UC San Diego

DSC 102
Systems for Scalable Analytics

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Topic 1: Basics of Machine Resources
Part 2: Operating Systems

Ch. 2, 4.1-4.2, 6, 7, 13, 14.1, 18.1, 21, 22, 26, 36, 37, 39, and 40.1-40.2 of Comet Book

Outline

- Basics of Computer Organization
  - Digital Representation of Data
  - Processors and Memory Hierarchy
- Basics of Operating Systems (OS)
  - Process Management: Virtualization; Concurrency
  - Filesystem and Data Files
  - Main Memory Management
- Persistent Data Storage

App Stores

"changed how software development worked, and expanded the ***number of people who could comfortably, safely use a computer*** *from a few hundred million to a few billion."*

[1] Benedict Evans, App stores, trust and anti-trust

Putting apps in a sandbox

Apps can only do things that Apple allows and cannot ask (or persuade, or trick) the user for permission to do 'dangerous' things.

- Would this break my phone?
- Would this run my battery down?
- Steal my bank details?

Q: *What is an OS? Why do we need it?*


legislature

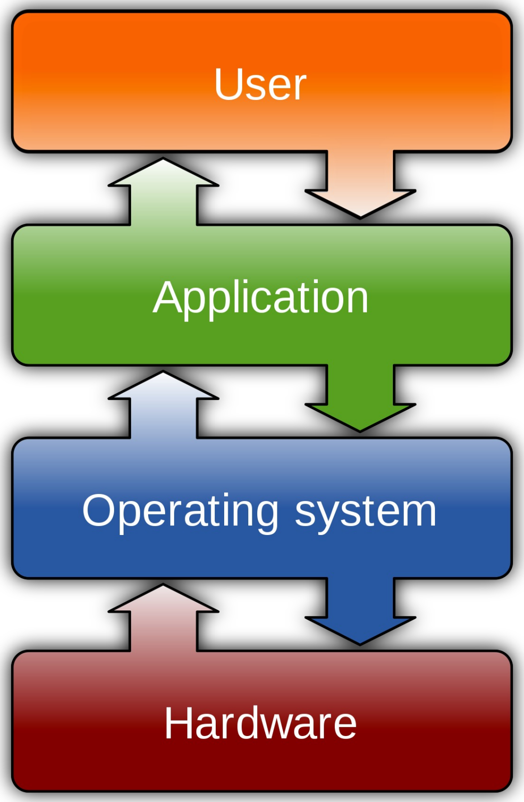

judiciary


executive

Role of an OS in a Computer

- An OS is a large set of interrelated programs that *make it easier* for applications and user-written programs to use computer hardware *effectively*, *efficiently*, and *securely*
  - Akin to a government's role in a country
- Without OS, computer users must speak machine code!
- 2 key principles in OS (any system) design & impl.:
  - **Modularity:** Divide system into *functionally cohesive components* that each do their jobs well
    - Akin to executive-legislature-judiciary split
  - **Abstraction:** *Layers of functionalities* from low-level (close to hardware) to high level (close to user)
    - Akin to local-city-county-state-federal levels?

Role of an OS in a Computer



APIs/Interface of Application Software

APIs of OS aka “System Calls”

Hardware-specific code parts of OS

“Application Software” notion is now more complex due to multiple tiers of abstraction; “Platform Software” or “Software Framework” is a new tier between “Application” and OS

Key Components of OS

- **Kernel:** The core of an OS with modules to abstract the hardware and APIs for programs to use
- Auxiliary parts of OS include shell/terminal, file browser for usability, extra programs installed by I/O devices, etc.

	"System Call" APIs				
Kernel Components	Process Management	Main Memory Management	Filesystems	Networking	Device Drivers
Functionality	*Virtualize* processor; "**Process**" abstraction; **Concurrency**	*Virtualize* Main Memory	*Virtualize* disks; "**File**" abstraction; **Persistence**	Commun. over network	Talk to other I/O devices
	Hardware device-specific programs				

Hardware

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You will face myriad and new data types

Compute hardware is evolving fast

You will need to use new methods on evolving data file formats on clusters / cloud

Storage hardware are evolving fast

The Abstraction of a Process

- **Process:** A *running* program, the central abstraction in OS
  - Started by OS when a program is executed by user
  - OS keeps inventory of “alive” processes (**Process List**) and handles apportioning of hardware among processes

***Q:** Why bother knowing process management in Data Science?*

- A *query* is a program that becomes a process
- A data system typically *abstracts away* process management because user specifies the queries / processes in system’s API

- But in the cloud era, things are up in the air! Will help to know a bit of how they handle data-intensive computations under the hood

The Abstraction of a Process

- High-level steps OS takes to get a process going:
  1. **Create** a process (get Process ID; add to Process List)
  2. Assign part of DRAM to process, aka its **Address Space**
  3. Load code and static data (if applicable) to that space
  4. Set up the inputs needed to run program's *main()*
  5. Update process' **State** to *Ready*
  6. When process is **scheduled** (*Running*), OS temporarily hands off control to process to run the show!
  7. Eventually, process finishes or run **Destroy**

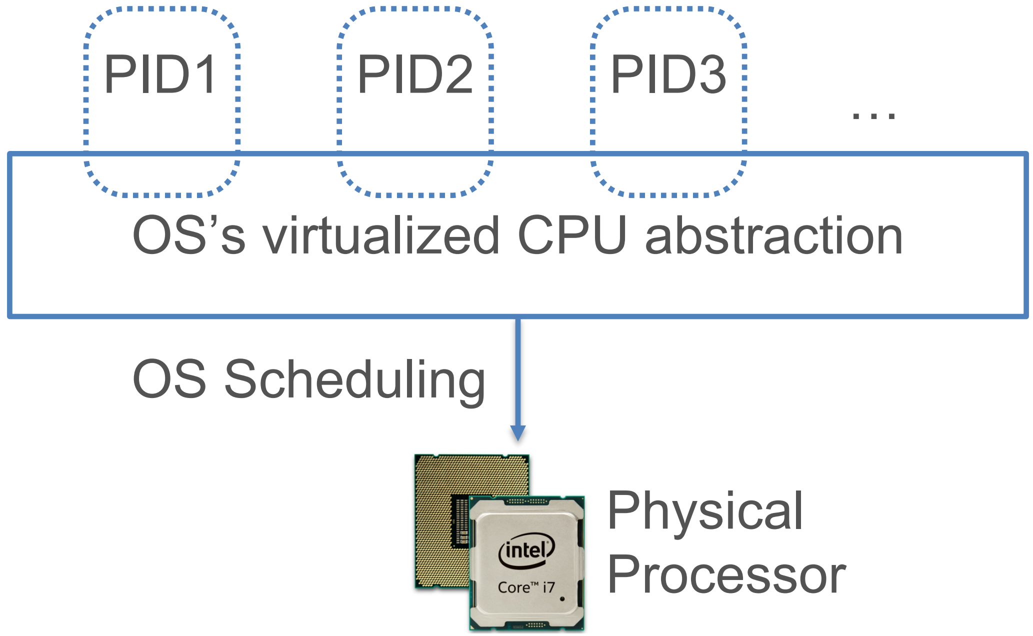
Virtualization of Hardware Resources

Q: *But is it not risky/foolish for OS to hand off control of hardware to a process (random user-written program)?!*

- OS has *mechanisms* and *policies* to regain control
- **Virtualization:**
  - Each hardware resource is treated as a virtual entity that OS can divvy up among processes in a controlled way
- **Limited Direct Execution:**
  - OS mechanism to time-share CPU and preempt a process to run a different one, aka “context switch”
  - A **Scheduling policy** tells OS what time-sharing to use
  - Processes also must transfer control to OS for “privileged” operations (e.g., I/O); **System Calls** API

Virtualization of Processors

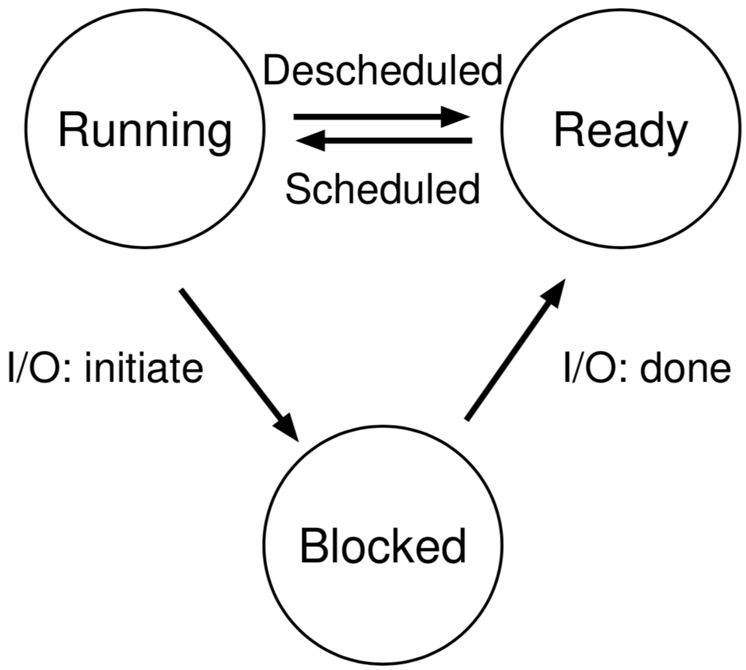
- Virtualization of processor enables process **isolation**, i.e., each process given an “illusion” that it alone runs



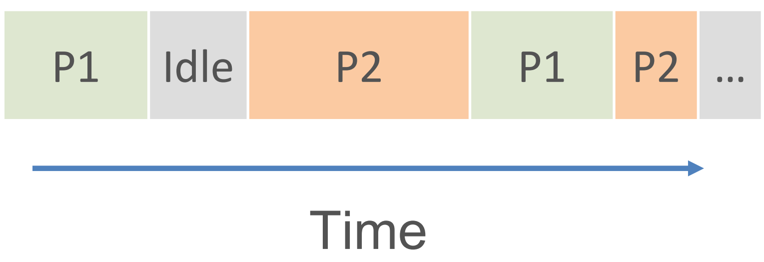
- Inter-process communication possible in System Calls API
- Later: Generalize to **Thread** abstraction for **concurrency**

Process Management by OS

- OS keeps moving processes between 3 states:



- Gantt Chart: A viz. to show what process runs when (on processor)



- Sometimes, if a process gets "stuck" and OS did not schedule something else, system **hangs**; need to reboot!

Scheduling Policies/Algorithms

- **Schedule:** Record of what process runs on each CPU when
- Policy controls how OS time-shares CPUs among processes
- Key terms for a process (aka **job**):
  - **Arrival** Time: Time when process gets created
  - **Job Length**: Duration of time needed for process
  - **Start** Time: Times when process first starts on processor
  - **Completion** Time: Time when process finishes/killed
  - **Response** Time = Start Time — Arrival Time
  - **Turnaround** Time = Completion Time — Arrival Time
- **Workload:** Set of processes, arrival times, and job lengths that OS Scheduler has to handle

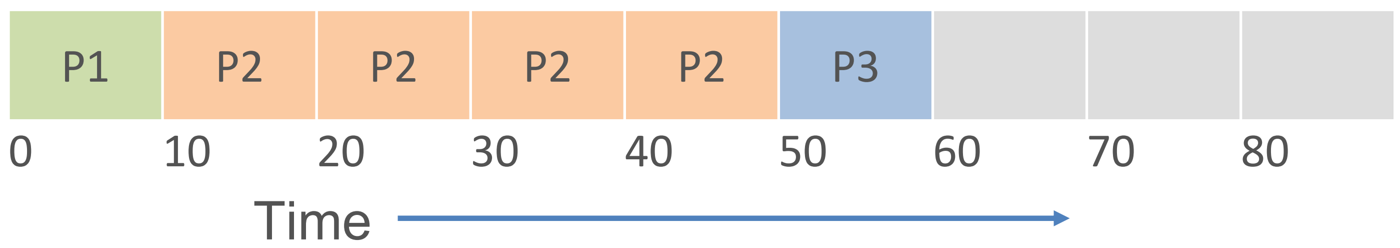
Scheduling Policies/Algorithms

- In general, not all Arrival Times and Job Lengths will be known beforehand. But **preemption** is possible.
- **Key Principle:** Inherent tension in scheduling between overall workload *performance* and allocation *fairness*
  - Performance metric is usually *Average Turnaround Time*
  - Many fairness metrics exist, e.g., Jain's fairness index
- 100s of scheduling policies studied! Well-known ones: FIFO, SJF, STCF, Round Robin, Random, etc.
  - Different criteria for ranking; preemptive vs not
  - Complex "multi-level feedback queue" schedulers
  - ML-based schedulers are "hot" nowadays!

Scheduling Policy: FIFO

- First-In-First-Out aka First-Come-First-Serve (FCFS)
- Ranking criterion: Arrival Time; no preemption allowed

Example: P1, P2, P3 of lengths 10,40,10 units arrive closely in that order



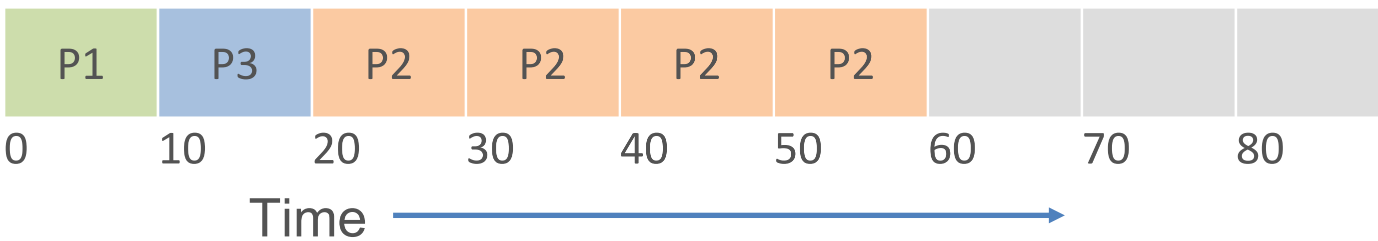
Process	Arrival Time	Start Time	Completion Time	Response Time	Turnaround Time
P1	0	0	10	0	10
P2	0	10	50	10	50
P3	0	50	60	50	60
			Avg:	20	40

- Main con: Short jobs may wait a lot, aka “Convoy Effect”

Scheduling Policy: SJF

- Shortest Job First
- Ranking criterion: Job Length; no preemption allowed

Example: P1, P2, P3 of lengths 10,40,10 units arrive closely in that order



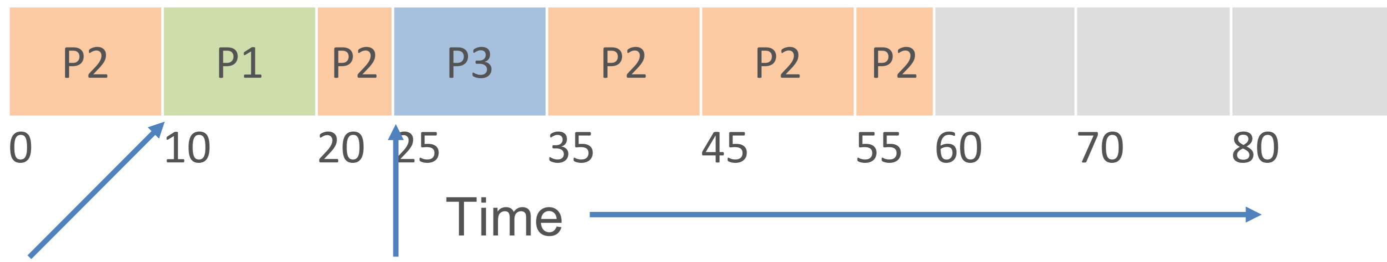
Process	Arrival Time	Start Time	Completion Time	Response Time	Turnaround Time
P1	0	0	10	0	10
P2	0	20	60	20	60
P3	0	10	20	10	20
	(FIFO Avg: 20 and 40)		Avg:	10	30

- Main con: Not all Job Lengths might be known beforehand

Scheduling Policy: SCTF

- Shortest Completion Time First
- Jobs might not all arrive at same time; preemption possible

Example: P1, P2, P3 of lengths 10,40,10 units arrive at different times



P1 arrives; switch

P3 arrives; switch

Process	Arrival Time	Start Time	Completion Time	Response Time	Turnaround Time
P1	10	10	20	0	10
P2	0	0	60	0	60
P3	25	25	35	0	10
	(SJF Avg: 10 and 30)		Avg:	0	26.7

- Main con same as SJF; Job Lengths might not be known

Scheduling Policy: Round Robin

- RR does not need to know job lengths
- Fixed time *quantum* given to each job; cycle through jobs

Example: P1, P2, P3 of lengths 10,40,10 units arrive closely in that order

P1	P2	P3	P1	P2	P3	P2	P2	P2	P2	P2	P2				
0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75

Quantum is 5

Time →

Process	Arrival Time	Start Time	Completion Time	Response Time	Turnaround Time
P1	0	0	20	0	20
P2	0	5	60	5	60
P3	0	10	30	10	30
			Avg:	5	36.7

(SJF Avg: 10 & 30; SCTF Avg: 0 & 26.7)

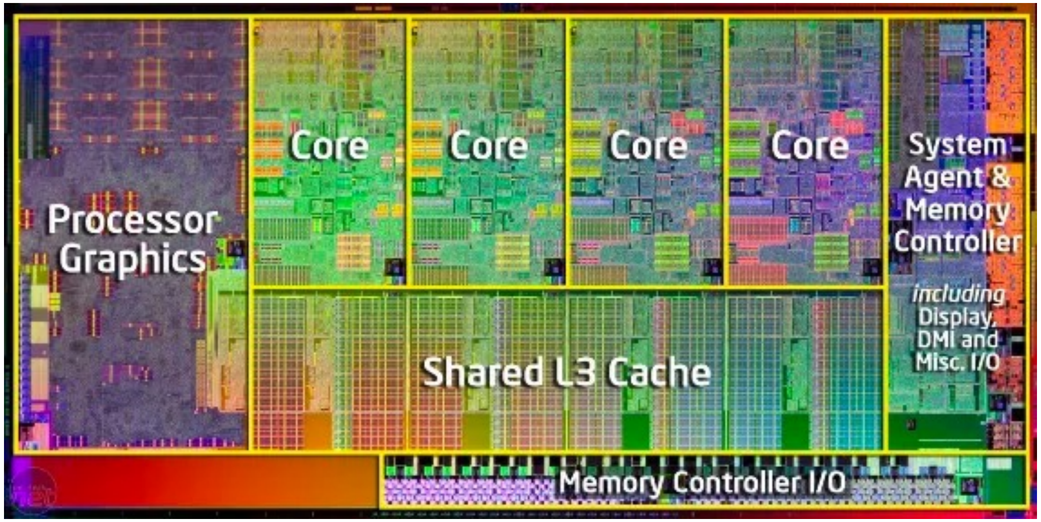
- RR is often very fair, but Avg Turnaround Time goes up!

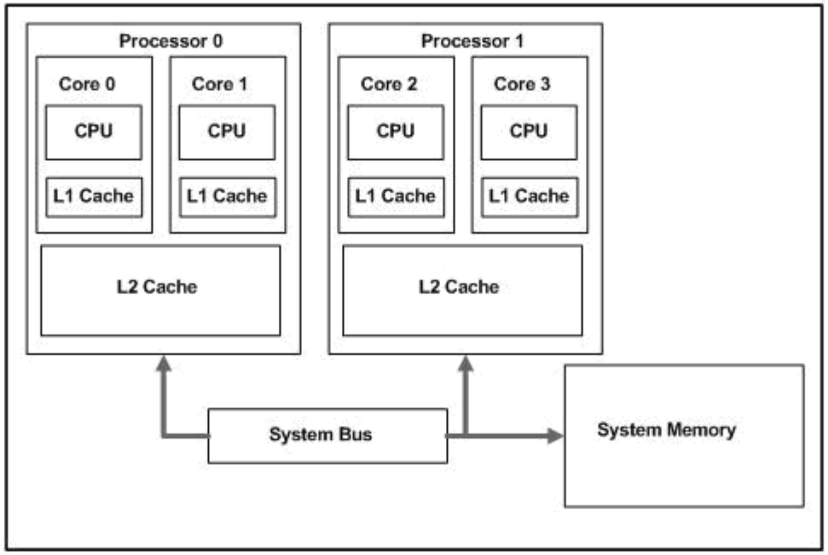
Peer Instruction Activity

(Switch slides)

Concurrency

- Modern computers often have multiple processors and multiple *cores* per processor
- **Concurrency:** Multiple processors/cores run different/same set of instructions simultaneously on different/*shared* data
- New levels of shared caches are added





Concurrency

- **Multiprocessing:** Different processes run on different cores (or entire CPUs) simultaneously
- **Thread:** Generalization of OS's Process abstraction
  - A program *spawns* many threads; each run parts of the program's computations simultaneously
  - **Multithreading:** Same core used by many threads

- Issues in dealing with multithreaded programs that *write shared data*:
  - Cache coherence
  - Locking; deadlocks
  - Complex scheduling

Concurrency

- Scheduling for multiprocessing/multicore is more complex
- **Load Balancing:** Ensuring different cores/proc. are kept roughly equally busy, i.e., reduce **idle times**
- Multi-queue multiprocessor scheduling (MQMS) is common
  - Each proc./core has its own job queue
  - OS moves jobs across queues based on load
  - Example Gantt chart for MQMS:

	0	10	20	30	40	50	60	70	80
CPU 1:	P1	P1	P3	P3	P3	P3	P1	P1	P1
CPU 2:	P2	P2	P2	P1	P1	P2	P2	P3	P3

Concurrency in Data Science

- Thankfully, most data-intensive computations in data science do not need concurrent writes on shared data!
  - Concurrent low-level ops abstracted away by libraries/APIs
  - **Partitioning / replication** of data simplifies concurrency
- Later topic (Parallelism Paradigms) will cover parallelism in depth:
  - Multi-core, multi-node, etc.
  - Task parallelism, Partitioned data parallelism, etc.

Review Questions

- If you can afford infinite DRAM, is there any reason not to use it?
- What is the purpose of an OS?
- Why is the design of an OS so modular?
- Why does an OS need to use a scheduling policy?
- Which quantity captures latency of a process starting: Response Time or Turnaround Time?
- What gives rise to different scheduling policies?
- Which scheduling policy is the fairest among the ones we covered?
- What is the Convoy Effect? Which sched. policy has that issue?
- Explain one pro and one con of Round Robin over SJF.

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Q: *What is a file?*


MORTGAGE
INVESTMENTS
SAVINGS

Abstractions: File and Directory

- **File:** A persistent sequence of bytes that stores a logically coherent digital object for an application
  - **File Format:** An application-specific standard that dictates how to interpret and process a file's bytes
  - 100s of file formats exist (e.g., TXT, DOC, GIF, MPEG); varying data models/types, domain-specific, etc.
  - **Metadata:** Summary or organizing info. about file content (aka *payload*) stored with file itself; format-dependent
- **Directory:** A cataloging structure with a list of references to files and/or (recursively) other directories
  - Typically treated as a special kind of file
  - Sub dir., Parent dir., Root dir.

Filesystem

- **Filesystem:** The part of OS that helps programs create, manage, and delete files on disk (sec. storage)
- Roughly split into *logical level* and *physical level*
  - Logical level exposes file and dir. abstractions and offers System Call APIs for file handling
  - Physical level works with disk firmware and moves bytes to/from disk to DRAM

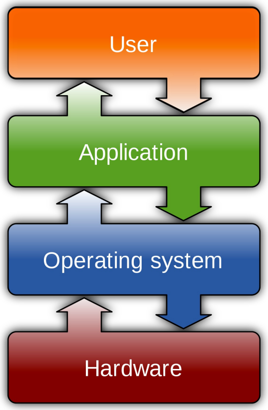
Filesystem

- Dozens of filesystems exist, e.g., ext2, ext3, NTFS, etc.
  - Differ on how they layer file and dir. abstractions as bytes, what metadata is stored, etc.
  - Differ on how data integrity/reliability is assured, support for editing/resizing, compression/encryption, etc.
  - Some can work with (“**mounted**” by) multiple OSs

Virtualization of File on Disk

- OS abstracts a file on disk as a virtual object for processes
- **File Descriptor:** An OS-assigned +ve integer identifier/reference for a file's virtual object that a process can use
  - 0/1/2 reserved for STDIN/STDOUT/STDERR
  - **File Handle:** A PL's abstraction on top of a file descr. (fd)

System Call API for File Handling:



API of OS called "System Calls"

- **open**(): Create a file; assign fd; optionally overwrite
- **read**(): Copy file's bytes on disk to in-mem. buffer; sized
- **write**(): Copy bytes from in-mem. buffer to file on disk
- **fsync**(): "Flush" (force write) "dirty" data to disk
- **close**(): Free up the fd and other OS state info on it
- **lseek**(): Position offset in file's fd (for random R/W later)
- Dozens more (rename, mkdir, chmod, etc.)

Q: *What is a database? How is it different from just a bunch of files?*

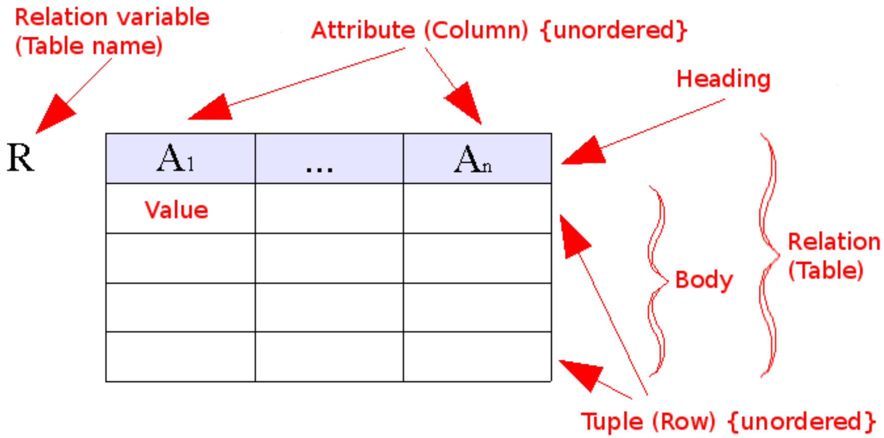
Files Vs Databases: Data Model

- **Database:** An *organized* collection of interrelated data
  - **Data Model:** An abstract model to define organization of data in a formal (mathematically precise) way
  - E.g., Relations, XML, Matrices, DataFrames
- Every database is just an *abstraction* on top of data files!
  - **Logical level:** Data model for higher-level reasoning
  - **Physical level:** How bytes are layered on top of files
  - All data systems (RDBMSs, Dask, Spark, TensorFlow, etc.) are application/platform software that use OS System Call API for handling data files

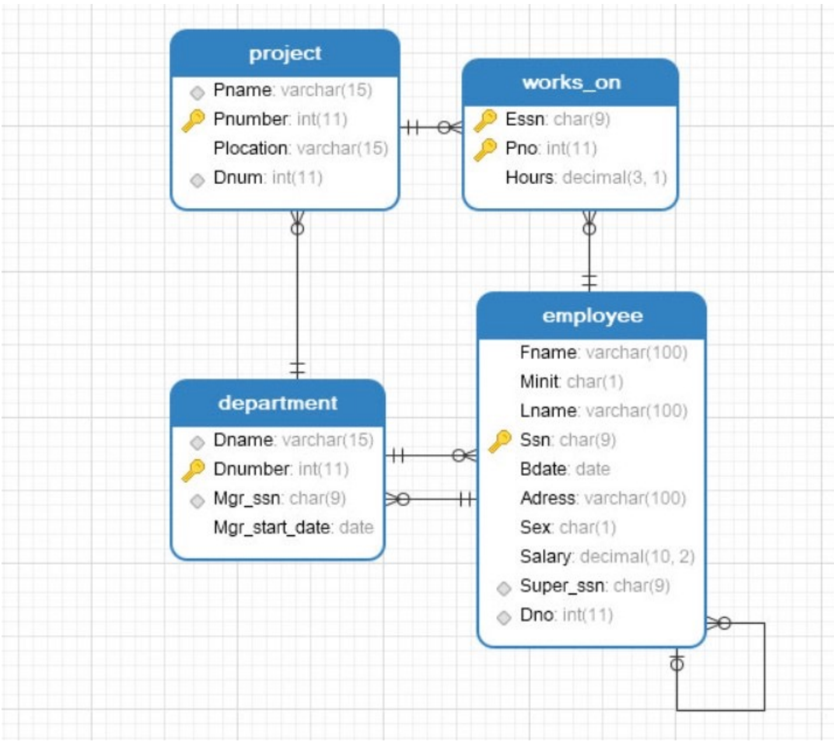
Data as File: Structured

- **Structured Data:** A form of data with regular substructure

Relation



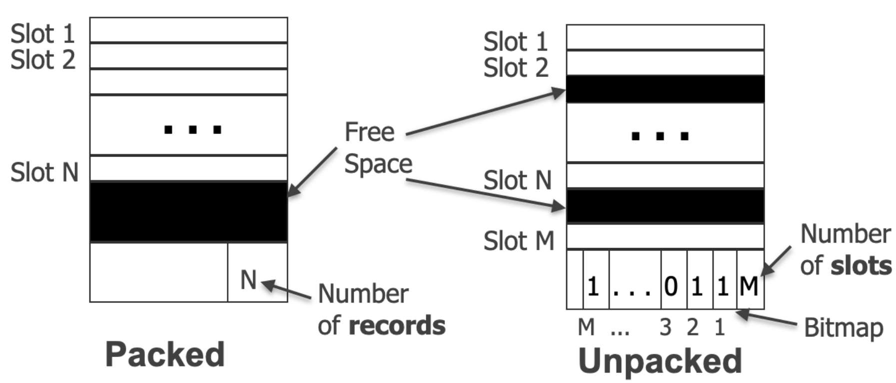
Relational Database



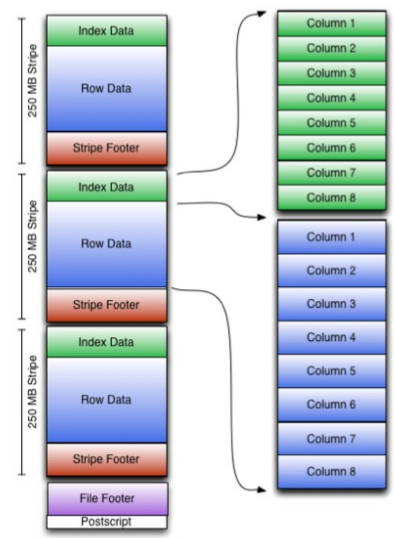
- Most RDBMSs and Spark serialize a relation as *binary* file(s), often compressed

Aside: Relational File Formats

- Different RDBMSs and Spark/HDFS-based tools serialize relation/tabular data in different binary formats, often compressed
  - One file per relation; *data layout* can be row vs columnar (e.g., ORC, Parquet) vs hybrid formats
  - RDBMS vendor-specific vs open Apache
  - Parquet becoming especially popular



Row-oriented



Columnar

Ad: Take CSE 132C for more on relational file formats

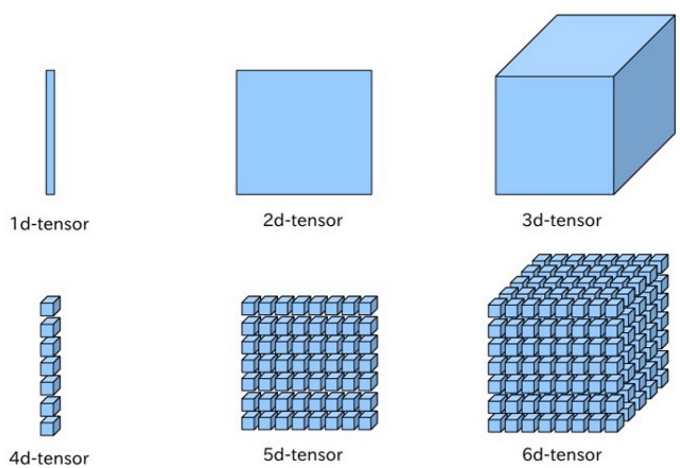
Data as File: Structured

- **Structured Data:** A form of data with regular substructure

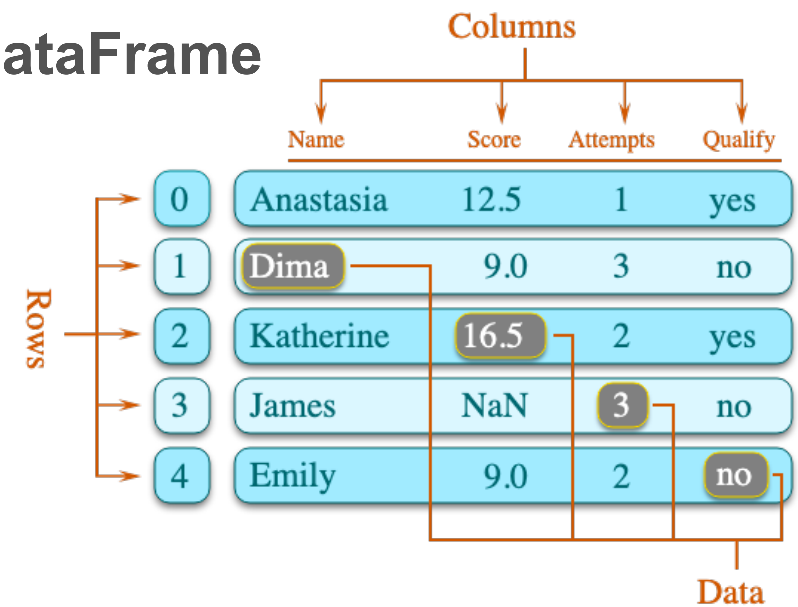
Matrix

$$
\begin{array}{c} \\ 1 \\ 2 \\ 3 \\ \vdots \\ m \end{array}
\begin{array}{c}
\begin{array}{cccc} 1 & 2 & \dots & n \end{array} \\
\begin{bmatrix}
a_{11} & a_{12} & \cdots & a_{1n} \\
a_{21} & a_{22} & \cdots & a_{2n} \\
a_{31} & a_{32} & \cdots & a_{3n} \\
\vdots & \vdots & \vdots & \vdots \\
a_{m1} & a_{m2} & \cdots & a_{mn}
\end{bmatrix}
\end{array}
$$

Tensor



DataFrame



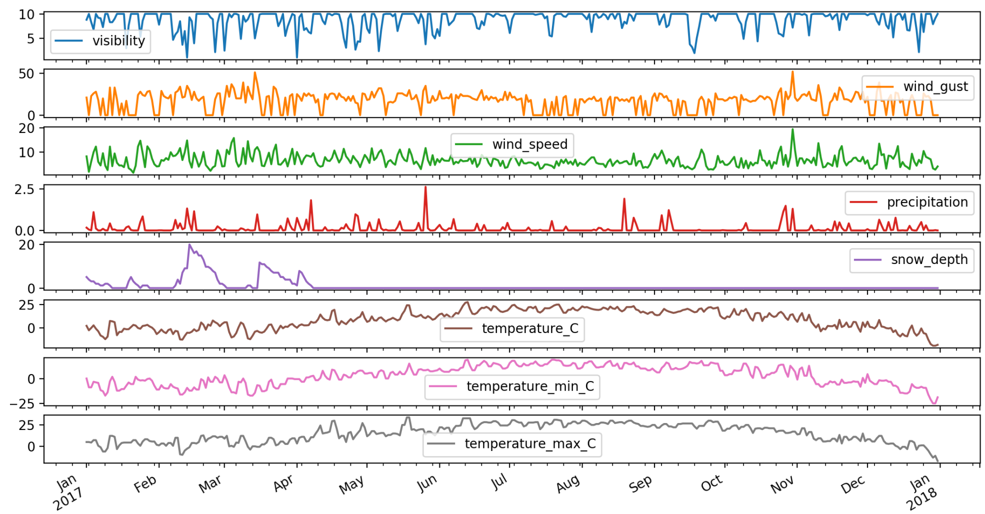
- Typically serialized as restricted ASCII text file (TSV, CSV, etc.)
- Matrix/tensor as binary too
- Can layer on Relations too!

Data as File: Structured

- **Structured Data:** A form of data with regular substructure

Sequence (Includes Time-series)

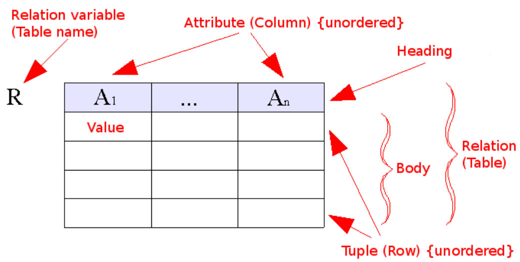
GAT AAAT CT GGTCTTATTTCC



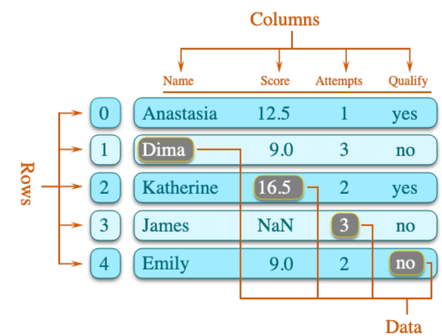
- Can layer on Relations, Matrices, or DataFrames, or be treated as first-class data model
- Inherits flexibility in file formats (text, binary, etc.)

Comparing Struct. Data Models

***Q:** What is the difference between Relation, Matrix, and DataFrame?*



$$\begin{array}{c} \\ 1 \\ 2 \\ 3 \\ \vdots \\ m \end{array} \begin{array}{c} \begin{array}{cccc} 1 & 2 & \cdots & n \end{array} \\ \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ a_{31} & a_{32} & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \end{array}$$



- **Ordering:** Matrix and DataFrame have row/col numbers; Relation is orderless on both axes!
- **Schema Flexibility:** Matrix cells are numbers. Relation tuples conform to pre-defined schema. DataFrame has no pre-defined schema but all rows/cols can have names; col cells can be mixed types!
- **Transpose:** Supported by Matrix & DataFrame, not Relation

If interested in reading more:

Data as File: Semistructured

- **Semistructured Data:** A form of data with less regular / more flexible substructure than structured data

Tree-Structured


```xml
<?xml version="1.0" encoding="UTF-8"?>
<customers>
    <customer>
        <customer_id>1</customer_id>
        <first_name>John</first_name>
        <last_name>Doe</last_name>
        <email>john.doe@example.com</email>
    </customer>
    <customer>
        <customer_id>2</customer_id>
        <first_name>Sam</first_name>
        <last_name>Smith</last_name>
        <email>sam.smith@example.com</email>
    </customer>
    <customer>
        <customer_id>3</customer_id>
        <first_name>Jane</first_name>
        <last_name>Doe</last_name>
        <email>jane.doe@example.com</email>
    </customer>
</customers>
```



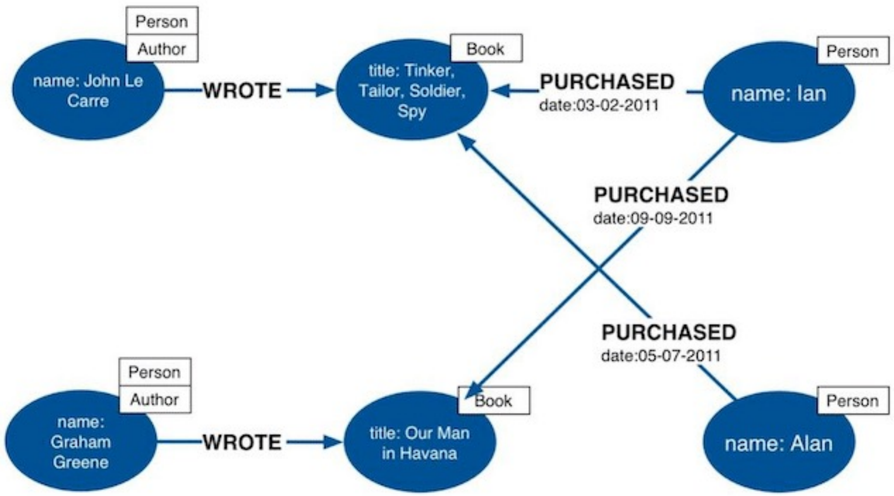
```
[
    {
        orderId: 1,
        date: '1/1/2014',
        orderItems: [
                {itemId: 1, qty: 3, price: 23.4},
                {itemId: 23, qty: 2, price: 3.3},
                {itemId: 7, qty: 5, price: 5.3}
            ]
    },
    {
        orderId: 2,
        date: '1/2/2014',
        orderItems: [
            {itemId: 31, qty: 7, price: 3.8},
            {itemId: 17, qty: 4, price: 9.2}
        ]
    },
    {
        orderId: 3,
        date: '1/5/2014',
        orderItems: [
            {itemId: 11, qty: 9, price: 13.3},
            {itemId: 27, qty: 2, price: 19.2},
            {itemId: 6, qty: 19, price: 3.6},
            {itemId: 7, qty: 22, price: 9.1}
        ]
    }
]
```


- Typically serialized as restricted ASCII text file (extensions XML, JSON, YML, etc.)
- Some data systems also offer binary file formats
- Can layer on Relations too

Data as File: Semistructured

- **Semistructured Data:** A form of data with less regular / more flexible substructure than structured data

Graph-Structured

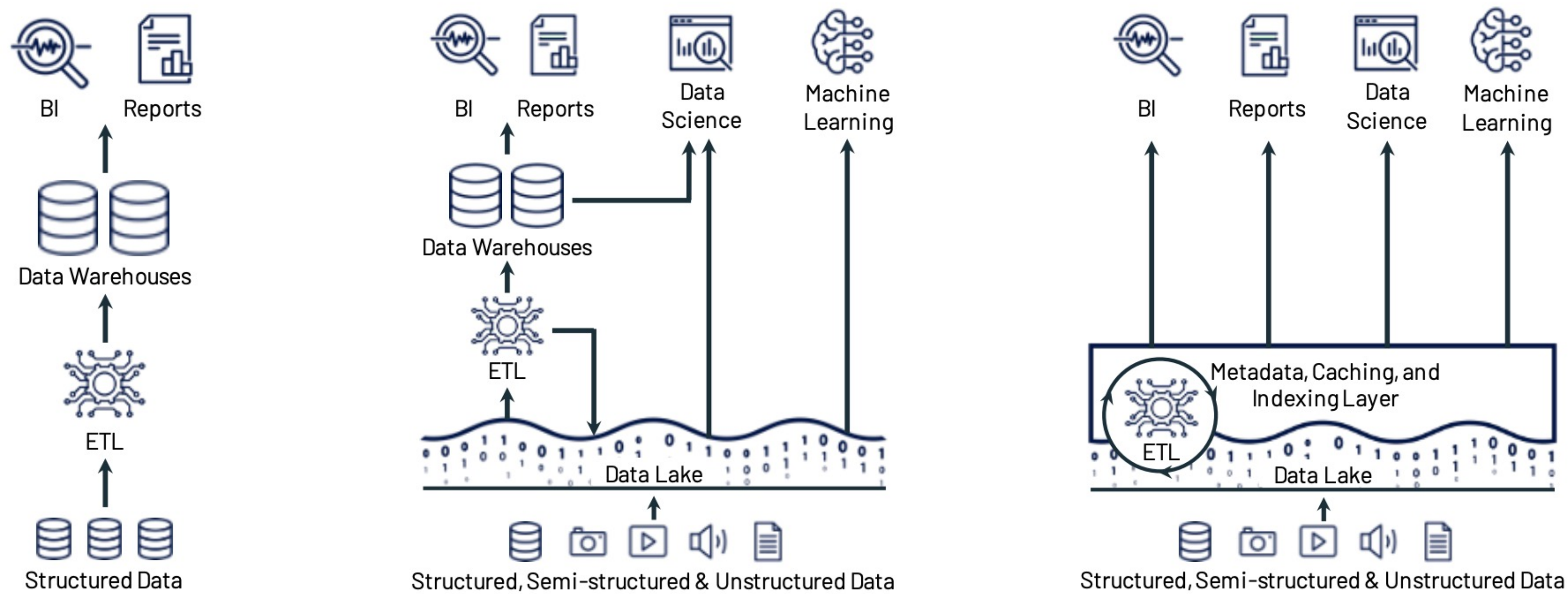


- Typically serialized with JSON or similar textual formats
- Some data systems also offer binary file formats
- Again, can layer on Relations too

Ad: Take DSC 104 for more on semistructured data

Data Files on Data "Lakes"

- **Data "Lake":** *Loose coupling* of data file format for storage and data/query processing stack (vs RDBMS's tight coupling)
  - JSON for raw data; Parquet processed is common



(a) First-generation platforms. **(b) Current two-tier architectures.** **(c) Lakehouse platforms.**

If interested, check out this vision paper on the future of data lakes:
http://cidrdb.org/cidr2021/papers/cidr2021_paper17.pdf

Data Lake File Format Tradeoffs

- Pros and cons of Parquet vs text-based files (CSV, JSON, etc.):
  - **Less storage**: Parquet stores in **compressed** form; can be much smaller (even 10x); less I/O to read
  - **Column pruning**: Enables app to read only columns needed to DRAM; even less I/O now!
  - **Schema on file**: Rich metadata, stats inside format itself
  - **Complex types**: Can store them in a column
  - **Human-readability**: Cannot open with text apps directly
  - **Mutability**: Parquet is immutable/read-only; no in-place edits
  - **Decompression/Deserialization overhead**: Depends on application tool; can go either way
  - **Adoption in practice**: CSV/JSON support more pervasive but Parquet is catching up

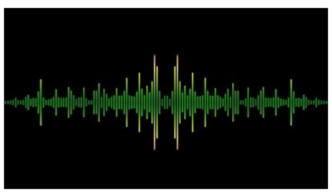
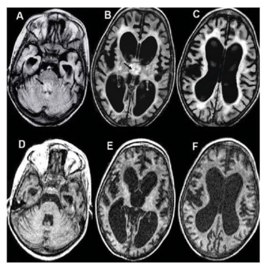
Data Lake File Format Tradeoffs

Dataset	Size on Amazon S3	Query Run Time	Data Scanned	Cost
Data stored as CSV files	1 TB	236 seconds	1.15 TB	$5.75
Data stored in Apache Parquet Format	130 GB	6.78 seconds	2.51 GB	$0.01
Savings	87% less when using Parquet	34x faster	99% less data scanned	99.7% savings

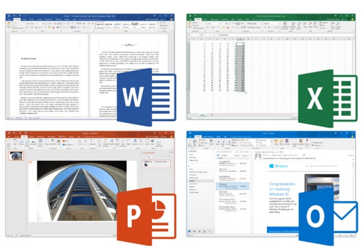
https://databricks.com/glossary/what-is-parquet

Data as File: Other Common Formats

- **Machine Perception** data layer on tensors and/or time-series
- Myriad binary formats, typically with (lossy) compression, e.g., WAV for audio, MP4 for video, etc.


- **Text File** (aka plaintext): Human-readable ASCII characters
- **Docs/Multimodal File:** Myriad app-specific rich binary formats



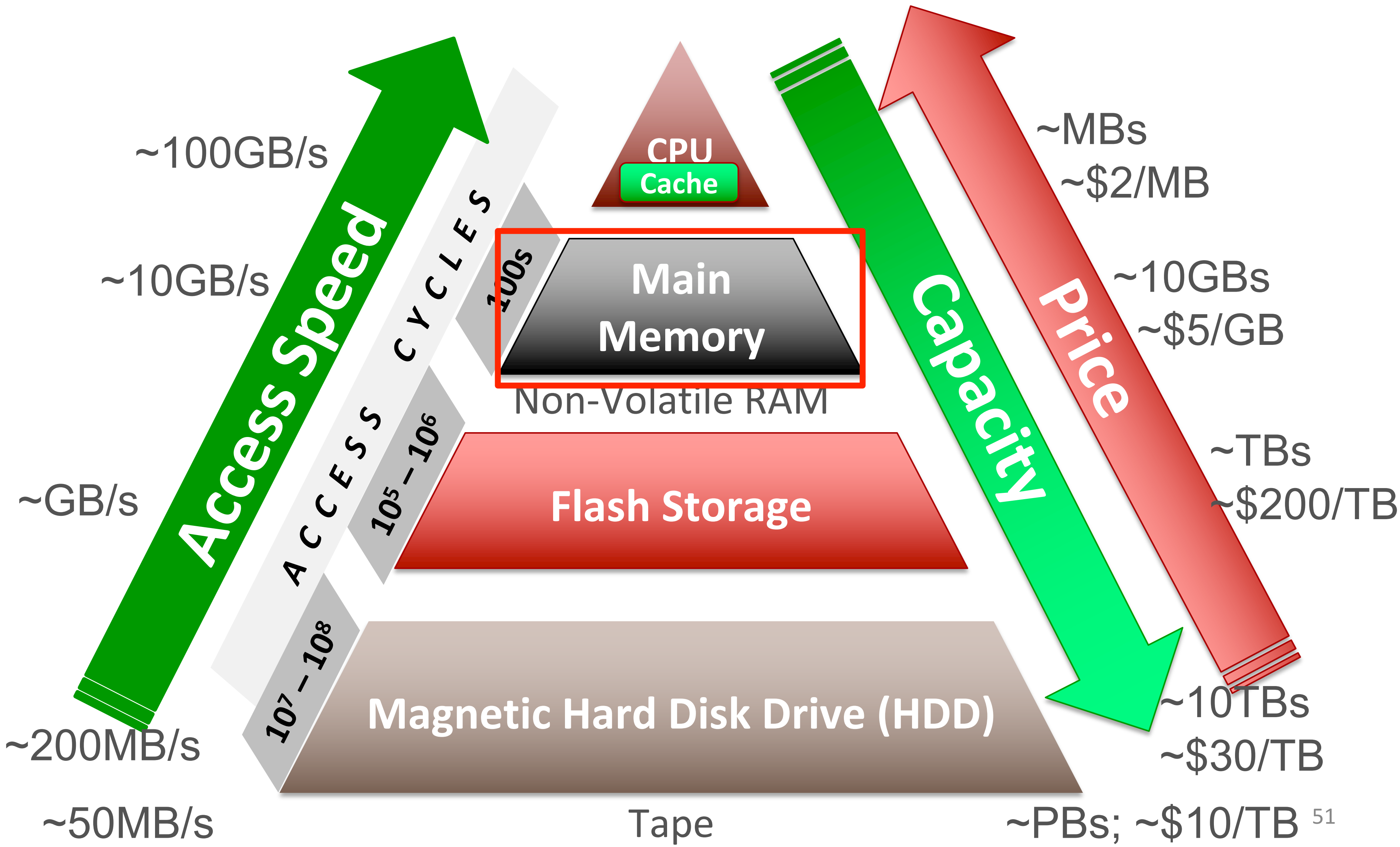
Peer Instruction Activity

(Switch slides)

Outline

- Basics of Computer Organization
  - Digital Representation of Data
  - Processors and Memory Hierarchy
- Basics of Operating Systems (OS)
  - Process Management: Virtualization; Concurrency
  - Filesystem and Data Files
  - Main Memory Management
- Persistent Data Storage

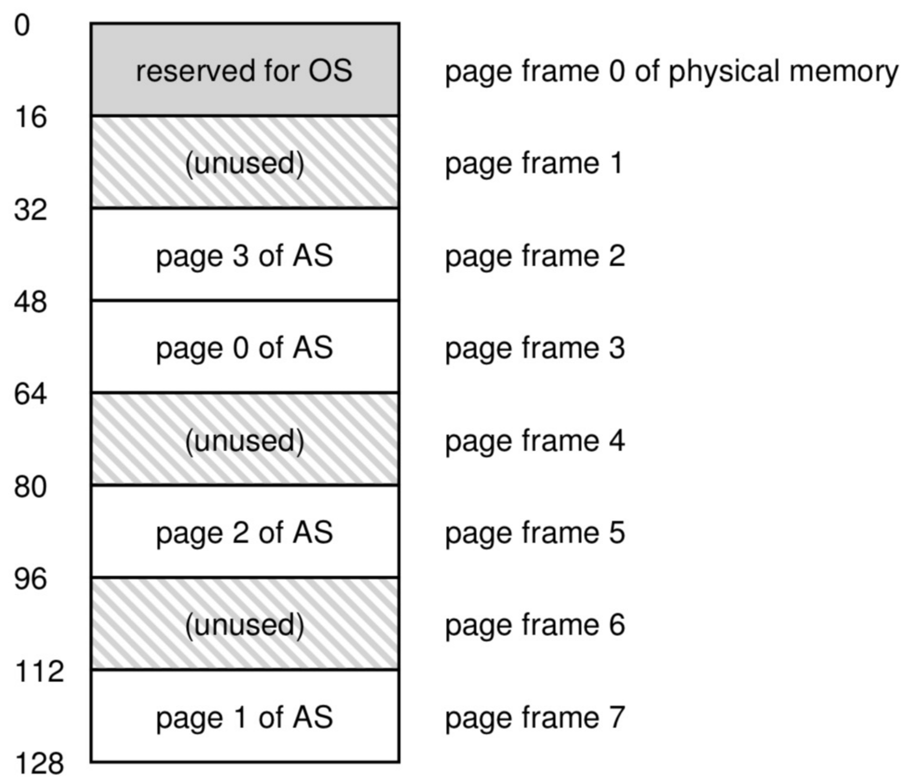
Memory/Storage Hierarchy



Virtualization of DRAM with Pages

- **Page**: An abstraction of *fixed* size chunks of memory/storage
  - Makes it easier to virtualize and manage DRAM
- **Page Frame**: Virtual slot in DRAM to hold a page's content

- Page size is usually an OS configuration parameter
  - E.g., 4KB to 16KB
- OS **Memory Management** has mechanisms to:
  - Identify pages uniquely
  - Read/write page from/to disk when requested by a process



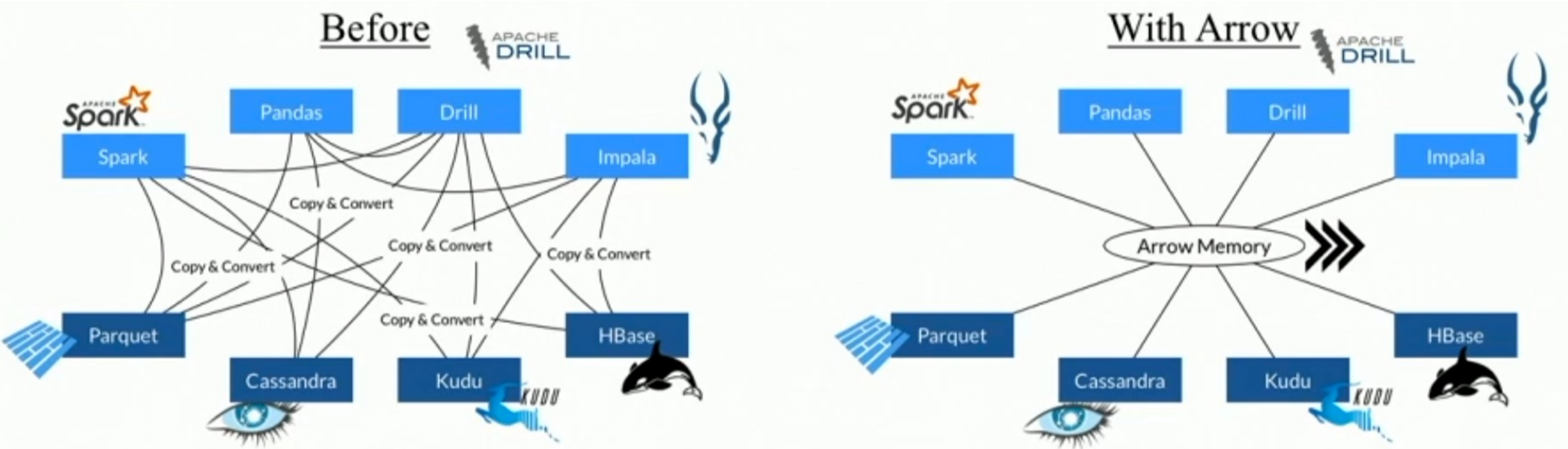
Apportioning of DRAM

- A process' **Address Space:**
  - Slice of virtualize DRAM assigned to it alone!
  - OS "translates" DRAM vs disk address
- **Page Replacement Policy:**
  - When DRAM fills up, which cached page to evict?
  - Many policies in OS literature
- **Memory Leaks:**
  - Process forgot to "free" pages used a while ago
  - Wastes DRAM and slows down system
- **Garbage Collection:**
  - Some PL impl. can auto-reclaim some wasted memory

Ad: Take CSE 120 or 132C for more on memory management

Storing Data In Memory

- Any data structure in memory is overlaid on pages
- Process can ask OS for more memory in System Call API
  - If OS denies, process may crash; your PA0 Dask crashes?
- **Apache Arrow:**
  - Emerging standard for columnar in-memory data layout
  - Compatible with Pandas, (Py)Spark, Parquet, etc.



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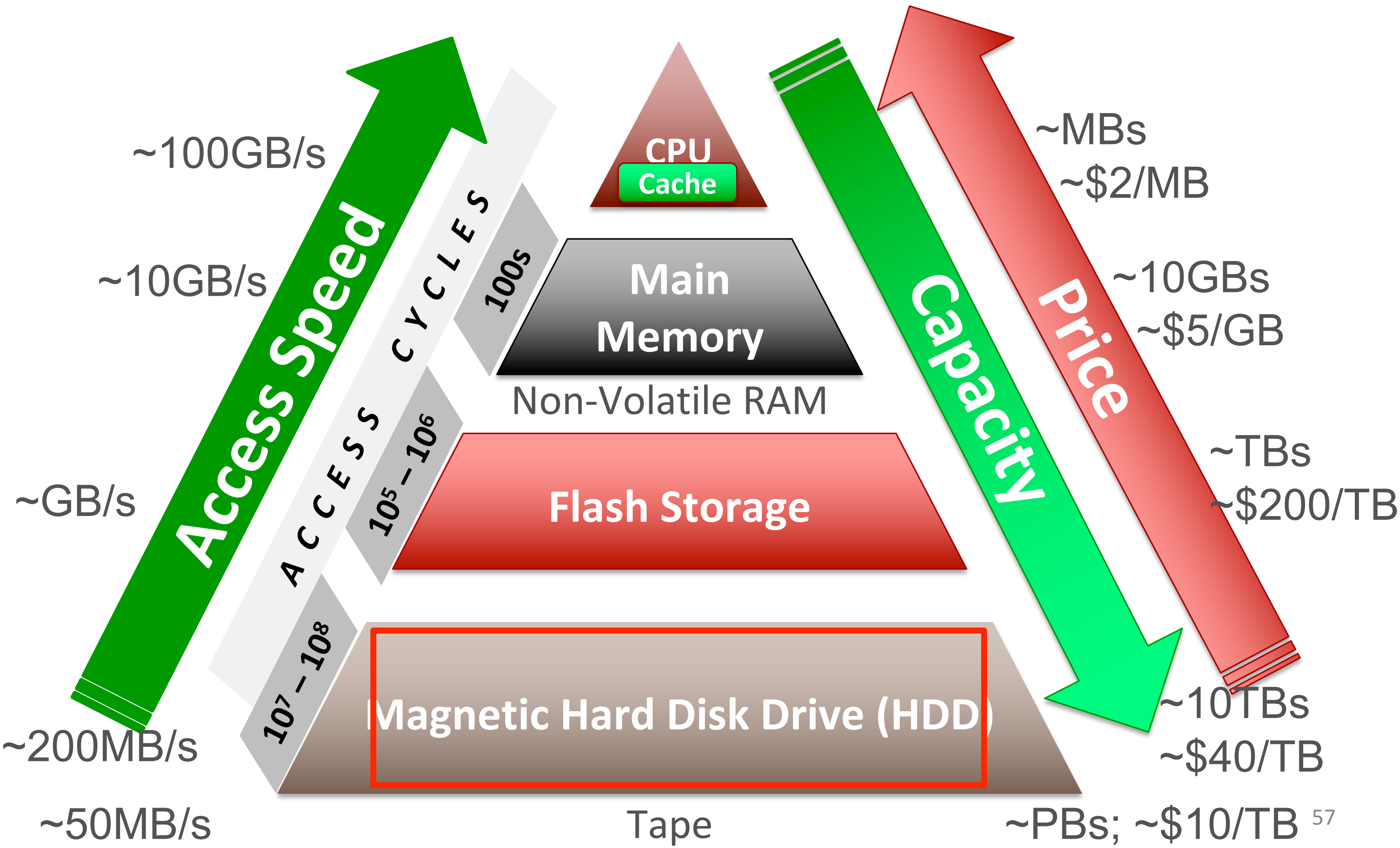
Persistent Data Storage

- **Persistence**: Program state/data is available intact even after process finishes
- **Volatile Memory**: A data storage device that needs power/electricity to store bits; e.g., DRAM, CPU caches (SRAM)
- **Non-Volatile** or **Persistent** mem./storage: A data storage device that retains bits intact after power cycling
  - E.g., all levels below DRAM in memory hierarchy
  - "**Persistent Memory** (PMEM)": Marketing term for large DRAM that is backed up by battery power!
  - **Non-Volatile RAM (NVRAM)**: Popular term for DRAM-like device that is genuinely non-volatile (no battery)

Memory/Storage Hierarchy



Disks

- Aka secondary storage; likely holds the vast majority of the world's day-to-day business-critical data!
- Data storage/retrieval units: **disk blocks** or **pages**
- Unlike RAM, different disk pages have different retrieval times based on location:
  - Need to optimize *data layout* on disk pages
  - Orders of magnitude performance gaps possible

Data Organization on Disk

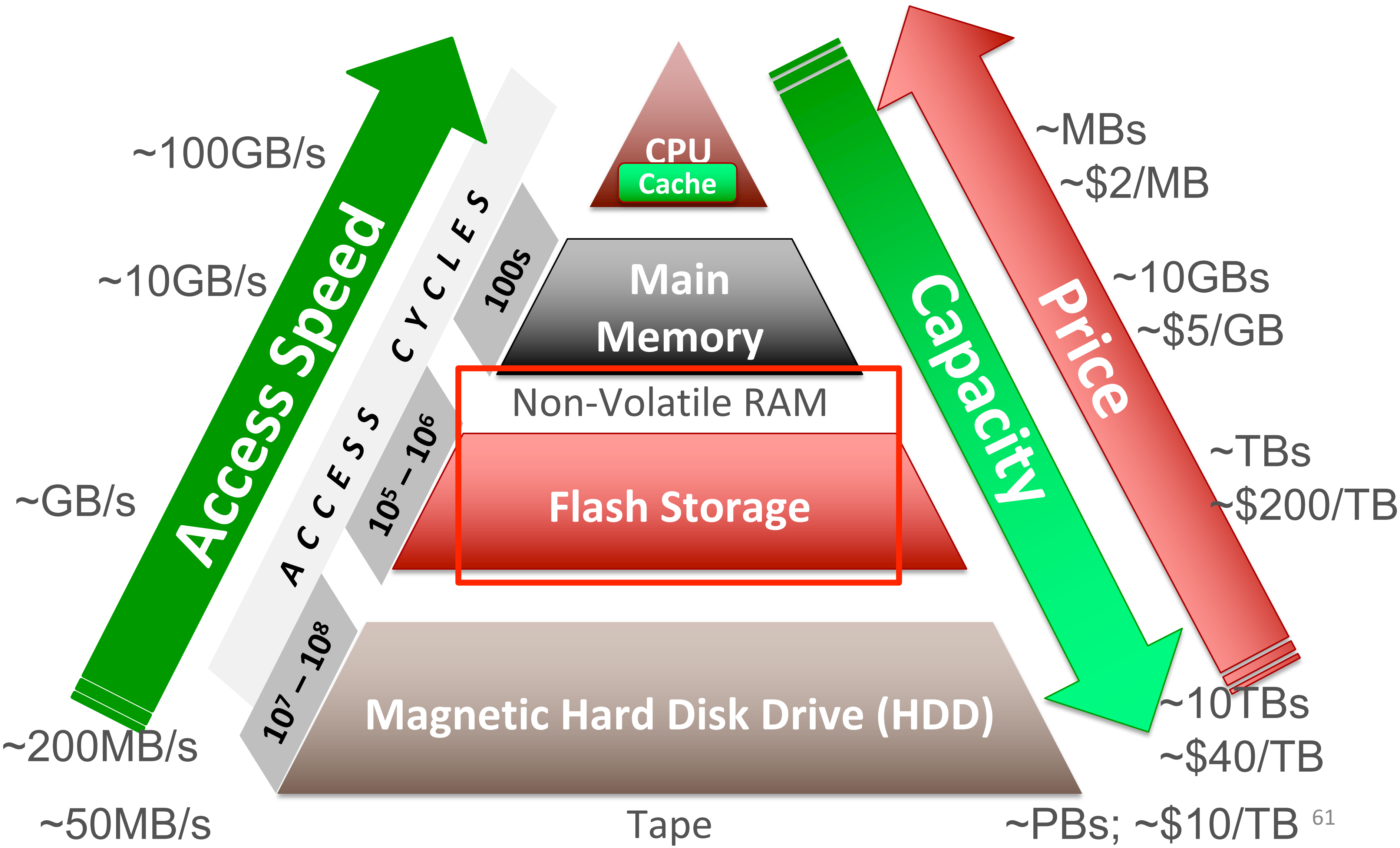
- Disk space is organized into **files**
- Files are made up of disk **pages** aka **blocks**
- Typical disk block/page size: 4KB or 8KB
  - Basic unit of reads/writes for a disk
  - OS/RAM page is *not* the same as disk page!
  - Typically, OS/RAM page size = disk page size but not always; disk page can be a multiple, e.g., 1MB
- File data (de-)allocated in increments of disk pages

Magnetic Disk Quirks

- **Key Principle**: Sequential v Random Access Dichotomy
- Accessing disk pages in sequential order gives *higher throughput*
  - Random reads/writes are OOM slower!
- Need to carefully lay out data pages on disk
- Abstracted away by data systems: Dask, Spark, RDBMSs, etc.

Ad: Take CSE 132C for more on quirks of magnetic disks

Memory/Storage Hierarchy



Flash SSD vs Magnetic Hard Disks

Roughly speaking, flash combines the speed benefits of DRAM with persistence of disks

- Random reads/writes are not much worse
  - Different locality of reference for data/file layout
  - But still block-addressable like HDDs
- Data access latency: 100x faster!
- Data transfer throughput: Also 10-100x higher
- Parallel read/writes more feasible
- Cost per GB is 5-15x higher!
- Read-write impact asymmetry; much lower lifetimes

NVRAM vs Magnetic Hard Disks

Roughly speaking, NVRAM is like a non-volatile form of DRAM, but with similar capacity as SSDs

- Random R/W with less to no SSD-style wear and tear
  - Byte-addressability (not blocks like SSDs/HDDs)
  - Spatial locality of reference like DRAM; radical change!
- Latency, throughput, parallelism, etc. similar to DRAM
- Alas, yet to see light of day in production settings
- Cost per GB: No one knows for sure yet!

Review Questions

- How is a database different from a file?
- What are the 2 levels of a database? Why the dichotomy?
- What type of data modality is JSON meant to capture?
- Explain 2 differences between a relation and a DataFrame.
- Can you store a relation as a DataFrame? Vice versa?
- Can you store a tensor as a relation? Vice versa?
- What is the address space of a process? What is a memory leak?
- What is Parquet? Explain 3 pros of Parquet over CSVs.
- What is Arrow? How is it different from Parquet?
- Which storage device has random-sequential access dichotomy?

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