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CS 561: Data Systems Architectures

class 2

Data Systems 101

Prof. Manos Athanassoulis

https://bu-disc.github.io/CS561/

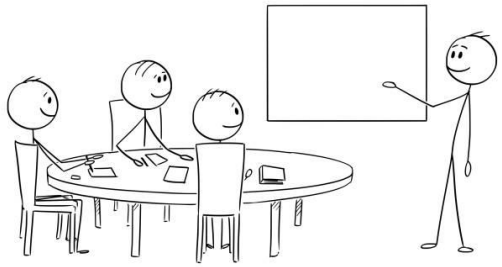
some reminders

no smartphones 

no laptop 

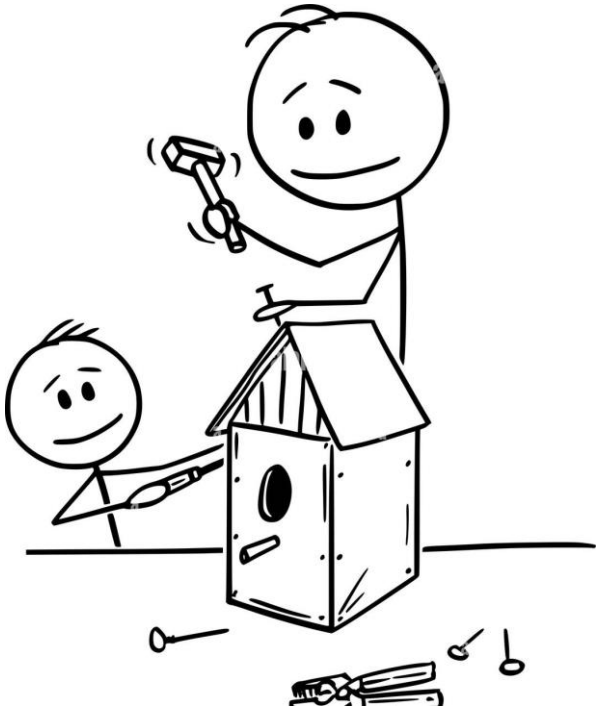
What do we do in this class?

reading papers



presentations

quizzes + exam



projects

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class summary

2 classes per week & OH/Labs 4 multiple per week

each student

1 paper discussion (as presenter or critic or proponent) + Quizzes + exam

project 0 (individual project) + project 1 (group project)

systems or research project (group project)

proposal + mid-semester report + final report/presentation

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Projects

project 0

A small implementation project
to sharpen dev skills

<u>independent project</u>

Due on Jan 31, 2025

AND

project 1

A medium project to give you a flavor of
large-scale production system

<u>groups of 3</u>

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Projects

AND

project 0

A small implementation project
to sharpen dev skills

<u>independent project</u>

Due on Jan 31, 2025

project 1

A medium project to give you a flavor of
large-scale production system

<u>groups of 3</u>

Start forming groups NOW!

Due on Feb 14, 2025

Projects

OR

systems project

groups of 3

implementation-heavy C/C++ project

research project

groups of 3

pick a subject (list available on the website)

design & analysis

experimentation

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Projects

OR

systems project

groups of 3

implementation-heavy C/C++ project

1. Proposal
2. Mid-semester report
3. Final report + Presentation

research project

groups of 3

pick a subject (list available on the website)

more to come!

design & analysis

experimentation

class timeline

discussions
interaction in OH & Lab
questions

Week 1
form groups for project 1

Week 2
project 0 by 31/1
start project 1

Week 4
project 1 by 2/14

Week 5
submit project proposal by 2/23

Week 9
submit mid-semester
project report by 3/22

Week 15: Project presentations
submit all material by 4/26

now

Quizzes may start from class 5!

Week 7 (March 3-7)
meeting with Project Mentor/TF

Week 11 (March 31-April 4)
meeting with Project Mentor/TF

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Piazza

2 classes per week & OH/Labs multiple times per week

all discussions & announcements

http://piazza.com/bu/spring2026/cs561/

also available on class website

We have added everyone who already registered!

Please double-check!

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size (volume)

rate (velocity)

sources (variety)

veracity & value

big data

(it's not only about size)

The 3 V's

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size (volume)

rate (velocity)

sources (variety)

veracity & value

big data

(it's not only about size)

The 3 V's

+ our ability to collect ***machine-generated*** data

 scientific experiments

 sensors

social 

Internet-of-things 

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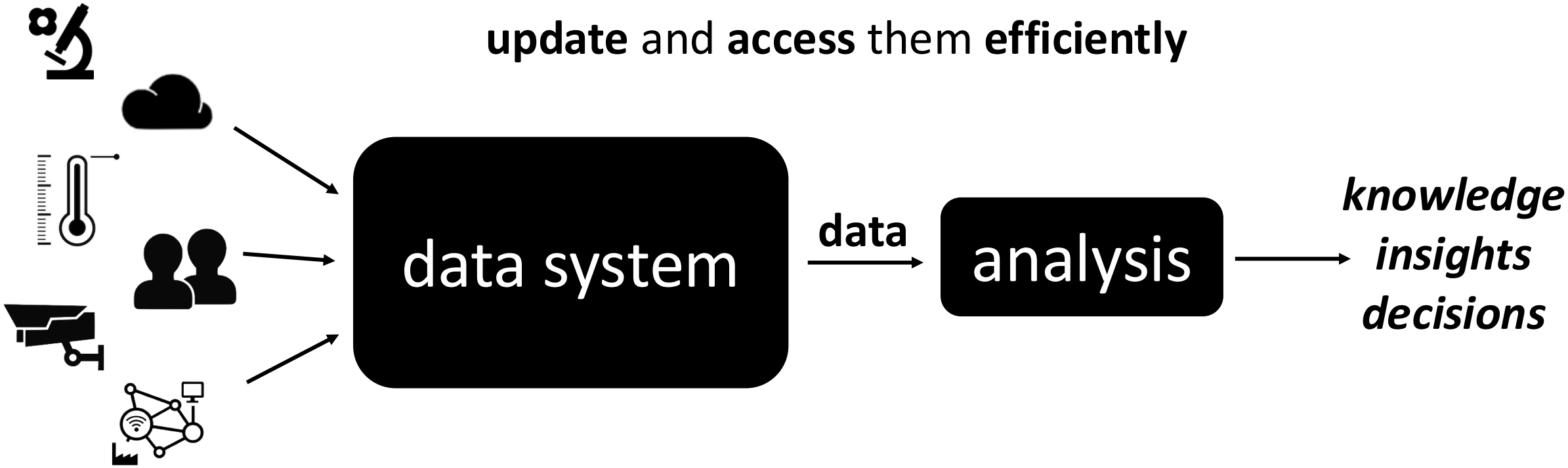
a **data system** is a large software system
that **stores data**, and provides the **interface** to
update and **access** them **efficiently**



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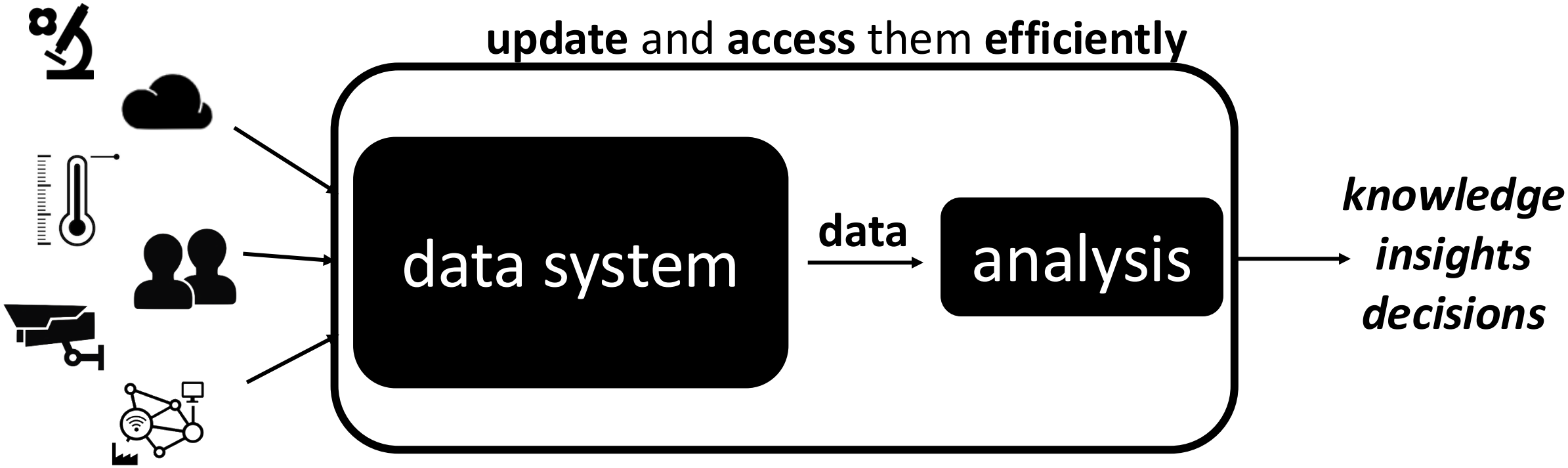

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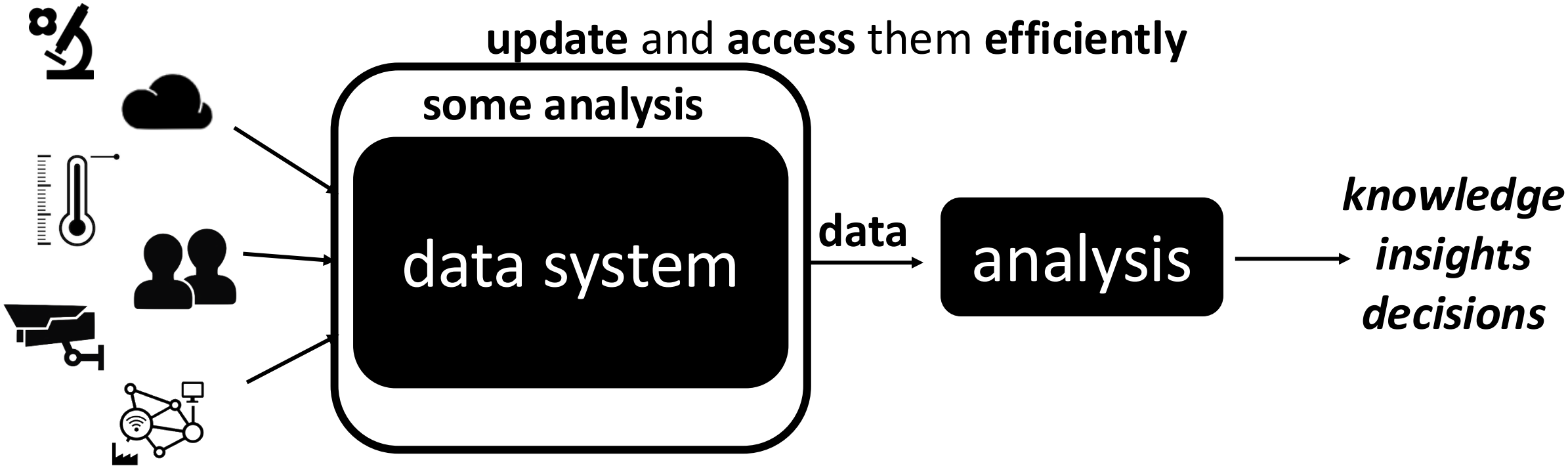
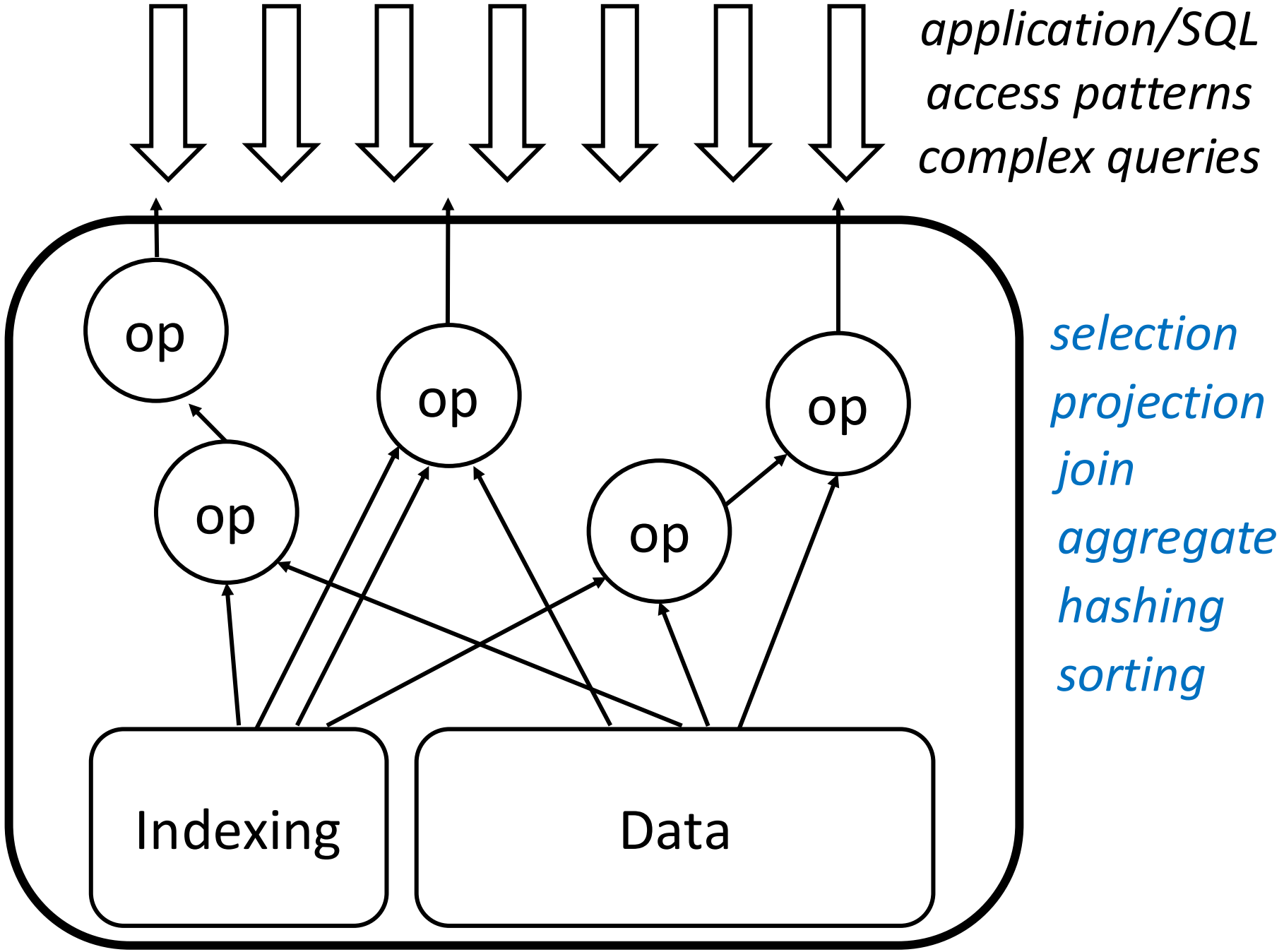


data system: breaking the blackbox

algorithms & operators

data & metadata



selection
projection
join
aggregate
hashing
sorting

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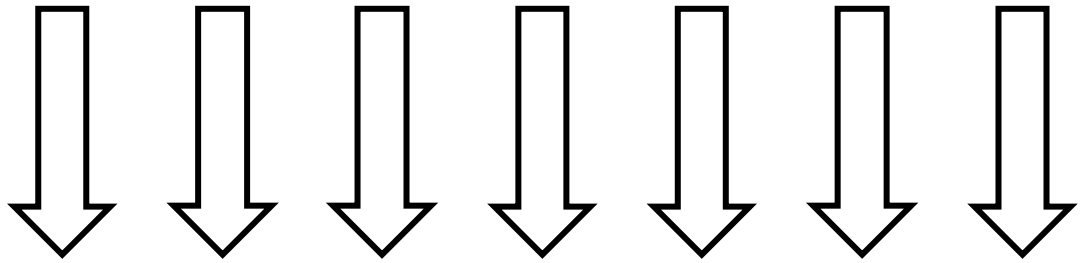

application/SQL
access patterns
complex queries

modules

Query Parser

Query Compiler

Optimizer

Evaluation Engine

Memory/Storage Management

Indexing

Transaction Management

memory hierarchy

CPU

Caches

Memory

Disk

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growing environment

DB

ACID
large systems
complex
lots of tuning

noSQL

BASE
simple, clean
“just enough”

>$200B by 2020, growing at 11.7% every year

[The Forbes, 2016]

growing environment

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$3B by 2020, growing at 20% every year

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growing environment

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large systems
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BASE
simple, clean
"just enough"

more **complex** applications

need for **scalability**

newSQL

>$200B by 2020, growing at 11.7% every year

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growing environment

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large systems
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more **complex** applications

need for **scalability**

>$200B by 2020, growing at 11.7% every year

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newSQL

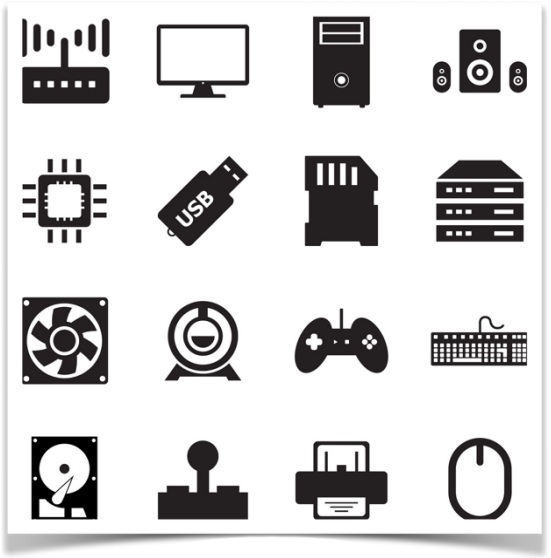
$3B by 2020, growing at 20% every year

[Forrester, 2016]

growing need for tailored systems

more data

new hardware



new applications

new performance goals

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data systems & the hardware

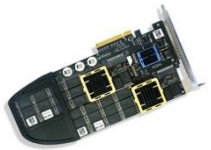
memory hierarchy

CPU

on-chip cache

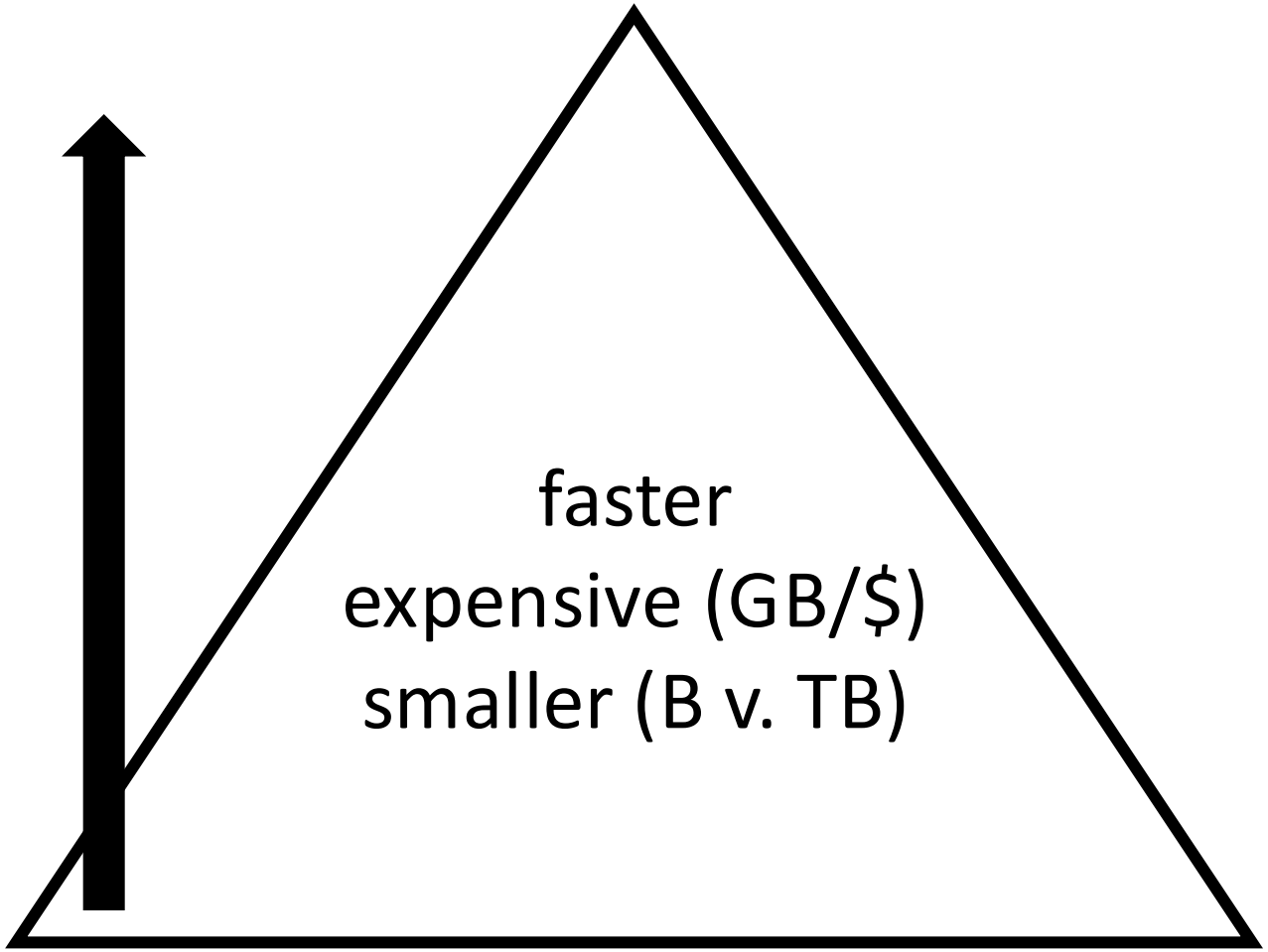
on-board cache

main memory



flash storage

magnetic disks



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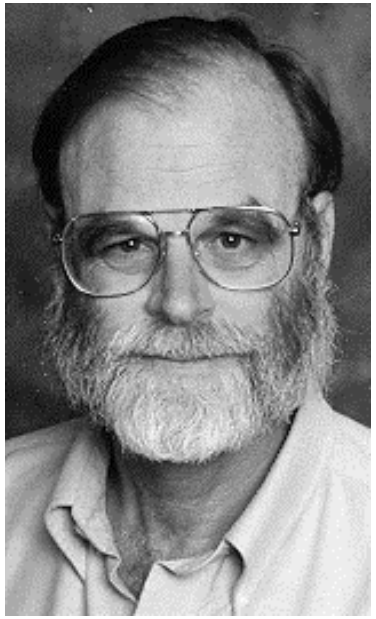
memory hierarchy (by Jim Gray)



Jim Gray, IBM, Tandem, Microsoft, DEC

ACM Turing Award 1998

ACM SIGMOD Edgar F. Codd Innovations award 1993

	registers/CPU	my head ~0
2x	**on chip cache**	this room 1min
10x	**on board cache**	this building 10min
100x	**memory**	Washington, DC 5 hours
10^6x	**disk**	Pluto 2 years
10^9x	**tape**	Andromeda 2000 years

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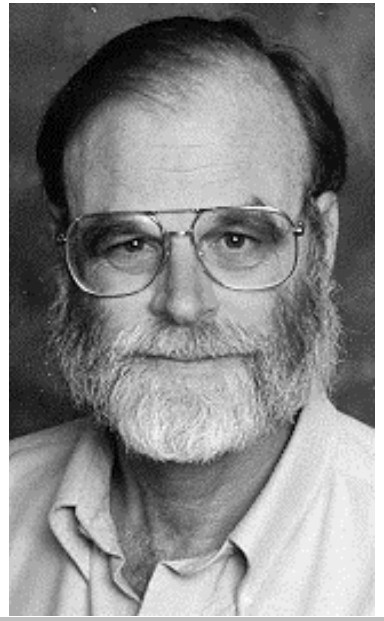
memory hierarchy (by Jim Gray)

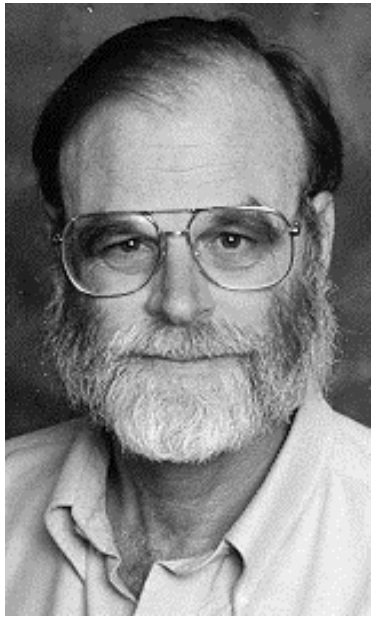


	registers/CPU	my head ~0
2x	**on chip cache**	this room 1min
10x	**on board cache**	this building 10min

45TB @ $150

tape?
sequential-only magnetic storage
still a multi-billion industry

Jim Gray (a great scientist and engineer)



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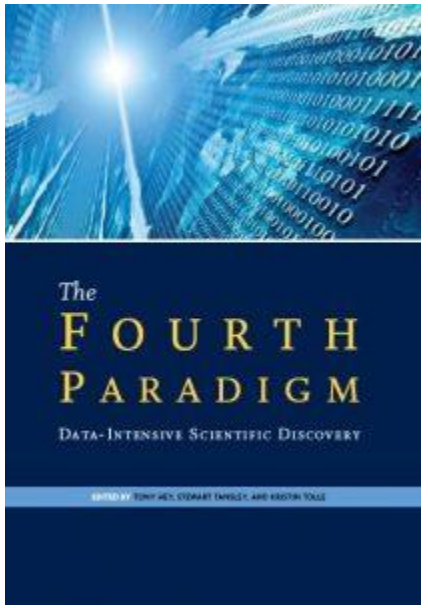
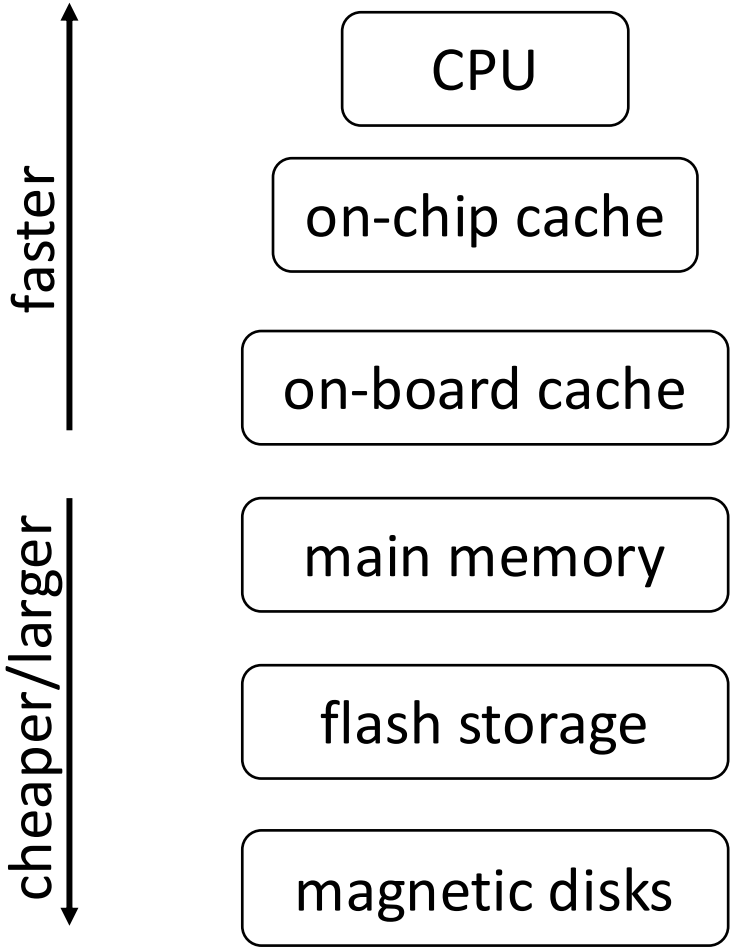
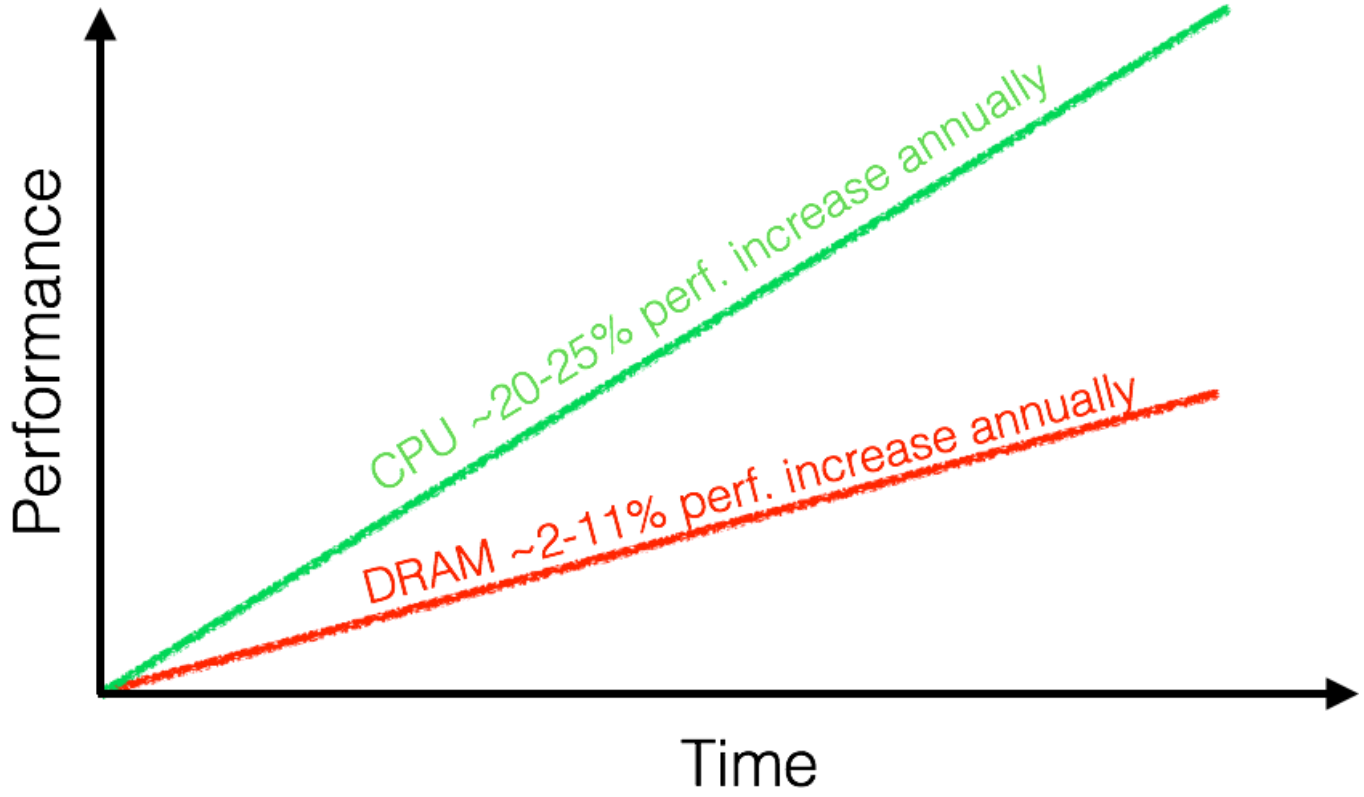


the first collection of
technical visionary research on
a data-intensive scientific discovery

memory wall





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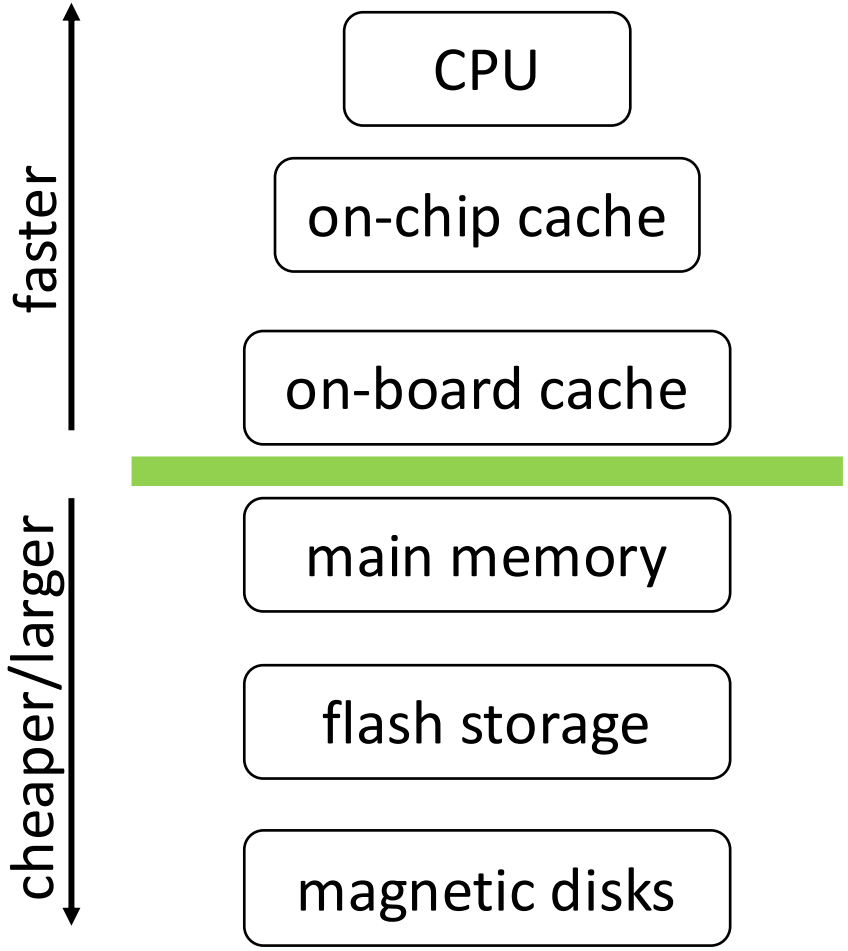
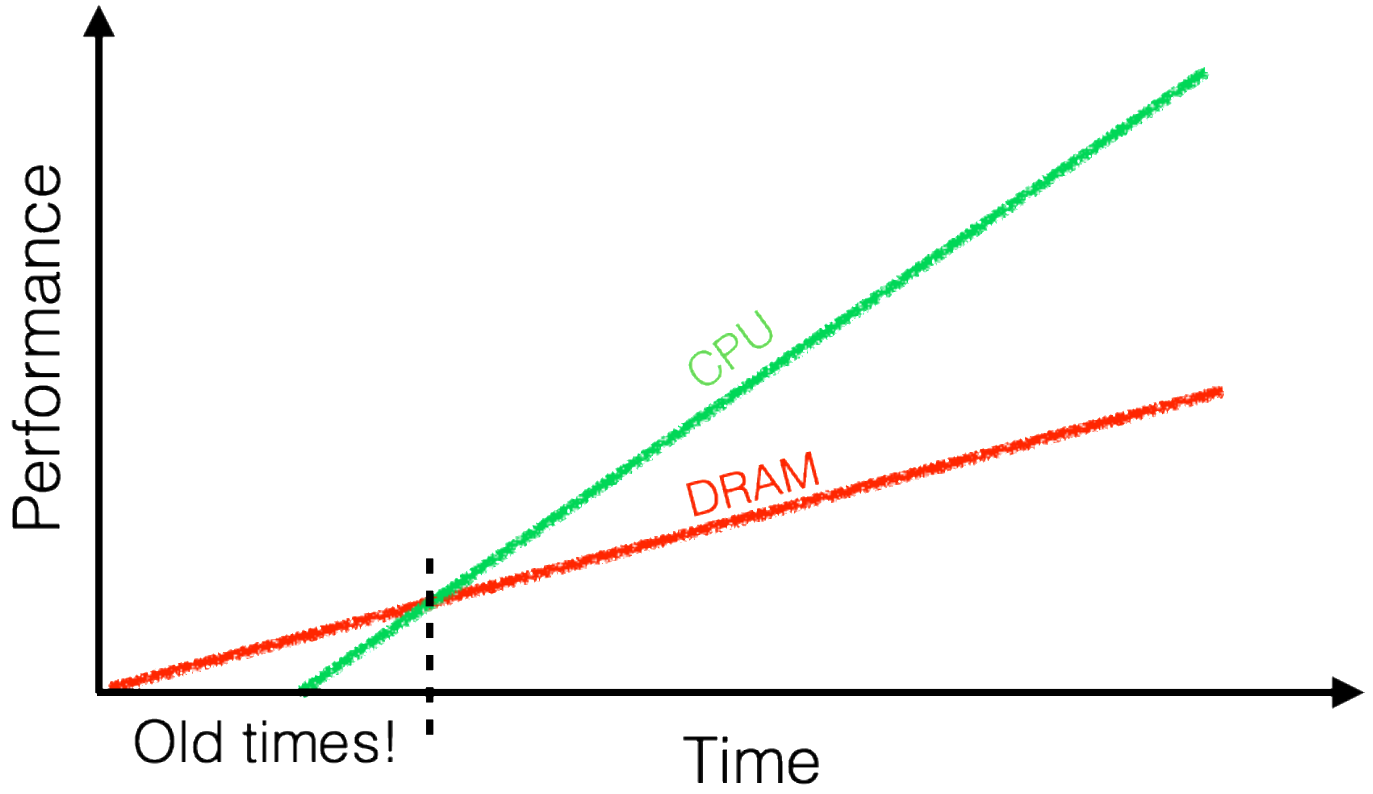
memory wall



be careful when you go below the green line



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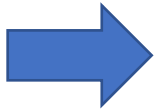
cache/memory misses

computations happen here



be careful when you go below the green line

cache miss: looking for something that is not in the cache

what happens if I miss?

memory miss: looking for something that is not in memory

what happens if I miss again?

be very careful when you go below the green line

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data movement

CPU

on-chip cache

on-board cache

main memory

flash storage

magnetic disks

data goes through
all necessary levels

also read
unnecessary data

Photo by Gary Dineen/NBAE via Getty Images

need to read only X
read the whole page

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data movement

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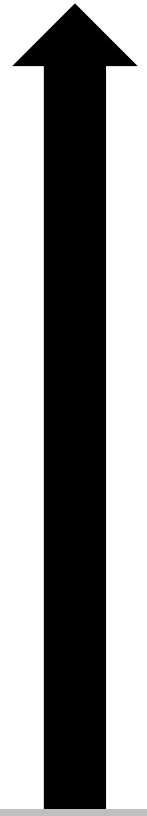

data goes through
all necessary levels

also read
unnecessary data

Photo by Gary Dineen/NBAE via Getty Images

need to read only X
read the whole page

remember!

disk is millions (mem, hundreds) of times slower than CPU

page-based access & random access

query x<7

size=120 bytes

memory (memory level N)

disk (memory level N+1)

1, 5, 12, 24, 23 | 2, 7, 13, 9, 8 | 10, 11, 6, 14, 15

page size = 5*8 = 40 bytes

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page-based access & random access

query x<7

scan

output

1, 5, 12, 24, 23

1, 5

size=120 bytes

memory (memory level N)

disk (memory level N+1)

1, 5, 12, 24, 23

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page-based access & random access

query x<7

scan

output

1, 5, 12, 24, 23

2, 7, 13, 9, 8

1, 5, 2

size=120 bytes

memory (memory level N)

disk (memory level N+1)

1, 5, 12, 24, 23

2, 7, 13, 9, 8

10, 11, 6, 14, 15

page size = 5*8 = 40 bytes

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page size = 5*8 = 40 bytes

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page-based access & random access

query x<7

scan

output

10, 11, 6, 14, 15

2, 7, 13, 9, 8

1, 5, 2, 6

size=120 bytes

memory (memory level N)

disk (memory level N+1)

1, 5, 12, 24, 23

2, 7, 13, 9, 8

10, 11, 6, 14, 15

page size = 5*8 = 40 bytes

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page-based access & random access

query x<7

scan

output (32 bytes)

10, 11, 6, 14, 15

2, 7, 13, 9, 8

1, 5, 2, 6

size=120 bytes

memory (memory level N)

disk (memory level N+1)

1, 5, 12, 24, 23

2, 7, 13, 9, 8

10, 11, 6, 14, 15

page size = 5*8 = 40 bytes

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what if we had an oracle (perfect index)?

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page-based access & random access

query x<7

size=120 bytes

memory (memory level N)

disk (memory level N+1)

1, 5, 12, 24, 23 | 2, 7, 13, 9, 8 | 10, 11, 6, 14, 15

page size = 5*8 = 40 bytes

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page-based access & random access

query x<7

oracle

output

1, 5, 12, 24, 23

1, 5

size=120 bytes

memory (memory level N)

disk (memory level N+1)

1, 5, 12, 24, 23

2, 7, 13, 9, 8

10, 11, 6, 14, 15

page size = 5*8 = 40 bytes

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page-based access & random access

query x<7

oracle

output

1, 5, 12, 24, 23

2, 7, 13, 9, 8

1, 5

size=120 bytes

memory (memory level N)

disk (memory level N+1)

1, 5, 12, 24, 23

2, 7, 13, 9, 8

10, 11, 6, 14, 15

page size = 5*8 = 40 bytes

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page-based access & random access

query x<7

oracle

output

1, 5, 12, 24, 23

2, 7, 13, 9, 8

1, 5, 2

size=120 bytes

memory (memory level N)

disk (memory level N+1)

1, 5, 12, 24, 23

2, 7, 13, 9, 8

10, 11, 6, 14, 15

page size = 5*8 = 40 bytes

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80 bytes

page-based access & random access

query x<7

oracle

output

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2, 7, 13, 9, 8

1, 5, 2

size=120 bytes

memory (memory level N)

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page-based access & random access

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2, 7, 13, 9, 8

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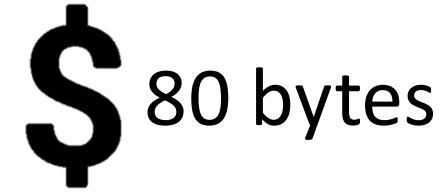
page-based access & random access



query x<7

oracle

output

10, 11, 6, 14, 15

2, 7, 13, 9, 8

1, 5, 2, 6

size=120 bytes

memory (memory level N)

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page size = 5*8 = 40 bytes

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page-based access & random access

was the oracle helpful?

query x<7

oracle

output (32 bytes)

10, 11, 6, 14, 15

2, 7, 13, 9, 8

1, 5, 2, 6

size=120 bytes

memory (memory level N)

disk (memory level N+1)

1, 5, 12, 24, 23

2, 7, 13, 9, 8

10, 11, 6, 14, 15

page size = 5*8 = 40 bytes

when is the oracle helpful?

for which query would an oracle help us?

how to decide whether to use the oracle or not?

1, 5, 12, 24, 23

2, 7, 13, 9, 8

10, 11, 6, 14, 15

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every **byte** counts

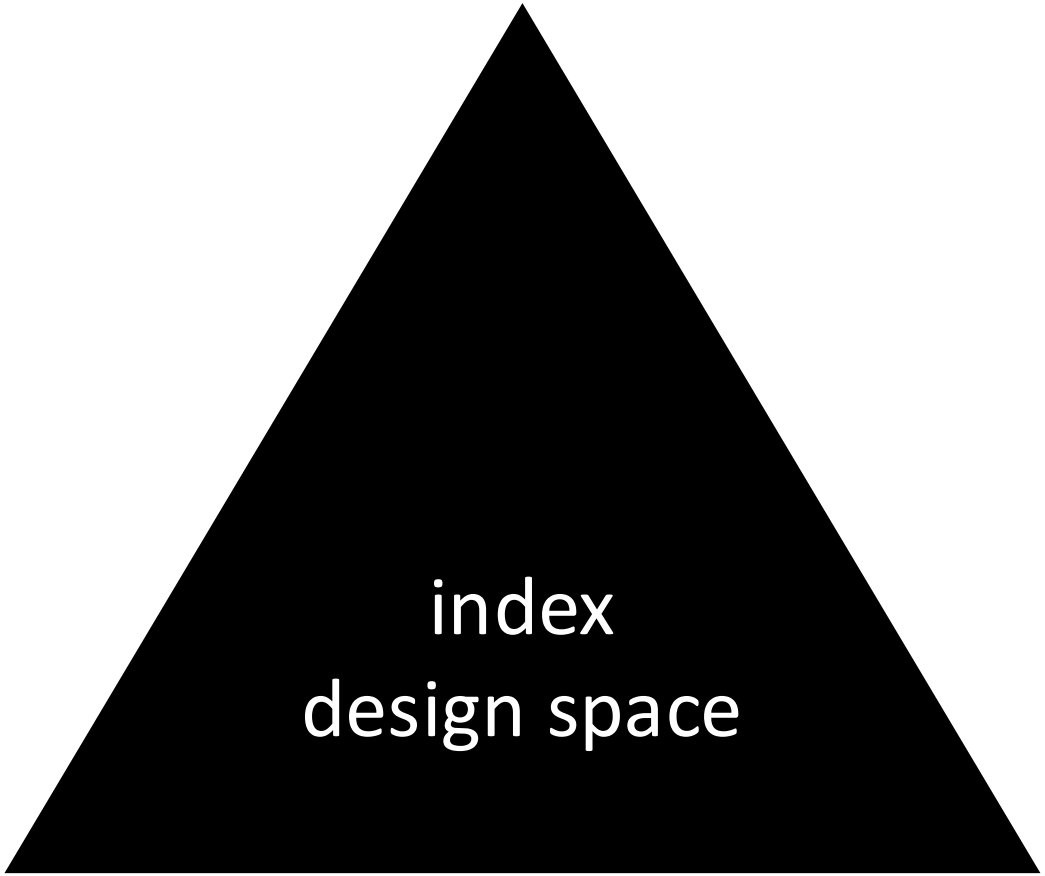
overheads and tradeoffs

how we store data

layouts, indexes

know the **query**

access path selection



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rules of thumb

sequential access

read one block; consume it completely; discard it; read next

hardware can predict and start prefetching

prefetching can exploit full memory/disk bandwidth

random access

read one block; consume it partially; discard it; (may re-use)

are random accesses always bad?

the one that helps us **avoid a large number of accesses** (random or sequential)

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a “simple” database operator

select operator (scan)

how to implement it?

```
result = new array[data.size];
j=0;
for (i=0; i<data.size; i++)
    if (data[i]<x)
        result[j++]=i;
```

qualifying positions

query: value<x
over an array of N slots

data

what if only 0.1% qualifies?

memory

data

result

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how to implement it?

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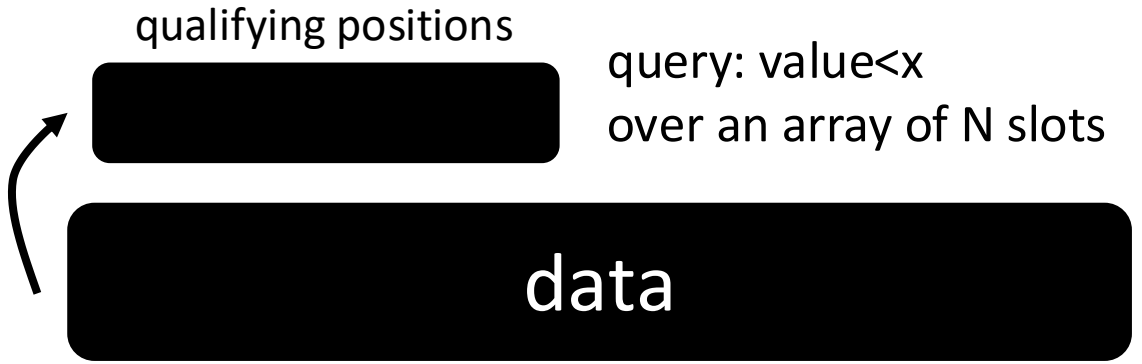
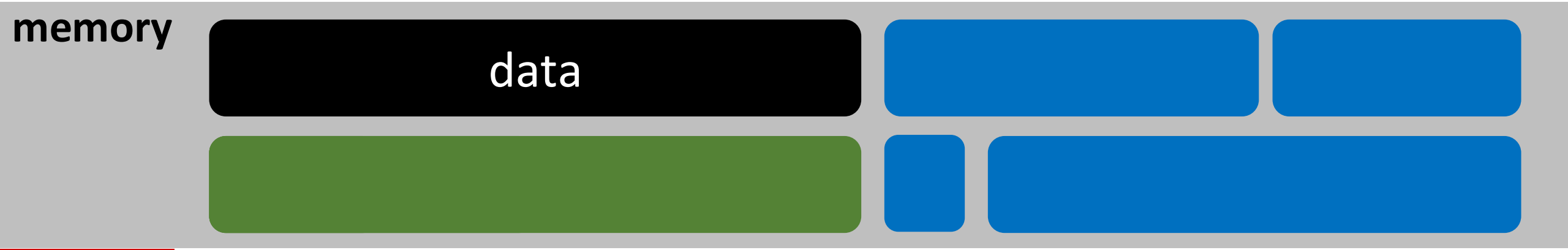


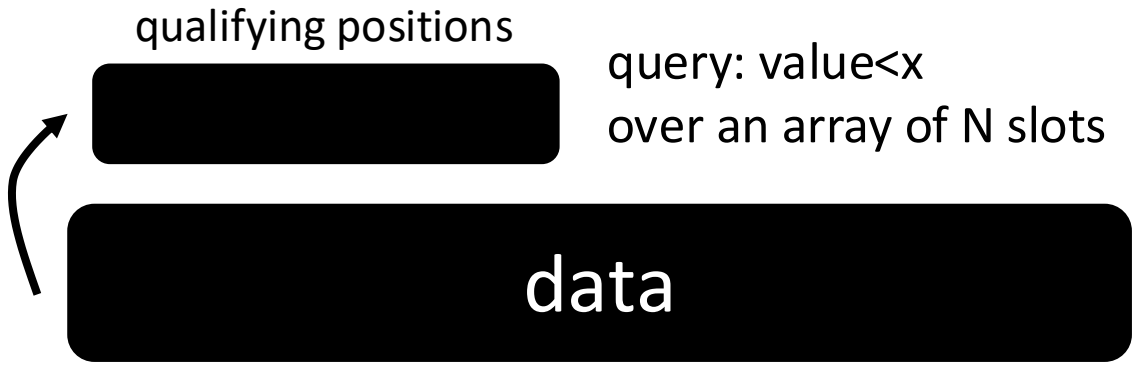
what if only 0.1% qualifies?



how to implement it?

```
result = new array[data.size];
j=0;
for (i=0; i<data.size; i++)
    if (data[i]<x)
        result[j++]=i;
```

```
result = new array[data.size];
j=0;
for (i=0; i<data.size; i++)
    result[j+=(data[i]<x)]=i;
```



what if 99% qualifies?

how can we know?

branches (if statements)
are bad for the processors,
can we avoid them?

how to bring the values?
(remember we have the positions)

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qualifying positions

query: value<x
over an array of N slots

data

```
result = new array[data.size];
j=0;
for (i=0; i<data.size; i++)
    if (data[i]<x)
        result[j++]=i;
```

what about multi-core?
NUMA? SIMD? GPU?

data

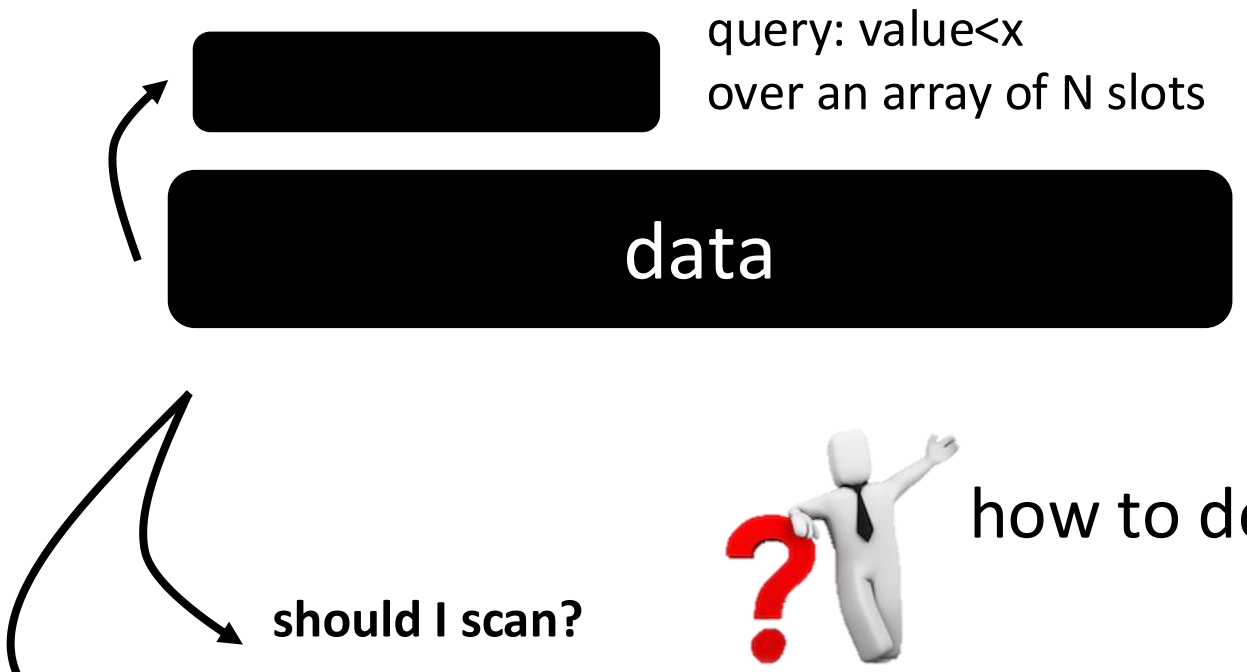
core1 core2 core3 core4

needs coordination!
what about result writing?

what about having multiple queries?

query1: value<x1
query2: value<x2 …


```
result = new array[data.size];
j=0;
for (i=0; i<data.size; i++)
    if (data[i]<x)
        result[j++]=i;
```



how to decide which one is best?

total data movement
&
computation

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zonemaps

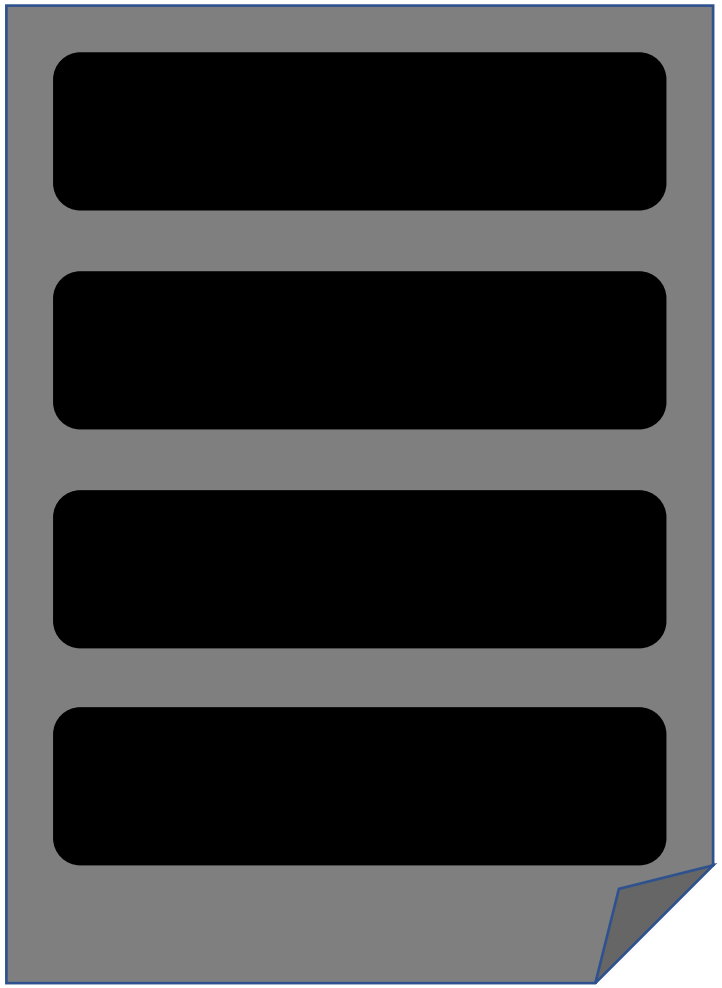
file = collection of pages

page 0

page 1

page 2

page 3



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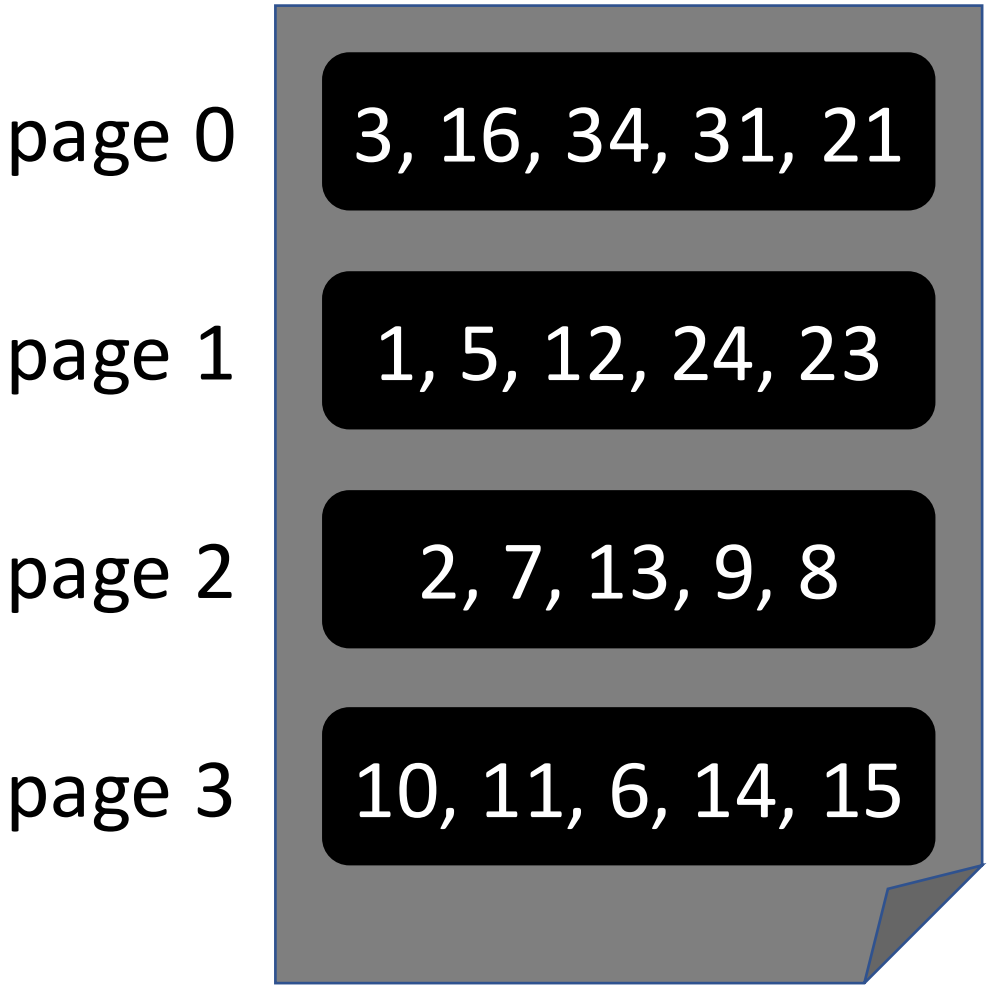
zonemaps

file = collection of pages



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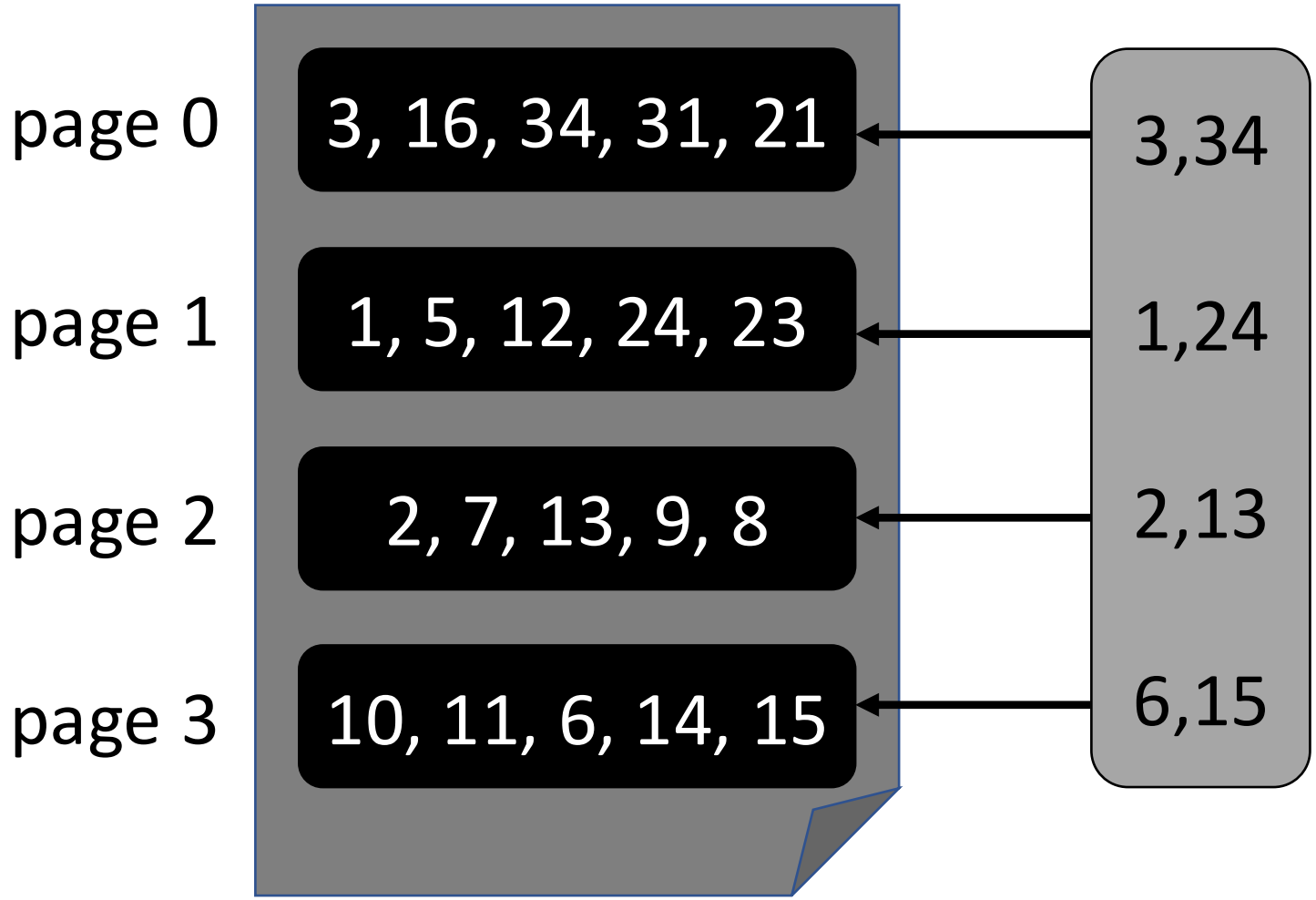
zonemaps

file = collection of pages



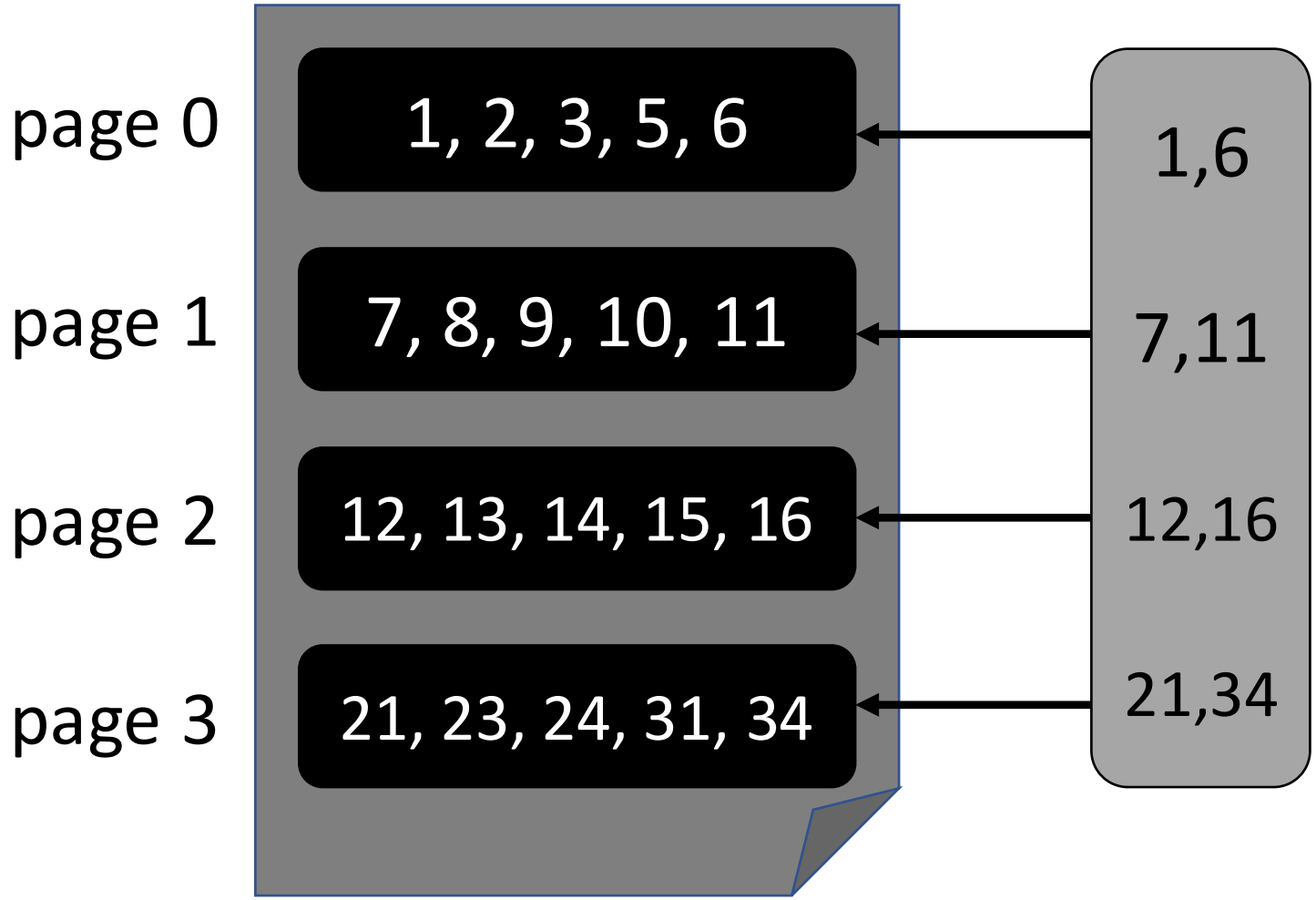
light-weight

typically retained in memory

But what if the data is sorted?

zonemaps

file = collection of pages



light-weight

typically retained in memory

But what if the data is sorted?

the language of efficient systems: C/C++

why?

fewer assumptions

low-level control over hardware

make decisions about physical data placement and consumptions

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the language of efficient systems: C/C++

why?

fewer assumptions

we want you in the project to make low-level decisions

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CS 561: Data Systems Architectures

class 2

Data Systems 101

next : modern main-memory data systems & semester project