CS2410: Computer Architecture

Storage systems

Sangyeun Cho

Computer Science Department
University of Pittsburgh

(Some slides borrowed from D. Patterson's lecture slides)

Case for storage

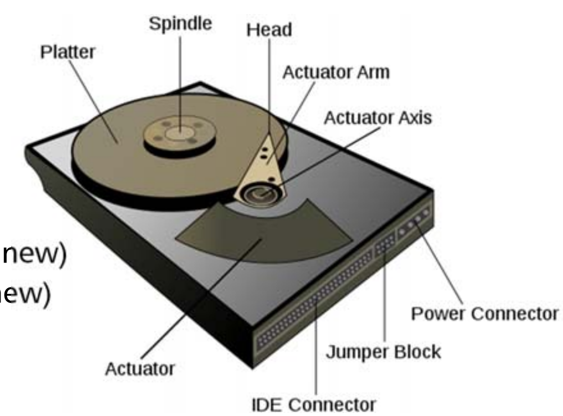
- Shift in focus from computation to communication & storage of information
  - E.g., Cray Research/Thinking Machines vs. Google/Yahoo!
  - "The Computing Revolution" (1960s to 1980s) ⇒ "The Information Age" (1990s to today)
- Storage emphasizes reliability and scalability as well as cost-performance
- What is "software king" that determines which hardware features are actually used?
  - OS for storage
  - Compiler for processor
- Also has own performance theory–queuing theory–balances throughput vs. latency time

Outline

- Magnetic disks
- RAID
- Dependability/reliability/availability
- I/O benchmarks, performance, and dependability

Magnetic disks

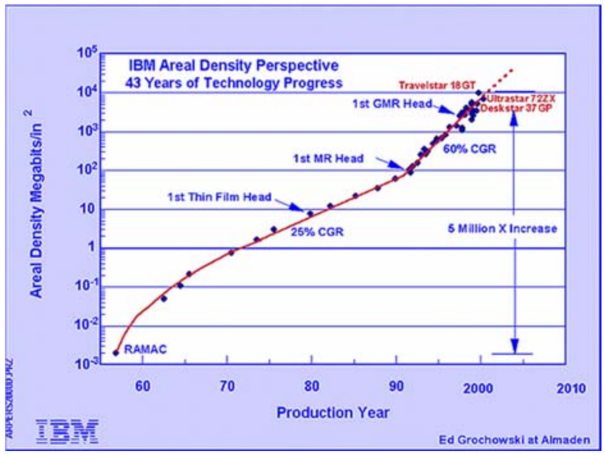
- Spindle, platters, head, head arm, head arm actuator
- Tracks, sectors
  - Tracks: concentric circles
  - Sectors: unit of data access



- Standard interface
  - ATA: parallel (old), serial (SATA, new)
  - SCSI: parallel (old), serial (SAS, new)
- Performance determined by
  - Seek (mechanical), rotation speed (mechanical)
  - Queuing/buffering, interface

Disk figure of merit: Areal density

- Bits recorded along a track
  - Metric is *bits per inch* (BPI)
- Number of tracks per surface
  - Metric is *tracks per inch* (TPI)
- Disk designs brag about bit density per unit area
  - Metric is *bits per square inch (areal density)* = BPI × TPI



Specific design ideas

- Zoned recording
  - Outer tracks are longer than inner tracks; why not allocate more sectors on outer tracks?
  - Drives usually have 15 to 25 zones
  - Defect management in zones
- Serpentine ordering of tracks; skewed ordering of sectors
  - Minimize arm movement!
- Command queuing
- Security support (data protection)

Historical perspective

- 1956 IBM RAMAC – early 1970s Winchester
  - Developed for mainframe computers, proprietary interfaces
  - Steady shrink in form factor: 27 inches to 14 inches

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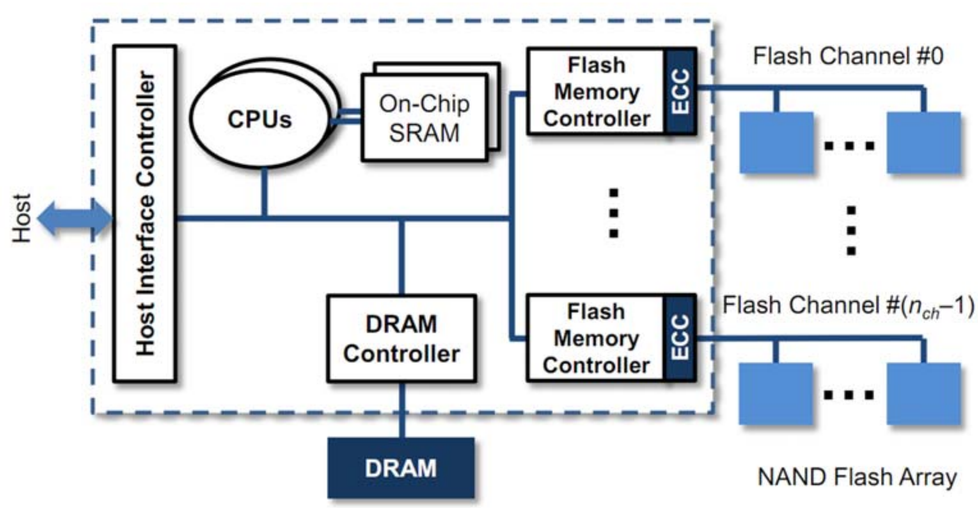
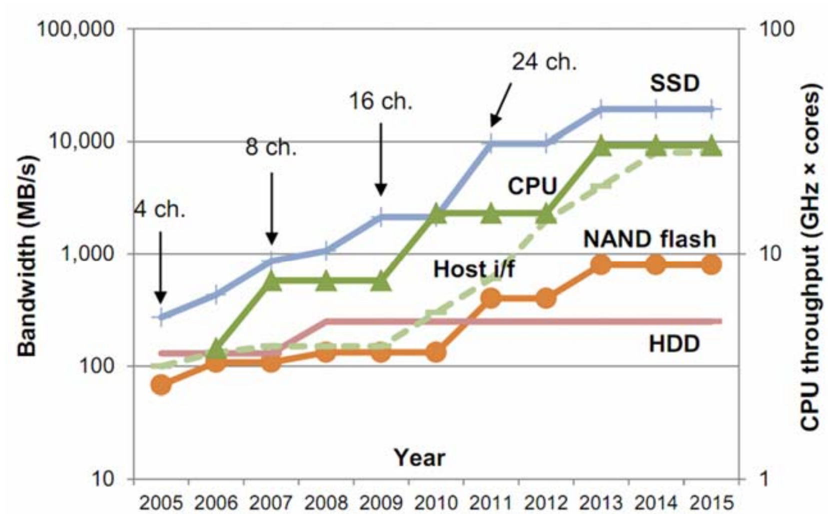
- Form factor and capacity drives market more than performance
- 1970s developments
  - 5.25-in. floppy disk form factor
  - Emergence of industry standard disk interfaces
- Early 1980s: PCs and first generation workstations
- Mid 1980s: Client-server computing
  - Centralized storage on file server ⇒ accelerates disk downsizing: 8 in. to 5.25 in.
  - Mass market disk drives become a reality ⇒ 5.25 in. to 3.5 in. drives for PCs, end of proprietary interfaces
- 1990s: Laptops ⇒ 2.5-in. drives
- 2000s: Continued areal density improvement, new solid-state devices entering hard disk designs

Solid-state drive



Solid-state drive



Solid-state drive

Time frame	Characteristics
2007–2008	4-way, 4 channels, 30–80 MB/s R/W performance; mostly SLC flash based;
2008–2009	8–10 channels, 150–200+ MB/s performance (SATA, consumer); 16+ channels, 600+ MB/s performance (PCI-e, enterprise); use of MLC flash in consumer products;
2009–2010	16+ channels, 200–300+ MB/s performance (SATA 6 Gbps); 20+ channels, 1+ GB/s performance (PCI-e); adoption of MLC in enterprise products;
2010–	16+ channels; wider acceptance of PCI-e;

Past and current design trends

- Fewer platters, lower diameter (thanks to high areal density)
  - 1~3 platters
  - 2.5-inch form factor
  - Slower rotational speeds
- More intelligence in the drive
  - Access scheduling (w/ help from native command queuing)
  - Integrated defect management
- Larger sector size (512B to 4kB)

Future disk sizes and performance

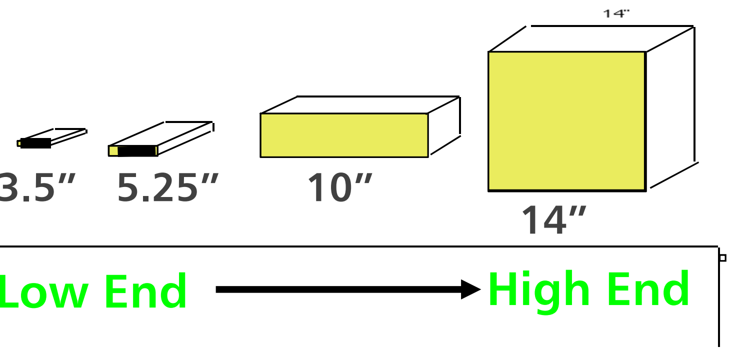
- Continued advance in capacity (60%/year) and bandwidth (40%/year)
- Slow improvement in seek, rotation (8%/year)
- Time to read whole disk

Year	Sequentially	Randomly (1 sector/seek)
1990	4 minutes	6 hours
2000	12 minutes	1 week
2006	56 minutes	3 weeks (SCSI)
2006	171 minutes	7 weeks (SATA)

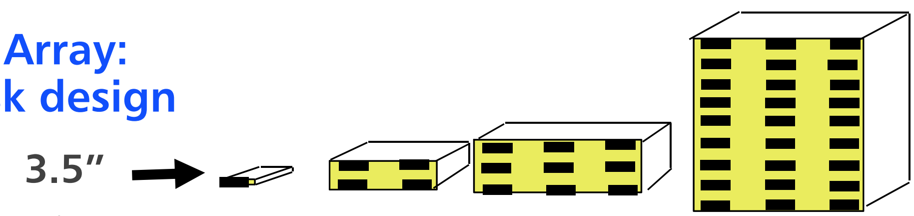
Use arrays of small disks?

- Katz and Patterson of Berkeley asked in 1987:
  - Can smaller disks be used to close gap in performance between disks and CPUs?

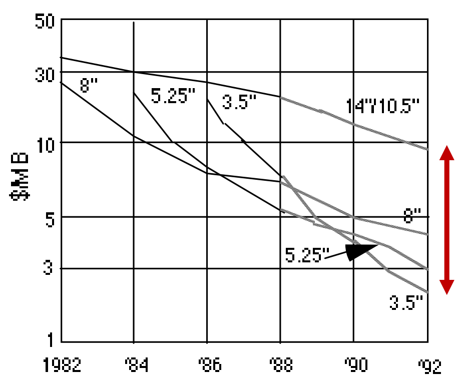
Conventional: 4 disk designs

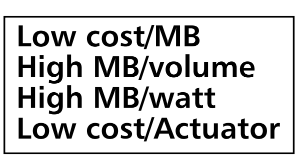


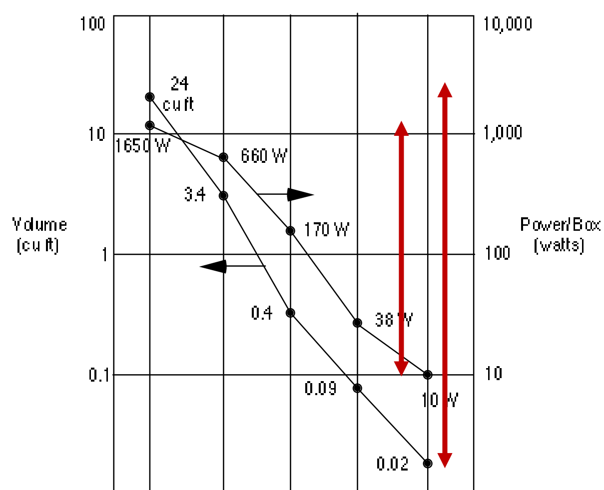
Disk Array: 1 disk design



Advantages of small form-factor disk drives







	14”	10.5”	8”	5.25”	3.5”
MB	7,500 F	1,320 F	1,000	765	200
MB/watt	4.54	2.0	5.88	20.13	20.0
MB/cu ft	313	388	2,500	8,500	10,000

Cost and Environmental Efficiencies

Replace small number of large disks with large number of small disks! (1988 disks)

	IBM 3390K	IBM 3.5" 0061	x70	
Capacity	20 GBytes	320 MBytes	23 GBytes	
Volume	97 cu. ft.	0.1 cu. ft.	11 cu. ft.	9X
Power	3 KW	11 W	1 KW	3X
Data Rate	15 MB/s	1.5 MB/s	120 MB/s	8X
I/O Rate	600 I/Os/s	55 I/Os/s	3900 IOs/s	6X
MTTF	250 KHrs	50 KHrs	??? Hrs	
Cost	$250K	$2K	$150K	

Disk Arrays have potential for large data and I/O rates, high MB per cu. ft., high MB per KW, but what about reliability?

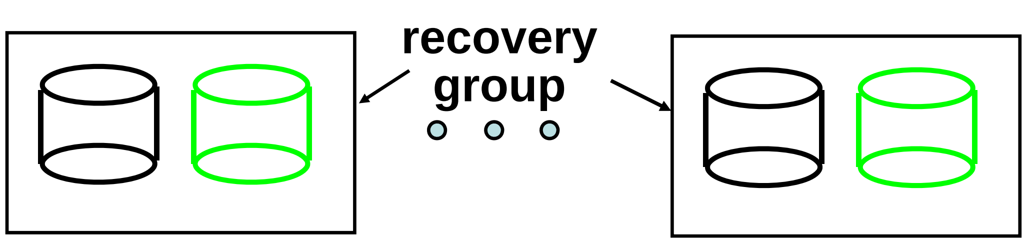
Array reliability

- Reliability of N disks = (Reliability of 1 disk)/N
  - 50,000 hours/70 disks = 700 hours
  - Disk system MTTF: drops from 6 years to 1 month!
- Arrays (without redundancy) too unreliable to be useful!
- Hot spares support reconstruction in parallel with access: Very high media availability can be achieved

Redundant array of (inexpensive) disks (RAID)

- Files are striped across multiple disks
- Redundancy yields high data availability
  - Availability: Service still provided to user, even if some components failed
- Disks will still fail
- Contents reconstructed from data redundantly stored in the array
  - Capacity penalty to store redundant information
  - Bandwidth penalty to update redundant information

RAID 1: Disk mirroring/shadowing



- Each disk is fully duplicated onto its “mirror”
  - High availability can be achieved
- Bandwidth sacrifice on write:
  - Logical write = two physical writes
- Most expensive solution: 100% capacity overhead

RAID 3: Parity disk

Striped physical records

P contains sum of other disks per stripe mod 2 ("parity")
If disk fails, subtract P from sum of other disks to find missing information

RAID 3

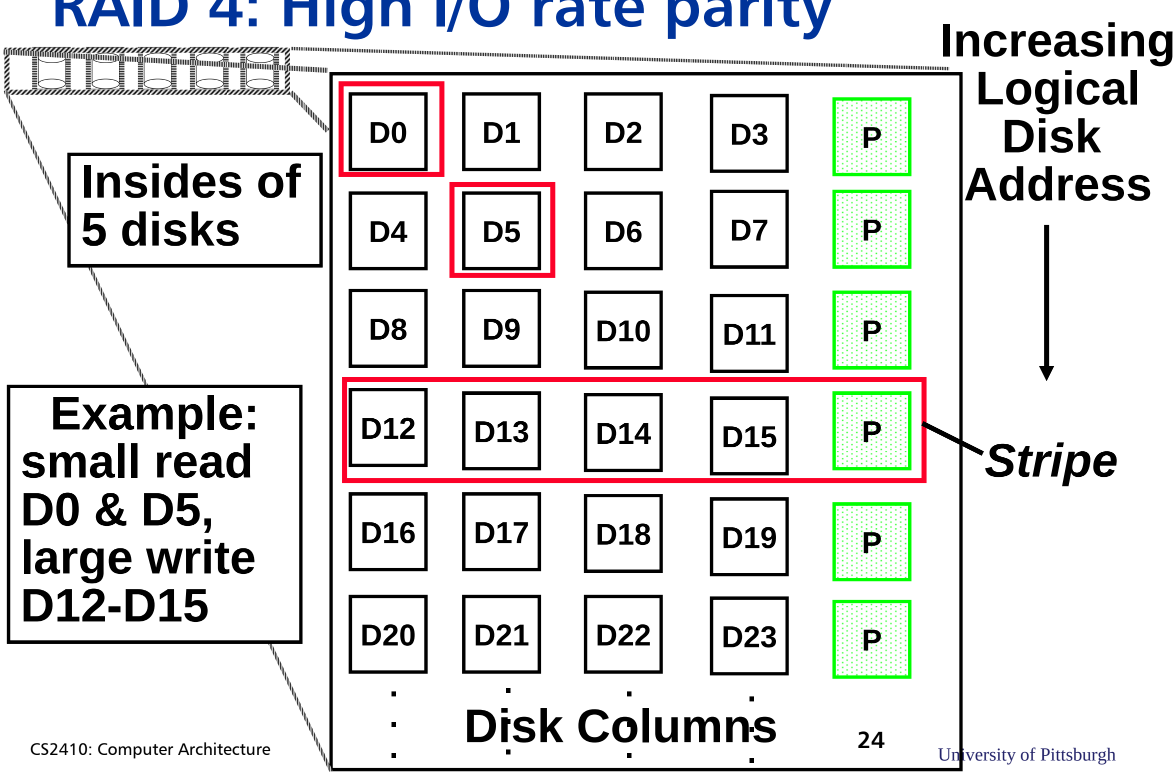
- Sum computed across recover group to protect against hard disk failures, stored in P disks
- Logically, a single high capacity, high transfer rate disk: Good for large transfers
- Wide arrays reduce capacity costs, but decreases availability
- 33% capacity cost for parity if 3 data disks and 1 parity disk

Inspiration for RAID 4

- RAID 3 relies on parity disk to discover errors on read
- But every sector has an error detection/correction field
- To catch errors on read, rely on error detection/correction field vs. the parity disk

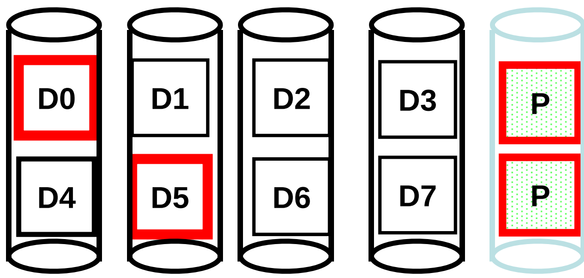
- Allows independent reads to different disks simultaneously

RAID 4: High I/O rate parity



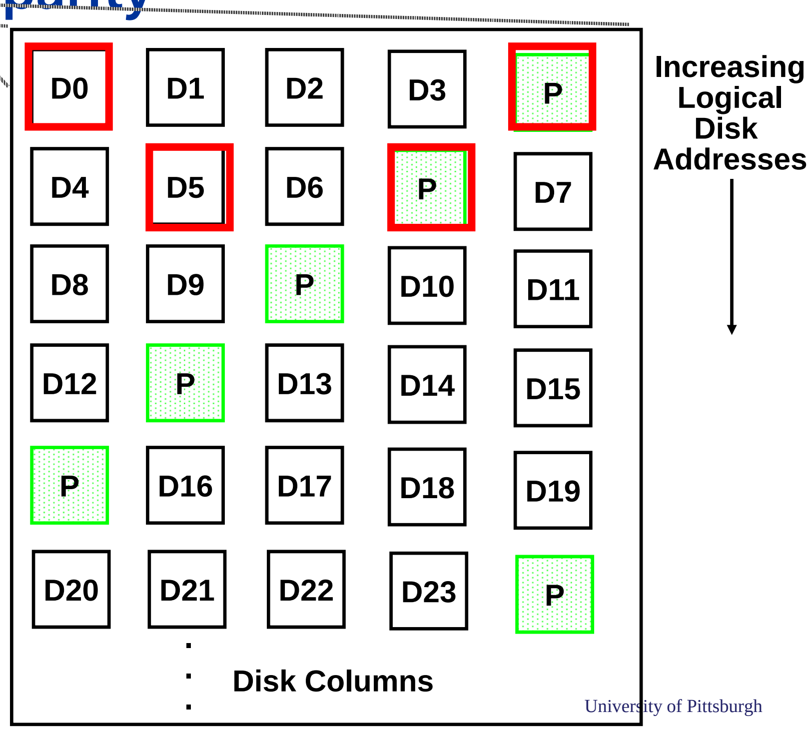
Inspiration for RAID 5

- RAID 4 works well for small reads
- Small writes (write to one disk):
  - Option 1: Read other data disks, create new sum and write to parity disk
  - Option 2: Since P has old sum, compare old data to new data, add the difference to P
- Small writes are limited by parity disk: Write to D0, D5 both also write to parity disk



RAID 5: High I/O rate, interleaved parity

Independent writes possible because of interleaved parity

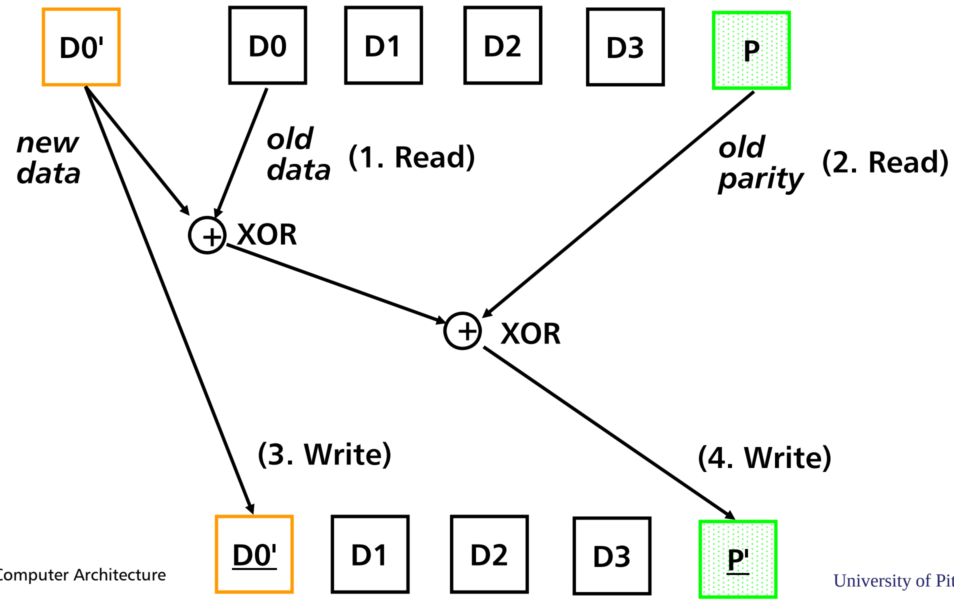


Example: write to D0, D5 uses disks 0, 1, 3, 4

Small writes

RAID 5: Small Write Algorithm

1 Logical Write = 2 Physical Reads + 2 Physical Writes



RAID 6: Recovering from 2 failures

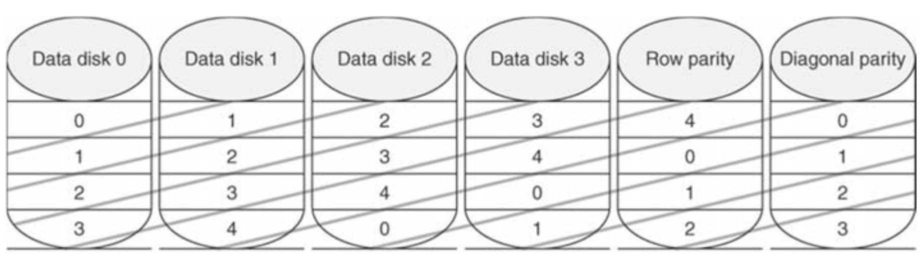
- Why > 1 failure recovery?
  - Operator accidentally replaces the wrong disk during a failure
  - Since disk bandwidth is growing more slowly than disk capacity, the mean time to repair a disk in a RAID system is increasing $\Rightarrow$ increases the chances of a 2nd failure during repair since repair takes longer

RAID 6: Recovering from 2 failures

- NetApp's row-diagonal parity or RAID-DP
- Like the standard RAID schemes, it uses redundant space based on parity calculation per stripe
- Since it is protecting against a double failure, it adds two check blocks per stripe of data
  - If p+1 disks total, p–1 disks have data
- Row parity disk is just like in RAID 4
- Each block of the diagonal parity disk contains the even parity of the blocks in the same diagonal

Example w/ p = 5

- Row diagonal parity starts by recovering one of the 4 blocks on the failed disk using diagonal parity
  - Since each diagonal misses one disk, and all diagonals miss a different disk, 2 diagonals are only missing 1 block
- Once the data for those blocks are recovered, then the standard RAID recovery scheme can be used to recover two more blocks in the standard RAID 4 stripes
- Process continues until two failed disks are restored

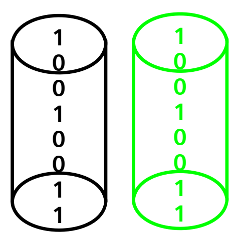


Berkeley RAID-I

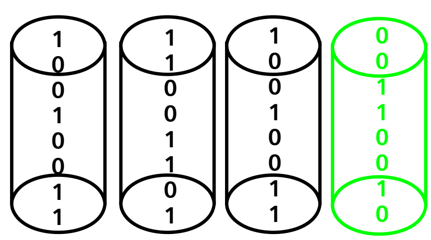
- RAID-I (1989)
  - Sun 4/280 w/ 128MB of DRAM
  - Four dual-string SCSI controllers
  - 28 5.25-in. SCSI disks and specialized disk striping software
- Today, RAID is $24B industry, 80% non-PC disks sold in RAIDs

Summary: RAID techniques

- Disk mirroring (RAID 1)
  - Each disk is fully duplicated onto its "mirror"
  - Logical write = two physical writes
  - 100% capacity overhead



- Parity data bandwidth array (RAID 3)
  - Parity computed horizontally
  - Logically a single high data bandwidth disk



- High I/O rate parity array (RAID 5)
  - Interleaved parity blocks
  - Independent reads and writes
  - Logical write = 2 reads + 2 writes