CS3.301 Operating Systems and Networks

Persistence: RAIDs

Karthik Vaidhyanathan

https://karthikvaidhyanathan.com

INTERNATIONAL INSTITUTE OF INFORMATION TECHNOLOGY HYDERABAD

Software Engineering Research Centre

Acknowledgement

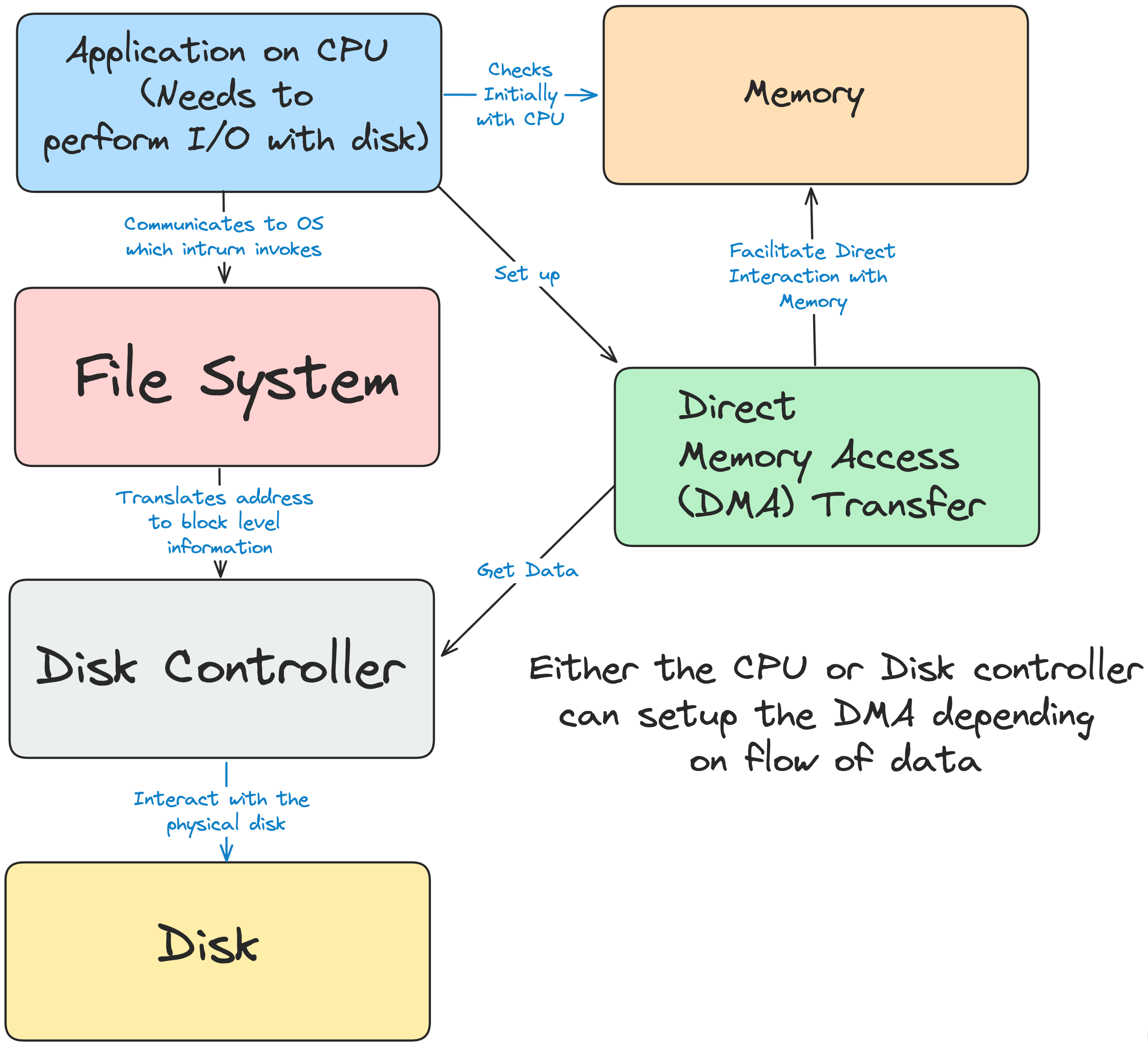
The materials used in this presentation have been gathered/adapted/generate from various sources as well as based on my own experiences and knowledge -- Karthik Vaidhyanathan

Sources:

- Operating Systems in Three Easy Pieces by Remzi et al.

The flow of access

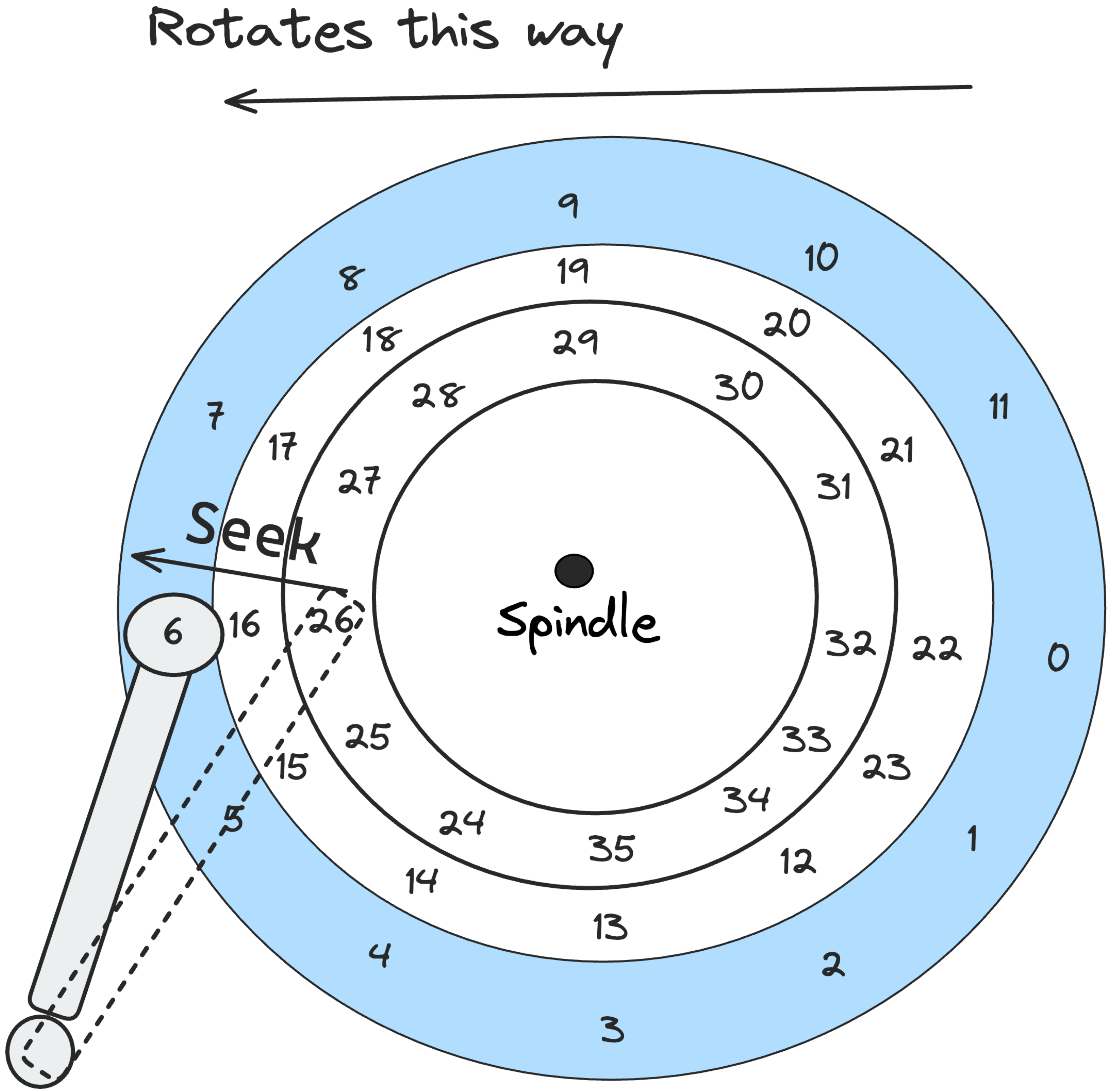
- Application performs read or write to a file
- CPU communicates to OS which invokes the File System (FS)
- The OS may check in its cache if its already there
- FS prepares block level information to disk controller
- A Direct Memory Access (DMA) is set up
- Disk controller performs the physical read or write based on commands from DMA and file system
- If its read, Disk -> DMA, for writes, DMA -> Disk



Modern Hard Disks

Source: Times of India

Quick Overview

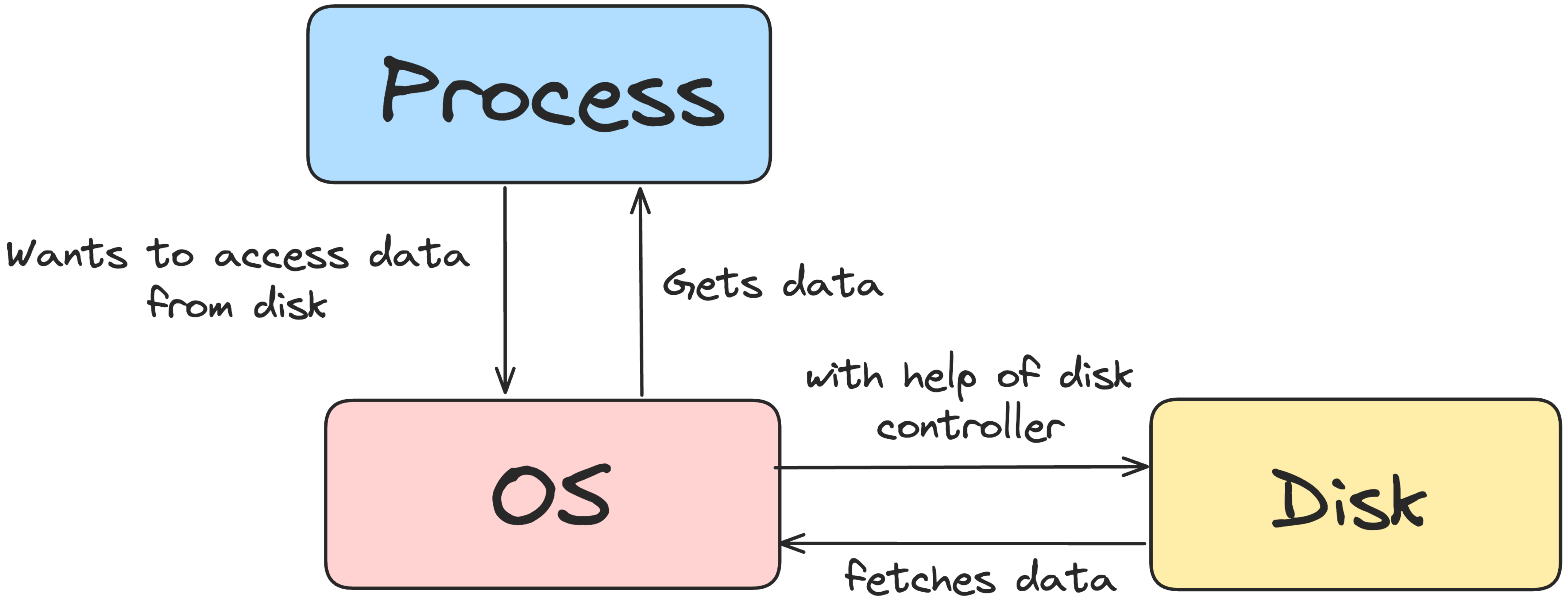


- Disk rotates on a spindle
  - The arm can move across (seek) or stay as the disk rotates
  - The head is used to read/write
- Data is arranged in tracks as blocks/ sectors
- There are 100s of tracks on a single disk
- **Seek, rotate and transfer** - three key phases

I/O Time of Disks

- **Random Workload**
  - Issues small (4 KB) reads to random locations on the disk
  - Very common in applications like Database management systems
- **Sequential Workload**
  - Reads large number of sectors consecutively from disk
  - These are also quite common!
- Given workload, we can perform some comparison on the disk performance
  - We would also need some disk characteristics

So far its about one disk!

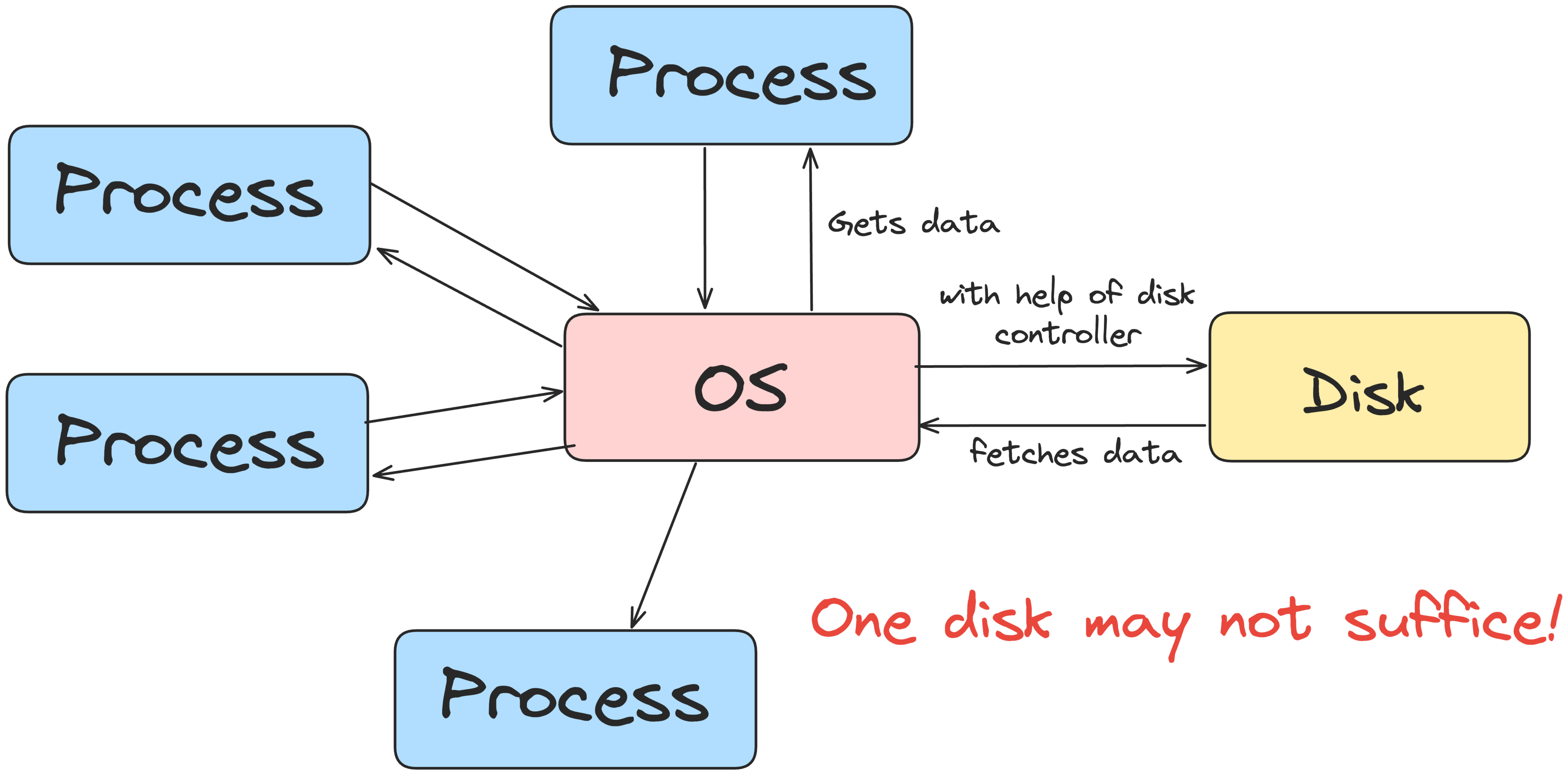


Will the idea of one disk be enough?

Consumer laptops

Data centers

We may need more!



- Disks are slower!
- I/O is slower - Bottleneck!
- Disks may get fuller
- Disk can also fail
- Multiple facets needs to be considered
- What can be a better mechanism?

Redundant Arrays of Inexpensive Disks (RAID)

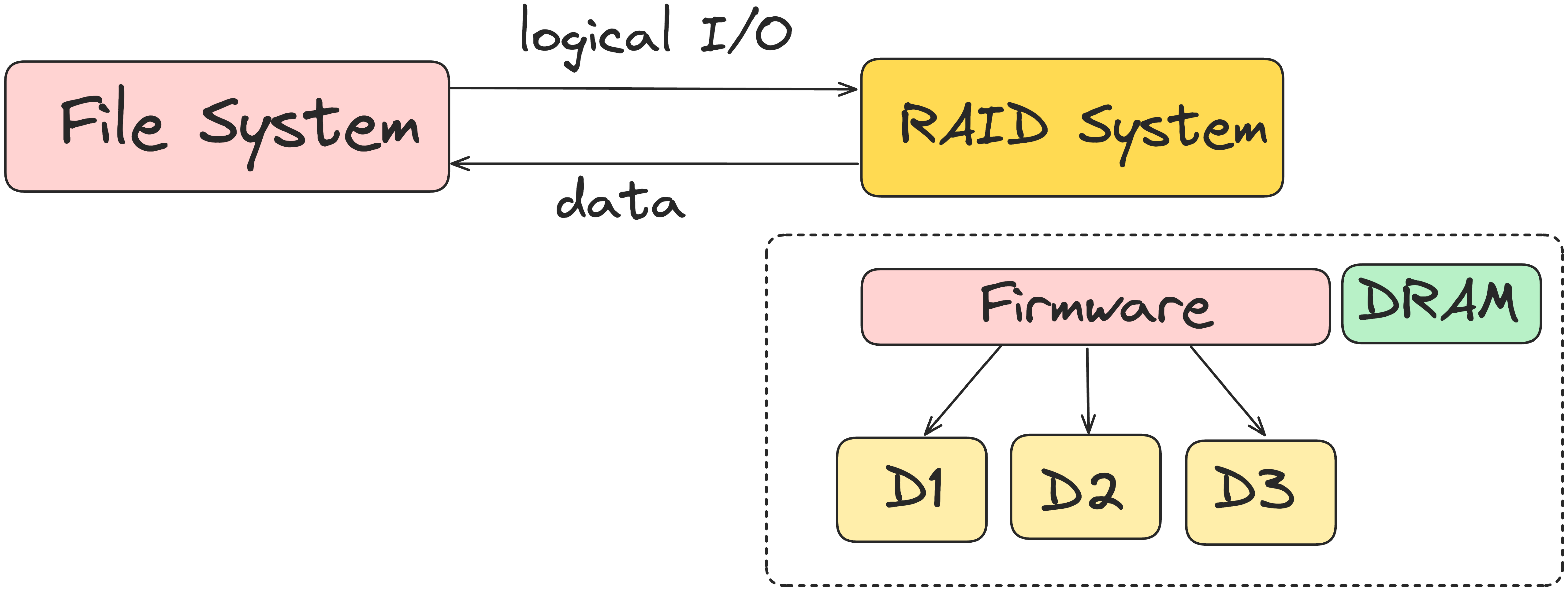
Redundant Arrays of Independent Disks!

- Techniques to use multiple disks in concert to build **faster, bigger and more reliable** disk system
- Term introduced in late 90's by a group of researchers in UC Berkley
- Externally RAIDs look just like group of blocks one can read or write
    - Internally RAID is very complex
        - Consisting of **multiple disks**
        - **Its own memory** - DRAM
        - **One or more processor** to manage the system

RAIDs vs Traditional Disks

- One advantage is **performance**
- Multiple disks in parallel can greatly enhance speed
- More disks => More **capacity** as well
- RAIDS can also enhance **reliability**
  - Without RAID techniques, the disk is vulnerable to loose data
  - RAIDs can tolerate loss of data and keep operating as if nothing went wrong - Redundant disks
- RAID provides advantages **transparently** to the system
  - OS feels that its just interacting with a single disk

RAIDs: Simple Illustration



- As far as **File System (the subcomponent inside OS) is concerned**
  - RAID is just like a disk
  - Linear array of blocks each of which can be read or written

RAID in Action

ThinkSystem ST250 V2 Tower Server Specs Features Models Starting at: **₹125,990** Shop

Expansion Slots	Slot 3: PCIe x4 slot with PCIe Gen3 x4 lanes Slot 4: PCIe x8 slot with PCIe Gen3 x4 lanes
Network Interface	2x GbE on-board ports (Broadcom BCM5720); 1x GbE port dedicated for XCC management
Ports	Front: 1x USB 3.2 G2 (10Gb) port, 1x USB 2.0 port for local management using the XCC Mobile app Rear: 4x USB 3.2 G2 (10Gb) ports, 2x RJ45 Gigabit Ethernet ports, 1x 1GbE dedicated XCC port for remote management, 1x Serial port and 1x VGA port
HBA/RAID Support	Intel® VROC Software RAID support with both simple-swap and hot-swap configuration; multiple hardware RAID configurations supported

https://www.lenovo.com/in/en/data-center/servers/towers/

RAIDs

- At a high level, RAIDs are like a computer system
    - RAID is like a box with standard (SCSI or SATA) to a host
    - Provides a consistent interface to the OS
- Internally RAIDs are very complex
    - Consists of a **microcontroller** that runs a firmware
    - **Volatile memory** such as DRAM to buffer data blocks as they are read and written
    - **Non-volatile memory** to buffer writes safely and for parity calculation as well
- Instead of running application RAID, runs specialised software designed to operate RAID

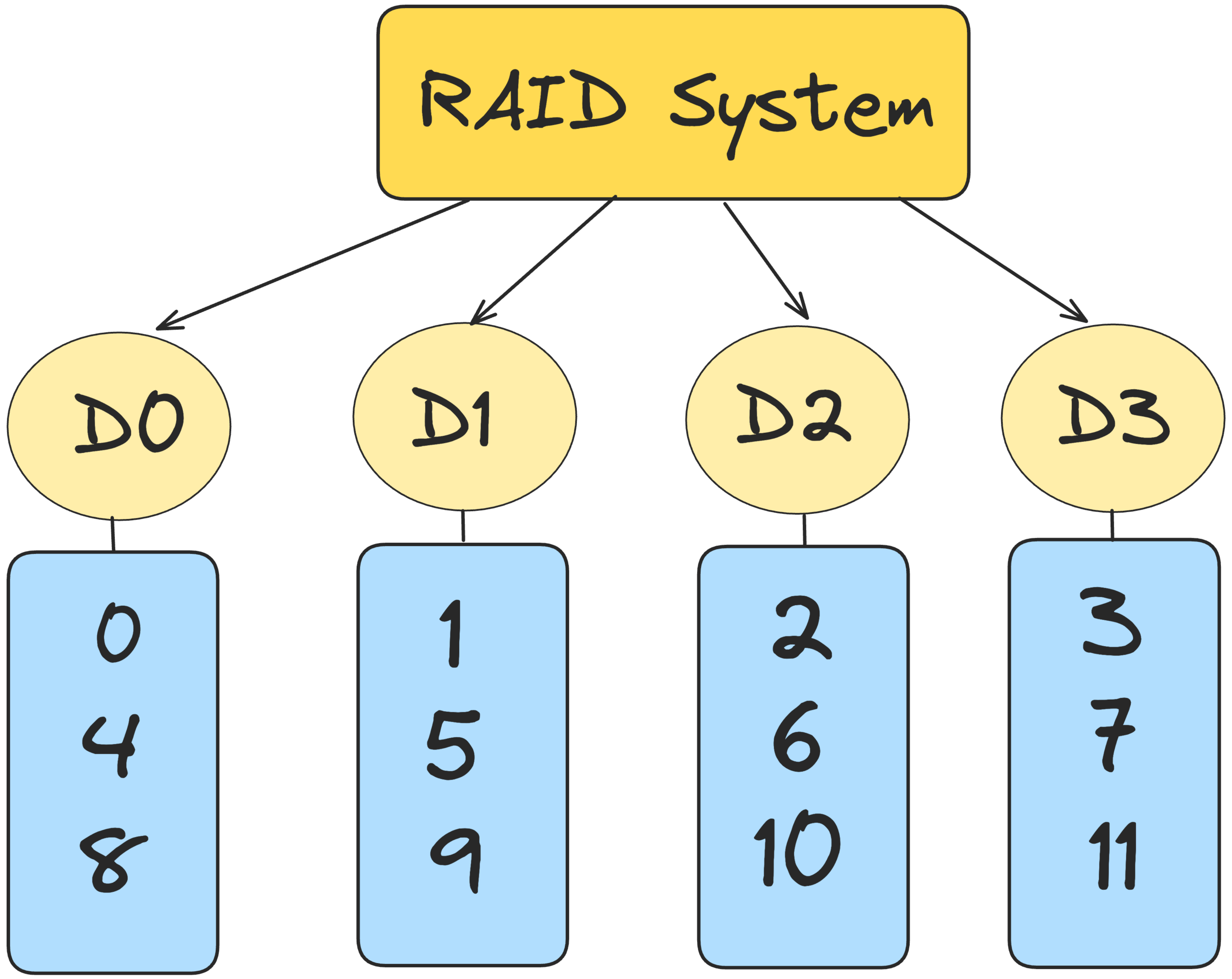
Evaluating RAIDs

- Many approaches are there to build a RAID system
  - Each has different characteristics
- Three axes can be used for evaluation
  - **Capacity**
  - **Reliability**
  - **Performance**

Evaluating RAIDs

- **Capacity**
  - Given a set of N disks each of size B blocks. How much capacity is available for usage?
    - Some redundancy may be required => N/2 when each is replicated
- **Performance**
  - What's the impact of different workload on the latency of I/O?
  - What's the throughput? Rate of transfer -Transfers/second!
- **Reliability**
  - How many failures/faults can the RAID system tolerate?
  - The fault model considered: A fault => total disk has failed!

RAID level 0: Striping

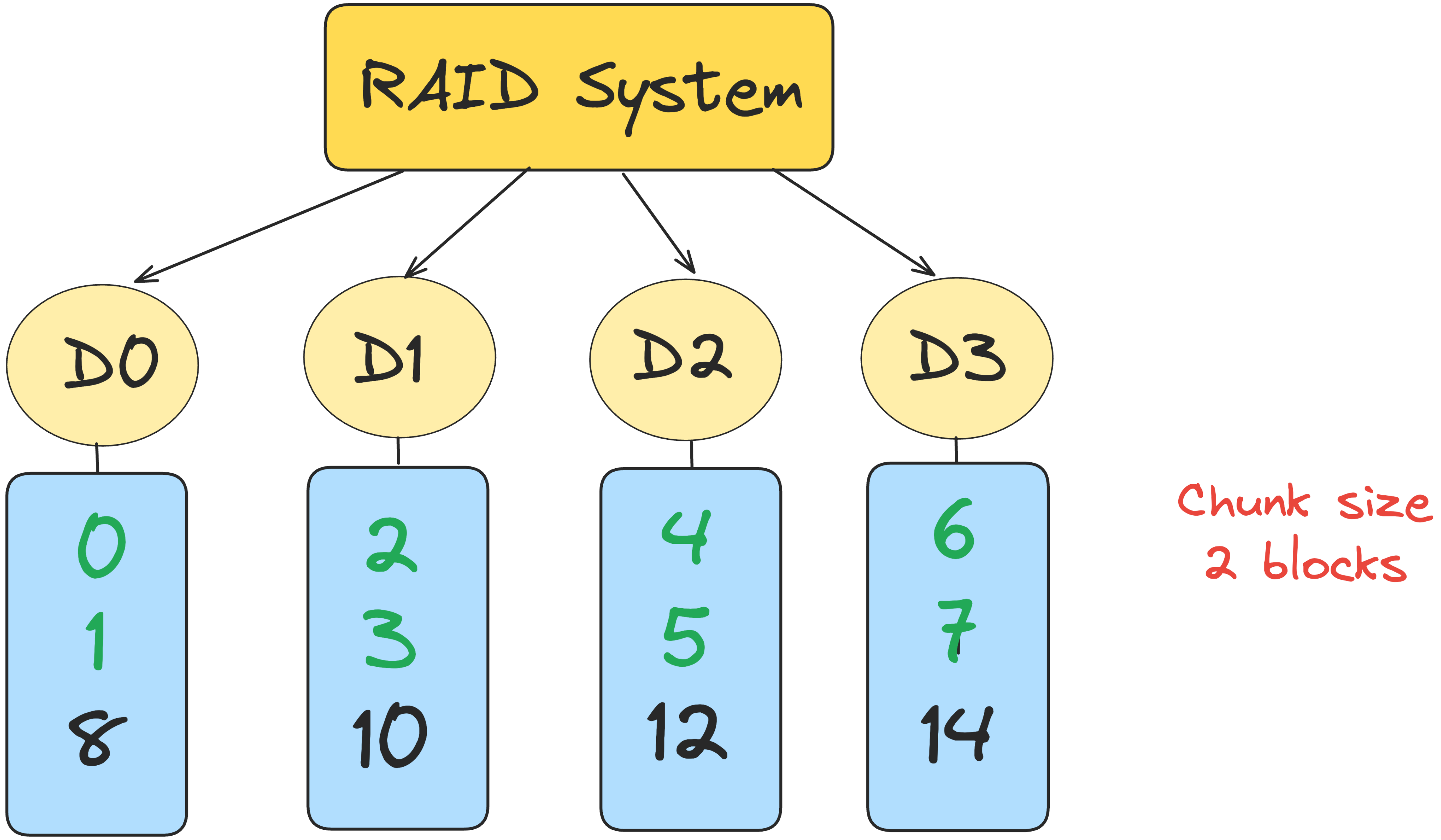


Here blocks 0, 1, 2 and 3 are in same stripe

Each block is of size 4 KB

- **Simple form:** Spread the blocks across the disks in a round robin fashion
- Blocks in the same row - **Stripe**
- No redundancy

RAID level 0: Striping



- Two 4 KB blocks are placed in one disk before moving to another
- Chunk size is 8 KB and a stripe consists of 4 chunks -> 32 KB of data
- Chunk size do have an impact on the performance! - **How?**

RAID Level 0: Impact of Chunk Size

- **Small chunk size**
  - Many files will get stripped across disks
  - Increases parallelisms of reads and writes
  - Positioning time to access blocks across disks increases
- **Big chunk size**
  - Reduces intra-file parallelism, relies on multiple concurrent request to achieve high throughput
  - Large chunk size reduces positioning time (One file in one disk) same as using one disk
- **Best chunk size is hard to get** - Depends on the workload!

RAID Level 0: Performance Analysis

- Two main things to evaluate:
  - **Single-request latency:** latency of single I/O request to RAID
  - **Steady-state throughput:** Total bandwidth of concurrent requests
- Two main workloads:
  - **Sequential:** Request to disk arrive in large contiguous chunks
  - **Random:** Each request is small to a random location on disk
- Assume disk transfers at **S MB/s** under sequential and **R MB/s** under random

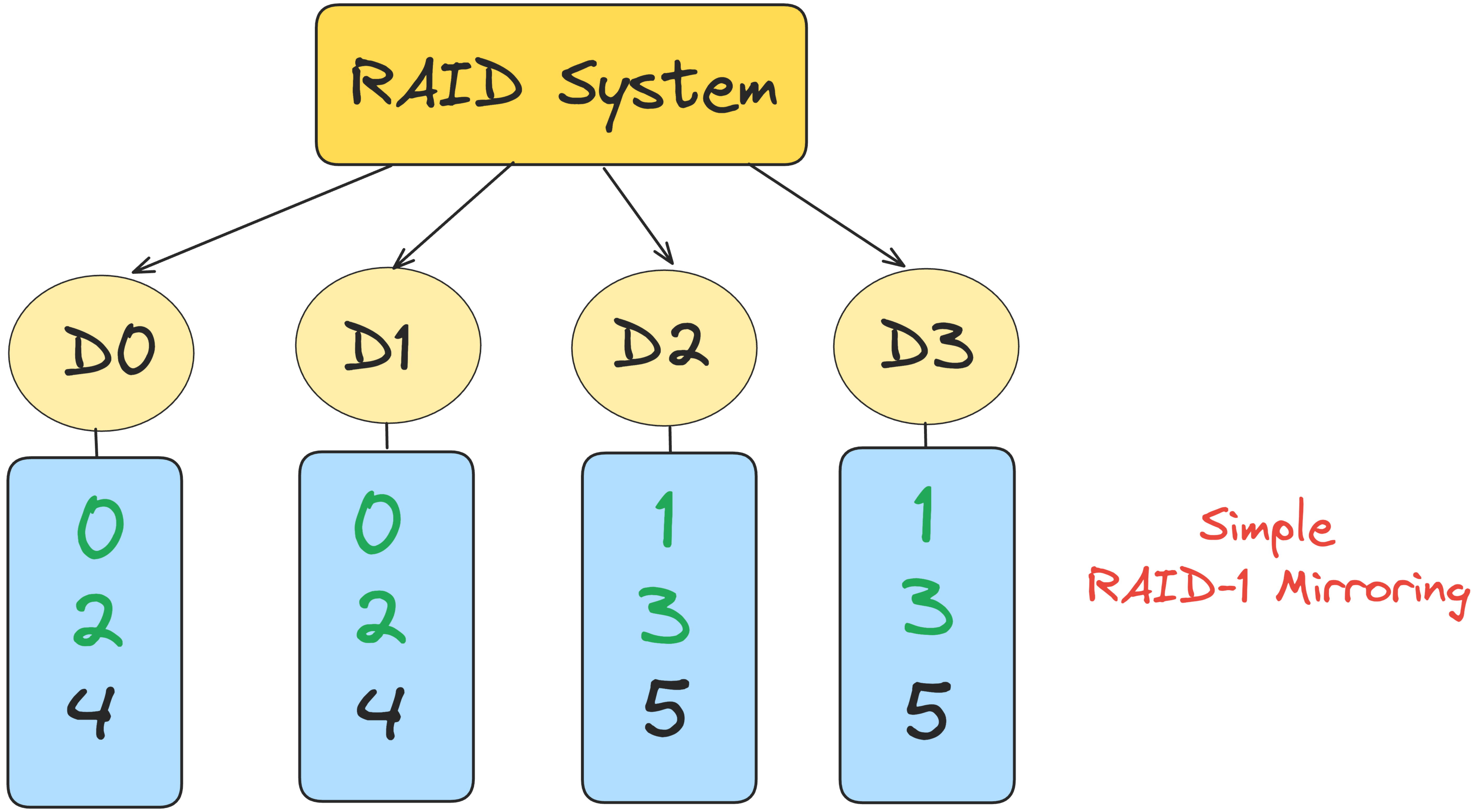
RAID Level 0: Performance Analysis

- Consider the following disk characteristics
  - Sequential transfer of size 10 MB on average
  - Random transfer of size 10 KB on average
  - Average seek time 7 ms
  - Average rotational delay 3 ms
  - Transfer rate of disk 50 MB/s
- How to calculate **S** and **R**?

RAID Level 0: Analysis

- 7 ms spend seeking and 3 ms spend in rotation => total: 10 ms
- 10 MB @ 50MB/s => 200 ms for transfer => total: 200 + 10 = 210 ms
- S = 10 MB / 210ms = 47.62 MB/s
- For R, 10 KB @ 50 MB/s => 0.195 ms => total: 10 +. 0.195 = 10.195 ms
- R = 10 KB / 10.195 ms = 0.981 MB/s
- Steady-state throughput equals N*S MB/s or N*R MB/s depending on workload
- RAID 0 is more like an upper bound

RAID level 1: Mirroring



- Copies are made, each copy is placed in a different disk - Handle failures!
- Data is stripped across mirrored pairs

RAID Level 1: Mirroring

- **Read**
  - When reading from a block, RAID has a choice!
  - Assume a read comes to 0, the system can either use Disk 0 or 1
- **Write**
  - No choice exists, the write needs to happen in both copies of data
  - This promotes reliability, writes can happen in parallel

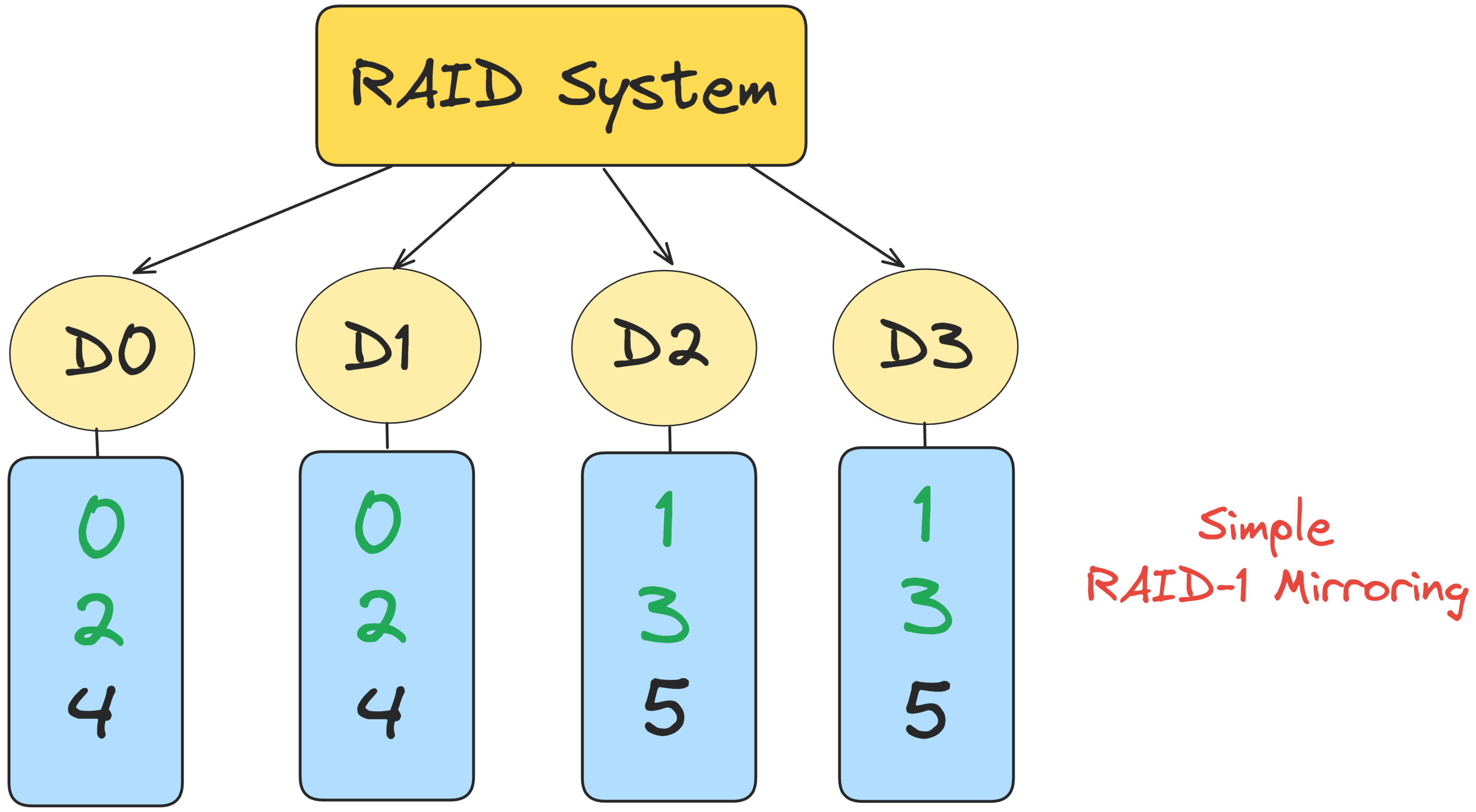
RAID 1: Analysis

- **Capacity**, with all replicated, achieved capacity: N/2
- **Reliability**, RAID 1 can tolerate failure of 1 disk
- **Performance**
    - For single read request, RAID-1 just needs to redirect to one of the copies
    - Write is little different: Two writes needs to happen and it will happen in parallel => time will be almost equal to single write
    - But, due to worst case rotational of two requests, it will be higher than write to a single disk

RAID 1: Analysis

- Steady state throughput
  - Bandwidth during sequential write is (N/2) * S MB/s or half the peak
    - Each write involves writing in two different locations
  - Sequential reads also has a similar bandwidth:
    - Consider reads that needs to be done on blocks: 0,1, 2, 3, 4, 5, 6, 7
    - What will be the bandwidth or steady state throughput in this case?

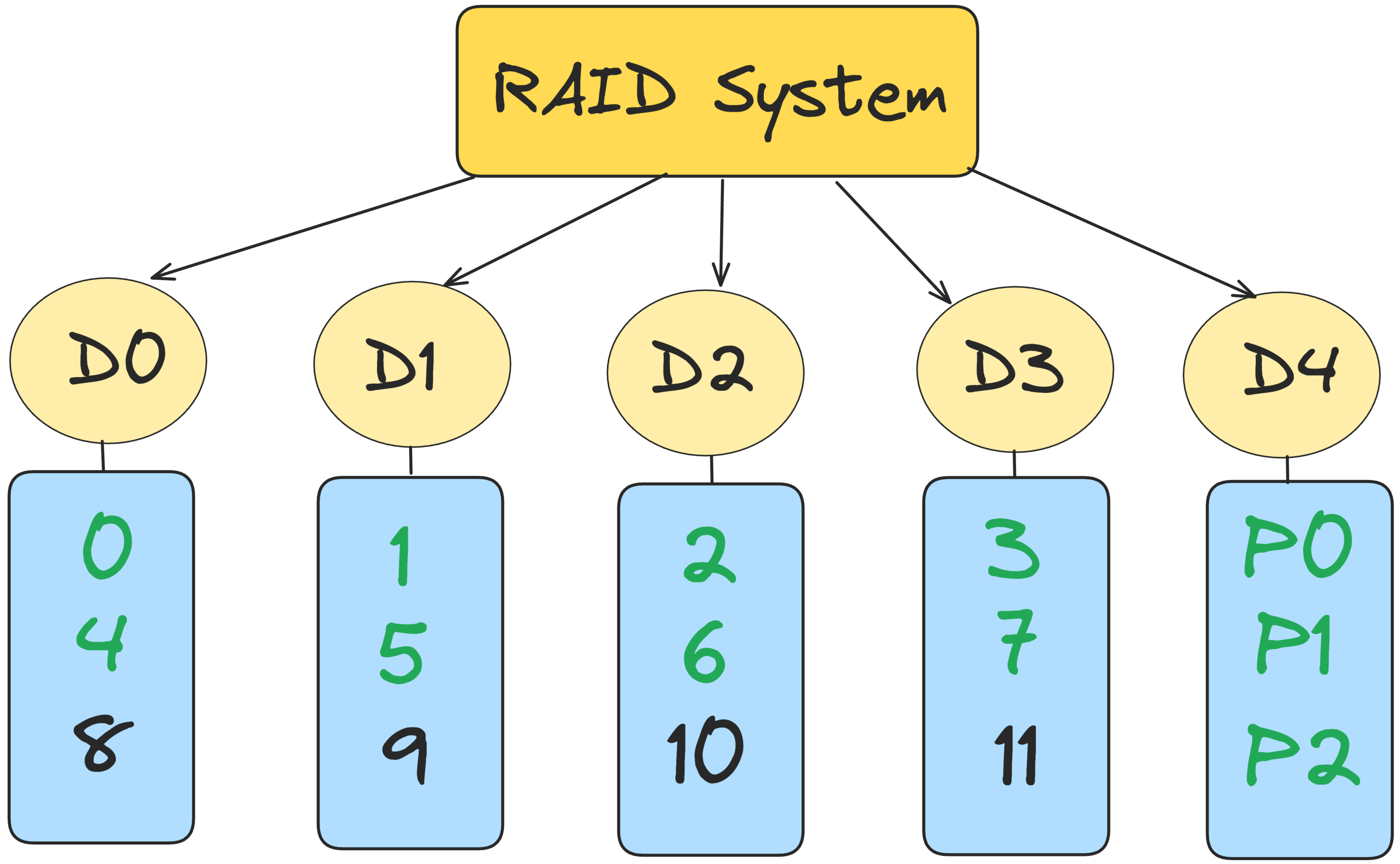
RAID 1: Analysis



- 0 is send to D0, 1 to D2, 2 to D1, 3 to D3….
- 0 comes to D0 then next one is 4, 2 is skipped (since it goes to D1)
- Simply keeps rotating without doing useful transfer (as D1 is taken care)
- Each disk will only deliver half the peak bandwidth, (N/2) * S MB/s for **Sequential reads**
- **Random reads** N*R and write (N/2) * R MB/s

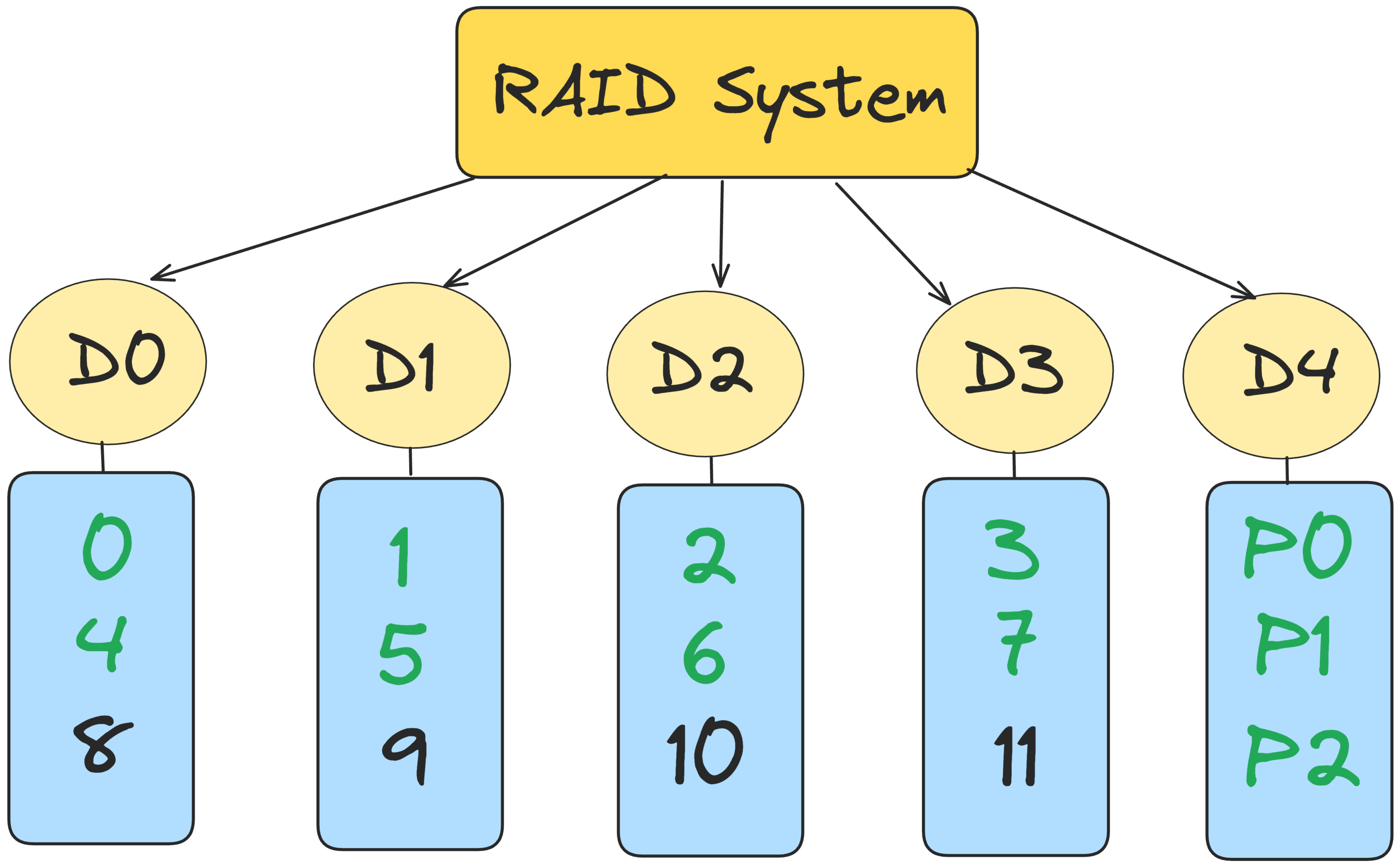
Redundancy is good but can we do better?

RAID Level 4: Introducing Parity



- Another method for better managing redundancy: **Parity**
- They aim to use less capacity and overcome space issues at cost of performance
- For each stripe of data above, a parity block is added that stores the redundant information for that block

RAID Level 4



- P1 has redundant information that it is calculated from blocks 4, 5, 6 and 7
- To compute parity **XOR** function is used
  - XOR returns 1 if there are odd no of 1's
  - XOR returns 0 if there are even no of 1's
- This allows to identify if there were some faults in any of the disks - **how?**

RAID Level 4

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

- The parity information can be used to recover from failure
- Assume **data in first row of C2 is lost (it was 1)**
    - Read all the other values in the row and reconstruct the answer
    - Without value of C2 (1), XOR (0,0,0,1) = 0; Hence we can find that C2 needs to be 1

RAID Level 4

Block 0	Block 1	Block 2	Block 3	Parity
00	10	11	10	11
10	01	00	1	10

- In the larger context perform bitwise XOR of all the bits
- Perform Bitwise XOR across each bit of data blocks
  - Put the result of each bit in the corresponding bit slot in parity block
  - Assume that Block 2 fails
  - Block 2 = (00) XOR (10) XOR (10) XOR (11) = 11

RAID Level 4: Analysis

- **Capacity:** 1 disk is for parity hence (N-1)*B
- **Reliability:** Tolerates 1 disk failure, if more than 1 is lost, no way to recover
- **Performance,** Steady-state-throughput:
  - **Sequential reads:** (N-1)*S MB/s
  - **Sequential writes:** (N-1)*S MB/s (write also parity in parallel, full-stripe write)
    - **Note:** writing to parity at same time is not performance gain for client! Hence N-1
  - **Random read:** (N-1)*R MB/s
  - **Random writes?**

RAID Level 4: Analysis

- Main operations involved in write, especially random write:
    - Update a block + update of parity
- Method 1: **Additive Parity**
    - Read in all of the other blocks in that stripe
    - XOR those blocks with the new block
    - **Problem:** As number of blocks increase, this can be challenging, reading of all blocks to perform XOR

RAID Level 4: Analysis

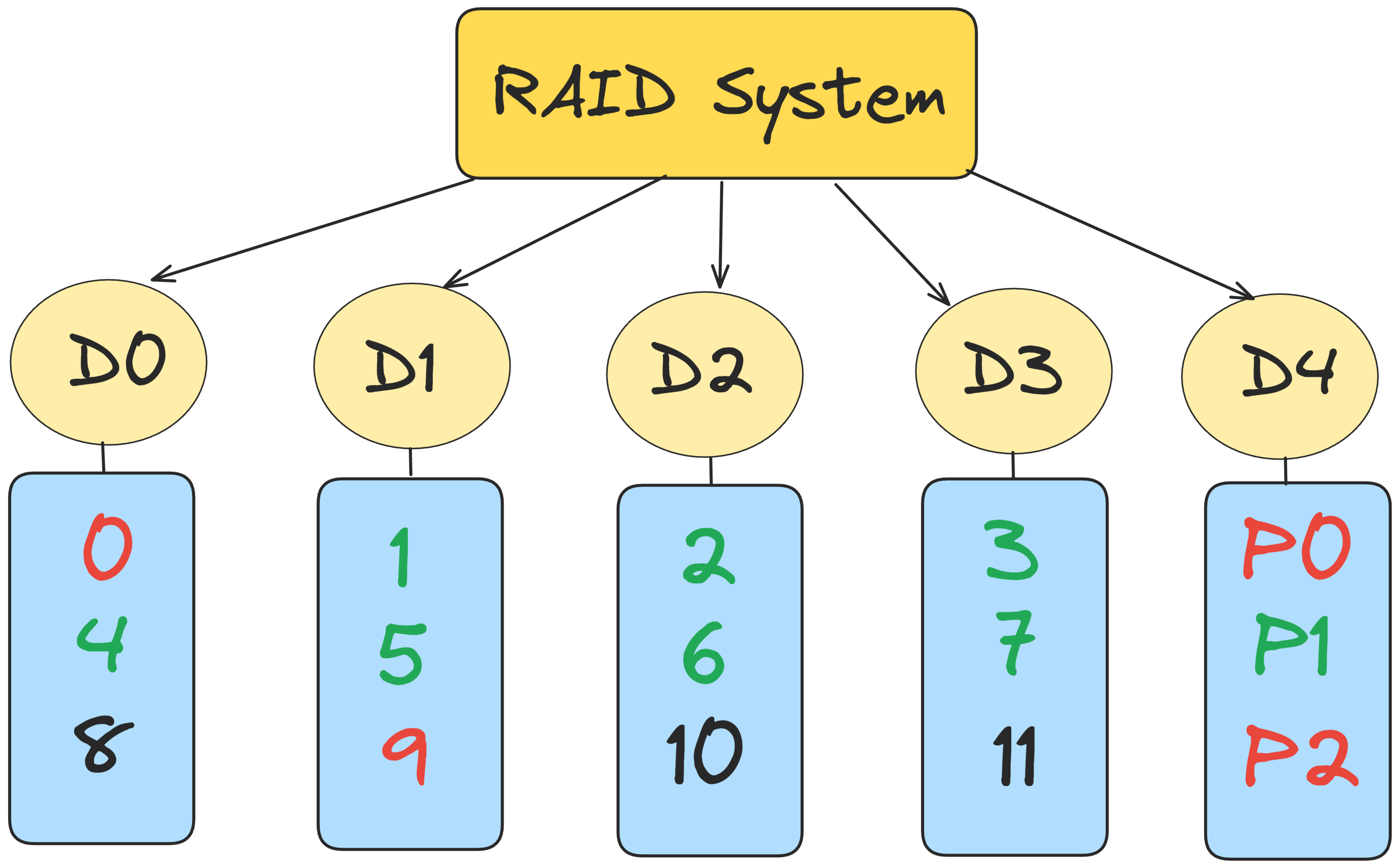
- Method 2: **Subtractive Parity**

C0	C1	C2	C3	P
0	0	1	1	XOR (0,0,1,1) = 0

- Update C2(old) -> C2 (new)
- Read old data in C2 (C2(old)=1) and old data in parity (P(old) = 0)
- Calculate *P(new)* = *(C2(old) XOR C2(new)) XOR P(old)*
  - If C2(new) == C2 (old) -> P(new) = P(old)
  - If C2(new)!=C2 (old) -> Flip the old parity bit

Small-write Problem

- The parity disk can be a bottleneck
  - Example: Writes to 0 and 9
  - Disk 0 and Disk 1 can be accessed in parallel
  - Disk 4 prevents any parallelism

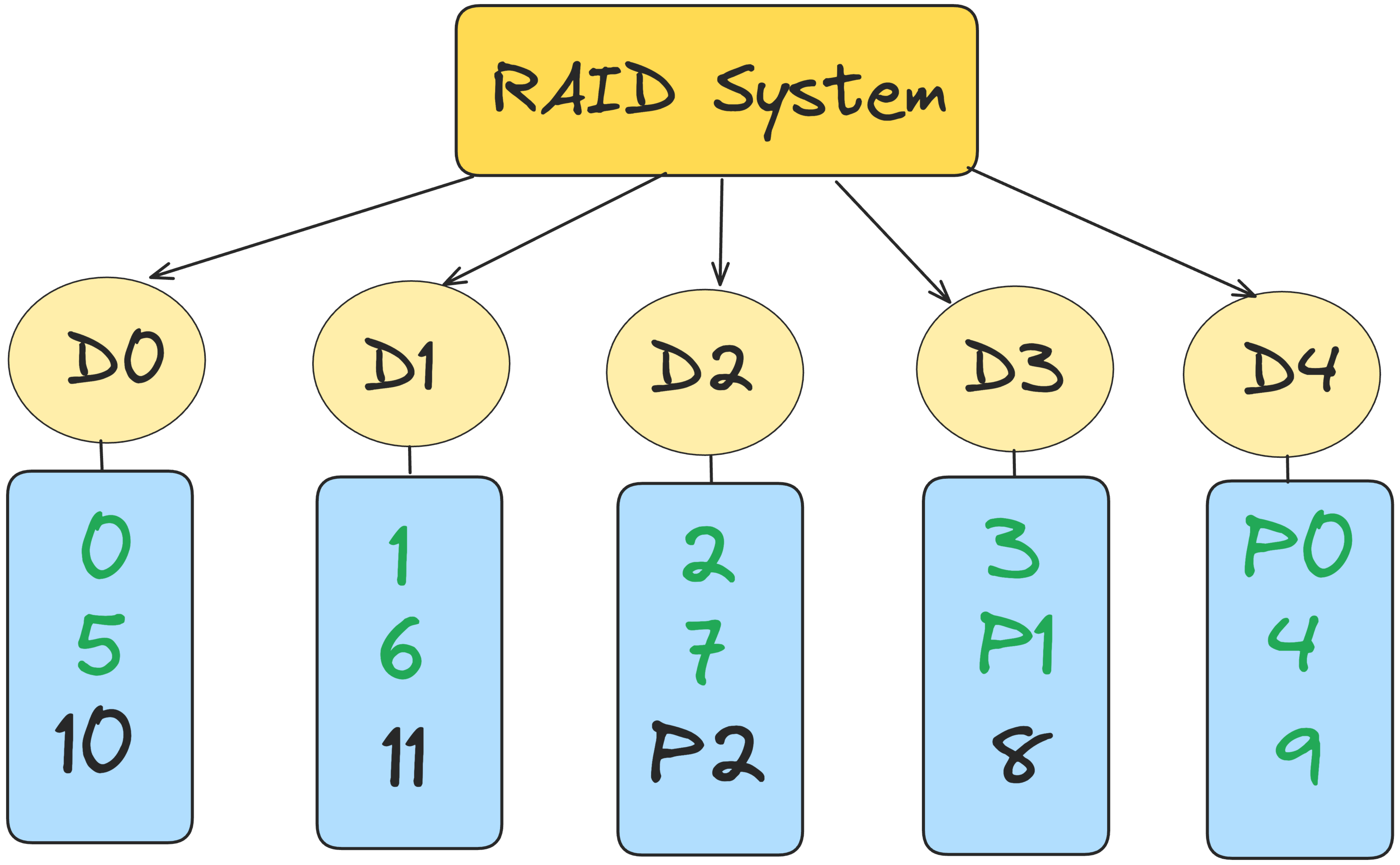


- RAID-4 under random workload, small writes is (R/2) MB/s - **terrible!**
- How to improve further?

I/O Latency in RAID-4

- A single read
  - Equivalent to latency of single disk request
- A single write
  - Two reads + Two writes
  - Data block + parity block
  - The reads and writes can happen in parallel
  - Total latency is twice that of single disk

RAID Level 5: Rotating Parity



- Addresses the small-write problem
- Similar to RAID-4 except that keeps rotating the parity block
- Removes the parity-disk bottleneck for RAID-4

RAID-5 Analysis

- **Capacity** and **reliability** identical to RAID-4
- Sequential read and write performance similar to RAID-4
- Random read performance is little better (utilize all disks)
- Random write performance
  - Here the write requests can be parallelized as parity is not bottleneck
  - Given large number of random write requests, all disks can be evenly kept busy, total bandwidth = (N/4)*R MB/s. Still 4 I/O operations (as parity is there)

Summarizing RAIDS

- **Performance** and do not care about reliability -> RAID-0 (Striping)
- **Random** I/O performance and **reliability** -> RAID-1 (Mirroring)
- **Capacity** and **Reliability** -> RAID-5
- **Sequential** I/O and Maximise **Capacity** -> RAID-5

SCAN ME

Thank you

Course site: karthikv1392.github.io/cs3301_osn
Email: karthik.vaidhyanathan@iiit.ac.in
Twitter: @karthi_ishere