Persistence: RAID

Questions answered in this lecture:

Why more than one disk?

What are the different RAID levels? (striping, mirroring, parity)

Which RAID levels are best for reliability? for capacity?

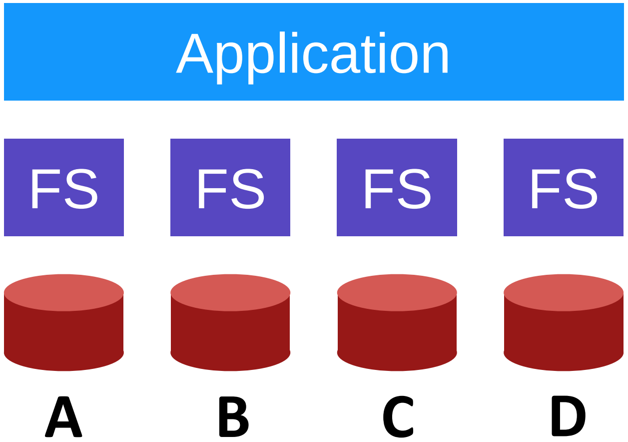
Which are best for performance? (sequential vs. random reads and writes)

Only One Disk?

- **Sometimes we want many disks — why?**
  - capacity
  - reliability
  - performance

- **Challenge: most file systems work on only one disk**

Solution 1: JBOD



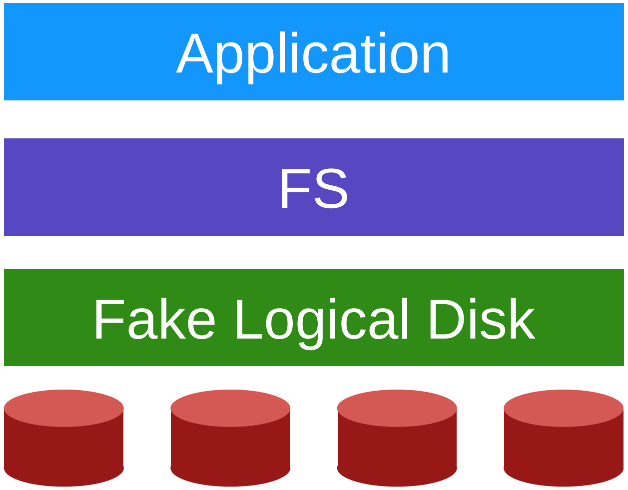
Application is smart, stores different files on different file systems.

JBOD: **J**ust a **B**unch **O**f **D**isks

Solution 2: RAID

RAID is:

- transparent
- deployable



Logical disk gives

- capacity
- performance
- reliability

Build logical disk from many physical disks.

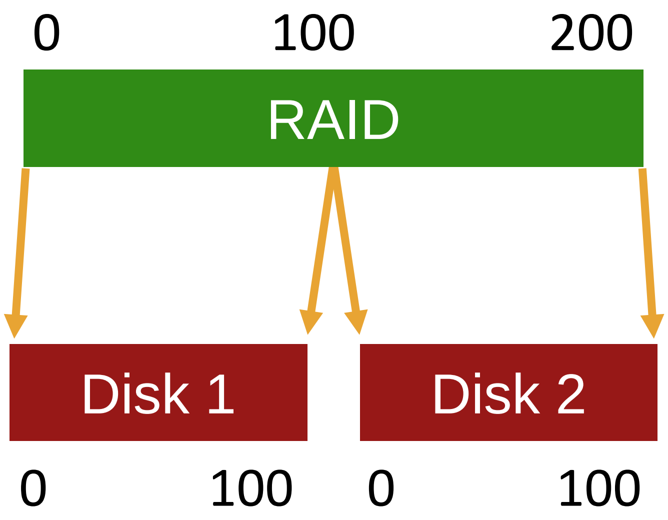
RAID: Redundant Array of Inexpensive Disks

Why *Inexpensive* Disks?

- Economies of scale! Commodity disks cost less
- Can buy many commodity H/W components for the same price as few high-end components
- Strategy: write S/W to build high-quality logical devices from many cheap devices
- Alternative to RAID: buy an expensive, high-end disk

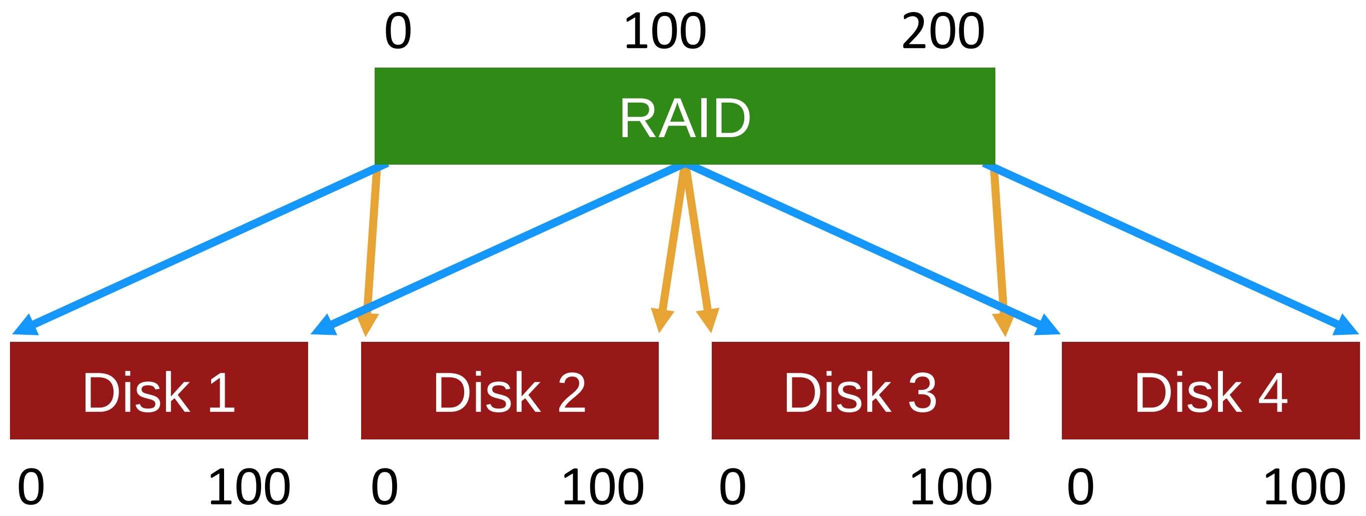
General Strategy: Mapping

Build fast, large disk from smaller ones.



General Strategy: Redundancy

Add even more disks for reliability.



Mapping

- **How should we map logical block addresses to physical block addresses?**
  - Some similarity to virtual memory

- **1) Dynamic mapping: use data structure (hash table, tree)**
  - page tables
- **2) Static mapping: use simple math**
  - RAID

Redundancy

- **Trade-offs to amount of redundancy**

- **Increase number of copies:**
  - improves reliability (and maybe performance)

- **Decrease number of copies (deduplication):**
  - improves space efficiency

Reasoning About RAID

- **RAID**: system for mapping logical to physical blocks
- **Workload**: types of reads/writes issued by applications (sequential vs. random)
- **Metric**: capacity, reliability, performance

RAID Decisions

- **Which logical blocks map to which physical blocks?**
- **How do we use extra physical blocks (if any)?**
- **Different RAID levels make different trade-offs**

Workloads

- **Reads**
  - One operation
  - Steady-state I/O
    - Sequential
    - Random

- **Writes**
  - One operation
  - Steady-state I/O
    - Sequential
    - Random

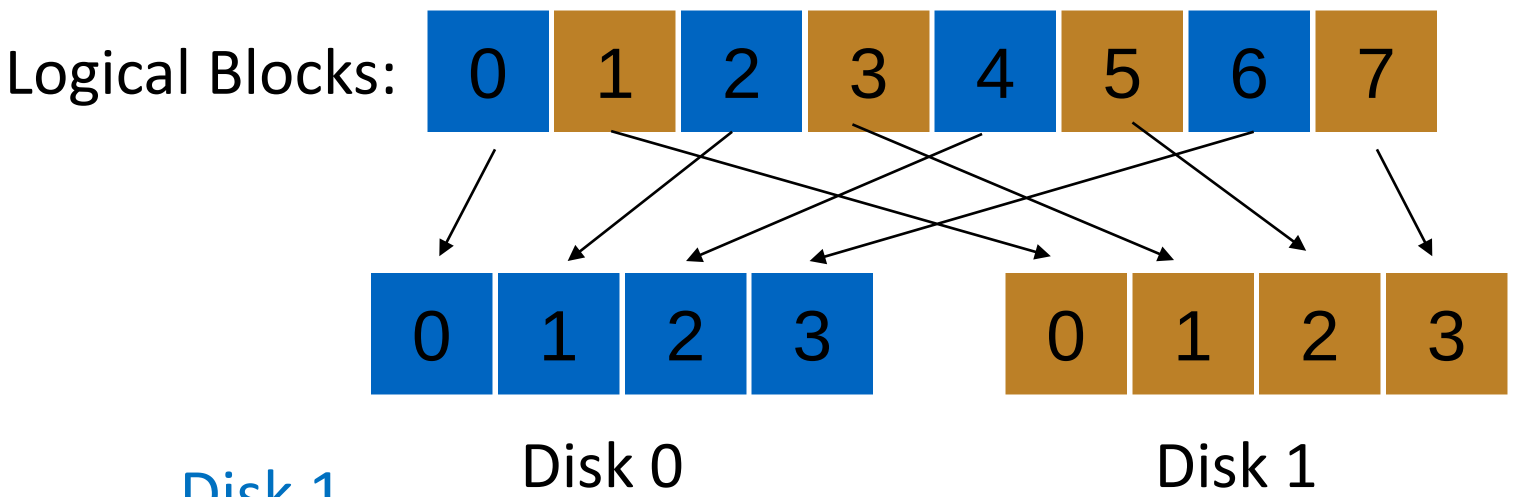
Metrics

- Capacity: how much space can apps use?
- Reliability: how many disks can we safely lose?
  (assume fail stop!)
- Performance: how long does each workload take?
- Normalize each to characteristics of one disk

N := number of disks
C := capacity of 1 disk
S := sequential throughput of 1 disk
R := random throughput of 1 disk
D := latency of one small I/O operation

RAID-0: Striping

- **Optimize for capacity. No redundancy**



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

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

Given logical address A, find:
Disk = ...
Offset = ...

Given logical address A, find:
Disk = A % disk_count
Offset = A / disk_count

Chunk Size

- 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
	1	3	5	7
stripe:	8	10	12	14
	9	11	13	15

assume chunk size of 1

Chunk Size

- **Larger chunk size**
  - Less intra-file parallelism
  - Reduces positioning time

- **Best chunk size?**
  - =1: 4KB (a block), =16: 64KB …
  - Depend on workload
  - Hard to decide

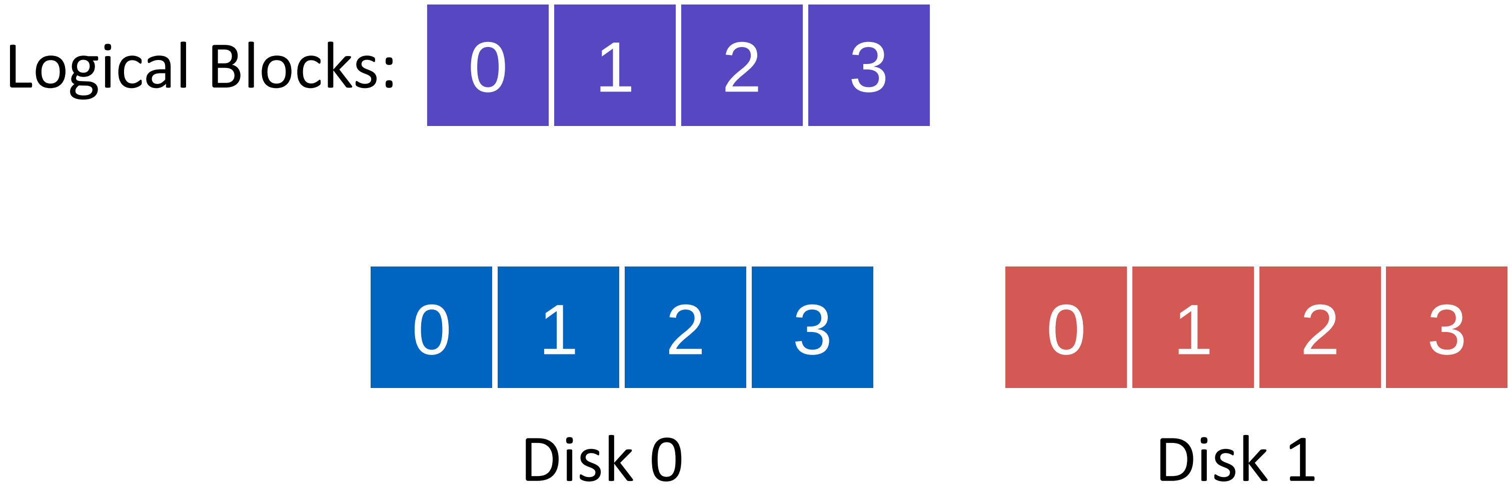
RAID-0: Analysis

- **What is capacity?** N * C
- **How many disks can fail without data loss?** 0
- **Latency** D
- **Throughput (sequential, random)?** N*S , N*R

Buying more disks improves throughput, but not latency!

N := number of disks
C := capacity of 1 disk
S := sequential throughput of 1 disk
R := random throughput of 1 disk
D := latency of one small I/O operation

RAID-1: Mirroring



Keep two copies of all data.

Raid-1 Layout

2 disks

Disk 0	Disk 1
0	0
1	1
2	2
3	3

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

Raid-1: 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 without data loss?

- Assume disks are **fail-stop**.
  - each disk works or it doesn't
  - system knows when disk fails
- Tougher Errors:
  - latent sector errors
  - silent data corruption

RAID-1: Analysis

- **What is capacity?** N/2 * C
- **How many disks can fail?** 1 (or maybe N / 2)
- **Latency (read, write)?** D

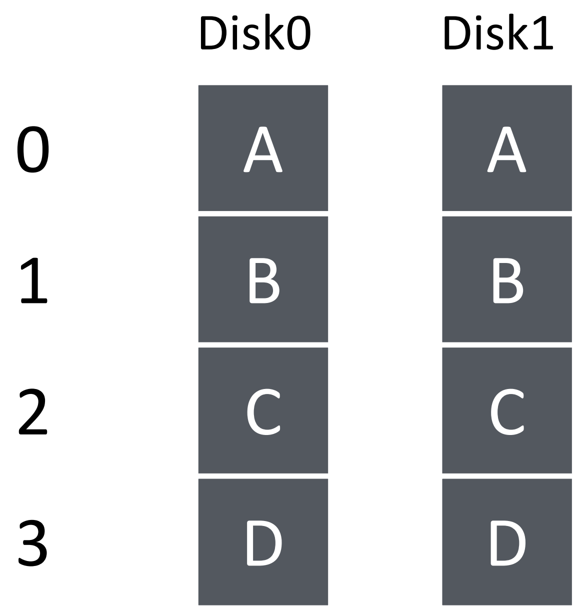
N := number of disks
C := capacity of 1 disk
S := sequential throughput of 1 disk
R := random throughput of 1 disk
D := latency of one small I/O operation

RAID-1: Throughput

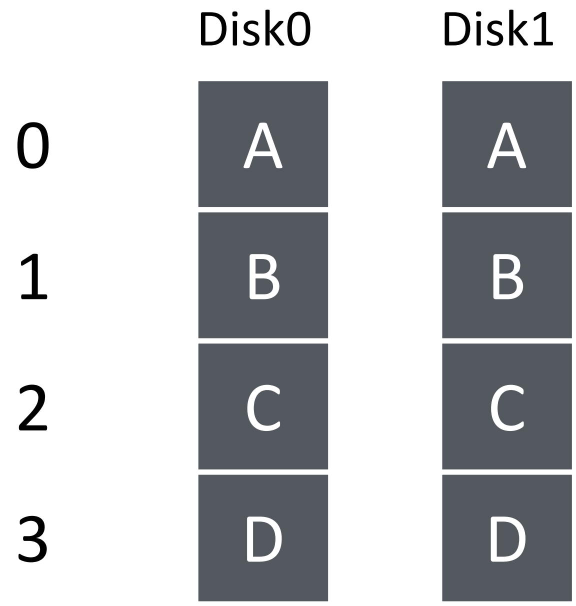
- **What is steady-state throughput for**
  - random reads? **N * R**
  - random writes? **N/2 * R**
  - sequential writes? **N/2 * S**
  - sequential reads? **Book: N/2 * S (other models: N * S)**

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

Crashes

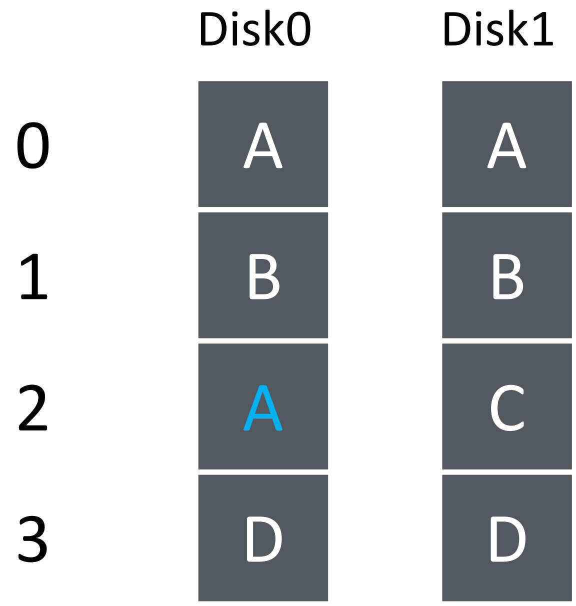


Crashes



write(A) to 2

Crashes



write(A) to 2

Crashes

	Disk0	Disk1
0	A	A
1	B	B
2	A	A
3	D	D

write(A) to 2

Crashes

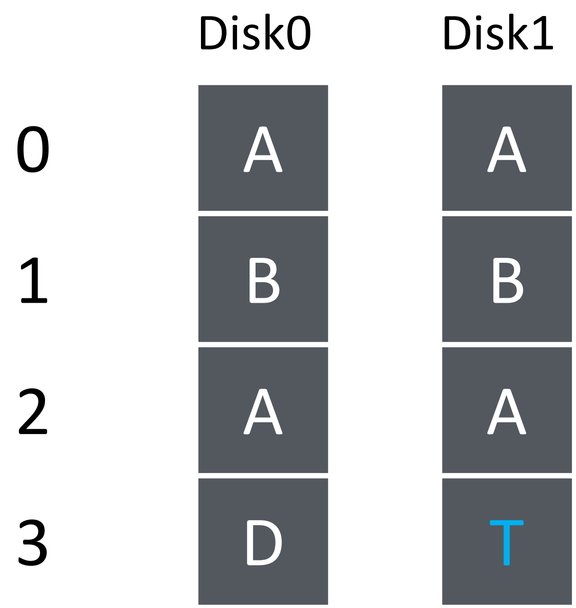
	Disk0	Disk1
0	A	A
1	B	B
2	A	A
3	D	D

Crashes

	Disk0	Disk1
0	A	A
1	B	B
2	A	A
3	D	D

write(T) to 3

Crashes



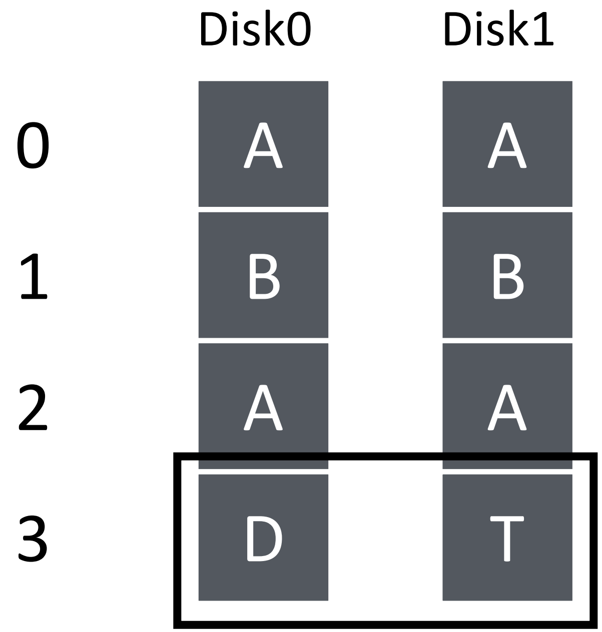
write(T) to 3

Crashes

	Disk0	Disk1
0	A	A
1	B	B
2	A	A
3	D	T

CRASH!!!

Crashes



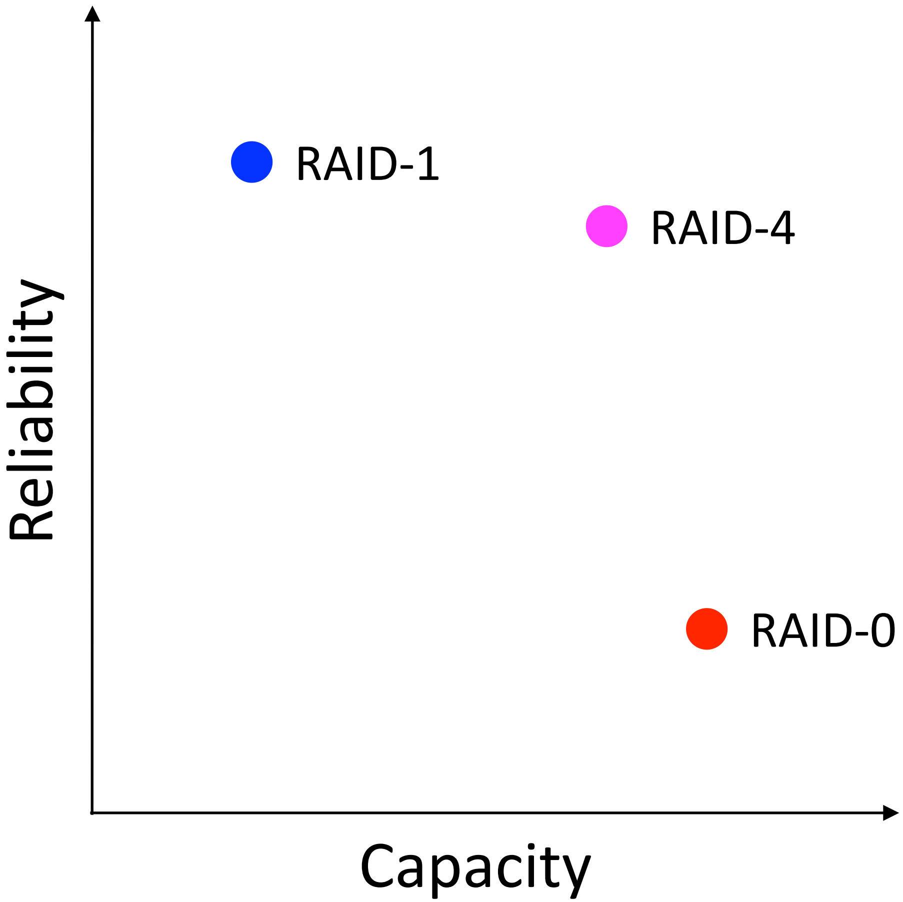
after reboot, how to tell which data is right?

H/W and S/W Solutions

- **Problem: Consistent-Update Problem**

- **H/W: Use non-volatile RAM in RAID controller.**

- **S/W: Write-ahead log (persistent)**
  - record what will be done in RAID


RAID-1
RAID-4
RAID-0
Reliability
Capacity

Raid-4 Strategy

- Use parity disk
- In algebra, if an equation has N variables, and N-1 are known, you can often solve for the unknown.
- Treat sectors across disks in a stripe as an equation.
- Data on bad disk is like an unknown in the equation.

Example

Disk0 Disk1 Disk2 Disk3 Disk4

Stripe:

Example

Disk0 Disk1 Disk2 Disk3 Disk4

Stripe:

(parity)

Example

	Disk0	Disk1	Disk2	Disk3	Disk4
Stripe:	5	3	0	1	
					(parity)

Example

	Disk0	Disk1	Disk2	Disk3	Disk4
Stripe:	5	3	0	1	9
					(parity)

Example

	Disk0	Disk1	Disk2	Disk3	Disk4
Stripe:	5	X	0	1	9
					(parity)

Example

	Disk0	Disk1	Disk2	Disk3	Disk4
Stripe:	5	3	0	1	9
					(parity)

Example

	Disk0	Disk1	Disk2	Disk3	Disk4
Stripe:	2	1	1	X	5
					(parity)

Example

	Disk0	Disk1	Disk2	Disk3	Disk4
Stripe:	2	1	1	1	5
					(parity)

Example

	Disk0	Disk1	Disk2	Disk3	Disk4
Stripe:	3	0	1	2	X
					(parity)

Example

	Disk0	Disk1	Disk2	Disk3	Disk4
Stripe:	3	0	1	2	6
					(parity)

Which functions are used to compute parity?

Example

- **Which functions are used to compute parity?**

- **XOR**
  - **0 if there are an even number of 1s in all corresponding bits**
  - **1 if odd number of 1s**

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

RAID-4: Analysis

- **What is capacity?** **(N-1) * C**
- **How many disks can fail?** **1**
- **Latency (read, write)?** **D, 2*D (read and write parity disk)**

Write: two rounds of four I/Os needed: two reads and two writes for Disk 1 and 4

Disk0	Disk1	Disk2	Disk3	Disk4
3	0	1	2	6
				(parity)

N := number of disks
C := capacity of 1 disk
S := sequential throughput of 1 disk
R := random throughput of 1 disk
D := latency of one small I/O operation

Disk 1 = 0, Disk 4 = 1
new = 0 => Disk 4 = 1
new = 1 => Disk 4 = 0
or all disks need to be read

RAID-4: Analysis

- **What is steady-state throughput for**
  - sequential reads? **(N-1) * S**
  - sequential writes? **(N-1) * S**
  - random reads? **(N-1) * R**
  - random writes? **R/2 (read and write block and parity disk)**

- Four I/Os needed: two reads and two writes

- [**full-stripe write**, write parity at the same time]
- [**subtractive parity**]

$$P_{new} = (C_{old} \oplus C_{new}) \oplus P_{old}$$

- how to avoid parity bottleneck?

Disk0	Disk1	Disk2	Disk3	Disk4
3	0	1	2	6

(parity)

RAID-5

Disk0	Disk1	Disk2	Disk3	Disk4
-	-	-	-	P
-	-	-	P	-
-	-	P	-	-

…

Rotate parity across different disks

RAID-5: Analysis

- What is capacity? **(N-1) * C**
- How many disks can fail? **1**
- Latency (read, write)? **D, 2*D (read and write parity disk)**

Same as RAID-4…

Disk0	Disk1	Disk2	Disk3	Disk4
-	-	-	-	P
-	-	-	P	-
-	-	P	-	-

…

N := number of disks
C := capacity of 1 disk
S := sequential throughput of 1 disk
R := random throughput of 1 disk
D := latency of one small I/O operation

RAID-5: Throughput

- **Four I/Os needed:**
two reads and two writes

- **Steady-state throughput for RAID-4:**
  - sequential reads? **(N-1) * S**
  - sequential writes? **(N-1) * S**
  - random reads? **(N-1) * R**
  - random writes? **R/2 (read and write parity disk)**

Disk0	Disk1	Disk2	Disk3	Disk4
3	0	1	2	6
				(parity)

- **What is steady-state throughput for RAID-5?**
  - sequential reads? **(N-1) * S**
  - sequential writes? **(N-1) * S**
  - random reads? **(N) * R**
  - random writes? **(N * R) / 4**

Disk0	Disk1	Disk2	Disk3	Disk4
-	-	-	-	P
-	-	-	P	-
-	-	P	-	-

...

RAID Level Comparisons

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

RAID LEVEL Comparisons

	Read Latency	Write Latency
RAID-0	D	D
RAID-1	D	D
RAID-4	D	2D
RAID-5	D	2D

RAID Level Comparisons

	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

RAID-5 is strictly better than RAID-4

RAID Level Comparisons

	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-5	(N-1)*S	(N-1)*S	N * R	N/4 * R

- RAID-0 is always fastest and has best capacity (but at cost of reliability)
- RAID-5 better than RAID-1 for sequential workloads
- RAID-1 better than RAID-5 for random workloads

Summary

- **Many engineering tradeoffs with RAID**
  - capacity, reliability, performance for different workloads

- **Block-based interface:**
  Very deployable and popular storage solution due to transparency