COSI 167A
Advanced Data Systems

Class 2

Data Systems 101

Prof. Subhadeep Sarkar

Brandeis University

https://ssd-brandeis.github.io/COSI-167A/

Today in COSI 167A

What's on the cards?

class **logistics**, **goals**, and **administrivia**

introduction to **NoSQL systems**

Project 1 details

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Recap: **Why** take the class?

Introduction to "modern" databases!

BIG data — **Data-driven world, Unstructured data**

store and **manage** data — Data is generated at an **unprecedented rate** and **volume** —**"Does your system SCALE?"**

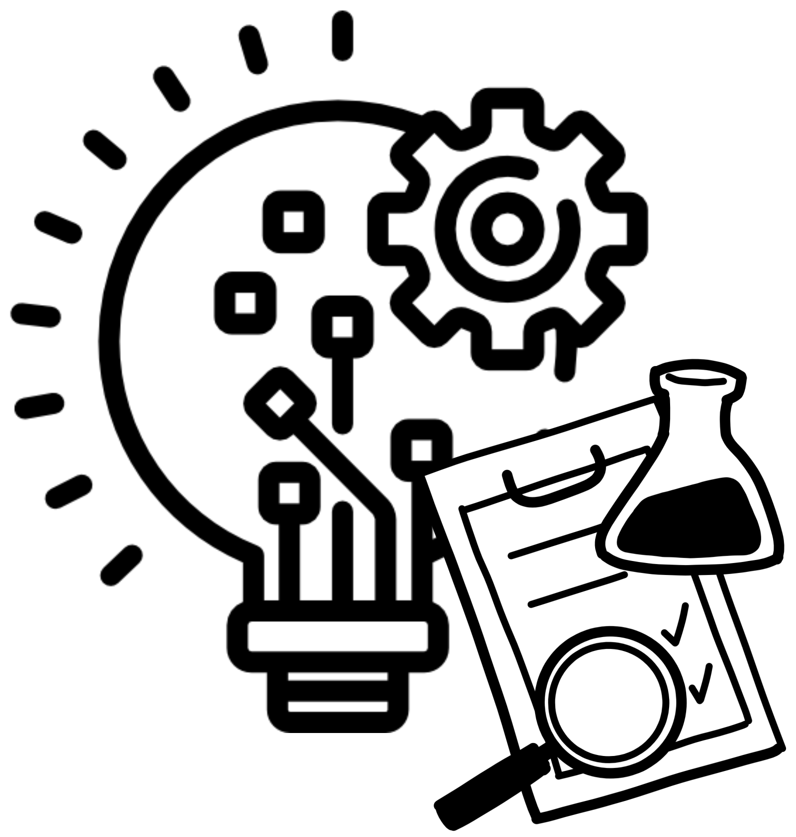
querying BIG data & querying **fast** — **Querying unstructured data, SQL?**

new **system designs** — **New application requirements = New design trends**

getting your **hands "dirty"** — **Play with large-scale, commercial storage engines**

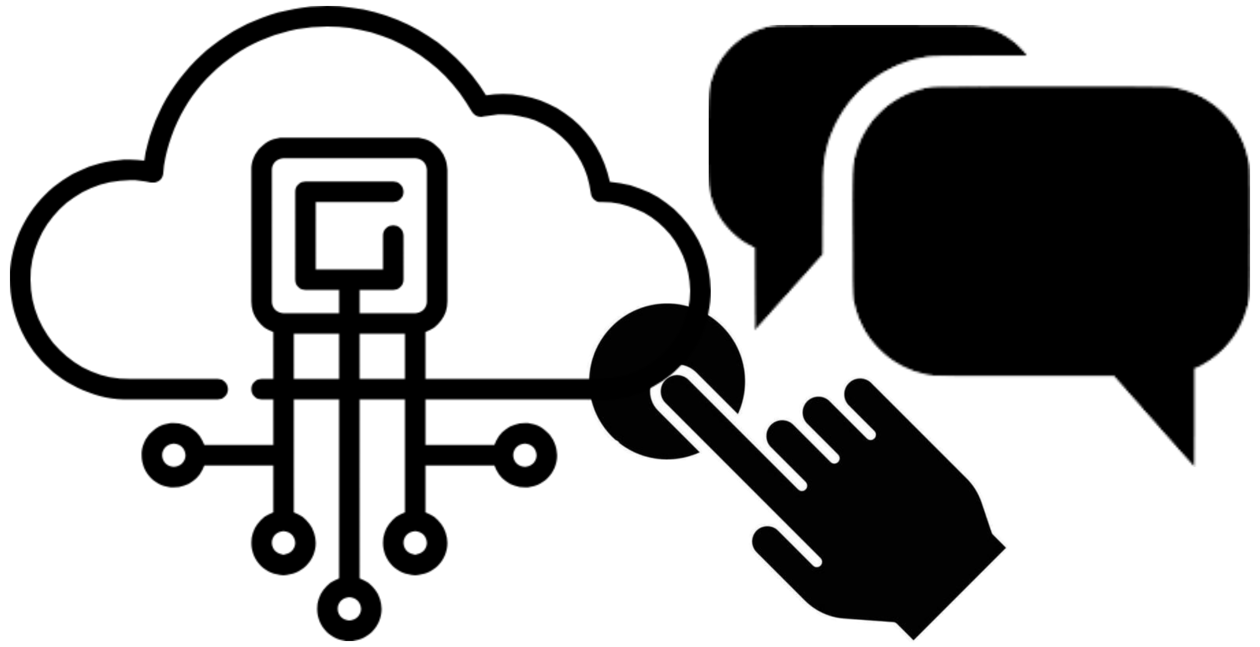
Recap: Class **Philosophy**

Principles to go by



cutting-edge research

question everything



interactive & collaborative

Learn to *think out of the box*!

Recap: **Readings**

Papers, papers, and papers

Architecture of a Database System
— J. Hellerstein, M. Stonebraker and J. Hamilton
Foundations and Trends in Databases, 2007

Chapters 1, 3, 5

The Design and Implementation of Modern Column-store Database Systems
— D. Abadi, P. Boncz, S. Harizopoulos, S. Idreos, S. Madden
Foundations and Trends in Databases, 2013

Chapters 1, 2, 3

Data Structures for Data-Intensive Applications
— Manos Athanassoulis, Stratos Idreos, and Dennis Shasha,
Foundations and Trends in Databases, 2023.

Semester reading!

Evaluation

A guide to success!

class participation

5%

in-class participation, SH visits

Ask questions!

& answer my questions!

goal: **learning through discussion**

There's NO stupid question!

Evaluation

A guide to success!

class participation	5%	in-class participation, SH visits
paper reviews	9%	**3 reviews** during the semester

goal: learn to **parse** and **critique** state-of-the-art research papers

no more than **one page**; more details before first review

Tuning NoSQL storage engines
ML and **systems**
Indexing

Evaluation

A guide to success!

class participation	5%	in-class participation, SH visits
paper reviews	9%	**3 reviews** during the semester
technical questions	16%	**8 technical questions** during the semester

goal: understand the **core concepts** presented in a paper

1-2 paragraphs; be concise and to the point

Evaluation

A guide to success!

class participation	5%	in-class participation, SH visits
paper reviews	9%	**3 reviews** during the semester
technical questions	16%	**8 technical questions** during the semester
paper presentation	15%	**2 students** per presentation

goal: learn to **present** technical papers & prepare **slides**

you choose the paper; registration link to open soon!

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Evaluation

A guide to success!

class participation	5%	in-class participation, SH visits
paper reviews	9%	3 reviews during the semester
technical questions	16%	8 technical questions during the semester
paper presentation	15%	**2 students** per presentation
projects	55%	**Project 1** + **Class project**

Evaluation

A guide to success!

class participation	5%	in-class participation, SH visits
paper reviews	9%	3 reviews during the semester
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paper presentation	15%	**2 students** per presentation
projects	55%	**Project 1** + **Class project**

Evaluation

A guide to success!

projects **55%**

Project 1 **15%**

individual project

released **tomorrow**; due on: **Sep 20**

more details **later in the class**

https://ssd-brandeis.github.io/COSI-167A/assets/PAs/PA1/PA-1.pdf

Class project **40%**

group (of 2) project

4 milestones

- project **proposal** **5%**
- **mid-term** report **5%**
- project **presentation** **10%**
- **code review** **20%**

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Data is **everywhere**!

Everyone produces data!

experimental **physics** (IceCube, CERN)
neuroscience
biology

data mining business datasets
machine learning and AI for corporate and consumer

online **gaming**
micro-transactions, economics

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How much data is generated **every day** in 2024?

500 TB

Data is **everywhere**!

Everyone produces data!

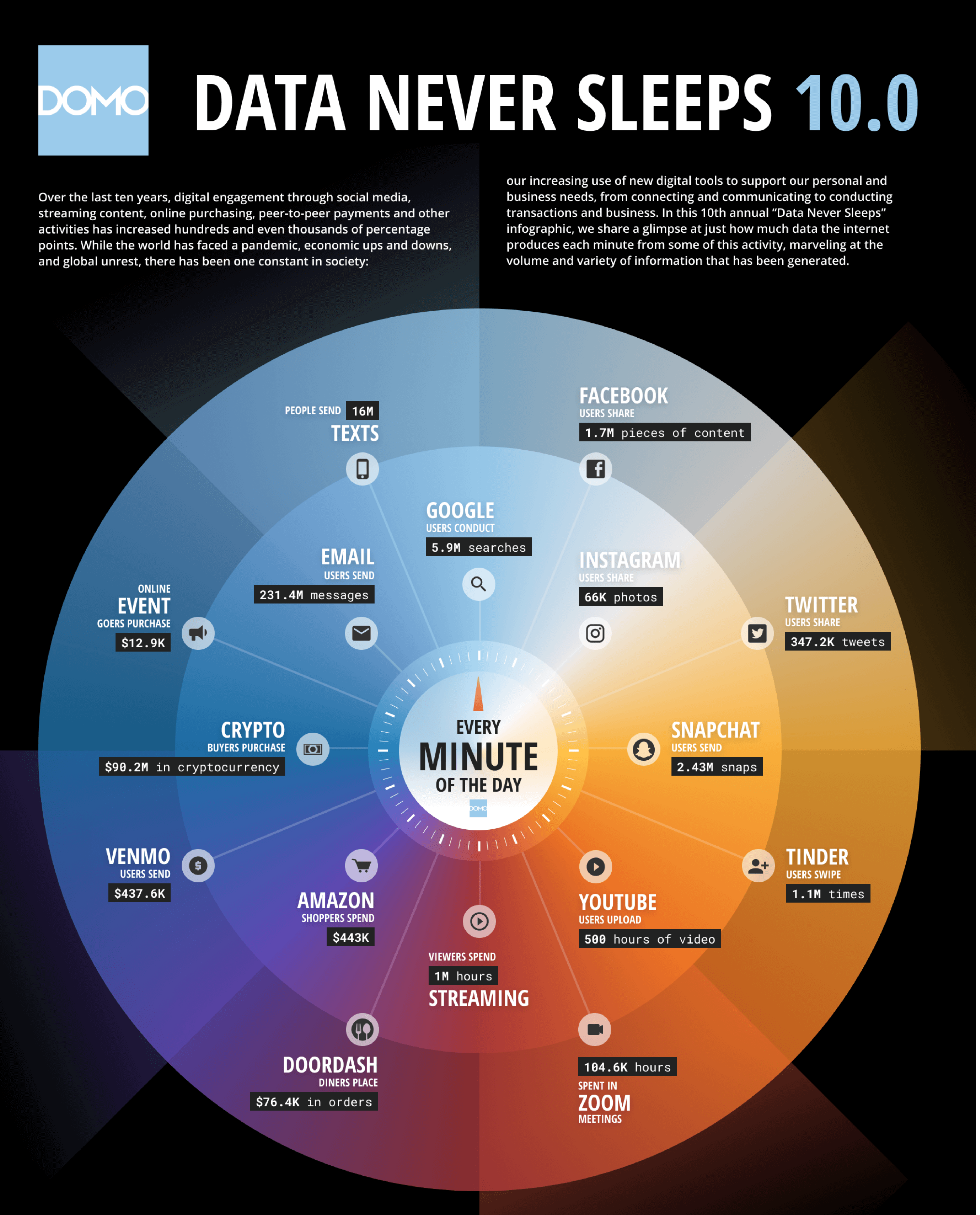
experimental **physics** (IceCube, CERN)
neuroscience
biology

data mining business datasets
machine learning and AI for corporate and consumer

online **gaming**
micro-transactions, economics

How much data is generated **every day** in 2024?

500M TB or 5 Exabytes

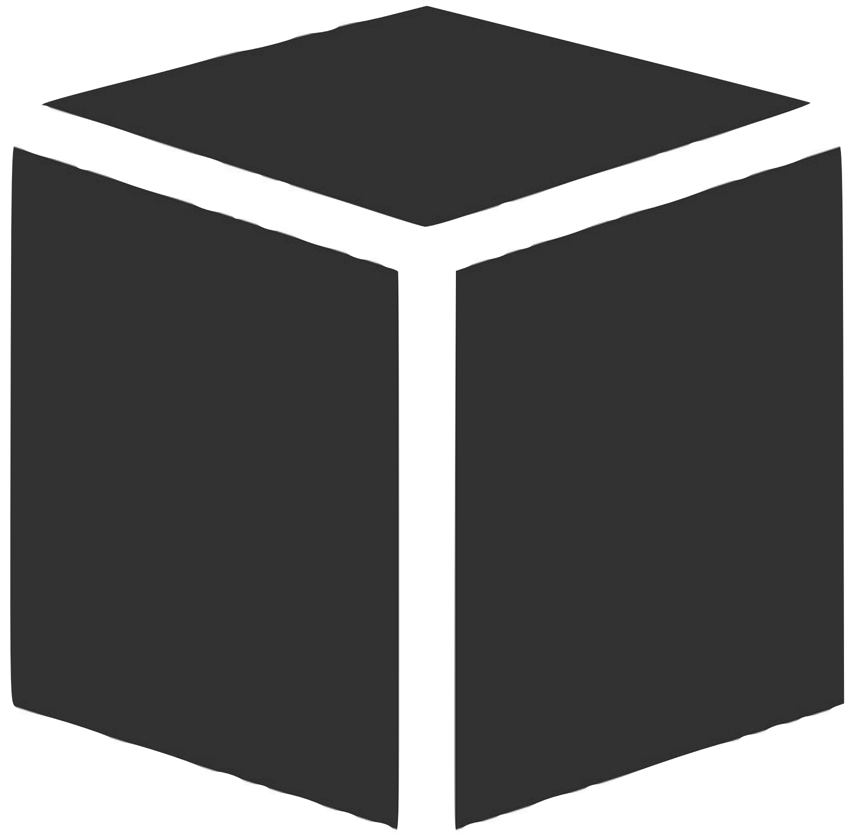


Managing **big data**

is a mammoth undertaking!

requires

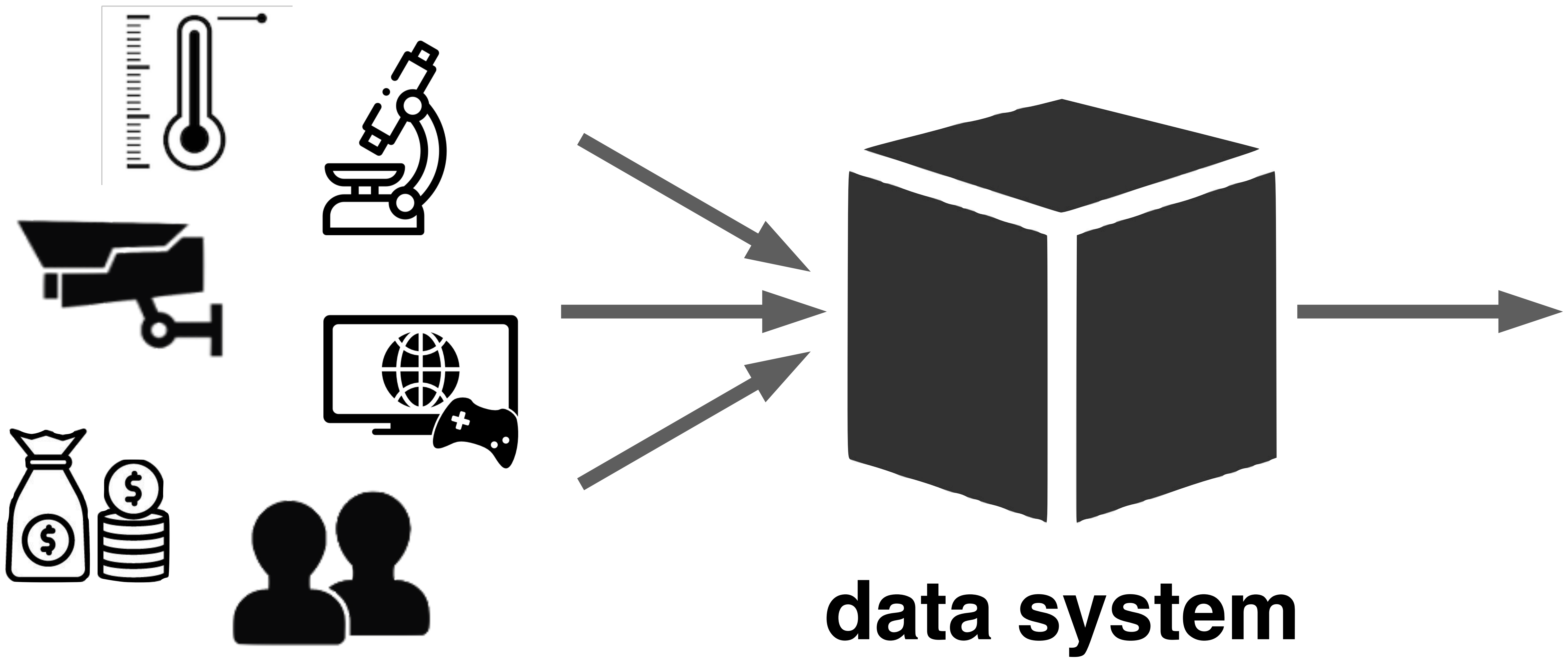
specialized systems



data system / data store / DB kernel

Data systems

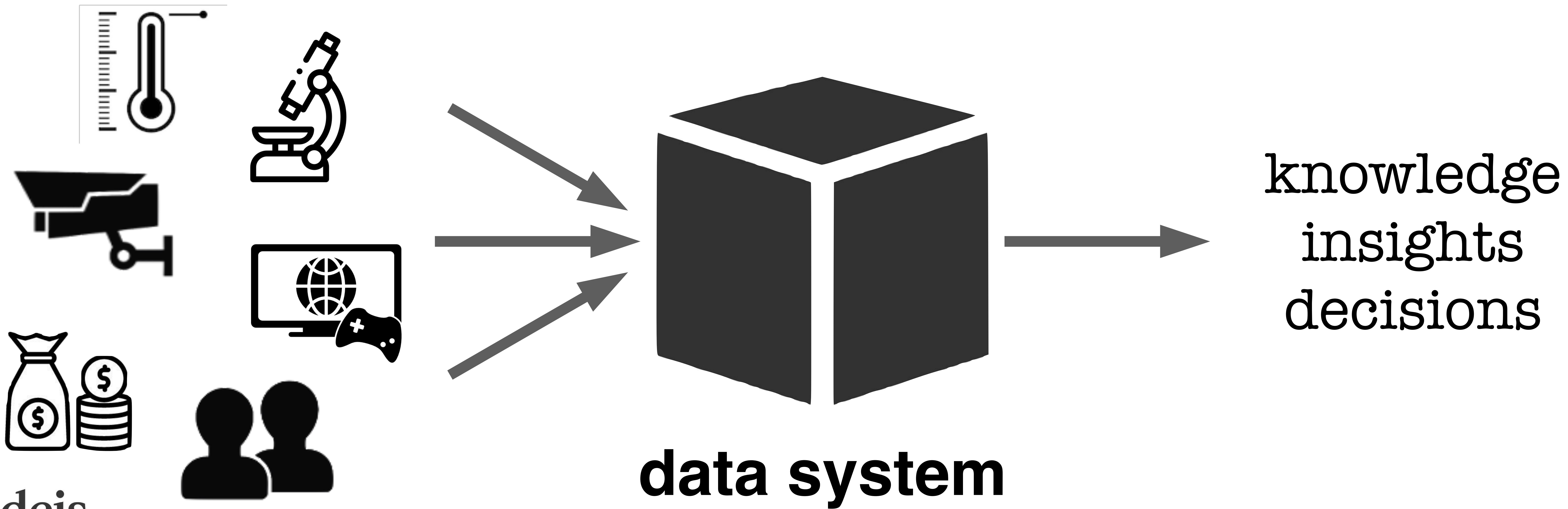
What are they, really?



Data systems

What are they, really?

A data system is an **end-to-end software system** that is responsible for storing data and providing access to the data through **efficient data movement.**



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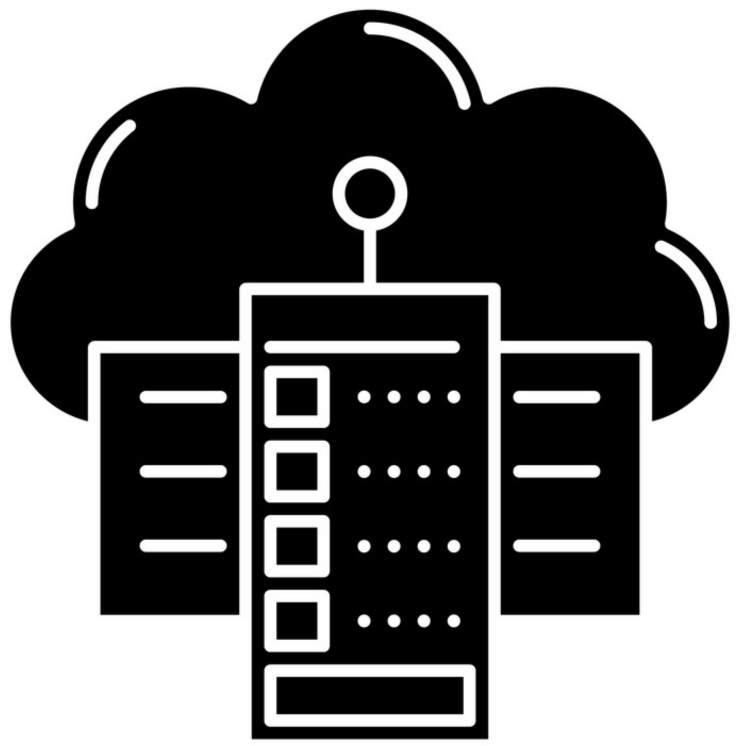
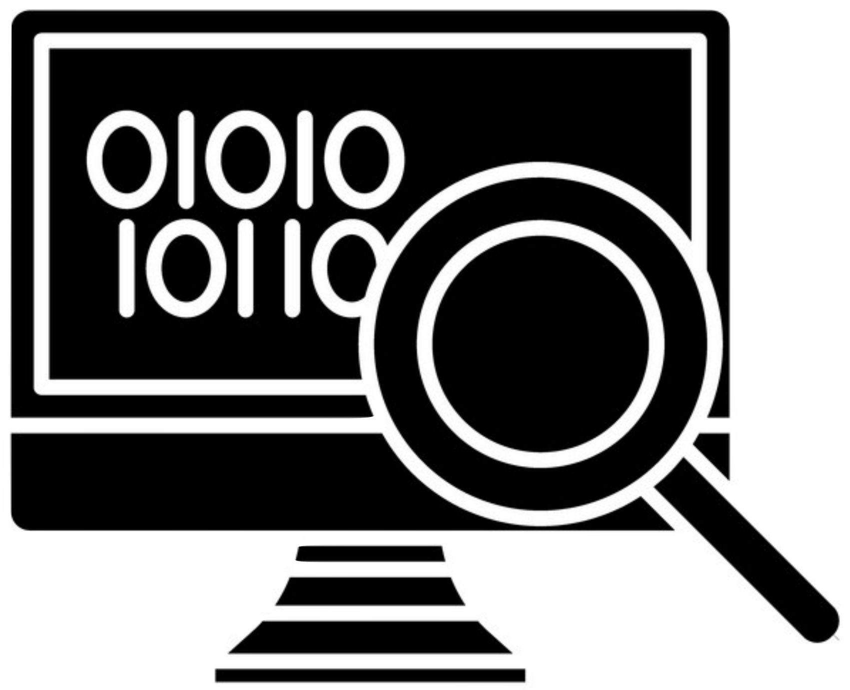


how we store data



how fast we can access and analyze data

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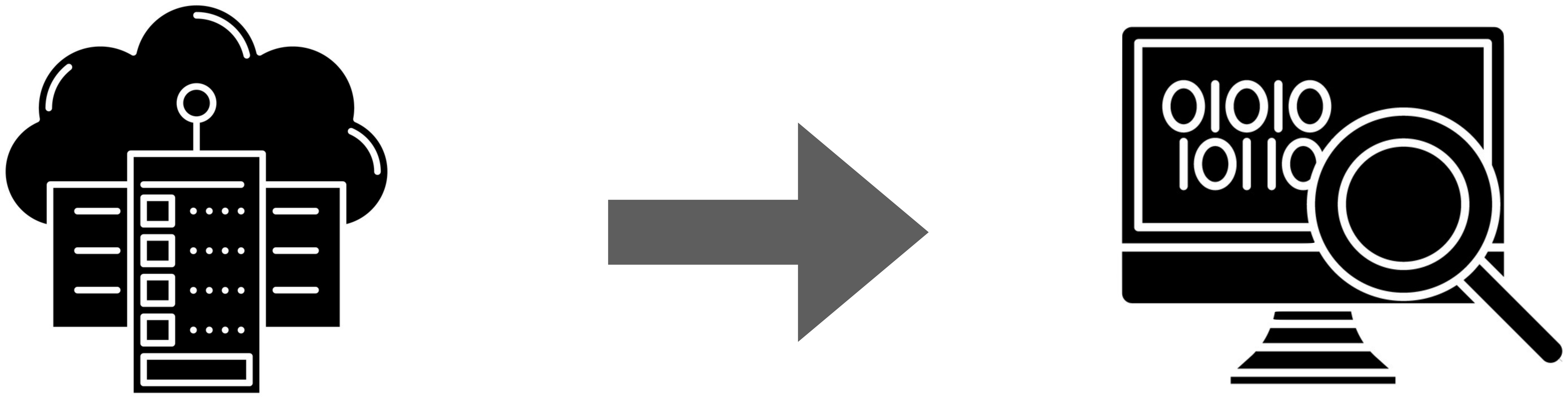
Data systems

What are they, really?



how we **store** data → how fast we can **access** and **analyze** data

70-80% of the **workload execution cost** comes from **data movement** | **20-30%** of it comes from **in-memory processing**

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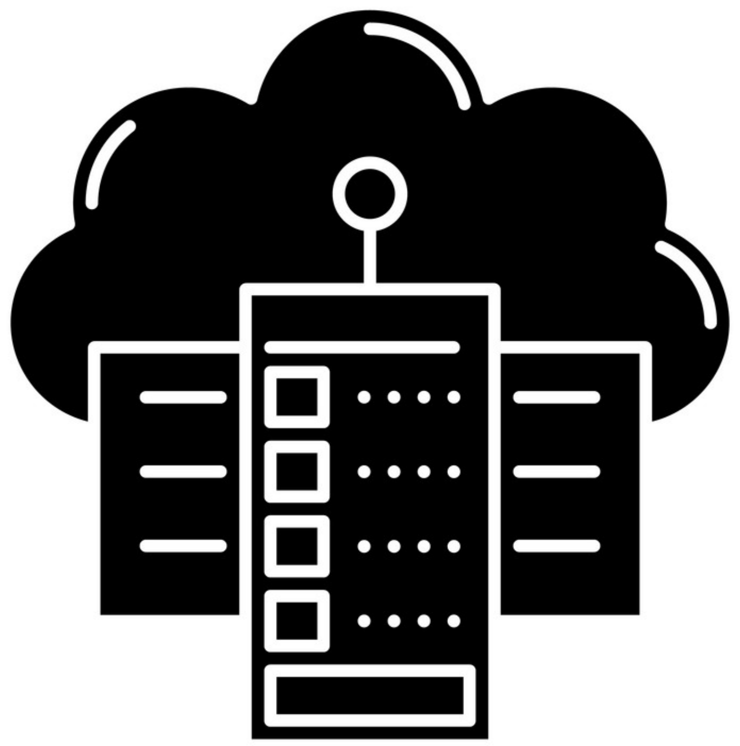
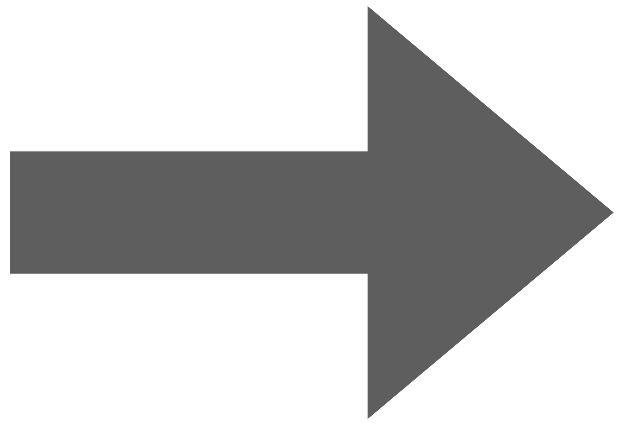
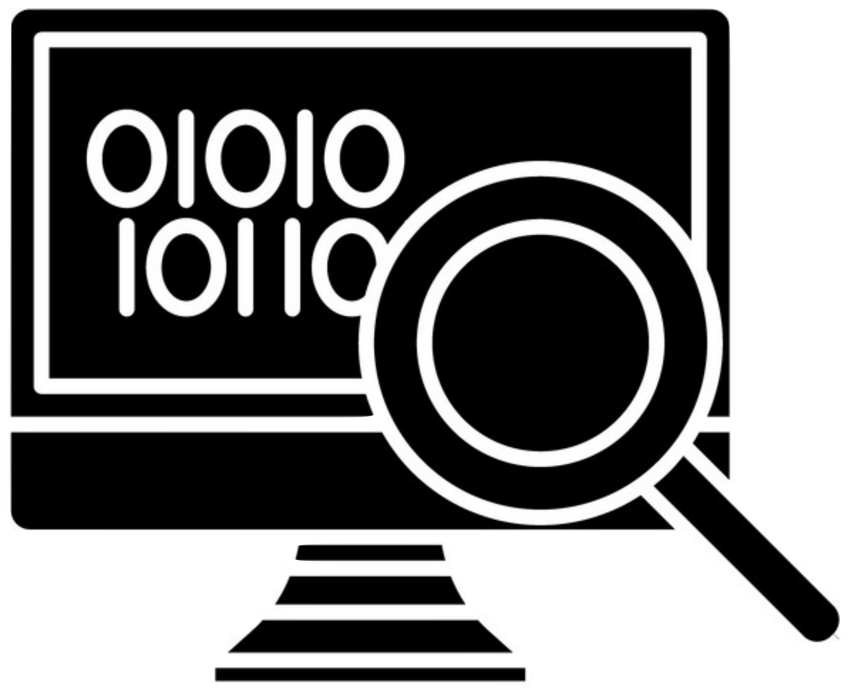
Data systems

What are they, really?



how we **store** data





how fast we can **access** and **analyze** data

70-80% of the **workload execution cost** comes from **data movement**

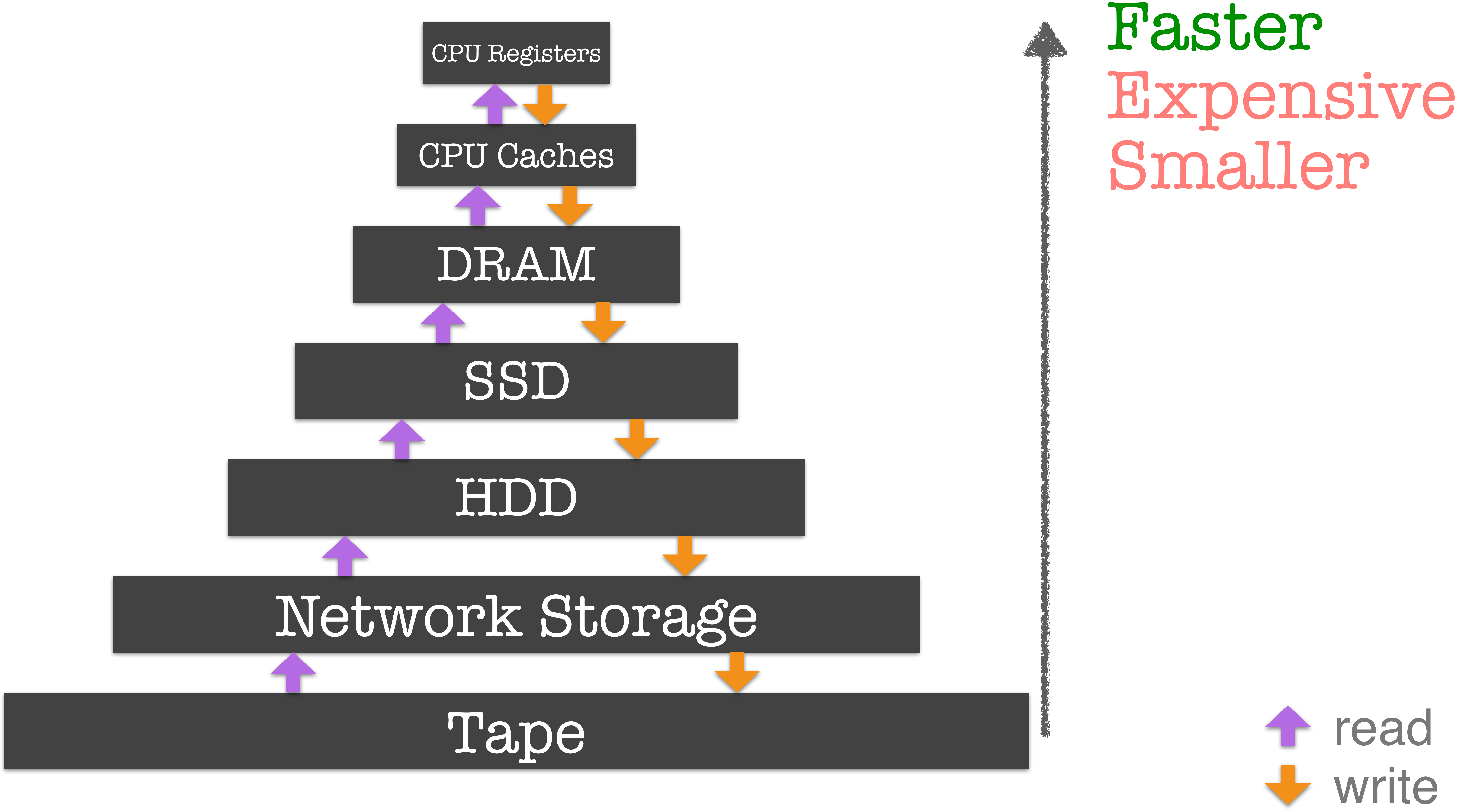
20-30% of it comes from **in-memory processing**

But why is **storage** such a **bottleneck**?

Storage hierarchy

Storage hierarchy

How data moves!



Storage hierarchy

How data moves!

Volatile

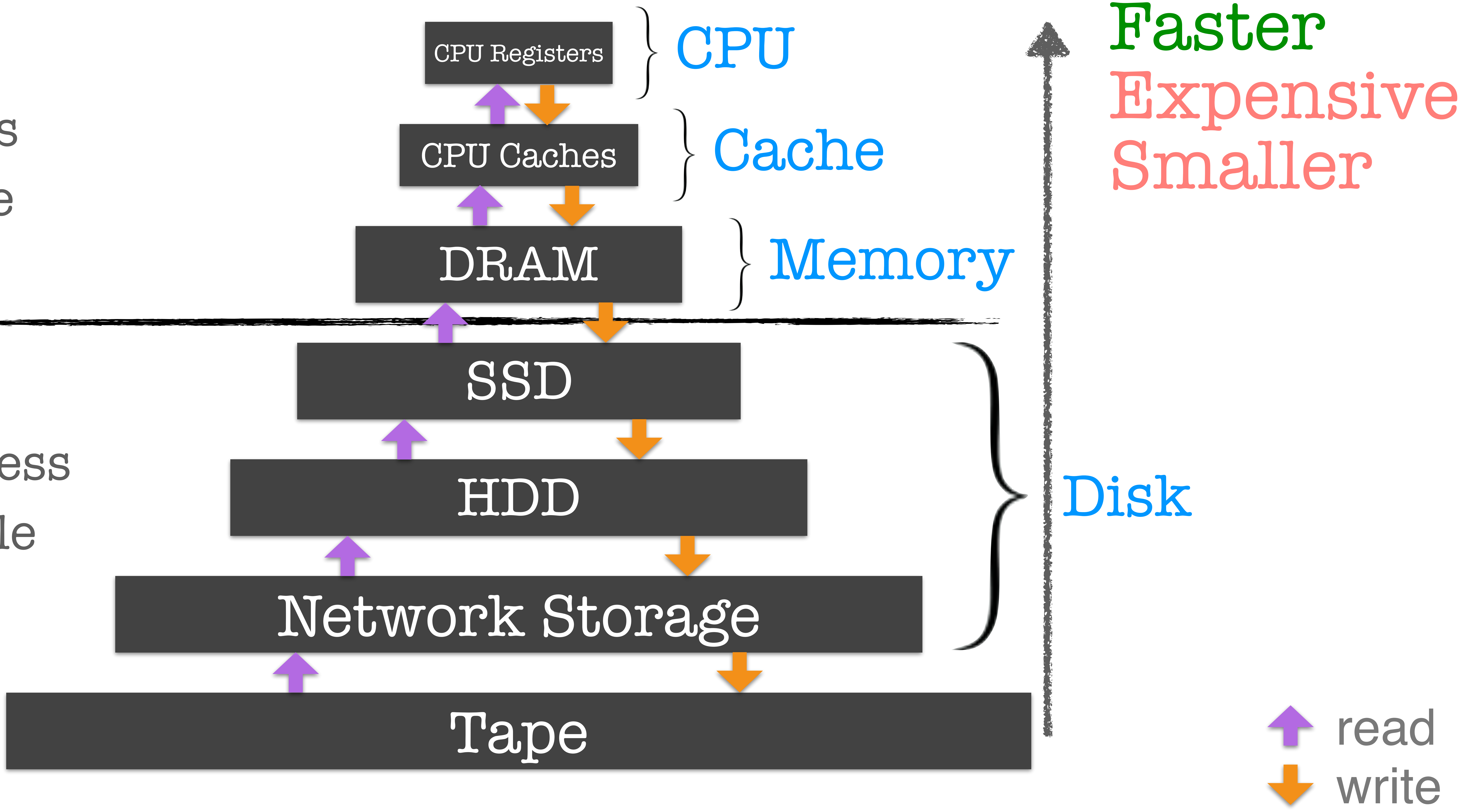
Random access

Byte accessible

Non-volatile

Sequential access

Block accessible



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Storage hierarchy

How data moves!

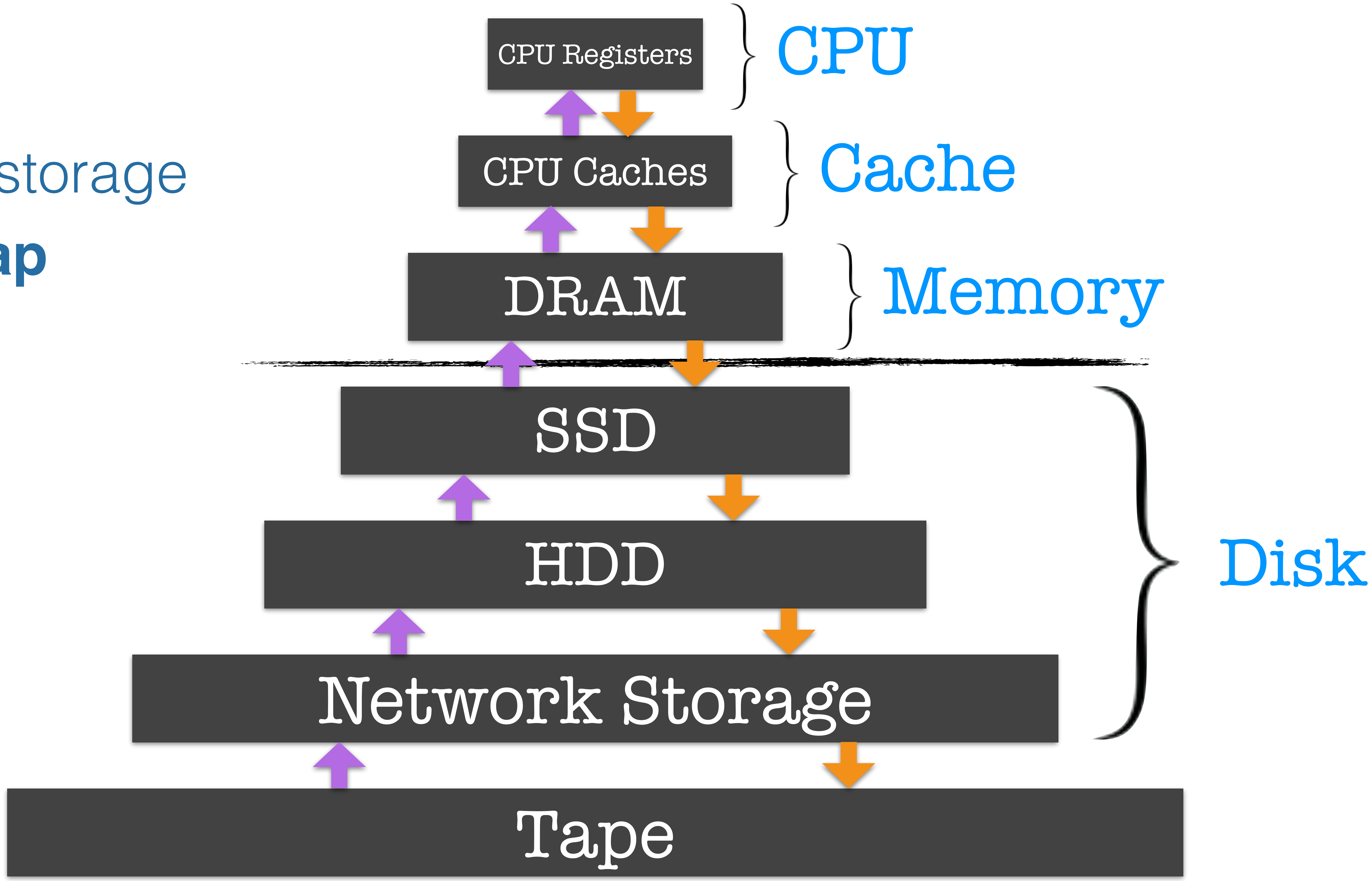
What is a **tape**?

sequential-only magnetic storage

super-slow but **super-cheap**

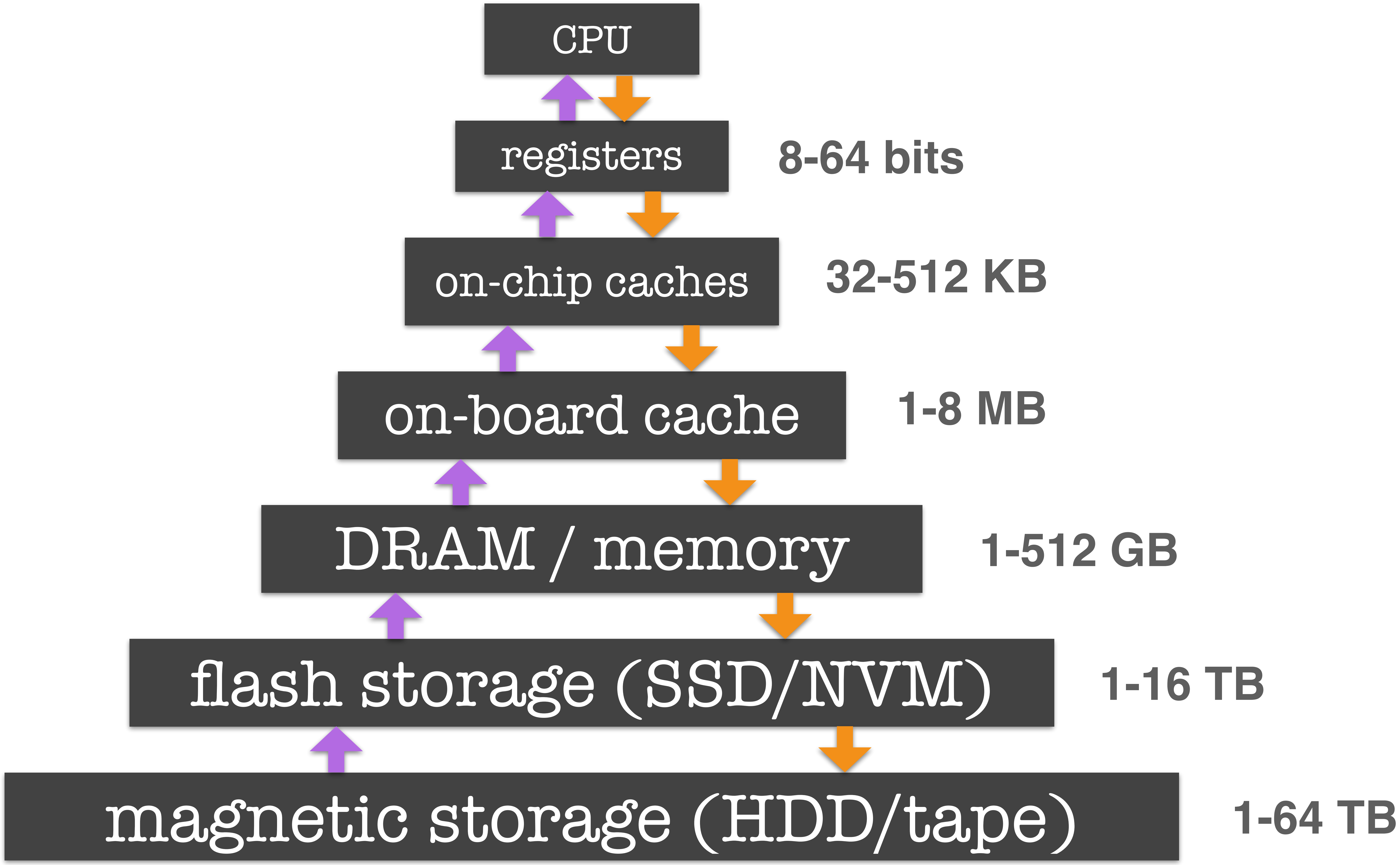
still a **multi-billion** industry

45TB @ $150



Storage hierarchy: updated

How data moves!



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Latency numbers

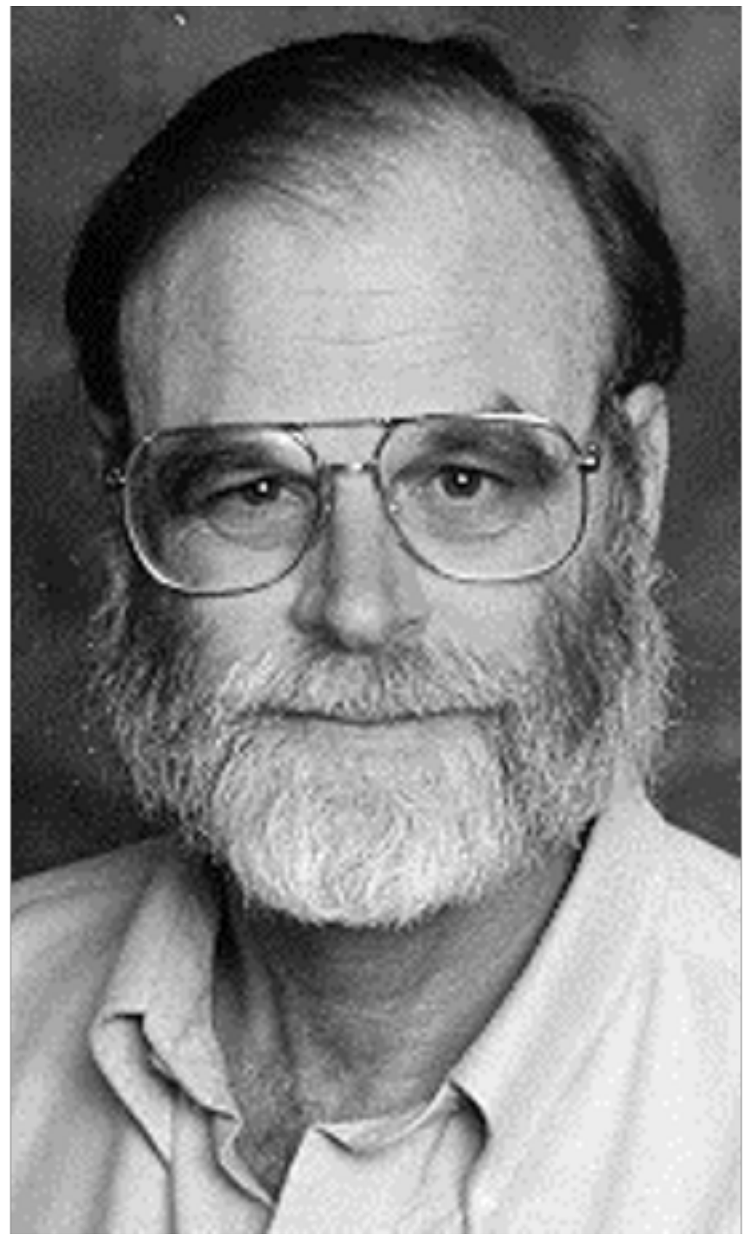
How fast is access?

Access latency	Memory type
1 ns	CPU/register
4 ns	on-chip cache
10 ns	on-board cache
100 ns	DRAM
16,000 ns	SSD
2,000,000 ns	HDD
1,000,000,000 ns	Tape

Latency numbers

How fast is access?

Access latency	Memory type	Scaling up
1 ns	CPU/register	1 s
4 ns	on-chip cache	4 s
10 ns	on-board cache	10 s
100 ns	DRAM	100 s
16,000 ns	SSD	4.44 hours
2,000,000 ns	HDD	3.3 weeks
1,000,000,000 ns	Tape	31.7 years



Jim Gray, IBM, Microsoft
ACM Turing Award 1998

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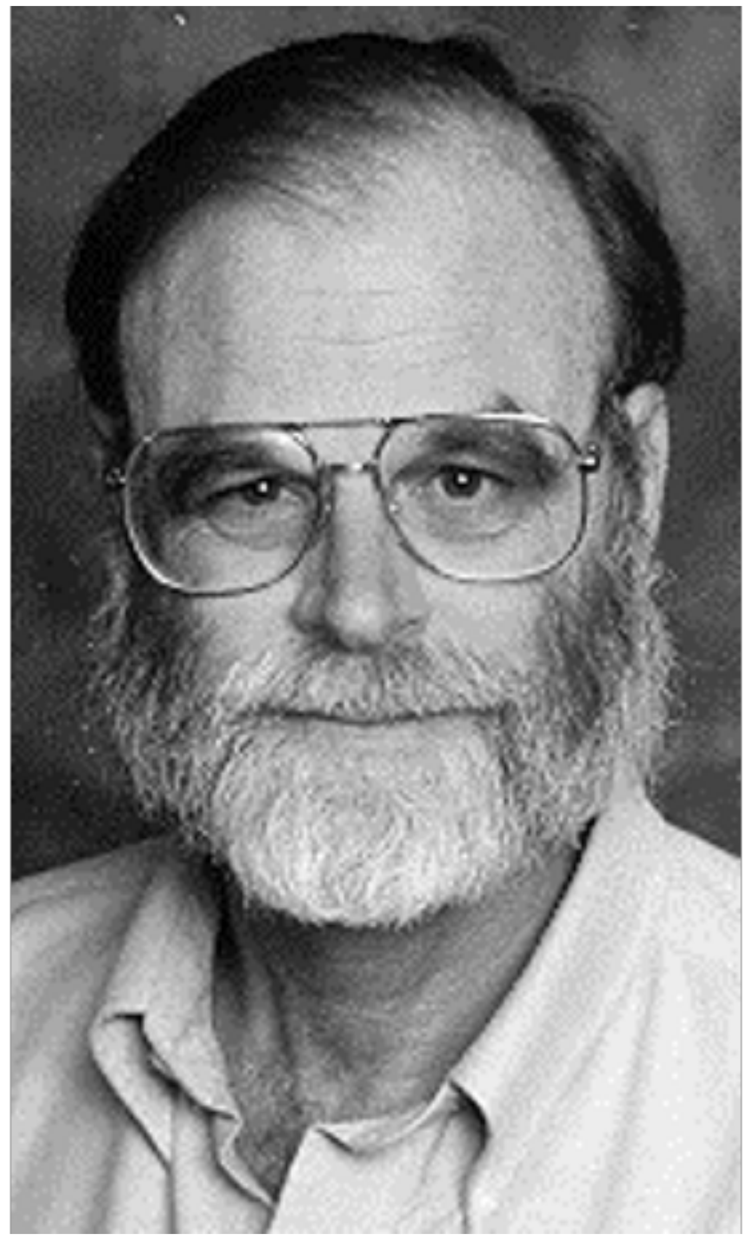
Latency numbers

How fast is access?



Jim Gray, IBM, Microsoft
ACM Turing Award 1998

Access latency	Memory type	Scaling up	Jim Gray's analogy
1 ns	CPU/register	**1 s**	**My head**
4 ns	on-chip cache	**4 s**	**This room**
10 ns	on-board cache	**10 s**	**This building**
100 ns	DRAM	**100 s**	**Washington, DC**
16,000 ns	SSD	**4.44 hours**	**-**
2,000,000 ns	HDD	**3.3 weeks**	**Pluto**
1,000,000,000 ns	Tape	**31.7 years**	**Andromeda**

Disk (secondary storage) is SLOW!

Memory wall

Try not to jump the wall

computations happen here

CPU

register

on-chip cache

on-board cache

memory

flash storage

magnetic storage

Thought Experiment 1

What if data is **not found in cache**?

cache miss!

Memory wall

Try not to jump the wall

computations happen here

CPU

register

on-chip cache

10 ns — on-board cache

100 ns — memory

flash storage

magnetic storage

Thought Experiment 1

What if data is **not found in cache**?

cache miss — looking for something that is **not in the cache**

be careful when you go below the green line

Memory wall

Try not to jump the wall

computations happen here

- CPU
- register
- on-chip cache
- 10 ns — on-board cache
- 100 ns — memory
- flash storage
- magnetic storage

be careful when you go below the green line

Thought Experiment 2

What if data is **not found in memory**?

memory miss!

Memory wall

Try not to jump the wall

computations happen here

Latency	Level
	CPU
	register
	on-chip cache
10 ns	on-board cache
100 ns	memory
16,000 ns	flash storage
2 ms	magnetic storage

be careful when you go below the green line

Thought Experiment 2

What if data is **not found in memory**?

memory miss looking for something that is **not in the memory**

be VERY careful when you go below the red line

Access granularity

How much data to move

CPU

register

on-chip cache

on-board cache

memory

flash storage

magnetic storage

data movement

how we access data

how we store data

throughput of the system

extra/unnecessary data movement

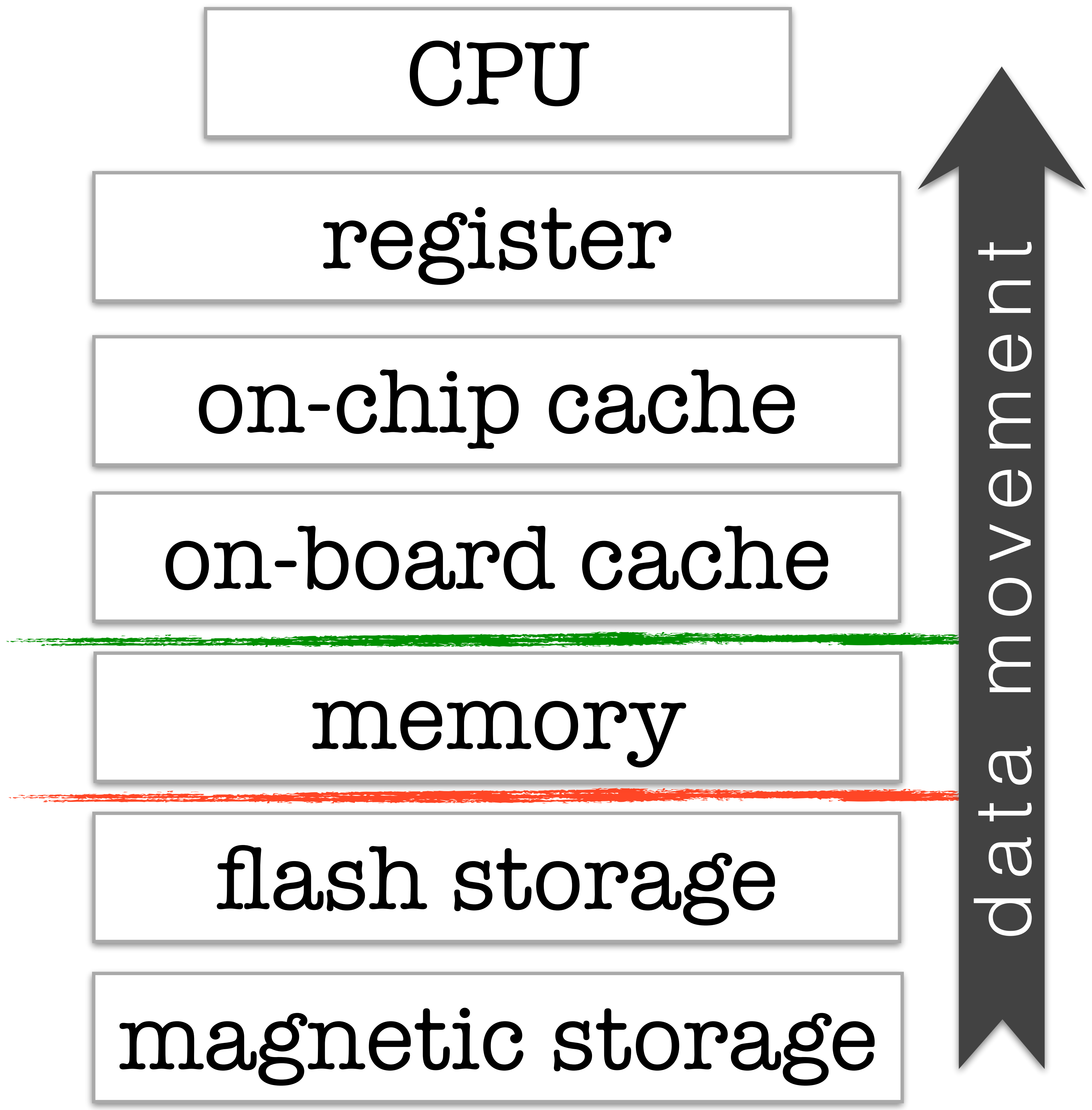
Thought Experiment 3

What causes this **unnecessary data movement**?

access granularity

Access granularity

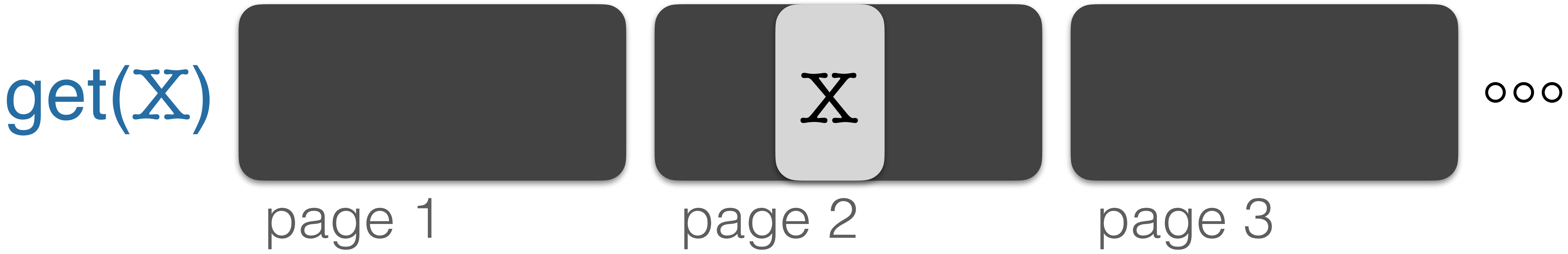
How much data to move



Thought Experiment 3

What causes this **unnecessary data movement**?

access granularity



we **cannot** read only X
have to read the **whole page**
this comes from the **hardware**

Let's **think** together

Understanding the implications of access granularity

memory
(size = 120 B)

40 B	40 B	40 B

SSD
(size = few GBs)

6 7 9 11 2	8 9 6 3 11	7 10 4 1 5	ooo
page 1	page 2	page 3	

page size = 5 x sizeof(integer) = 5 x 8 B = 40 B

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Let's **think** together

Understanding the implications of access granularity

query: **x<4**

memory
(size = 120 B)

SSD
(size = few GBs)

page 1	page 2	page 3	
6 7 9 11 2	8 9 6 3 11	7 10 4 1 5	ooo

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Understanding the implications of access granularity

query: **x<4**

~~binary search~~

memory
(size = 120 B)

6 7 9 11 2		

SSD
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6 7 9 11 2	8 9 6 3 11	7 10 4 1 5	ooo
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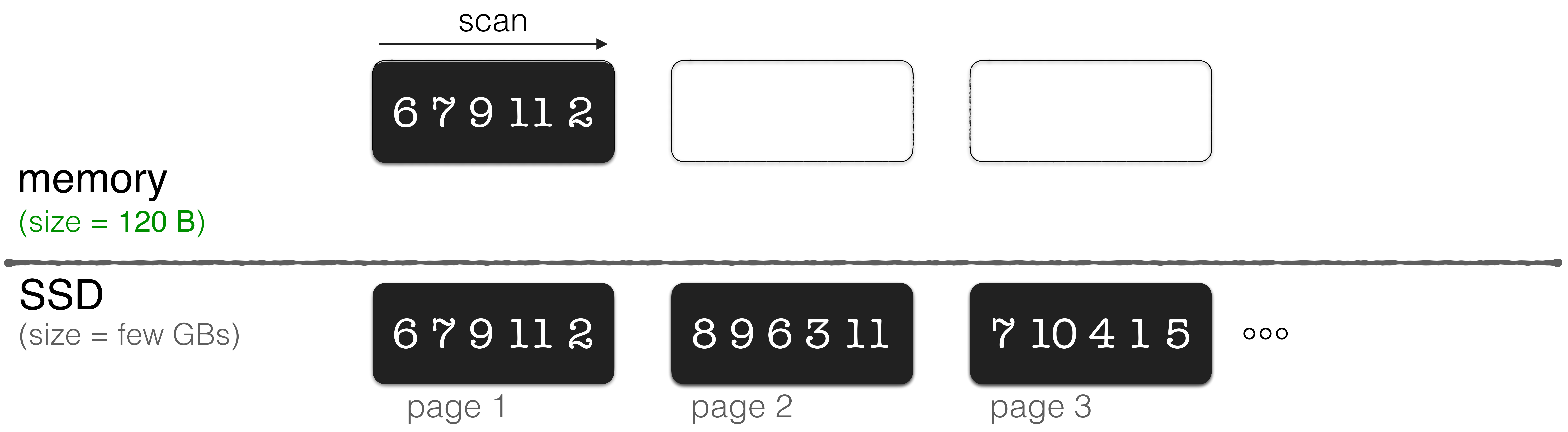

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Let's **think** together

Understanding the implications of access granularity

query: x<4

scan →

memory
(size = 120 B)

6 7 9 11 2		2
		output buffer

SSD
(size = few GBs)

page 1	page 2	page 3	
6 7 9 11 2	8 9 6 3 11	7 10 4 1 5	ooo

page size = 5 x sizeof(integer) = 5 x 8 B = 40 B

Let's **think** together

Understanding the implications of access granularity

query: x<4

40 B (1 I/O)

scan →

memory
(size = 120 B)

6 7 9 11 2		2
		output buffer

SSD
(size = few GBs)

6 7 9 11 2	8 9 6 3 11	7 10 4 1 5	ooo
page 1	page 2	page 3	

page size = 5 x sizeof(integer) = 5 x 8 B = 40 B

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Understanding the implications of access granularity

query: x<4

40 B (1 I/O)

scan → scan →

6 7 9 11 2 | 8 9 6 3 11 | 2 3

output buffer

memory
(size = 120 B)

SSD
(size = few GBs)

6 7 9 11 2 | 8 9 6 3 11 | 7 10 4 1 5 | ooo

page 1 | page 2 | page 3

page size = 5 x sizeof(integer) = 5 x 8 B = 40 B

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Let's **think** together

Understanding the implications of access granularity

query: x<4

80 B (2 I/O)

memory
(size = 120 B)

scan → 6 7 9 11 2

scan → 8 9 6 3 11

2 3
output buffer

SSD
(size = few GBs)

6 7 9 11 2 (page 1)

8 9 6 3 11 (page 2)

7 10 4 1 5 (page 3)

ooo

page size = 5 x sizeof(integer) = 5 x 8 B = 40 B

Let's **think** together

Understanding the implications of access granularity

query: x<4

80 B (2 I/O)

scan → scan →

7 10 4 1 5 | 8 9 6 3 11 | 2 3 1

output buffer

memory
(size = 120 B)

SSD
(size = few GBs)

6 7 9 11 2 | 8 9 6 3 11 | 7 10 4 1 5 | ooo

page 1 | page 2 | page 3

page size = 5 x sizeof(integer) = 5 x 8 B = 40 B

Let's **think** together

Understanding the implications of access granularity

query: x<4

$ 120 B (3 I/O)

scan → scan →

size of result set = 24 B

7 10 4 1 5	8 9 6 3 11	2 3 1

output buffer

memory
(size = 120 B)

SSD
(size = few GBs)

6 7 9 11 2	8 9 6 3 11	7 10 4 1 5	ooo
page 1	page 2	page 3	

page size = 5 x sizeof(integer) = 5 x 8 B = 40 B

What if we had an **oracle**?

What if we had the **perfect index**?

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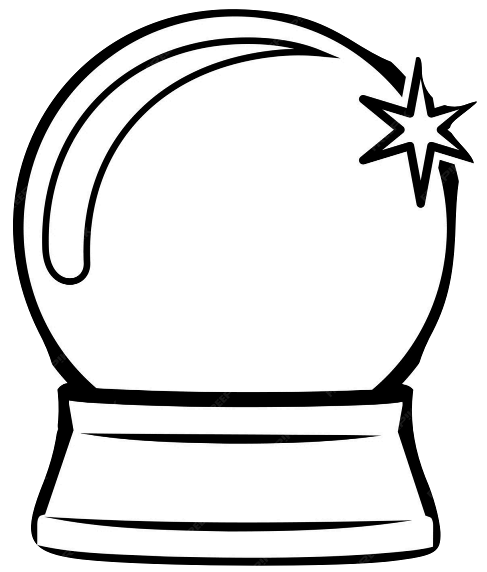
Let's **think** together

Understanding the implications of access granularity

query: x<4



gives us the **exact position** of the **qualifying entries**

memory
(size = 120 B)

SSD
(size = few GBs)

page 1	page 2	page 3	
6 7 9 11 2	8 9 6 3 11	7 10 4 1 5	ooo

page size = 5 x sizeof(integer) = 5 x 8 B = 40 B

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Understanding the implications of access granularity

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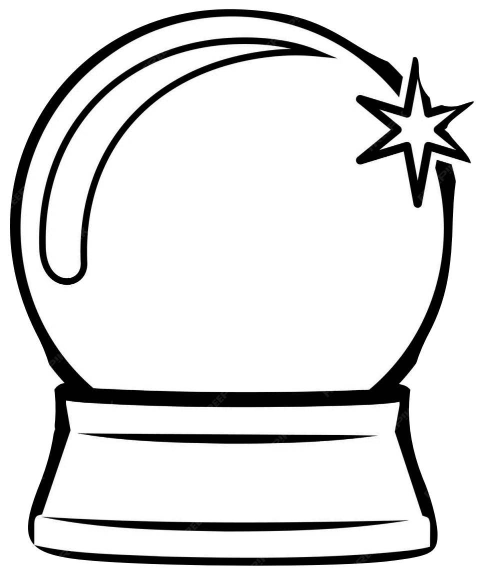

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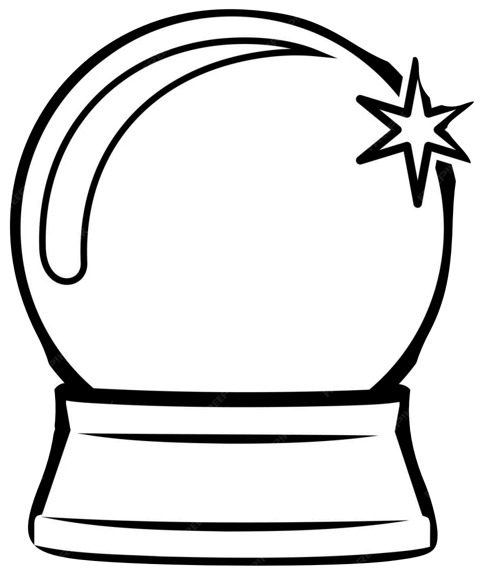

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oracle

memory (size = 120 B)

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SSD (size = few GBs)

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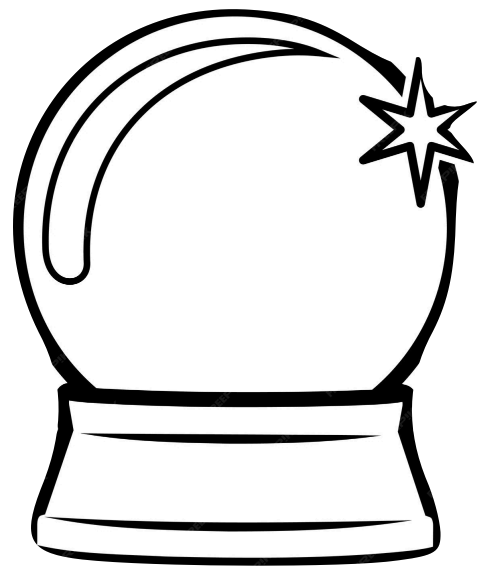

query: x<4

gives us the **exact position** of the **qualifying entries**

oracle

6 7 9 11 2

2

output buffer

memory
(size = 120 B)

SSD
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6 7 9 11 2 — page 1

8 9 6 3 11 — page 2

7 10 4 1 5 — page 3

ooo

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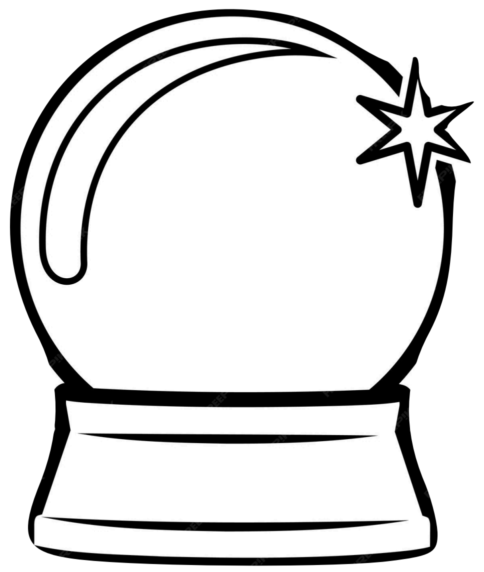

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40 B (1 I/O)

oracle

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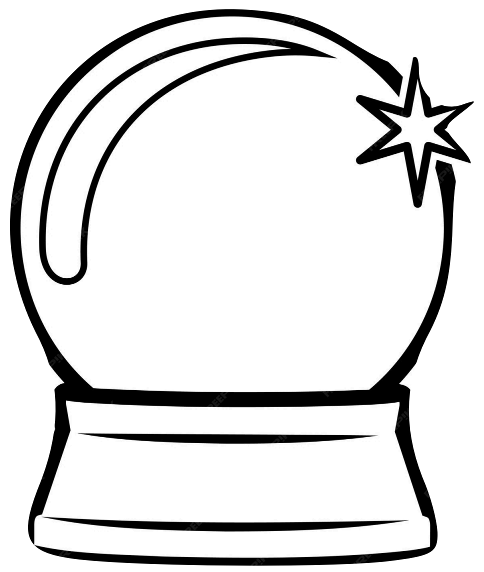

gives us the **exact position** of the **qualifying entries**

query: x<4

$ 40 B (1 I/O)

oracle oracle

memory
(size = 120 B)

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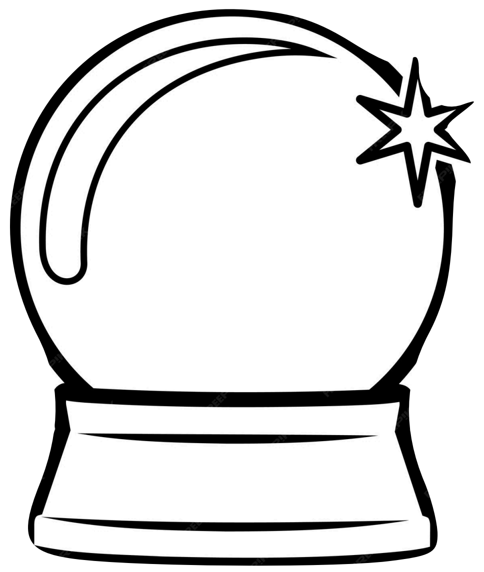

gives us the **exact position** of the **qualifying entries**

oracle

oracle

memory (size = 120 B)

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		output buffer

SSD (size = few GBs)

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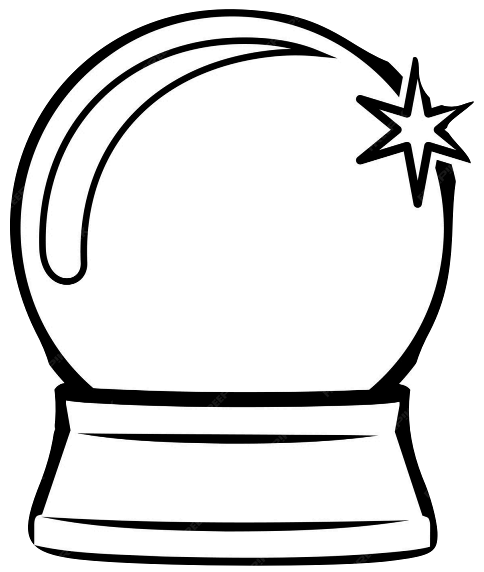

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memory (size = 120 B)

oracle ↓	oracle ↓	
7 10 4 1 5	8 9 6 3 11	2 3 1
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SSD (size = few GBs)

page 1	page 2	page 3	
6 7 9 11 2	8 9 6 3 11	7 10 4 1 5	ooo

page size = 5 x sizeof(integer) = 5 x 8 B = 40 B

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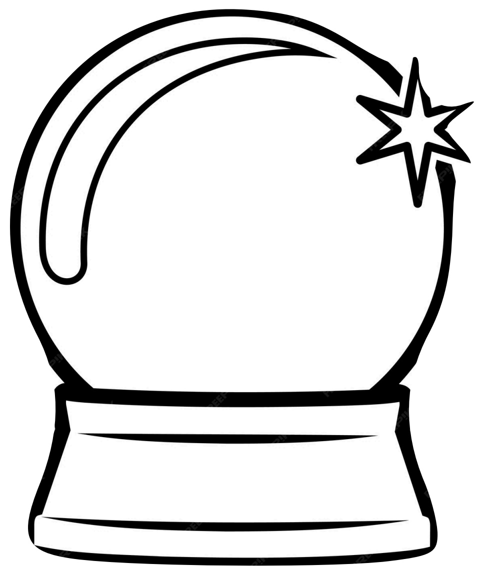
Let's **think** together

Understanding the implications of access granularity



query: x<4

120 B (3 I/O)

gives us the **exact position** of the **qualifying entries**

oracle

oracle

size of result set = 24 B

7 10 4 1 5	8 9 6 3 11	2 3 1
		output buffer

memory
(size = 120 B)

SSD
(size = few GBs)

6 7 9 11 2	8 9 6 3 11	7 10 4 1 5	ooo
page 1	page 2	page 3	

page size = 5 x sizeof(integer) = 5 x 8 B = 40 B

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Was the index **helpful**?

Let's **think** together

Understanding the implications of access granularity

gives us the **exact position** of the **qualifying entries**

Thought Experiment 4

For which **query** would an oracle **help us**?

Thought Experiment 5

When do we **use an oracle** and when **not**?

memory
(size = 120 B)

SSD
(size = few GBs)

page 1	page 2	page 3	
6 7 9 11 2	8 9 6 3 11	7 10 4 1 5	ooo

page size = 5 x sizeof(integer) = 5 x 8 B = 40 B

Storing data

Things to keep in mind

How we store (write) data heavily determines the performance of the system

Disk is 6 orders of magnitude slower than CPU

SSDs are 4 orders of magnitude slower

Memory is 3 orders of magnitude slower

Random vs. **Sequential** access

So, be VERY careful!

Avoid disk accesses (reads/writes) whenever possible

I/Os to secondary storage is *always* **slow**!

Sequential access

read **each block exactly once**; process it; discard it; read next block

modern hardware can predict and **prefetch**; maximize performance

Random access

read a block; process it **partially**; discard it; may **read** the block **again**

often leads to **read amplification**

Random vs. **Sequential** access

So, be VERY careful!

Sequential access

read **each block exactly once**; process it; discard it; read next block

modern hardware can predict and **prefetch**; maximize performance

Random access

read a block; process it **partially**; discard it; may **read** the block **again**

often leads to **read amplification**

Thought Experiment 6

Are **random accesses** always **bad**?

Not, if we can avoid a large number of I/Os

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Project 1

Testing the waters!

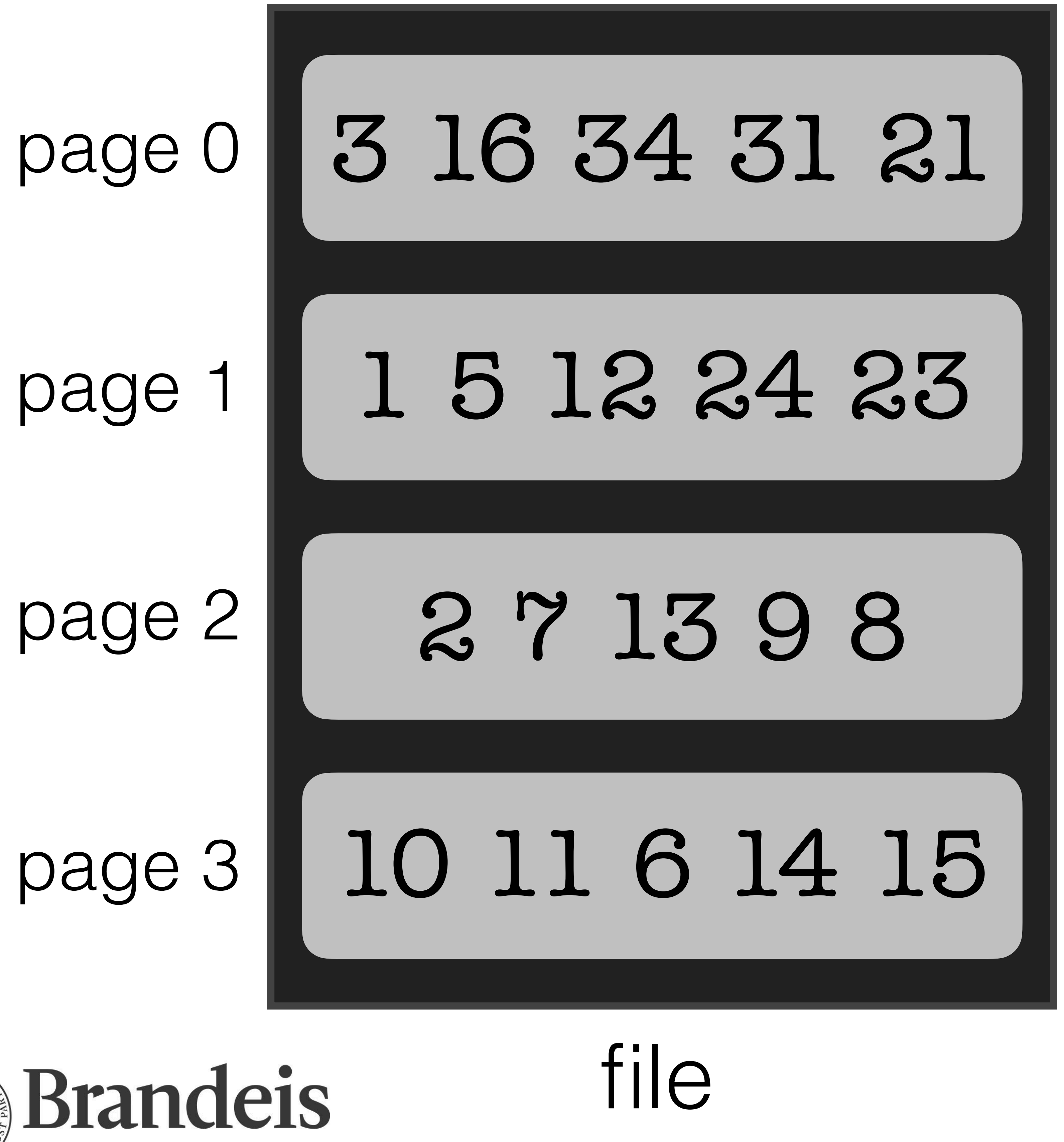
Implementing a Simple Zone Map

zone map: A **light-weight index** data structure that helps in **avoiding expensive I/Os** to secondary storage

Project 1

Testing the waters!

Implementing a Simple Zone Map



data on disk is stored in **files** (heap, sorted)

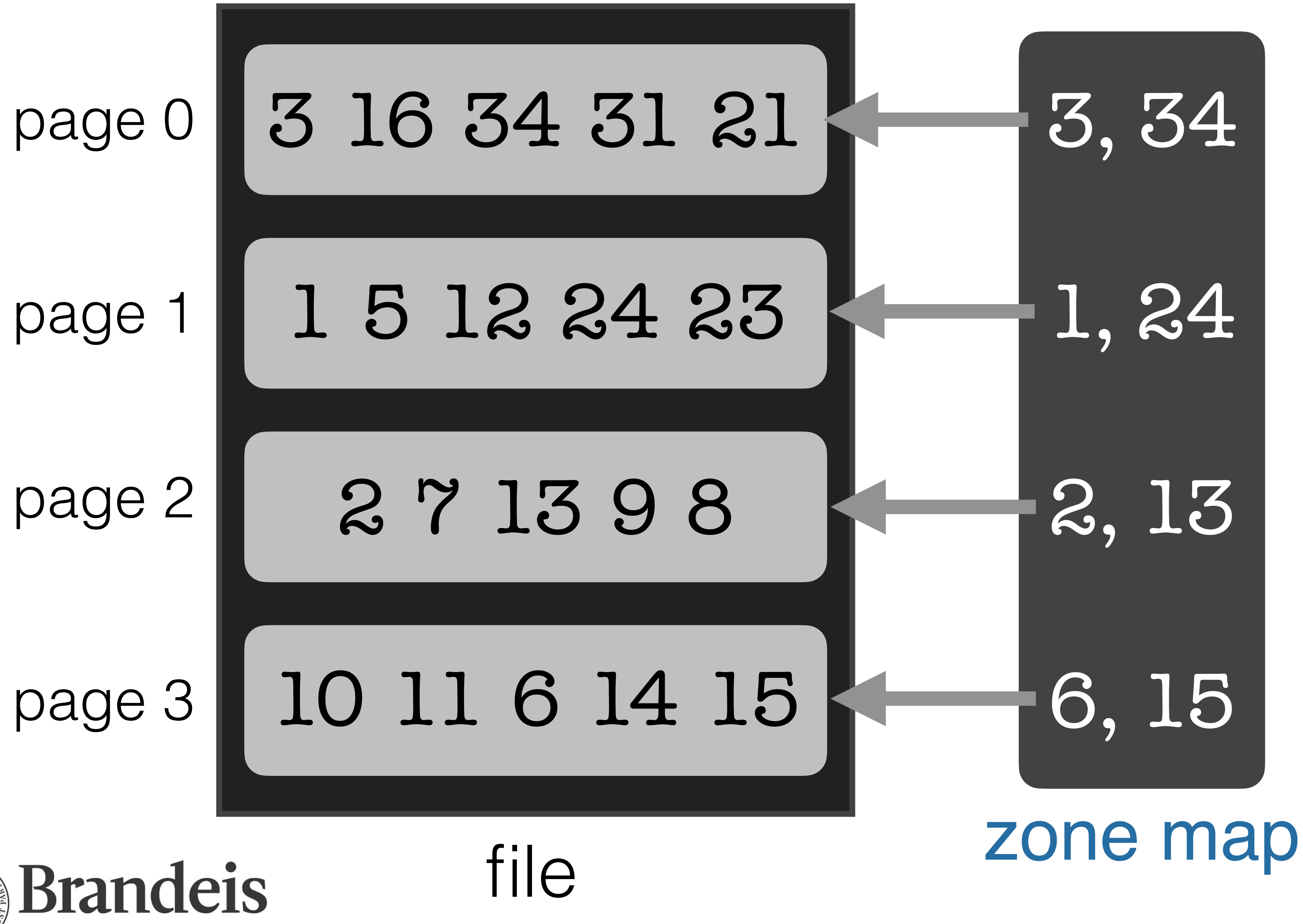
a file is a collection of **pages** (blocks)

within the page there are **data entries**

Project 1

Testing the waters!

Implementing a Simple Zone Map



w/o ZM: queries take 4 I/Os

with ZM: query: x<4: 3 I/Os

x<12: 4 I/O

x=1: 1 I/O

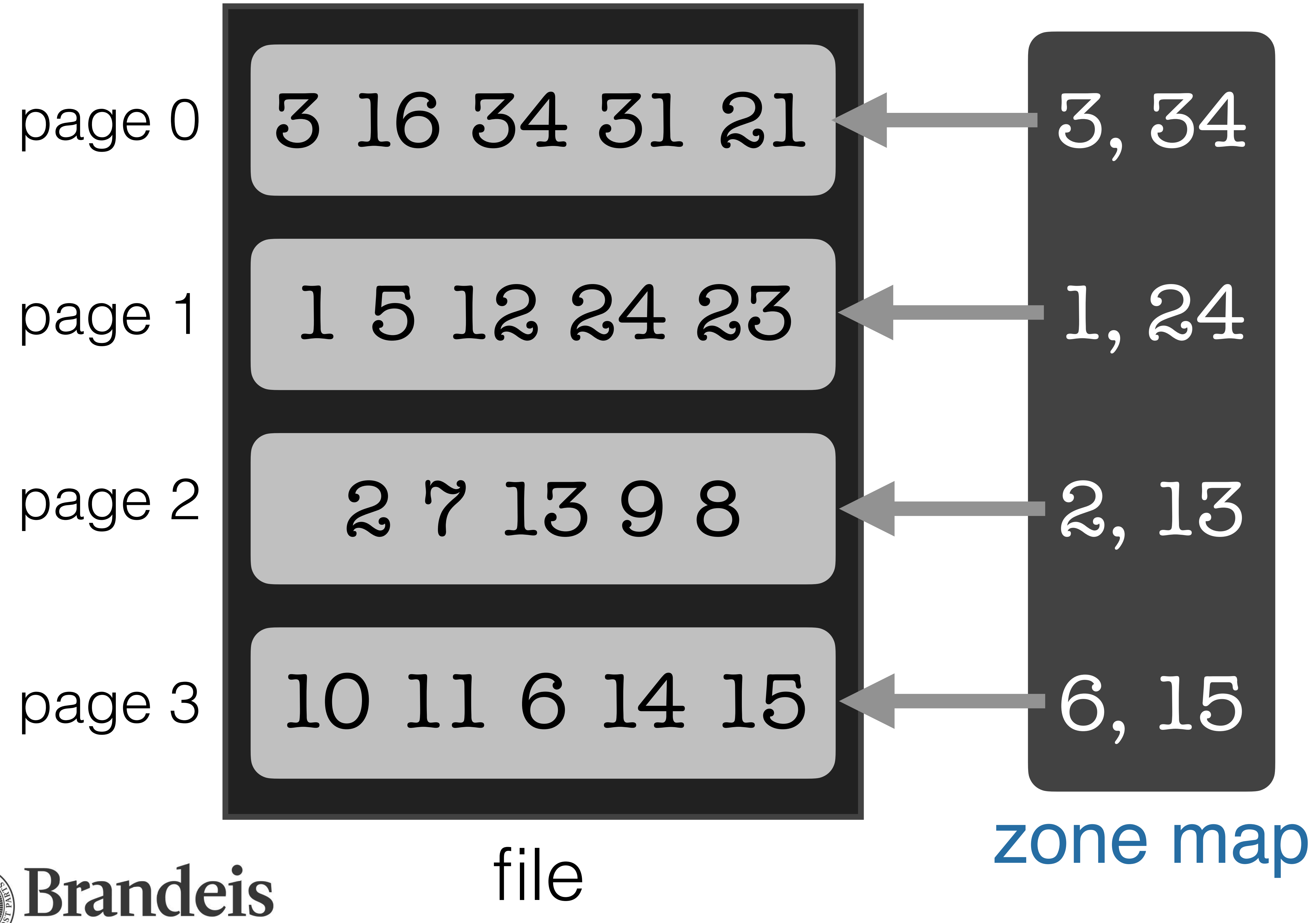
x=20: 4 I/O

Useful for some queries;
but never harmful!

Project 1

Testing the waters!

Implementing a Simple Zone Map



w/o ZM: queries take 4 I/Os

with ZM: query: x<4: 3 I/Os

x<12: 4 I/O

x=1: 1 I/O

x=10: 4 I/O

Thought Experiment 6

Are **zone maps** more or less useful if data is **sorted**?

Readings for next class

Papers, papers, and papers

<u>The Seattle Report on Database Research</u>
— J. Hellerstein, M. Stonebraker and J. Hamilton
SIGMOD Record, 2022

<u>The Seattle Report on Database Research</u>
— D. Abadi, P. Boncz, S. Harizopoulos, S. Idreos, S. Madden
SIGMOD Record, 2018

learn to **read technical papers**

learn to **critique constructively**

learn to **prepare slides & present**

Your Lecturer

That's me!

Subhadeep Sarkar

Name in Bengali: শুভদীপ সরকার

Post-doc 2: Boston University
Post-doc 1: Inria, France
PhD: Indian Institute of Technology, Kharagpur

Things I love: sports, adventure, animals, board games

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Assignment submission

And grading!

gradescope

Code: **PYG88X**

don't be late in your submissions!

Next time in COSI 167A

Introduction to column stores

fundamentals of data **storage**

introduction to **row-stores** and **column-stores**

COSI 167A
Advanced Data Systems

Class 2

Data Systems 101

Prof. Subhadeep Sarkar

https://ssd-brandeis.github.io/COSI-167A/

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