416 Distributed Systems

Errors and RAID

February 23, 2021

Types of Errors

- **Hard errors**: The component is dead.
- **Soft errors**: A signal or bit is wrong, but it doesn’t mean the component must be faulty
- Note: You can have recurring soft errors due to faulty, but not dead, hardware

Examples

- DRAM errors
  - Hard errors: Often caused by motherboard - faulty traces, bad solder, etc.
  - Soft errors: Often caused by cosmic radiation or alpha particles (from the chip material itself) hitting memory cell, changing value. (Remember that DRAM is just little capacitors to store charge... if you hit it with radiation, you can add charge to it.)

Measuring Availability

- Mean time to failure (MTTF)
- Mean time to repair (MTTR)
- MTBF = MTTF + MTTR (mean time between failure)

$$Availability = \frac{\text{time system was running}}{\text{time system should have been running}}$$

- Availability = MTTF / (MTTF + MTTR)

$$\text{Down time} = (1 - Availability)$$

  - = (time sys operational) / (time sys should have been operational)
  - Suppose OS crashes once per month, takes 10min to reboot.
  - MTTF = 720 hours = 43,200 minutes
    MTTR = 10 minutes
  - Availability = 43200 / 43210 = 0.997 (~"3 nines")

Availability

Availability %	Downtime per year	Downtime per month*	Downtime per week
90% ("one nine")	36.5 days	72 hours	16.8 hours
95%	18.25 days	36 hours	8.4 hours
97%	10.96 days	21.6 hours	5.04 hours
98%	7.30 days	14.4 hours	3.36 hours
99% ("two nines")	3.65 days	7.20 hours	1.68 hours
99.50%	1.83 days	3.60 hours	50.4 minutes
99.80%	17.52 hours	86.23 minutes	20.16 minutes
99.9% ("three nines")	8.76 hours	43.8 minutes	10.1 minutes
99.95%	4.38 hours	21.56 minutes	5.04 minutes
99.99% ("four nines")	52.56 minutes	4.32 minutes	1.01 minutes
99.999% ("five nines")	5.26 minutes	25.9 seconds	6.05 seconds
99.9999% ("six nines")	31.5 seconds	2.59 seconds	0.605 seconds
99.99999% ("seven nines")	3.15 seconds	0.259 seconds	0.0605 seconds

For a reliable component, may have to wait a long time to determine its availability/downtime!

Availability in practice

- Carrier airlines (2002 FAA fact book)
  - 41 accidents, 6.7M departures
  - 99.9993% availability
- 911 Phone service (1993 NRIC report)
  - 29 minutes per line per year
  - 99.994%
- Standard phone service (various sources)
  - 53+ minutes per line per year
  - 99.99+%
- End-to-end Internet Availability
  - 95% - 99.6%

Coping with failures...

- A failure
  - Let’ s say one bit in your DRAM fails.
- Propagates
  - Assume it flips a bit in a memory address the kernel is writing to. That causes a big memory error elsewhere, or a kernel panic.
  - Your program is running one of a dozen storage servers for your distributed filesystem.
  - A client can’t read from NFS, so it hangs.

Recovery Techniques

- We've already seen some: e.g., retransmissions in TCP and in your RPC system
- Modularity can help in failure isolation: preventing an error in one component from spreading.
  - Analogy: The firewall in your car keeps an engine fire from affecting passengers
- Redundancy and Retries
  - Network: retransmit an RPC
  - Specific techniques used in file systems, disks (RAID)

What are our options?

1. Silently return the wrong answer.

2. Detect failure.

3. Correct / mask the failure

Options in dealing with failure

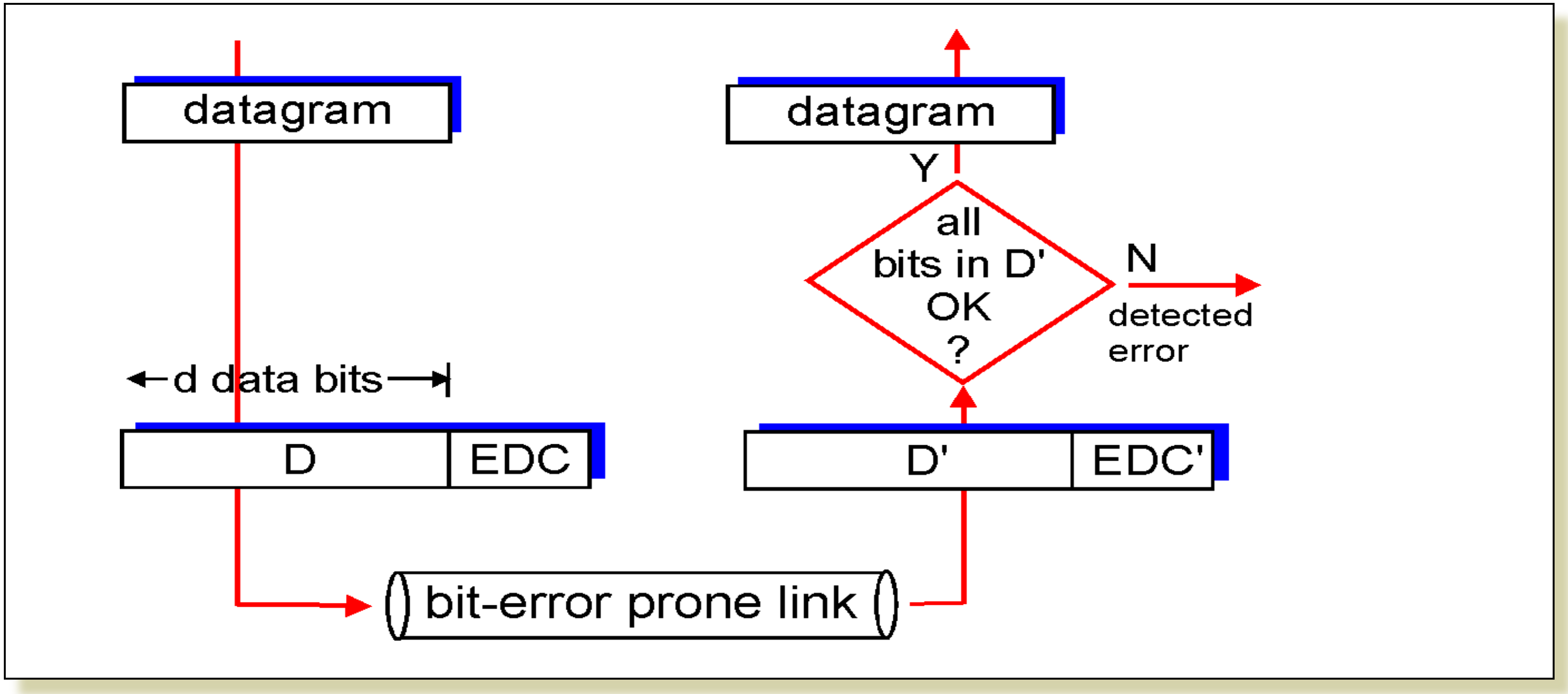
1. Silently return the wrong answer.

2. Detect failure.

3. Correct / mask the failure

Block error detection/correction

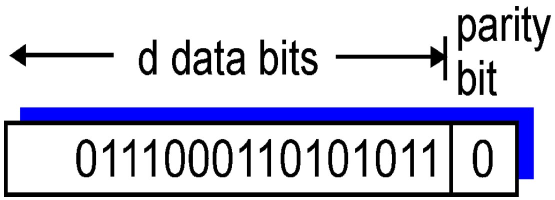
- EDC= Error Detection and Correction bits (redundancy)
- D = Data protected by error checking, may include header fields
- Error detection not 100% reliable!
  - Protocol may miss some errors, but rarely
  - Larger EDC field yields better detection and correction



Parity Checking

Single Bit Parity:

Detect single bit errors



Calculated using XOR over data bits:

- 0 bit: even number of 0s
- 1 bit: odd number of 0s

Error Detection - Checksum

- Used by TCP, UDP, IPv4 (not IPv6)
- Ones complement sum of all 16-bits in packet
- Simple to implement
  - Break up packet into 16-bits strings
  - Sum all the 16-bit strings
  - Take complement of sum = checksum; add to header
  - One receiver, compute same sum, add sum and checksum, check that the result is 0 (no error)
- Relatively weak detection
  - Easily tricked by typical loss patterns (bursty errors)

Example: Internet Checksum

- Goal: detect “errors” (e.g., flipped bits) in transmitted segment

Sender

- Treat segment contents as sequence of 16-bit integers
- Checksum: addition (1’s complement sum) of segment contents
- Sender puts checksum value into checksum field in header

Receiver

- Compute checksum of received segment
- Check if computed checksum equals checksum field value:
  - NO - error detected
  - YES - no error detected. But maybe errors nonethless?

Options in dealing with failure

1. Silently return the wrong answer.
2. Detect failure.
3. Correct / mask the failure

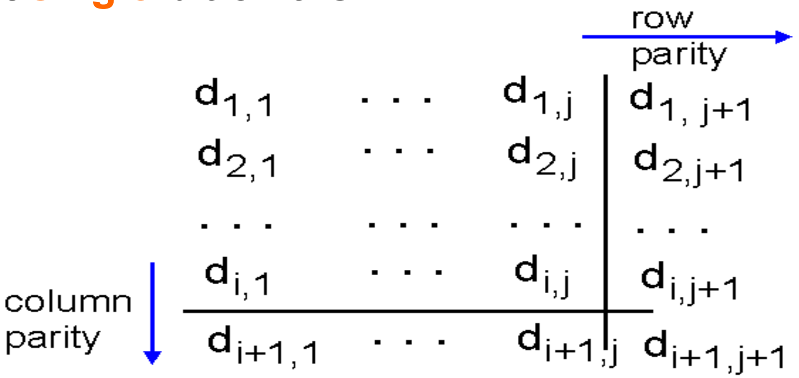
Error Recovery

- Two forms of error recovery
  - Redundancy
    - Error Correcting Codes (ECC)
    - Replication/Voting
  - Retry
- ECC
  - Keep encoded redundant data to help repair losses
  - Forward Error Correction (FEC) – send bits in advance
    - Reduces latency of recovery at the cost of bandwidth

Error Recovery – Error Correcting Codes (ECC)

Two Dimensional Bit Parity:

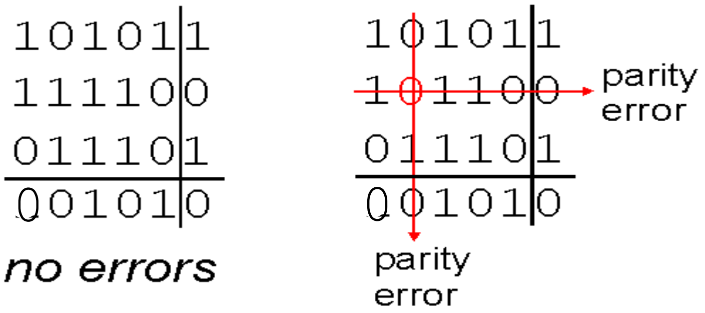
Detect *and correct* single bit errors



row parity

column parity

$$\begin{array}{ccc|c}
d_{1,1} & \cdots & d_{1,j} & d_{1,\ j+1} \\
d_{2,1} & \cdots & d_{2,j} & d_{2,j+1} \\
\cdots & \cdots & \cdots & \cdots \\
d_{i,1} & \cdots & d_{i,j} & d_{i,j+1} \\
\hline
d_{i+1,1} & \cdots & d_{i+1,j} & d_{i+1,j+1}
\end{array}$$



$$\begin{array}{c|c}
10101 & 1 \\
11110 & 0 \\
01110 & 1 \\
\hline
00101 & 0
\end{array}$$

no errors

$$\begin{array}{c|c}
10101 & 1 \\
10110 & 0 \\
01110 & 1 \\
\hline
00101 & 0
\end{array}$$

parity error

parity error

correctable single bit error

Replication/Voting

- If you take this to the extreme, three software versions:

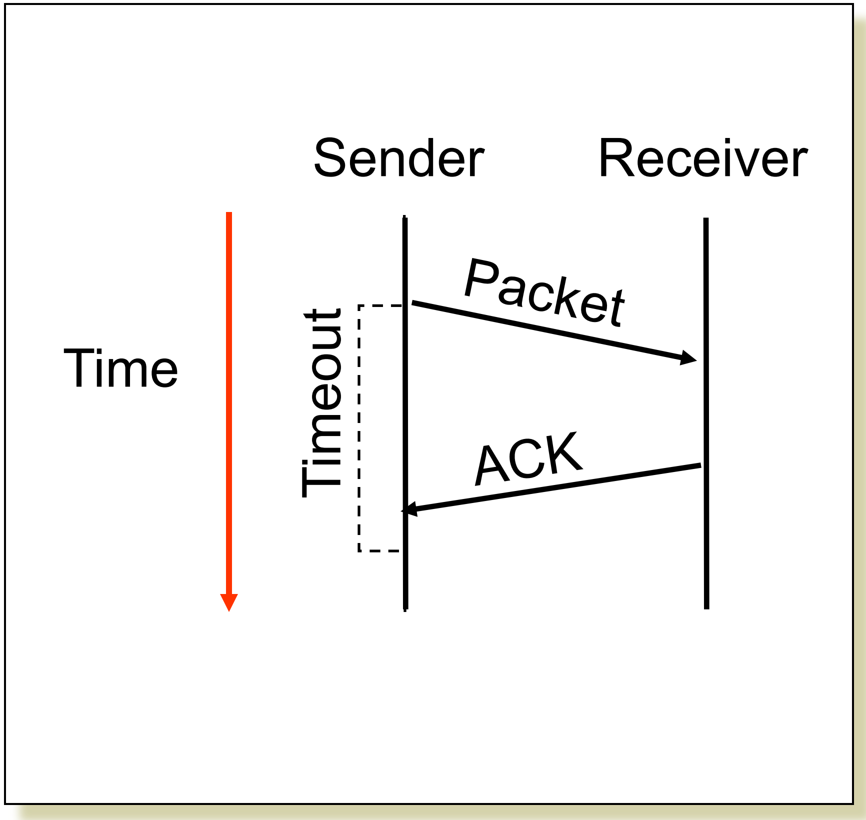
  [r1] [r2] [r3]

- Send requests to all three versions of the software: Triple modular redundancy
  - Compare the answers, take the majority
  - Assumes no error detection

- In practice - used mostly in space applications; some extreme high availability apps (stocks & banking? maybe. But usually there are cheaper alternatives if you don’t need real-time)

Retry – Network Example

- Sometimes errors are transient / need to mask
- Need to have error detection mechanism
    - E.g., timeout, parity, checksum
    - No need for majority vote



One key question

- How correlated are failures?
- Can you assume independence?
  - If the failure probability of a computer in a rack is p,
  - What is p(computer 2 failing) | computer 1 failed?
    - Maybe it’ s p... or maybe they’ re both plugged into the same UPS...
- Why is this important?

On disk errors
What are our options?

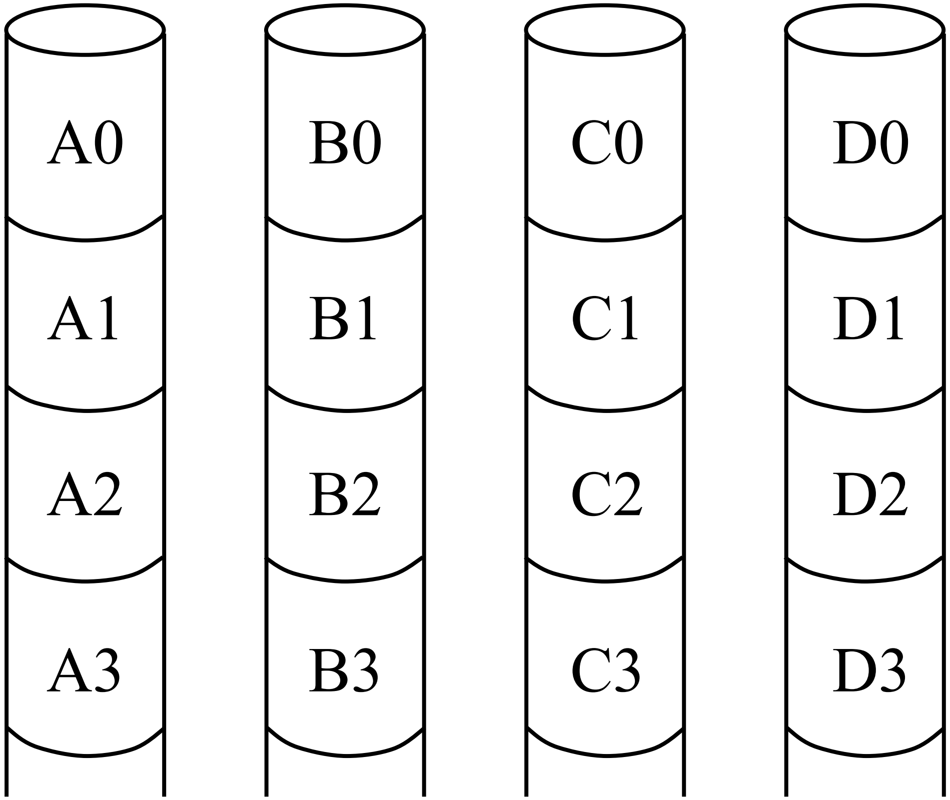
1. Silently return the wrong answer.
2. Detect failure.
   - Every sector has a header with a checksum. Every read fetches both, computes the checksum on the data, and compares it to the version in the header. Returns error if mismatch.
3. Correct / mask the failure
   - Re-read if the firmware signals error (may help if transient error, may not)
   - Use an error correcting code (what kinds of errors do they help?)
     - Bit flips? Yes. Block damaged? No
   - **Have the data stored in multiple places (RAID)**

Motivation: Why use multiple disks?

- Capacity
  - More disks allows us to store more data
- Performance
  - Access multiple disks in parallel
  - Each disk can be working on independent read or write
  - Overlap seek and rotational positioning time for all
- Reliability
  - Recover from disk (or single sector) failures
  - Will need to store multiple copies of data to recover

- So, what is the simplest arrangement?

Just a bunch of disks (JBOD)



A0 B0 C0 D0

A1 B1 C1 D1

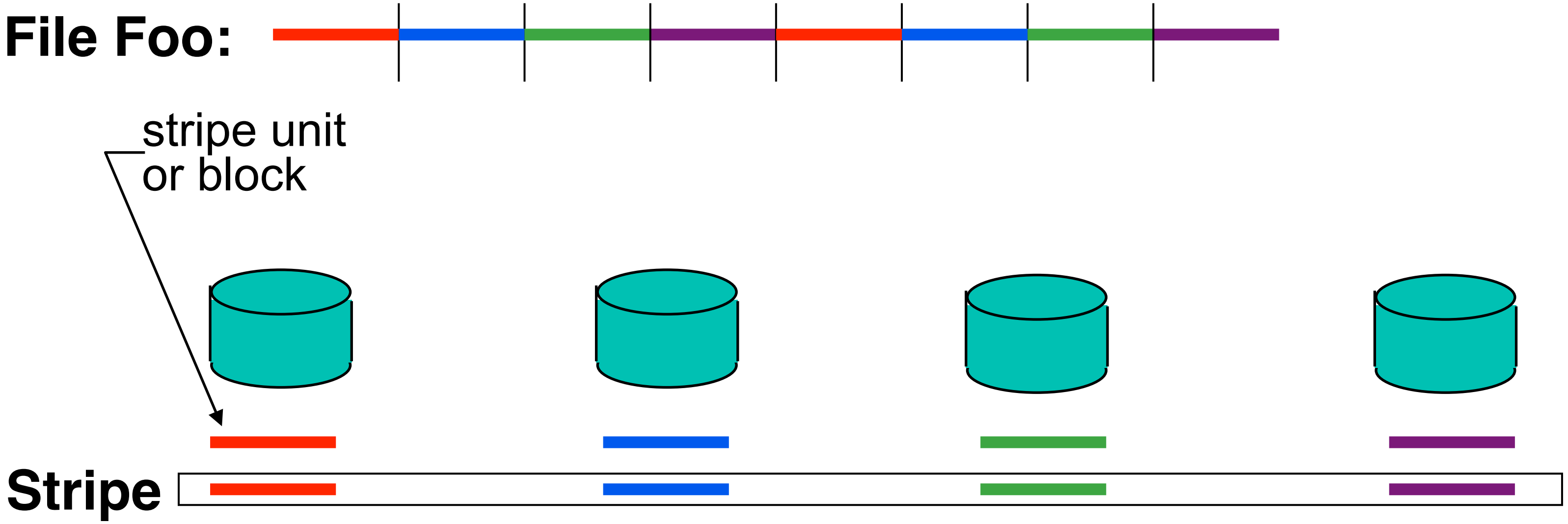
A2 B2 C2 D2

A3 B3 C3 D3

- Yes, it's a goofy name
  - industry really does sell "JBOD enclosures"

Disk Striping

- Interleave data across multiple disks
  - Large file streaming can enjoy parallel transfers
  - High throughput requests can enjoy good load balancing
    - If blocks of hot files equally likely on all disks (really?)



Disk striping details

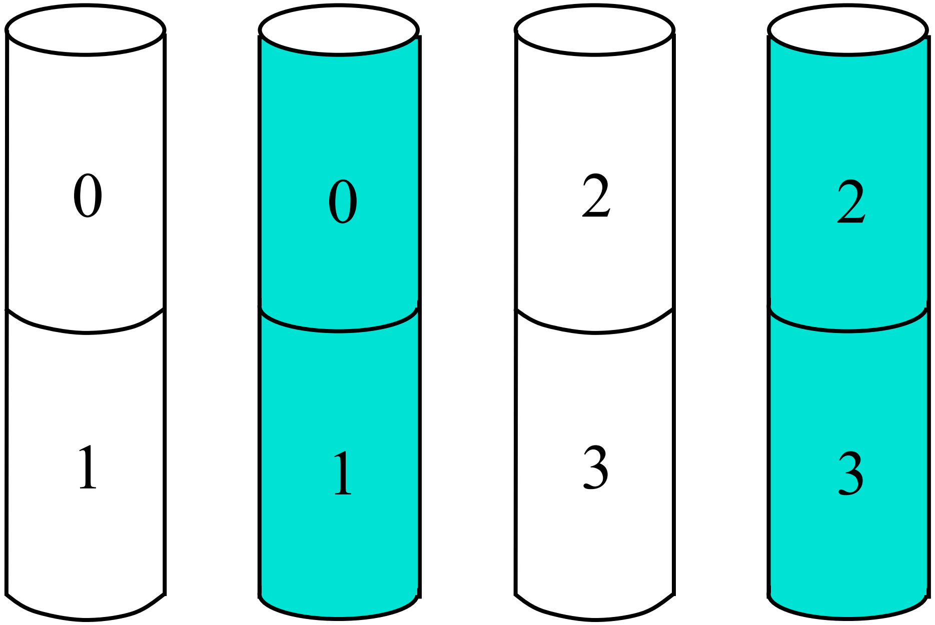
- How disk striping works
  - Break up total space into fixed-size stripe units
  - Distribute the stripe units among disks in round-robin
  - Compute location of block #B as follows
    - disk# = B%N (%=modulo,N = #ofdisks)

Now, What If A Disk Fails?

- In a JBOD (independent disk) system
  - one or more file systems lost
- In a striped system
  - a part of each file system lost
- Backups can help, but
  - backing up takes time and effort
  - backup doesn’t help recover data lost during that day
    - Any data loss is a big deal to a bank or stock exchange

Redundancy via replicas

- Two (or more) copies
    - mirroring, shadowing, duplexing, etc.
- Write both, read either

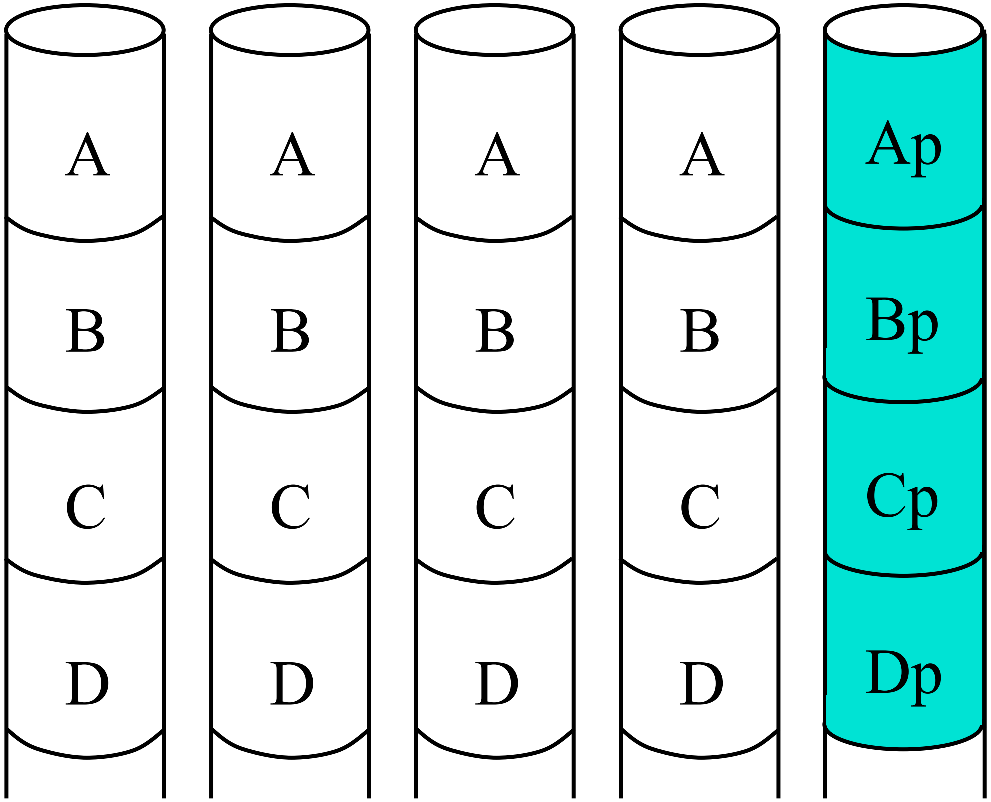


Lower Cost Data Redundancy

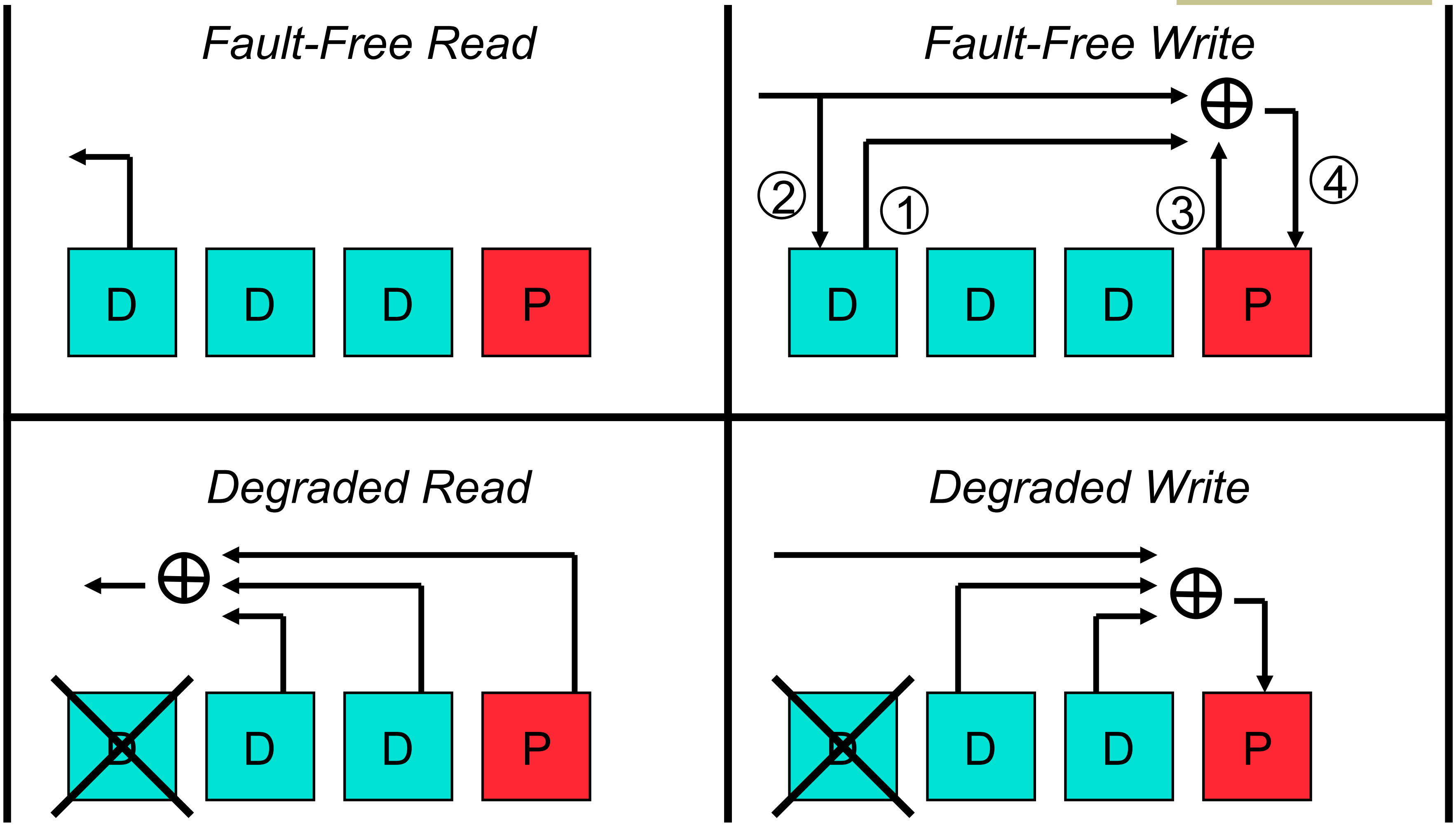
- Single failure protecting codes
    - general single-error-correcting code is overkill
        - General code finds error and fixes it
- Disk failures are self-identifying (a.k.a. erasures)
    - Don’t have to find the error
- Parity is single-disk-failure-correcting code
    - recall that parity is computed via XOR
    - it’s like the low bit of the sum

Simplest approach: Parity Disk

- One extra disk
- All writes update parity disk
  - Potential bottleneck
  - (different data in different As, Bs, Cs, Ds)
  - (Ap contains parity for all As)



Updating and using the parity



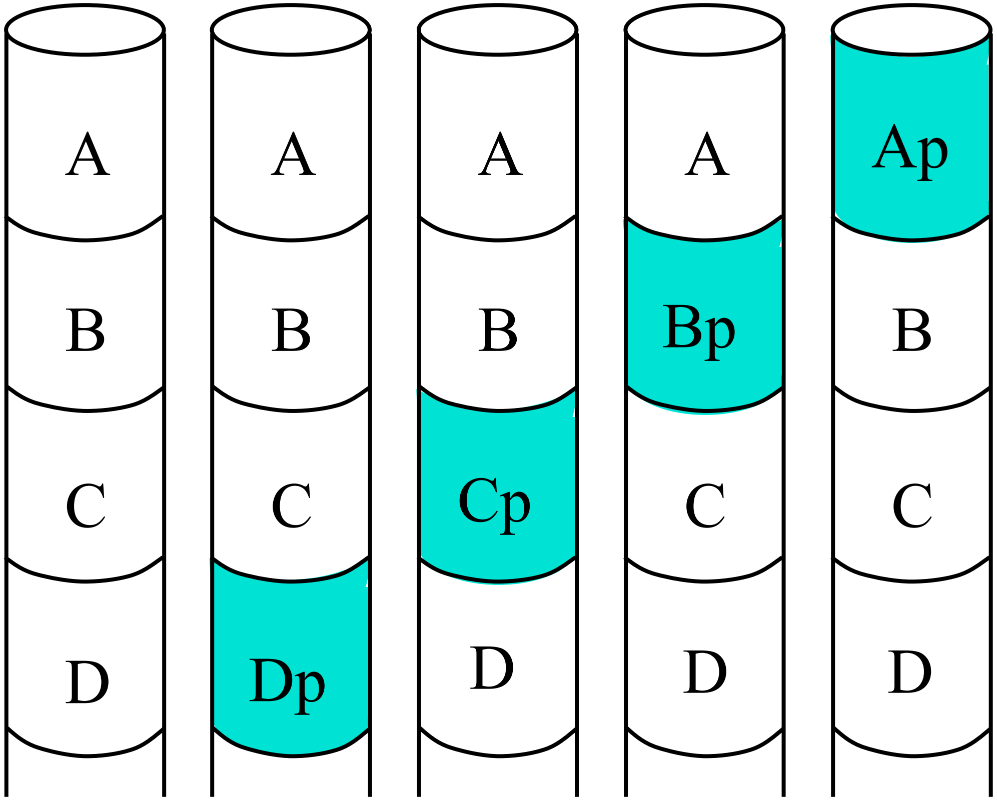
The parity disk bottleneck

- Reads go only to the data disks
  - But, hopefully load balanced across the disks

- All writes go to the parity disk
  - And, worse, usually result in Read-Modify-Write sequence
  - So, parity disk can easily be a bottleneck

Solution: Striping the Parity

- Removes parity disk bottleneck

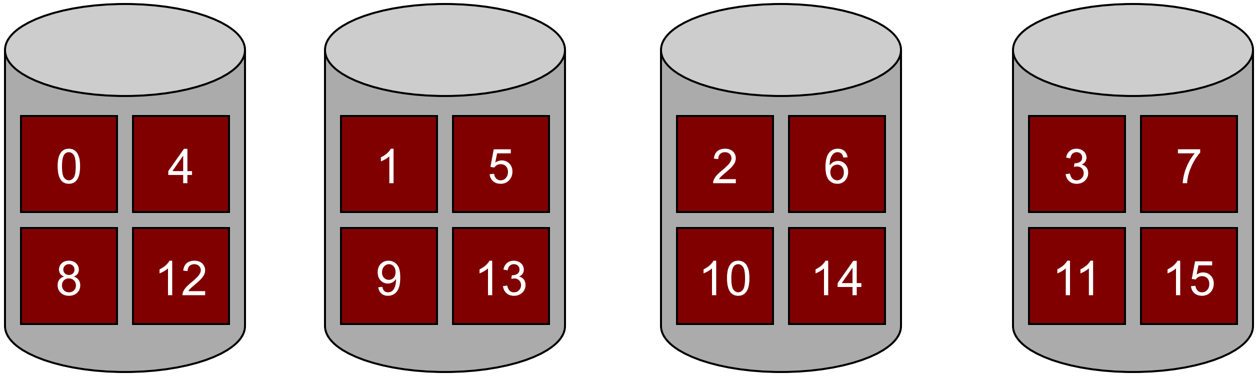


RAID Taxonomy

- Redundant Array of Inexpensive Independent Disks
  - Constructed by UC-Berkeley researchers in late 80s (Garth)
- RAID 0 – Coarse-grained Striping with no redundancy
- RAID 1 – Mirroring of independent disks
- RAID 2 – Fine-grained data striping plus Hamming code disks
  - Uses Hamming codes to detect and correct multiple errors
  - Originally implemented when drives didn’t always detect errors
  - Not used in real systems
- RAID 3 – Fine-grained data striping plus parity disk
- RAID 4 – Coarse-grained data striping plus parity disk
- RAID 5 – Coarse-grained data striping plus striped parity
- RAID 6 – Coarse-grained data striping plus 2 striped codes

RAID-0: Striping

- Stripe blocks across disks in a “chunk” size
  - How to pick a reasonable chunk size?

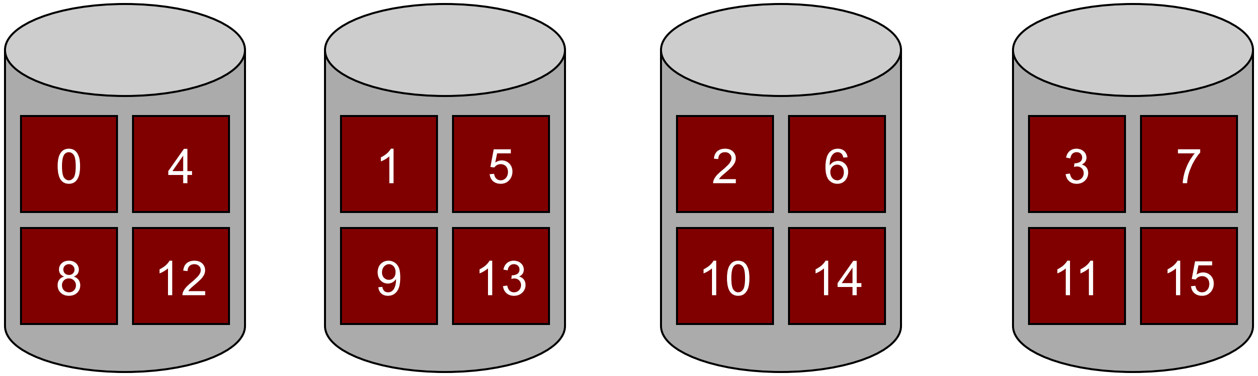


How to calculate where chunk # lives?

Disk #:

Offset within disk:

RAID-0: Striping



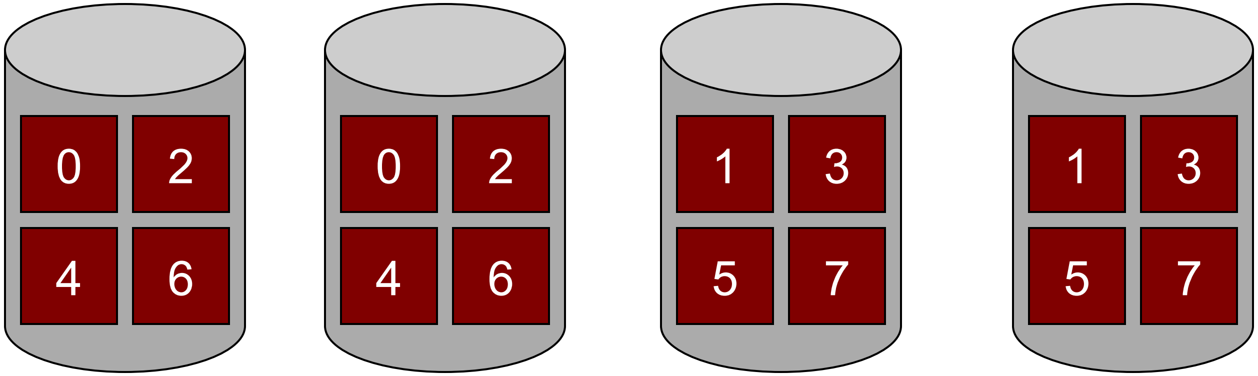
- Evaluate for D disks

- Performance: How much faster than 1 disk? (best case)

- Reliability: More or less reliable than 1 disk?

RAID-1: Mirroring

- Motivation: Handle disk failures
- Put copy (mirror or replica) of each chunk on another disk

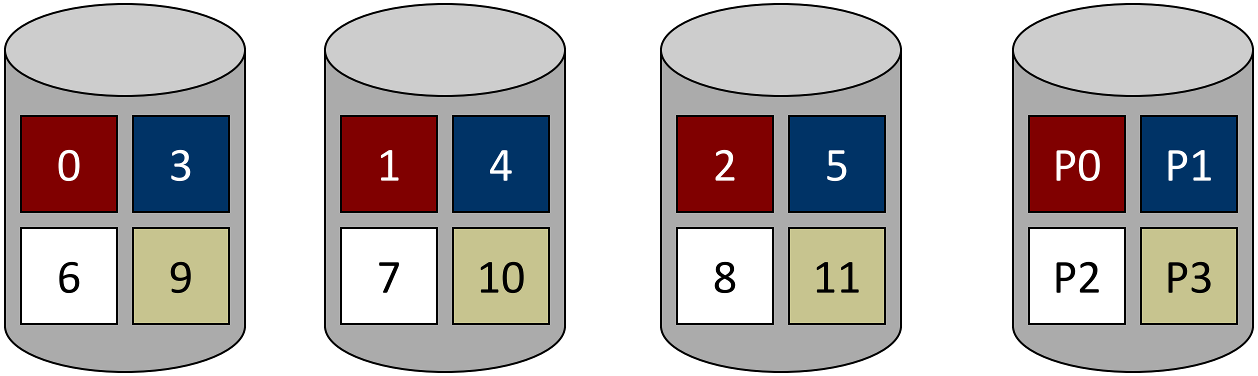


- Capacity
- Reliability
- Performance

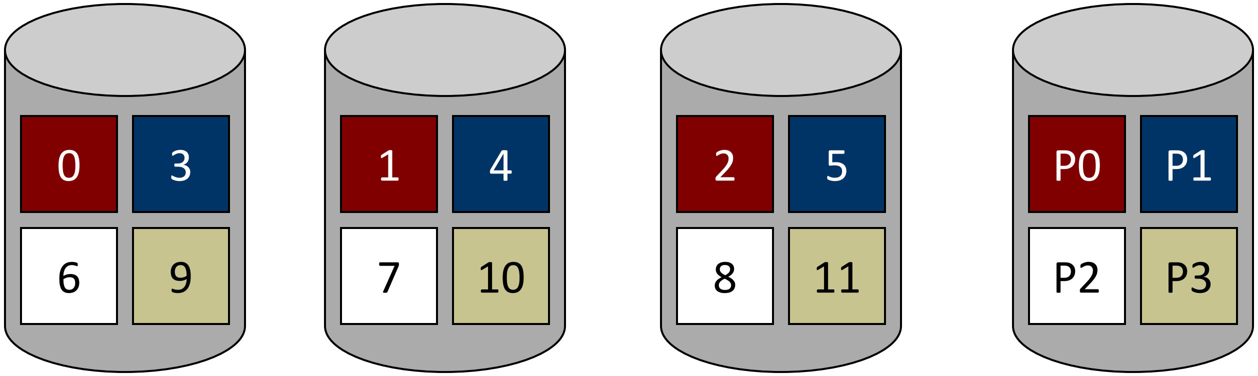
RAID-4: Parity

- Motivation: Improve capacity
- Idea: Allocate parity block to encode info about blocks
    - Parity checks all other blocks in stripe across other disks
- Parity block = XOR over others (gives "even" parity)
    - Example: 0 1 0 → Parity value?
- How do you recover from a failed disk?
    - Example: x 0 0 and parity of 1
    - What is the failed value?

A	B	XOR
0	0	0
0	1	1
1	0	1
1	1	0

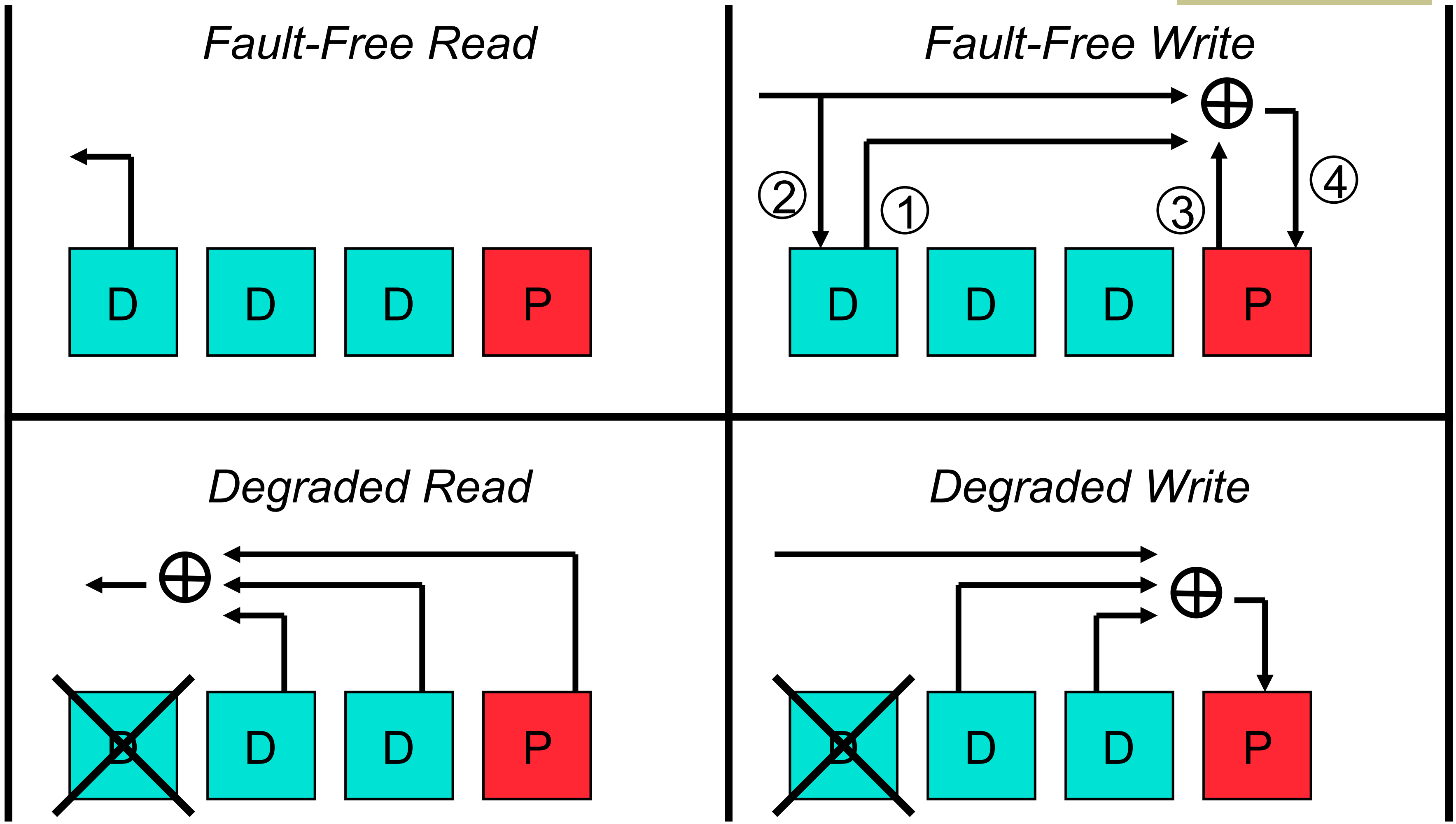


RAID-4: Parity



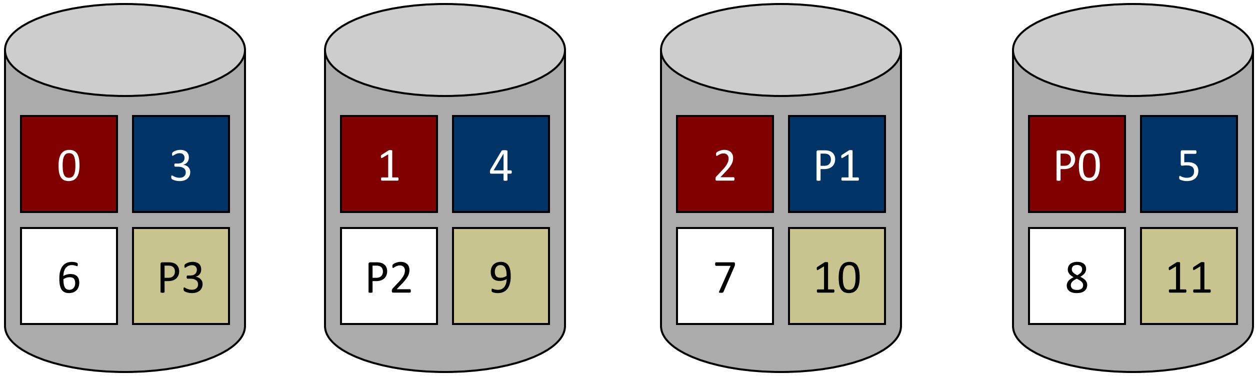
- Capacity:
- Reliability:
- Performance:
  - Reads
  - Writes: How to update parity block?
    - Two ways:
      - Use parity disk
      - Re-compute parity from non-parity disks
    - (Parity disk is the bottleneck)

Updating and using the parity



RAID-5: Rotated/Striped Parity

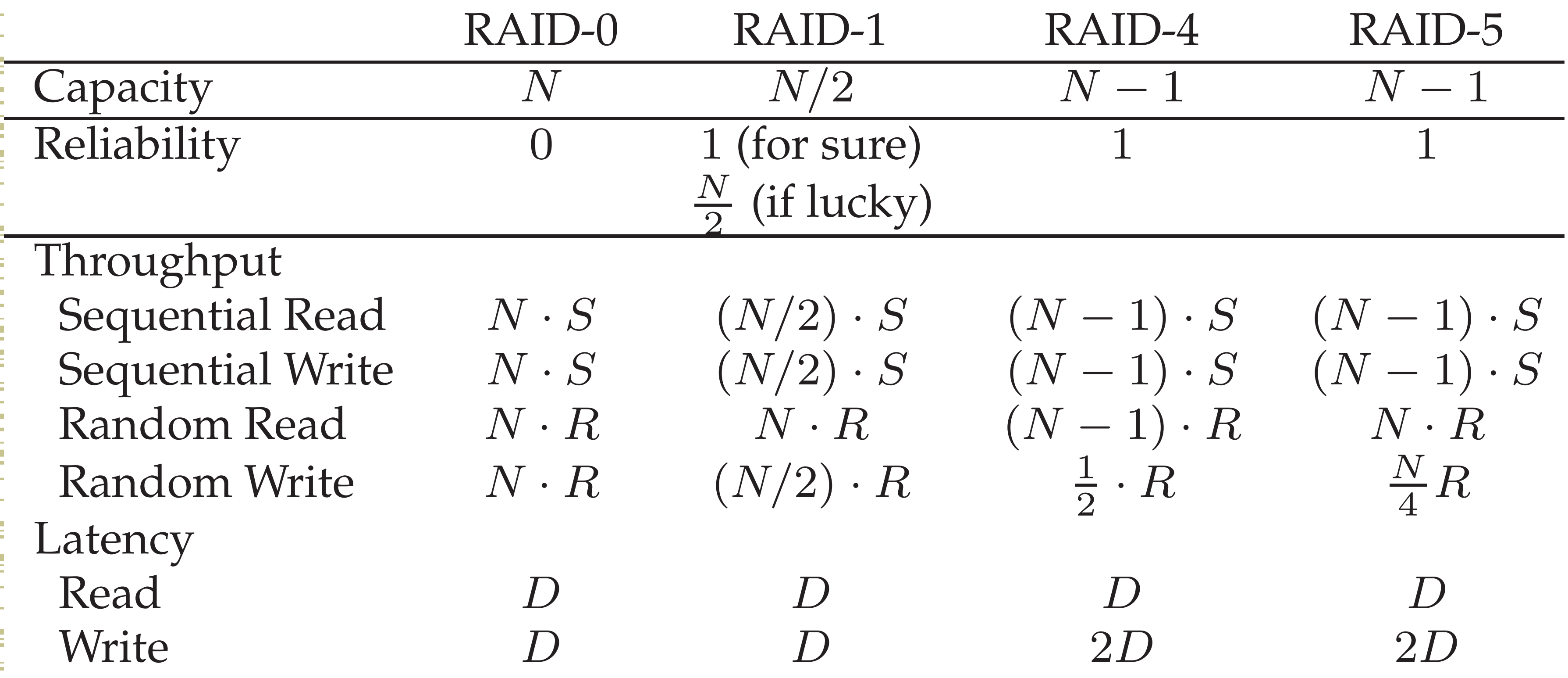
Rotate location of parity across all disks



- Capacity:
- Reliability:
- Performance:
  - Reads:
  - Writes:
  - Still requires 4 I/Os per write, but not always to same parity disk

Comparison

N: number of disks
S: throughput of 1 disk sequential read/write
R: throughput of 1 disk random read/write
D: delay to read/write from 1 disk



	RAID-0	RAID-1	RAID-4	RAID-5
Capacity	N	$N/2$	$N-1$	$N-1$
Reliability	0	1 (for sure) $\frac{N}{2}$ (if lucky)	1	1
Throughput				
Sequential Read	$N \cdot S$	$(N/2) \cdot S$	$(N-1) \cdot S$	$(N-1) \cdot S$
Sequential Write	$N \cdot S$	$(N/2) \cdot S$	$(N-1) \cdot S$	$(N-1) \cdot S$
Random Read	$N \cdot R$	$N \cdot R$	$(N-1) \cdot R$	$N \cdot R$
Random Write	$N \cdot R$	$(N/2) \cdot R$	$\frac{1}{2} \cdot R$	$\frac{N}{4} R$
Latency				
Read	D	D	D	D
Write	D	D	$2D$	$2D$

Table 38.7: **RAID Capacity, Reliability, and Performance**

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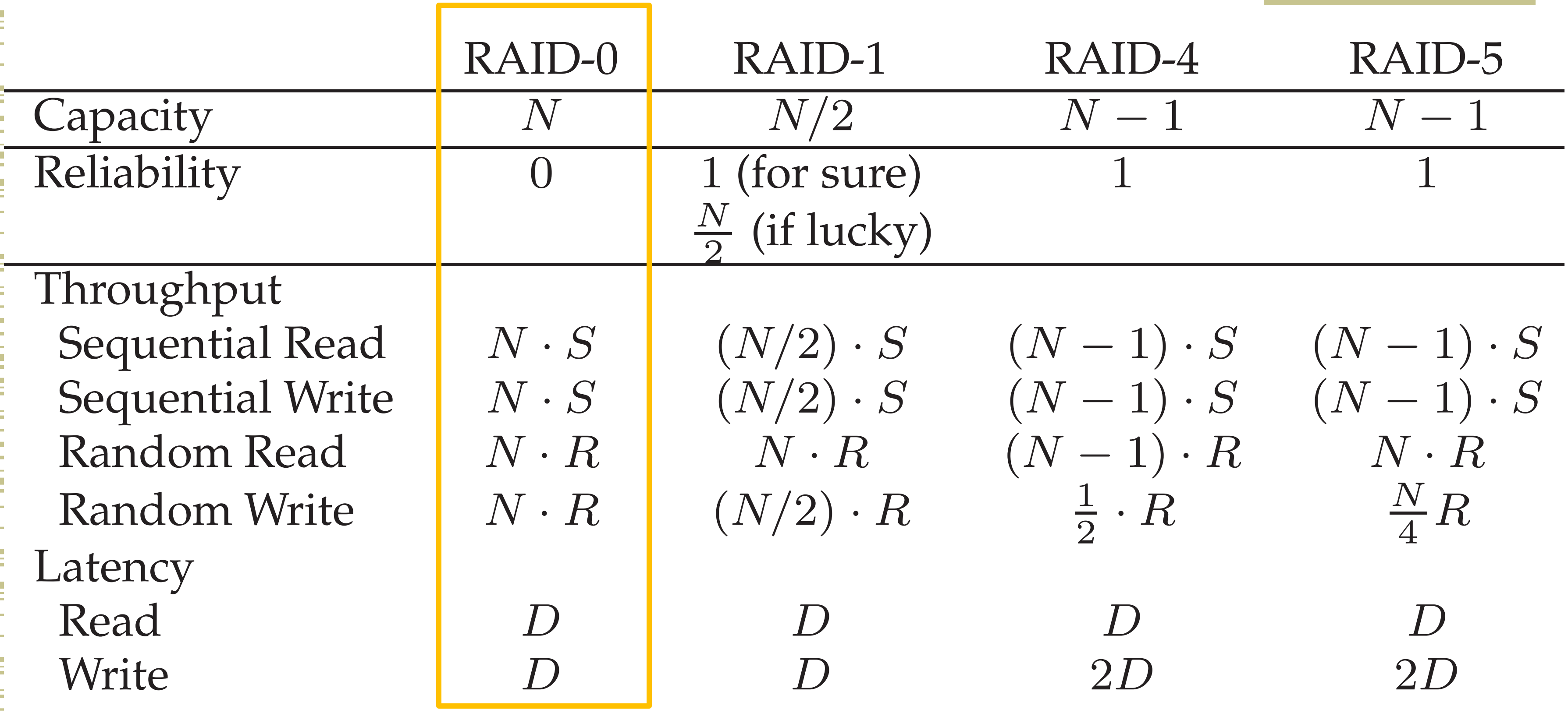

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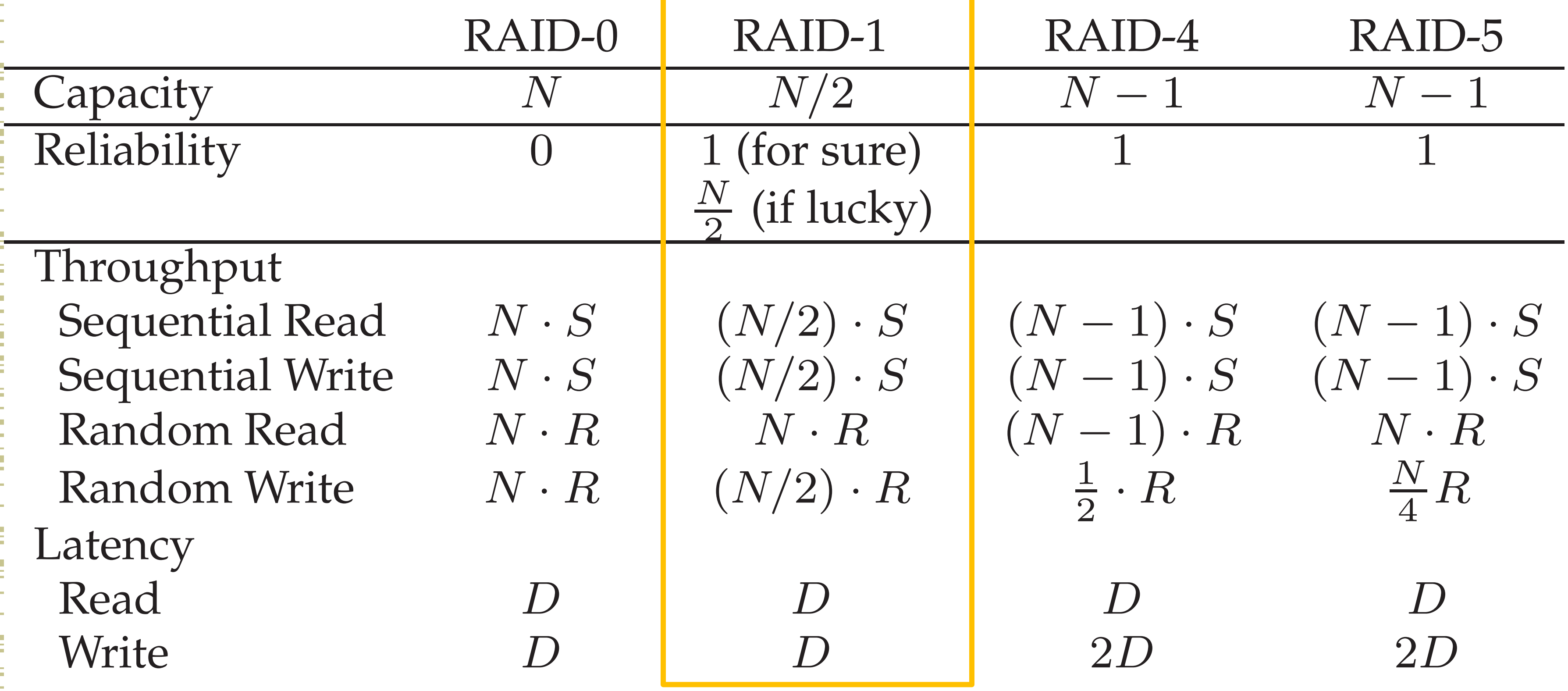

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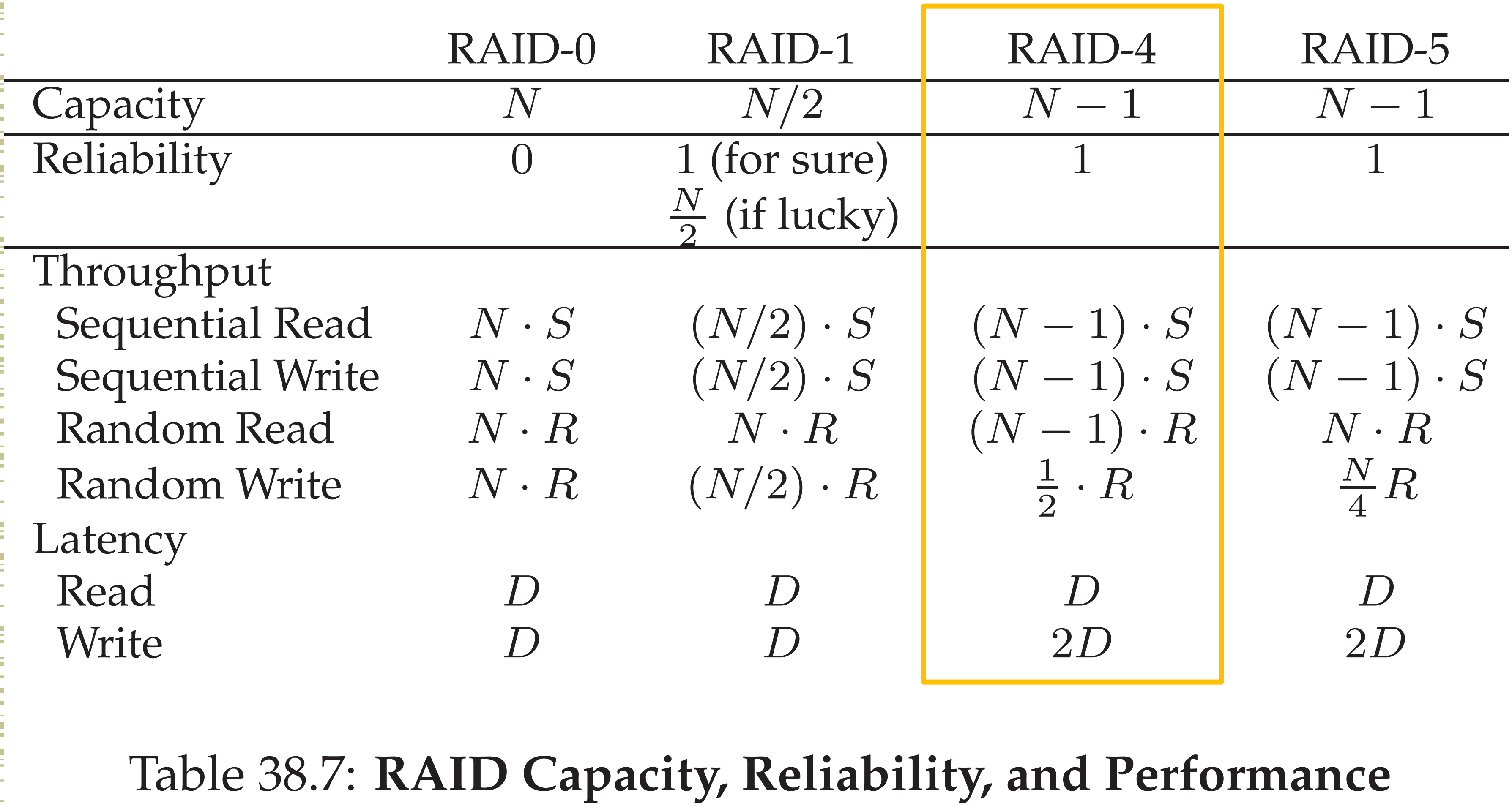

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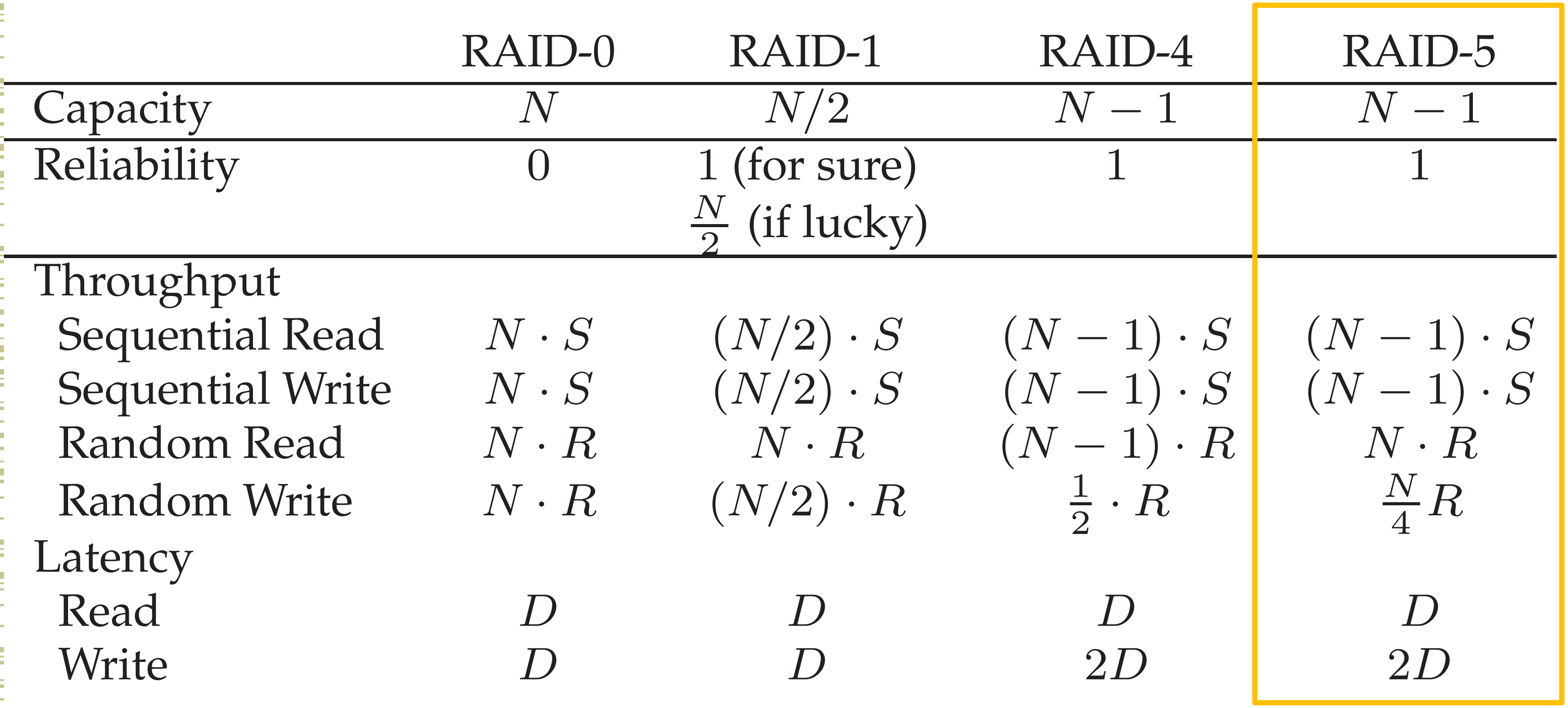

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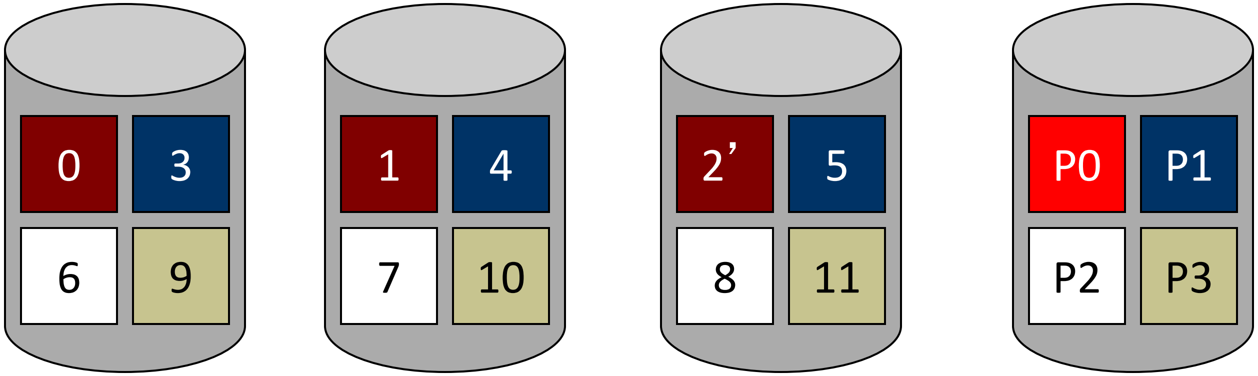
Latency				
Read	D	D	D	D
Write	D	D	$2D$	$2D$

Table 38.7: **RAID Capacity, Reliability, and Performance**

Advanced Issues

- What happens if more than one fault?
  - Example: One disk fails plus “latent sector error” on another
  - RAID-5 cannot handle two faults
  - Solution: RAID-6: add multiple parity blocks
- Why is NVRAM useful?
  - Example: What if update 2, don’t update P0 before power failure (or crash), and then disk 1 fails?
  - NVRAM solution: Use to store blocks updated in same stripe
    - If power failure, can replay all writes in NVRAM
  - Software RAID solution: Perform parity scrub over entire disk



Conclusions

- RAID turns multiple disks into a larger, faster, more reliable disk
- RAID-0: Striping
  Good when performance and capacity really matter, but reliability doesn't
- RAID-1: Mirroring
  Good when reliability and write performance matter, but capacity (cost) doesn't
- RAID-4: Parity disk
- RAID-5: Rotating parity
  Good when capacity and cost matter or workload is read-mostly
  - Good compromise choice

Summary

- Definition of MTTF/MTBF/MTTR: Understanding availability in systems.
- Failure detection and fault masking techniques
- Engineering tradeoff: Cost of failures vs. cost of failure masking.
  - At what level of system to mask failures?
- Replication as a general strategy for fault tolerance: RAID today, next: replicated services
- Thought to leave you with:
  - What if you have to survive the failure of entire machine? Of a rack of machines? Of a datacenter?