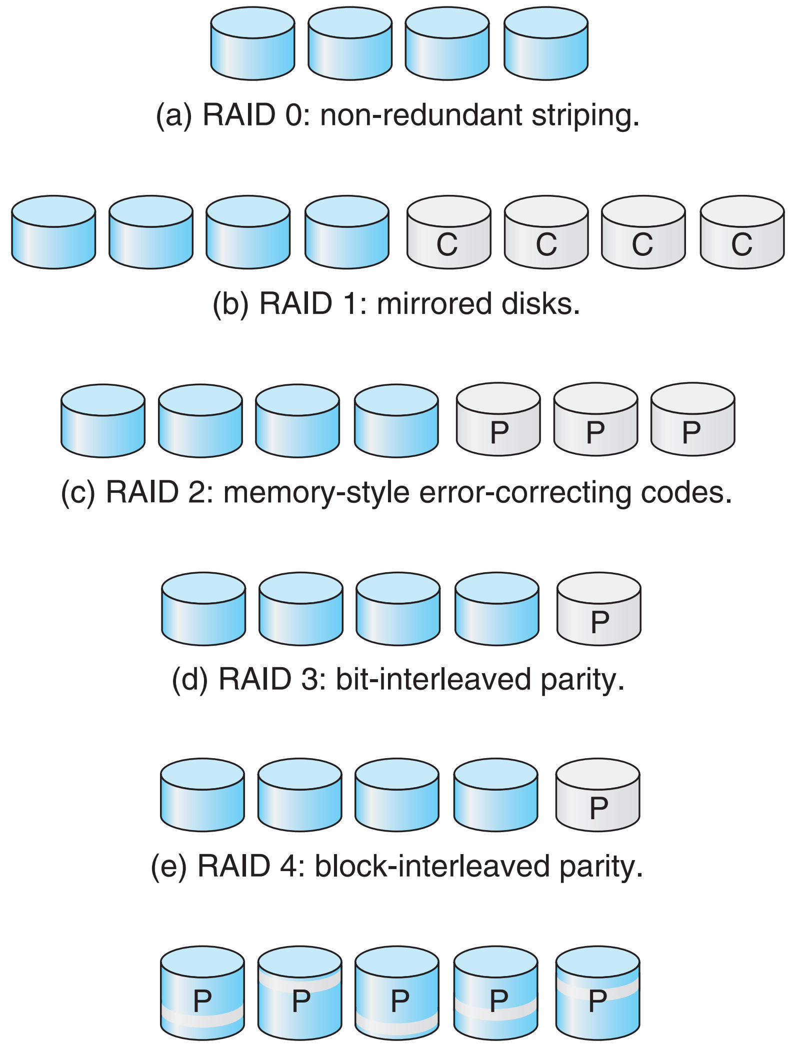
RAID-4 Analysis: Random Write

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; and each **logical** I/O generates two **physical** I/Os (**one read and one write for parity P1**)

RAID Level 5



(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 (Block 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 (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

3. Write (10) 4. Write (P2)

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 (Disk 0) · Write 2 (Disk 1) · Write 1 touches P2 (Disk 2) · Write 2 touches P0 (Disk 4)

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	N-1
RAID-5	1	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

DO Read the Textbook!

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