UC San Diego

DSC 102
Systems for Scalable Analytics

Haojian Jin

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

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


legislature


judiciary


executive

Role of an OS in a Computer

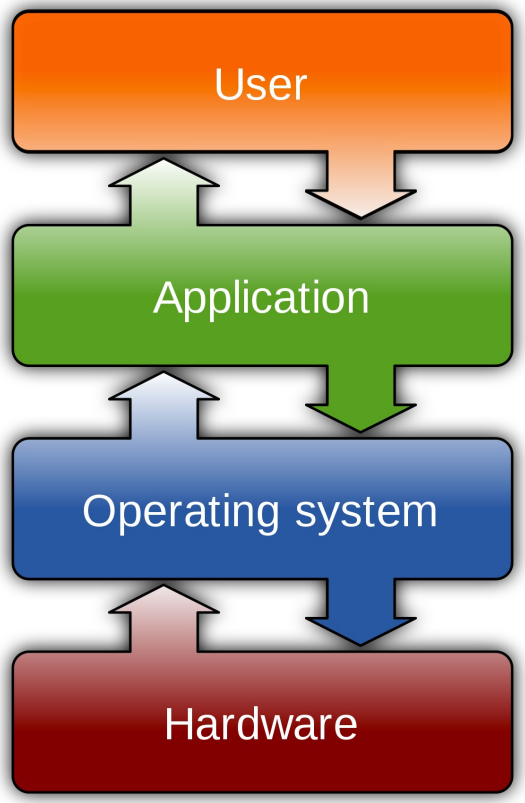
- An OS is a large set of interrelated programs that *make it easier* for applications and user-written programs to use computer hardware *effectively*, *efficiently*, and *securely*
  - Akin to a government's role in a country
- Without OS, computer users must speak machine code!
- 2 key principles 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?

Logistics

- **Midterm: the week of May 11-16 (Monday? Wednesday? Friday?)**
- **Assignment due: 04/24/2023 23:59.**
- **No late days for submitting the PAs.**

PIA Links:
https://bit.ly/DSC102PIA2

Role of an OS in a Computer



APIs/Interface of Application Software

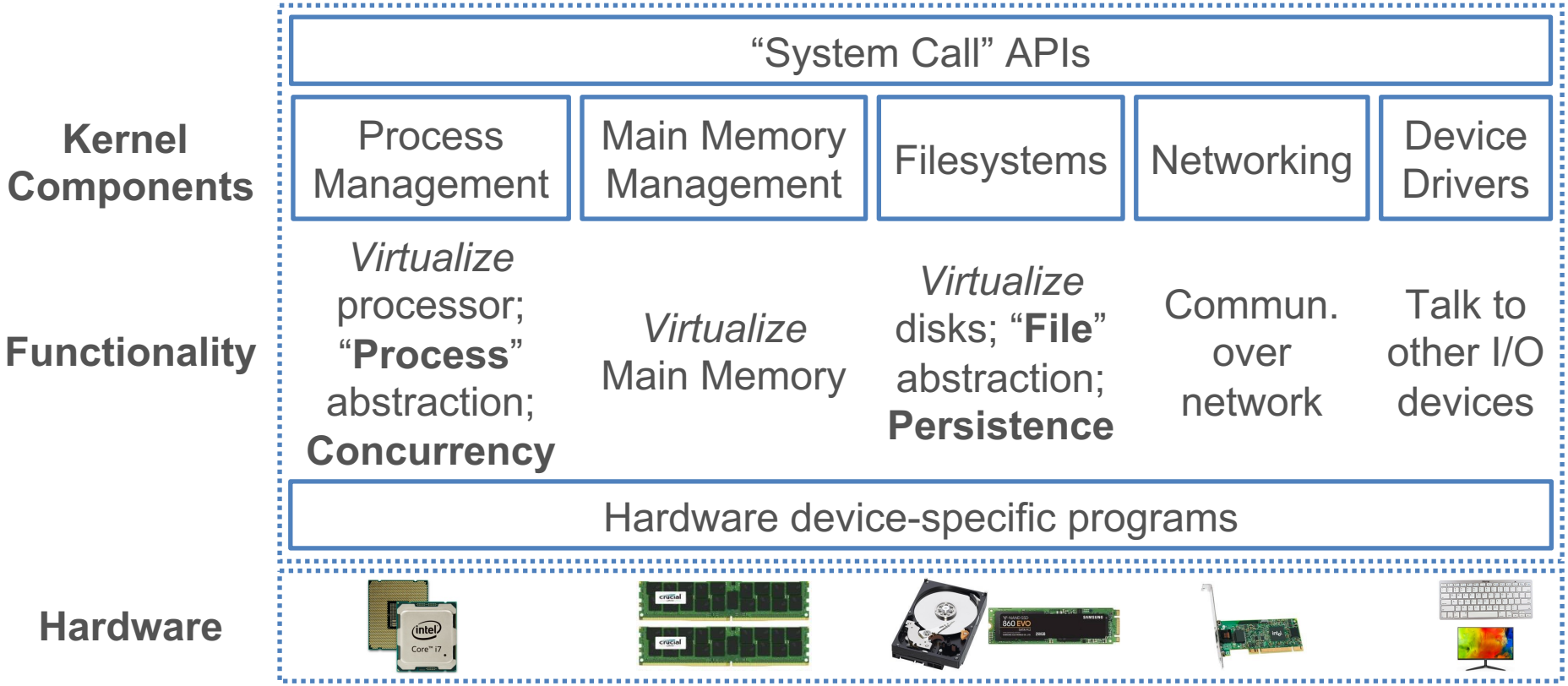
APIs of OS aka “System Calls”

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.



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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**

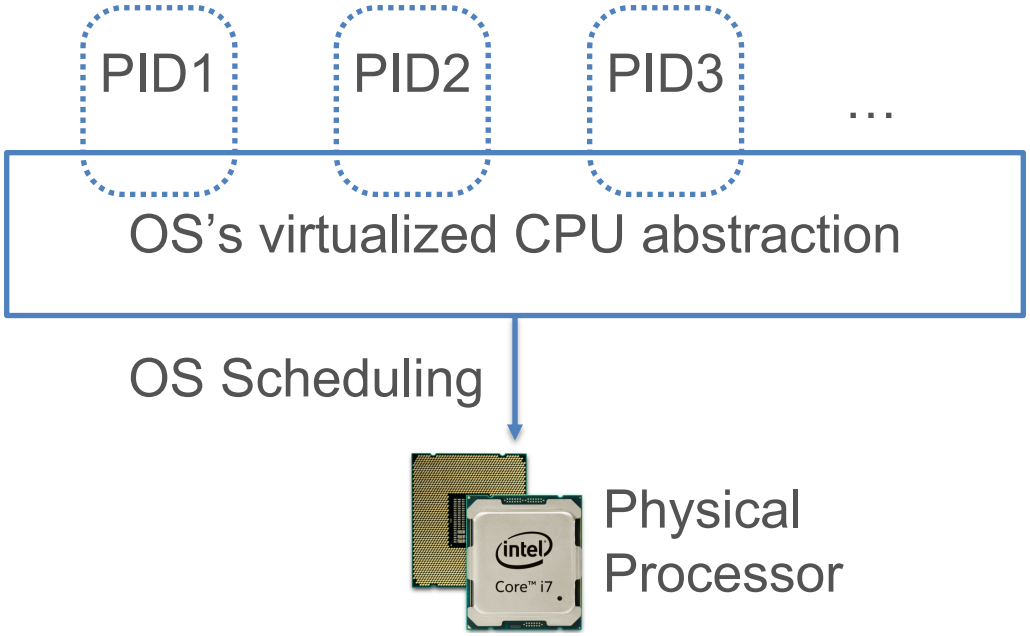
Virtualization of Hardware Resources

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

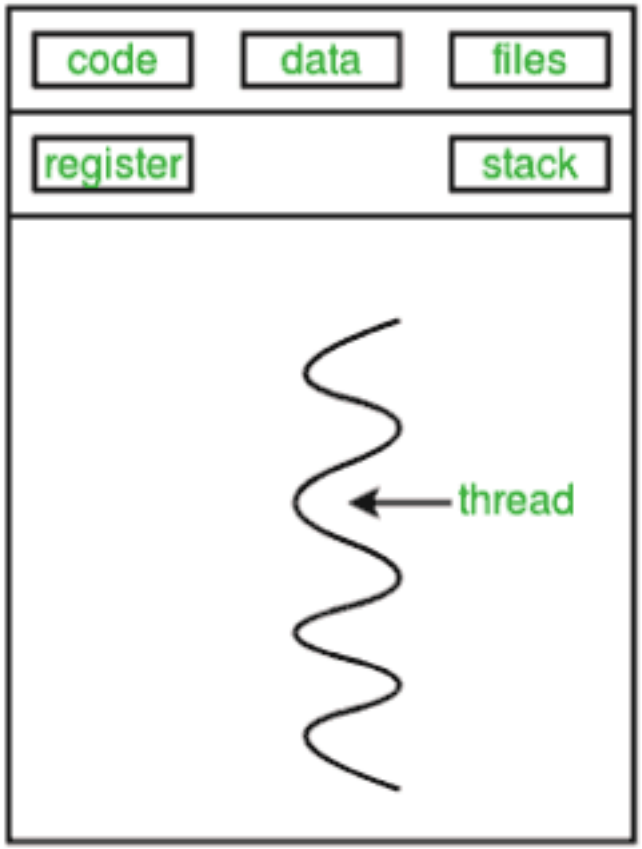
Virtualization of Processors

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

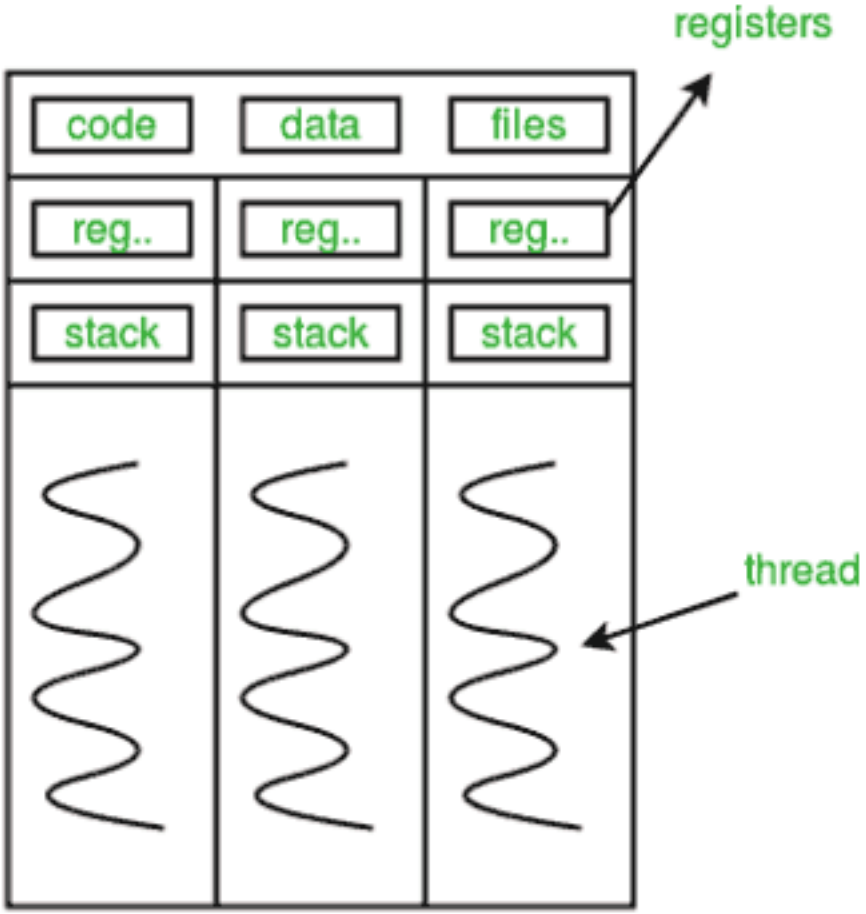


- Inter-process communication possible in System Calls API
- Later: Generalize to **Thread** abstraction for **concurrency**

Thread vs process

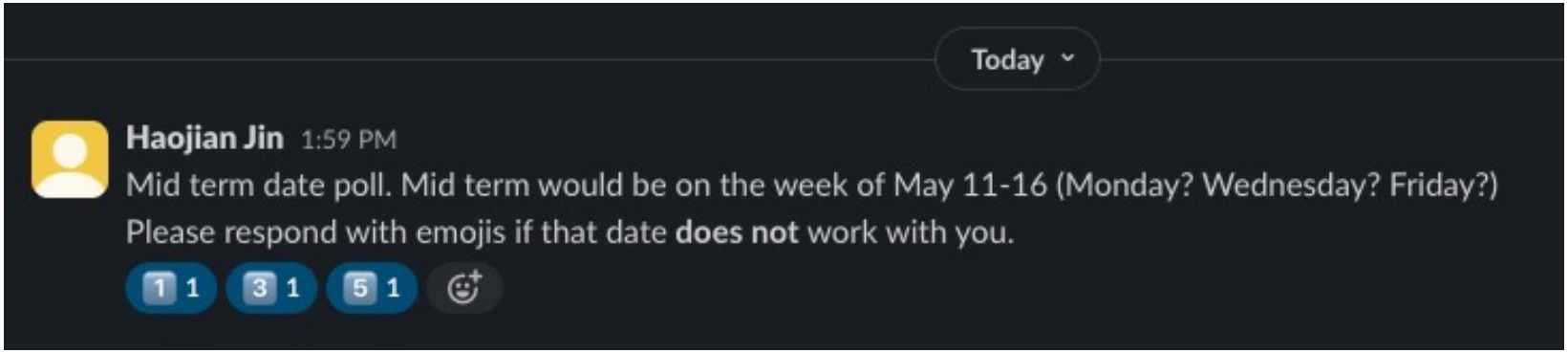


single-threaded process



multithreaded process

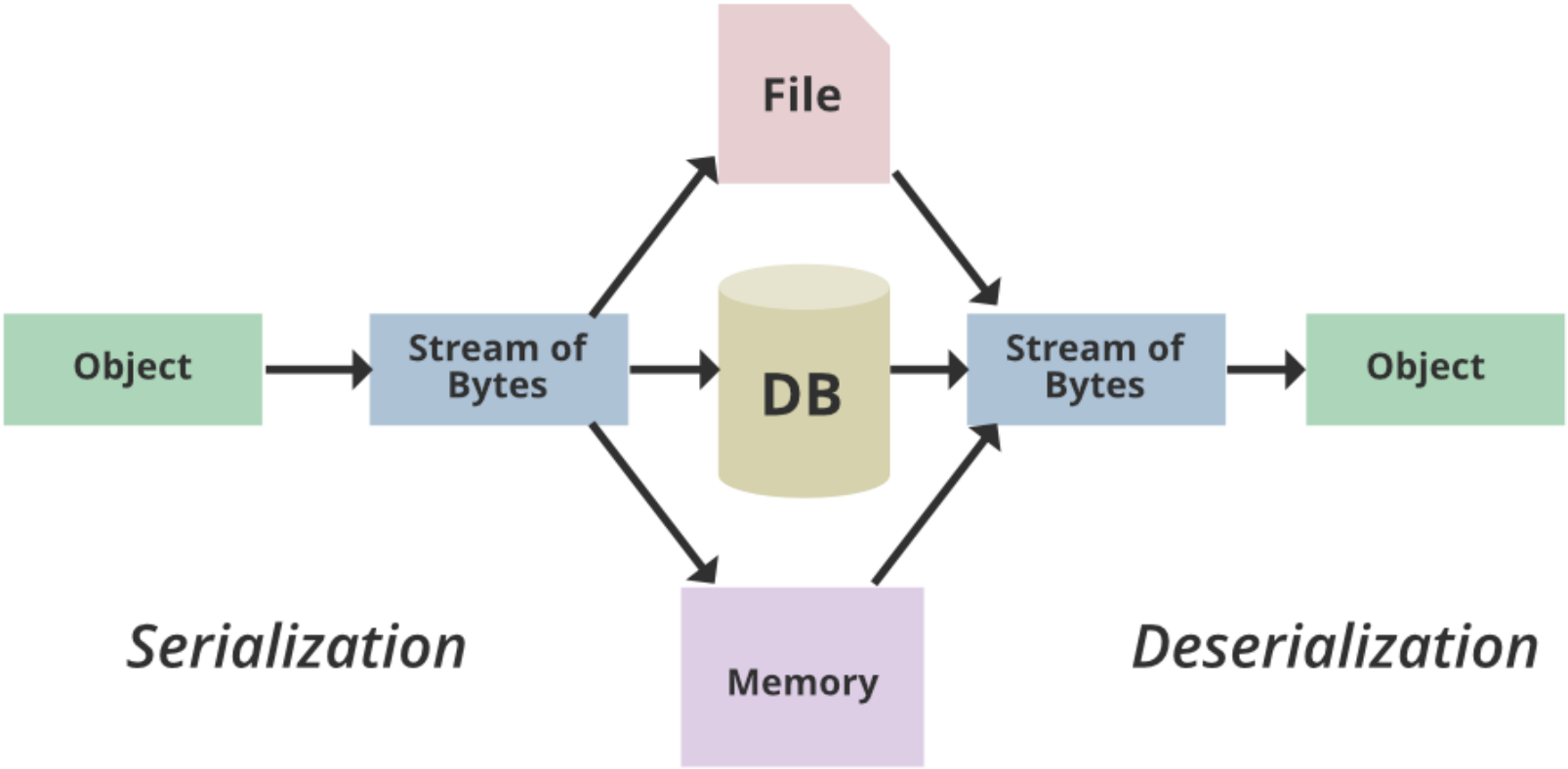
Logistics



- It is okay to discuss about the assignment with your peers at a conceptual level. It is also okay to post conceptual or high-level questions, logistical questions, and useful references on Slack. But do not share any code across teams and do not post any of your solution code for discussion on the public channels. A team's code submission must be entirely their own.

Questions: Serialization

- **Serialization:** binary & strings

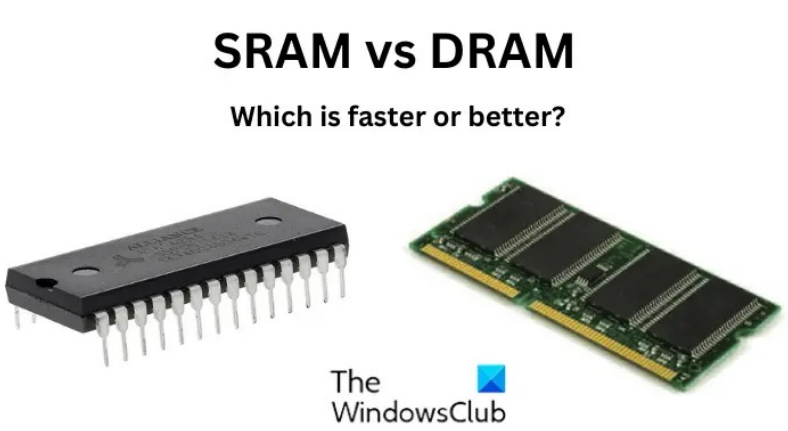


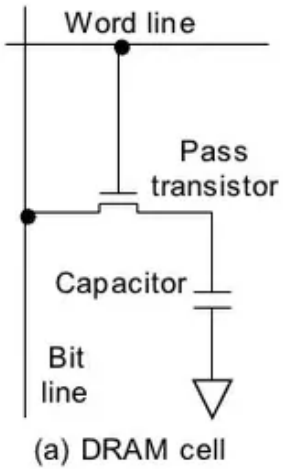
Questions: Object-oriented programming

How do we represent objects in memory?

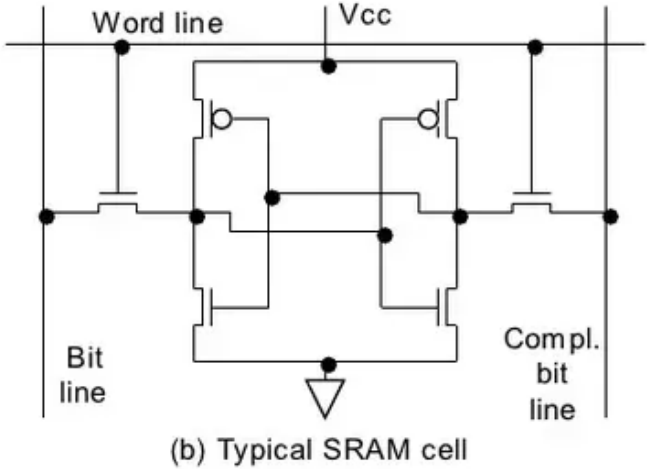
Pointers (i.e., memory addresses).
DRAM => Dynamic Random Access Memory
Disk & network are sequential.

Questions: SRAM v.s. DRAM





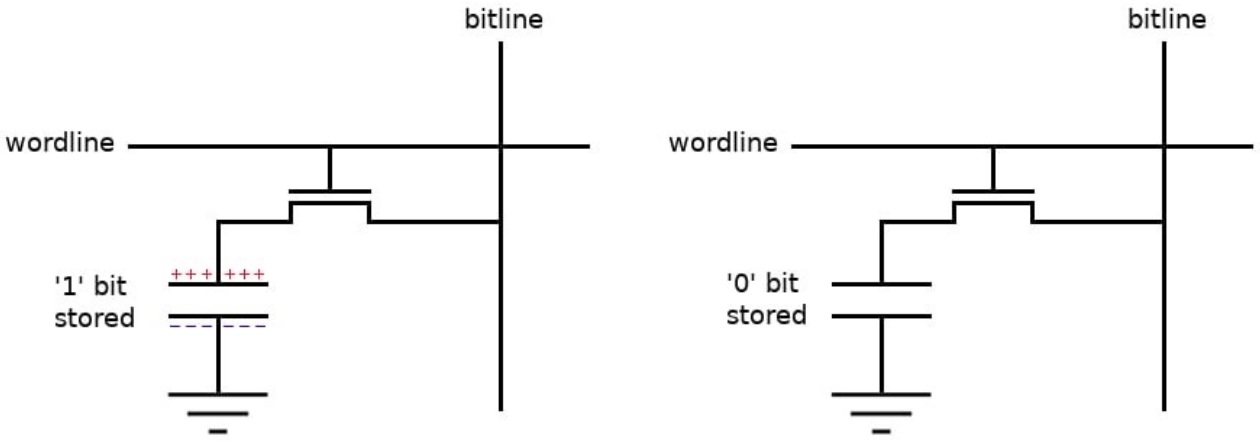
(a) DRAM cell



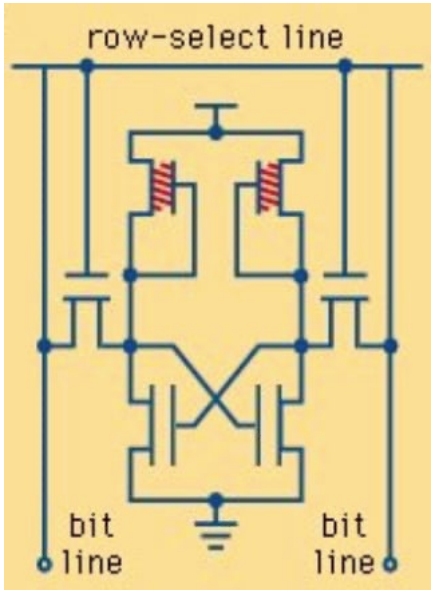
(b) Typical SRAM cell

- Cycle time of SRAM 10 to 20 times faster than DRAM
- For same technology, capacity of DRAM 5 to 10 times that of SRAM
- Hence
  - Main memory is DRAM
  - On-chip caches are SRAM
  - Off-chip caches (it depends)

Questions: SRAM v.s. DRAM



Destructive read.
Require a transistor and capacitor.

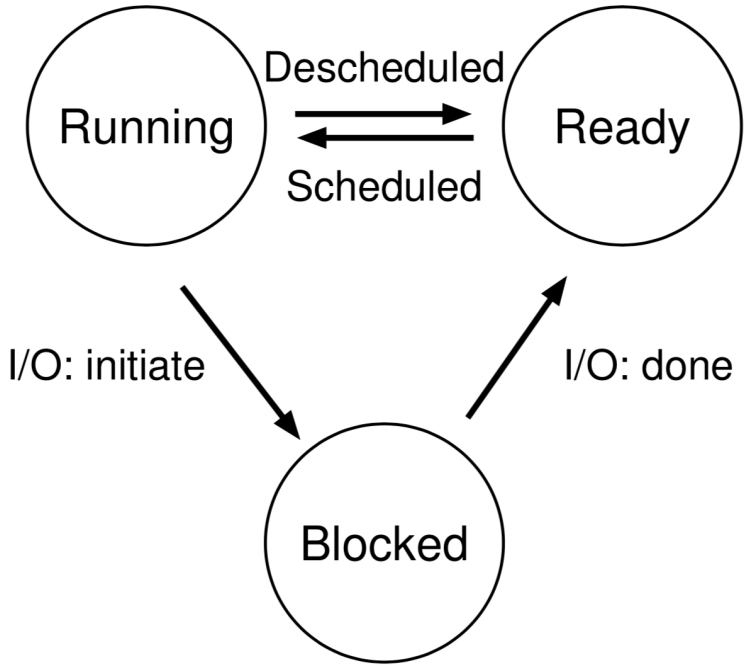


Non-destructive read.
Requires six transistors

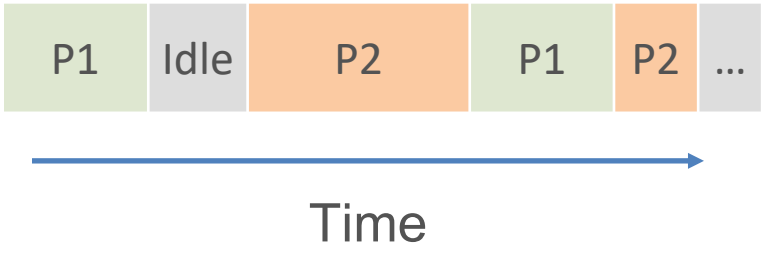

-30
01:24

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


50/50
RAFFLE
APART

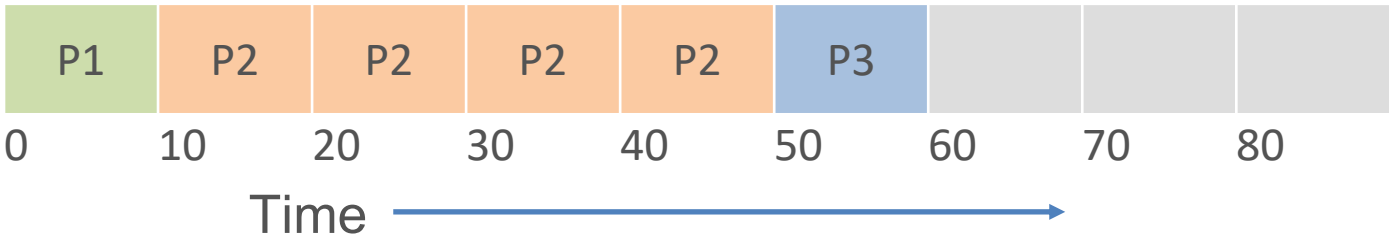
Scheduling Policies/Algorithms

- 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



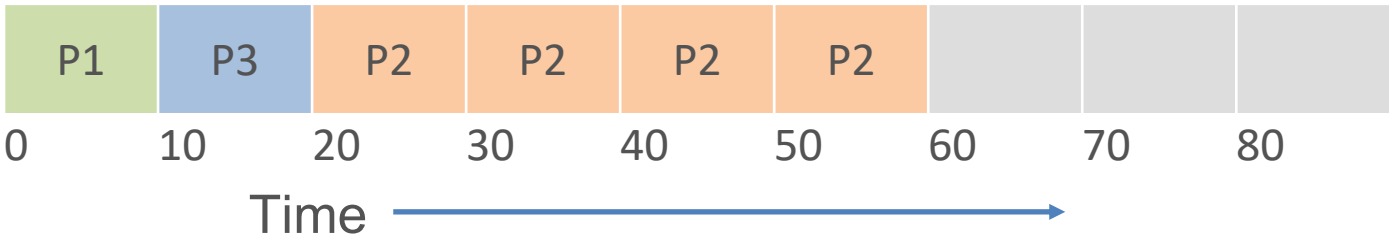
Process	Arrival Time	Start Time	Completion Time	Response Time	Turnaround Time
P1	0	0	10	0	10
P2	0	10	50	10	50
P3	0	50	60	50	60
			Avg:	20	40

- 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
			Avg:	10	30

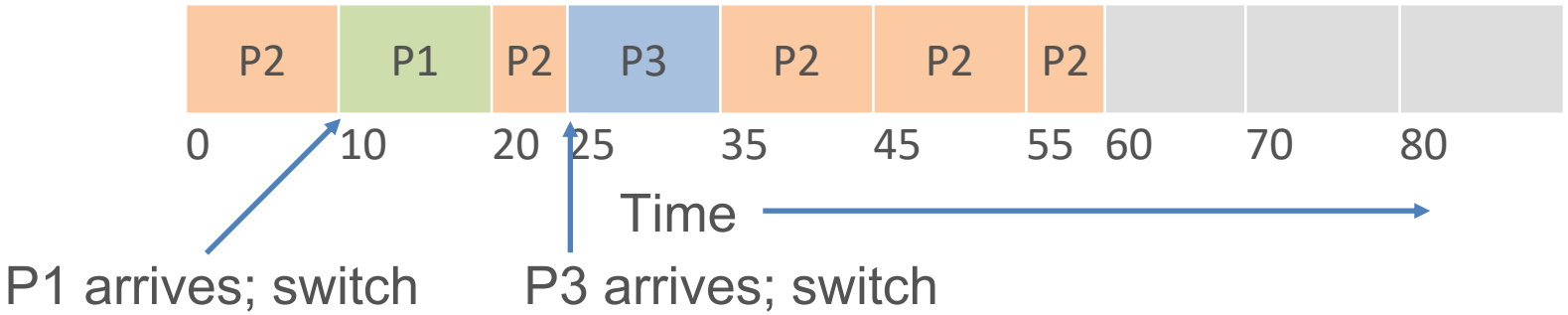
(FIFO Avg: 20 and 40)

- 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



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
			Avg:	0	26.7

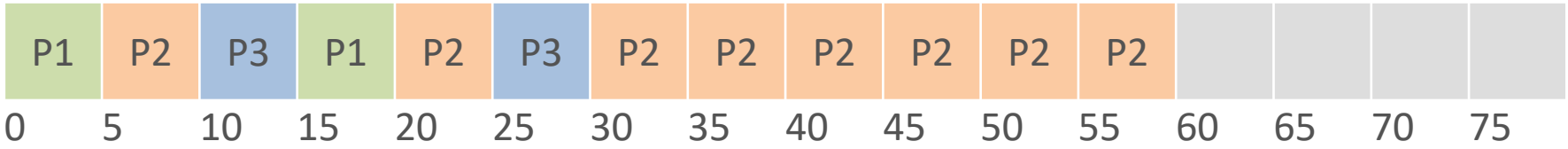
(SJF Avg: 10 and 30)

- 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



Quantum is 5

Time

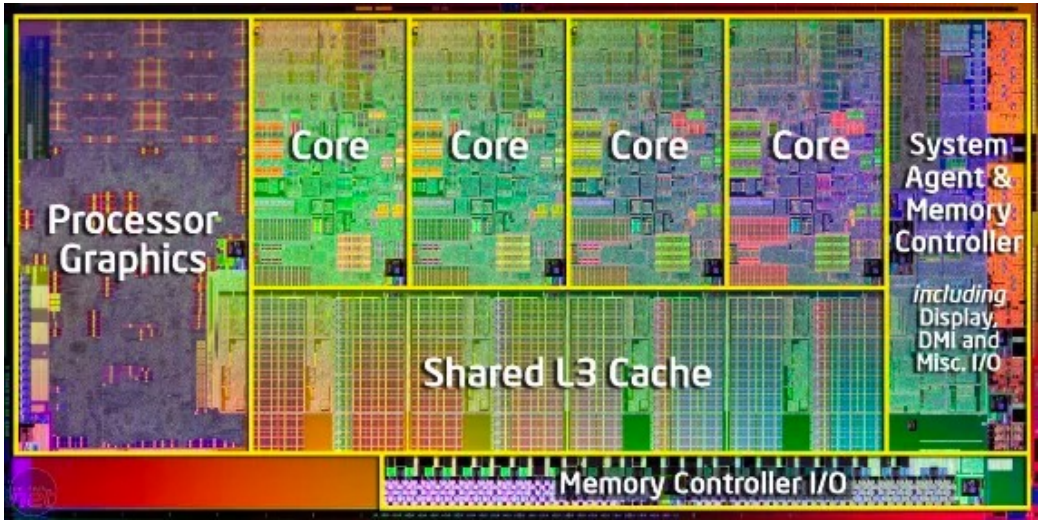
Process	Arrival Time	Start Time	Completion Time	Response Time	Turnaround Time
P1	0	0	20	0	20
P2	0	5	60	5	60
P3	0	10	30	10	30
			Avg:	5	36.7

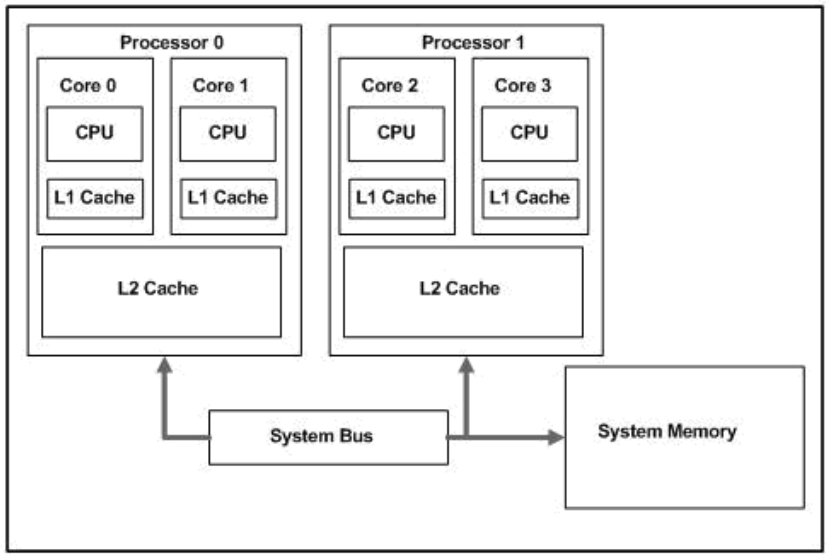
(SJF Avg: 10 & 30; SCTF Avg: 0 & 26.7)

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

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



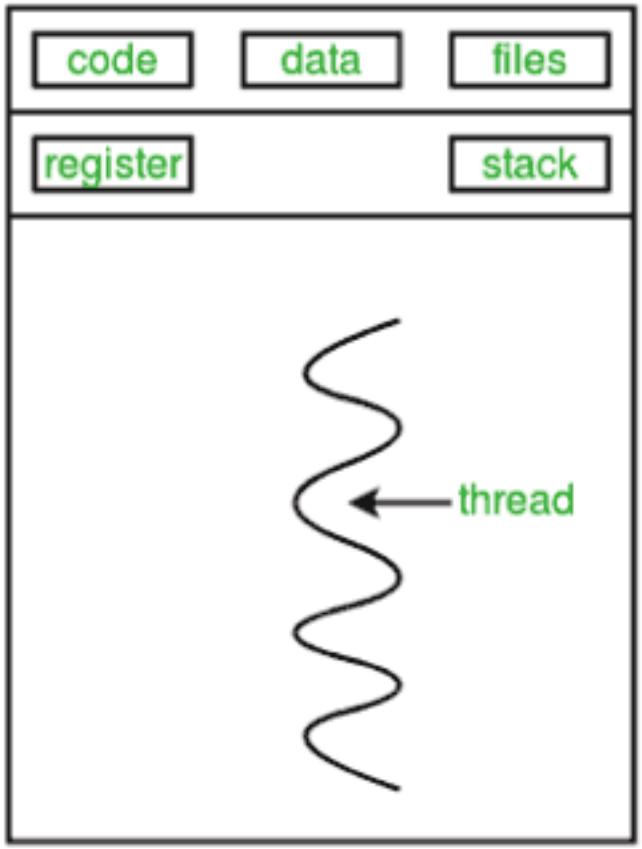


Concurrency

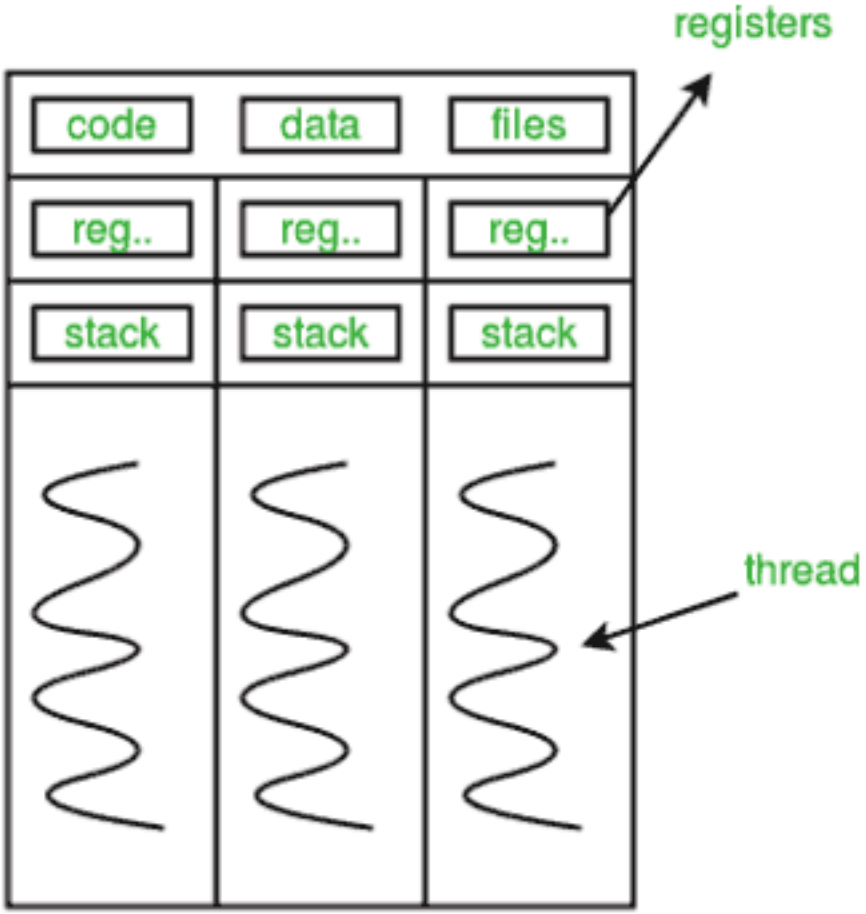
- **Multiprocessing:** Different processes run on different cores (or entire CPUs) simultaneously
- **Thread:** Generalization of OS's Process abstraction
  - A program *spawns* many threads; each run parts of the program's computations simultaneously
  - **Multithreading:** Same core used by many threads

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

Thread vs process



single-threaded process



multithreaded process

Example thread code

```
# Python program to illustrate the concept
# of threading
# importing the threading module
import threading


def print_cube(num):
    # function to print cube of given num
    print("Cube: {}" .format(num * num * num))


def print_square(num):
    # function to print square of given num
    print("Square: {}" .format(num * num))


if __name__ =="__main__":
    # creating thread
    t1 = threading.Thread(target=print_square, args=(10,))
    t2 = threading.Thread(target=print_cube, args=(10,))

    # starting thread 1
    t1.start()
    # starting thread 2
    t2.start()

    # wait until thread 1 is completely executed
    t1.join()
    # wait until thread 2 is completely executed
    t2.join()

    # both threads completely executed
    print("Done!")
```

Inter-thread communication

```
from queue import Queue
from threading import Thread

# A thread that produces data
def producer(out_q):
    while True:
        # Produce some data
        ...
        out_q.put(data)

# A thread that consumes data
def consumer(in_q):
    while True:
        # Get some data
        data = in_q.get()
        # Process the data
        ...

# Create the shared queue and launch both threads
q = Queue()
t1 = Thread(target = consumer, args =(q, ))
t2 = Thread(target = producer, args =(q, ))
t1.start()
t2.start()
```

Inter-process communication

Your server could listen to receive python objects:

```
from multiprocessing.connection import Listener

address = ('localhost', 6000)     # family is deduced to be 'AF_INET'
listener = Listener(address, authkey=b'secret password')
conn = listener.accept()
print 'connection accepted from', listener.last_accepted
while True:
    msg = conn.recv()
    # do something with msg
    if msg == 'close':
        conn.close()
        break
listener.close()
```

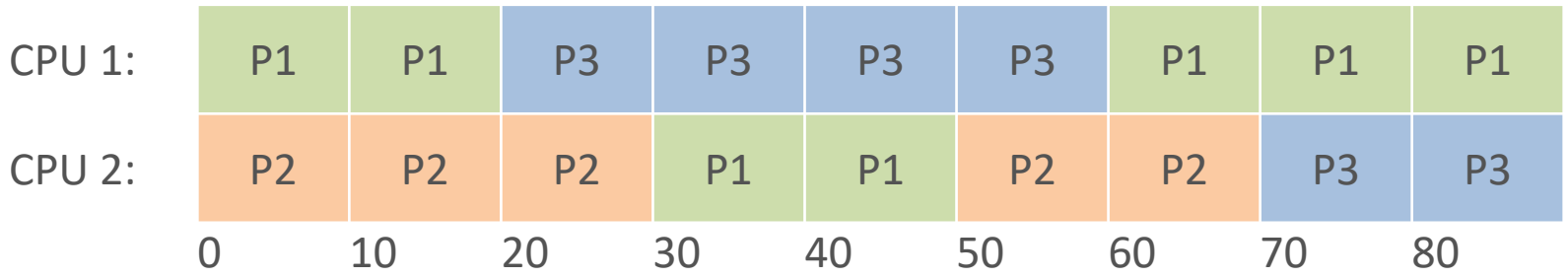
Your client could send commands as objects:

```
from multiprocessing.connection import Client

address = ('localhost', 6000)
conn = Client(address, authkey=b'secret password')
conn.send('close')
# can also send arbitrary objects:
# conn.send(['a', 2.5, None, int, sum])
conn.close()
```

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:



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.

Peer Instruction Activity

(Switch slides)

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Q: *What is a file?*


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

Filesystem

Question **Copy/Paste speed difference: macOS vs. Windows PC**

Endre · May 8, 2019 · Apple windows

Forums › Software › macOS

Not open for further replies.

Endre
Reputable

Apr 30, 2019
1,102
214
5,840

May 8, 2019 #1

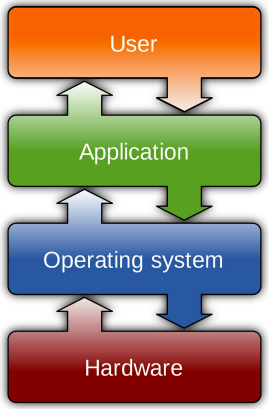
A friend of mine owns a macOS laptop (CPU: Intel i5, 16GB DDR4, OSX on SSD). He copied a 33GB file from his internal drive to the desktop in about 1 second!
I own a Desktop PC (CPU: Intel i7-9700K, 16GB DDR4, Windows 10 x64 on SATA-SSD). I copied a 16GB file from Local Disk C to the Desktop in... A LOT LONGER TIME THAN 1 second!

QUESTION#1: Why is Windows copying files so slow?
QUESTION#2: Would an M.2 NVMe SSD or an Intel Optane Memory match the speed of the macOS?

Virtualization of File on Disk

- OS abstracts a file on disk as a virtual object for processes
- **File Descriptor:** An OS-assigned 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?*

Collection of files?

Virtualization of Files

Binary Representation on Disk storage

- Maintenance
- Performance
- Usability
- Security & privacy
- …

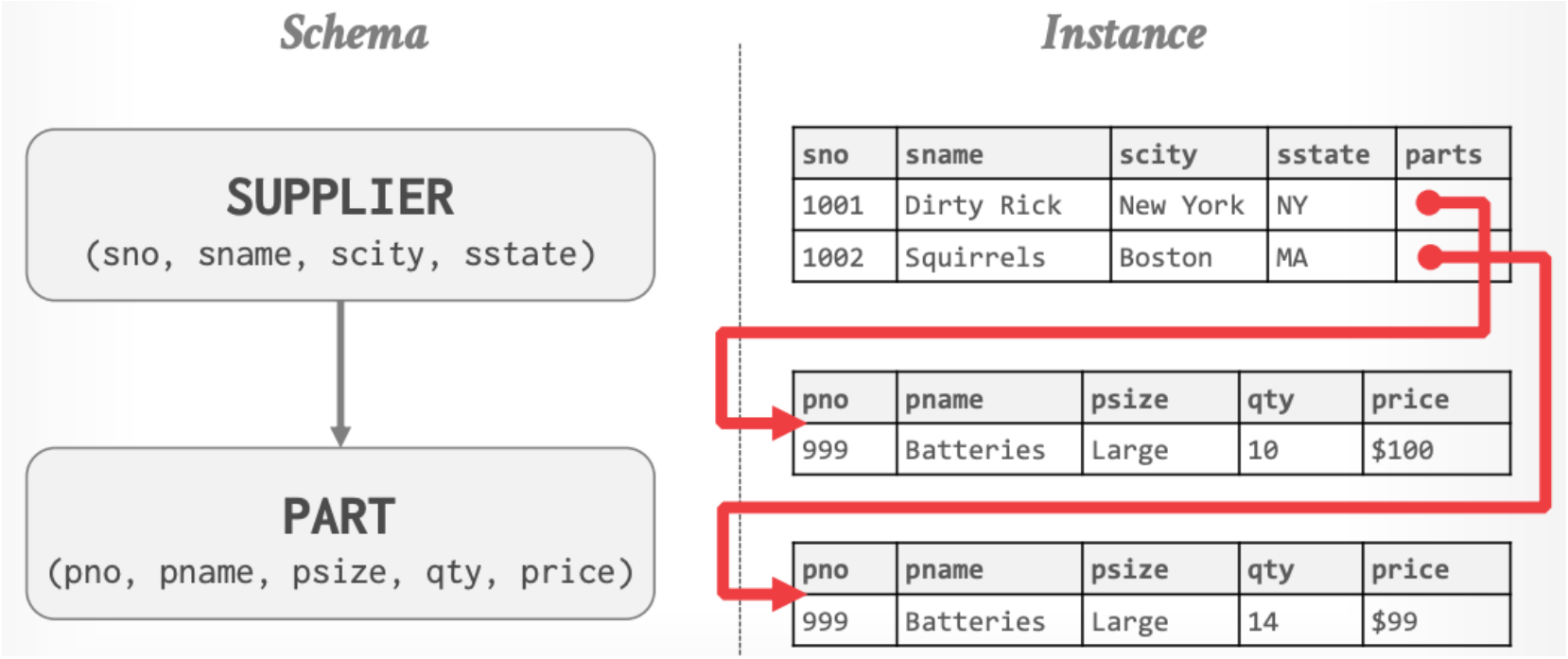
Files Vs Databases: Data Model

- **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

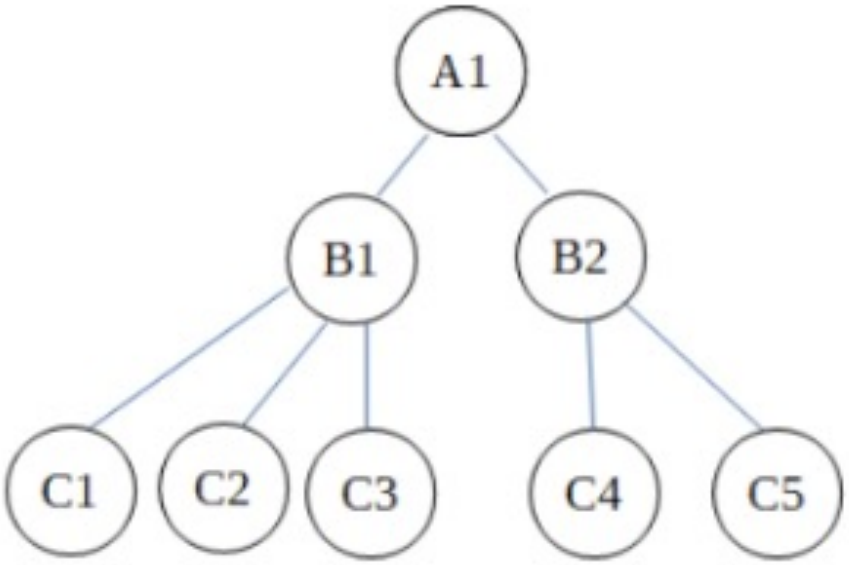
Principles and classical ideas (will discuss more later)

- Old ideas are still relevant today.
  - Most of the ideas are not new.
- People re-invent tools based on the classical ideas every decade.
  - It then fails and the later tools absorbs the key ideas.
- Tools change constantly, since we have new tasks and new hardware.

Hierarchical Data Model

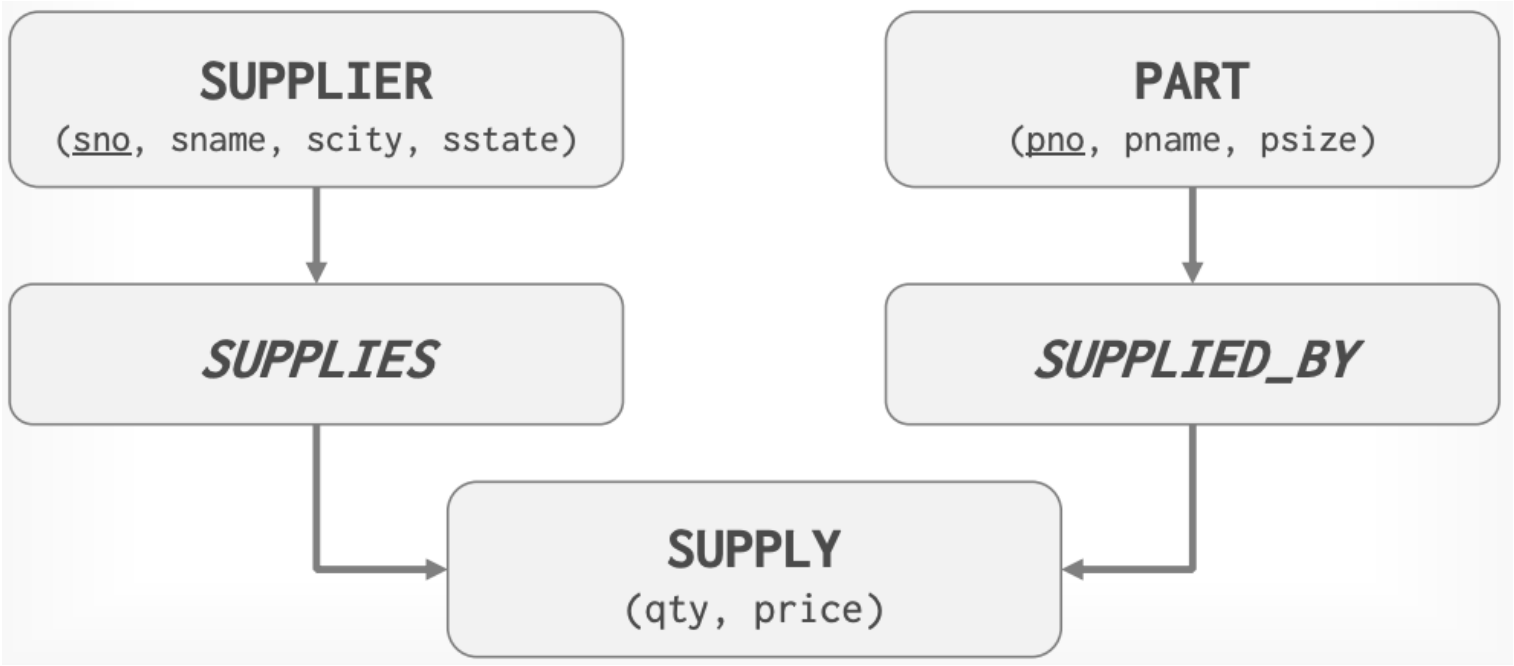


Hierarchical Data Model

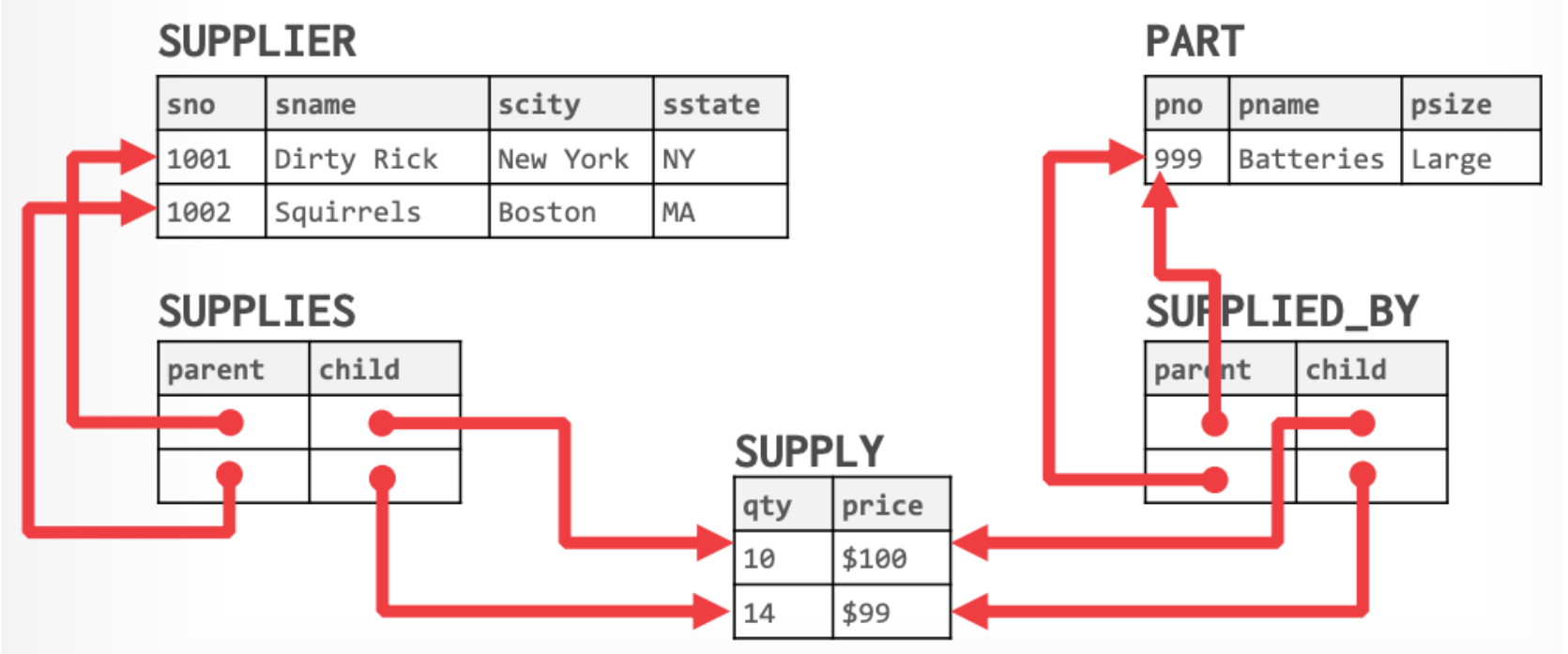


- Initially file-based model.
- Good for one-to-many relationships.
- Bad for many-to-many relationships.

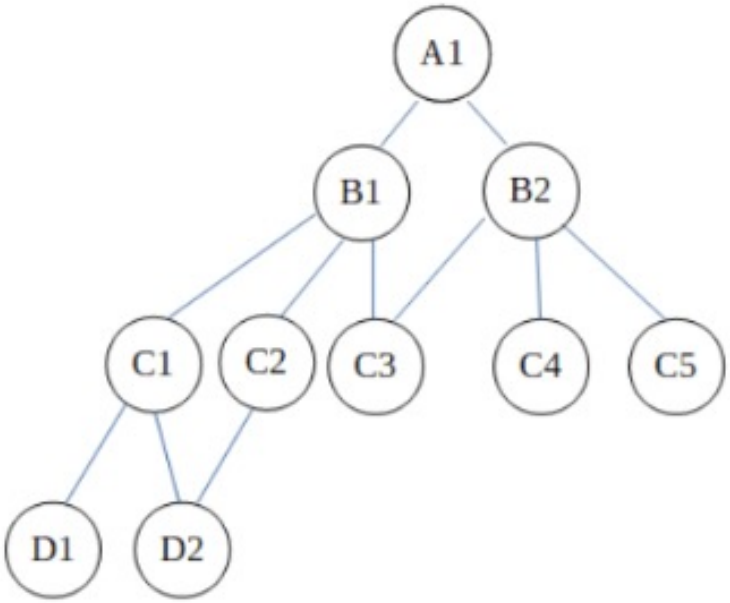
Network Data Model (schema)



Network Data Model (Instance)

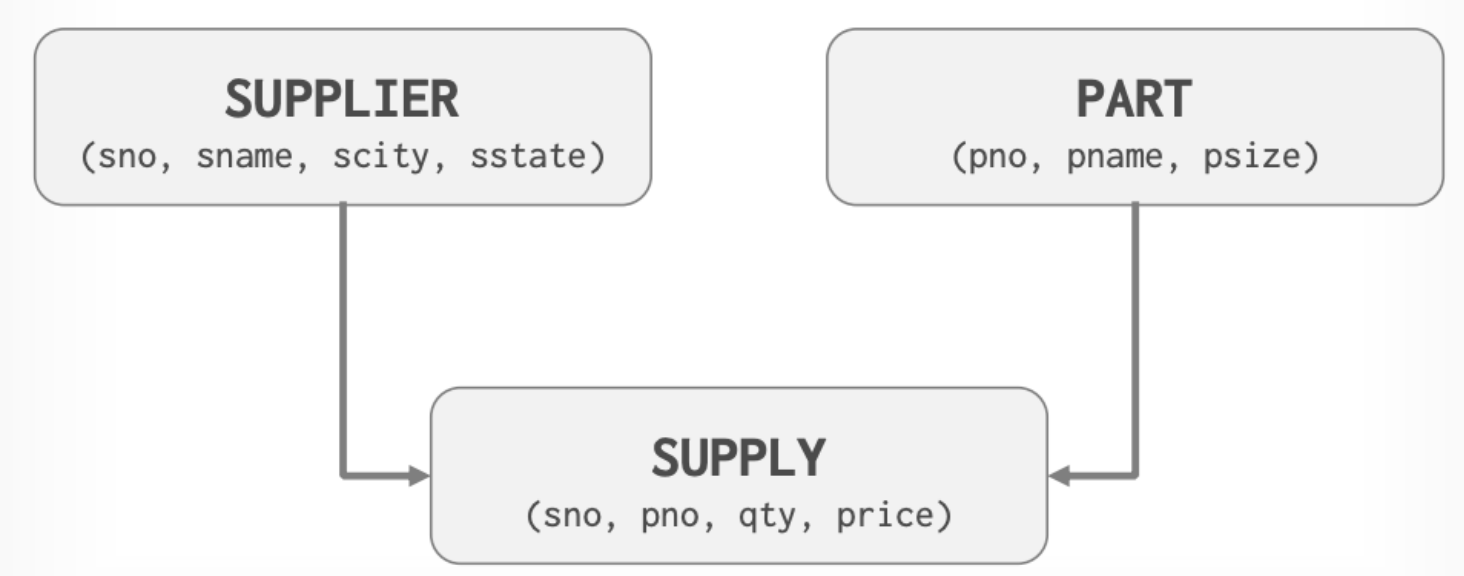


Network Data Model

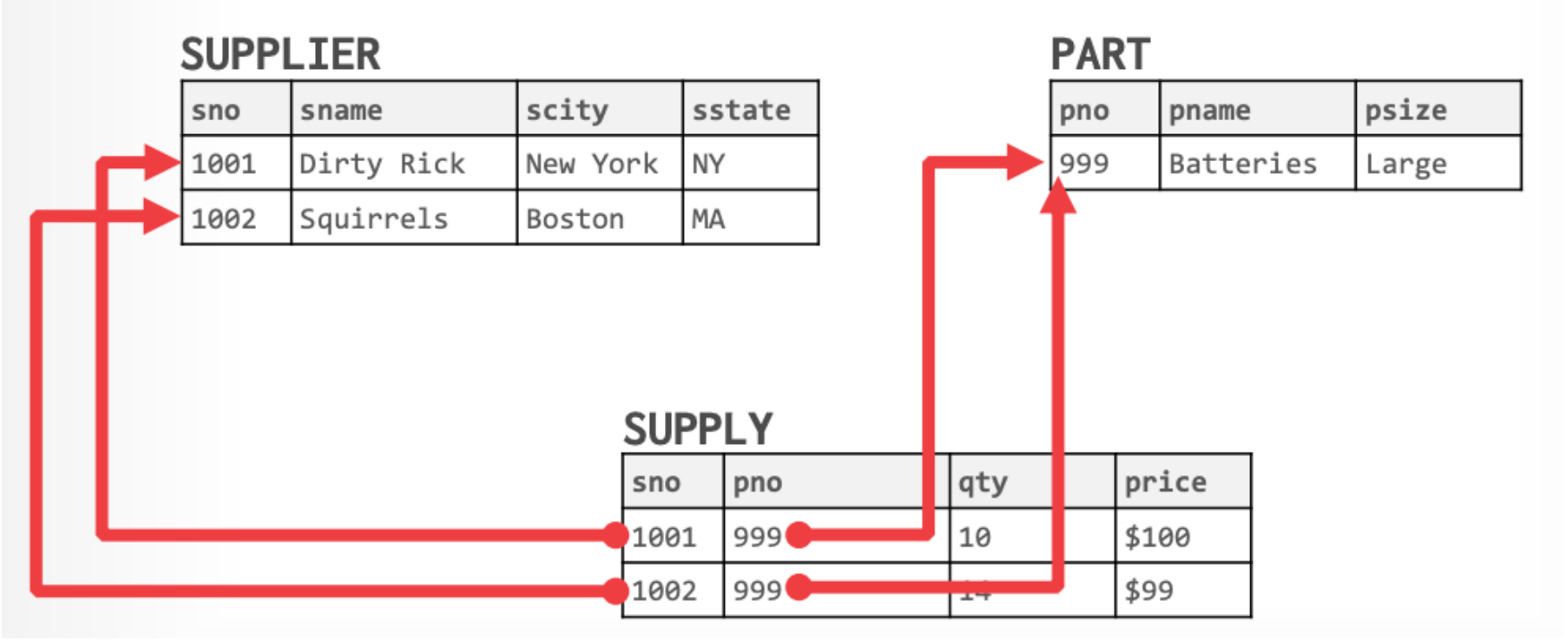


- Support many-to-many relationships.
- Bad for many-to-many relationships.

Relational Data Model (Schema)



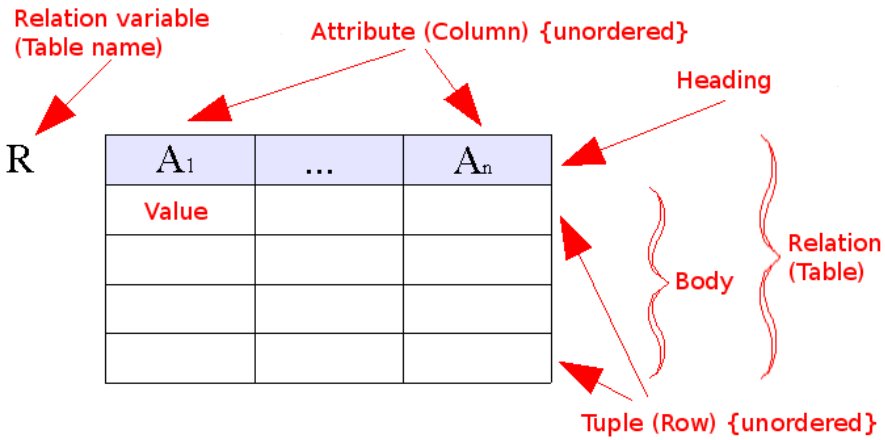
Relational Data Model (Instance)



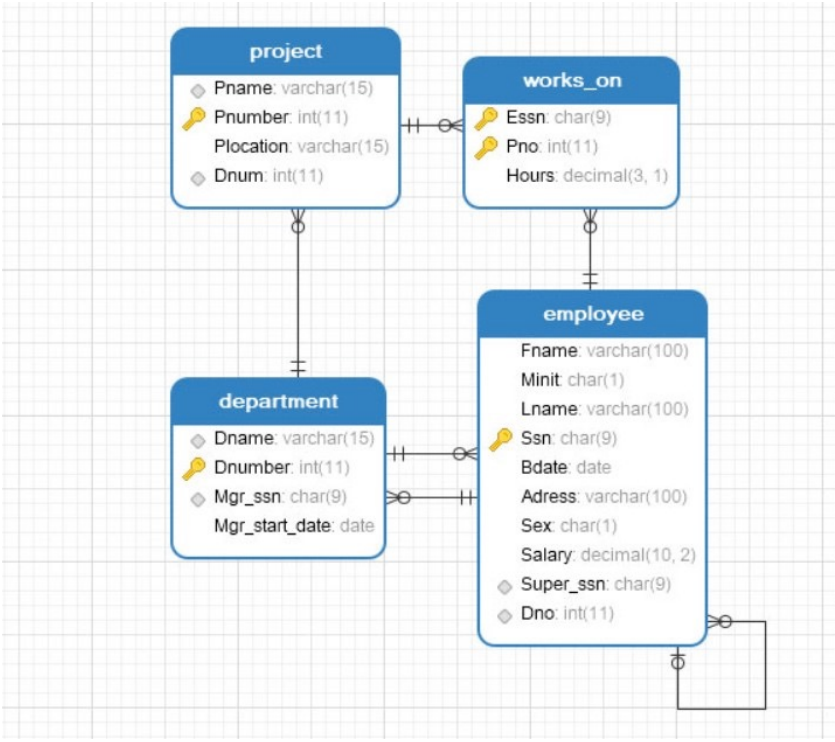
Data as File: Structured

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

Relation



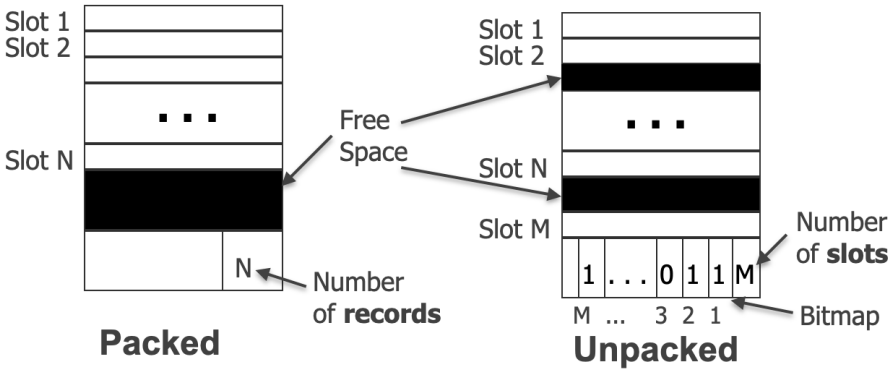
Relational Database

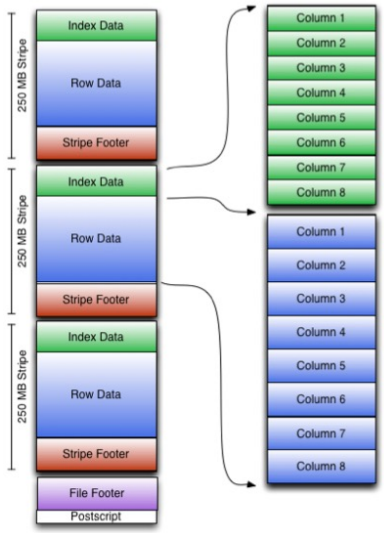


- Most RDBMSs and Spark serialize a relation as *binary* file(s), often compressed

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





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

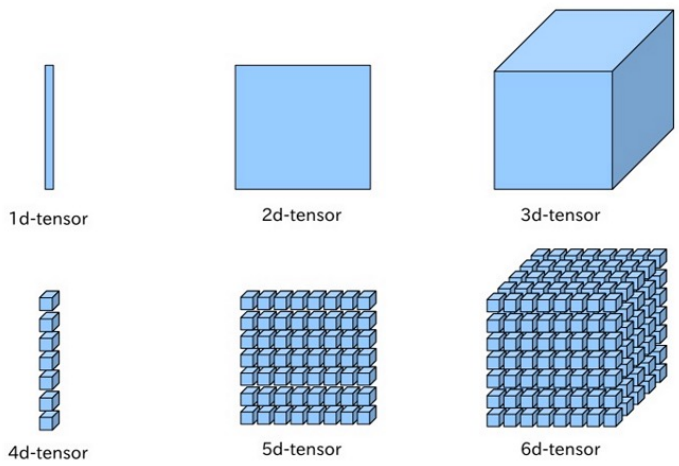
Data as File: Structured

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

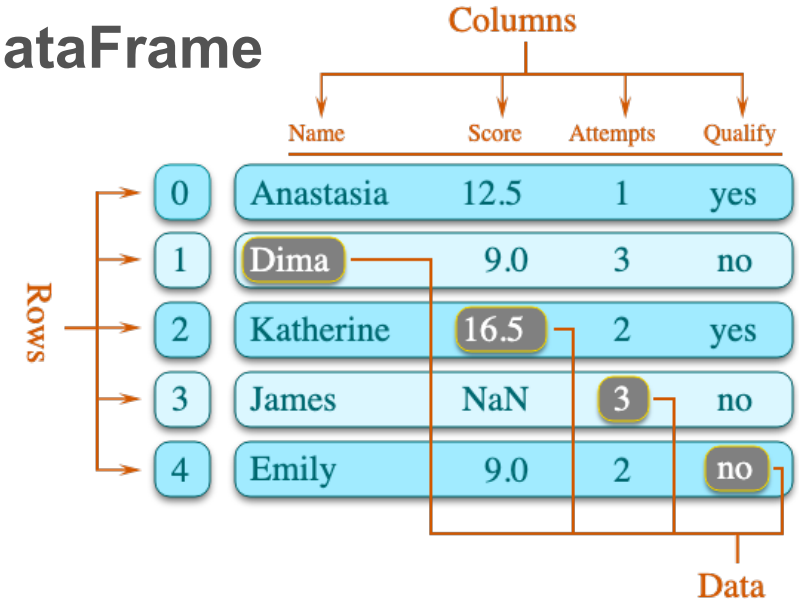
Matrix

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

Tensor



DataFrame

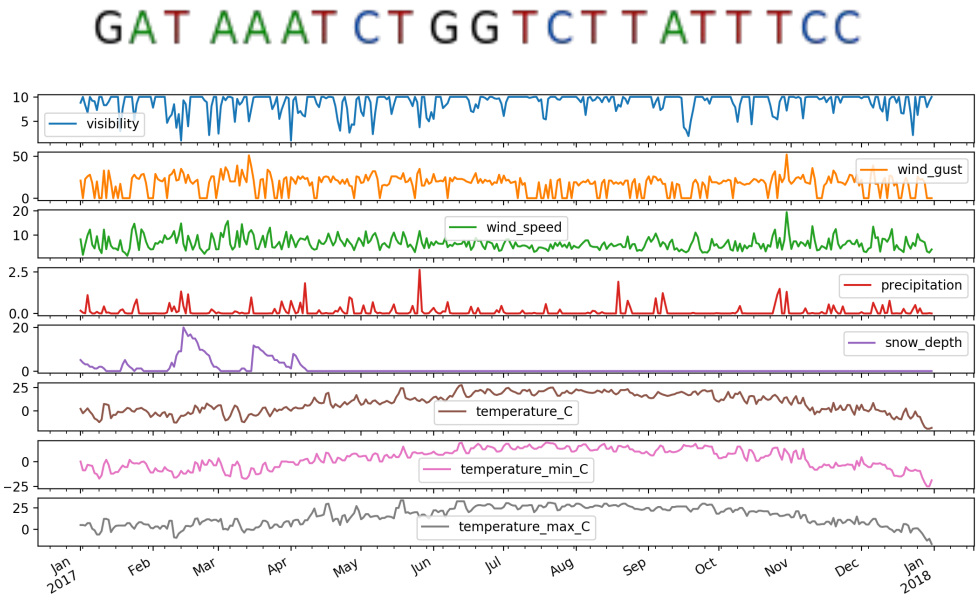


- Typically serialized as restricted ASCII text file (TSV, CSV, etc.)
- Matrix/tensor as binary too
- Can layer on Relations too!

Data as File: Structured

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

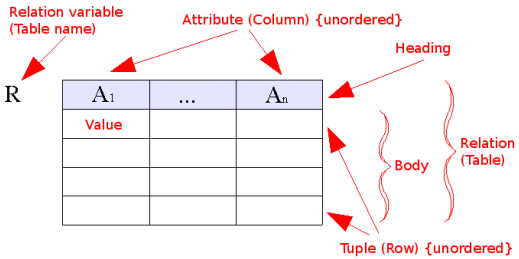
Sequence (Includes Time-series)

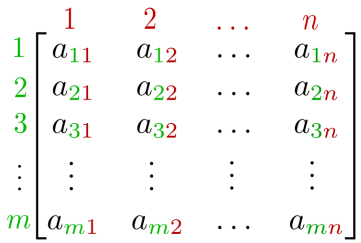


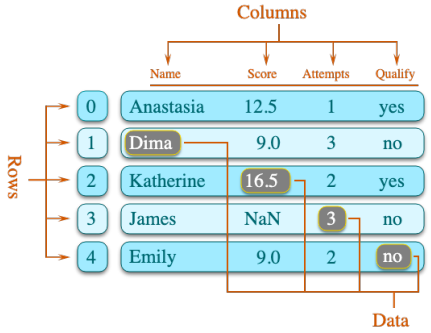
- Can layer on Relations, Matrices, or DataFrames, or be treated as first-class data model
- Inherits flexibility in file formats (text, binary, etc.)

Comparing Struct. Data Models

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







- **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>
```

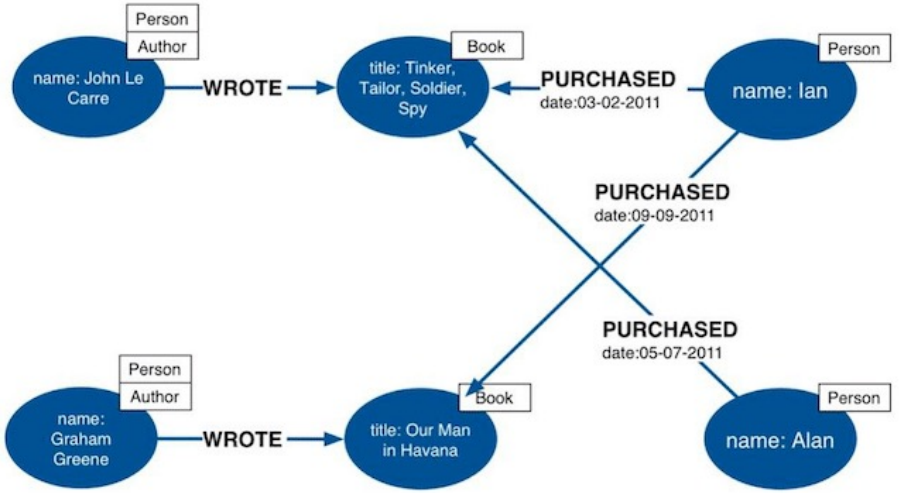
```
[
    {
        orderId: 1,
        date: '1/1/2014',
        orderItems: [
                {itemId: 1, qty: 3, price: 23.4},
                {itemId: 23, qty: 2, price: 3.3},
                {itemId: 7, qty: 5, price: 5.3}
            ]
    },
    {
        orderId: 2,
        date: '1/2/2014',
        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

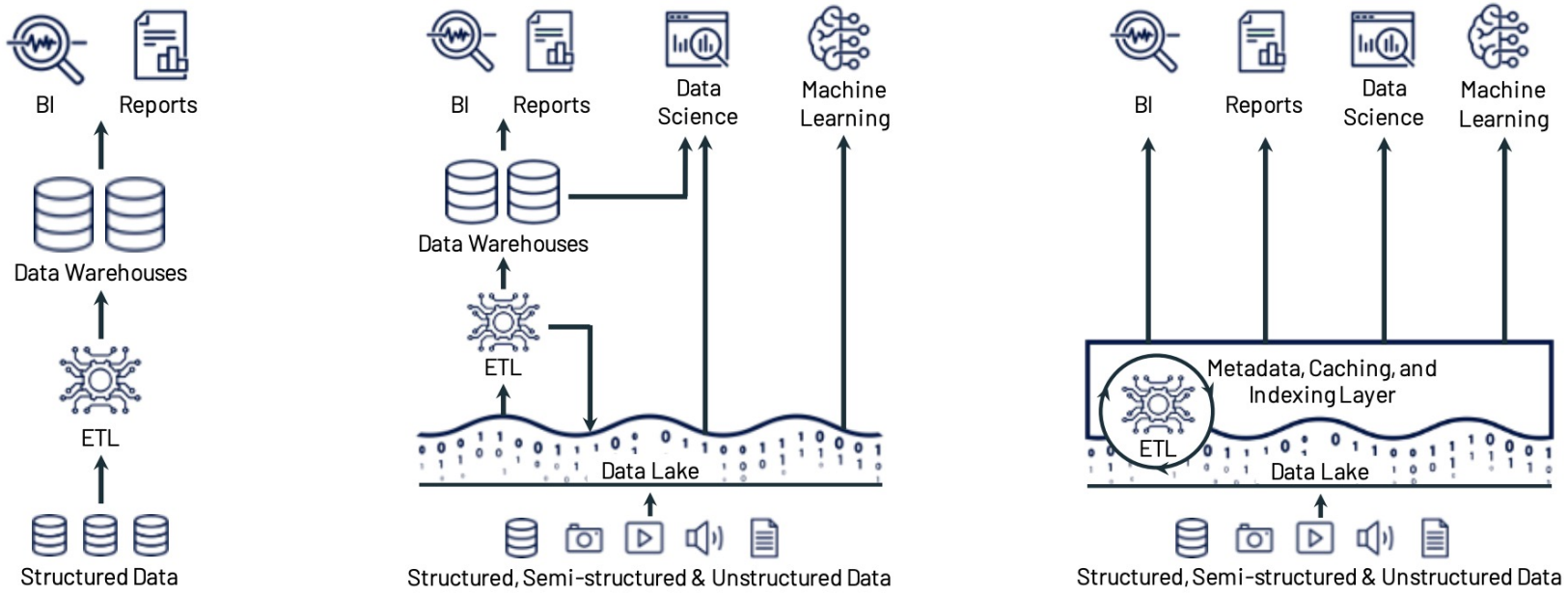


- Typically serialized with JSON or similar textual formats
- Some data systems also offer binary file formats
- Again, can layer on Relations too

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

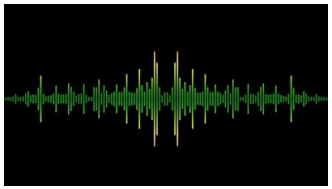
Data Lake File Format Tradeoffs

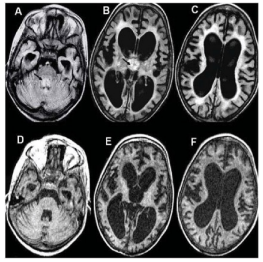
Dataset	Size on Amazon S3	Query Run Time	Data Scanned	Cost
Data stored as CSV files	1 TB	236 seconds	1.15 TB	$5.75
Data stored in Apache Parquet Format	130 GB	6.78 seconds	2.51 GB	$0.01
Savings	87% less when using Parquet	34x faster	99% less data scanned	99.7% savings

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

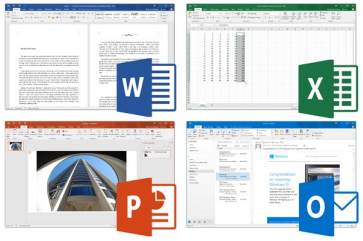
Data as File: Other Common Formats

- **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



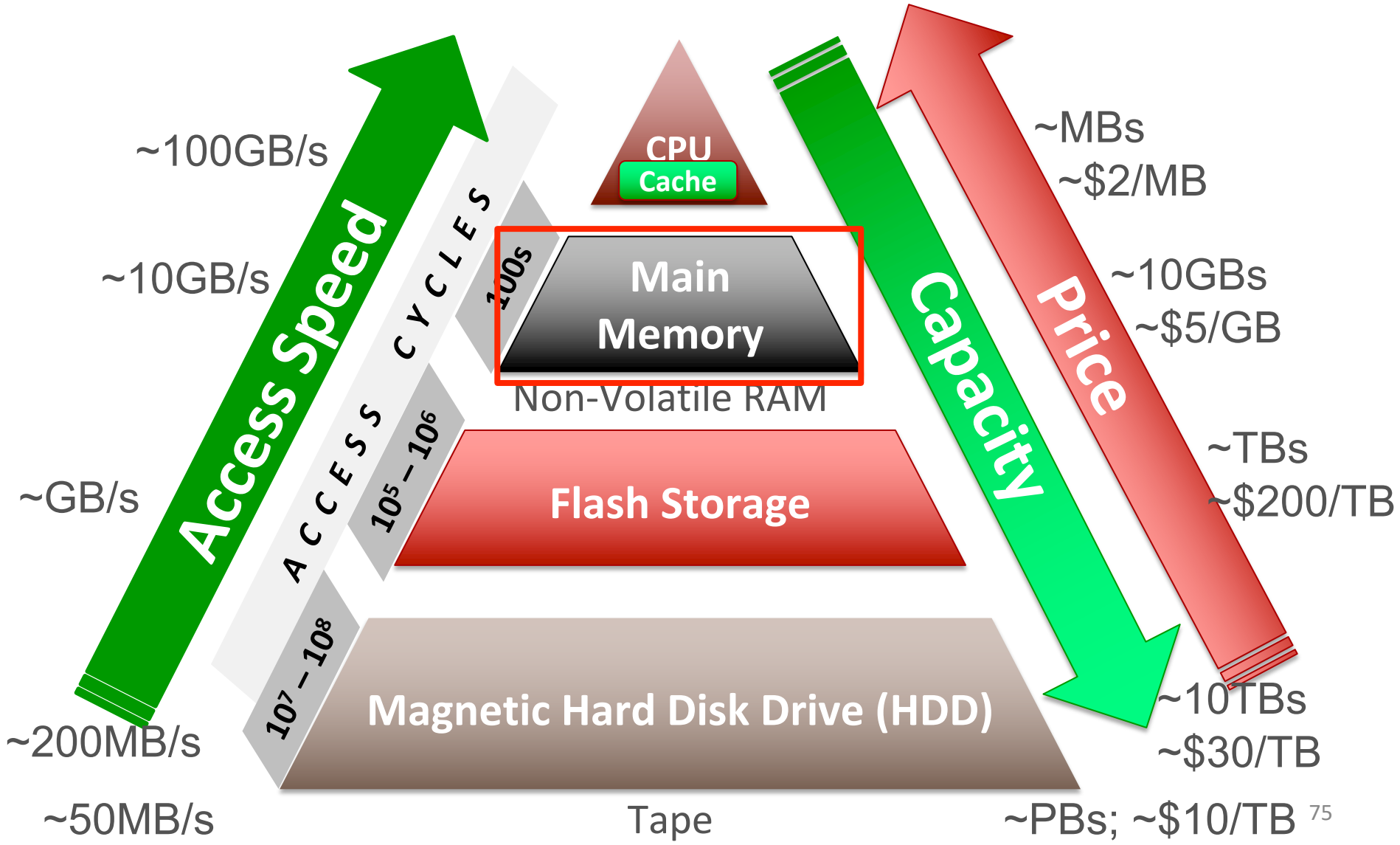
Peer Instruction Activity

(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

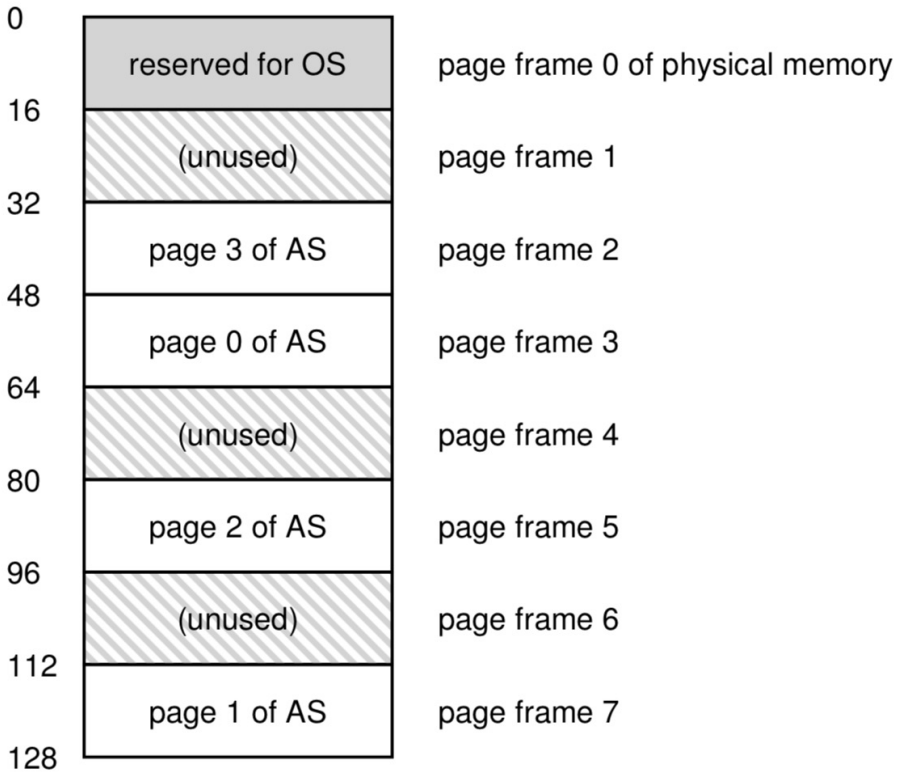
Memory/Storage Hierarchy



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



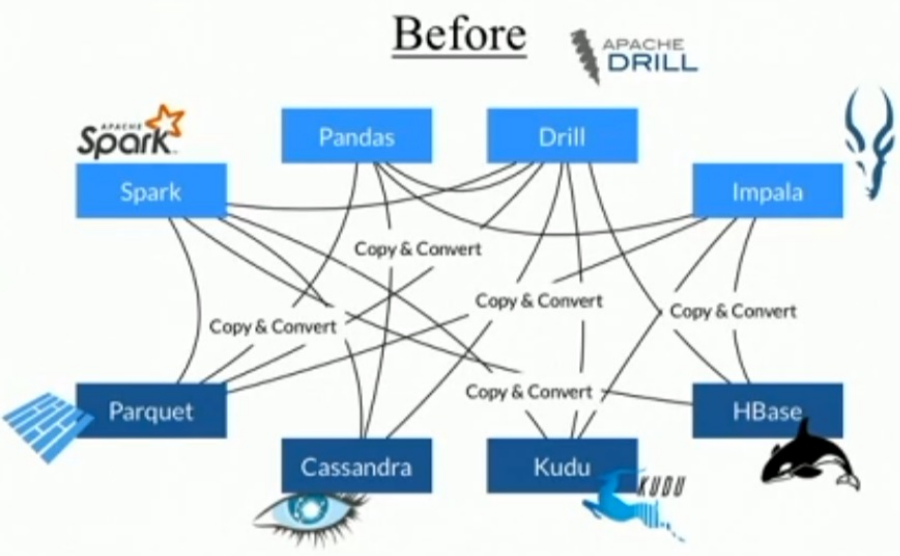
Apportioning of DRAM

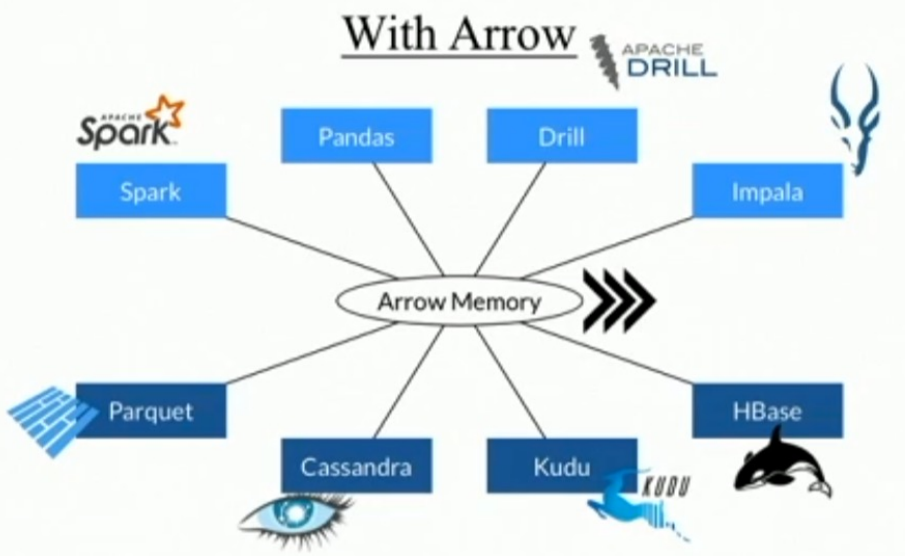
- A process' **Address Space:**
  - Slice of virtualize DRAM assigned to it alone!
  - OS "translates" DRAM vs disk address
- **Page Replacement Policy:**
  - When DRAM fills up, which cached page to evict?
  - Many policies in OS literature
- **Memory Leaks:**
  - Process forgot to "free" pages used 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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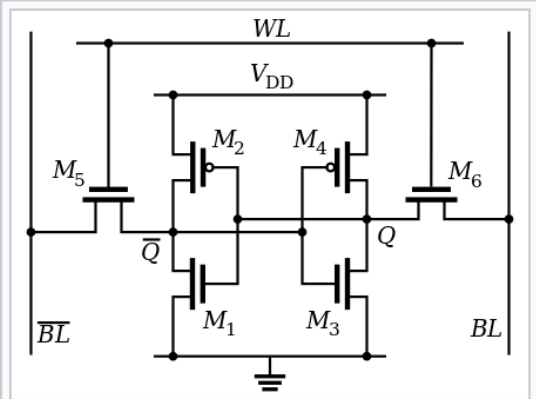
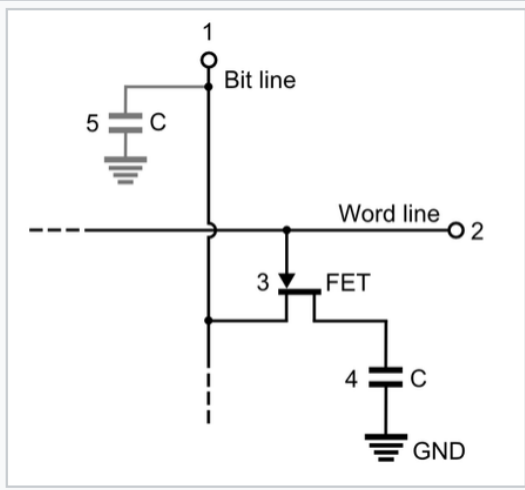
- Persistent Data Storage

DRAM & SRAM

- **DRAM: Constant charging & updating.**
- **SRAM: Constant charging &**
- **Bonus: ROM (read-only memory)**



SRAM Cell (6 Transistors)



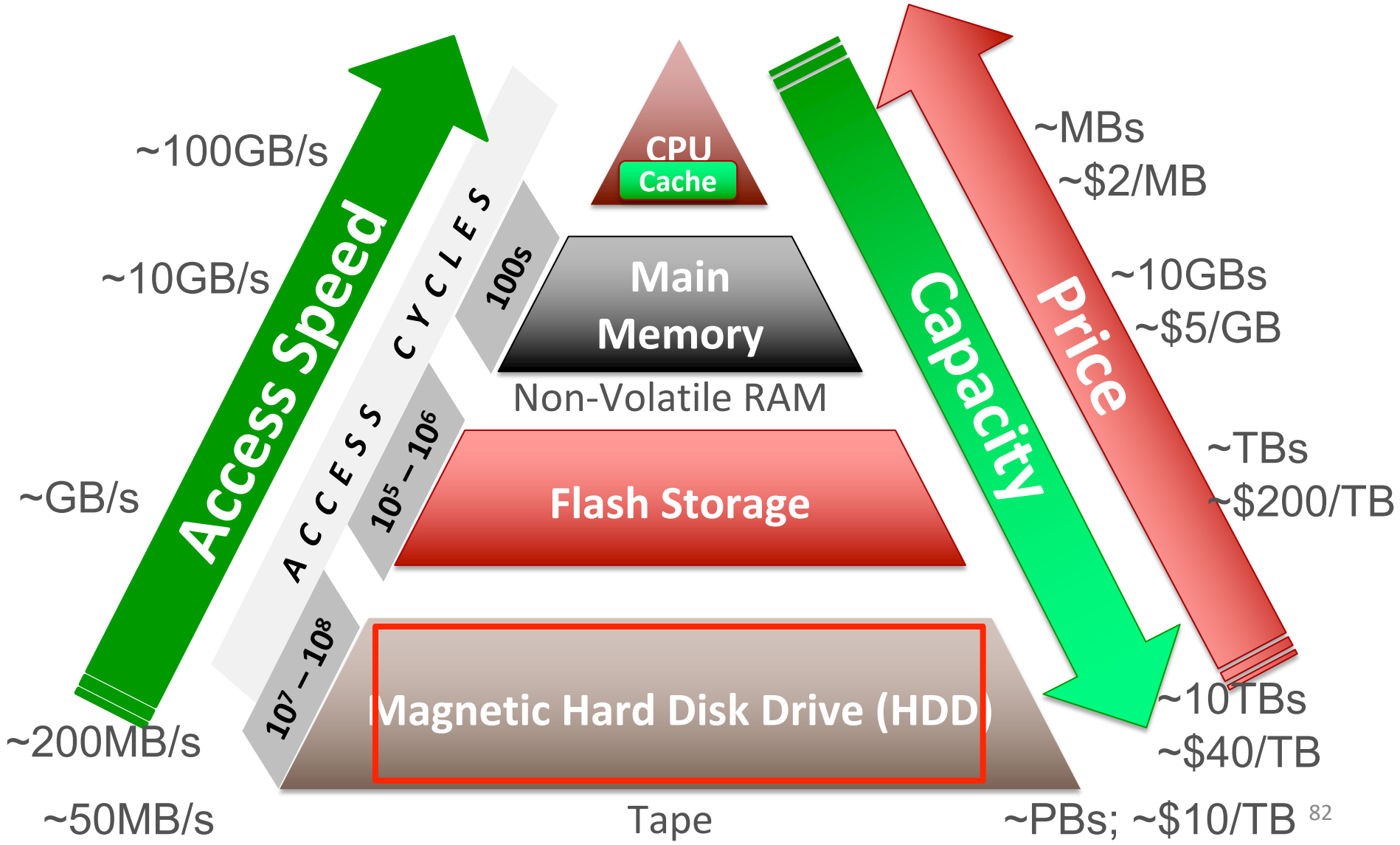
DRAM Cell (1 Transistor and one capacitor)

https://youtu.be/cFvh7qM6LdA?si=AqeJP9WBdj8VX1-E&t=197

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

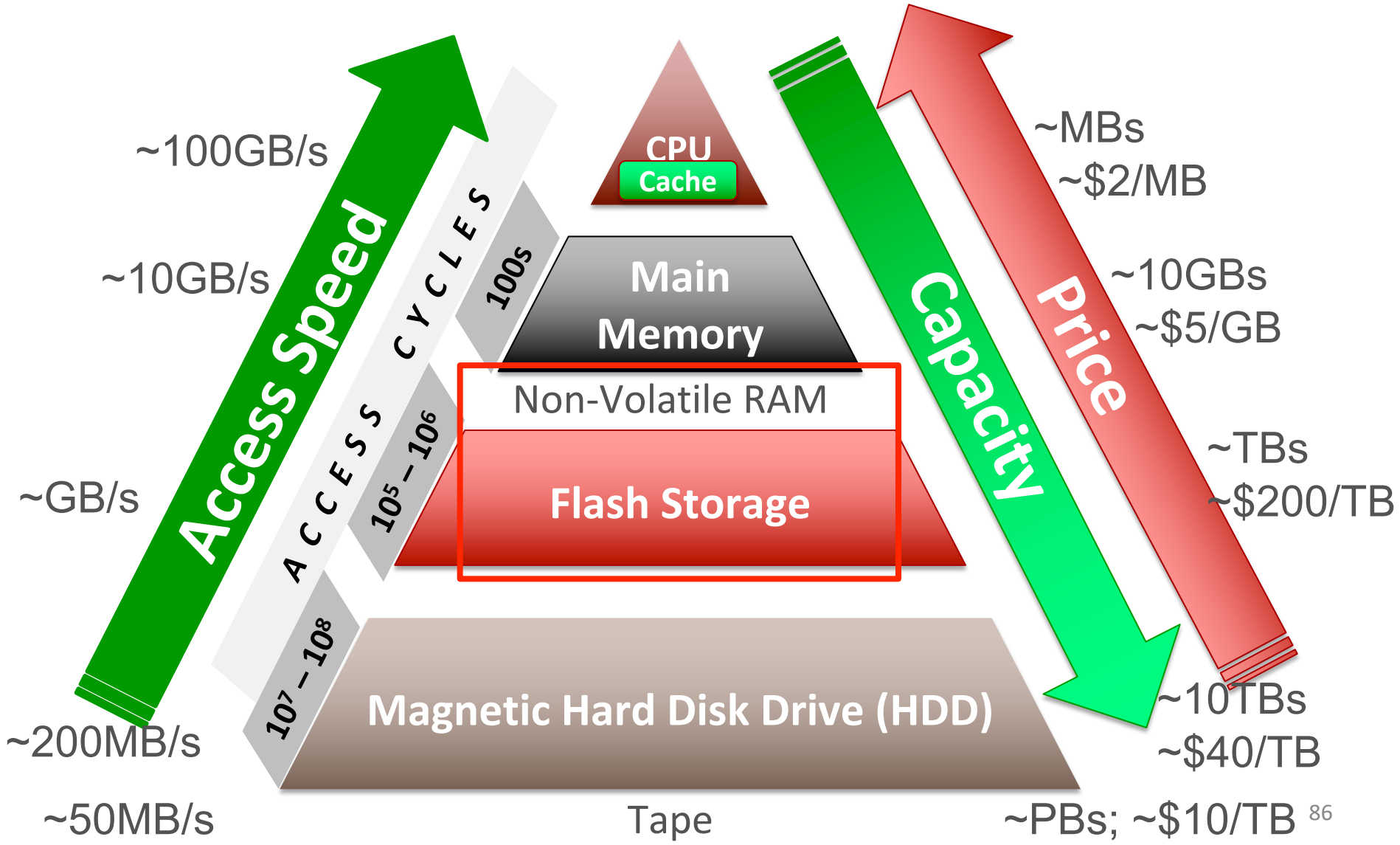
- Disk space is organized into **files**
- Files are made up of disk **pages** aka **blocks**
- Typical disk block/page size: 4KB or 8KB
  - Basic unit of reads/writes for a disk
  - OS/RAM page is *not* the same as disk page!
  - Typically, OS/RAM page size = disk page size but not always; disk page 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?

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