Database Architecture 2 & Storage

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Outline

Relational DBMS architecture

Alternative architectures & tradeoffs

Storage hardware

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

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	B-trees, row oriented storage	Column-oriented storage
Locking	Fine-grained, very optimized	Coarse-grained (few writes)
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: “data lake” architecture (Hadoop, S3, etc)

MapReduce, Apache Giraph, Apache Spark, Apache Storm, presto, TensorFlow — Processing engines

Parquet, protobuf Protocol Buffers, {JSON} JavaScript Object Notation, Hive — File formats & metadata

GFS, hadoop HDFS, Amazon S3 — Large-scale file systems or blob stores

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

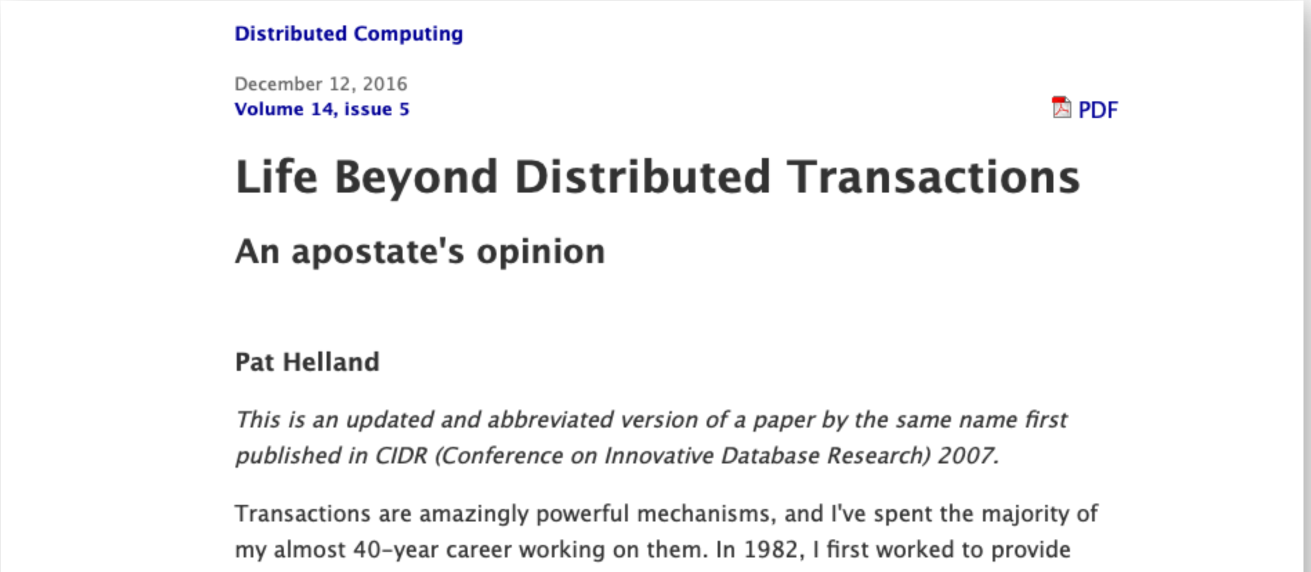
Message queues: data is only accessed in a specific FIFO order; limited operations

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

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.

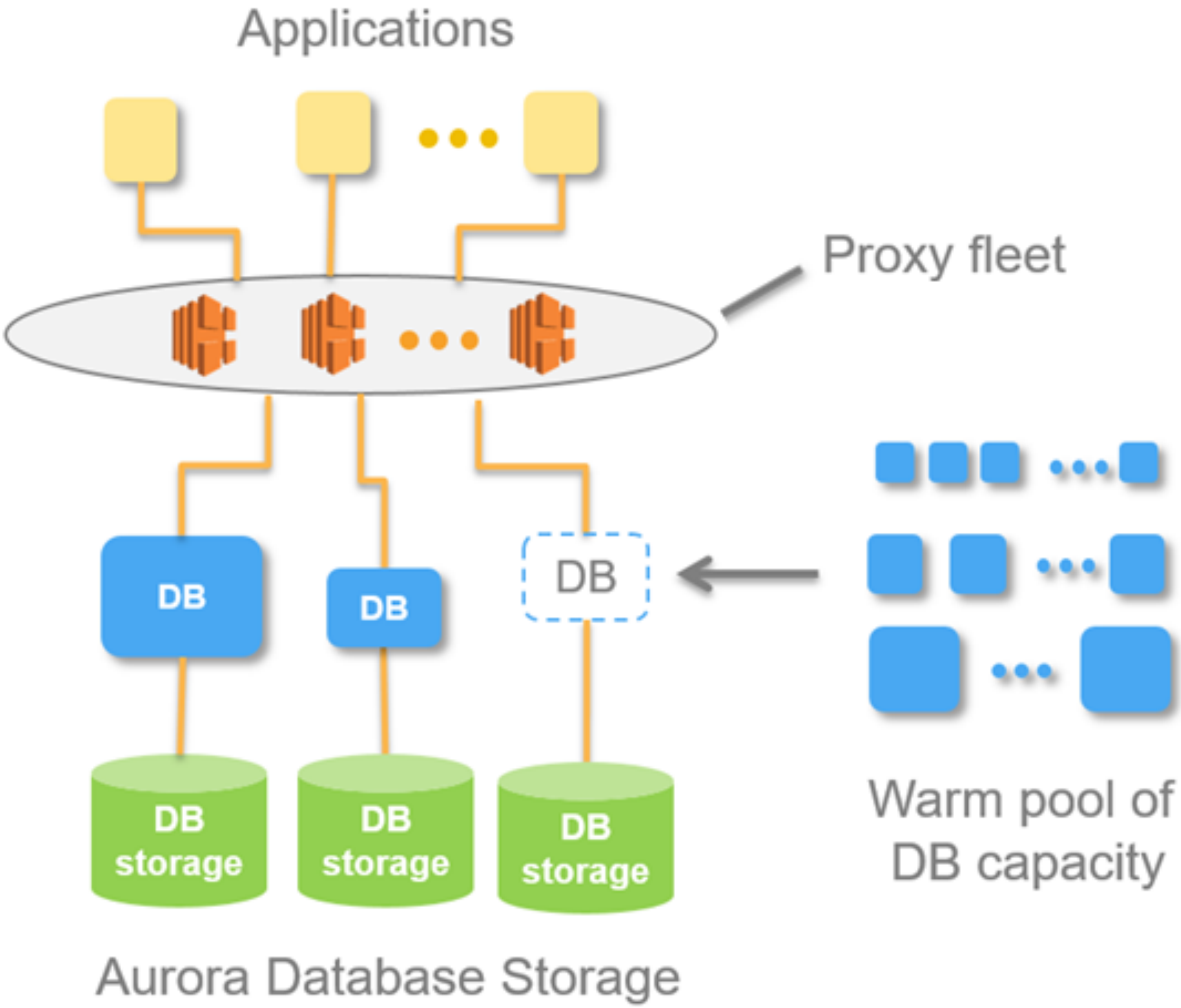
Transactions are amazingly powerful mechanisms, and I've spent the majority of my almost 40-year career working on them. In 1982, I first worked to provide

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)

Example: AWS Aurora Serverless



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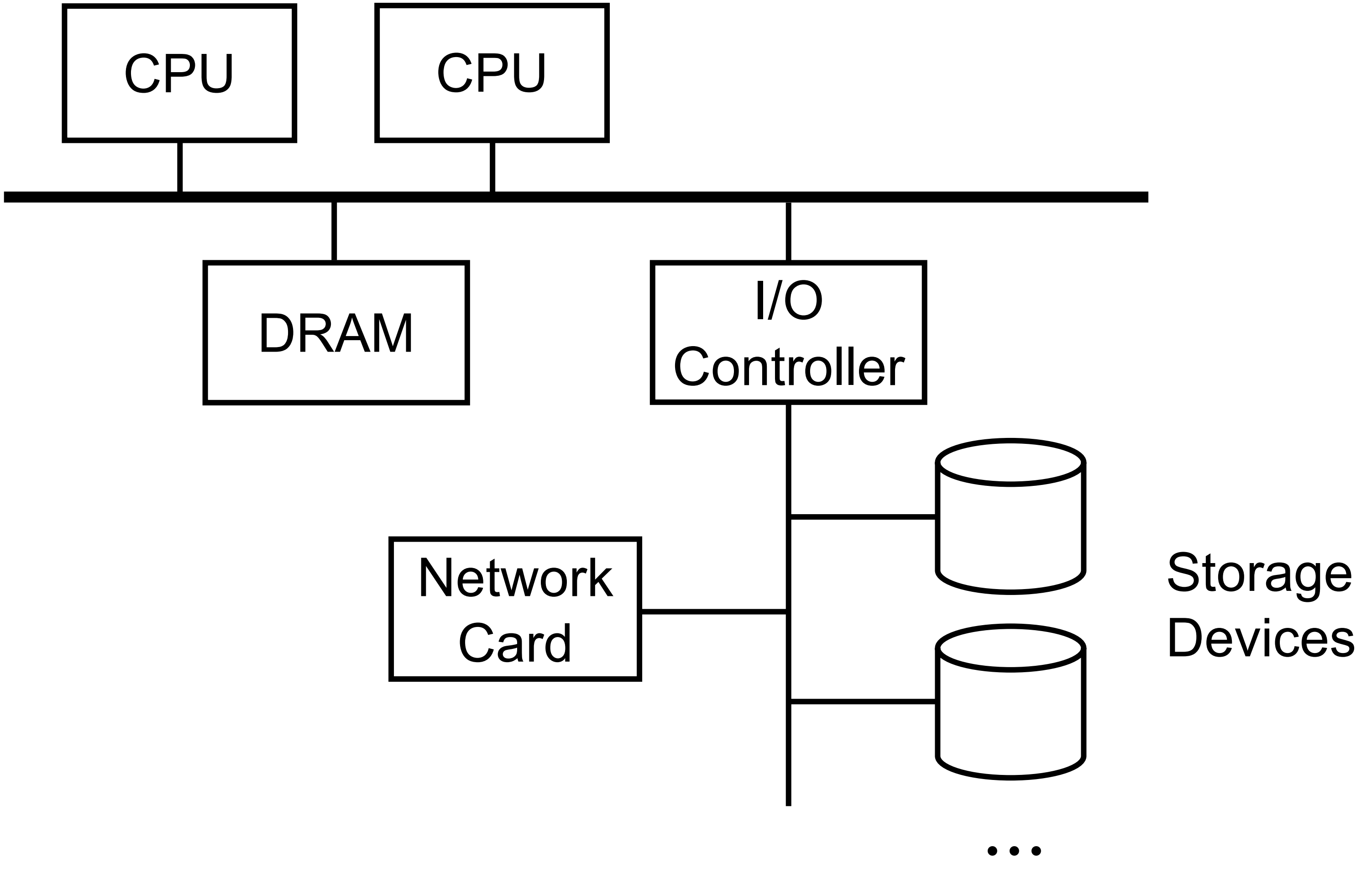
Typical Server



CPU

CPU

DRAM

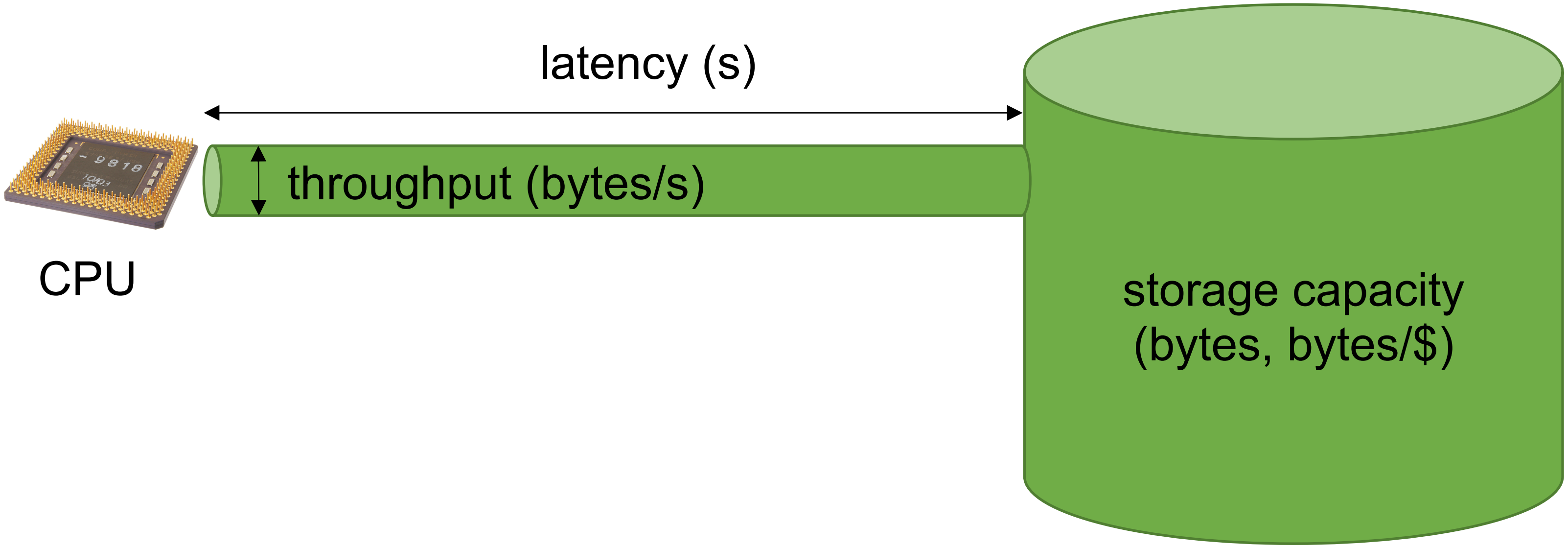
I/O
Controller

Network
Card

Storage
Devices

…

Storage Performance Metrics



latency (s)

throughput (bytes/s)

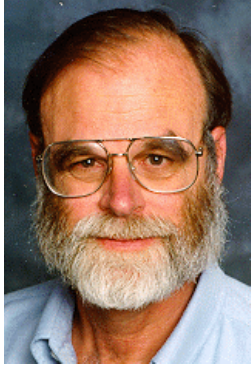
CPU

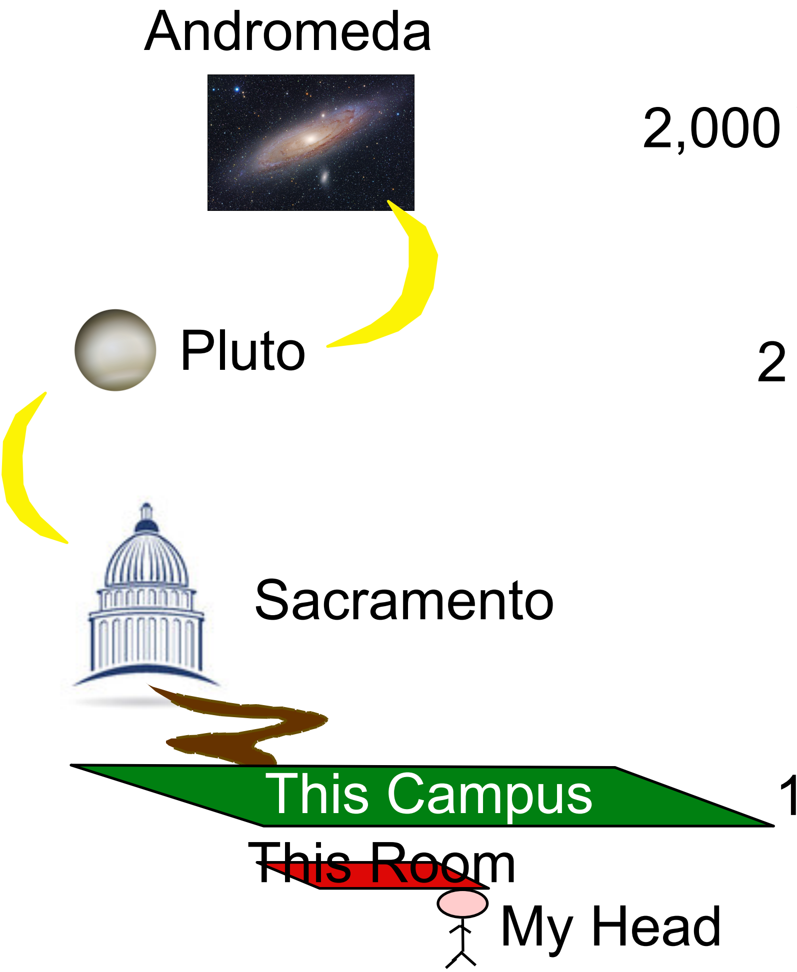
storage capacity
(bytes, bytes/$)

"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	Andromeda	2,000 Years
10^6	Disk	Pluto	2 Years
150	Memory	Sacramento	2 hr
10	L2 Cache	This Campus	10 min
2	L1 Cache	This Room	
1	Registers	My Head	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:

- 0.25 TB of RAM
- 9 TB of NVMe SSD
- 50 TB of magnetic disk

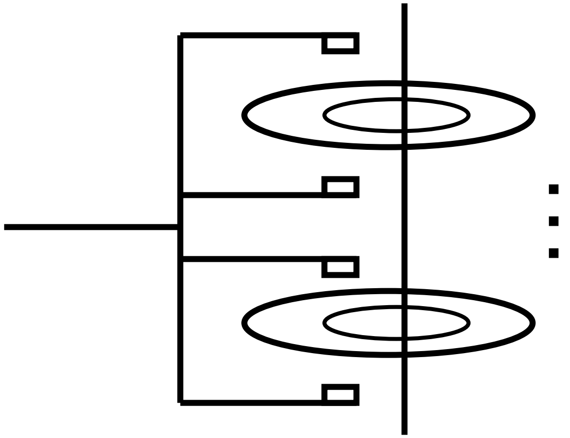
Hardware Trends over Time

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

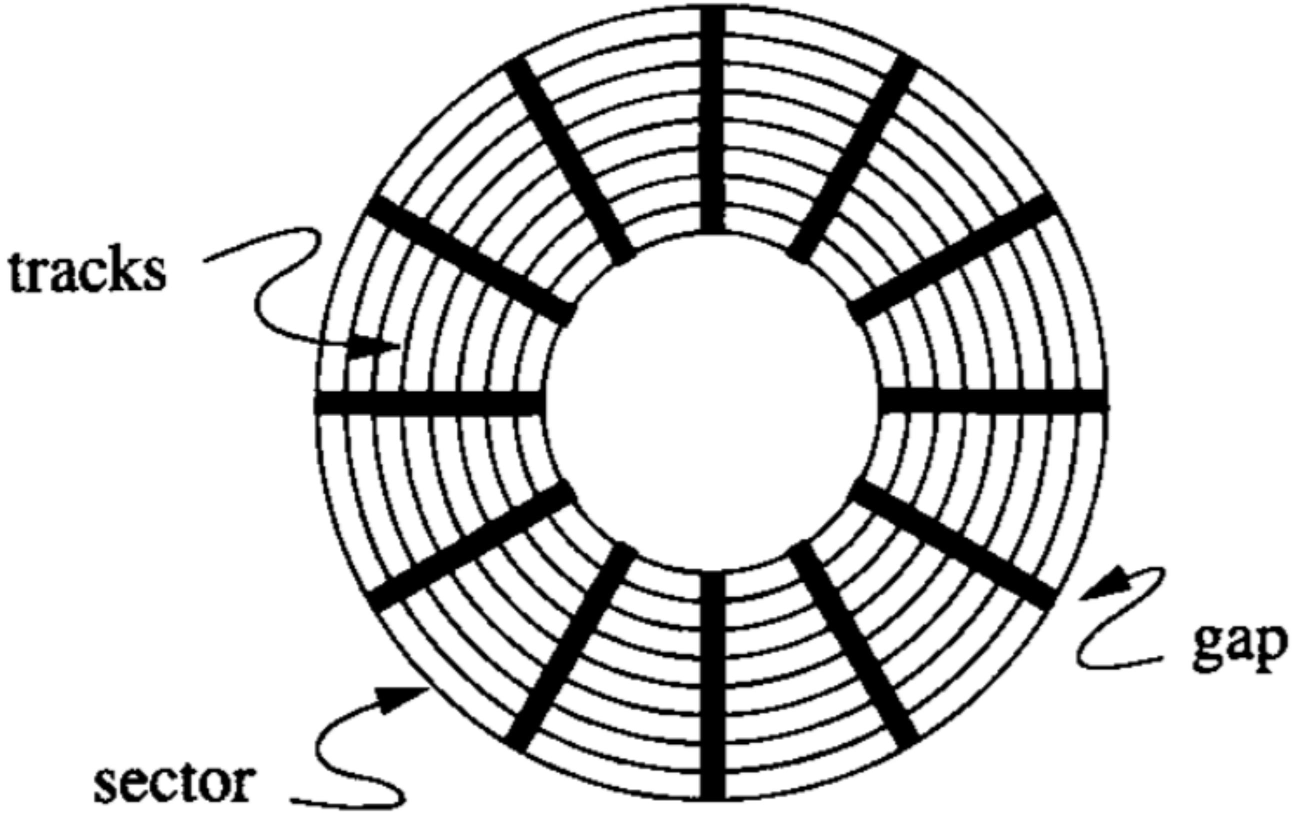
Latency does not improve much over time

Most Common Permanent Storage: Hard Disks

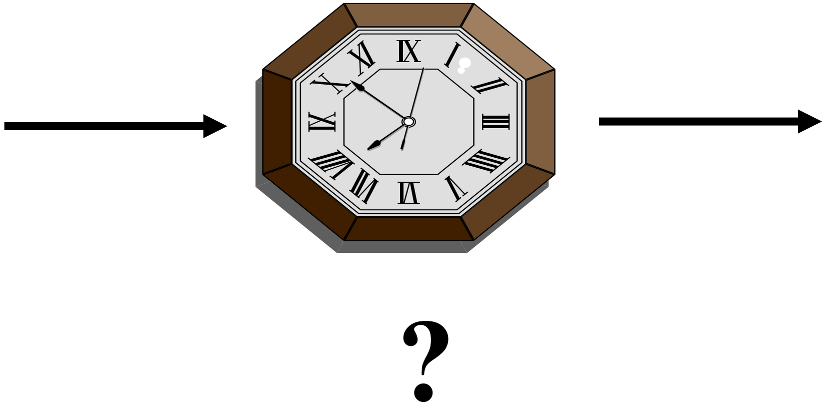


Terms: Platter, Head, Actuator
Cylinder, Track
Sector (physical),
Block (logical), Gap

Top View



Disk Access Time



I want
block X

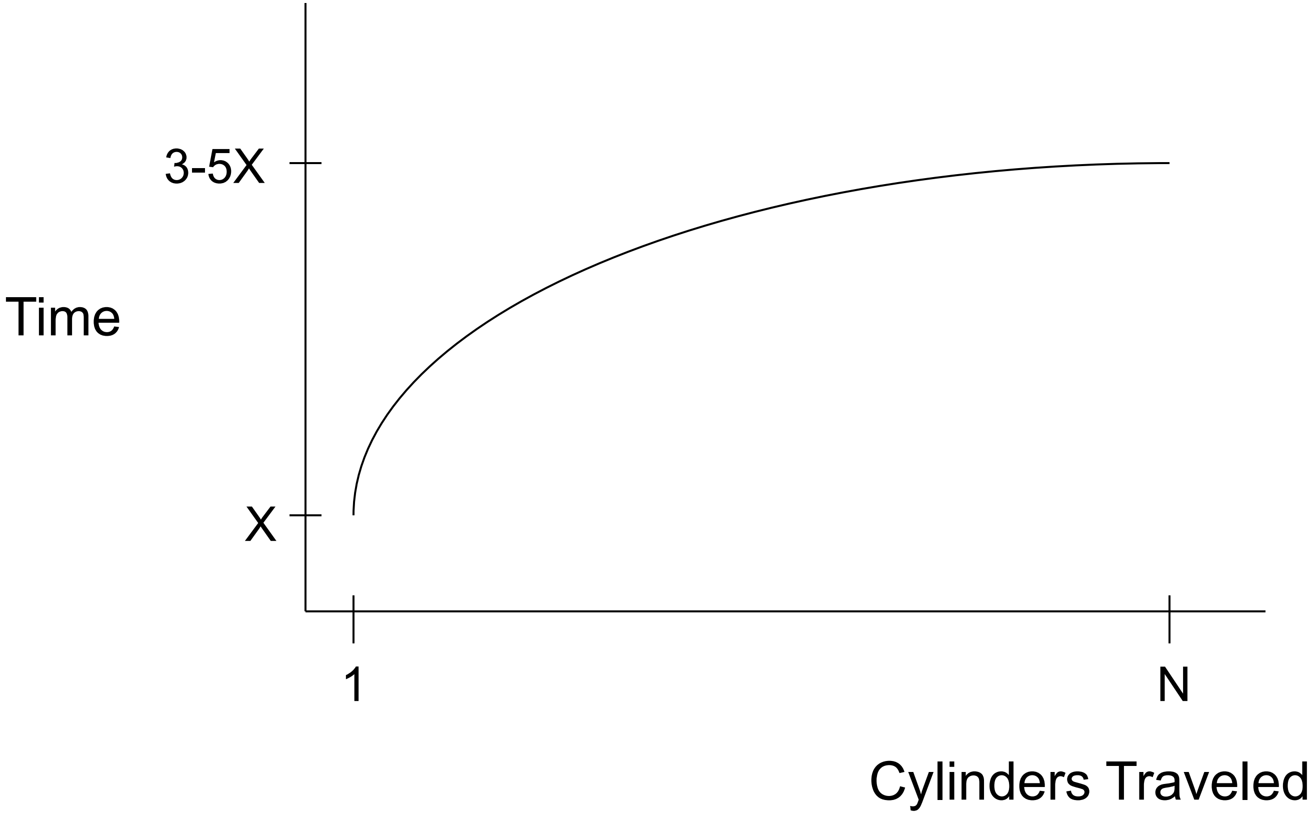
block x
in memory

?

Disk Access Time

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

Seek Time



Typical Seek Time

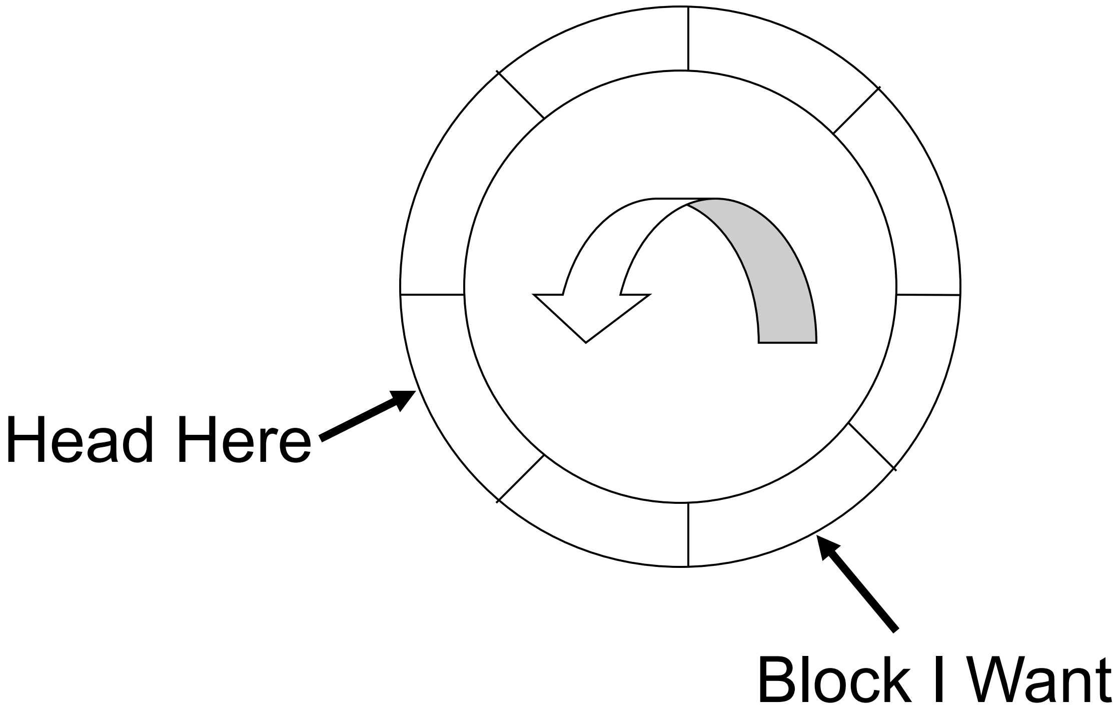
Ranges from

- » 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 (Double Buffer, etc)

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

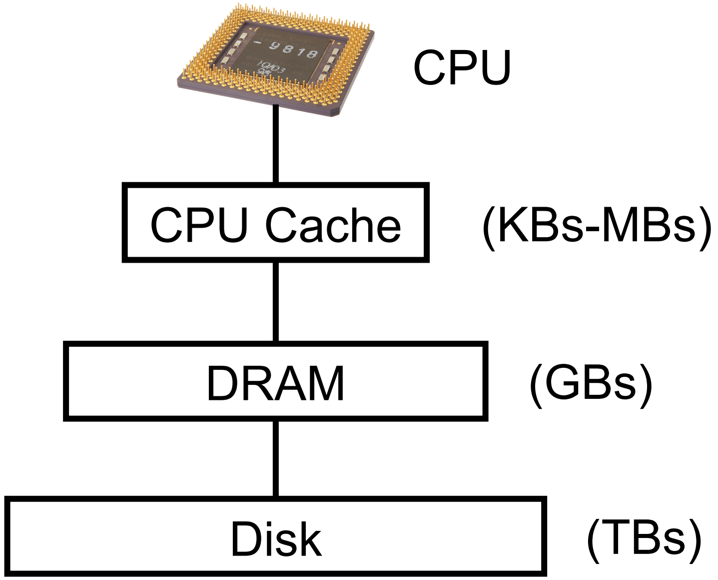
Suppose we're accessing 8-byte records in a DRAM with 64-byte cache line sizes

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

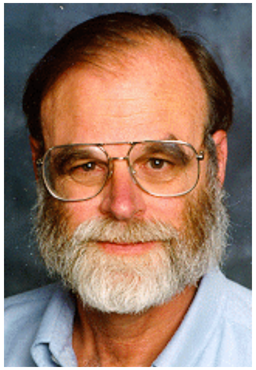
Typically want to **cache** frequently accessed data at a high level of the storage hierarchy to improve performance



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

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

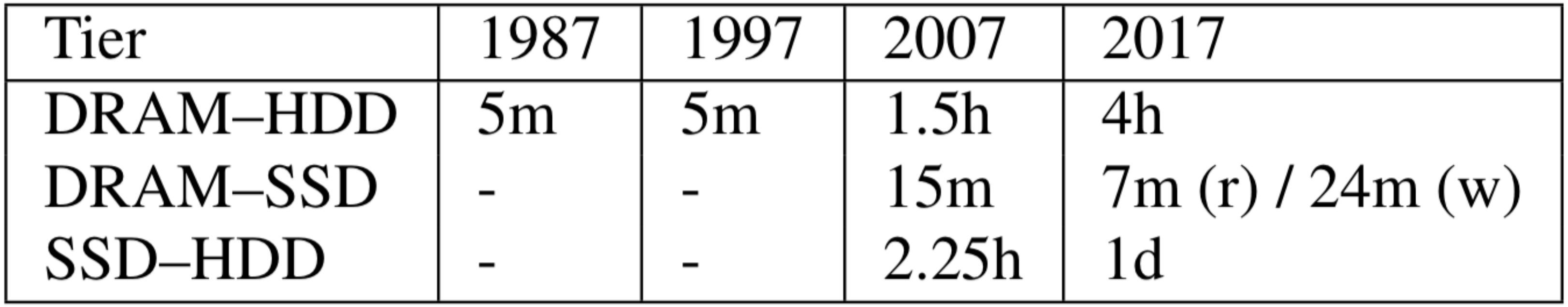
Assume 1 MB of RAM costs M dollars and holds P pages; then the cost of keeping it in DRAM is:

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

Five Minute Rule

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

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

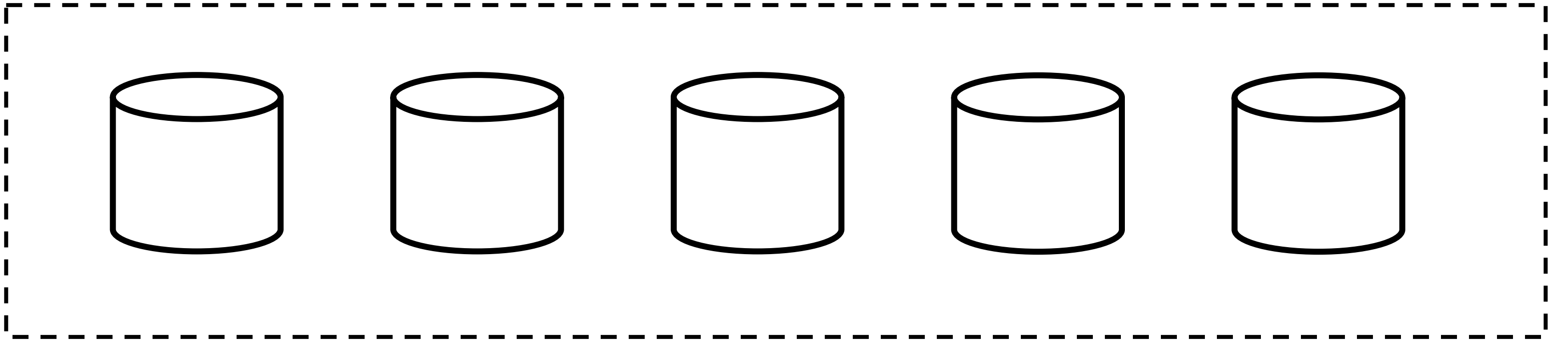


Tier	1987	1997	2007	2017
DRAM–HDD	5m	5m	1.5h	4h
DRAM–SSD	-	-	15m	7m (r) / 24m (w)
SSD–HDD	-	-	2.25h	1d

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

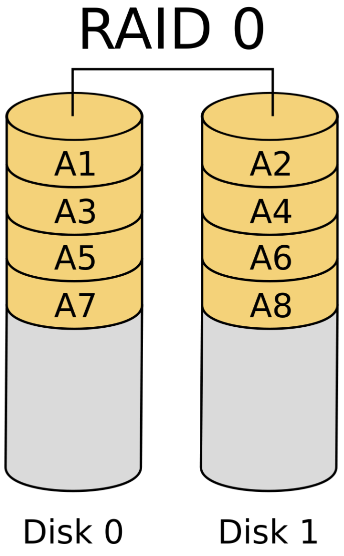
Disk Arrays

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

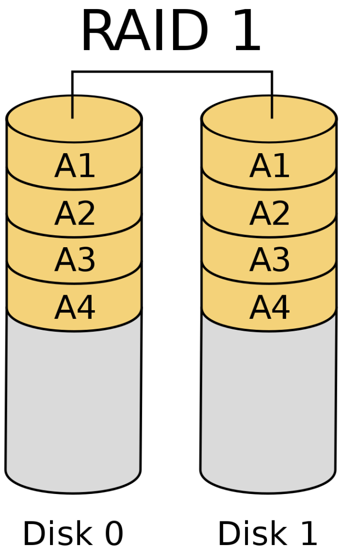


logically one disk

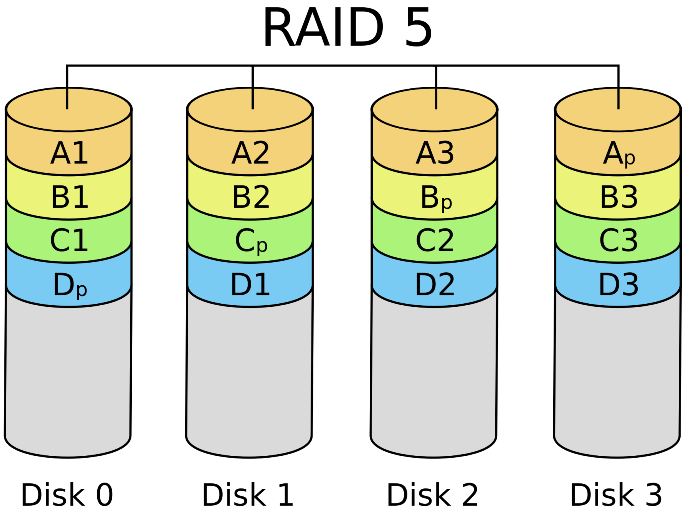
Common RAID Levels



Striping across 2 disks: adds performance but not reliability



Mirroring across 2 disks: adds reliability but not performance (except for reads)



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

Image source: Wikipedia

Coping with Disk Failures

Detection

- E.g. checksum

Correction

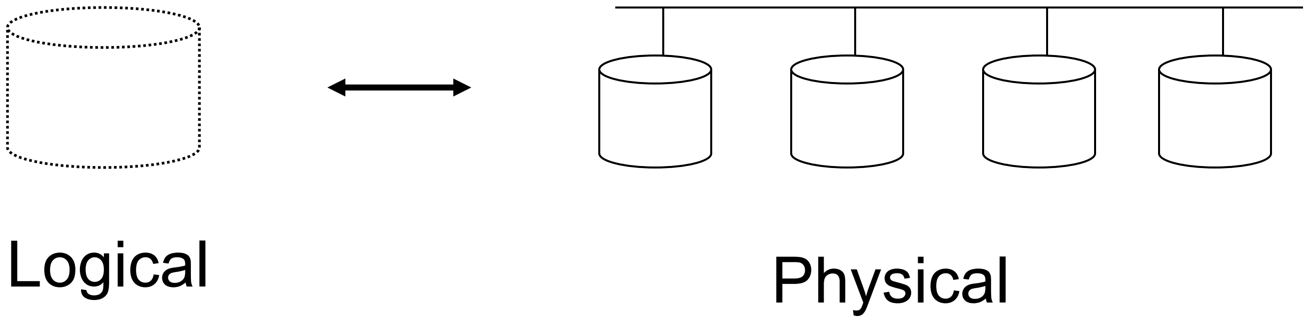
- Requires redundancy

At What Level Do We Cope?

Single Disk

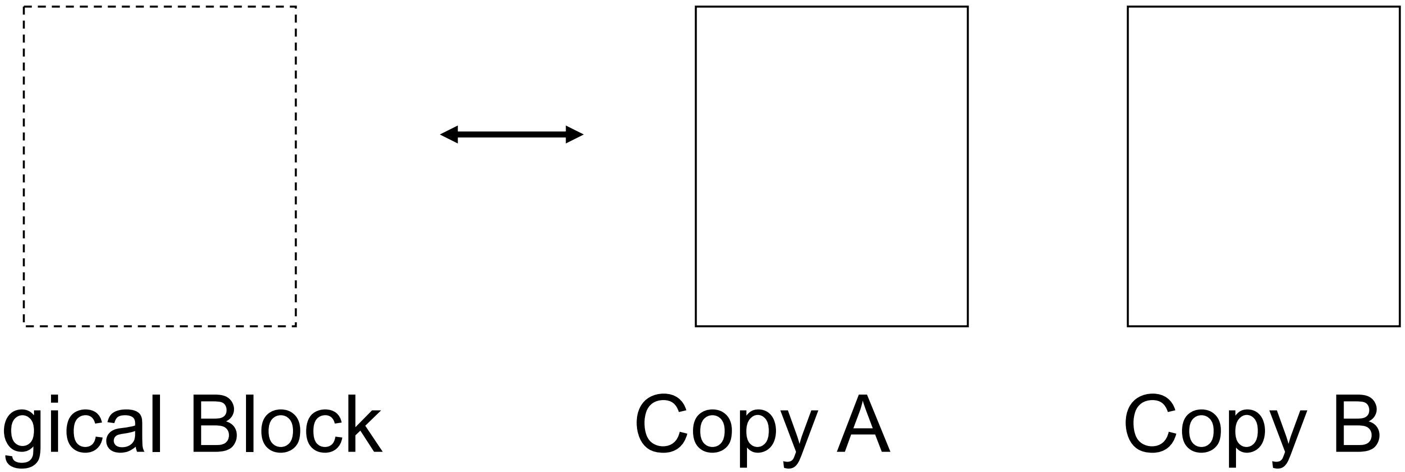
- » E.g., error-correcting codes on read

Disk Array



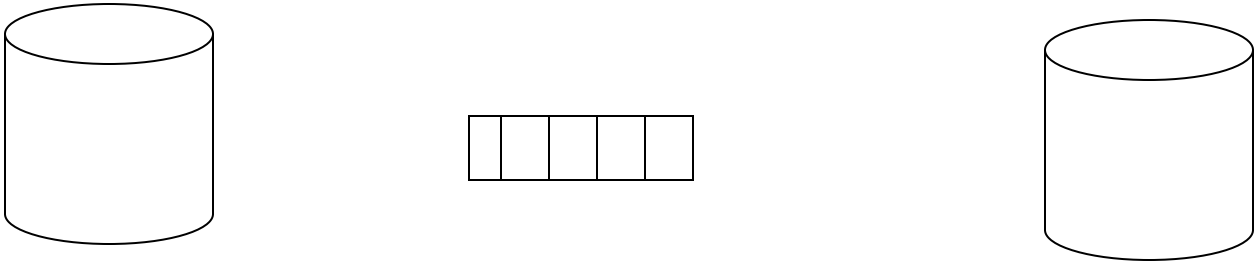
Operating System

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 ≪ 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!

Now posted on website!