UNIVERSITY of WISCONSIN-MADISON
Computer Sciences Department

CS 537
Introduction to Operating Systems

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

Why *Inexpensive* Disks?

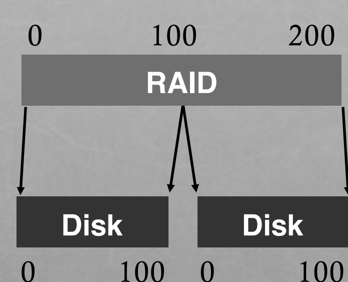
Alternative to RAID: buy an expensive, high-end disk

RAID Approach

- Economies of scale! Commodity disks cost less
- Can buy **many** commodity H/W components for same price as few high-end components
- Write software to build high-quality logical devices from many cheap devices

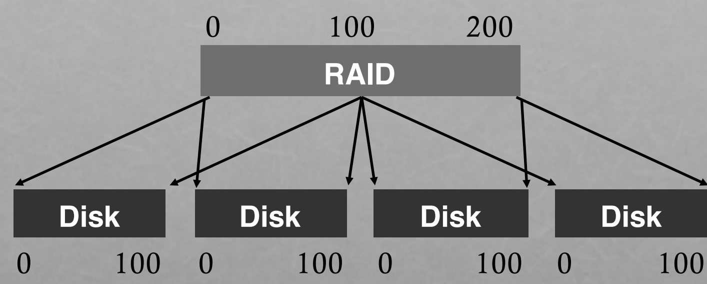
General Strategy: Mapping

Build fast, large disk from smaller disks



General Strategy: Redundancy

Add even more disks for reliability.



Mapping

How should RAID map logical block addresses to physical block addresses?

- Some similarity to virtual memory

1) Dynamic mapping: use data structure (array, hash table, tree)

- page tables

2) Static mapping: use simple math

- RAID

Redundancy

How many copies should RAID keep for every block?

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 to 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 applications use?

Reliability: how many disks can RAID safely lose?
(assume fail stop!)

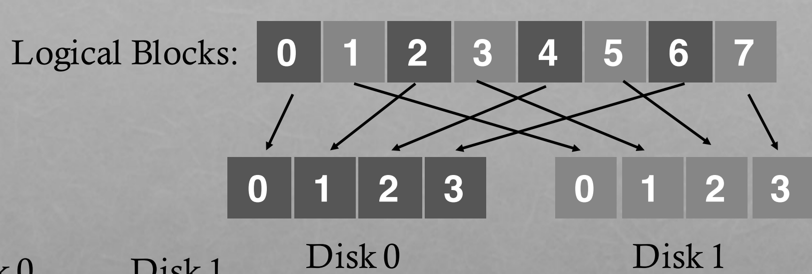
Performance: how long does each workload take?

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

RAID-0: 4 Disks

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

RAID-0: 4 Disks

	Disk 0	Disk 1	Disk 2	Disk 4
	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

Real Systems: Chunk Size

Chunk size = 1

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

Simplification: assume chunk size of 1

RAID-0: Analysis

What is capacity? **N * C**

How many disks can fail? **0**

Latency **D**

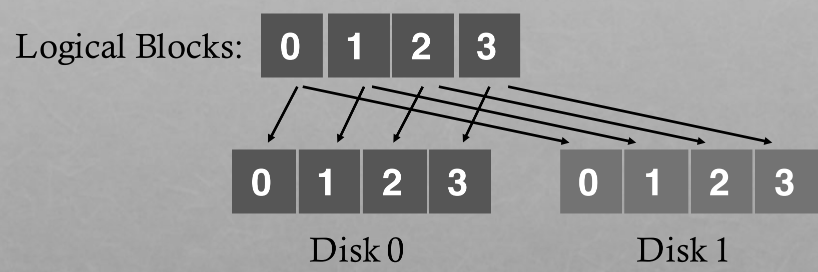
Throughput (sequential, random)? **N*S , N*R**

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

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

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

How many disks can fail?

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

Always handle 1 disk failure
May handle N/2 if to different replicas

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

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

RAID-1: Throughput

What is steady-state throughput for

- sequential reads?
- sequential writes?
- random reads?
- random writes?

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

Crashes

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

Crashes

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

write(A) to 2

Crashes

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

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

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

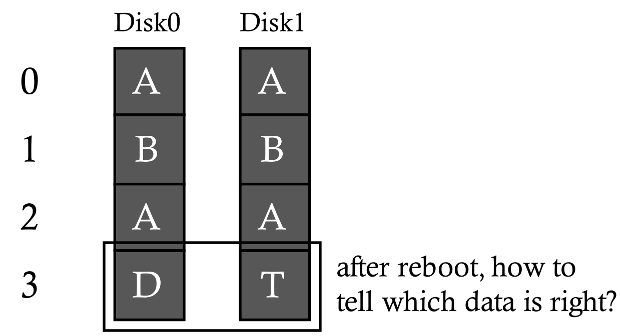
write(T) to 3

Crashes

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

CRASH!!!

Crashes

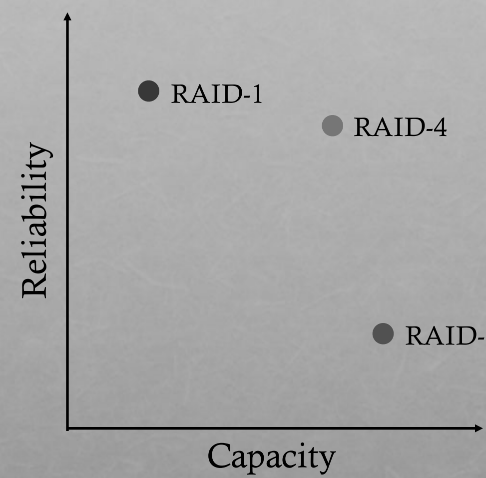


H/W Solution

Problem: Consistent-Update Problem

Use non-volatile RAM in RAID controller

Software RAID controllers (e.g., Linux md) don't have this option



RAID-4 Strategy

Use parity disk

In algebra, for equation with N variables and N-1 are known, can often solve for unknown

Treat sectors across disks in a stripe as equation

Data on bad disk is unknown in equation

Parity Example: 1

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

Parity Example: 1

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

Parity Example: 1

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

Parity Example: 2

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

Parity Example: 2

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

Parity Example: 3

	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?

UPDATING PARITY: XOR

If write "0110" to block 0, how should parity be updated?

Read old value at block 0
- 1100

Read old value for parity
- 0101

Calculate new parity
- 1111
- Write out new parity
- → 2 reads and 2 writes (1 read and 1 write to parity block)

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)**

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

RAID-4: Throughput

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 parity disk)**

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

Left-Symmetric RAID-5

D0	D1	D2	D3	D4
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: 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

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

RAID Summary

Many engineering tradeoffs with RAID

- Capacity, reliability, performance for different workloads

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