I/O and Storage:
RAID

CS 571: Operating Systems (Spring 2020)

Lecture 10b

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  - 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

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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

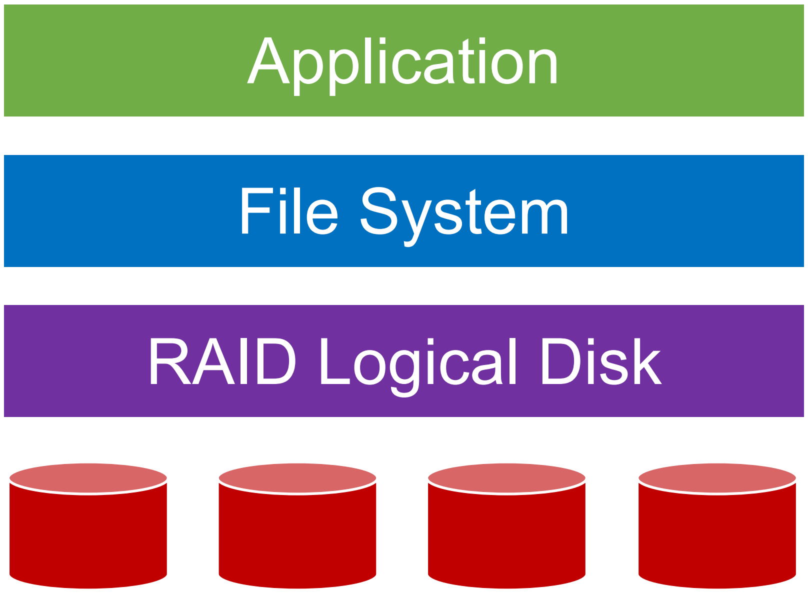
Only One Disk?

- 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: Redundant Array of Inexpensive Disks

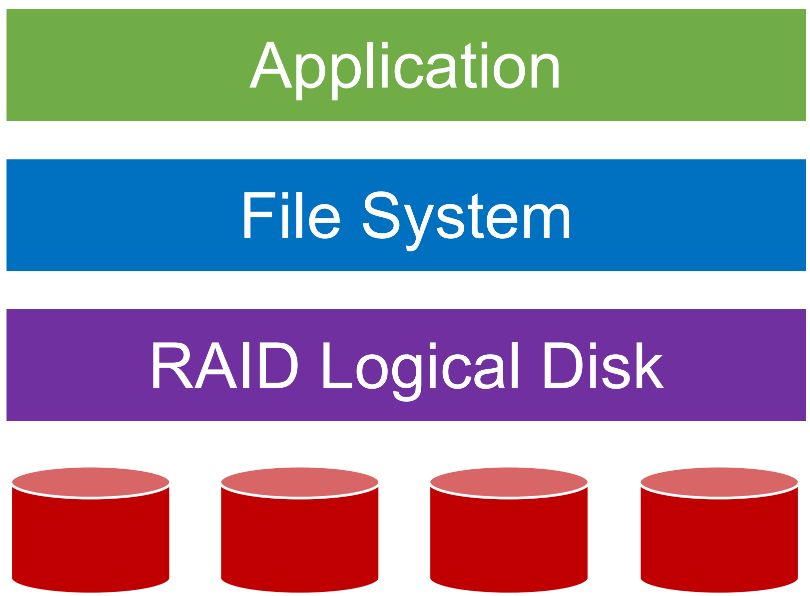


Build a logical disk from many physical disks

Solution: RAID

RAID: Redundant Array of Inexpensive Disks

RAID is
- Transparent
- Deployable



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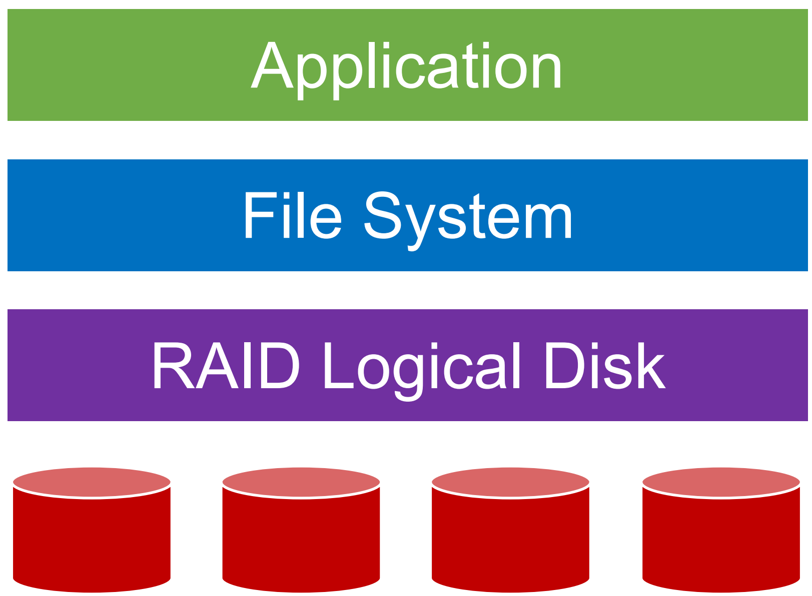

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- Performance
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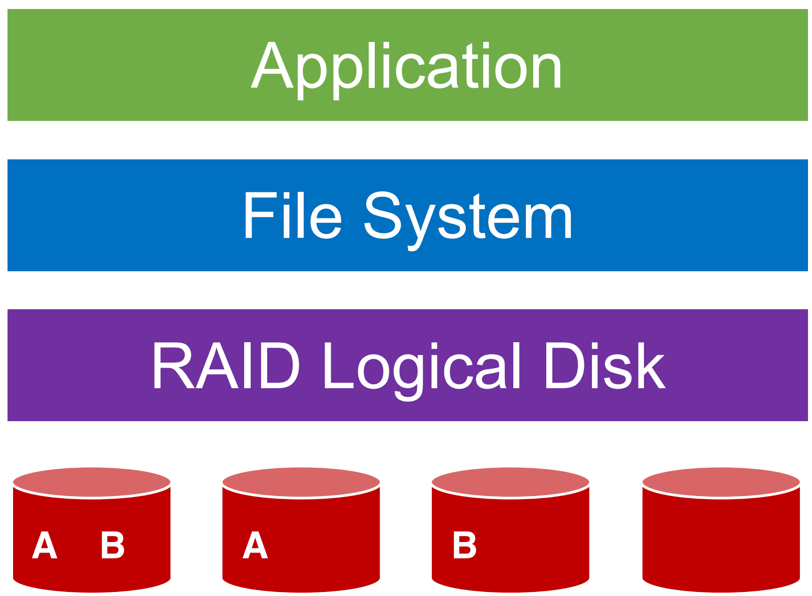

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- Performance
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Build a logical disk from many physical disks

Why Inexpensive Disks?

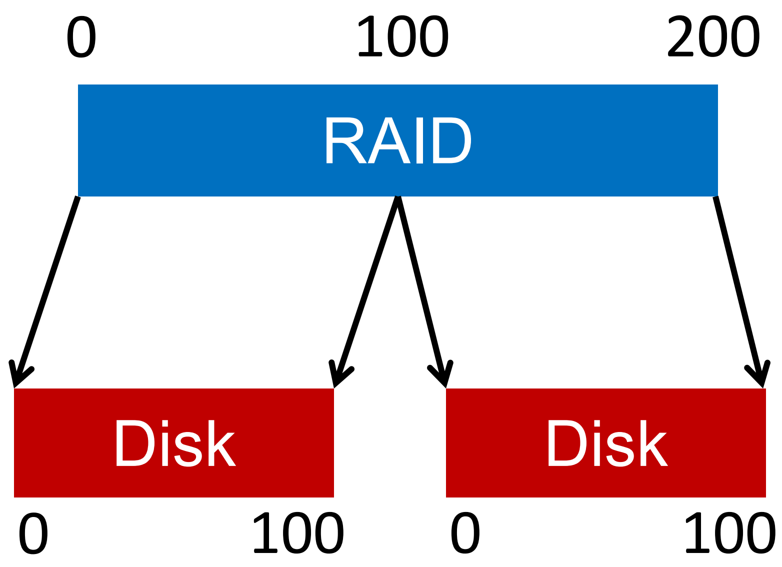
- Economies of scale! Cheap disks are popular.
- You can often get many commodity hardware components for the same price as a few expensive components

Why Inexpensive Disks?

- Economies of scale! Cheap disks are popular.
- 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

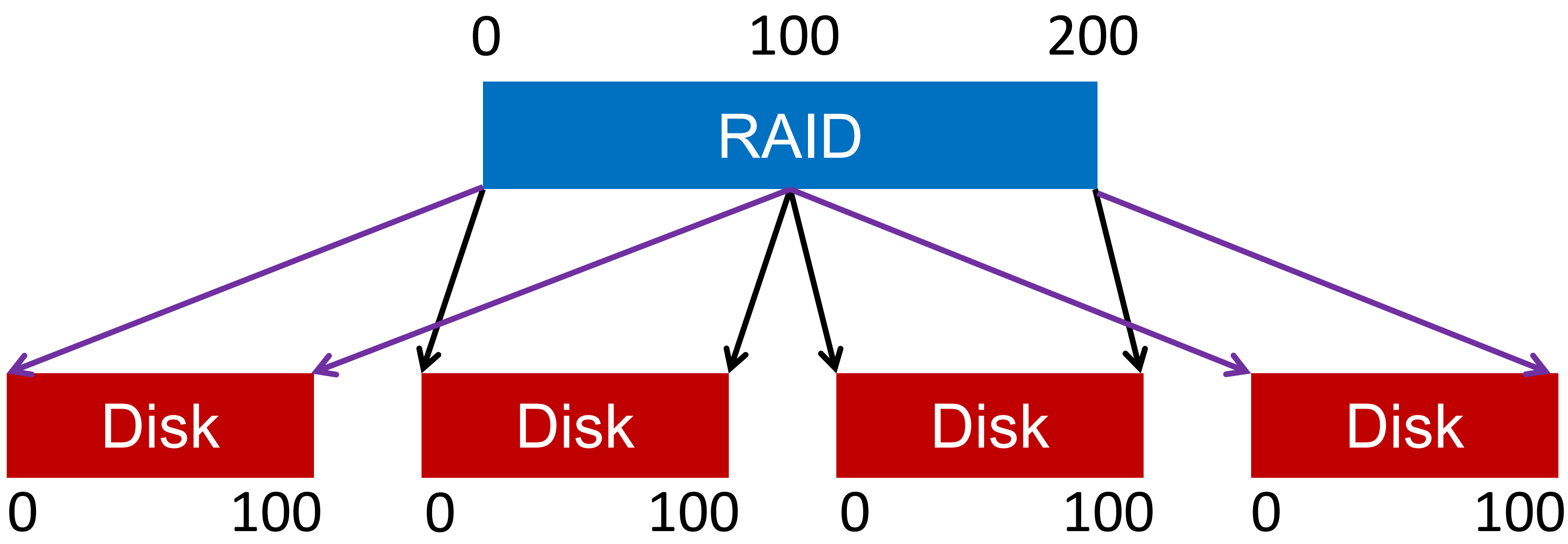
Build fast and large disks from smaller ones



General Strategy

Build fast and large disks from smaller ones

Add more disks for reliability++!



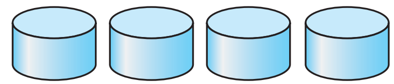
RAID Metrics

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

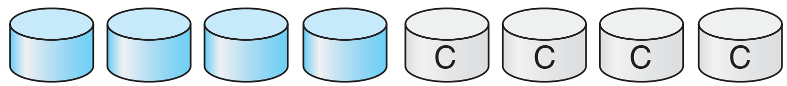
RAID Metrics

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

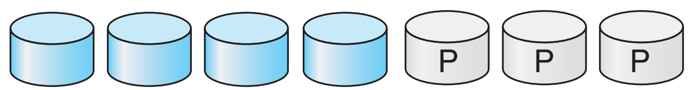
RAID Levels



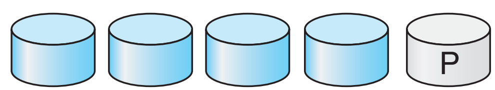
(a) RAID 0: non-redundant striping.



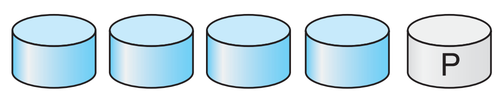
(b) RAID 1: mirrored disks.



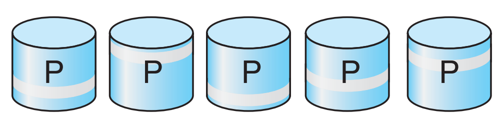
(c) RAID 2: memory-style error-correcting codes.



(d) RAID 3: bit-interleaved parity.

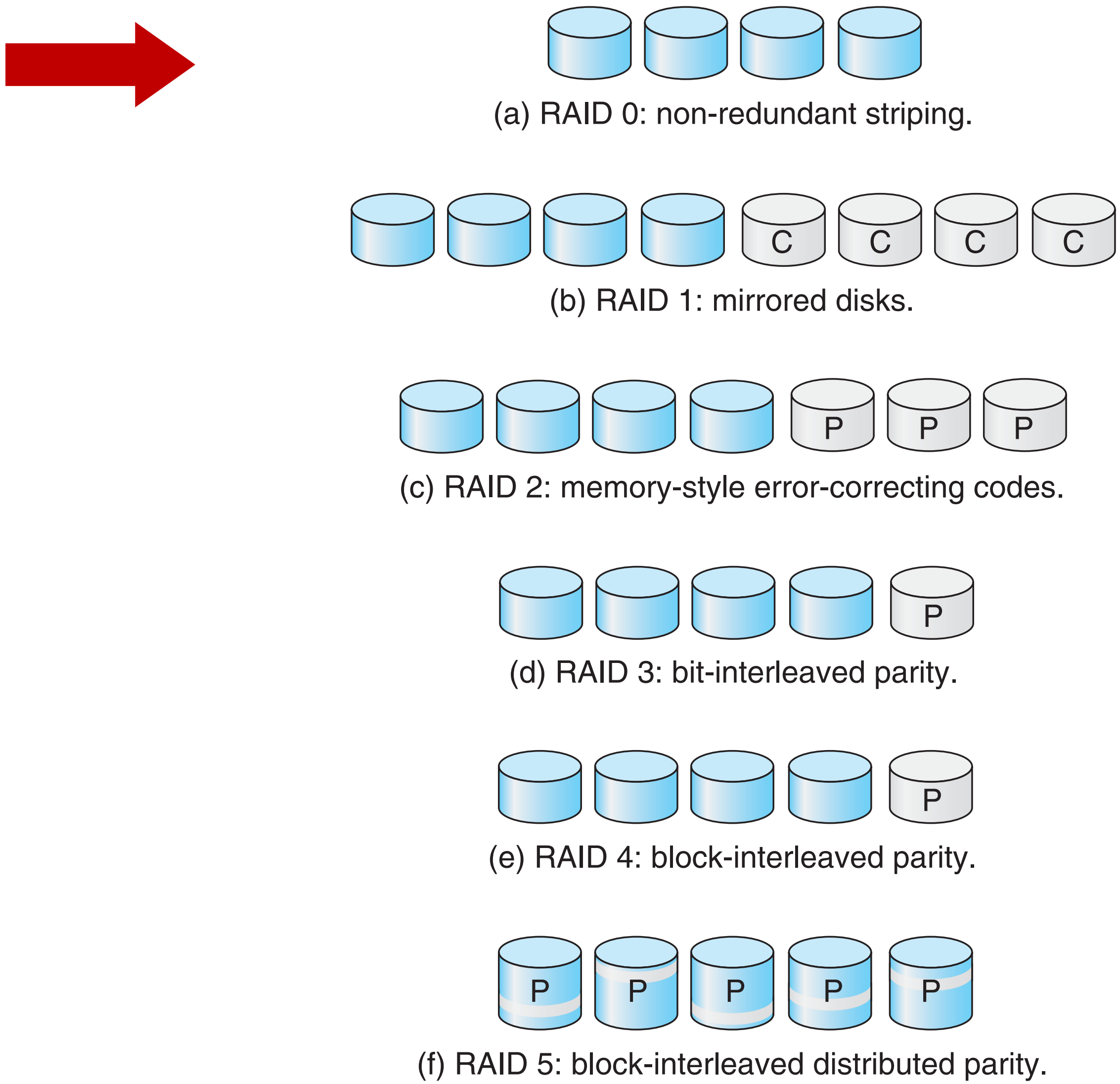


(e) RAID 4: block-interleaved parity.



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

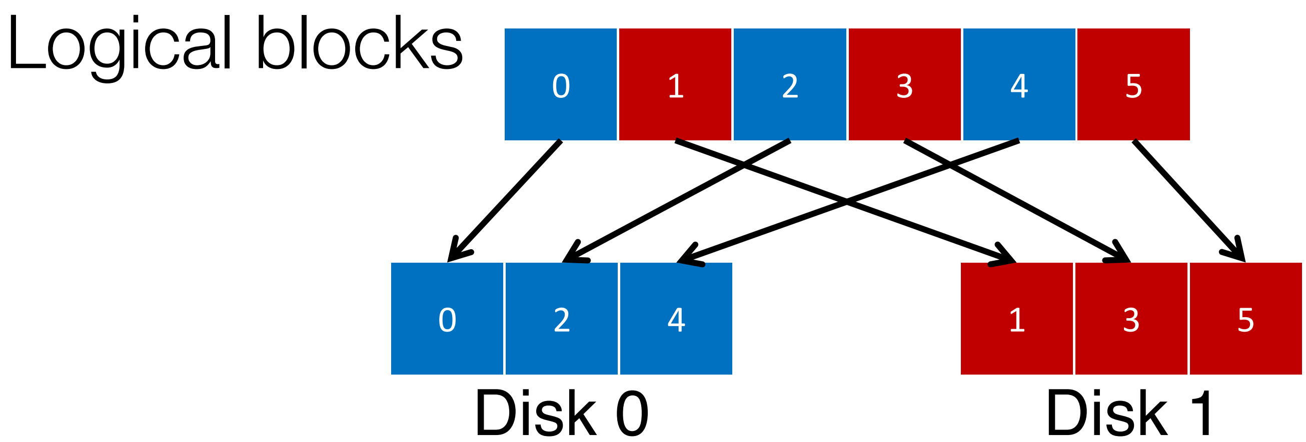
RAID Level 0



(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-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

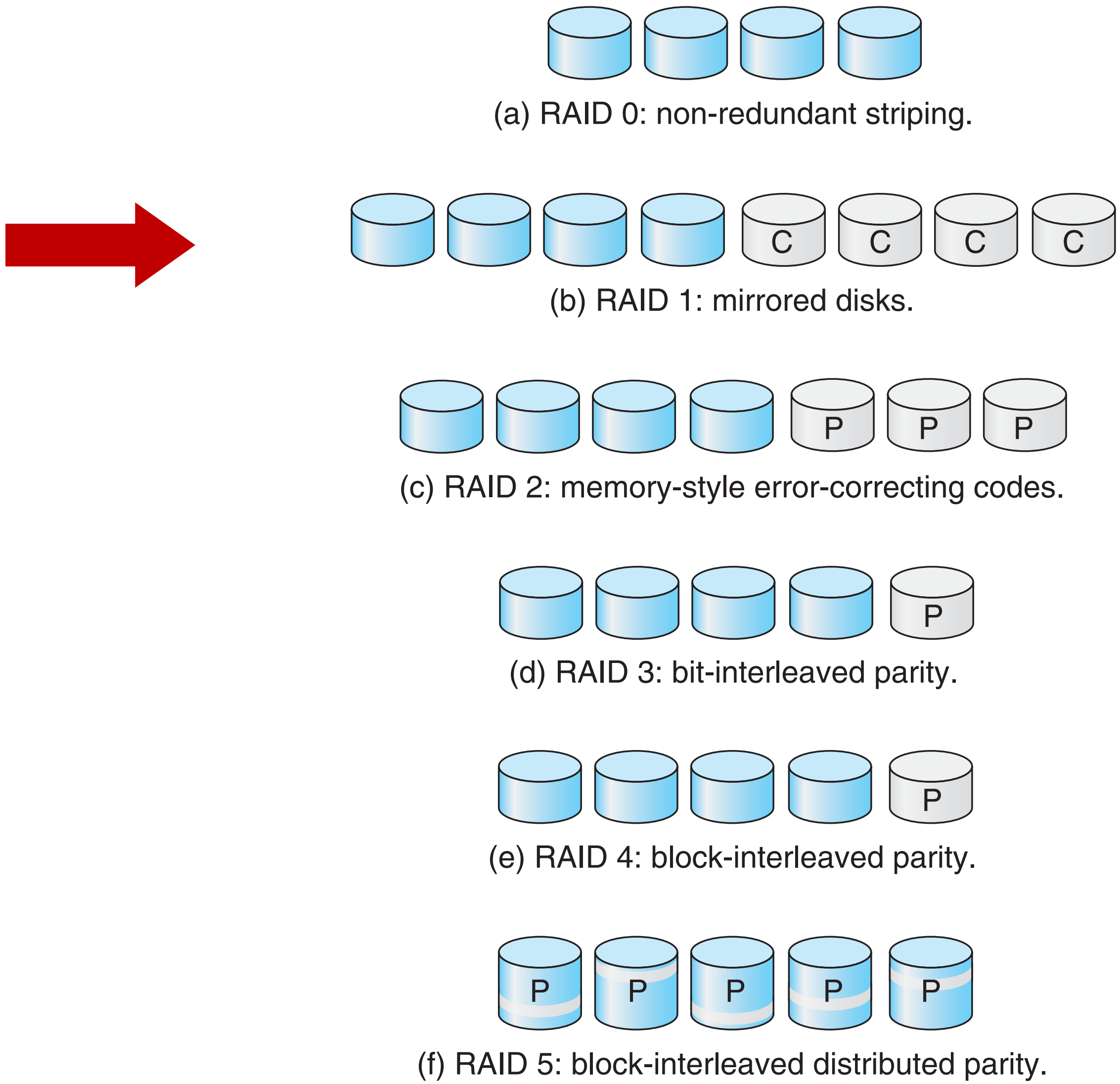
1. What is capacity? N * C

2. How many disks can fail? 0

3. Throughput? N * S and N * R

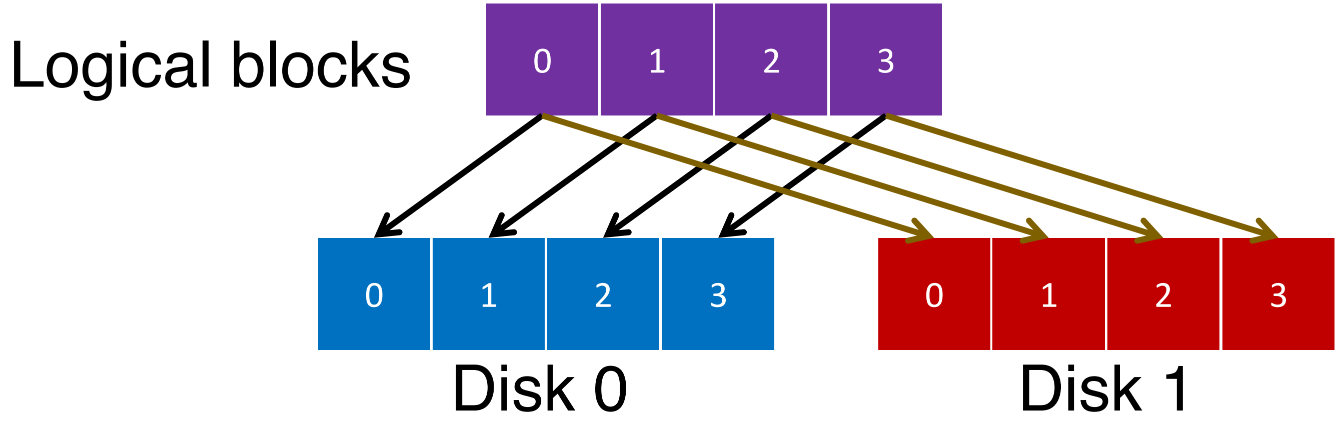
4. Latency? D

RAID Level 1


C
C
C
C
P
P
P
P
P
P
P
P
P
P
(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

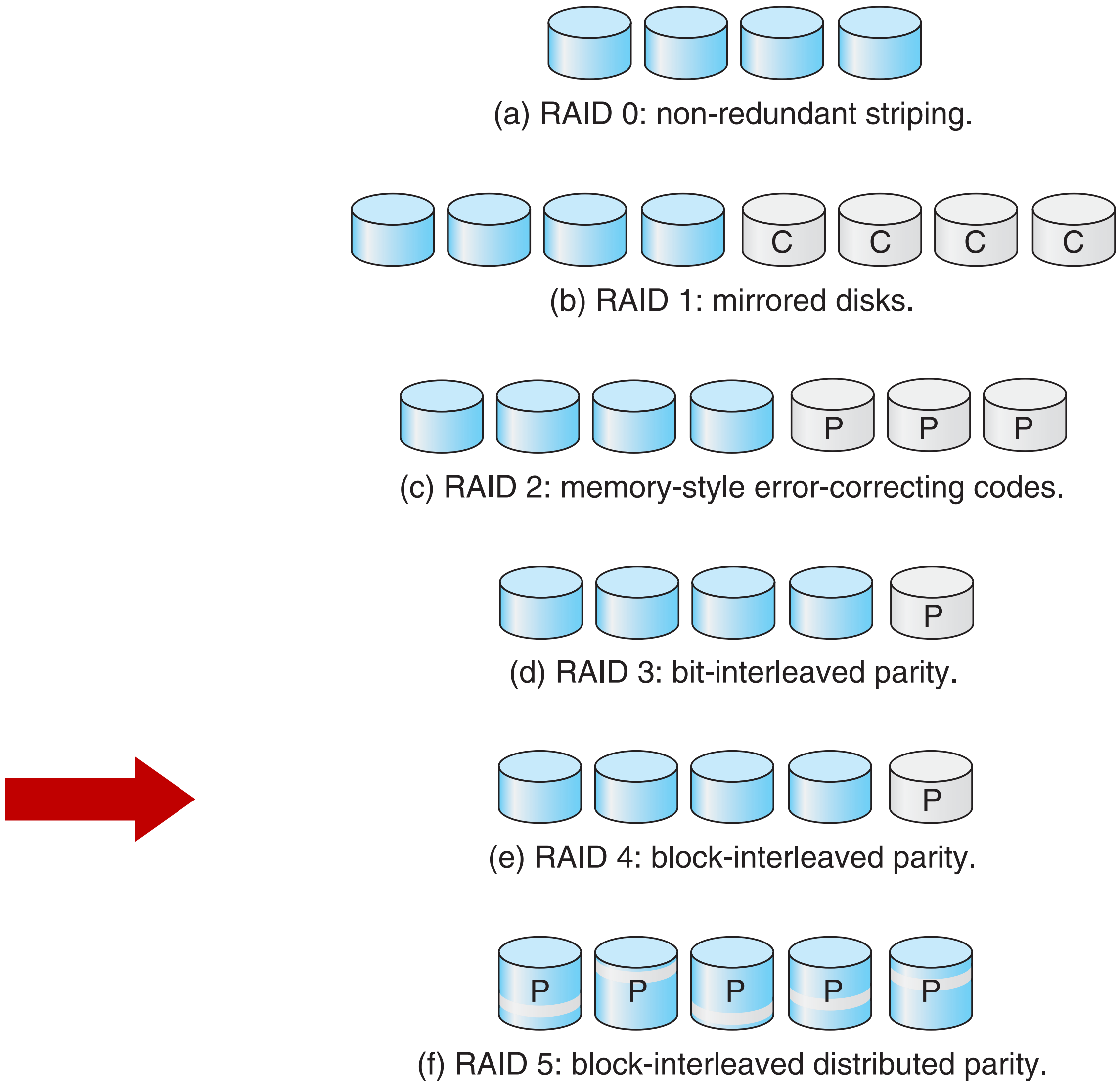
1. What is capacity? N/2 * C

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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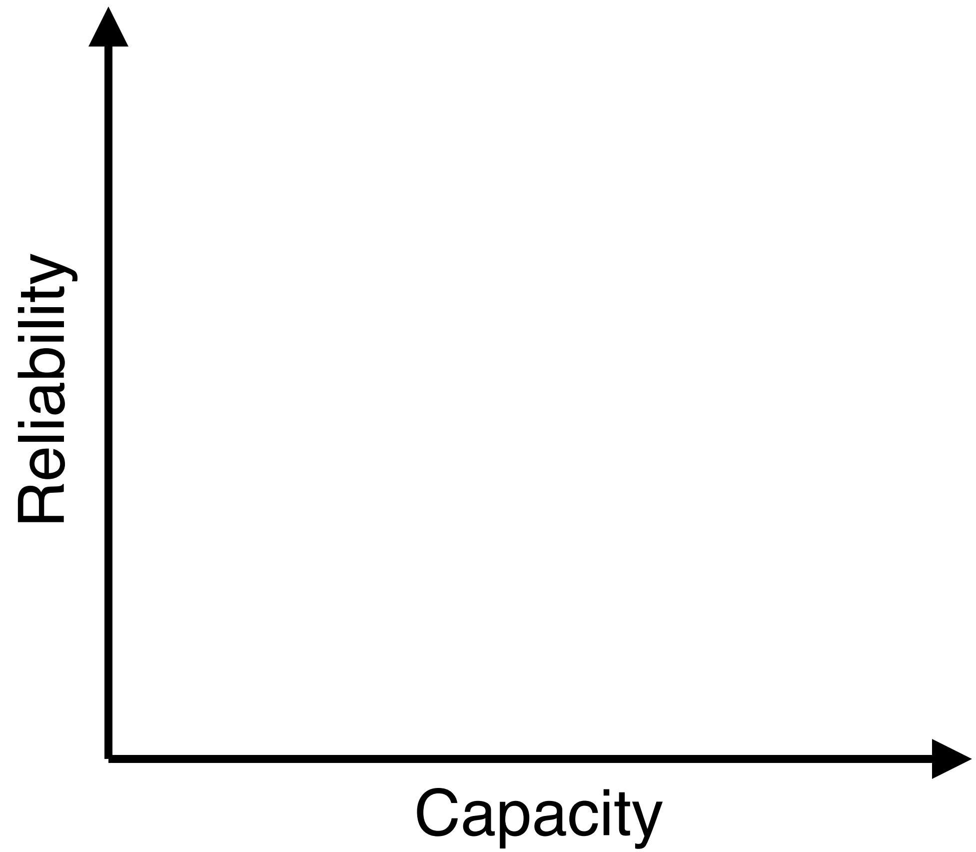
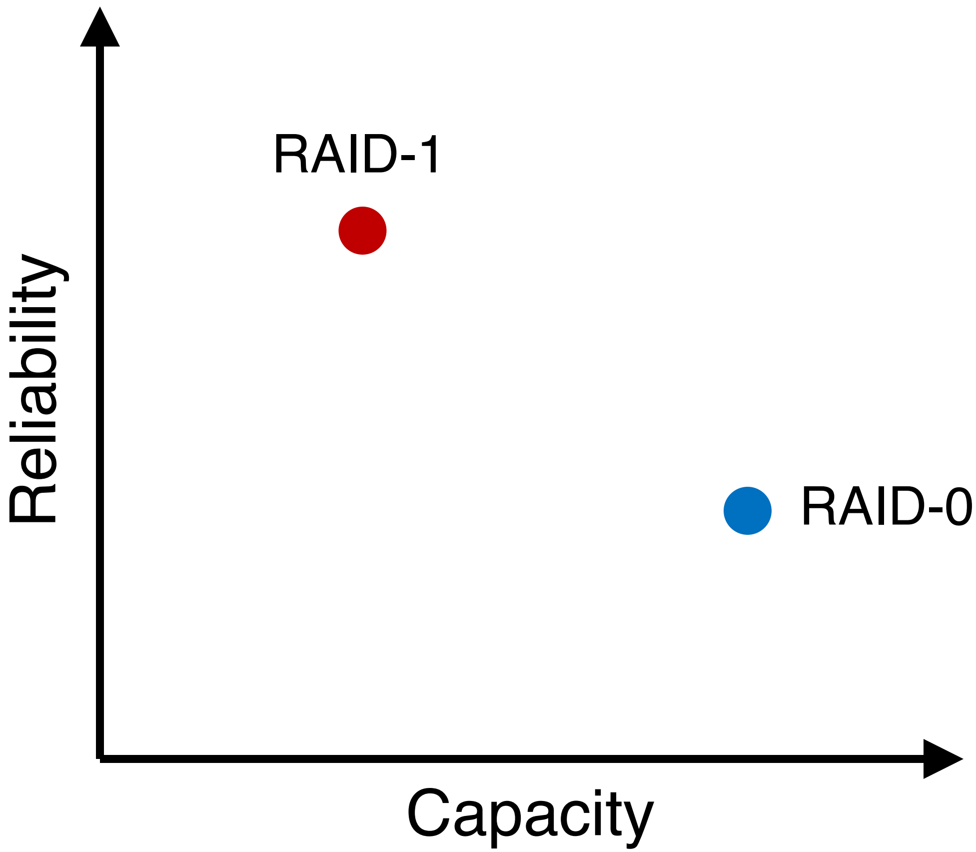
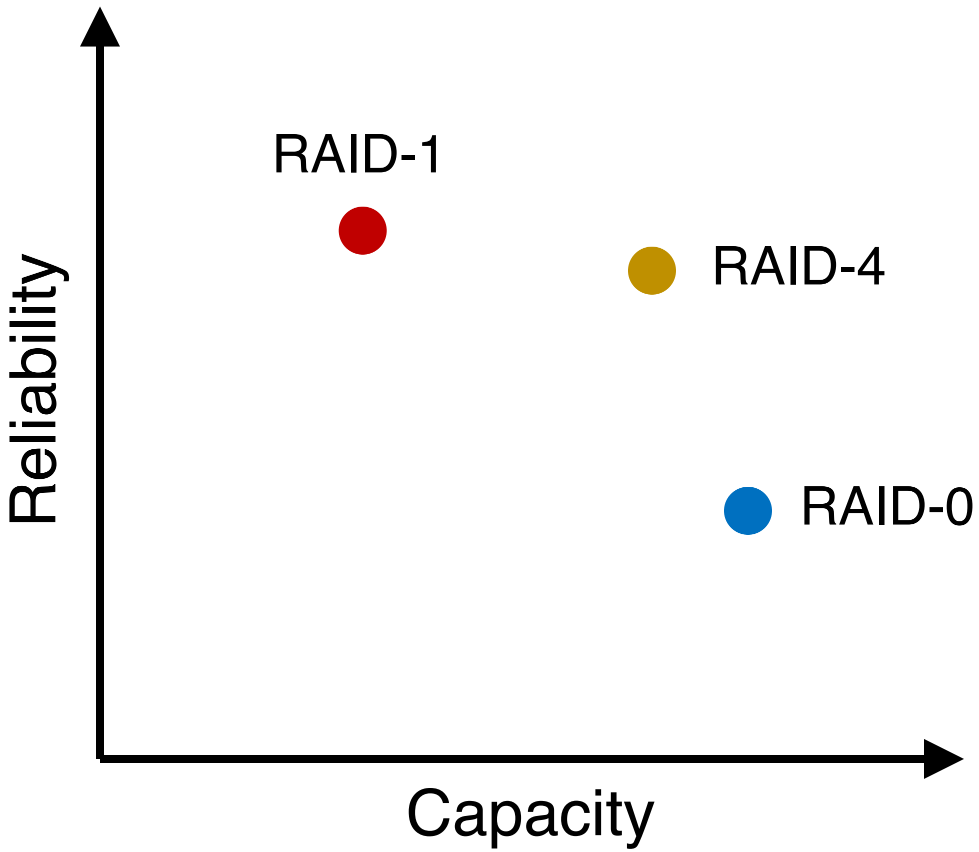
RAID-4



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

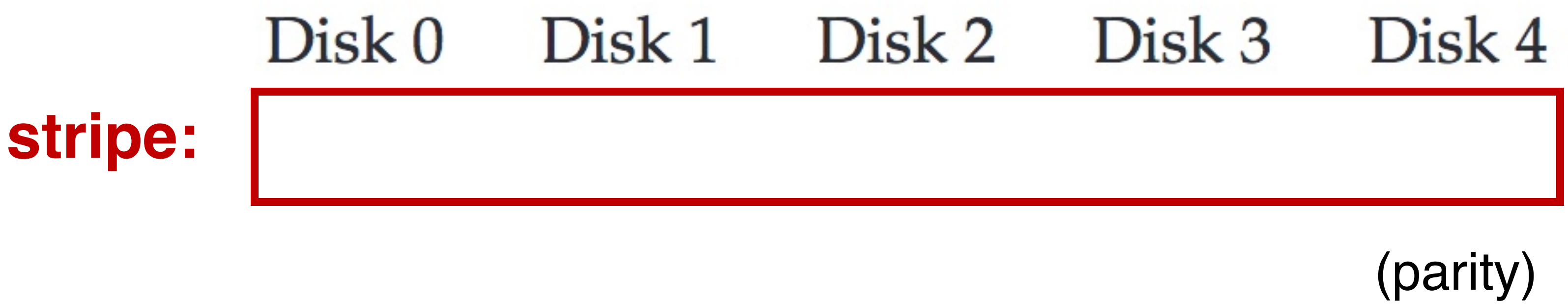
RAID-4: Strategy

- 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

	Block0	Block1	Block2	Block3	Parity
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	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

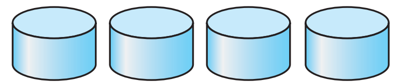
RAID-4 Analysis: Random Write

Random write to 4, 13, and respective parity blocks

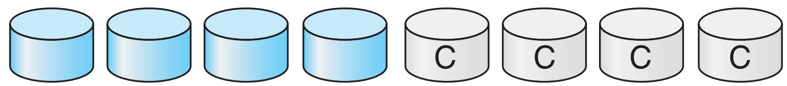
Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	1	2	3	P0
*4	5	6	7	+P1
8	9	10	11	P2
12	*13	14	15	+P3

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**)

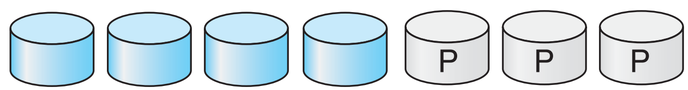
RAID Level 5



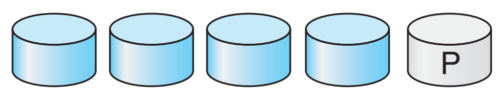
(a) RAID 0: non-redundant striping.



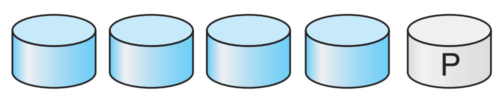
(b) RAID 1: mirrored disks.



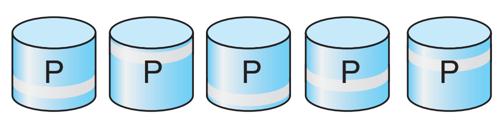
(c) RAID 2: memory-style error-correcting codes.



(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

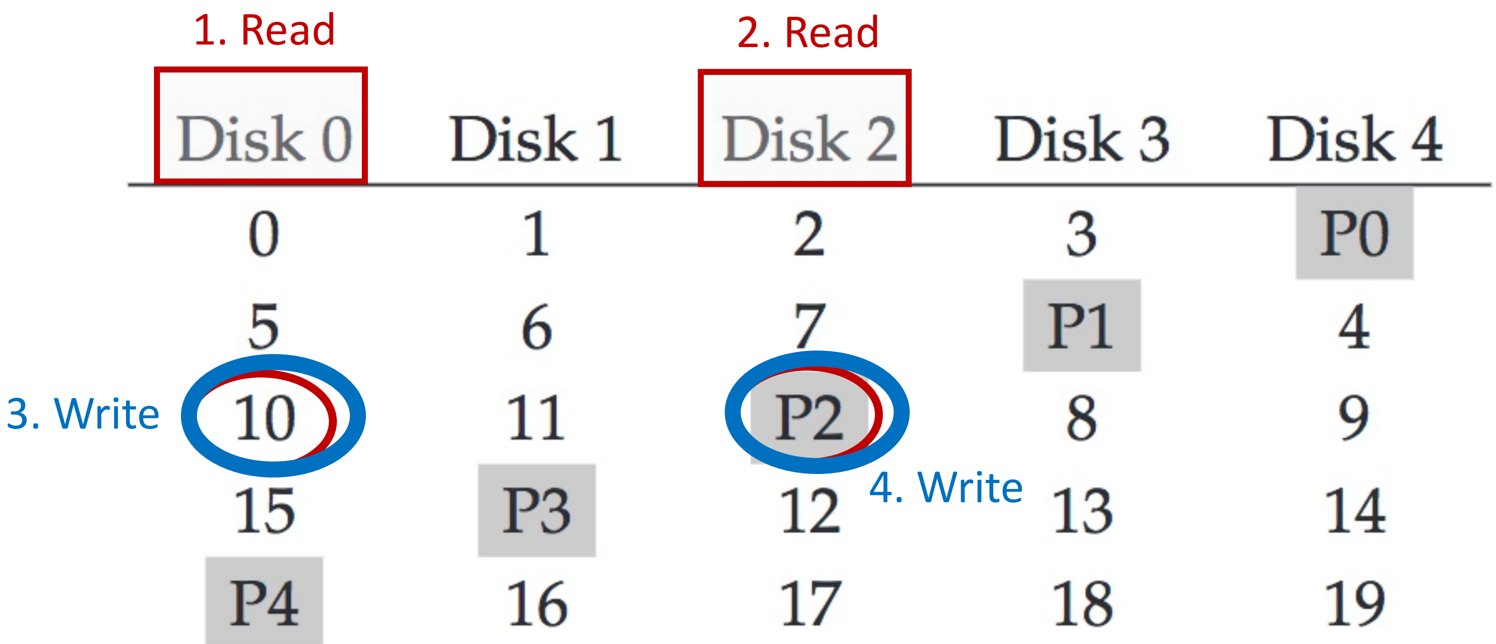
1. Read (Disk 0) 2. Read (Disk 2) 3. Write (Block 10)

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

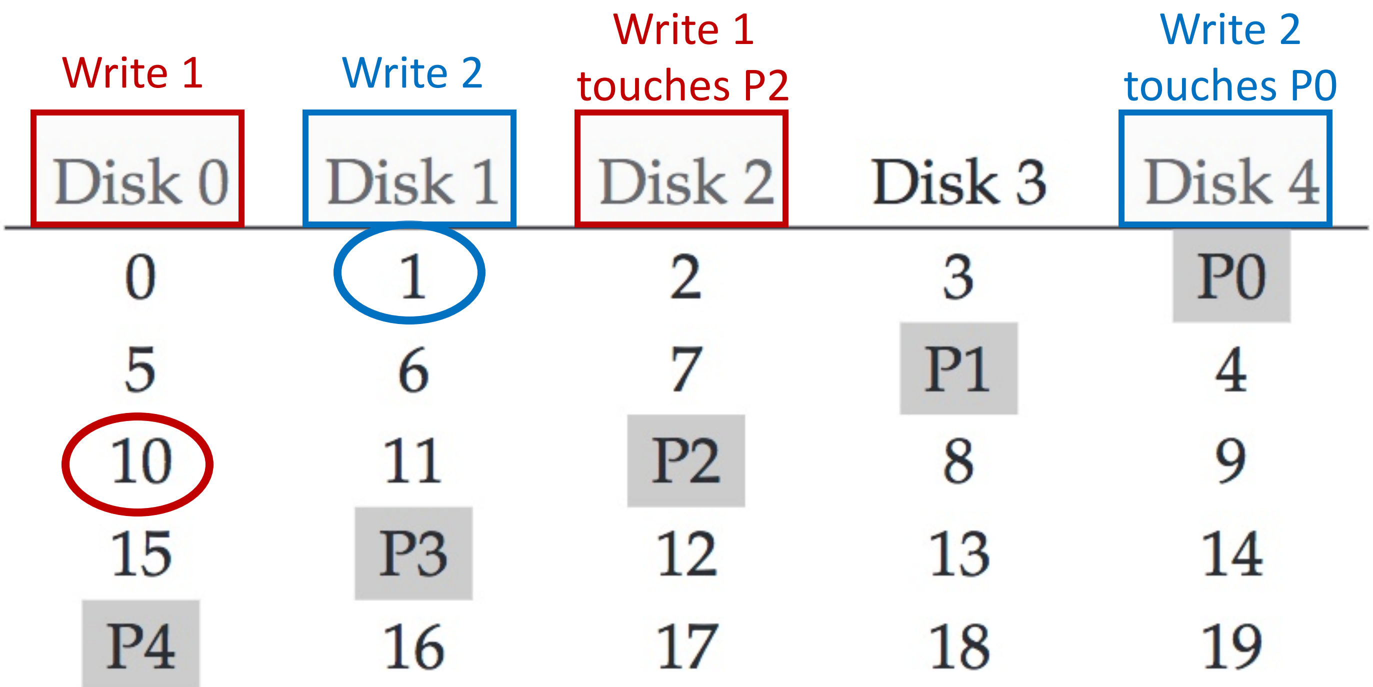
RAID-5: Random Write



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	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.