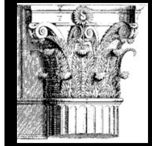


Storage management: talk roadmap

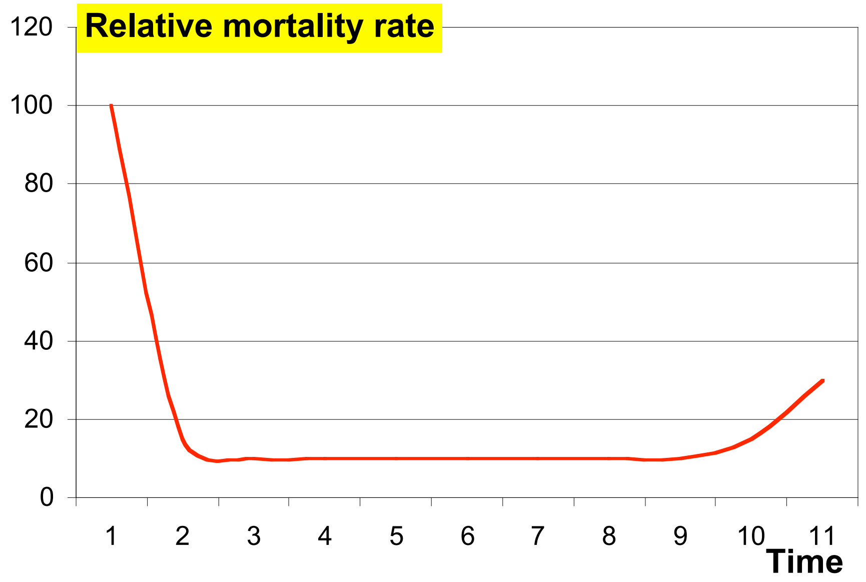
- Why disk arrays?
  - Failures
  - Redundancy
- RAID
- Performance considerations
  - normal and degraded modes
- Disk array designs and implementations
- Case study: HP AutoRAID

Why disk arrays?

Because *stuff* happens.

Failures

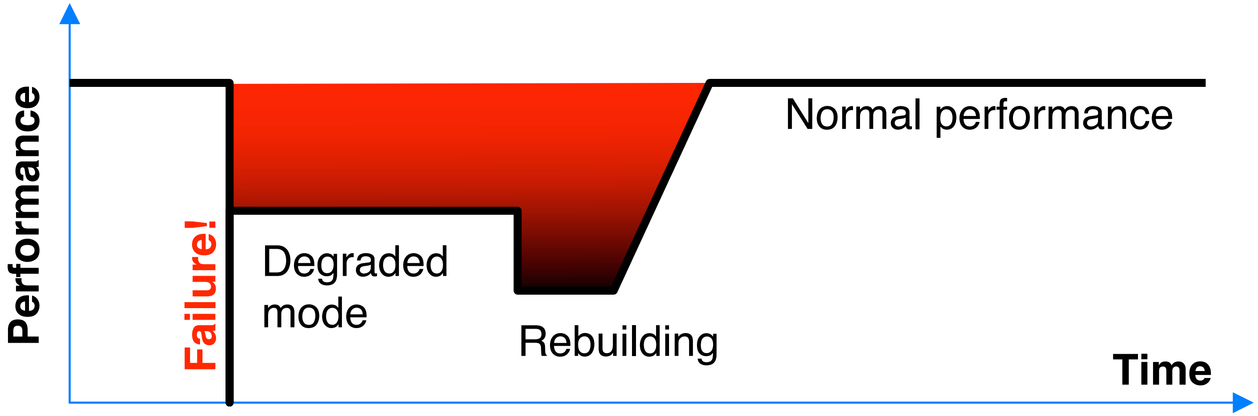
- Things break -- in a moderately predictable way in aggregate



- Metrics:
  - MTTF: “mean time to failure” -- *a rate, not a period*
  - AFR: annual failure rate (better -- but still just middle of “bathtub”)
  - MTTR: “mean time to repair”

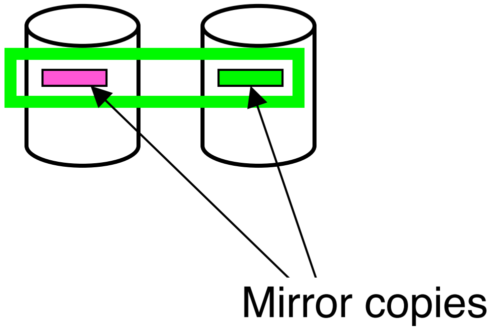
Definitions

- **Reliability**
  - *R(t)* = likelihood system *up continuously* from time 0 to time *t*
- **Availability**
  - *A(t)* = likelihood system *will be up* at time *t*
- **Performability**
  - *P(t,p)* = likelihood system *will be providing performance p* at time *t*

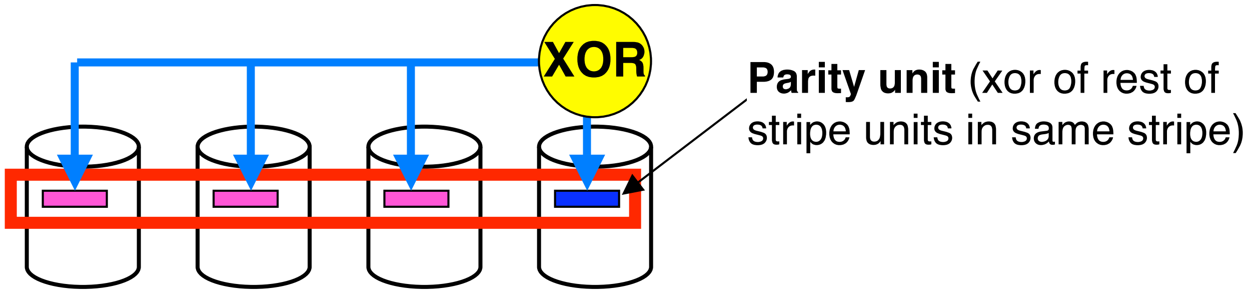


Solution: introduce redundancy!

- **Complete copies**
  - **replication, “mirroring”**



- **Partial redundancy**
  - **Hamming codes/ECC**
    - **tolerates mangling of elements**
    - **unnecessarily strong: we know when disks are broken**
  - **Parity**
    - **XOR sets (stripes) of data blocks to calculate a “parity block”**
    - **any data block in a stripe can be reconstructed from the others + parity**



Redundancy helps

- **For disks:**
  - originally (mid-1980s), these were the most unreliable components
  - nowadays, they're one of the more reliable ones (AFR of 1-2%)
  - but failure rates are proportional to numbers …

- **Assume: independent failures**

  warning! danger! caution! error!

- **With no redundancy …**

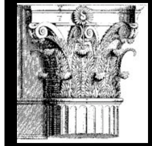
  $AFR_{disks} \sim= N_{disks} * AFR_{disk}$

- **With one degree of redundancy …**

  $AFR_{raid} \sim= AFR_{disks}(N_{disks}) * MTTR_{disk} * AFR_{disks}(N_{disks}-1)$

Redundancy hurts, too

- Cost
  - replicating everything costs 2x as much storage
  - solution: partial redundancy
- Slower updates
  - 2x as many copies to write to
  - … even worse with partial redundancy
- Greater complexity
  - 80-90% of disk array firmware is error handling
  - lots and lots of configuration choices ...



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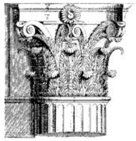


RAID

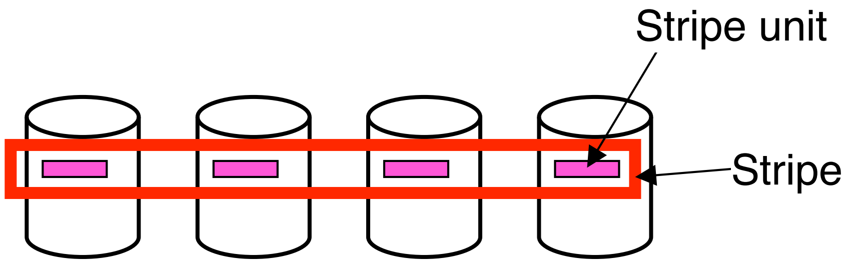
- **Originally (like everything else?) invented by IBM**
  - **striping explored at Univ. Maryland**
  - **catchy terminology popularized by UC Berkeley:**
    - **Patterson, Gibson & Katz: "The case for Redundant Arrays of Inexpensive Disks (RAID)",** ***ACM SIGMOD, 1988***
  - **comparison point: slow, large expensive disks (SLED)**
    - **goal was to compete with IBM mainframe disks using cheap, unreliable PC drives**

Now:

- **RAID: Redundant Arrays of Independent Disks**

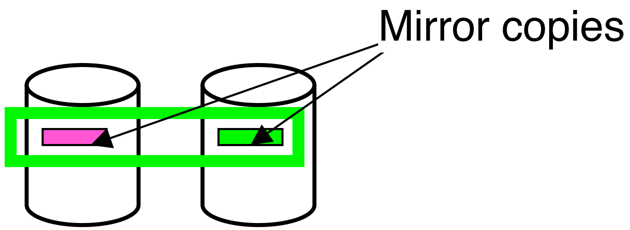
RAID levels 0, 1, 10

- **RAID0: striping** (no redundancy)



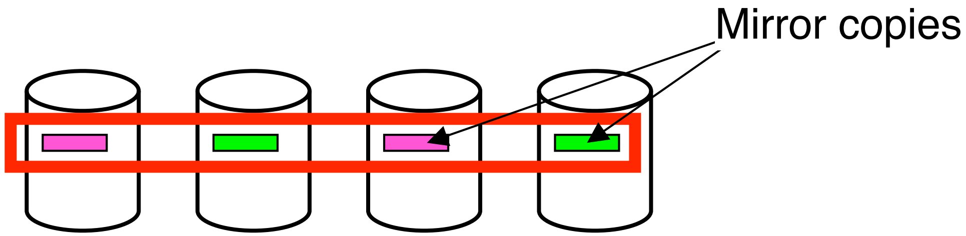
Striping **balances the load and allows large transfers to happen in parallel**

- **RAID1: aka mirroring** (full redundancy)



Mirroring **gives 2x the read bandwidth per disk, but writes have to go to both**

- **RAID10: striped mirroring** (full redundancy)

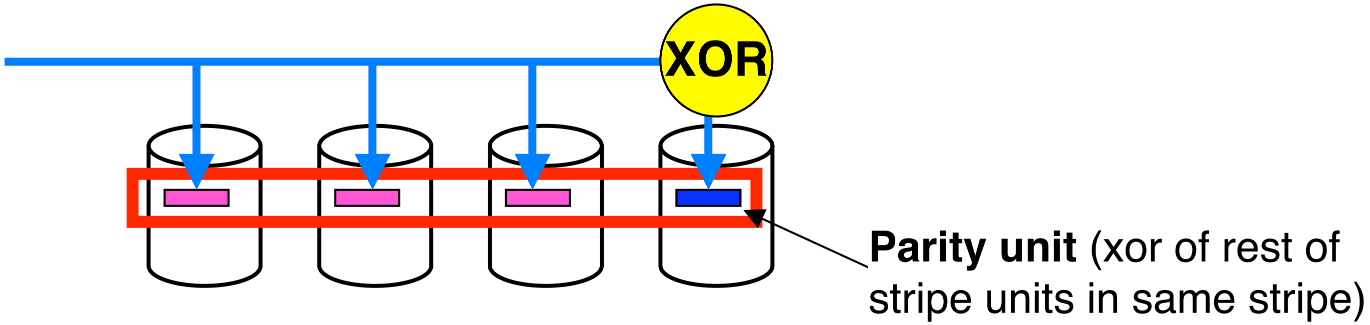


RAID level 3 - parity-protected striping

- **RAID3: byte-interleaved**
  - all disks read/written in lock step
  - parity on dedicated disk
    (ok: sees same load as remainder)
  - great for high-bandwidth, large transfers; otherwise poor

XOR parity **is single-bit ECC that can correct single-bit erasures**

If a disk is missing, XORing the others will give you its contents

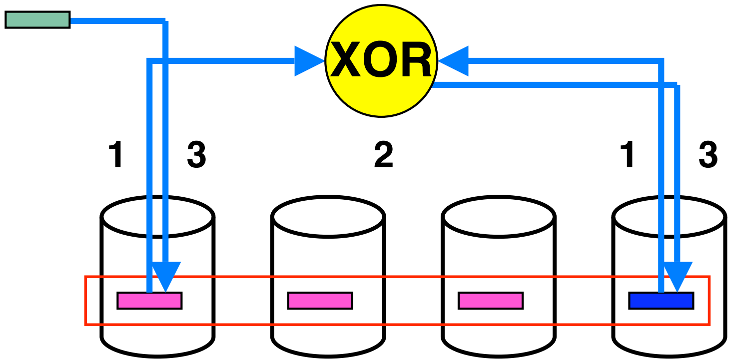


Parity unit (xor of rest of stripe units in same stripe)

RAID level 4 - block-interleaved stripes

- **RAID4: block-interleaved**
  - **independent reads/writes possible**
  - **parity on dedicated disk (hot spot!)**

- **Updating parity is expensive for small writes**
  - **one effect: write-caching becomes especially important**

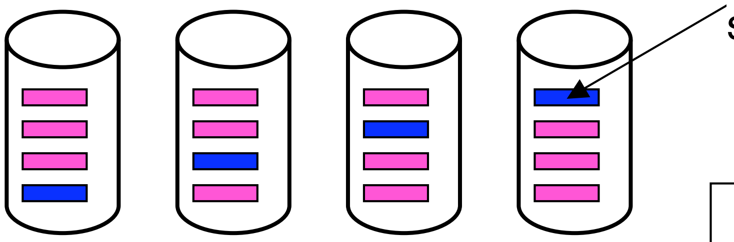


1. Read old data & parity
2. Compute new parity
3. Write new data + parity

=> 4x I/O operations per small write

RAID level 5

- **RAID5 - rotated-parity-protected striping to balance the load**



Parity unit (xor of rest of stripe units in same stripe)

Rotating the parity **balances the parity load across all the disks; striping allows fast large transfers**

RAID5 is the configuration of choice for all but performance-intensive loads

RAID “levels”

Currently accepted RAID levels

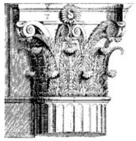
- **0: no redundancy**
- **1: full copy (mirrors)**
- **10: striped mirrors**

Note: not really levels, just a list

- 2: Hamming-code/ECC (not used)

- **3: byte-interleaved parity**

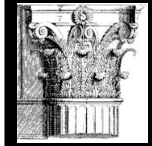
- **4: block-interleaved parity** (more useful variant of RAID3)
- **5: rotated block-interleaved parity**
- **6: double parity** (“P+Q parity” -- rare)



RAID: some tricky points

- **Updates in flight at time of power failure can corrupt the parity**
  - **either: an expensive parity rebuild on power up**
  - **or: keep a non-volatile intentions log**

- **Reliability calculations based on disks alone are bogus**
  - **power source is single largest problem**
  - **then controller failures, cooling, backplane, connections, ...**
  - **redundancy helps here, too**
  - nobody likes to talk about software …



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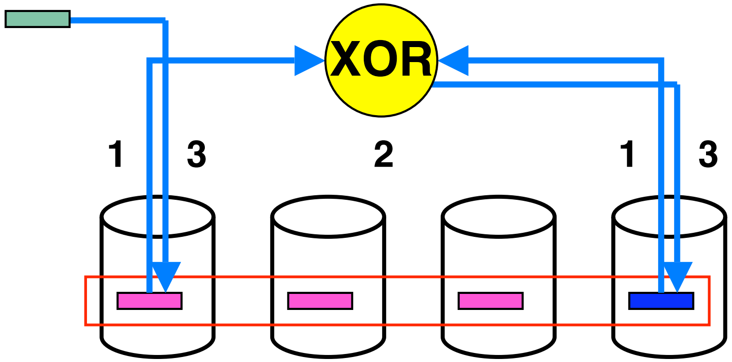
Improving performance: RAID 4/5

- **Floating parity [Menon92]**
  - **write parity anywhere -- saves one revolution**

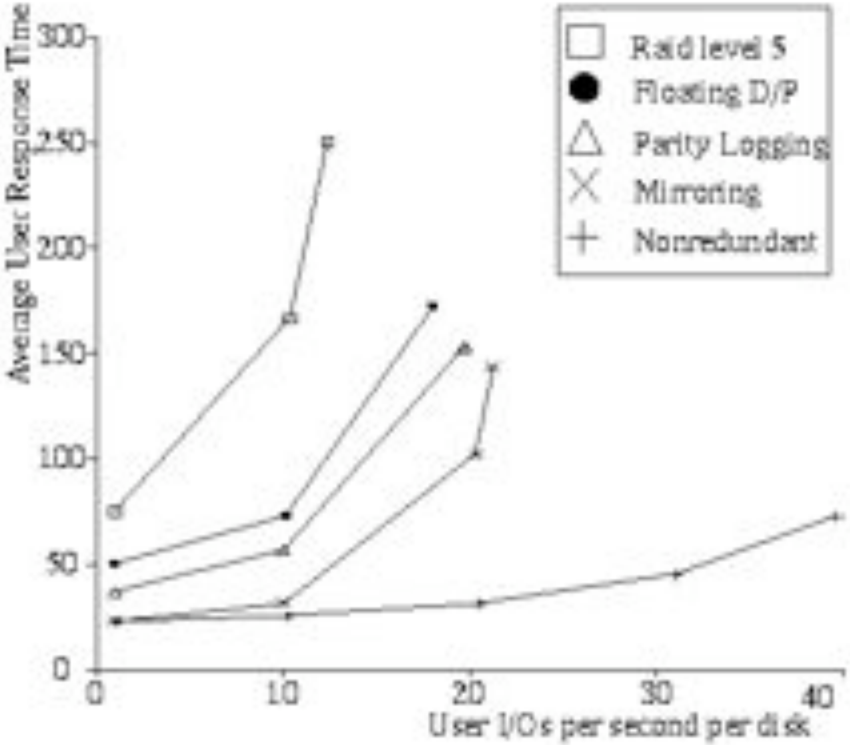


1. Read old data & parity
   *** claim: old data is already cached**
2. Compute new parity
3. Write new data + parity
   *** parity write is “free”**

=> **~2x** I/O operations per small write

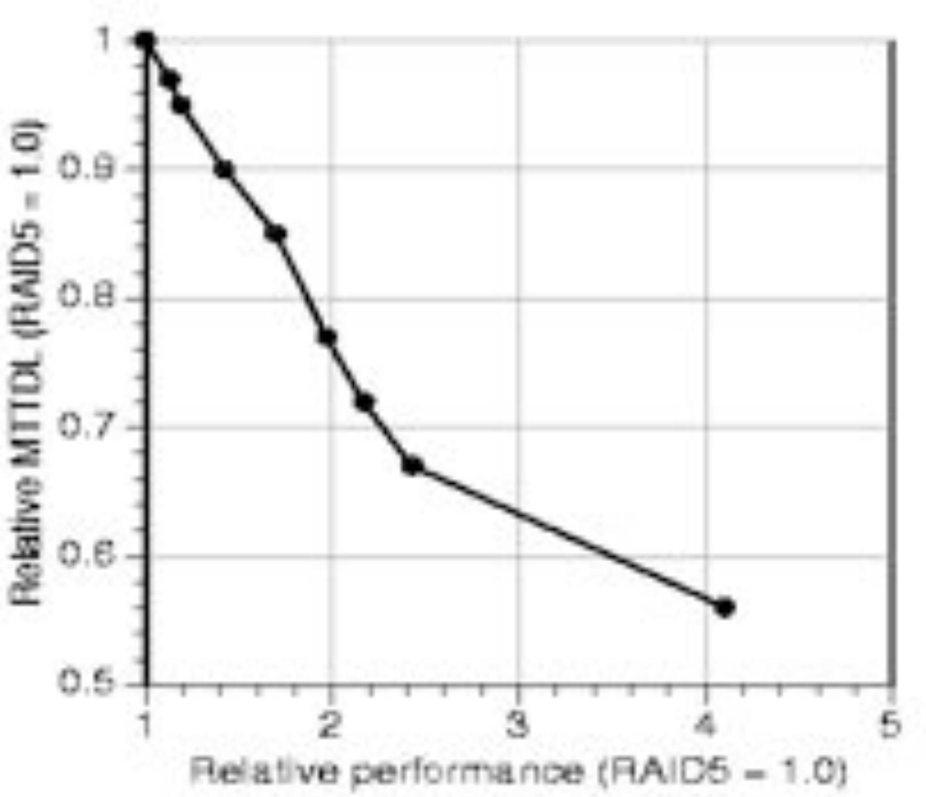
Improving performance: RAID 4/5

- **Parity logging [Stodolsky94]**
  - aggregate parity updates into an append-only log
  - propagate log in background



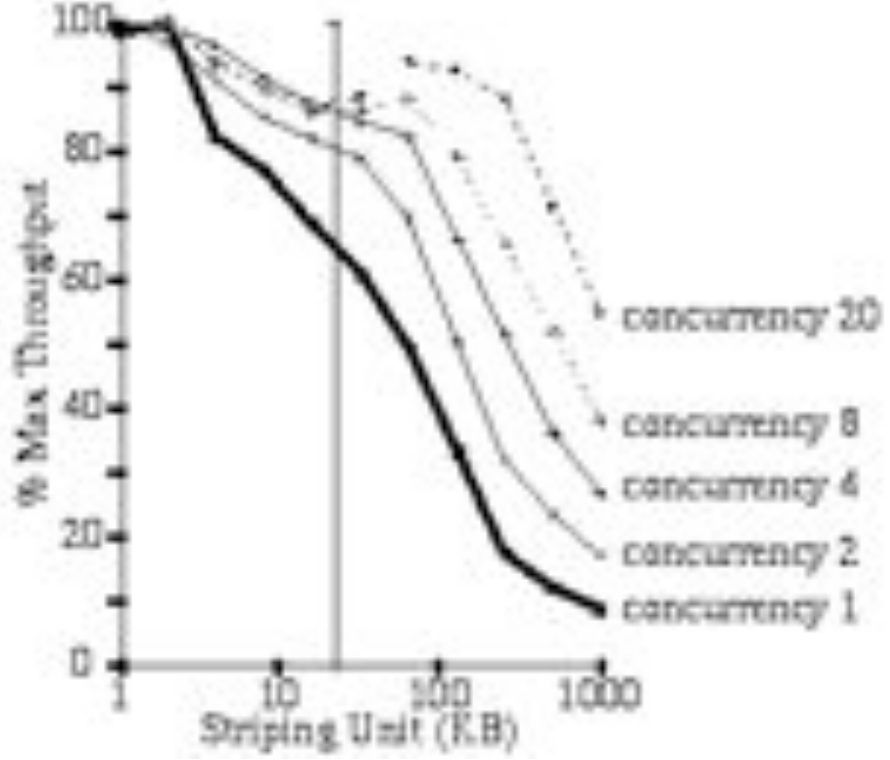
Improving performance: AFRAID

- A Frequently Redundant Array of Independent Disks [Savage&Wilkes96]
  - live (a little) dangerously ...
  - update parity opportunistically in the background
  - gives smooth tradeoff between availability and performance



Improving performance: choice of stripe size

- Optimum size is dependent on:
  - read:write mix
  - data layout (RAID1 vs RAID5)
  - concurrency level
  - back-end disk characteristics (e.g., track size)

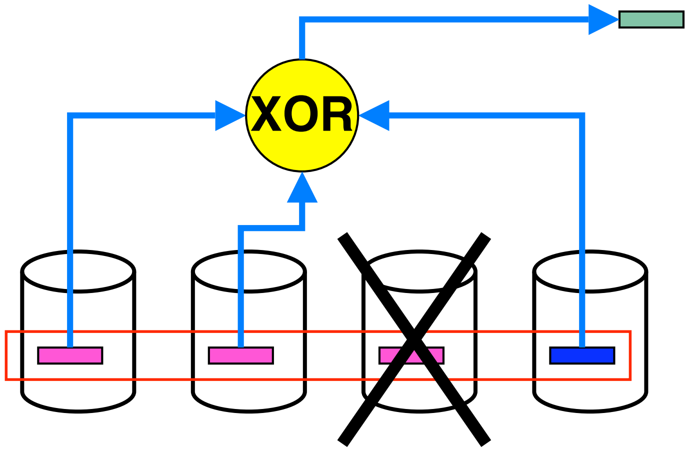


- Choices are a daunting problem for sysadmins

[Chen90] for RAID1, [Chen95] for RAID5

Degraded-mode performance

- Reading RAID4/5 when a disk is broken is expensive

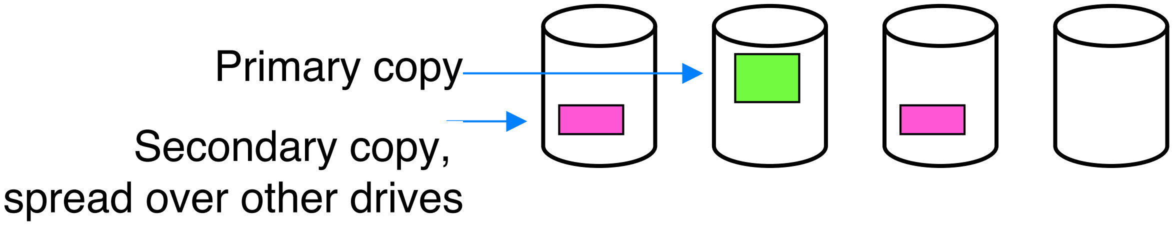


1. Read all surviving data & parity
2. Compute missing data (XOR)

=> all surviving disks are involved

Improving RAID5 degraded mode performance

- **Chained declustering [Hsaio+DeWitt90]**
  - **spread the second copy out over other disks**
  - **when the primary copy breaks, each secondary disk takes up only a portion of the slack**



Improving RAID5 degraded mode performance

- Declustering [Muntz90]
  - make stripes narrower than whole array
    - only stripes that have the broken disk need pay performance penalty
  - each stripe uses a different set of disks
    - some complexity in the mappings that do this nicely
    - but “close enough” works just fine
  - better degraded-mode performance, at the cost of more disks
    - stripes are smaller => more parity
  - improvements
    - Approximate block designs
    - Prime/Relpr [Alvarez98] - better-spread large-transfer load

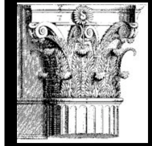
Recovery/rebuild after a disk failure

- Reduce MTTR: keep an online spare
  - e.g., XP256: up to 4 spares per rack of 64 drives
- Distributed sparing [Menon92] makes the spare useful
  - spread its “contents” across all the disks
  - effectively adds an extra disk’s performance to the array

Recovery/rebuild after a disk failure

- Reconstruction after failure
  - sweep across data: read every stripe, rewrite parity/missing data
    - poor performance if done too simply: data transfers are too small; too much blocking
    - better: disk-oriented reconstruction [Holland93]
      - keep >= one outstanding read for each disk
  - can also piggyback updates on foreground activity
    - requires keeping a map of reconstructed stripes

  - big tradeoff: faster recovery or slower foreground activity?



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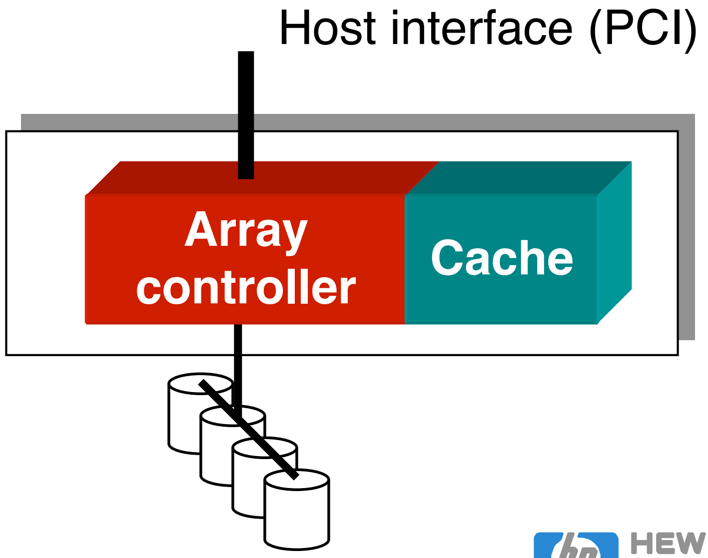
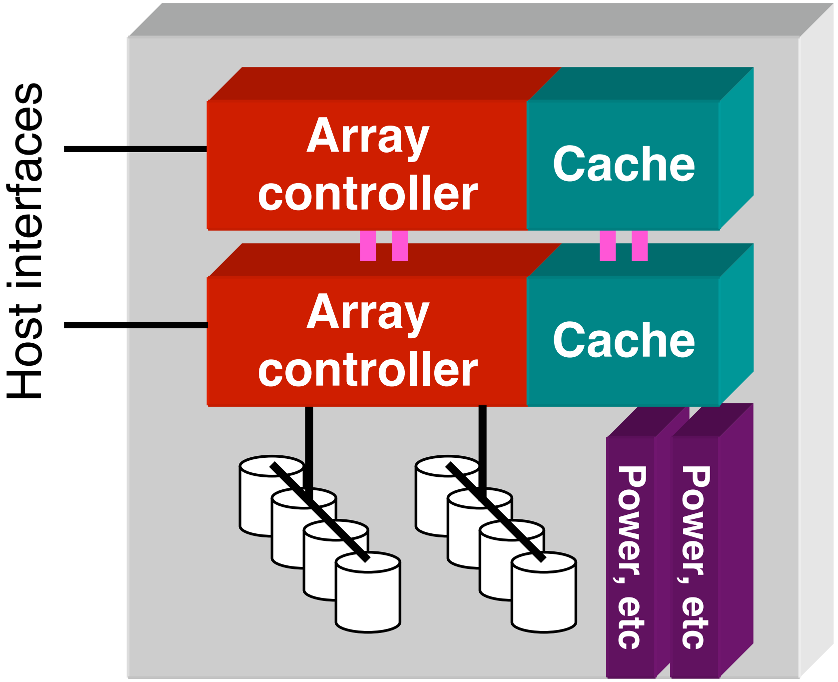
Array implementations

- In software
  - cheapest, but consumes memory (and cpu) cycles
  - usually mirroring, in OS Logical Volume Manager
- In host bus adapter
  - common in PC servers
  - big win is from the read/write cache
  - fault handling is very limited

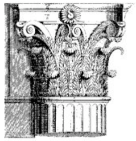


Array implementations

- **Mid-range array** (e.g., HP FC60)
  - **sometimes separate controller and disk boxes**
  - **up to 1-2TB disk, 0.5Gb cache RAM**
  - **can saturate a 100MB/s FibreChannel link; O(10,000 IOs/s)**



Packaging:
- whole array is in a single box, or
- array controller is in separate box

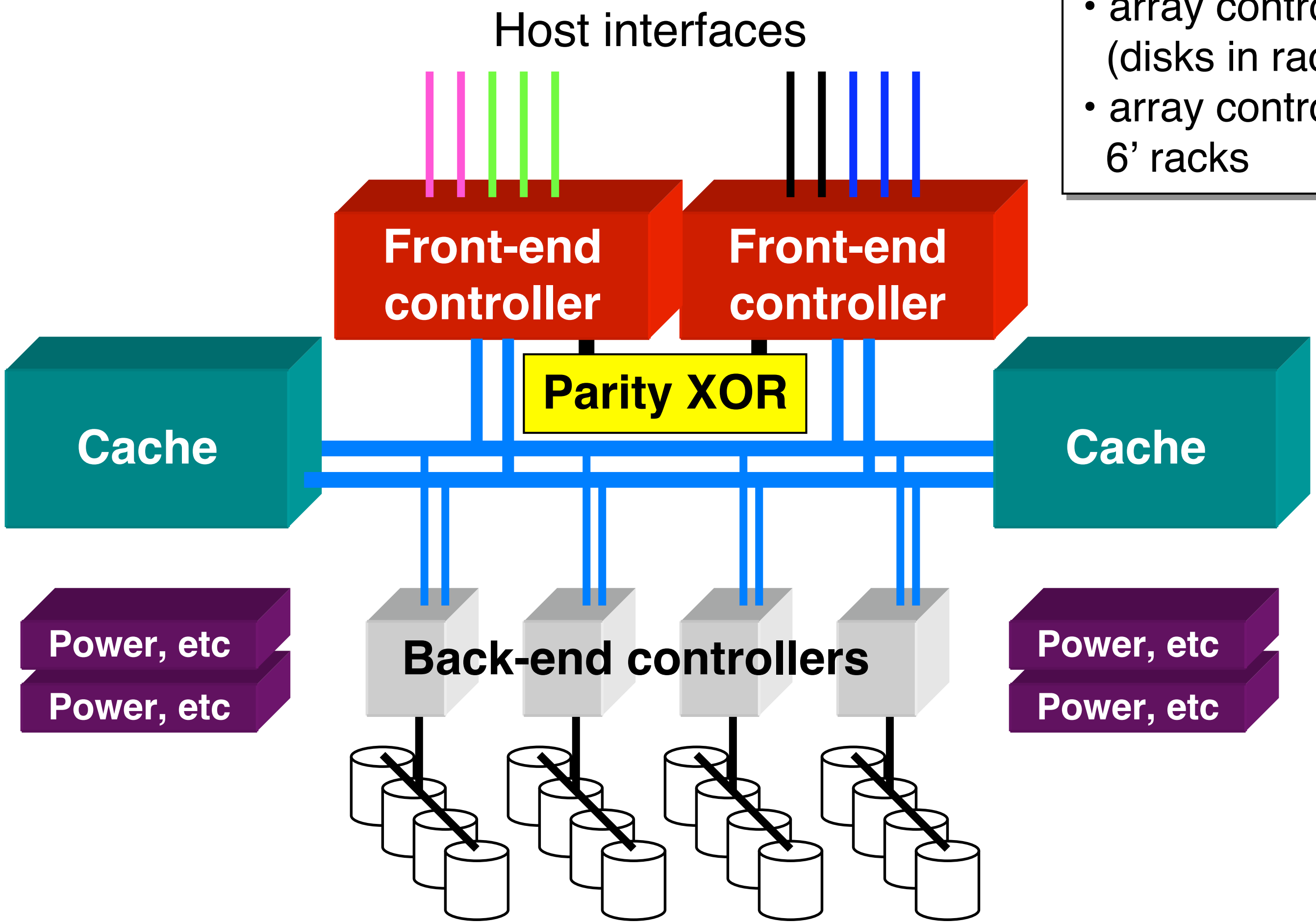


Array implementations

- **High-end array: integrated box** (e.g., HP XP256; EMC Symmetrix)
  - **up to a few TB of disk**
  - **up to a few GB of cache**
  - **up to a few $million**

- **What you pay for:**
  - **lots of caching (vital to performance)**
  - **multiple host interface types**
    - **e.g., HP XP256: SCSI, FibreChannel, and ESCON**
  - **quality power distribution, cabling, cooling, vibration isolation**
  - **phone-home, remote management, support infrastructure**
  - **can saturate a few 100MB/s FibreChannel links; O(50,000+ IOs/s)**

Disk array architecture - high end

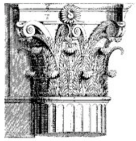


Packaging:
- array controller in a separate box (disks in rack-mountable trays), to
- array controller is one of several 6’ racks

Disk arrays: Logical UNits

- **Most arrays provide multiple LUNs (SCSI Logical UNits)**
  - **one or more disk drives bound together into a common layout**
  - **different LUNs can have different sizes, different layouts**
  - **LUN 0 is often special** (used for controlling the array as a whole)
  - **at low end: 8-32 LUNs**
  - **at high end: thousands of LUNs**
    - **SCSI limit: 4096 LUNs, from a 12 bit LUNid**

- **A few common variations (there are many more):**
  - **parts of disks instead of whole disks**
  - **LUNs may be named relative to ports, not uniquely**
  - **LUNs can have different caching behavior**

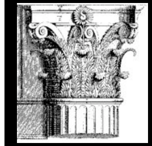


Summary

- **Disk arrays use redundancy to protect against disk (and other storage component) failures**
  - **rest easy: the storage system is no longer the main problem!**

- **They can also provide performance benefits**
  - **caching can easily provide 10-100x performance boost**

- **But … at cost of lots of complexity**
  - **algorithms**
  - **configuration choices**
  - **implementation options**



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