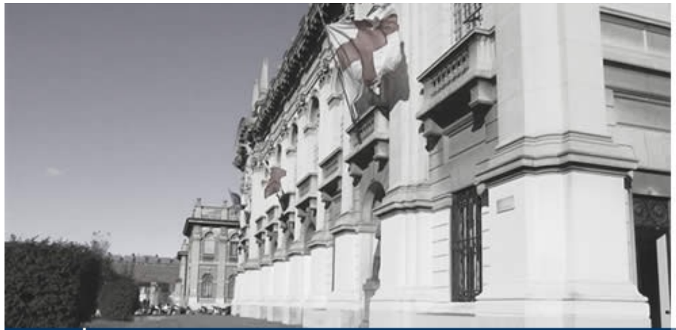
Computing Infrastructure



POLITECNICO DI MILANO

RAID disks

HW Infrastructures:

System-level: Computing Infrastructures and Data Center Architectures, Rack/Structure;

Node-level: Server (computation, HW accelerators), **Storage (Type, technology),** Networking (architecture and technology);

Building-level: Cooling systems, power supply, failure recovery

SW Infrastructures:

Virtualization: Process/System VM, Virtualization Mechanisms (Hypervisor, Para/Full virtualization)

Computing Architectures: Cloud Computing (types, characteristics), Edge/Fog Computing, X-as-a service

Methods:

Reliability and availability of datacenters (definition, fundamental laws, RBDs)

Disk performance (**Type, Performance, RAID**)

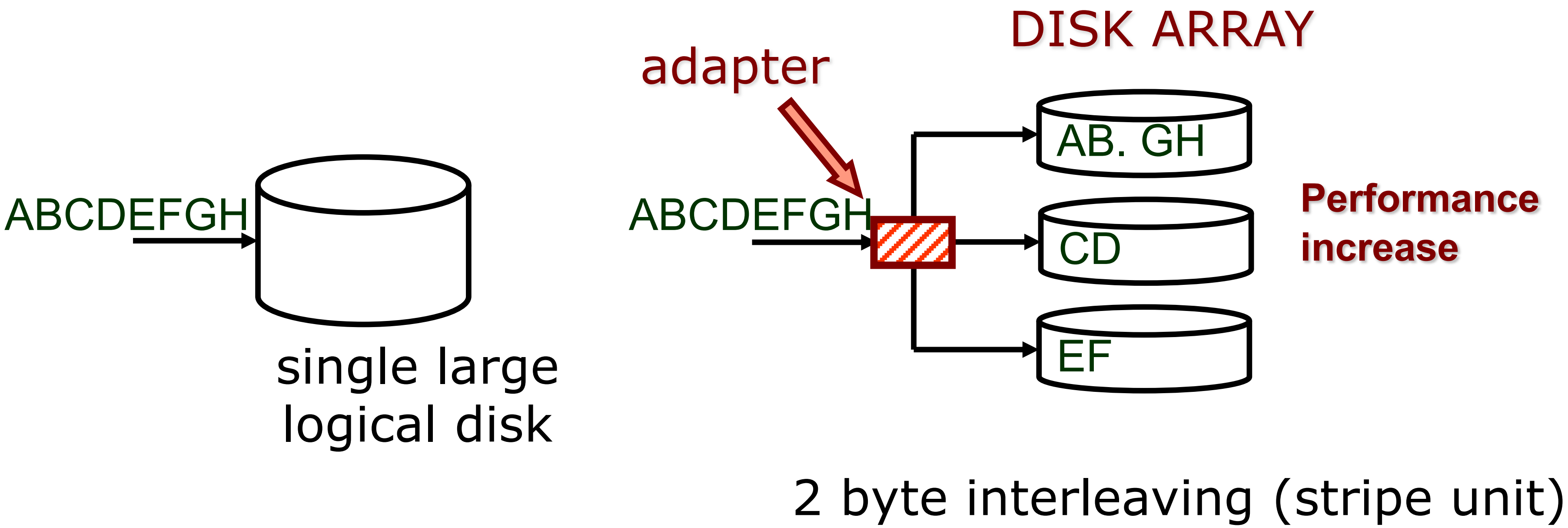
Scalability and performance of datacenters (definitions, fundamental laws, queuing network theory)

Redundant Arrays of Independent (Inexpensive) Disks

- Disk Arrays: proposed in the 1980's [PATTERSON]
- Need to increase the performance, the size and the reliability of storage systems
- Several *independent* disks that are considered as a single, large, high-performance logical disk
  - In contrast with the JBOD (Just a Bunch of Disks) method where each disk is a separate device with a different mount point
- the data are *striped* across several disks accessed in parallel:
  - high data transfer rate: large data accesses (heavy I/O op.)
  - high I/O rate: small but frequent data accesses (light I/O op.)
  - load balancing across the disks

Two orthogonal techniques:

- data striping: to improve performance
- redundancy: to improve reliability



- *I/O virtualization*
  - data are distributed transparently over the disks (no action is required to the users)

data striping

- striping: data are written sequentially (a vector, a file, a table, ...) in units (stripe unit: bit, byte, blocks) on multiple disks according to a cyclic algorithm (*round robin*)
- stripe unit: dimension of the unit of data that are written on a single disk
- stripe width: number of disks considered by the striping algorithm
  1. multiple independent I/O requests will be executed in parallel by several disks decreasing the queue length (and time) of the disks
  2. single multiple-block I/O requests will be executed by multiple disks in parallel increasing of the transfer rate of a single request

the more physical disks in the array

the larger the size and performance gains

but ... ...

the larger the probability of failure of a disk

$\Downarrow$

this is the main motivation for the introduction of

redundancy

Overall reliability decreases with redundancy

- The probability of a failure (assuming independent failures) in an array of 100 disks is 100 higher the probability of a failure of a single disk
  - if a disk has an Mean Time To Failure (MTTF) of 200,000 hours (~23 years) an array of 100 disks will show a MTTF of 2000 hours (~ 3 months)
- Redundancy: Data duplication or error correcting codes (stored on disks different from the ones with the data) are computed to tolerate loss due to disk failures
- Since write operations must update also the redundant information, their performance is worse than the one of the traditional writes

Example of a data duplication/reconstruction

Data duplication

Values

Disk 0	Disk 1	redundant data Disk 0	redundant data Disk 1
10	8	10	**8**
10	failed	10	**8**

failed = 8 from Redundant Disk 1

Data reconstruction

Values

Disk 0	Disk 1	Disk 2	redundant data
10	8	2	**20**
10	failed	2	**20**

Sum of the data

failed = 20 – (10 + 2) = 8

RAID

Beyond Single Disks

Hard drives are great devices

- Relatively fast, persistent storage

Shortcomings:

- How to cope with disk failure?
  - Mechanical parts break over time
  - Sectors may become silently corrupted
- Capacity is limited
  - Managing files across multiple physical devices is cumbersome
  - Can we make 10x 1 TB drives look like a 10 TB drive?

Redundant Array of Inexpensive Disks

RAID: use multiple disks to create the illusion of a large, faster, more reliable disk

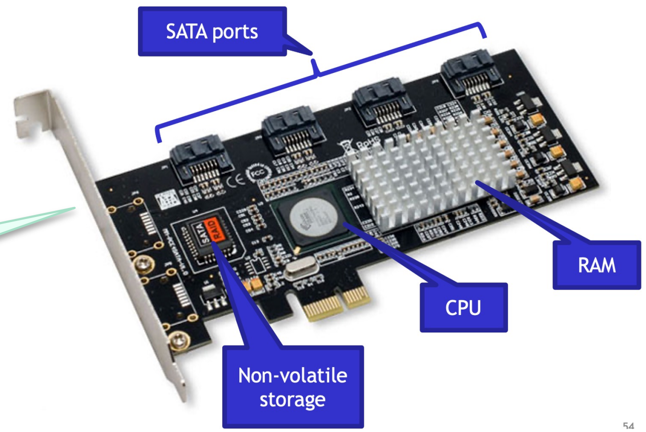
Externally, RAID looks like a single disk

- i.e. RAID is transparent
- Data blocks are read/written as usual
- No need for software to explicitly manage multiple disks or perform error checking/recovery

Internally, RAID is a complex computer system

- Disks managed by a dedicated CPU + software
- RAM and non-volatile memory
- Many different configuration options
  - RAID levels

RAID Controller



RAID levels

- ***RAID 0*** striping only
- ***RAID 1*** mirroring only
  - ***RAID 0+1*** (nested levels)
  - ***RAID 1+0*** (nested levels)
- *RAID 2 bit interleaving (not used)*
- *RAID 3 byte interleaving - redundancy (parity disk)*
- *RAID 4* block interleaving - redundancy (parity disk)
- *RAID 5* block interleaving - redundancy (parity block distributed)
- *RAID 6* greater redundancy (2 failed disks are tolerated)

Only ***«RED ARCHITECTURES»*** are part of the course

RAID level 0: *striping, no redundancy*

Data are written on a single logical disk and splitted in several blocks distributed across the disks according to a striping algorithm

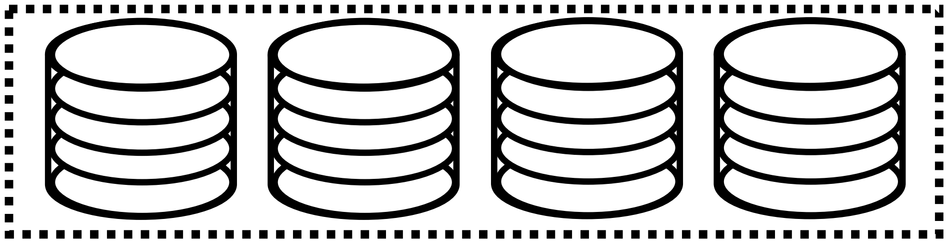
- used where performance and capacity, rather than reliability, are the primary concerns, minimum two drives required

+ lowest cost because it does not employ redundancy (no error-correcting codes are computed and stored)
+ best write performance (it does not need to update redundant data and it is parallelized)

– single disk failure will result in data loss

disk array

data

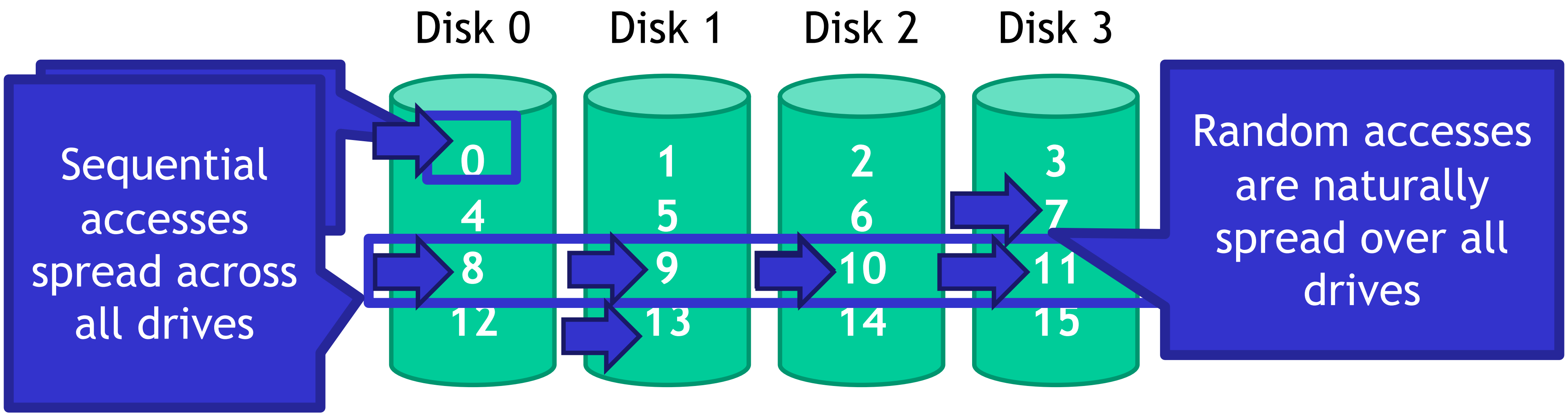


user capacity of 4 physical disks configured as a single logical disk RAID 0

used by the servers with read-only data

	Disk **0**	Disk 1	Disk 2	Disk 3	
Stripe **1**	*Block 1*	*Block 2*	*Block 3*	*Block 4*	
Stripe **2**	*Block 5*	*Block 6*	*Block 7*	*Block 8*	

- Key idea: present an array of disks as a single large disk
- Maximize parallelism by striping data cross all *N* disks



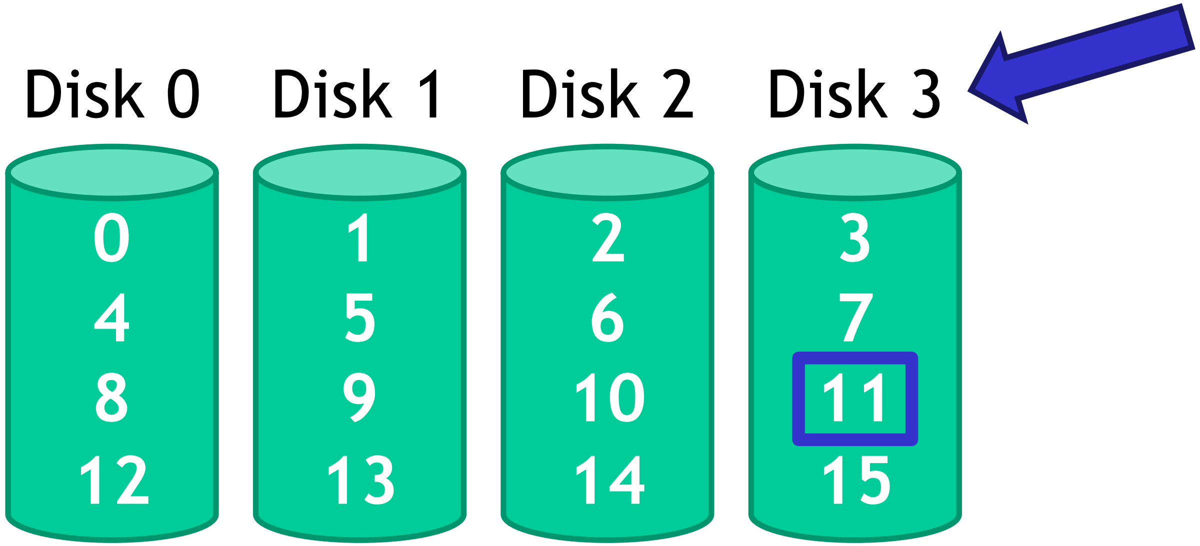
Addressing Blocks

How do you access specific data blocks?

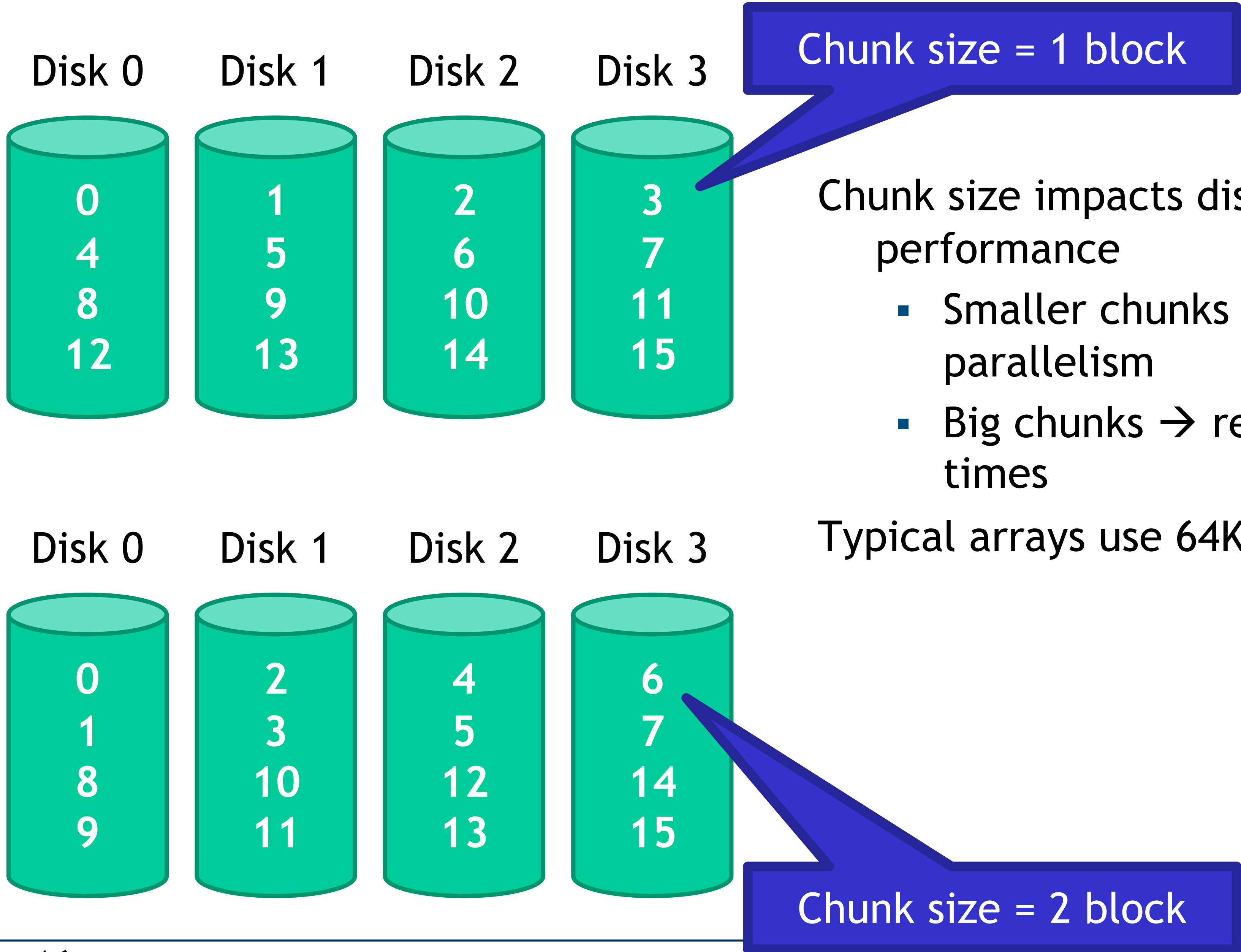
- Disk = logical_block_number % number_of_disks
- Offset = logical_block_number / number_of_disks

Example: read block 11

- 11 % 4 = Disk 3
- 11 / 4 = Physical Block 2 (starting from 0)



Chunk Sizing



Chunk size impacts disk array performance

- Smaller chunks → greater parallelism
- Big chunks → reduced seek times

Typical arrays use 64KB chunks

Measuring RAID Performance (1) - Seq. Transfer Rate

As usual, we focus on sequential and random workloads

Assume disks in the array have **sequential transfer rate *S***

E.g. Single large transfer

- 10 MB transfer
- *S = transfer_size / time_to_access*
- 10 MB / (7 ms + 3 ms + 10 MB / 50 MB/s) = 47.62 MB/s

Average seek time	7 ms
Average rotational delay	3 ms
Transfer rate	50 MB/s

Measuring RAID Performance (2) - Rnd. Transfer Rate

As usual, we focus on sequential and random workloads

Assume disks in the array have **random transfer rate *R***

E.g. Set of small files

- 10 KB transfer
- *R = transfer_size / time_to_access*
- 10 KB / (7 ms + 3 ms + 10 KB / 50 MB/s) = 0.98 MB/s

Average seek time	7 ms
Average rotational delay	3 ms
Transfer rate	50 MB/s

Analysis of RAID 0

Capacity: *N*

- All space on all drives can be filled with data

Reliability: 0

- If any drive fails, data is permanently lost
- MTTDL = MTTF

Sequential read and write: *N* * *S*

- Full parallelization across drives

Random read and write: *N* * *R*

- Full parallelization across all drives

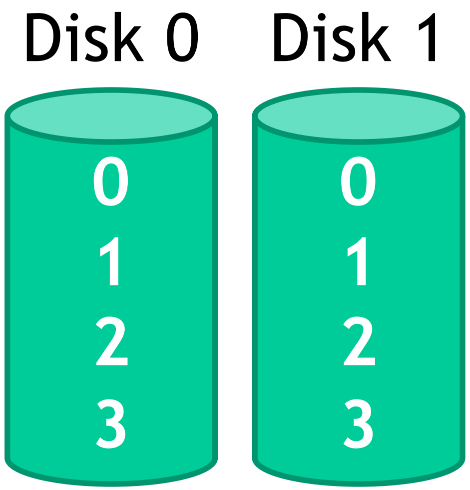
RAID 1: Mirroring - Key Idea

- RAID 0 offers high performance, but zero error recovery
- Key idea: make two copies of all data (minimum 2 disk drives)

\+ high reliability: when a disk fails the second copy is used

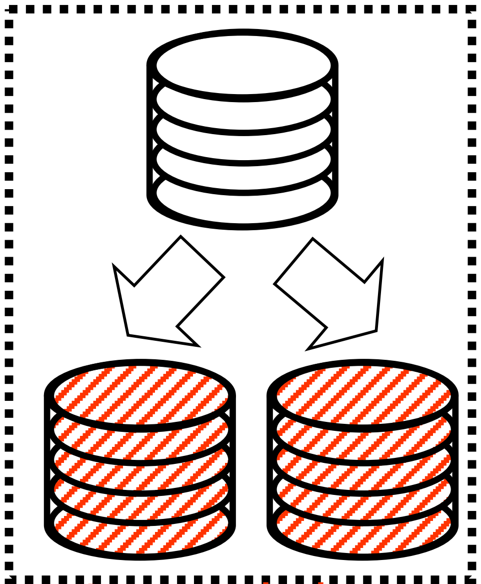
\+ fast writes (no error correcting code should be computed) – but still slower than standard disks (due to duplication)

– high costs (50% of the capacity is used)



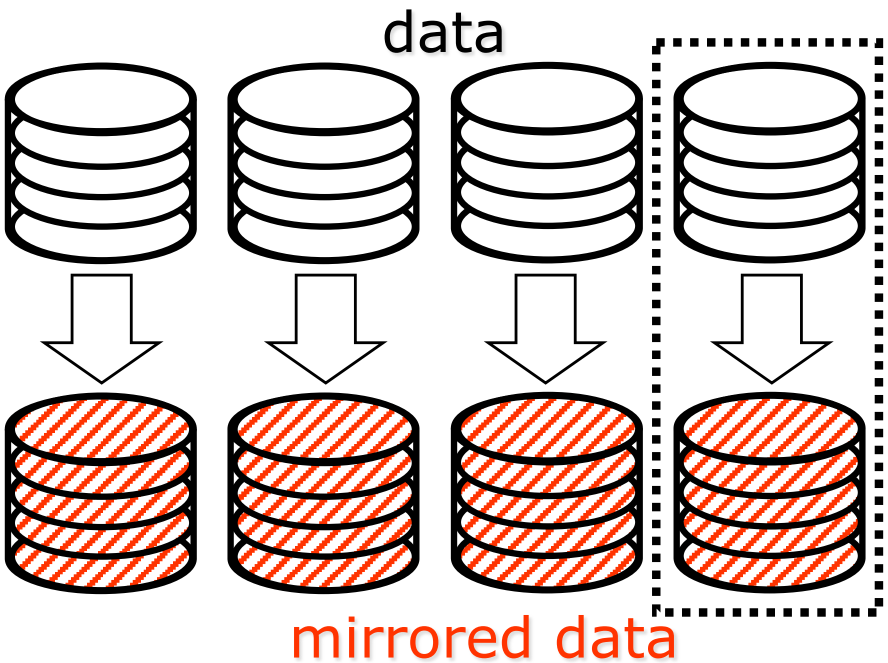
RAID level 1: *mirroring (Theoretical)*

- In principle, a RAID 1 can mirror the content over more than one disk.
  - This give resiliency to errors even if more than one disk breaks
  - It allows with a *voting mechanism* to identify errors not reported by the disk controller.
- In practice this is never used, because the overhead and costs are too high.



- However, if several disks are available (always in an even number), disks could be coupled.
- The total capacity is halved.
- Each disk has a mirror.
- How to organize this? RAID levels can be combined
  - Raid 0 + 1
  - Raid 1 + 0

user capacity of 4 disks (for data)

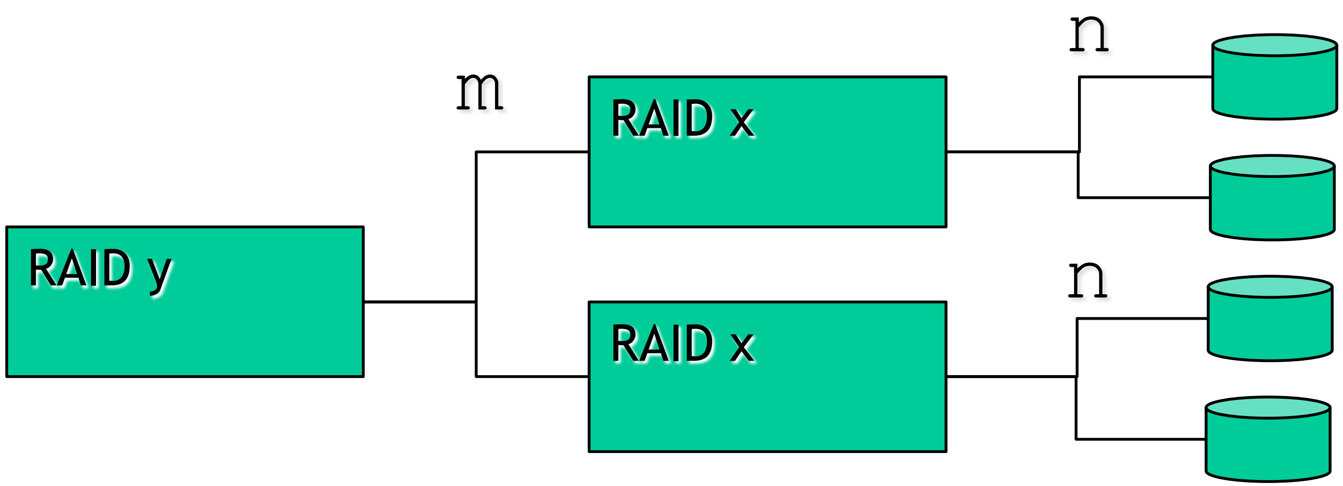


RAID levels (combined)

RAID levels can be combined

RAID *x* + *y* (or RAID *xy*) =>

- *n* x *m* disks in total
- Consider *m* groups of *n* disks
- Apply RAID *x* to each group of *n* disks
- Apply RAID *y* considering the *m* groups as single disks

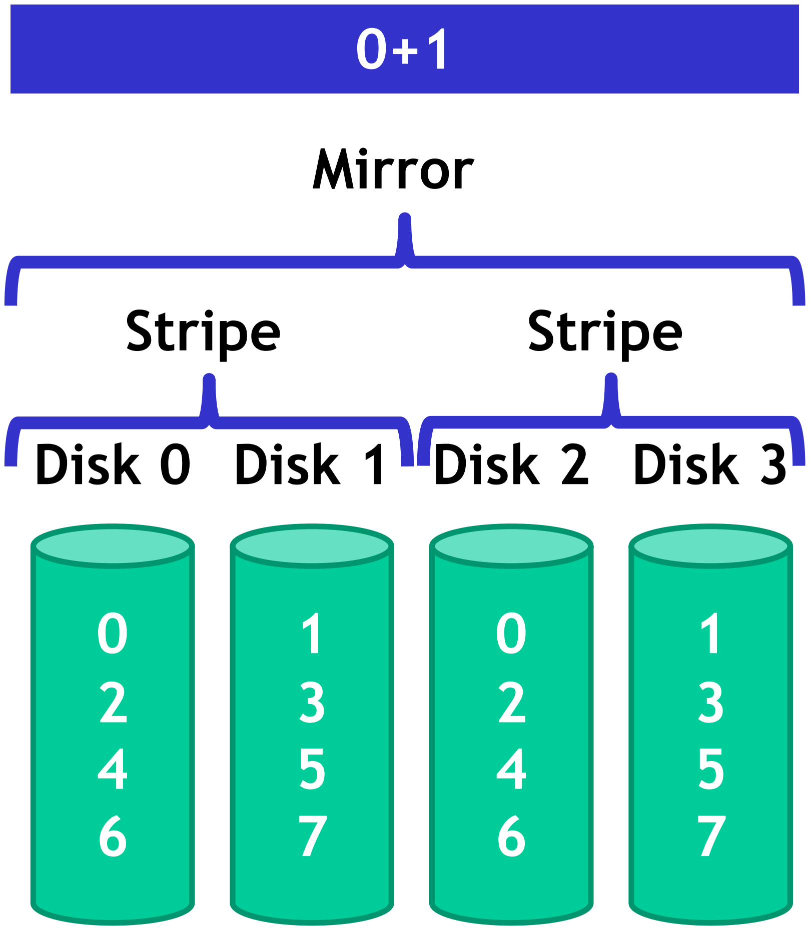


RAID level 0 + 1

"Group of striped disks (RAID 0) that are then mirrored (RAID 1)"

mirroring first (RAID 1)
then striping (RAID 0)

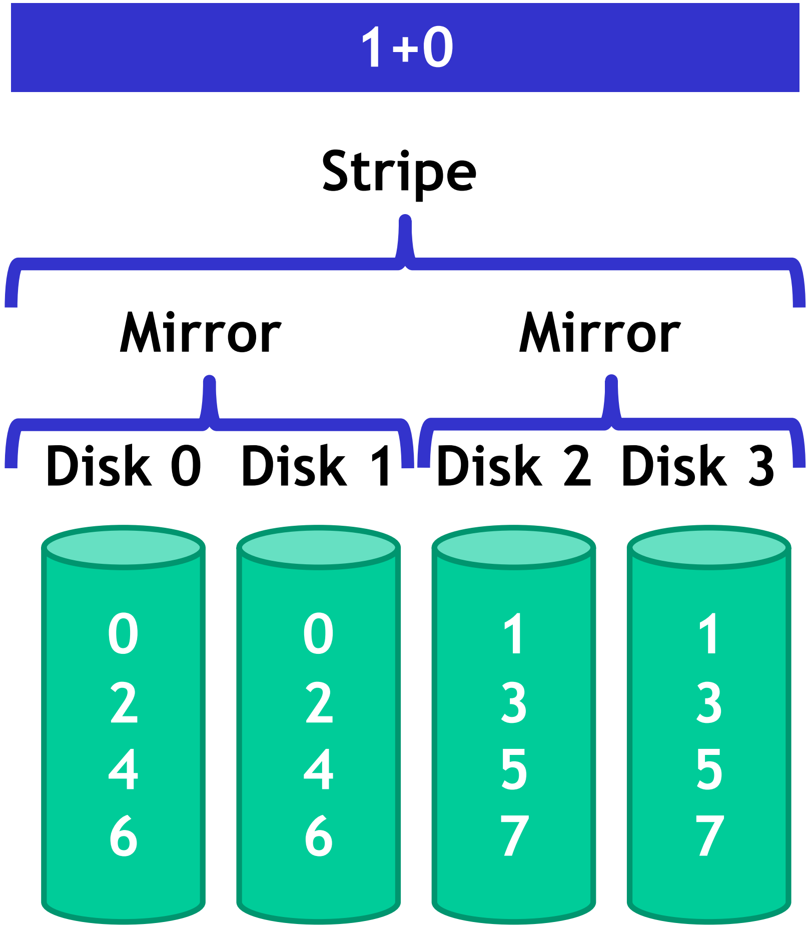
- minimum 4 drives
- after the first failure the model becomes as a RAID 0



"Group of mirrored disks (RAID 1) that are then striped (RAID 0)"

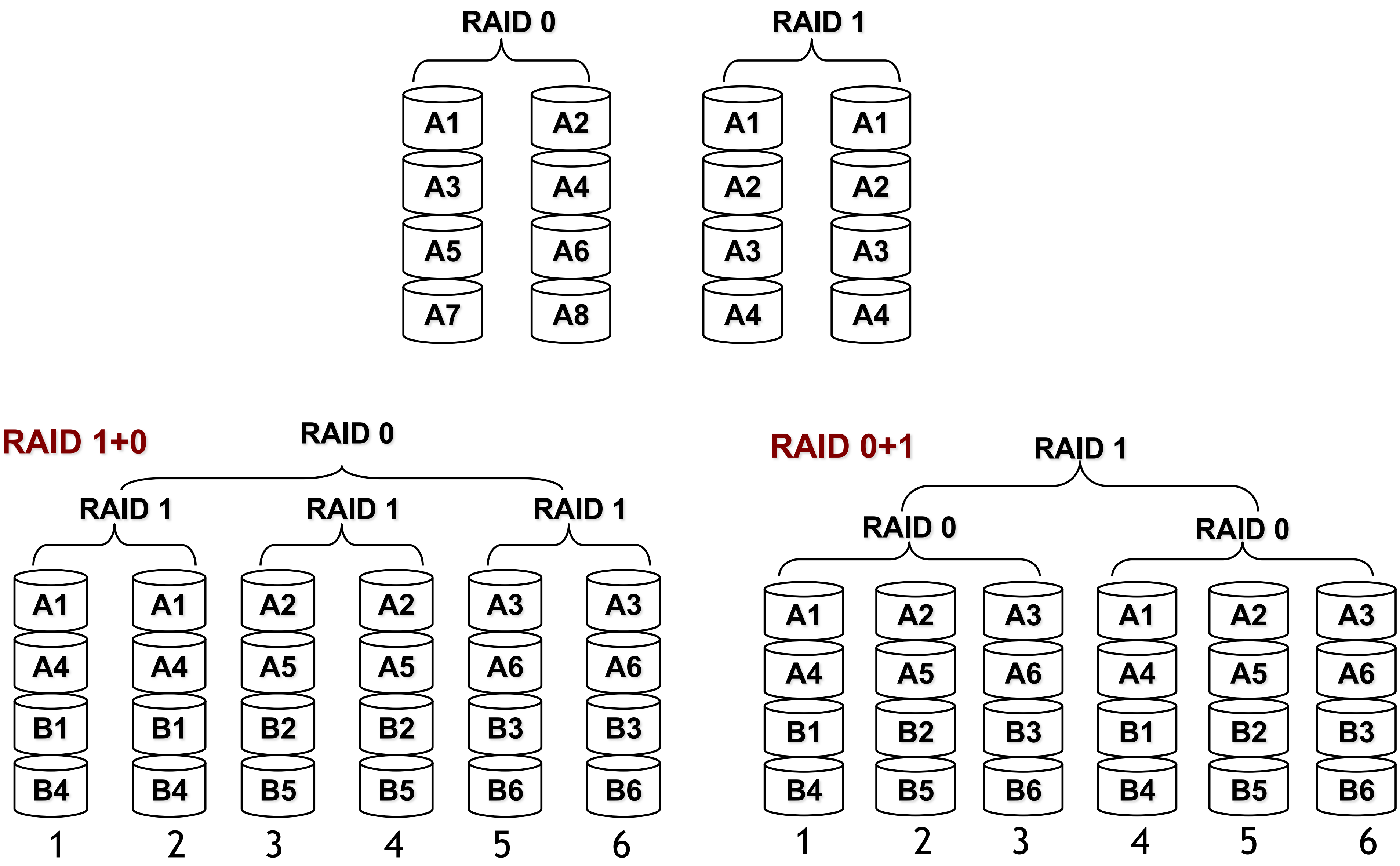
striping first (RAID 0)

then mirroring (RAID 1)



- minimum 4 drives are required
- used in databases with very high workload (fast writes)

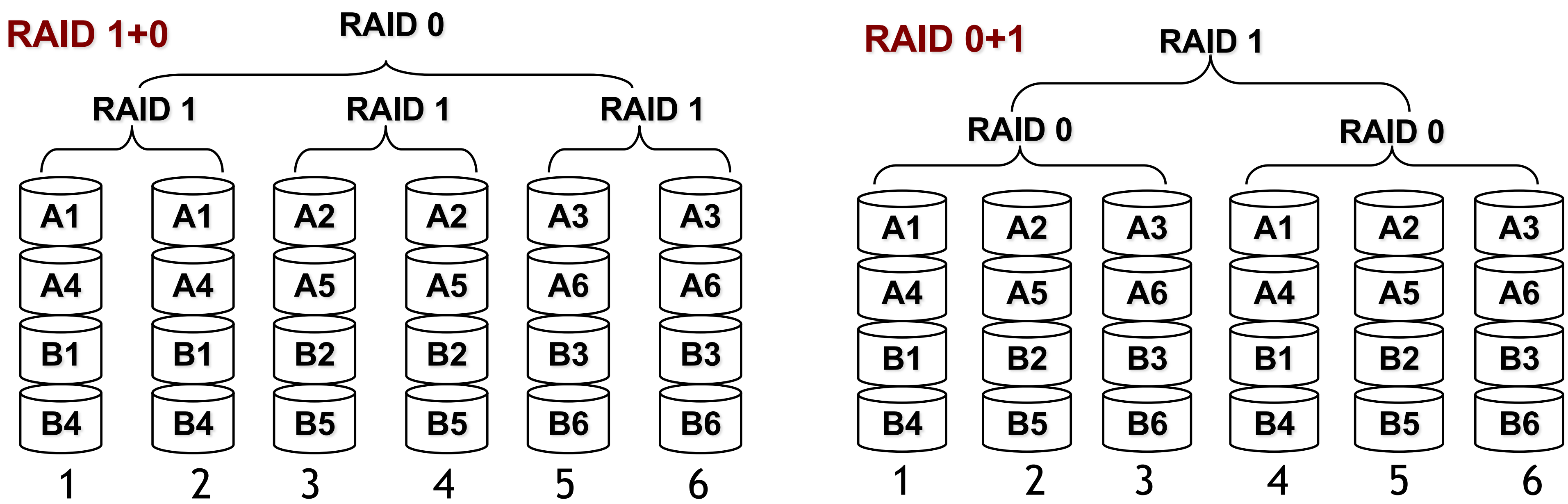
RAID 0, 1, 0+1 and 1+0 organizations



RAID 0, 1, 0+1 and 1+0 organizations

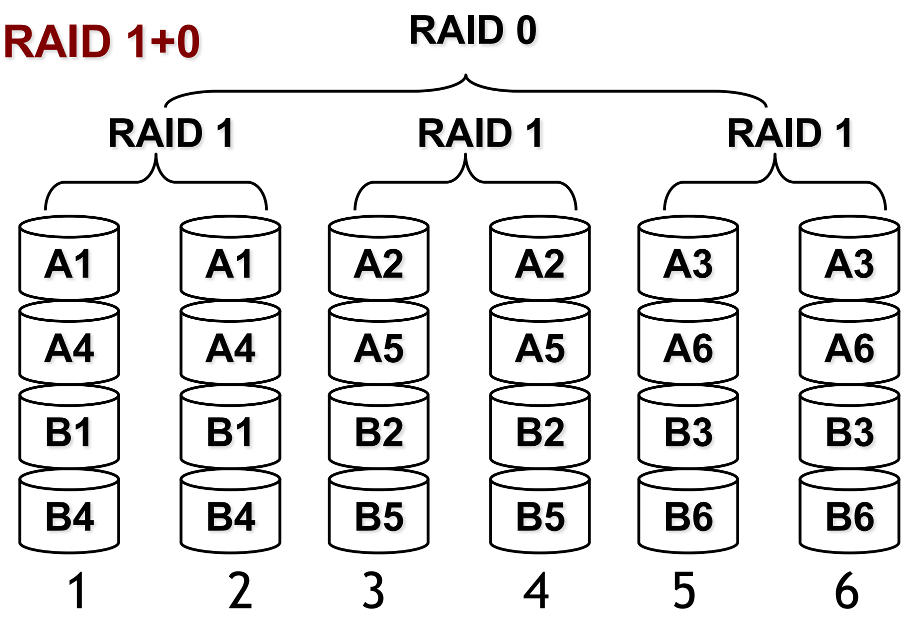
- The blocks are the same but are allocated in a different order
- Performance on both RAID 10 and RAID 01 are the same.
- The storage capacity of RAID 10 and RAID 01 is the same.

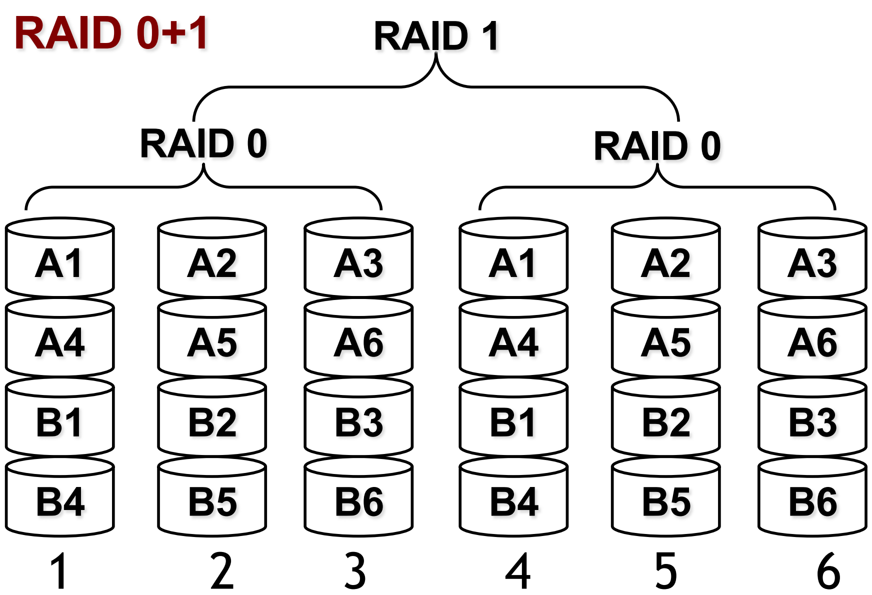
Where is the difference?



RAID 0, 1, 0+1 and 1+0 organizations

- The main difference is the **fault tolerance level:**
  - ✓On most implementations of RAID controllers,
    - ✓**RAID 0+1 fault tolerance is less.**
    - ✓**RAID 1+0 fault tolerance is larger.**





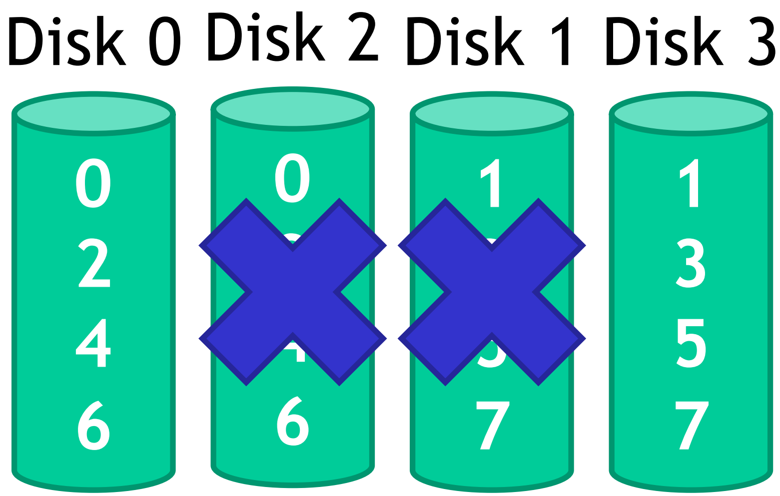
Analysis of RAID 1 (1)

Capacity: *N / 2*

- Two copies of all data, thus half capacity

Reliability: 1 drive can fail, sometime more

- If you are lucky, *N / 2* drives can fail without data loss



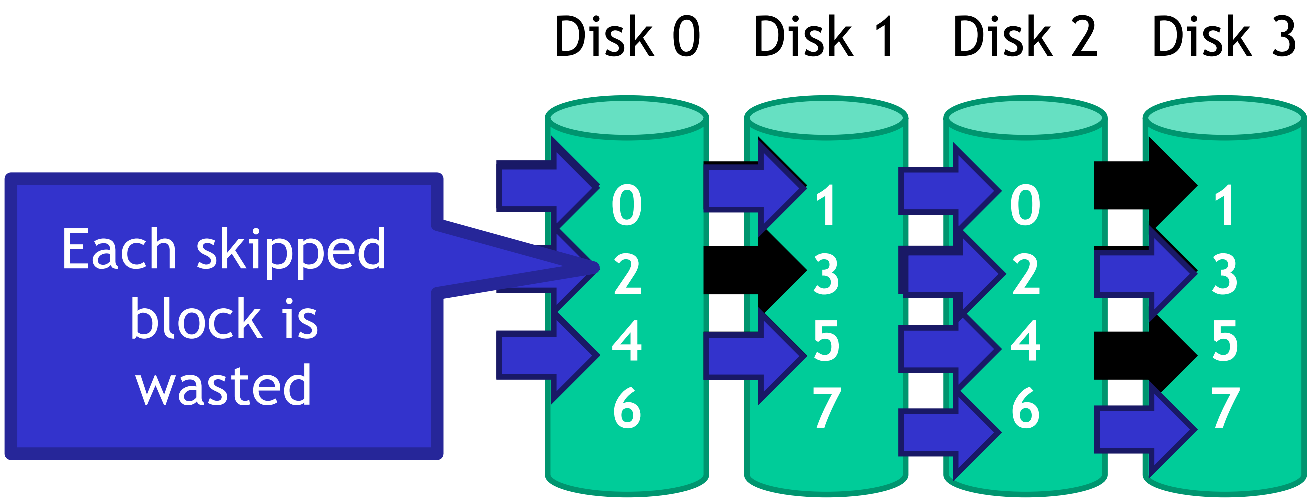
Analysis of RAID 1 (2)

Sequential write: *(N / 2) * S*

- Two copies of all data, thus half throughput

Sequential read: *(N / 2) * S*

- Half of the read blocks are wasted, thus halving throughput



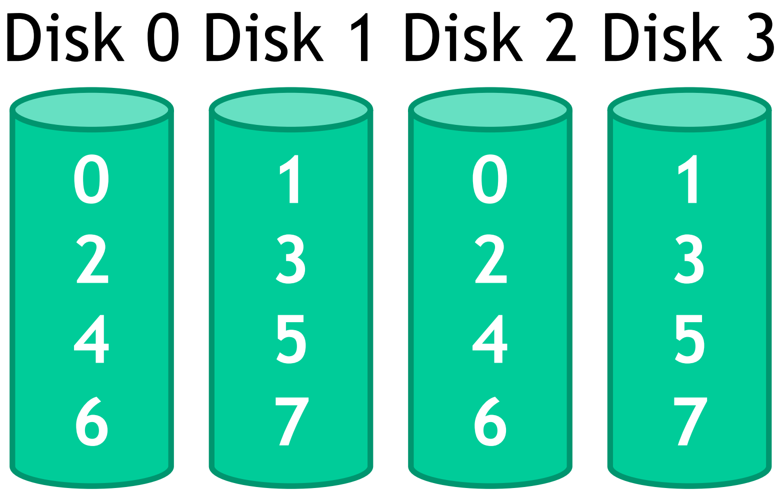
Analysis of RAID 1 (3)

Random read: *N * R*

- Best case scenario for RAID 1
- Reads can parallelize across all disks

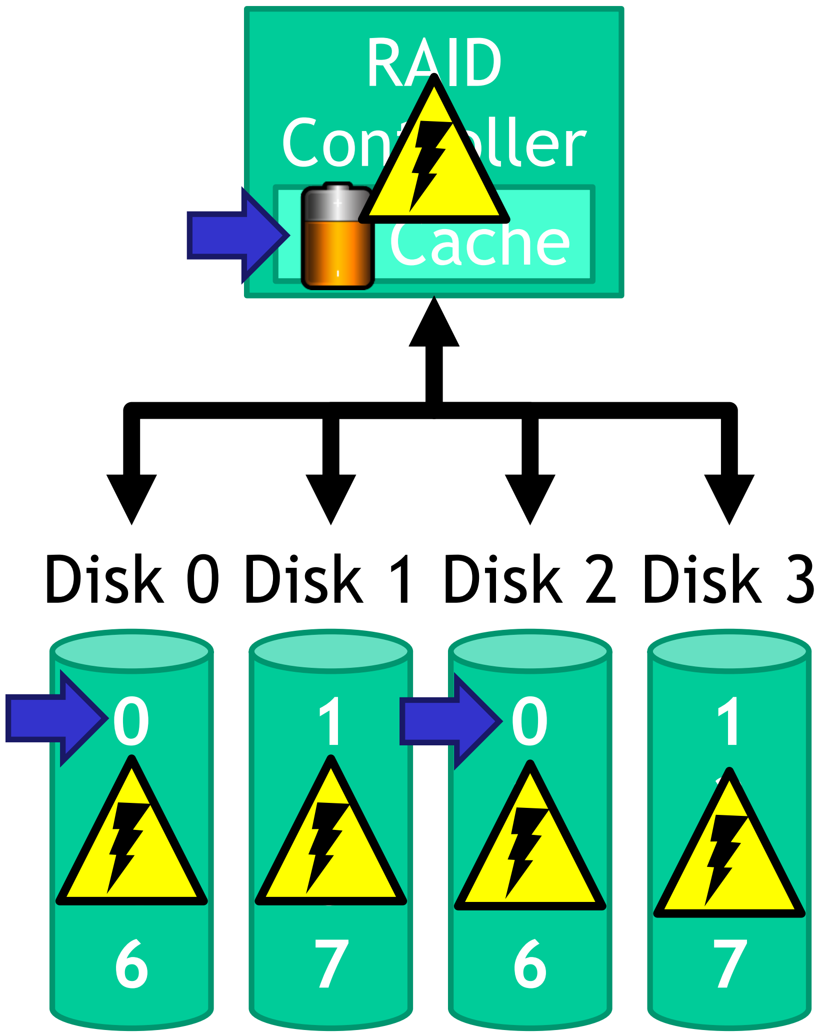
Random write: *(N / 2) * R*

- Two copies of all data, thus half throughput



The Consistent Update Problem

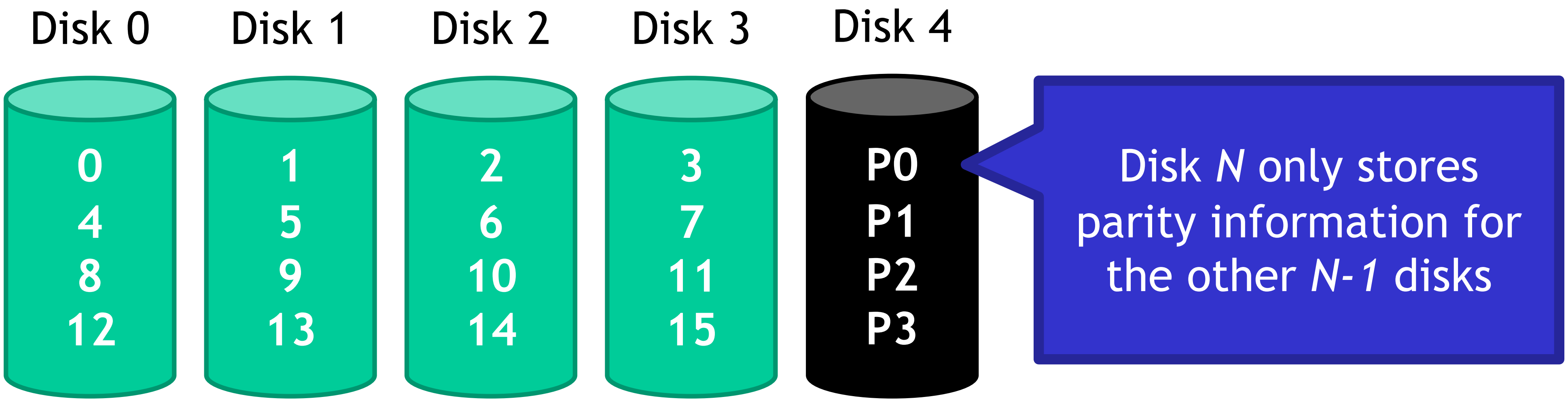
- Mirrored writes should be atomic
  - All copies are written, or none are written
- However, this is difficult to guarantee
  - Example: power failure
- Many RAID controllers include a write-ahead log
  - Battery backed, non-volatile storage of pending writes
  - A recovery procedure ensures to recover the out-of-sync mirrored copies



Decreasing the Cost of Reliability

- RAID 1 offers highly reliable data storage
- But, it uses *N / 2* of the array capacity
- Can we achieve the same level of reliability without wasting so much capacity?
  - Yes!
  - Use information coding techniques to build light-weight error recovery mechanisms

RAID 4: Parity Drive



Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	0	1	1	0 ^ 0 ^ 1 ^ 1 = 0
0	1	0	0	0 ^ 1 ^ 0 ^ 0 = 1
1	1	1	1	1 ^ 1 ^ 1 ^ 1 = 0
0	1	1	1	0 ^ 1 ^ 1 ^ 1 = 1

Parity calculated using XOR

Updating Parity on Write

How is parity updated when blocks are written?

1. Additive parity

Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	0	0	1	0 ^ 0 ^ 0 ^ 1 = 1

Read other blocks

Update parity block

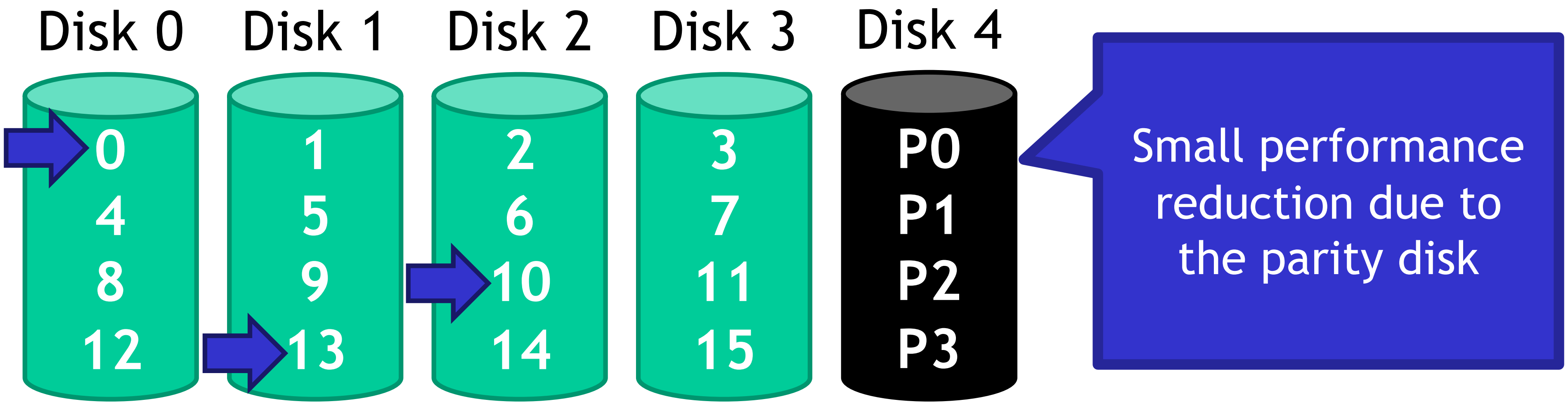
2. Subtractive parity

Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	0	1 0	1	0 ^ 0 ^ 1 ^ 1 1

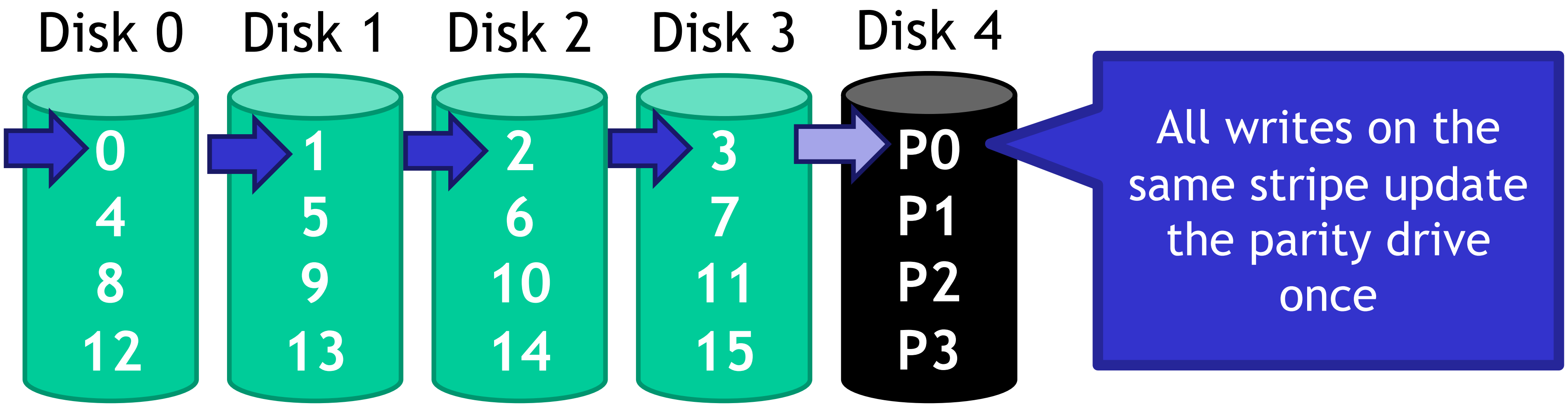
$P_{new} = D_{old} \wedge D_{new} \wedge P_{old}$

Reads and on RAID 4

- Reads (Serial or Random) are not a problem in RAID 4
- Parallelization across all non-parity blocks in the stripe



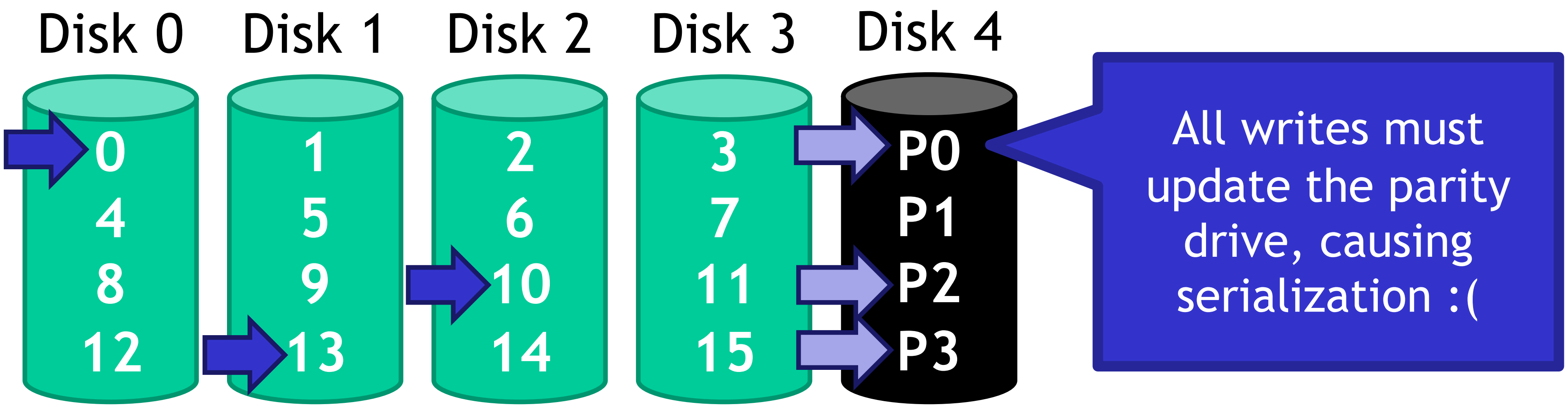
Serial Writes and RAID 4



RAID 4 has the same Read and Write write performance

- Parallelization across all non-parity blocks in the stripe

Random Writes and RAID 4



Random writes in RAID 4

1. Read the target block and the parity block
2. Use subtraction to calculate the new parity block
3. Write the target block and the parity block

RAID 4 has terrible write performance

- Bottlenecked by the parity drive
  - For each write, two operations are shipped to the parity drive

Analysis of RAID 4

Capacity:

- *N - 1*
- Space on the parity drive is lost

Reliability:

- 1 drive can fail
- Massive performance degradation during partial outage

Sequential Read and write: *(N – 1) * S*

- Parallelization across all non-parity blocks in the stripe

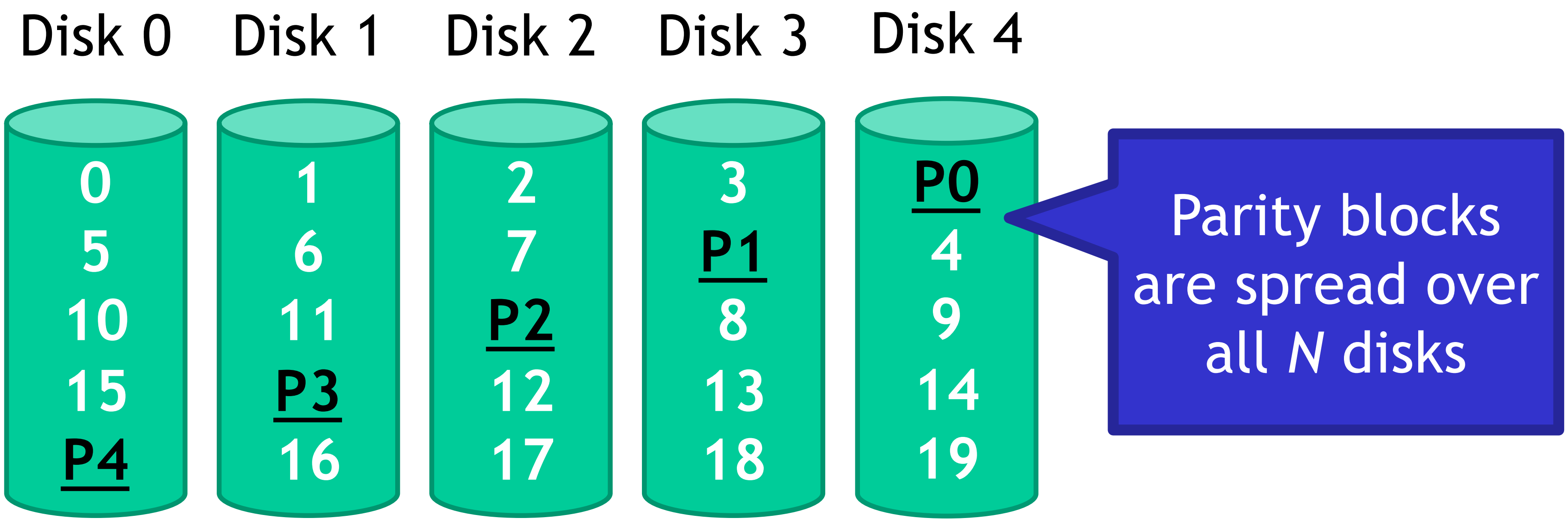
Random Read: *(N – 1) * R*

- Reads parallelize over all but the parity drive

Random Write: *R / 2*

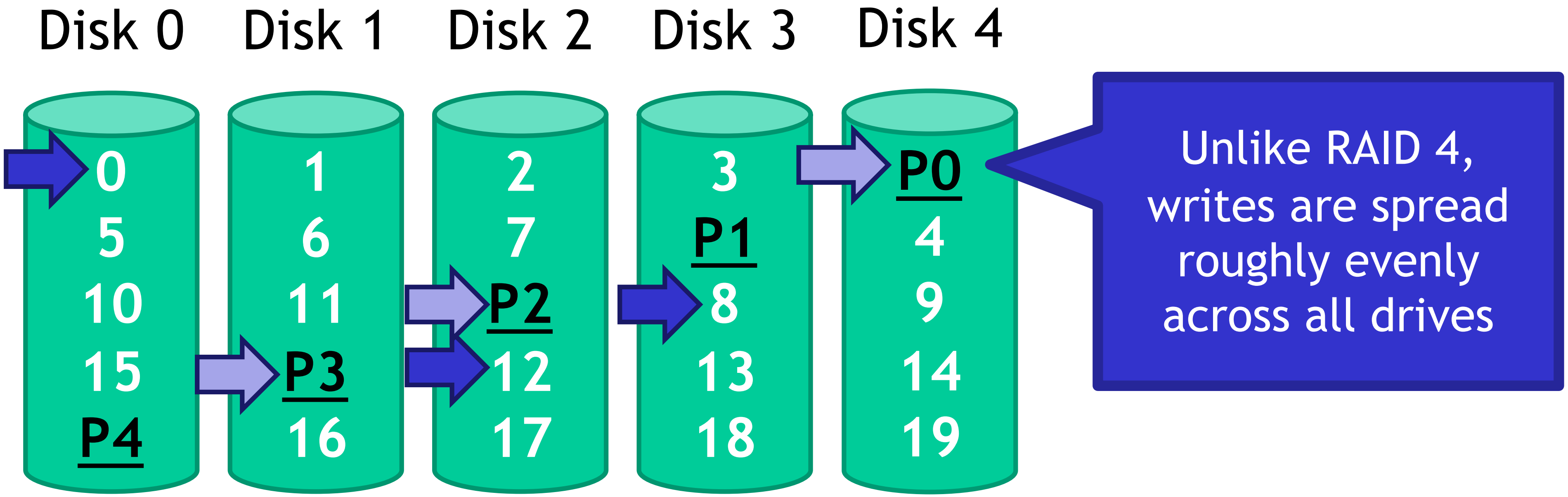
- Writes serialize due to the parity drive
- Each write requires 1 read and 1 write of the parity drive, thus *R / 2*

RAID 5: Rotating Parity



Disk 0	Disk 1	Disk 2	Disk 3	Disk 4
0	0	1	1	0 ^ 0 ^ 1 ^ 1 = 0
1	0	0	0 ^ 1 ^ 0 ^ 0 = 1	0
1	1	1 ^ 1 ^ 1 ^ 1 = 0	1	1
1	0 ^ 1 ^ 1 ^ 1 = 1	0	1	1

Random Writes and RAID 5



Random writes in RAID 5

1. Read the target block and the parity block
2. Use subtraction to calculate the new parity block
3. Write the target block and the parity block

Thus, 4 total operations (2 reads, 2 writes)

- Distributed across all N drives

Analysis of Raid 5

Capacity: [same as RAID 4]

- *N – 1*

Reliability: [same as RAID 4]

- 1 drive can fail
- Massive performance degradation during partial outage

Sequential Read and write:

- *(N – 1) * S* [same]
- Parallelization across all non-parity blocks

Random Read:

- *N * R* [vs. *(N – 1) * R*]
- Unlike RAID 4, reads parallelize over all drives

Random Write:

- *(N / 4) * R* [vs. *R / 2* for RAID 4]
- Unlike RAID 4, writes parallelize over all drives
- Each write requires 2 reads and 2 write, hence *N / 4*

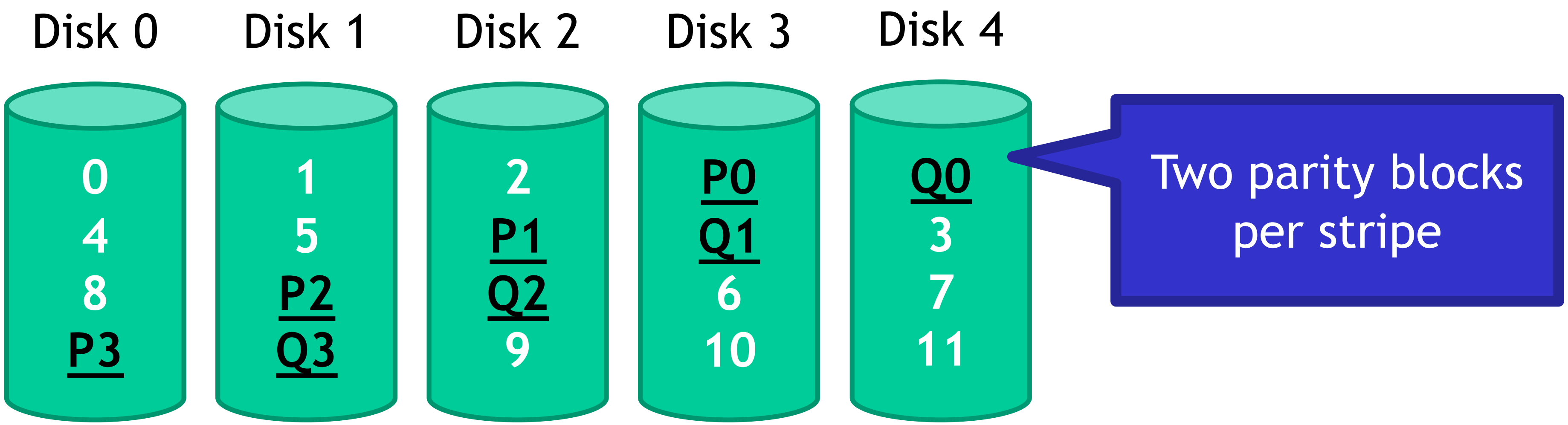
Comparison of RAID Levels

- *N* – number of drives
- *S* – sequential access speed
- *R* – random access speed
- *D* – latency to access a single disk

		RAID 0	RAID 1	RAID 4	RAID 5
	Capacity	***N***	*N / 2*	*N - 1*	*N - 1*
	Reliability	*0*	***1* (maybe *N / 2*)**	*1*	*1*
Throughput	Sequential Read	***N * S***	*(N / 2) * S*	*(N - 1) * S*	*(N - 1) * S*
	Sequential Write	***N * S***	*(N / 2) * S*	*(N - 1) * S*	*(N - 1) * S*
	Random Read	***N * R***	***N * R***	*(N - 1) * R*	***N * R***
	Random Write	***N * R***	*(N / 2) * R*	*R / 2*	*(N / 4) * R*
Latency	Read	***D***	***D***	***D***	***D***
	Write	***D***	***D***	*2 * D*	*2 * D*

RAID level 6

- More *fault tolerance* with respect RAID5
  - 2 concurrent failures are tolerated
  - Uses Solomon-Reeds codes with two redundancy schemes
    - (P+Q) distributed and independent
  - N + 2 disks required
  - High overhead for writes (computation of parities)
    - each write require 6 disk accesses due to the need to update both the P and Q parity blocks (slow writes)
  - Minimum set of 4 data disks



Characteristics of RAID levels

RAID level	Capacity	Reliability	R/W performance	Rebuild performance	Suggested applications
0	100%	N/A	Very good	Good	Non critical data
1	50%	Excellent	Very good / good	good	Critical information
5	(n-1)/n	Good	Good/ fair	Poor	Database, transaction based applications
6	(n-2)/n	Excellent	Very good/ poor	Poor	Critical information, w/minimal
1+0	50%	Excellent	Very good/ good	Good	Critical information, w/better performance

Best performance and most capacity? -> RAID 0

Greatest error recovery? -> RAID 1 (1+0 better than 0+1) or RAID 6

Balance between space, performance, and recoverability? -> RAID 5

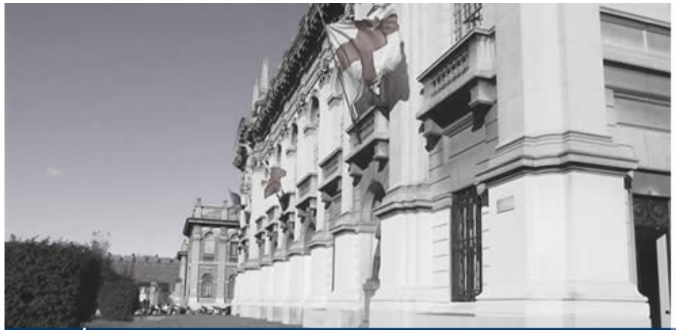
Other Considerations

Many RAID systems include a hot spare

- An idle, unused disk installed in the system
- If a drive fails, the array is immediately rebuilt using the hot spare

RAID can be implemented in hardware or software

- Hardware is faster and more reliable…
- But, migrating a hardware RAID array to a different hardware controller almost never works
- Software arrays are simpler to migrate and cheaper, but have worse performance and weaker reliability
  - Due to the consistent update problem



RAID Disks: Reliability Calculation

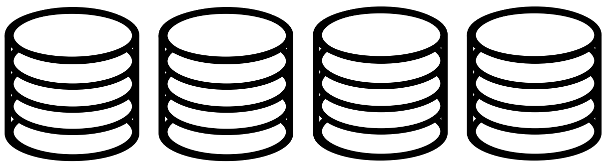
MTTF for an Array of Disks

- Let's assume a costant Failure Rate, an exponentially distributed time to failure, and the case of independent failures
  - Conditions normally used to determin the disk MTTF

- $MTTF_{diskArray} = MTTF_{singleDisk} / \#Disks$

- Without any fault tolerance approach, large disk arrays are *too instable to be used*
  - Disks do not have very large MTTF since is highly probable that will be replaced in "short-time"

- RAID0 has no redundancy
  - $MTTF_{RAID0} = MTTF_{diskArray} = MTTD_{singleDisk} / \#Disks$



Reliability calculations

- RAID levels (>0) uses redundancy to improve reliabilty
- When a disk fails, it should be replaced and the information reconstructed on the new disk using the redundant information
- MTTR is the time needed for this action
- N is the number of disks (#Disks) in the array

- $MTTF_{RAID} = (MTTF_{singleDisk}/N)*(\ 1/Probabilty_{additionalCriticalFailuresInMTTR}\ )$

MTTF for the array of N disks

Probability of other critical failures in the array before repairing the failed disk

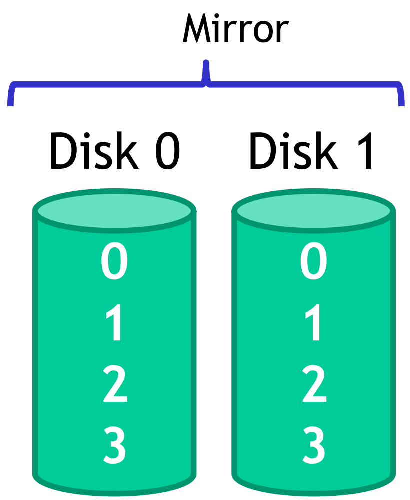
Determined by the RAID level and type of redundancy

RAID1 - MTTF

- With a single copy of each disk, 1 drive can fail
  - If you are lucky, *N / 2* drives can fail without data loss

- $MTTF_{RAID} = (MTTF_{singleDisk}/N)*(1 / Probabilty_{2ndCriticalFailureInMTTR})$

- $Probabilty_{2ndCriticalFailureInMTTR} = (1/ MTTF_{singleDisk}) * MTTR$
  - $1/ MTTF_{singleDisk}$ is the failure rate for the copy of the failed disk
  - MTTR is the period of interest before replacement

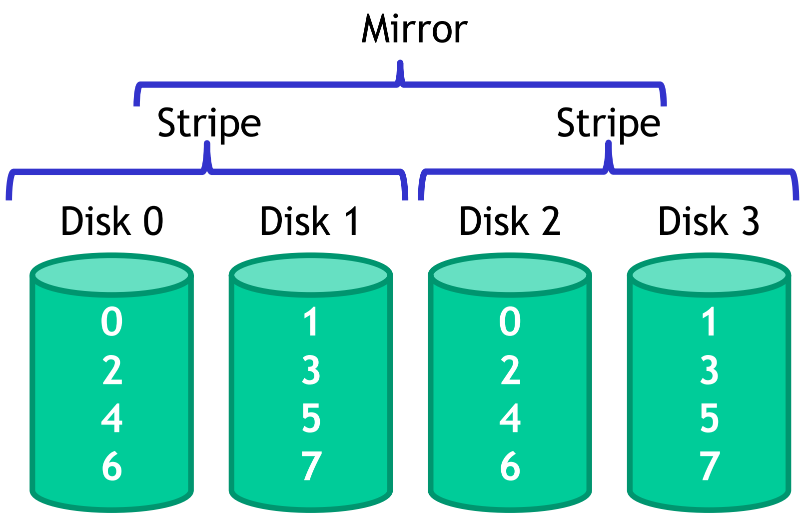


RAID0+1 - MTTF

- When 1 disk in a stripe group fails the entire group goes off

- $MTTF_{RAID}$ =($MTTF_{singleDisk}$/N)*(1 / $Probabilty_{2ndCriticalFailureInMTTR}$)

- $Probabilty_{2ndCriticalFailureInMTTR}$= (G/ $MTTF_{singleDisk}$) * MTTR
  - G is the number of disks in a stripe group
  - G/$MTTF_{singleDisk}$ is the failure rate for one of the disks in the other group (the other one w.r.t. the failed disk)
  - MTTR is the period of interest before replacement

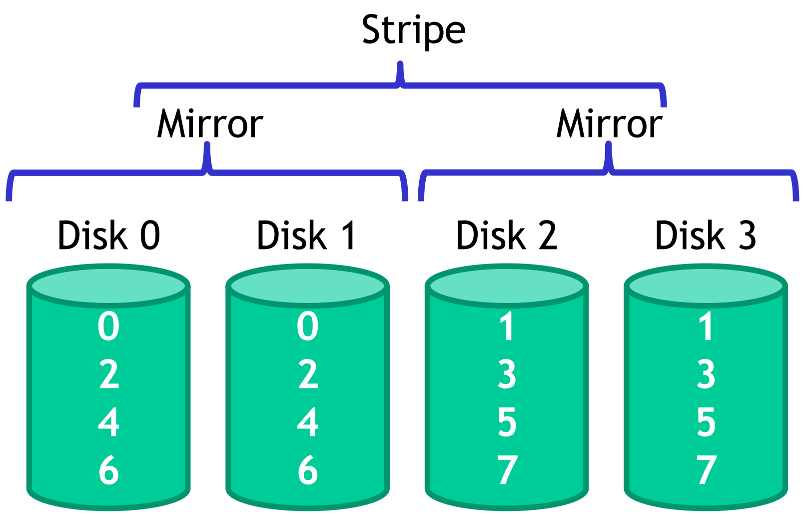


RAID1+0 - MTTF

- To fail, the same copy in both groups has to fail
  - Multiple failure can be tolerated

- $MTTF_{RAID}$ =($MTTF_{singleDisk}$/N)*(1 / $Probabilty_{2ndCriticalFailureInMTTR}$)

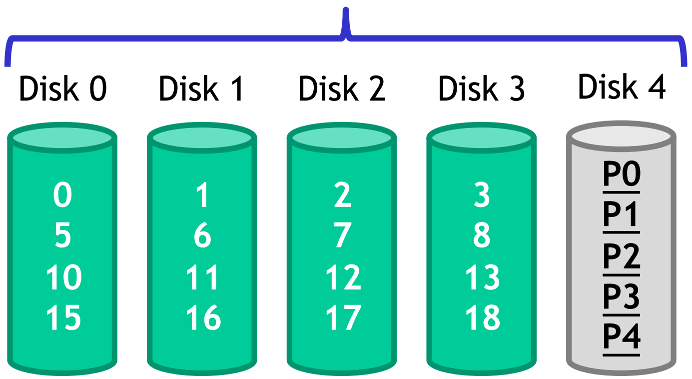
- $Probabilty_{2ndCriticalFailureInMTTR}$= (1/ $MTTF_{singleDisk}$) * MTTR
  - 1/ $MTTF_{singleDisk}$ is the failure rate for the copy of the failed disk
  - MTTR is the period of interest before replacement



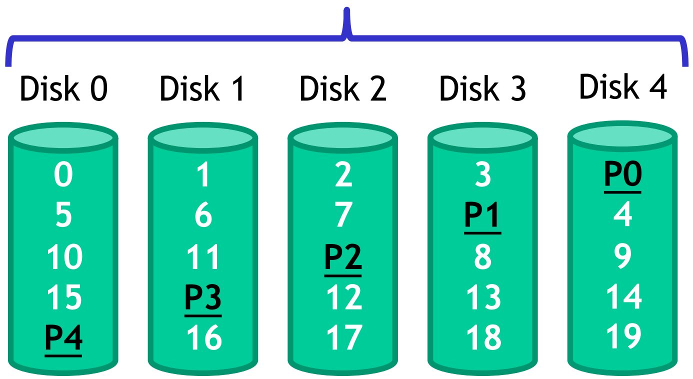
RAID4 and RAID5 - MTTF

- To fail, two disks have to fail before replacement
- $MTTF_{RAID} = (MTTF_{singleDisk}/N) * (1 / Probabilty_{2ndFailureInMTTR})$
- $Probabilty_{2ndFailureInMTTR} = ((N-1) / MTTF_{singleDisk}) * MTTR$
  - $(N-1)/MTTF_{singleDisk}$ is the failure rate for one of the other disks
  - MTTR is the period of interest before replacement

RAID4

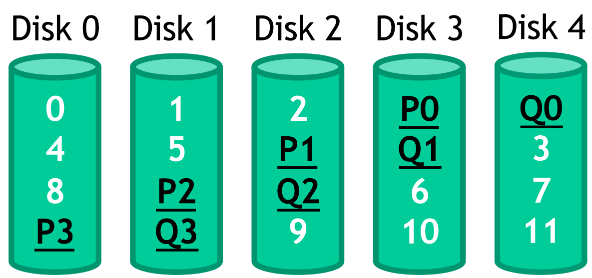


RAID5



RAID6 - MTTF

- Two disk failures at the same time are tolerated
- $MTTF_{RAID}$ =($MTTF_{singleDisk}$/N)*(1 / $Prob_{2ndAnd3rdFailureInMTTR}$)
- $Probabilty_{2ndAnd3rdFailureInMTTR}$=$Probabilty_{2ndFailure}$*$Probabilty_{3rdFailure}$
- $Probabilty_{2ndFailure}$= ((N-1)/ $MTTF_{singleDisk}$) * MTTR
  - (N-1)/$MTTF_{singleDisk}$ is the failure rate for one of the other disks
  - MTTR is the period of interest before the replacement
- $Probabilty_{3ndFailure}$= ((N-2)/ $MTTF_{singleDisk}$) * MTTR/2
  - (N-2)/$MTTF_{singleDisk}$ is the failure rate for one of the remaining disks
  - MTTR/2 is the average overlapping period between 1^{st} and 2^{nd} disk replacement (both disk not yet replaced)



Summary

- RAID0
  - $MTTF_{RAID0} = (MTTF_{singleDisk}/N)$
- RAID1+0
  - $MTTF_{RAID1+0} = (MTTF_{singleDisk})^2/(N*MTTR)$
- RAID0+1
  - $MTTF_{RAID0+1} = (MTTF_{singleDisk})^2/(N*G*MTTR)$
- RAID4
  - $MTTF_{RAID4} = (MTTF_{singleDisk})^2/(N*N-1*MTTR)$
- RAID5
  - $MTTF_{RAID5} = (MTTF_{singleDisk})^2/(N*N-1*MTTR)$
- RAID6
  - $MTTF_{RAID6} = 2*(MTTF_{singleDisk})^3/(N*N-1*N-2*MTTR^2)$