15-410

"...Failure is not an option..."

Disk Arrays
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Dave Eckhardt

Bruce Maggs

Contributions by
Michael Ashley-Rollman

Synchronization

Today: Disk Arrays

- Text: 14.5 (a good start)
  - Please read remainder of chapter
- www.acnc.com 's "RAID.edu" pages
  - Pittsburgh's own RAID vendor!
- www.uni-mainz.de/~neuffer/scsi/what_is_raid.html
- Papers (@ end)

Overview

Historical practices

- Striping, mirroring

The reliability problem

Parity, ECC, why parity is enough

RAID “levels” (really: flavors)

Applications

Papers

Striping

Goal

- High-performance I/O for databases, supercomputers
- “People with more money than time”

Problems with disks

- Seek time
- Rotational delay
- Transfer time

Seek Time

Technology issues evolve slowly

- **Weight of disk head**
- **Stiffness of disk arm**
- **Positioning technology**

Hard to dramatically improve for niche customers

Sorry!

Rotational Delay

How fast *can* we spin a disk?

- Fancy motors, lots of power – spend more money

Probably limited by data rate

- Spin faster $\Rightarrow$ must process analog waveforms faster
- Analog $\Rightarrow$ digital via *serious* signal processing

Special-purpose disks generally spin *a little* faster

- 1.5X, 2X – not 100X

Transfer Time

Transfer time ≡

- Assume seek & rotation complete
- How fast to transfer ____ kilobytes?

How to transfer faster?

Parallel Transfer?

Reduce transfer time (without spinning faster)

Read from multiple heads at same time?

Practical problem

- Disk needs N copies of analog $\Rightarrow$ digital hardware
- Expensive, but we have *some* money to burn

Marketing wants to know...

- Do we have *enough* money to buy a new factory?
- Can't we use our existing product somehow?

Striping

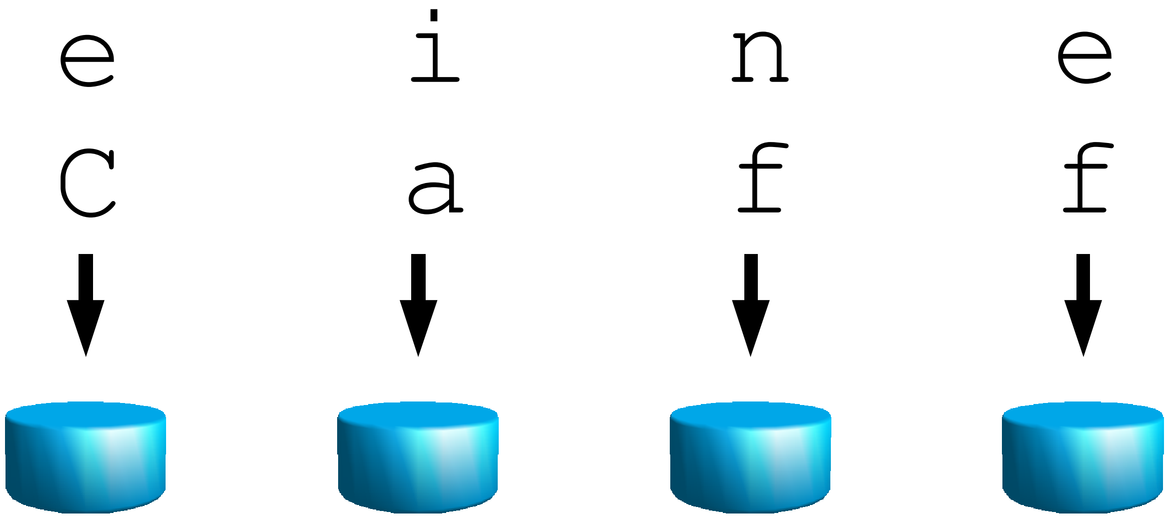
Goal

- High-performance I/O for databases, supercomputers

Solution: parallelism

- Gang *multiple disks* together

Striping



Striping

Stripe *unit* (what each disk gets) can vary

- Byte
- Bit
- Sector (typical)

Stripe *size* = stripe unit X #disks

Behavior: “fat sectors”

- File system maps bulk data request ⇒ N disk operations
- Each disk reads/writes 1 sector

Striping Example

Simple case – stripe sectors

- 4 disks, stripe unit = 512 bytes
- Stripe size = 2K

Results

- Seek time: 1X base case (ok)
- Transfer rate: 4X base case (great!)

But there's a problem...

High-Performance Striping

Rotational delay *gets worse*

- Stripe not done until *fourth* disk rotates to right place
- I/O to 1 disk pays *average* rotational cost (50%)
- N disks converge on *worst-case* rotational cost (100%)

Spindle synchronization!

- Make sure N disks are always aligned
- Sector 0 passes under each head at "same" time

Result

- Commodity disks with extra synchronization hardware
  - Not *insanely* expensive ⇒ some supercomputer applications

Less Esoteric Goal: Capacity

Users always want more disk space

Easy answer

- Build a larger disk!
- IBM 3380 (early 1980's)
  - 14-inch platter(s)
  - Size of a *refrigerator*
  - 1-3 GByte (woo!)

"Marketing on line 1"...

- These monster disks sure are expensive to build!
  - Especially compared to those dinky 5¼-inch PC disks...
- Can't we hook small disks together like last time?

Striping Example Revisited

Simple case – stripe sectors

- 4 disks, stripe unit = 512 bytes
- Stripe size = 2K

Results

- Seek time: 1X base case (ok)
- Rotation time : 1X base case using special hardware (ok)
- Transfer rate: 4X base case (great!)
- Capacity: 4X base case (great!)

Now what could go wrong?

The Reliability Problem

MTTF = Mean time to failure

MTTF(array) = MTTF(disk) / #disks

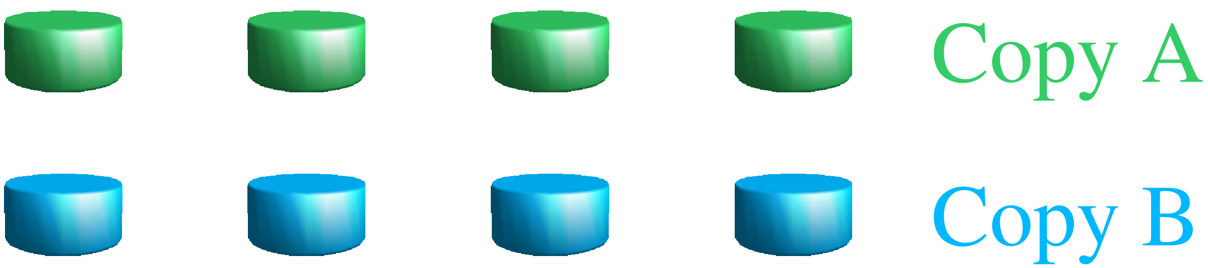
Example from original 1988 RAID paper

- Conner Peripherals CP3100 (100 megabytes!)
- MTTF = 30,000 hours = 3.4 years

Array of 100 CP3100's

- 10 Gigabytes (good)
- MTTF = 300 hours = *12.5 days* (not so good)
- Reload file system from tape every 2 weeks???

Mirroring



Mirroring

Operation

- Write: write to *both* mirrors
- Read: read from *either* mirror

Cost per byte *doubles*

Performance

- Writes: a little slower
- Reads: maybe 2X faster

Reliability *vastly* increased

Mirroring

When a disk breaks

- Identify it to system administrator
  - Beep, blink a light
- System administrator provides blank disk
- Copy contents from surviving mirror

Result

- Expensive but safe
- Banks, hospitals, etc.
- Home PC users???

Error Coding

If you are good at math

- Error Control Coding: Fundamentals & Applications
  - Lin, Shu, & Costello

If you are like me

- Commonsense Approach to the Theory of Error Correcting Codes
  - Arazi

Error Coding In One Easy Lesson

Data vs. message

- Data = what you want to convey
- Message = data plus extra bits (“code word”)

Error detection

- Message indicates: something got corrupted

Error *correction*

- Message indicates: bit 37 should be 0, not 1
- Very useful!

Trivial Example

Transmit *code words* instead of data bits

- Data 0 ≡ code word 0000
- Data 1 ≡ code word 1111

Transmission "channel" corrupts code words

- Send 0000, receive 0001

Error detection

- 0001 isn't a valid code word - Error!

Error *correction*

- Gee, that looks more like "0000" than "1111"

Lesson 1, Part B

Error codes can be overwhelmed

- Is “0011” a corrupted “0000” or a corrupted “1111”?

“Too many” errors: *wrong answers*

- Series of corruptions
  - 0000 $\Rightarrow$ 0001 $\Rightarrow$ 0101 $\Rightarrow$ 1101
  - “Looks like 1111, doesn't it?”

Codes typically detect more errors than can correct

- A possible example code
  - Can *detect* 1..4 errors, can *fix* any single error
  - Five errors will report “fix” - to a *different* user data word!

Parity

Parity = XOR "sum" of bits

- $0 \oplus 1 \oplus 1 = 0$

Parity provides *single error detection*

- Sender provides *code word* and *parity bit*
- Correct: 011,0
- Incorrect: 011,1
  - Something is wrong with this picture – *but what?*
  - Parity provides *no* error correction

Cannot detect (all) multiple-bit errors

ECC

ECC = error correcting code

"Super parity"

- Code word, *multiple* "parity" bits
- Mysterious math computes parity from data
  - Hamming code, Reed-Solomon code
- Can detect N *multiple-bit* errors
- Can *correct* M (< N) bit errors!
- Often M ~ N/2

Parity revisited

Parity provides single ***erasure*** correction!

Erasure channel

- Knows when it doesn't know something
- Example: each bit is 0 or 1 or “don't know”

Sender provides code word, parity bit: (0 1 1 , 0)

Channel provides corrupted message: (0 ? 1 , 0)

$? = \mathbf{0 \oplus 1 \oplus 0 = 1}$

Erasure channel???

Are erasure channels real?

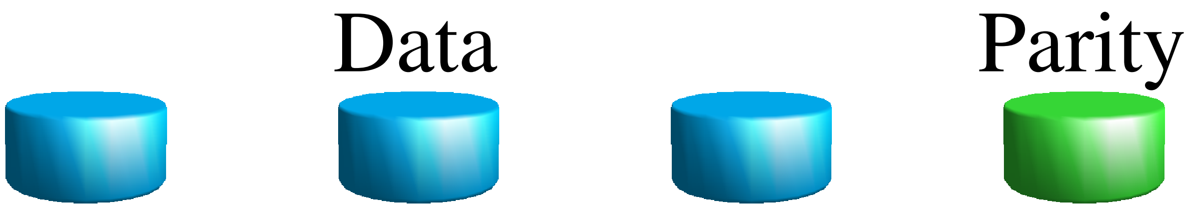
Radio

- modem stores signal strength during reception of each bit

Disk drives!

- Disk hardware adds “CRC code word” to each sector
- CRC = Cyclic redundancy check
  - Very good at detecting random data corruption
- Disks “know when they don't know”
  - Read sector 42 from 4 disks
  - Receive 0..4 good sectors, 4..0 errors (sector erasures)
- “Drive not ready” = “erasure” of all sectors

"Fractional mirroring"

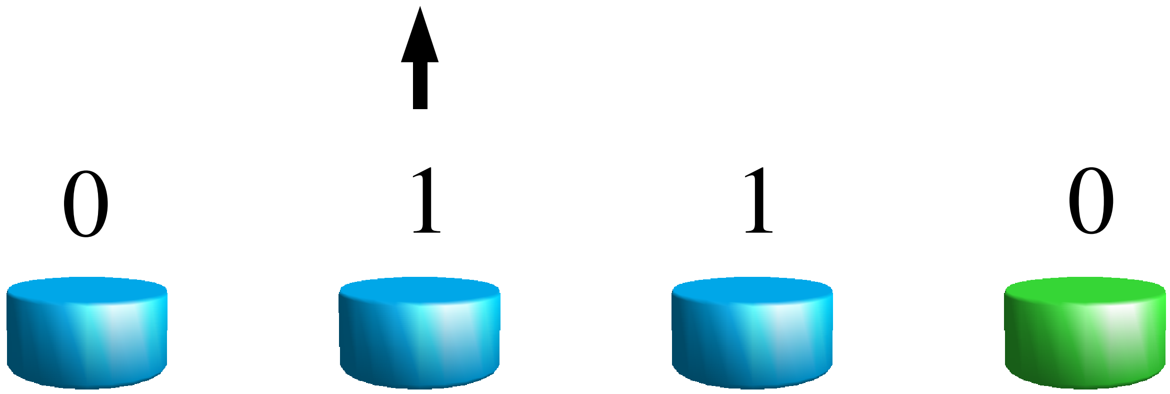


“Fractional mirroring”

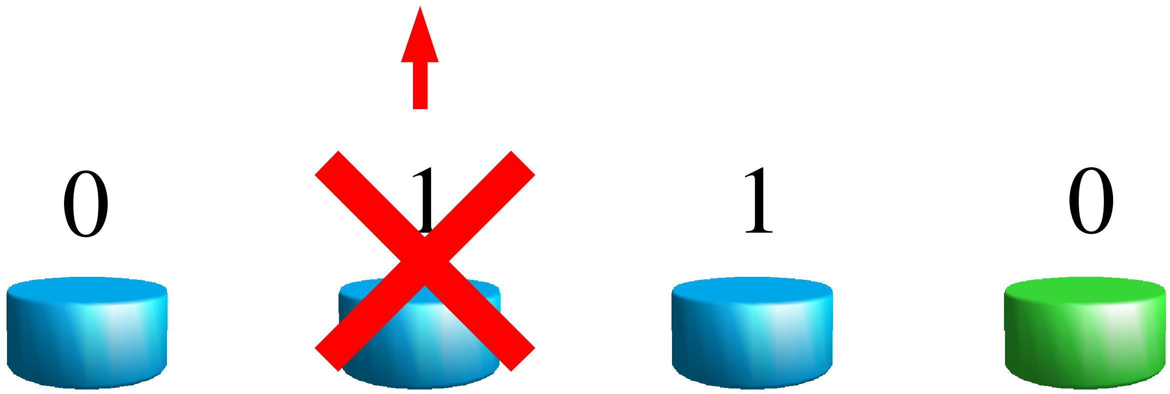
Operation

- **Read: read data disks**
  - **Error? Read parity disk, compute lost value**
- **Write: write data disks *and parity disk***

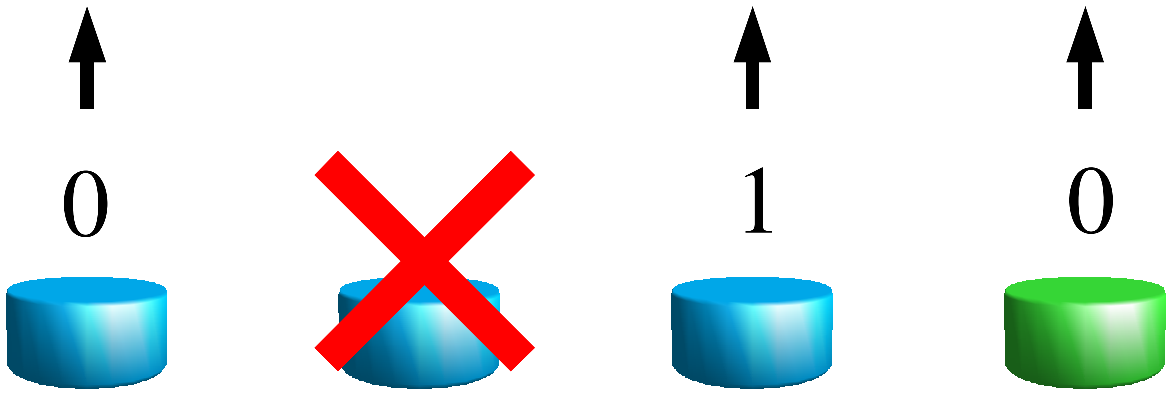
Read



Read Error



Read Reconstruction



$$\text{Missing} = 0 \oplus 1 \oplus 0 = 1$$

"Fractional mirroring"

Performance

- Writes: slower (see "RAID 4" below)
- Reads: unaffected

Reliability *vastly* increased

- Not quite as good as mirroring
  - Why not?

Cost

- *Fractional* increase (50%, 33%, ...)
- Cheaper than mirroring's 100%

RAID

RAID

- Redundant Arrays of Inexpensive Disks

SLED

- Single Large Expensive Disk

Terms from original RAID paper (@end)

Different ways to aggregate disks

- Paper presented a number-based taxonomy
- Metaphor tenuous then, stretched ridiculously now

RAID “levels”

They're not really levels

- RAID 2 isn't “more advanced than” RAID 1
  - People really do RAID 1
  - People basically never do RAID 2

People invent new ones randomly

- RAID 0+1 ???
- JBOD ???

Easy cases

JBOD = "just a bunch of disks"

- N disks in a box pretending to be 1 large disk
- Box controller maps "logical sector" ⇒ (disk, real sector)

RAID 0 = striping

RAID 1 = mirroring

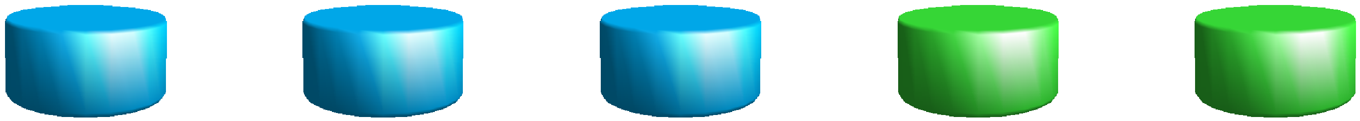
RAID 2

Stripe size = *byte* (unit = 1 bit per disk)

N data disks, M parity disks

Use ECC to get multiple-error correction

Very rarely used



RAID 3

Stripe size = *byte* (unit = 1 bit per disk)

Use parity instead of ECC (disks report erasures)

N data disks, 1 parity disk

Used in some high-performance applications

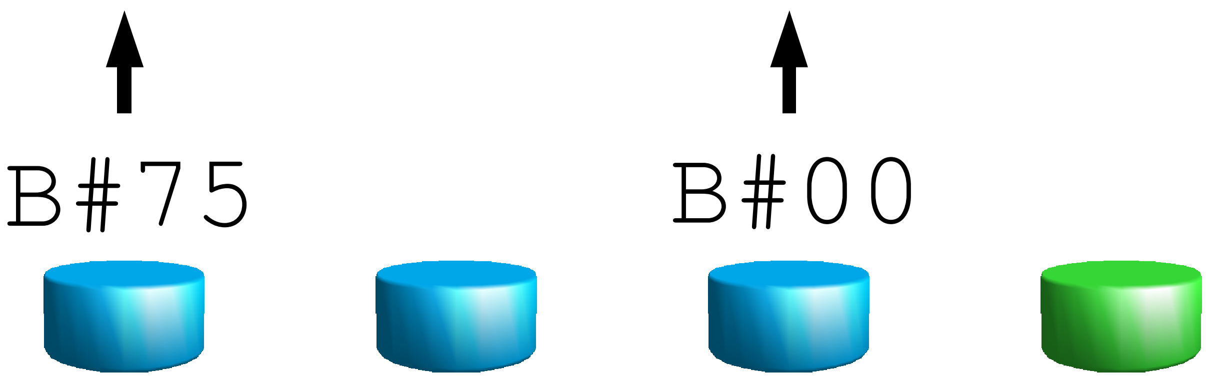
RAID 4

Like RAID 3

- Uses parity, relies on erasure signals from disks
- But unit = *sector* instead of *bit*

Single-sector reads involve only 1 disk

- Can handle multiple single-sector reads in parallel



Single-sector *writes*

Modifying a single sector is harder

Must fetch old version of sector

Must maintain parity invariant for stripe

Sector Write

Parity Disk is a "Hot Spot"

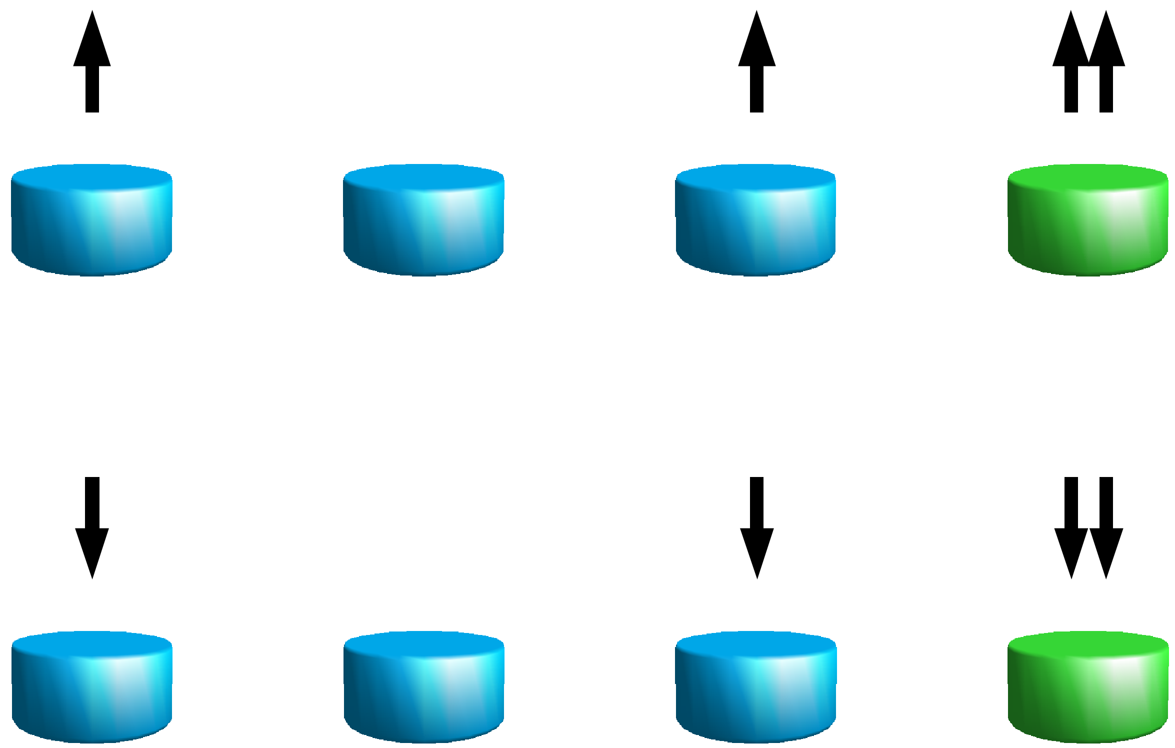
Single-sector reads can happen in parallel

- **Each 1-sector read affects only one disk**

Single-sector writes *serialize*

- **Each 1-sector write needs the parity disk**
  - **Twice!**

Sector-Write Hot Spot



RAID 4

Like RAID 3

- Uses parity, relies on erasure signals from disks
- But unit = *sector* instead of *bit*

Single-sector reads involve only 1 disk

- Can handle multiple single-sector reads in parallel

Single-sector writes: read, read, write, write!

Rarely used: parity disk is a *hot spot*

RAID 5

RAID 4, distribute parity among disks

No more "parity disk hot spot"

- Each small write still reads 2 disks, writes 2 disks
- But if you're lucky the sets don't intersect

Frequently used

Other fun flavors

RAID 6, 7, 10, 53

- Esoteric, single-vendor, non-standard terminology

RAID 0+1

- Stripe data across half of your disks
- Use the other half to mirror the first half

Characteristics

- RAID 0 lets you scale to arbitrary size
- Mirroring gives you safety, good read performance
- "Imaging applications"

Applications

RAID 0

- Supercomputer temporary storage / swapping
- Not reliable!

RAID 1

- Simple to explain, reasonable performance, expensive
- Traditional high-reliability applications (banking)

RAID 5

- Cheap reliability for large on-line storage
- AFS servers (*your* AFS servers!)

Are failures independent?

With RAID (1-5) disk failures are "ok"

***Array* failures are never ok**

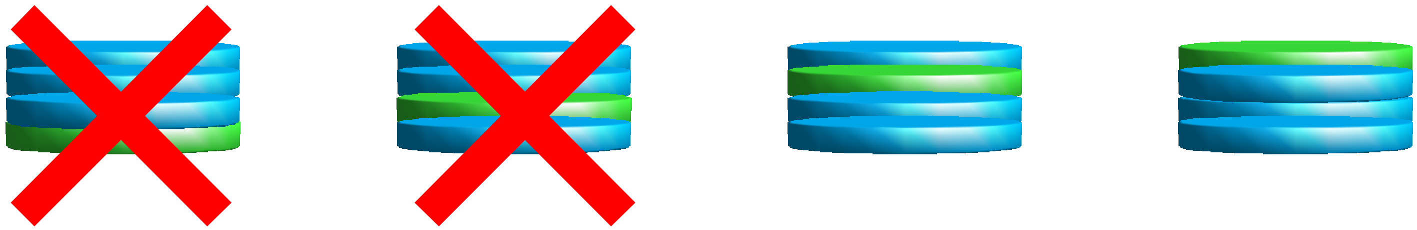
- Cause: "Too many" disk failures "too soon"
- Result: No longer possible to XOR back to original data
- Hope your backup tapes are good...
- ...and your backup system is tape-drive-parallel!

Luckily, multi-disk failures are "very rare"

- After all, disk failures are "independently distributed"...

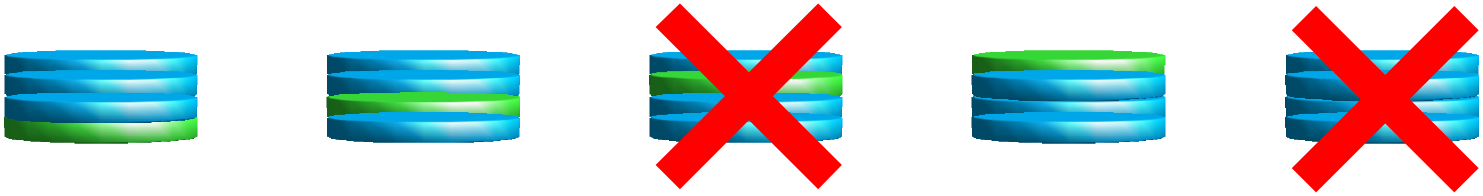
#insert <quad-failure.story>

Are failures independent?



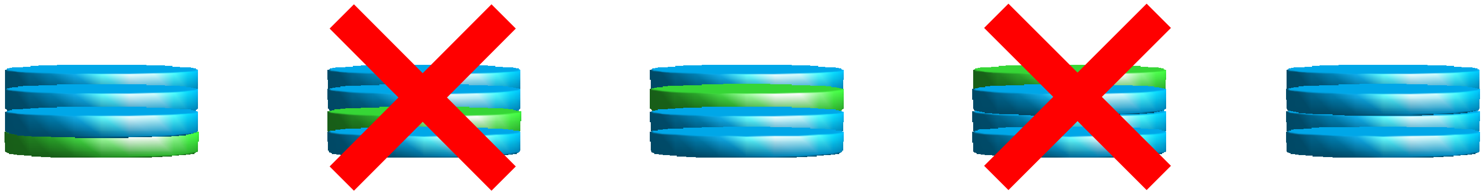
[See Hint 1]

Are failures independent?



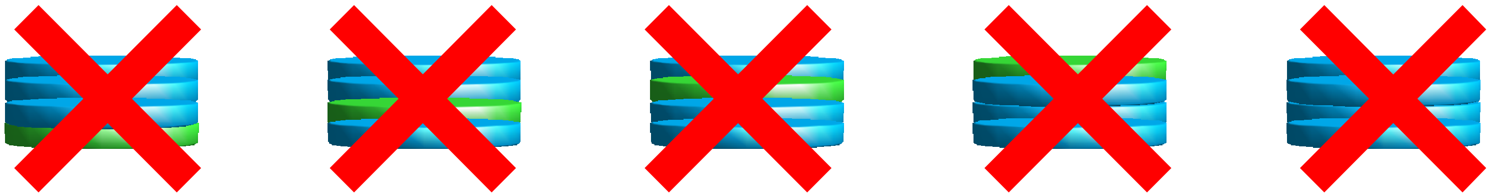
[See Hint 2]

Are failures independent?



[See Hint 3]

Are failures independent?



[See Hint 4]

Hints

Hint 1: 2 disks per IDE cable

Hint 2: If you never use it, does it still work?

Hint 3: Some days are bad days

Hint 4: "Tunguska impact event" (1908, Russia)

RAID Papers

1988: Patterson, Gibson, Katz: A Case for Redundant Arrays of Inexpensive Disks (RAID), www.cs.cmu.edu/~garth/RAIDpaper/Patterson88.pdf

1990: Chervenak, Performance Measurements of the First RAID Prototype, www.isi.edu/~annc/papers/masters.ps

- This is a carefully-told sad story.

Countless others

Other Papers

Dispersed Concentration: Industry Location and Globalization in Hard Disk Drives

- David McKendrick, UCSD Info. Storage Industry Center
- Some history of disk market (1956-1998)
- isic.ucsd.edu/papers/dispersedconcentration/index.shtml

Summary

Need more disks!

- **More space, lower latency, more throughput**

Cannot **tolerate 1/N reliability**

Store information carefully and redundantly

Lots of variations on a common theme

You should understand RAID 0, 1, 5