Database Architecture 2 & Storage

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Summary from Last Time

System R mostly matched the architecture of a modern RDBMS

- » SQL
- » Many storage & access methods
- » Cost-based optimizer
- » Lock manager
- » Recovery
- » View-based access control

A Note on Recovery Methods

In retrospect, we regret not supporting the LOG and NO SHADOW option. As explained in Section 3.8, the log makes shadows redundant, and the shadow mechanism is quite expensive for large files.

Jim Gray, “The Recovery Manager of the System R Database Manager”, 1981

Outline

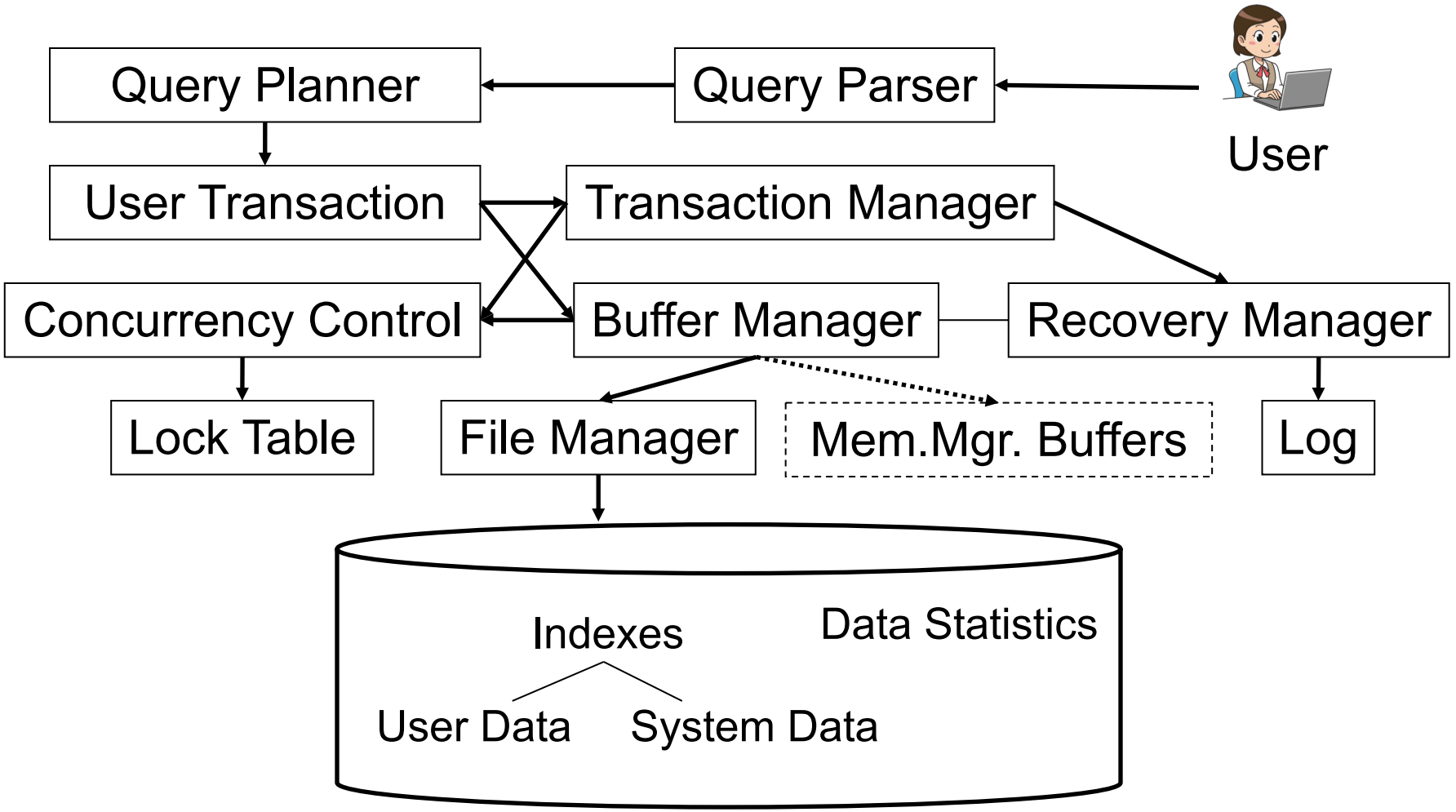
System R discussion

Relational DBMS architecture

Alternative architectures & tradeoffs

Storage hardware

Typical RDBMS Architecture



Boundaries

Some of the components have clear boundaries and interfaces for modularity

- » SQL language
- » Query plan representation (relational algebra)
- » Pages and buffers

Other components can interact closely

- » Recovery + buffers + files + indexes
- » Transactions + indexes & other data structures
- » Data statistics + query optimizer

Differentiating by Workload

Two big classes of commercial RDBMS today

Transactional DBMS: focus on concurrent, small, low-latency transactions (e.g. MySQL, Postgres, Oracle, DB2) → real-time apps

Analytical DBMS: focus on large, parallel but mostly read-only analytics (e.g. Teradata, Redshift, Vertica) → "data warehouses"

How To Design Components for Transactional vs Analytical DBMS?

Component	Transactional DBMS	Analytical DBMS
Data storage		
Locking		
Recovery		

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Locking	Fine-grained, very optimized	Coarse-grained (few writes)
Recovery		

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Recovery	Log data writes, minimize latency	Log queries

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How Can We Change the DBMS Architecture?

Decouple Query Processing from Storage Management

Example: big data ecosystem (Hadoop, GFS, etc)

Processing engines

File formats & metadata

Large-scale file systems or blob stores

"Data lake" architecture

Decouple Query Processing from Storage Management

Pros:

- » Can scale compute independently of storage (e.g. in datacenter or public cloud)
- » Let different orgs develop different engines
- » Your data is “open” by default to new tech

Cons:

- » Harder to guarantee isolation, reliability, etc
- » Harder to co-optimize compute and storage
- » Can’t optimize across many compute engines
- » Harder to manage if too many engines!

Change the Data Model

Key-value stores: data is just key-value pairs, don't worry about record internals

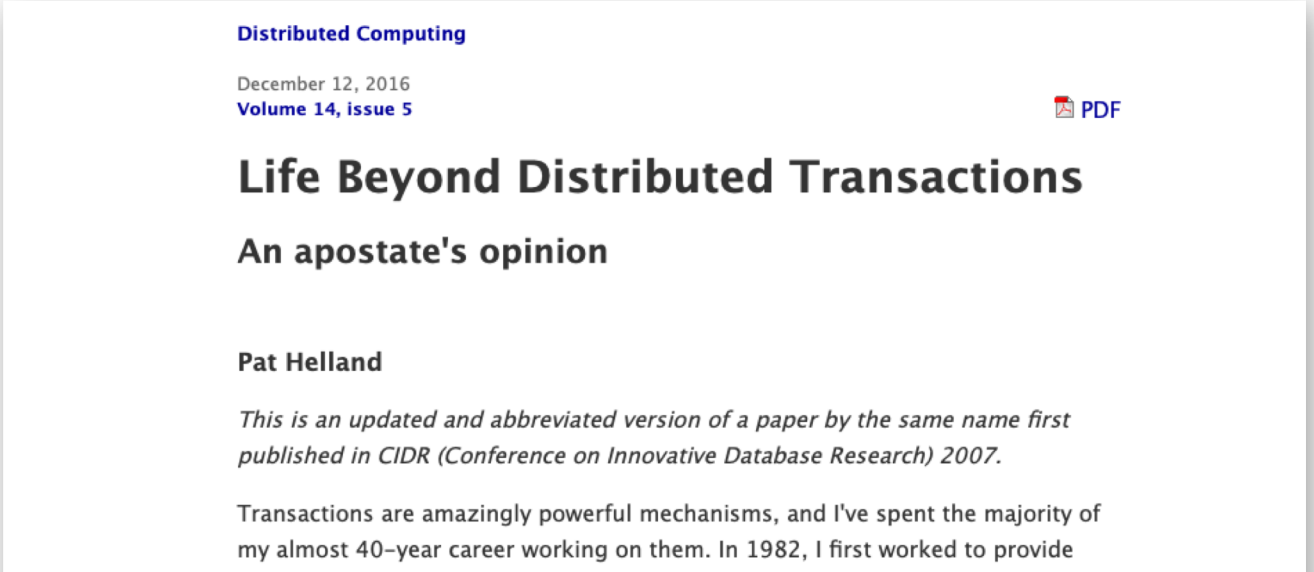
Message queues: data is only accessed in a specific FIFO order; limited operations

ML frameworks: data is tensors, models, etc

Change the Compute Model

Stream processing: Apps run continuously and system can manage upgrades, scaleup, recovery, etc

Eventual consistency: handle it at app level



Distributed Computing

December 12, 2016
Volume 14, issue 5

PDF

Life Beyond Distributed Transactions

An apostate's opinion

Pat Helland

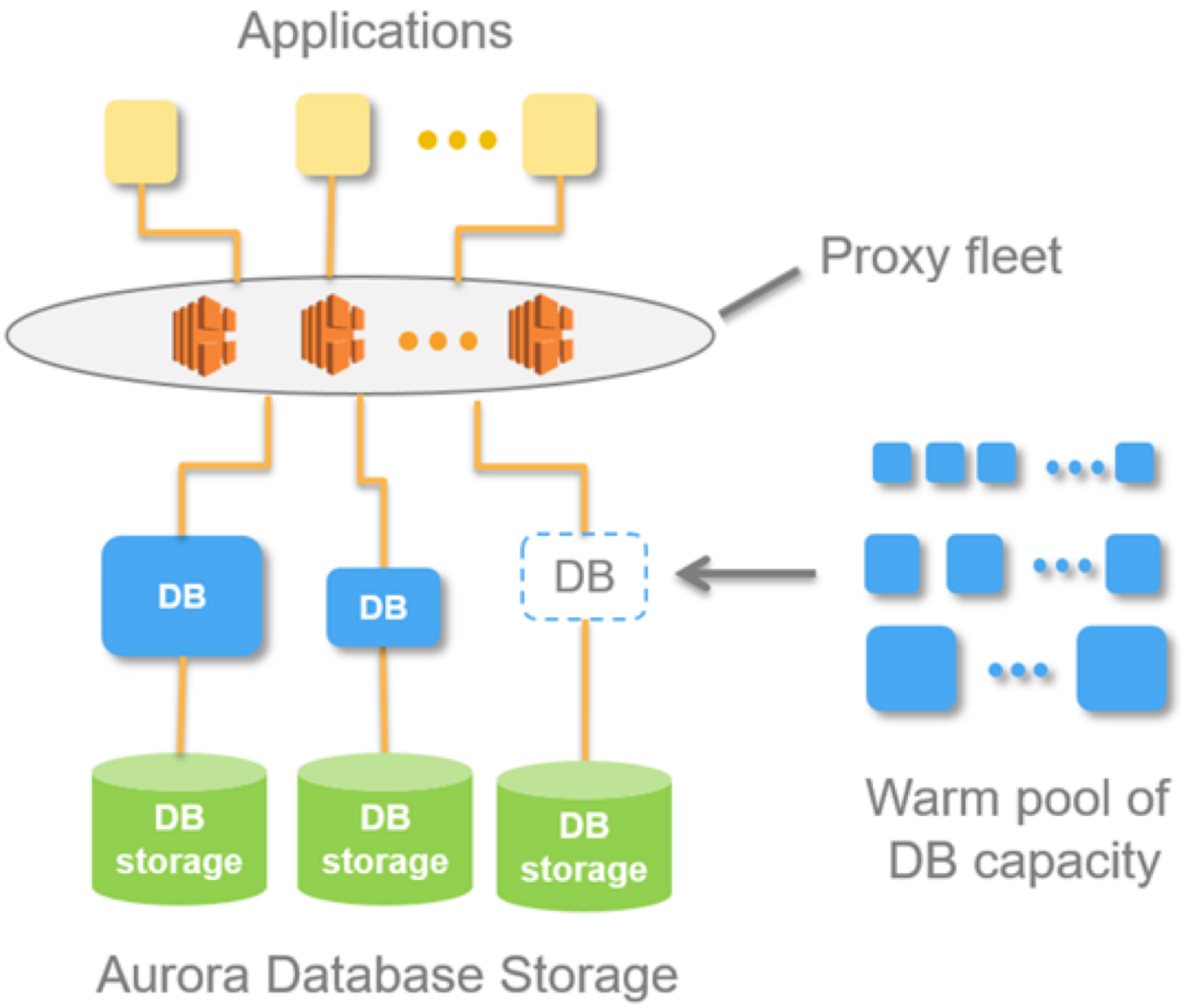
This is an updated and abbreviated version of a paper by the same name first published in CIDR (Conference on Innovative Database Research) 2007.

Transactions are amazingly powerful mechanisms, and I've spent the majority of my almost 40-year career working on them. In 1982, I first worked to provide

Different Hardware Setting

Distributed databases: need to distribute your lock manager, storage manager, etc, or find system designs that eliminate them

Public cloud: “serverless” databases that can scale compute independently of storage (e.g. AWS Aurora, Google BigQuery)



AWS Aurora Serverless

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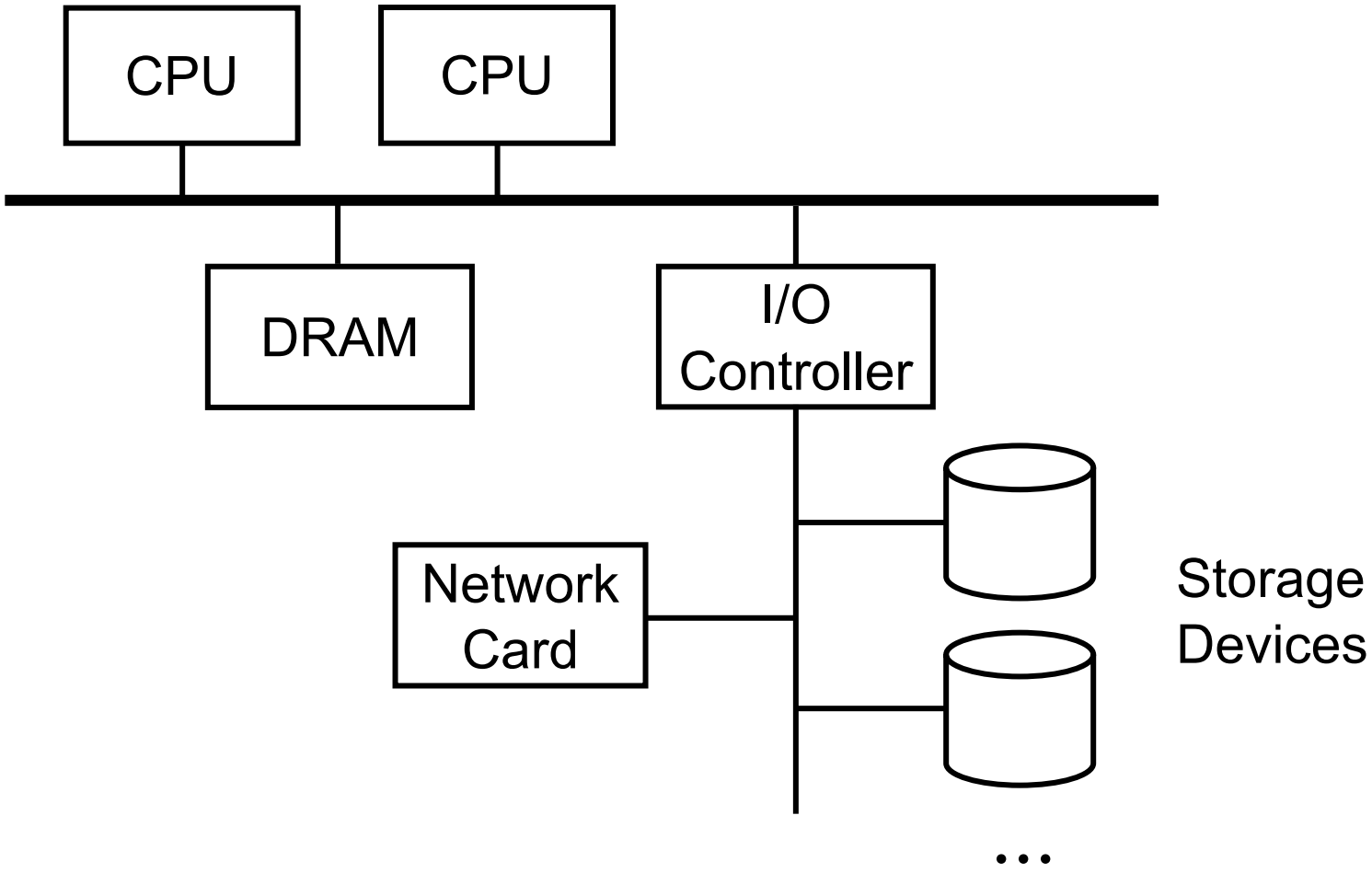
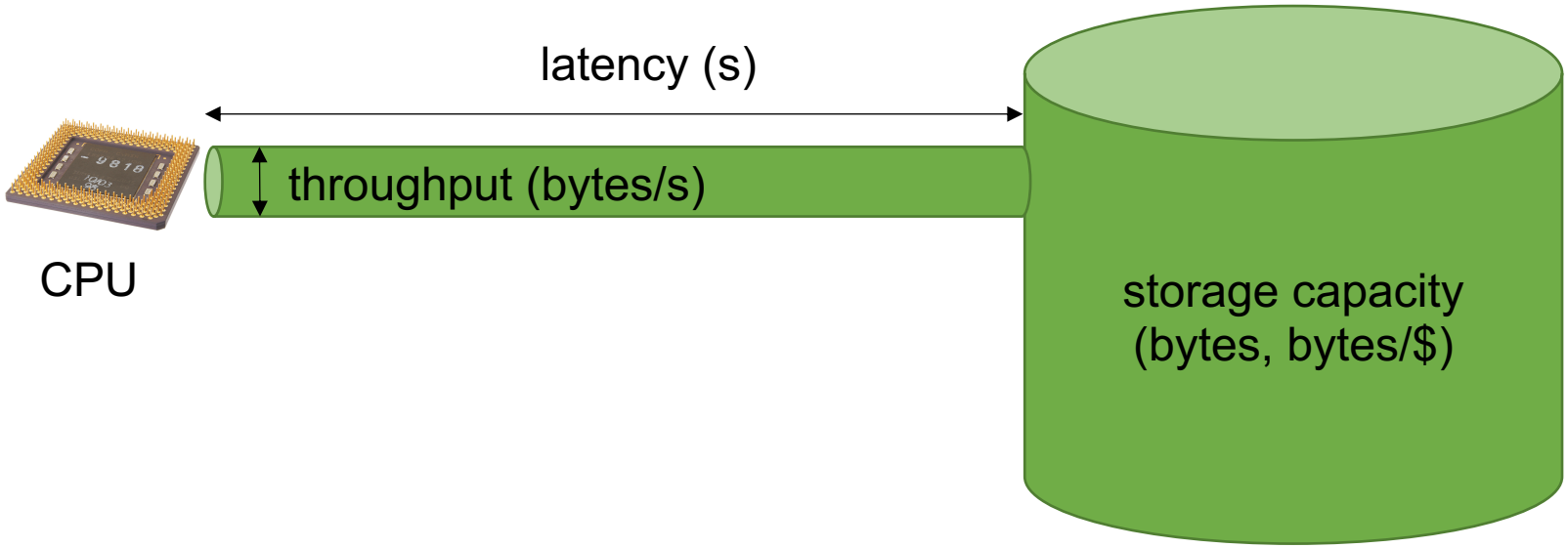
Typical Server



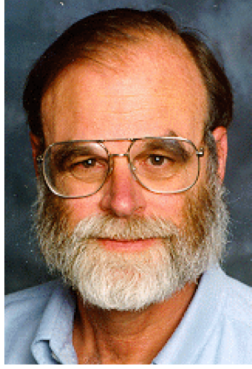
Storage Performance Metrics



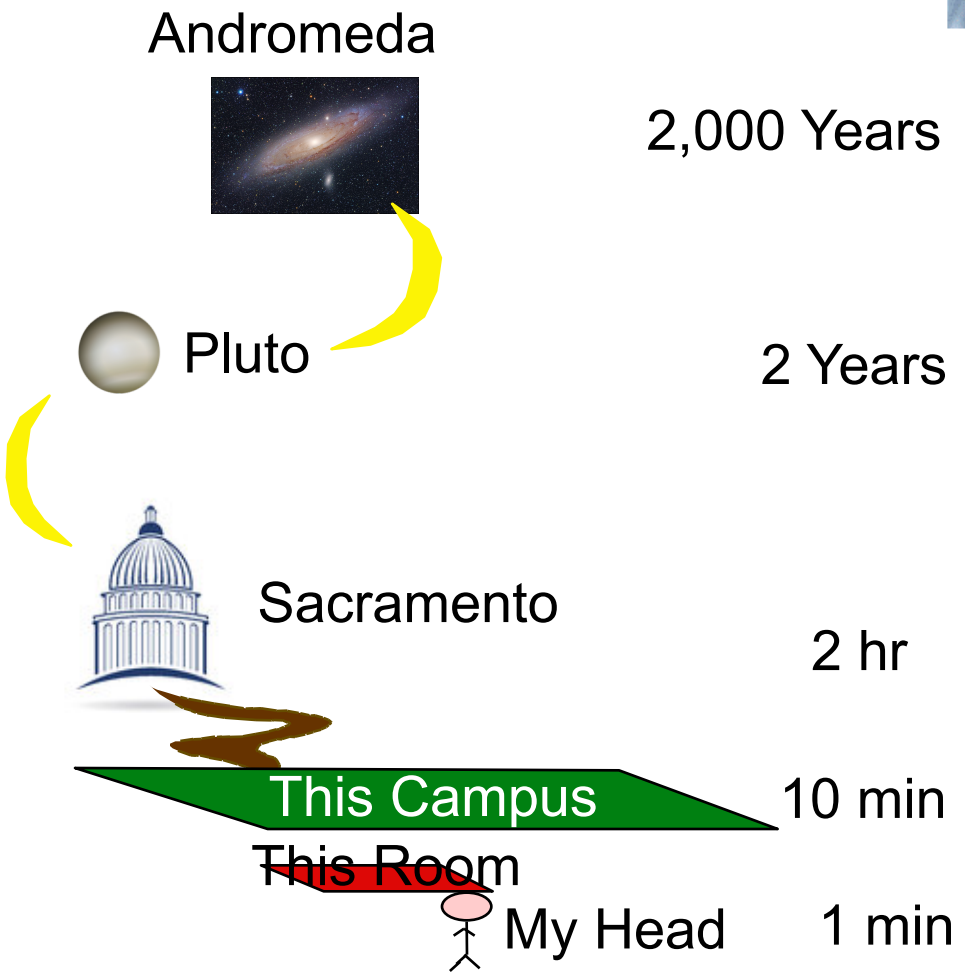
"Numbers Everyone Should Know" from Jeff Dean

L1 cache reference	0.5 ns	
Branch mispredict	5 ns	
L2 cache reference	7 ns	
Mutex lock/unlock	100 ns	
Main memory reference	100 ns	
Compress 1K bytes with Zippy	10,000 ns	0.01 ms
Send 1K bytes over 1 Gbps network	10,000 ns	0.01 ms
Read 1 MB sequentially from memory	250,000 ns	0.25 ms
Round trip within same datacenter	500,000 ns	0.5 ms
Disk seek	10,000,000 ns	10 ms
Read 1 MB sequentially from network	10,000,000 ns	10 ms
Read 1 MB sequentially from disk	30,000,000 ns	30 ms
Send packet CA->Netherlands->CA	150,000,000 ns	150 ms

Storage Latency



10^9	Tape /Optical Robot	2,000 Years
10^6	Disk	2 Years
150	Memory	2 hr
10	L2 Cache	10 min
2	L1 Cache	
1	Registers	1 min



Max Attainable Throughput

Varies significantly by device

- » 100 GB/s for RAM
- » 2 GB/s for NVMe SSD
- » 130 MB/s for hard disk

Assumes large reads (≫1 block)!

Storage Cost

$1000 at NewEgg today buys:

- » 0.2 TB of RAM
- » 9 TB of NVMe SSD
- » 33 TB of magnetic disk

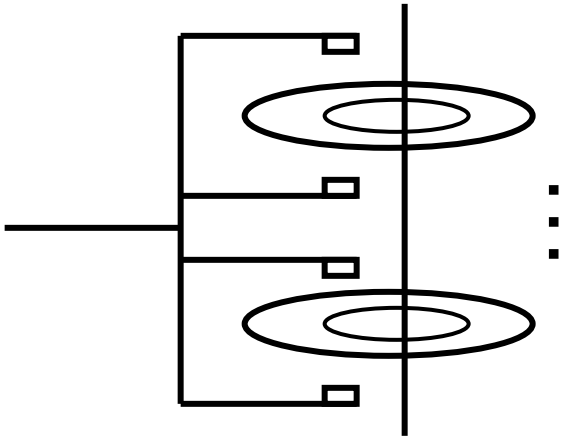
Hardware Trends over Time

Capacity/$ grows exponentially at a fast rate (e.g. double every 2 years)

Throughput grows at a slower rate (e.g. 5% per year), but new interconnects help

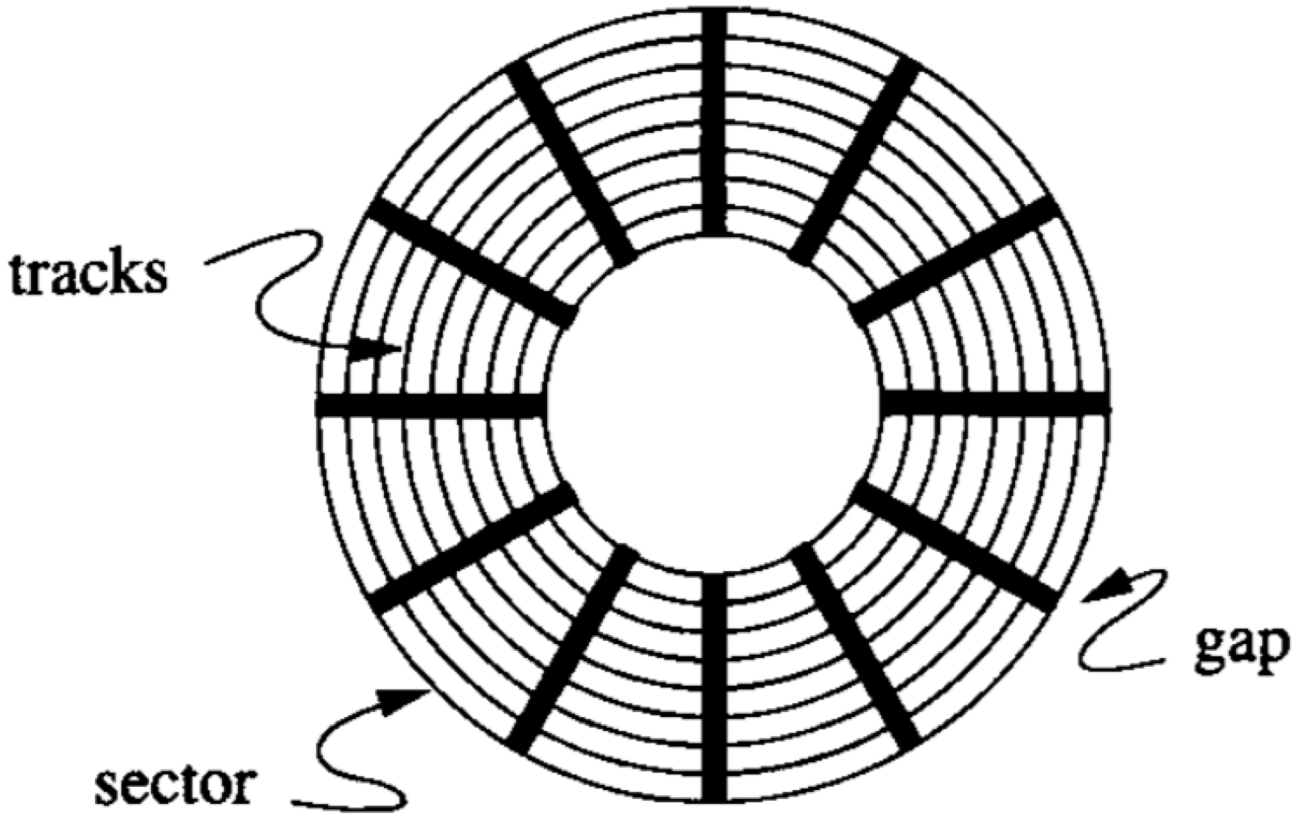
Latency does not improve much over time

Most Common Permanent Storage: Hard Disks



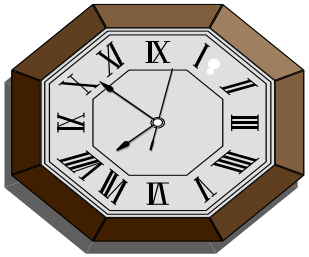
Terms: Platter, Head, Actuator
Cylinder, Track
Sector (physical),
Block (logical), Gap

Top View



Disk Access Time

I want block X



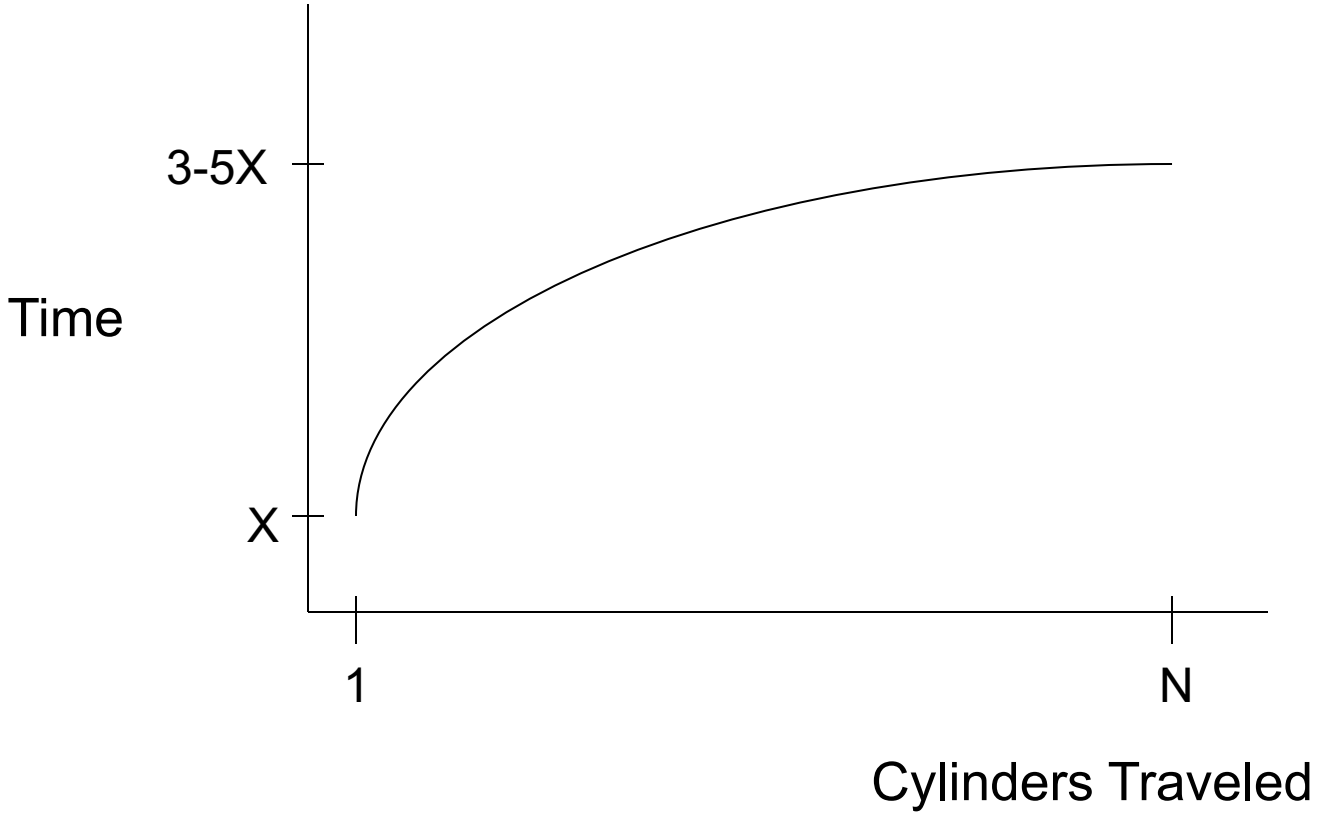
block x in memory

?

Disk Access Time

Time = Seek Time +
Rotational Delay +
Transfer Time +
Other

Seek Time



Typical Seek Time

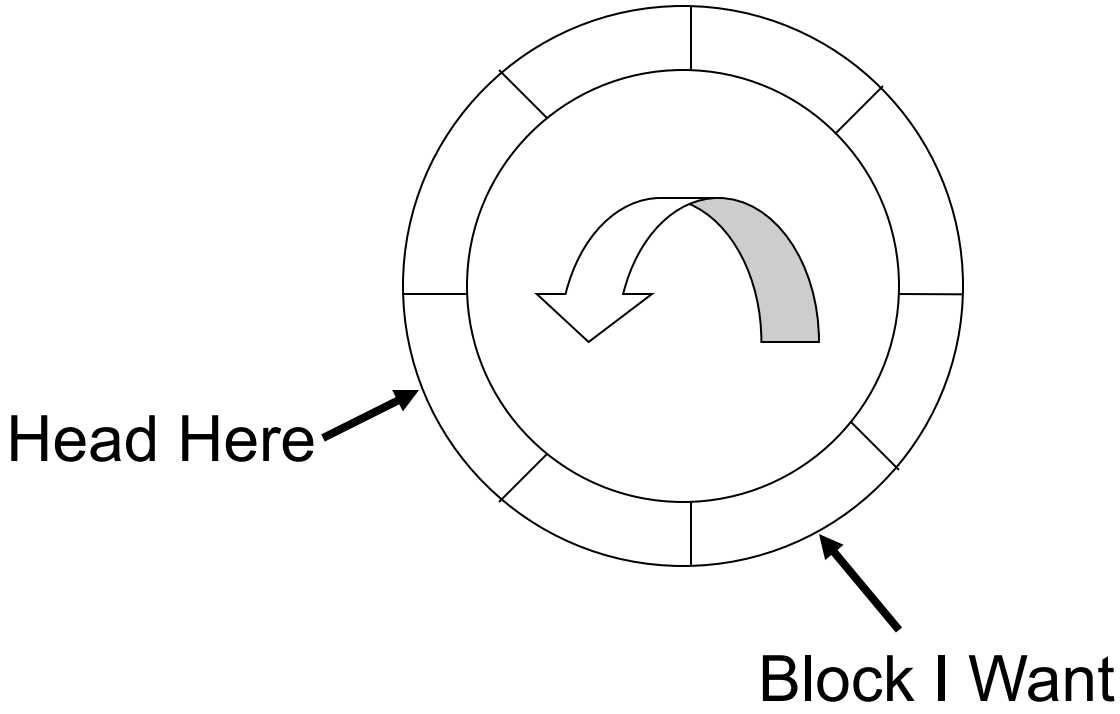
Ranges from

- » 4 ms for high end drives
- » 15 ms for mobile devices

In contrast, SSD access time ranges from

- » 0.02 ms: NVMe
- » 0.16 ms: SATA

Rotational Delay



Average Rotational Delay

R = 1/2 revolution R=0 for SSDs

Typical HDD figures

HDD Spindle [rpm]	Average rotational latency [ms]
4,200	7.14
5,400	5.56
7,200	4.17
10,000	3.00
15,000	2.00

Source: Wikipedia, "Hard disk drive performance characteristics"

Transfer Rate

Transfer rate T is around 50-130 MB/s

Transfer time: size / T for contiguous read

Block size: usually 512-4096 bytes

So Far: Random Block Access

What about reading the “next” block?

If we do things right (i.e., Double Buffer, Stagger Blocks…)

Time to get = block size / t + negligible

Potential slowdowns:

» Skip gap
» Next track
» Discontinuous block placement

Sequential access generally much faster than random access

Cost of Writing: Similar to Reading

…. unless we want to verify!

need to add (full) rotation + block size / t

Cost To Modify a Block?

To Modify Block:

(a) Read Block

(b) Modify in Memory

(c) Write Block

[(d) Verify?]

Performance of DRAM

The same basic issues with “lookup time” vs throughput apply to DRAM

Min read from DRAM is a cache line (64 bytes)

Even 64-byte random reads may not be as fast as sequential ones due to prefetching, page table, controllers, etc

Place co-accessed data together!

Example

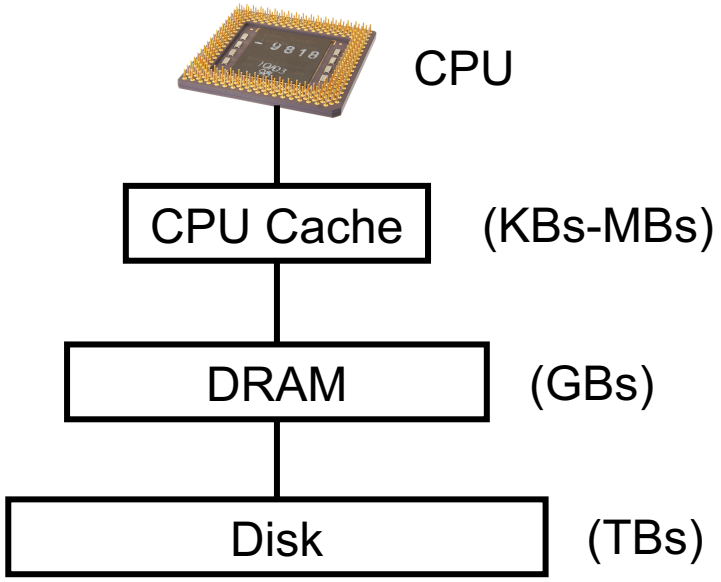
Suppose we're accessing 8-byte records in a DRAM with 64-byte cache line sizes

How much slower is random vs sequential?

In the random case, we are reading 64 bytes for every 8 bytes we need, so we expect to max out the throughput at least **8x** sooner.

Storage Hierarchy

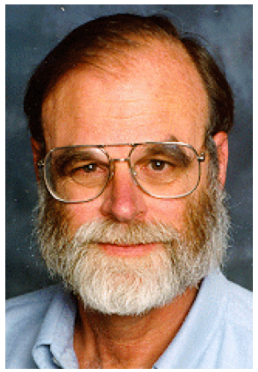
Typically want to **cache** frequently accessed data at a high level of the storage hierarchy to improve performance



Sizing Storage Tiers

How much high-tier storage should we have?

Can determine based on workload & cost



The 5 Minute Rule for Trading Memory Accesses for Disc Accesses
Jim Gray & Franco Putzolu
May 1985

The Five Minute Rule

Say a page is accessed every X seconds

Assume a disk costs D dollars and can do I operations/sec; cost of keeping this page on disk is

$$C_{disk} = C_{iop} / X = D / (I X)$$

Assume 1 MB of RAM costs M dollars and holds P pages; then the cost of keeping it in DRAM is:

$$C_{mem} = M / P$$

Five Minute Rule

This tells us that the page is worth caching when $C_{mem} < C_{disk}$, i.e.

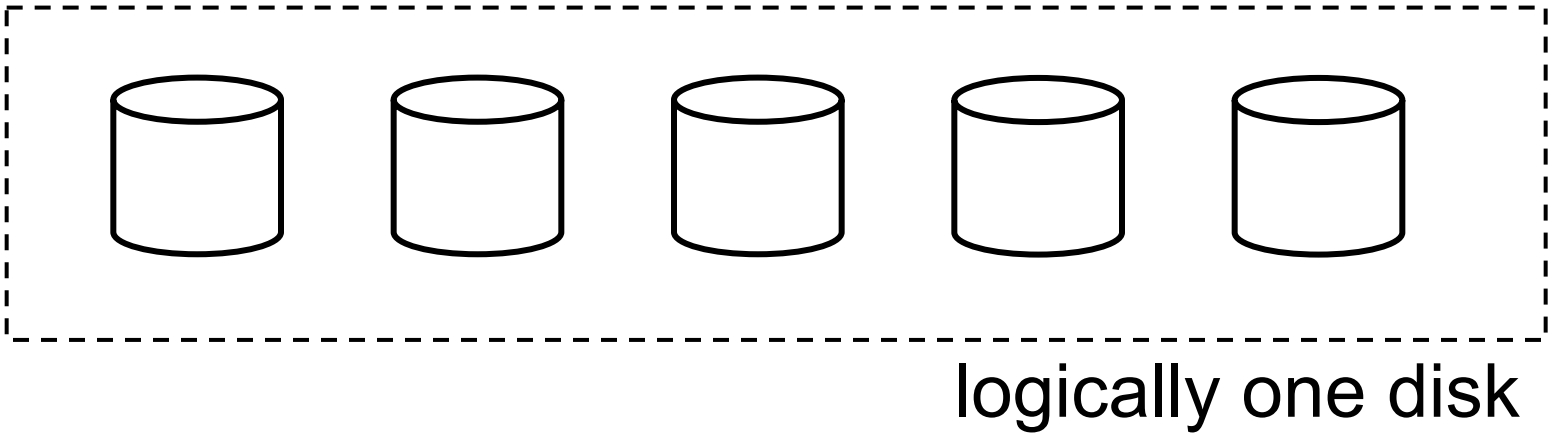
$$X < \frac{PagesPerMBofDRAM}{AccessesPerSecondPerDisk} \times \frac{PricePerDiskDrive}{PricePerMBofDRAM}$$

Tier	1987	1997	2007	2017
DRAM–HDD	5m	5m	1.5h	4h
DRAM–SSD	-	-	15m	7m (r) / 24m (w)
SSD–HDD	-	-	2.25h	1d

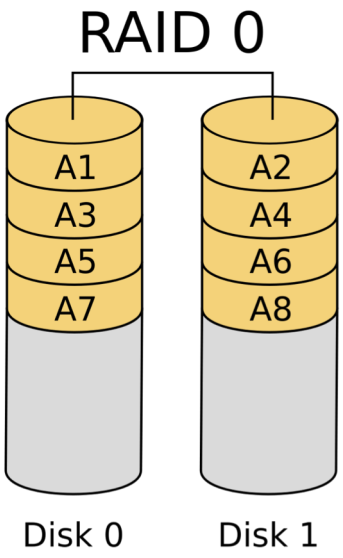
Source: The Five-minute Rule Thirty Years Later and its Impact on the Storage Hierarchy

Disk Arrays

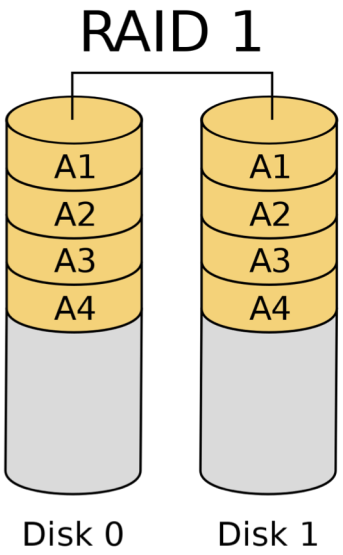
Many flavors of “RAID”: striping, mirroring, etc to increase **performance** and **reliability**



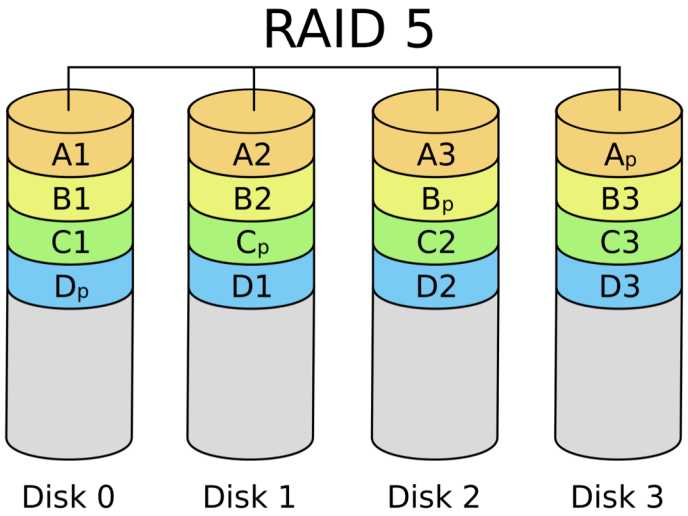
Common RAID Levels



Striping across 2 disks: adds performance but not reliability



Mirroring across 2 disks: adds reliability but not performance



Striping + 1 parity disk: adds performance and reliability at lower storage cost

Image source: Wikipedia

Coping with Disk Failures

Detection

» E.g. checksum

Correction

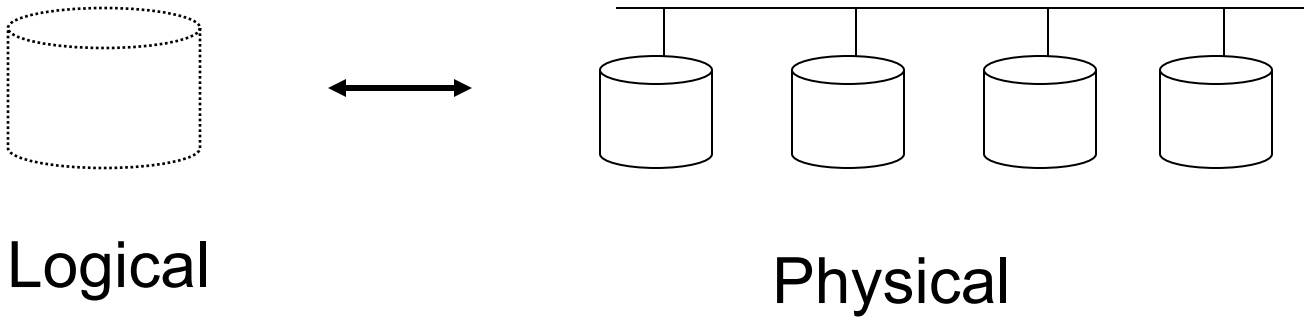
» Requires redundancy

At What Level Do We Cope?

Single Disk

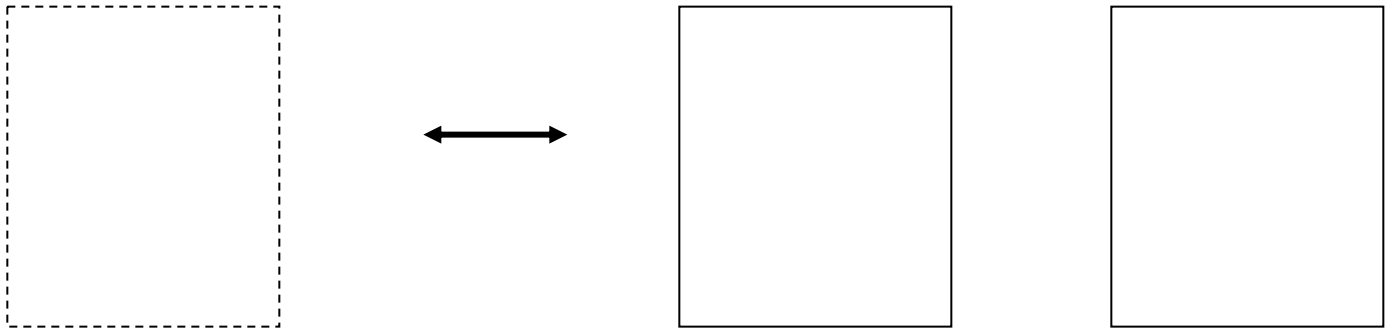
» E.g., error-correcting codes on read

Disk Array



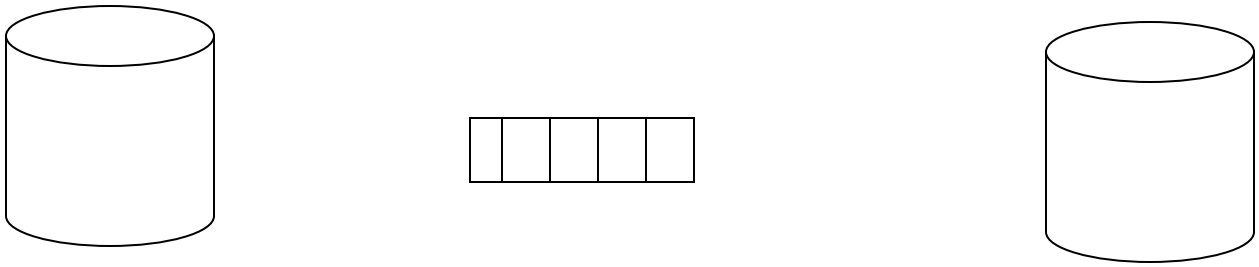
Operating System

E.g., network-replicated storage



Database System

E.g.,



Log

Current DB

Last week's DB

Summary

Storage devices offer various tradeoffs in terms of latency, throughput and cost

In **all** cases, data layout and access pattern matter because random $\ll$ sequential access

Most systems will combine multiple devices

Assignment 1

Explores the effect of data layout for a simple in-memory database

- » Fixed set of supported queries
- » Implement a row store, column store, indexed store, and your own custom store!

Will be posted soon on website!