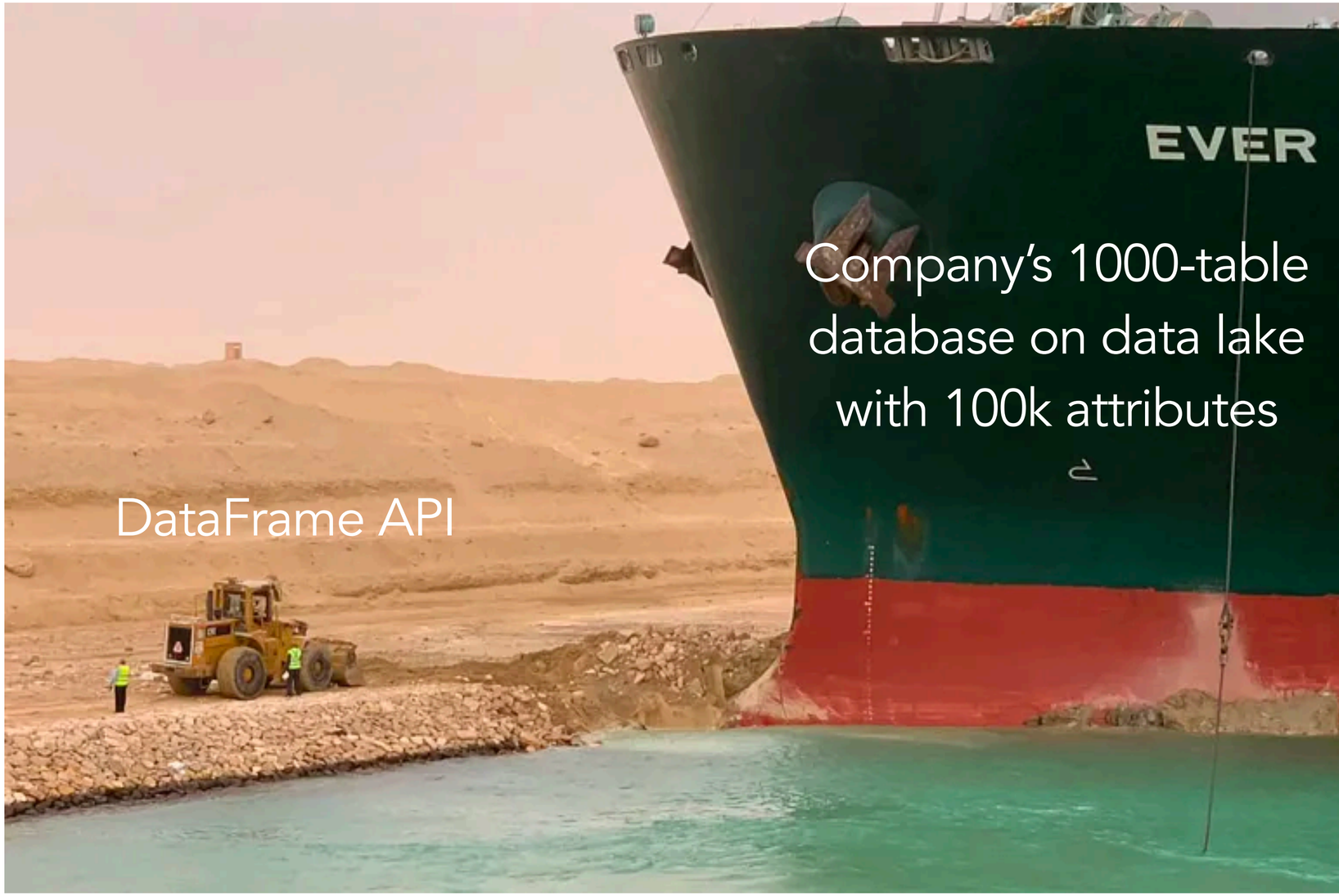
DSC 204a Scalable Data Systems

- Haojian Jin



Meme idea credit: https://datasystemsfun.tumblr.com/

Where are we in the class?

Foundations of Data Systems (2 weeks)

- Digital representation of Data → Computer Organization → Memory hierarchy → **Process** → Storage

Scaling Distributed Systems (3 weeks)

- Cloud → Distributed storage → Partition and replication (HDFS) → Distributed computation

Data Processing and Programming model (5 weeks)

- Data Models evolution → Data encoding evolution → → IO & Unix Pipes → Batch processing (MapReduce) → Stream processing (Spark)

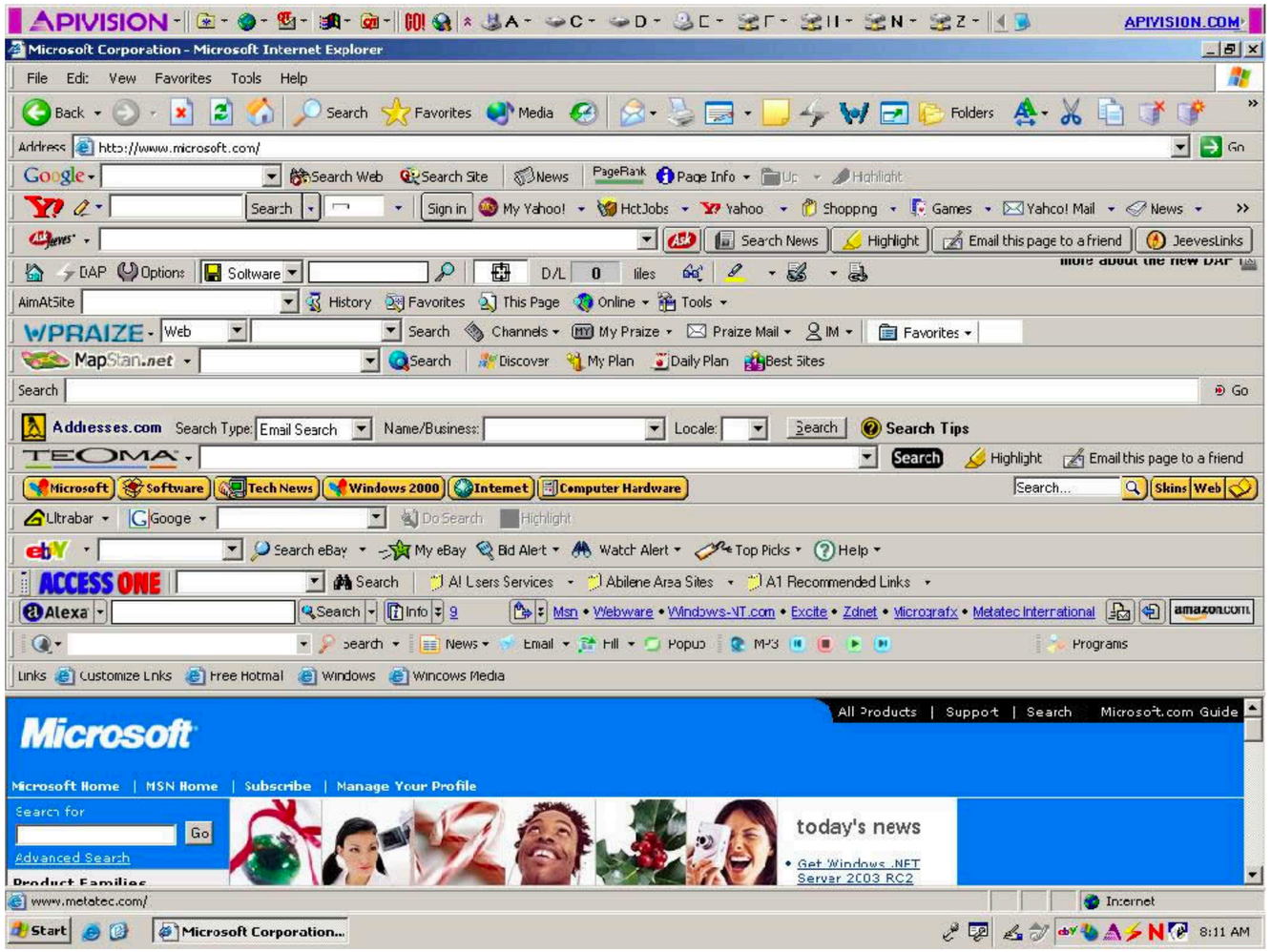
Today

Virtualization
Concurrency

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

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!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Back Search Favorites Media Folders
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Go
Google Search Web Search Site News PageRank Page Info Highlight
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MapStan.net Search Discover My Plan Daily Plan Best Sites
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Addresses.com Search Type: Email Search Name/Business: Locale: Search Search Tips
TEOMA Search Highlight Email this page to a friend
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Get Windows .NET Server 2003 RC2
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SAVING THE WORLD FOR 20 YEARS

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

Technical idea #1

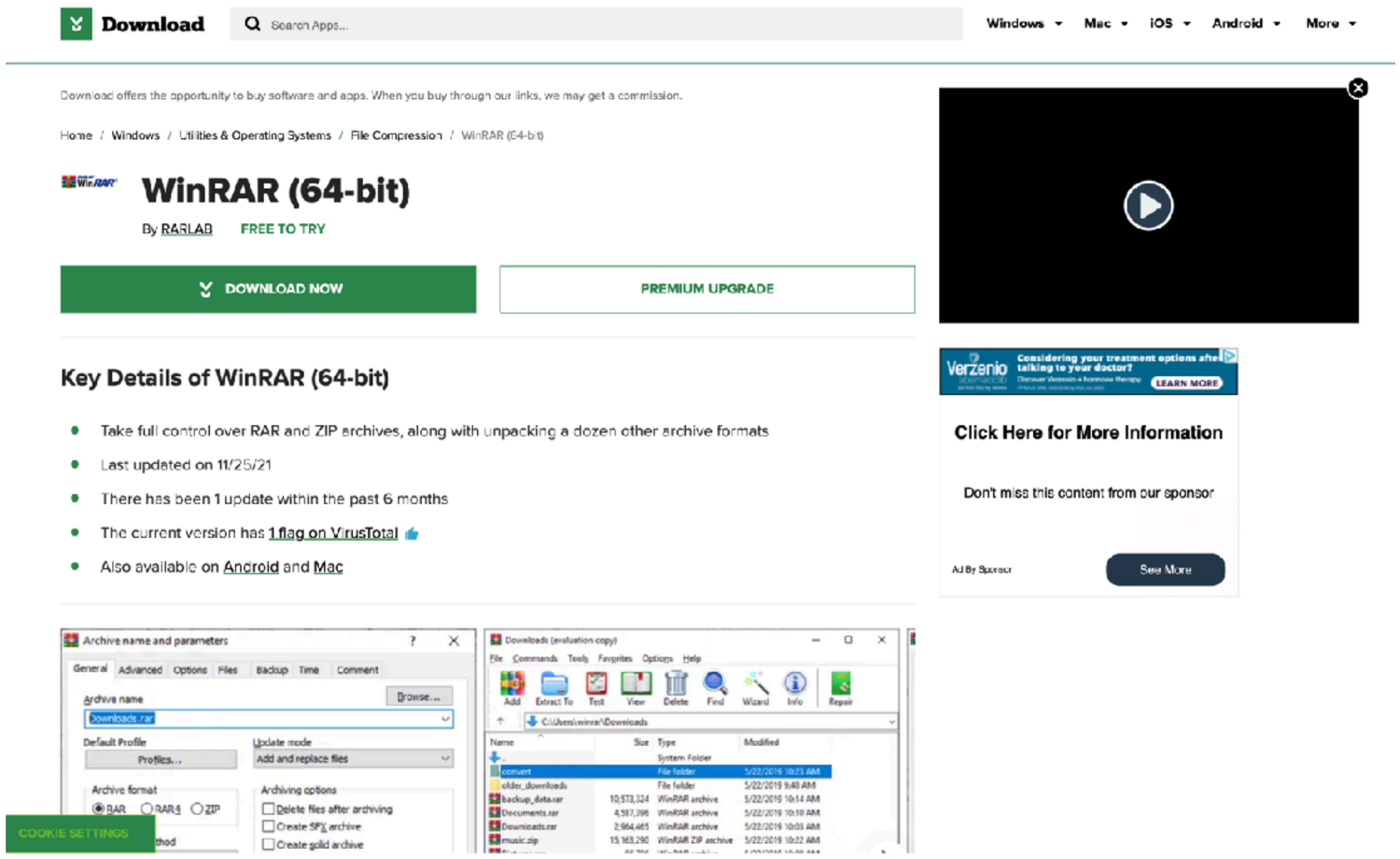
Putting apps in a sandbox

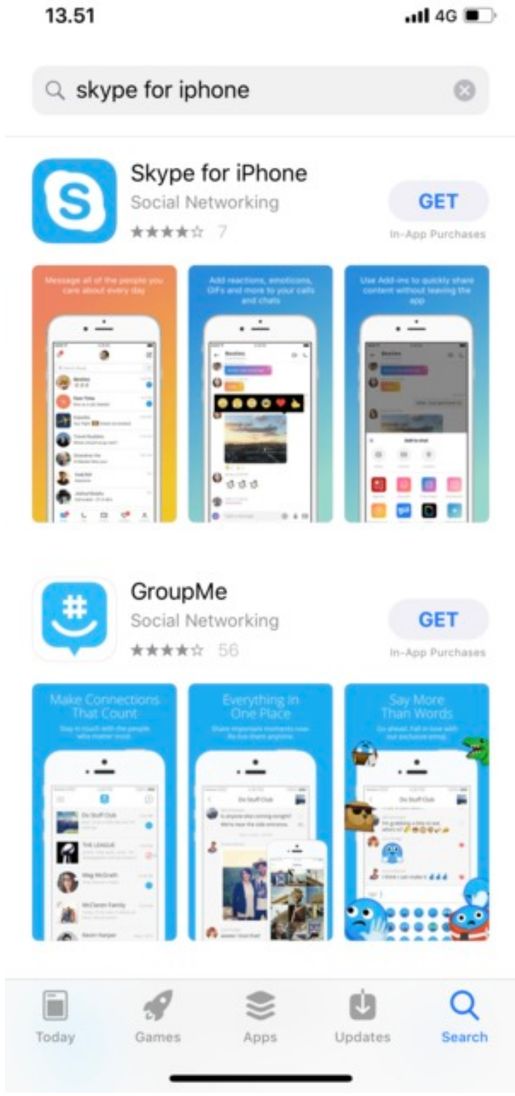
Apps can only do things that Apple allows and cannot ask (or persuade, or trick) the user for permission to do ‘dangerous’ things.

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

Technical idea #2

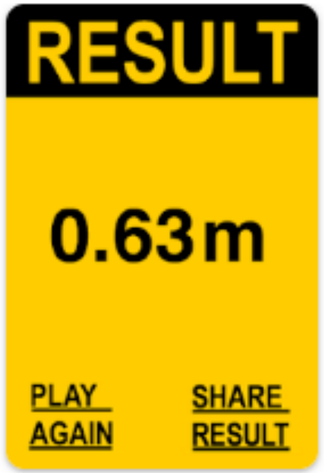
Distributing software through a centralized app store



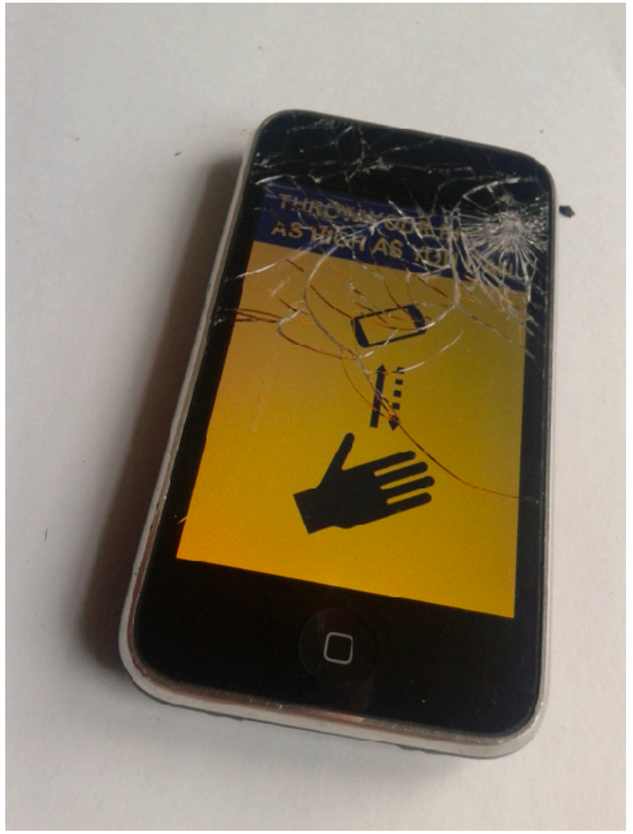


Technical idea #2

Distributing software through a centralized app store



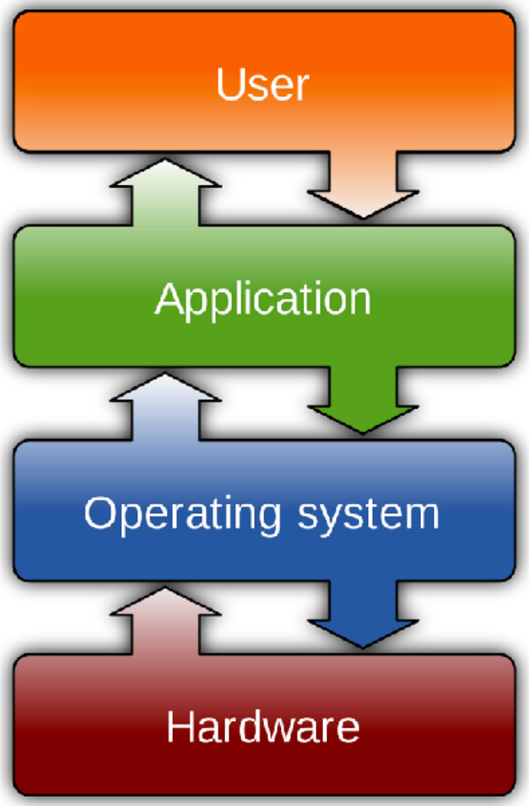
S.M.T.H.: Send Me to Heaven



Role of an OS in a Computer

- 2 key principles in OS (any system) design & impl.:
  - **Modularity:** Divide system into *functionally cohesive components* that each do their jobs well
    - Separation of concerns: https://en.wikipedia.org/wiki/Separation_of_concerns
    - Akin to executive-legislature-judiciary split
  - **Abstraction:** *Layers of functionalities* from low-level (close to hardware) to high level (close to user)
    - Principle of least privilege: https://en.wikipedia.org/wiki/Principle_of_least_privilege
    - Akin to local-city-county-state-federal levels?

Abstraction (layers)



APIs/Interface of Application Software

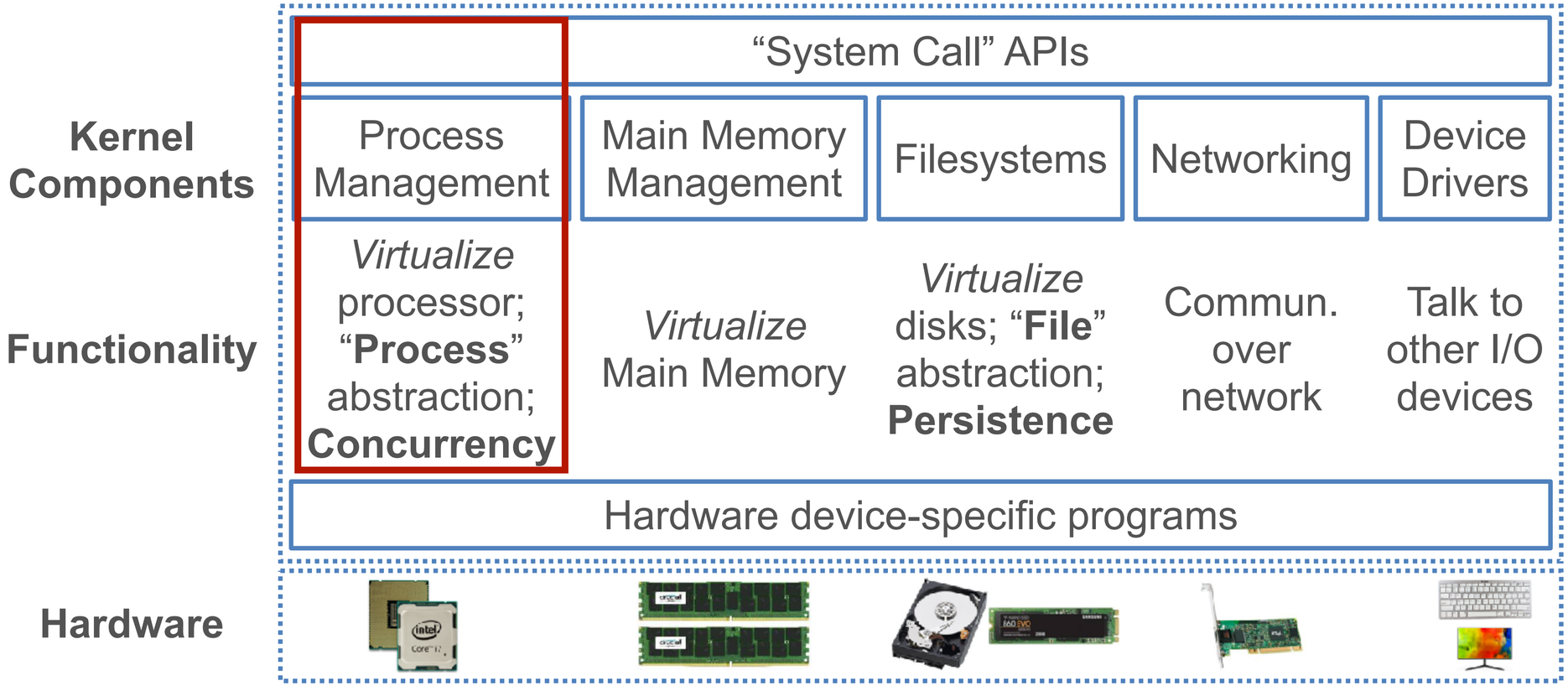
APIs of OS aka “System Calls”

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

Modules

- **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.

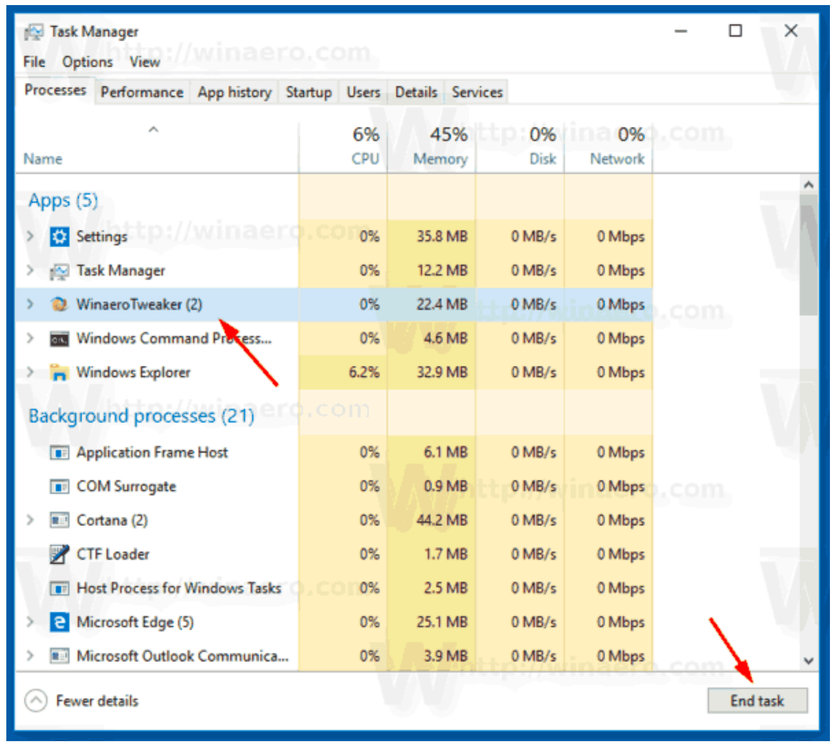


Processes - the central abstraction in OS

Definition: A *process* is an instance of a running program.

One of the most profound ideas in computer science

Not the same as "program" or "processor"



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

Processes - the central abstraction in OS

Process provides each program with two key abstractions:

Logical control flow

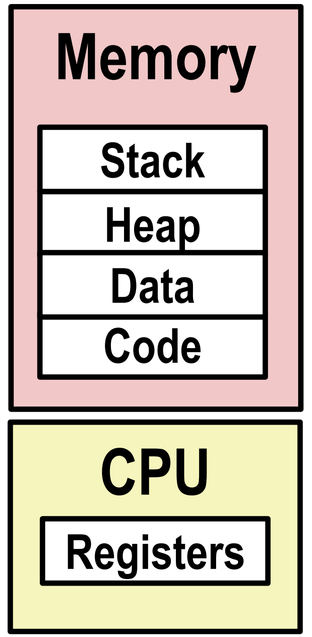
Each program seems to have exclusive use of the CPU

Provided by kernel mechanism called *context switching*

Private address space

Each program seems to have exclusive use of main memory.

Provided by kernel mechanism called *virtual memory*



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()*

Main function in python

test.py

```
1   print("Good Morning")
2
3
4   def main():
5       print("Hello Python")
6
7
8   print("Good Evening")
9
10
11  if __name__ == "__main__":
12      main()
13
```

```
Good Morning
Good Evening
Hello Python

Process finished with exit code 0
```

The Abstraction of a Process

- High-level steps OS takes to get a process going:

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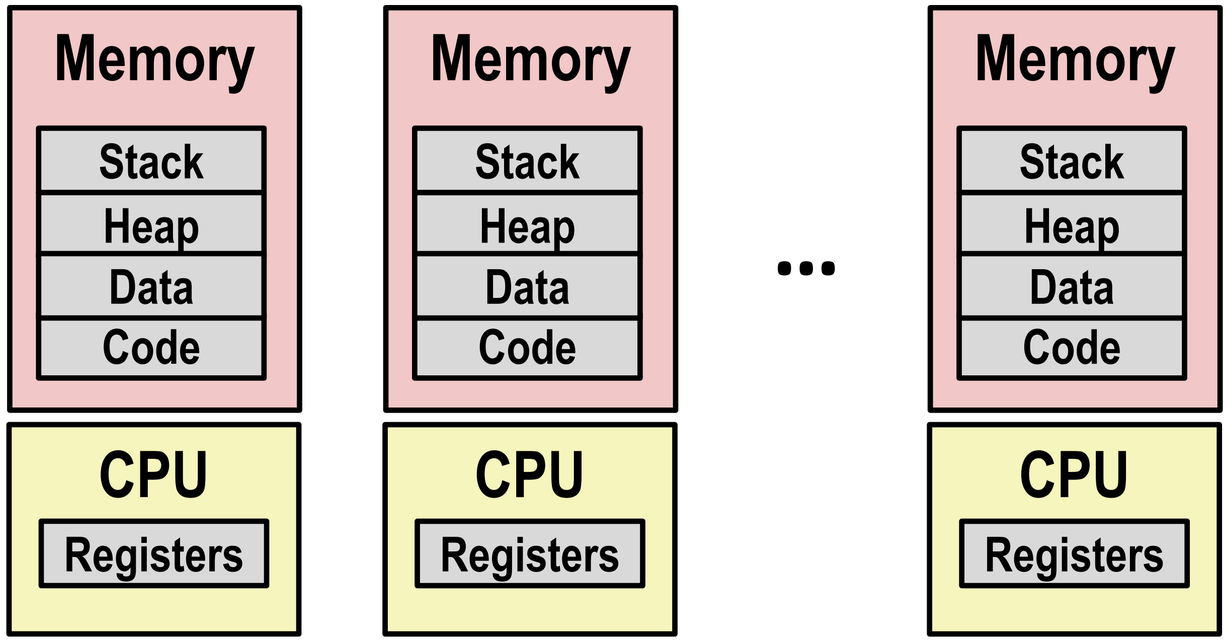
2. Assign part of DRAM to process, aka its **Address Space**
3. Load code and static data (if applicable) to that space
4. Set up the inputs needed to run program's *main()*
5. Update process' **State** to *Ready*
6. When process is **scheduled** (*Running*), OS temporarily hands off control to process 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

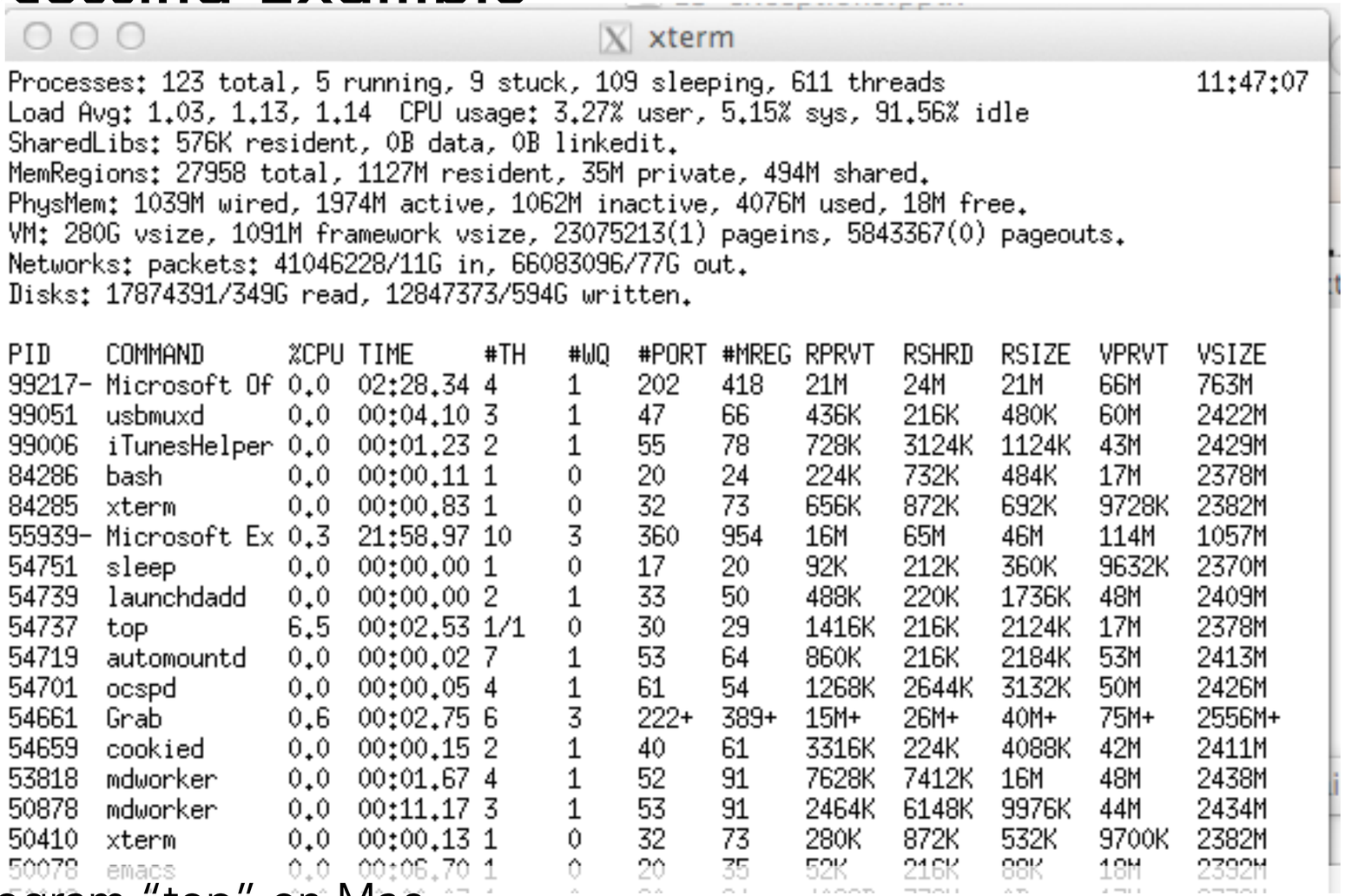
Multiprocessing: The Illusion



Computer runs many processes simultaneously

- Applications for one or more users
  - Web browsers, email clients, editors, …
- Background tasks
  - Monitoring network & I/O devices

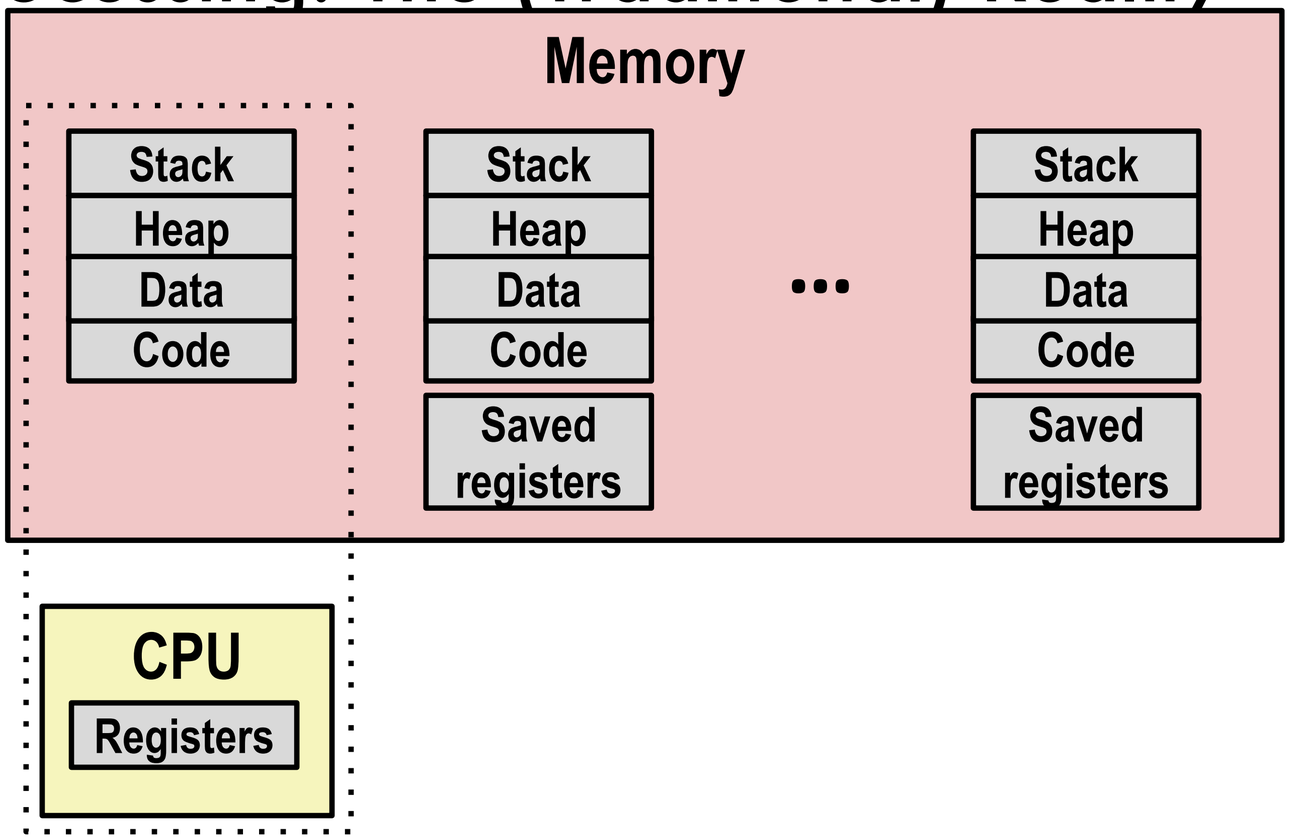
Multiprocessing Example



Running program "top" on Mac

- System has 123 processes, 5 of which are active
- Identified by Process ID (PID)

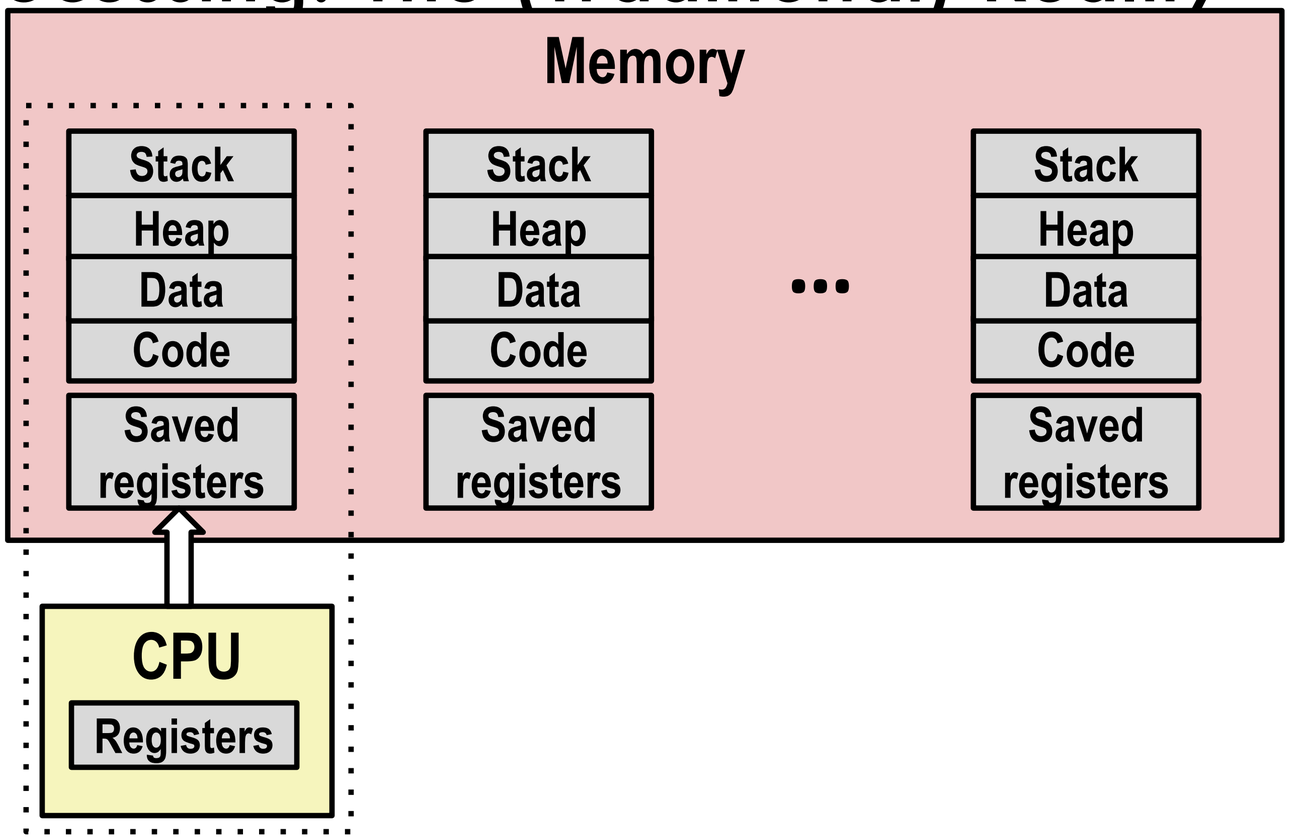
Multiprocessing: The (Traditional) Reality



Single processor executes multiple processes concurrently

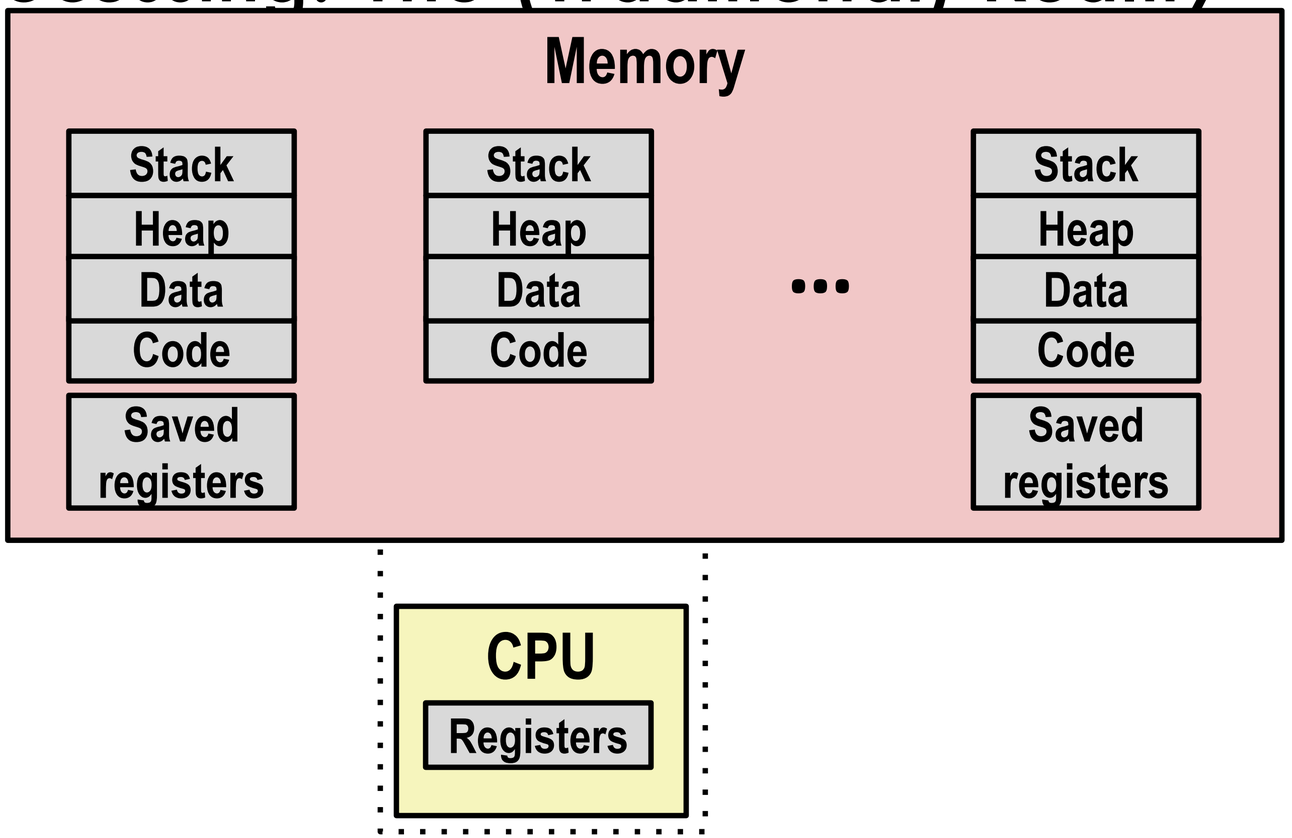
- Process executions interleaved (multitasking)
- Address spaces managed by virtual memory system (like last week)
- Register values for nonexecuting processes saved in memory

Multiprocessing: The (Traditional) Reality



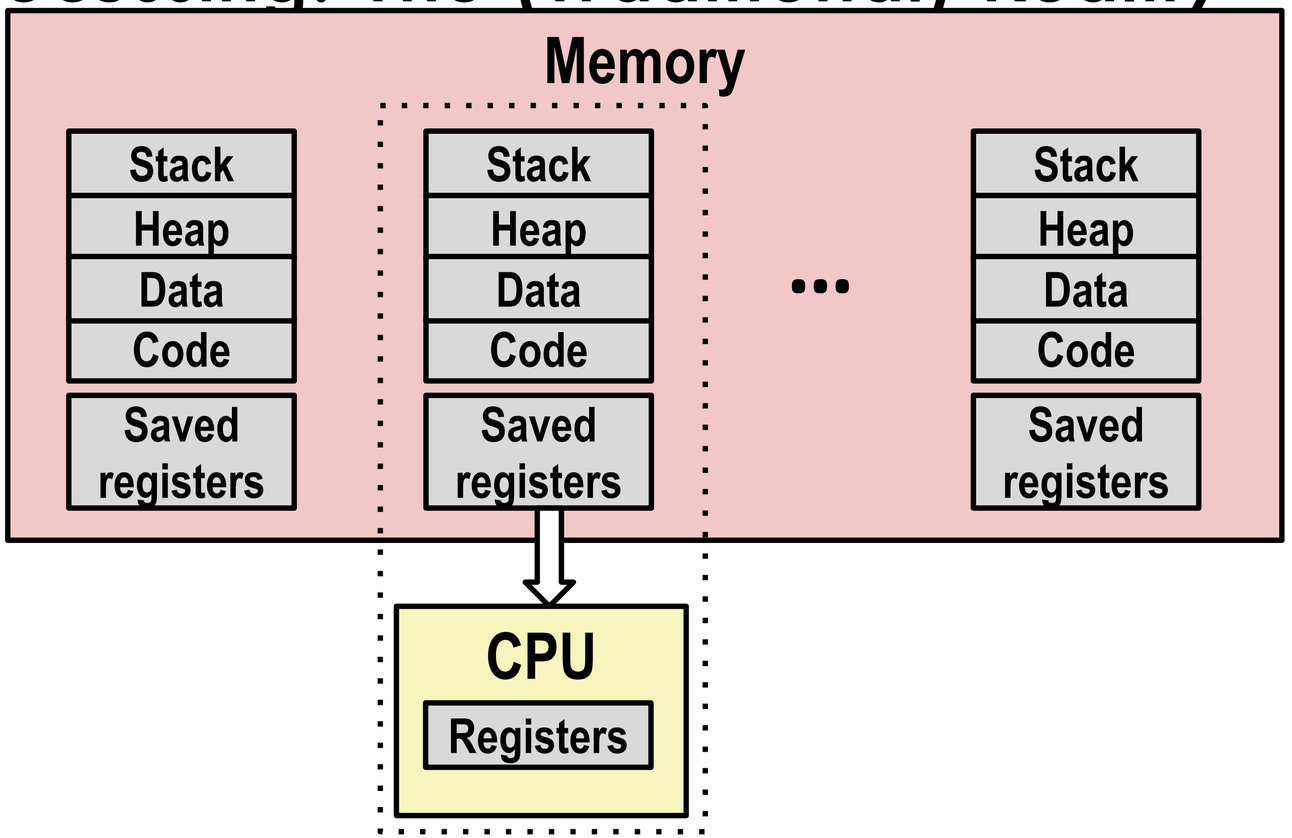
Save current registers in memory

Multiprocessing: The (Traditional) Reality



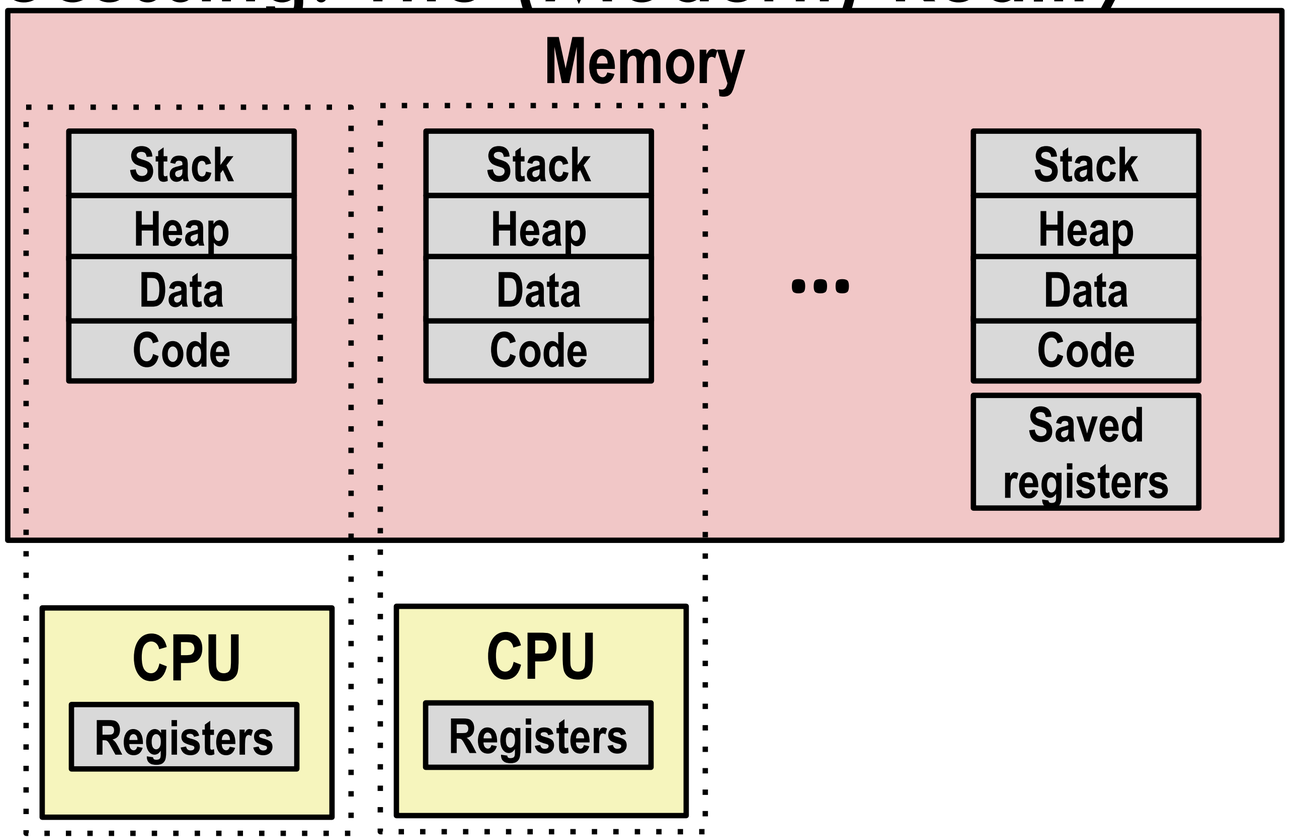
Schedule next process for execution

Multiprocessing: The (Traditional) Reality



Load saved registers and switch address space (context switch)

Multiprocessing: The (Modern) Reality

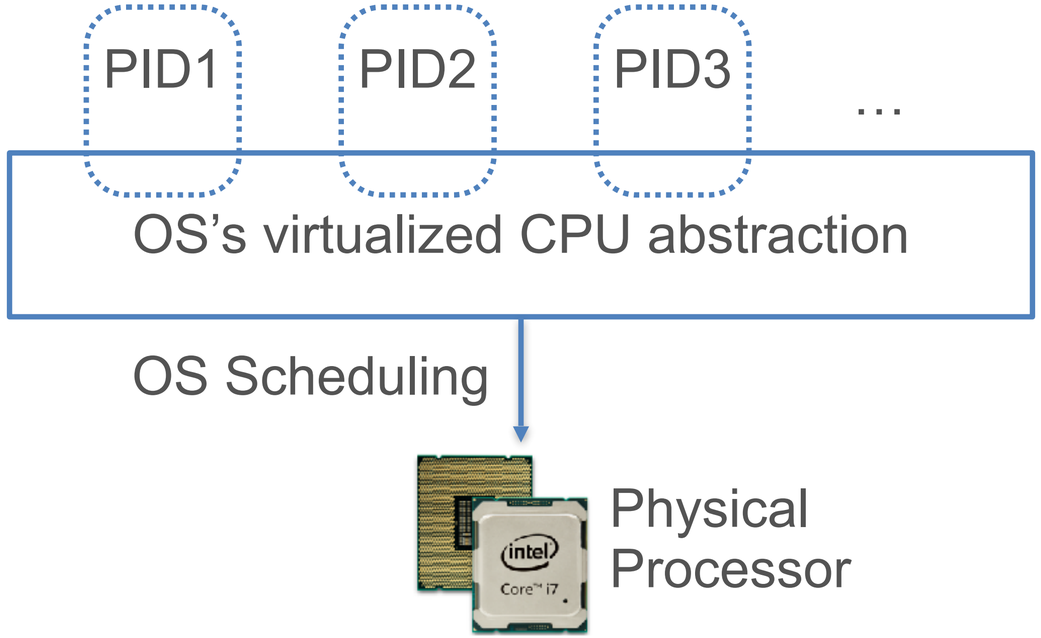


Multicore processors

- Multiple CPUs on single chip
- Share main memory (and some caches)
- Each can execute a separate process
  - Scheduling of processors onto cores done by kernel

Inter-process communication

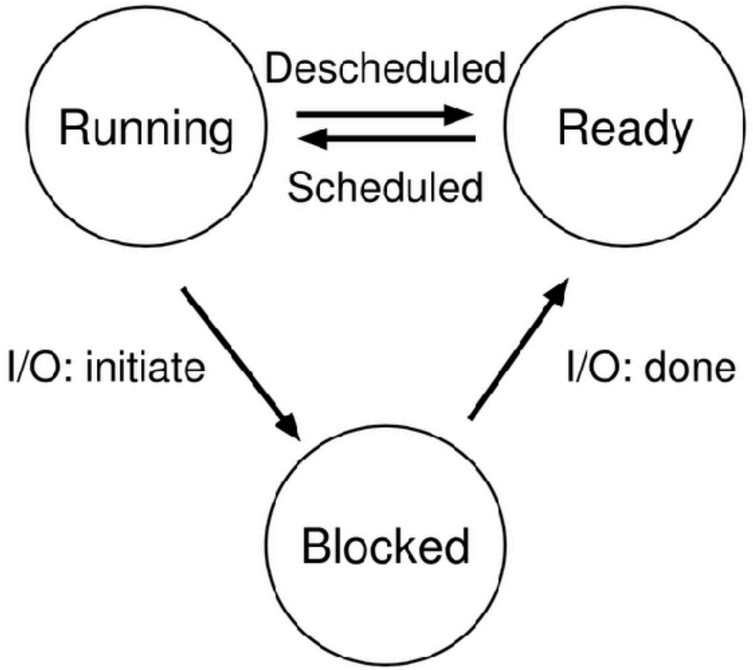
- Virtualization of processor enables process **isolation**, i.e., each process given an “illusion” that it alone runs



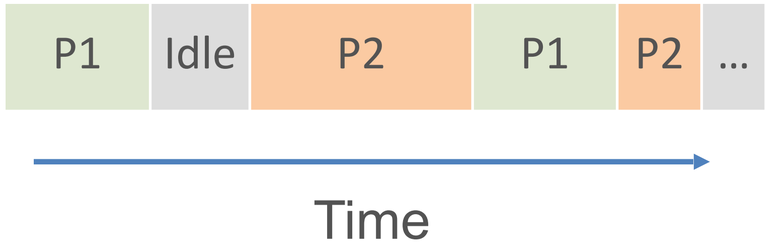
- Inter-process communication possible in System Calls API

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**: Time 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

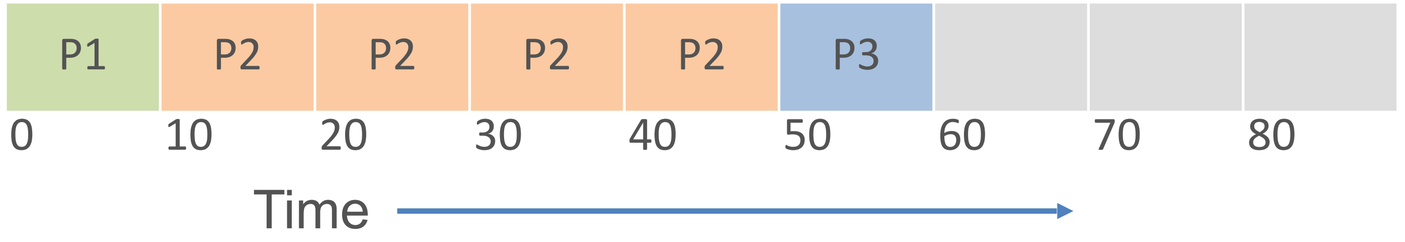
Scheduling Policies/Algorithms

- 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



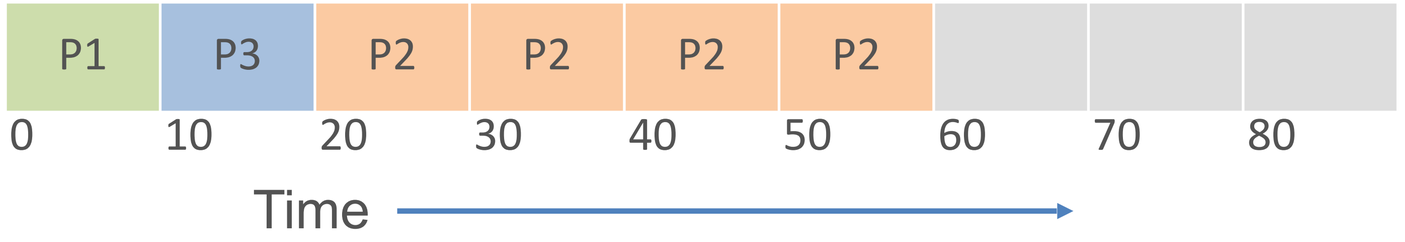
Process	Arrival Time	Start Time	Completion Time	Response Time	Turnaround Time
P1	0	0	10	0	10
P2	0	10	50	10	50
P3	0	50	60	50	60
			Avg:	20	40

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

Scheduling Policy: SJF

- Shortest Job (next) 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

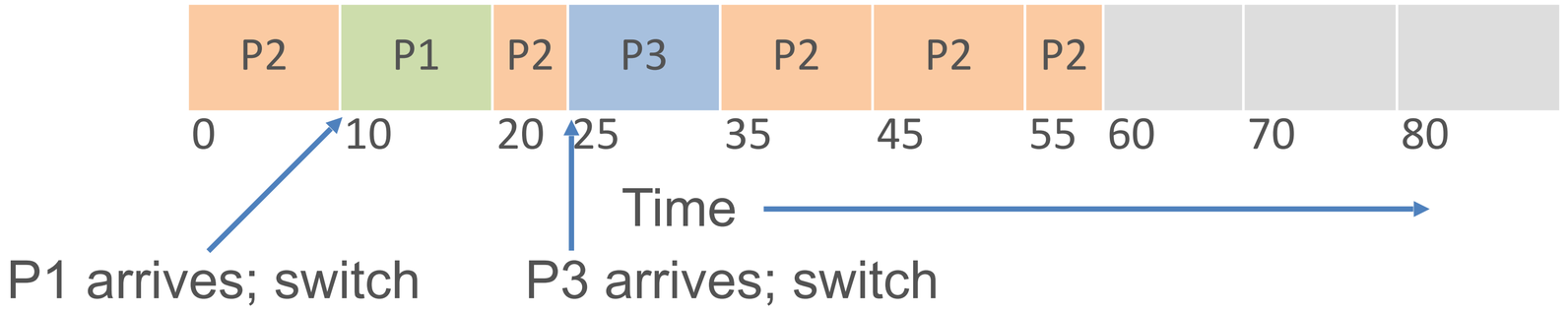
(FIFO Avg: 20 and 40)

- Main con: Not all Job Lengths might be known beforehand
- Long processes may be held off indefinitely

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



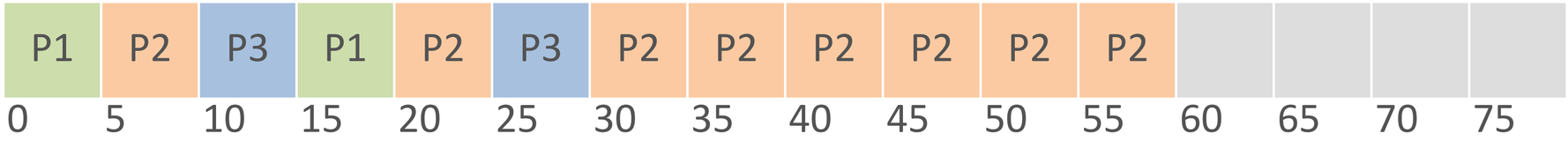
Process	Arrival Time	Start Time	Completion Time	Response Time	Turnaround Time
P1	10	10	20	0	10
P2	0	0	60	0	60
P3	25	25	35	0	10
		(SJF Avg: 10 and 30)	Avg:	0	26.7

- Main con: Not all Job Lengths might be known beforehand
- Long processes may be held off indefinitely

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 →

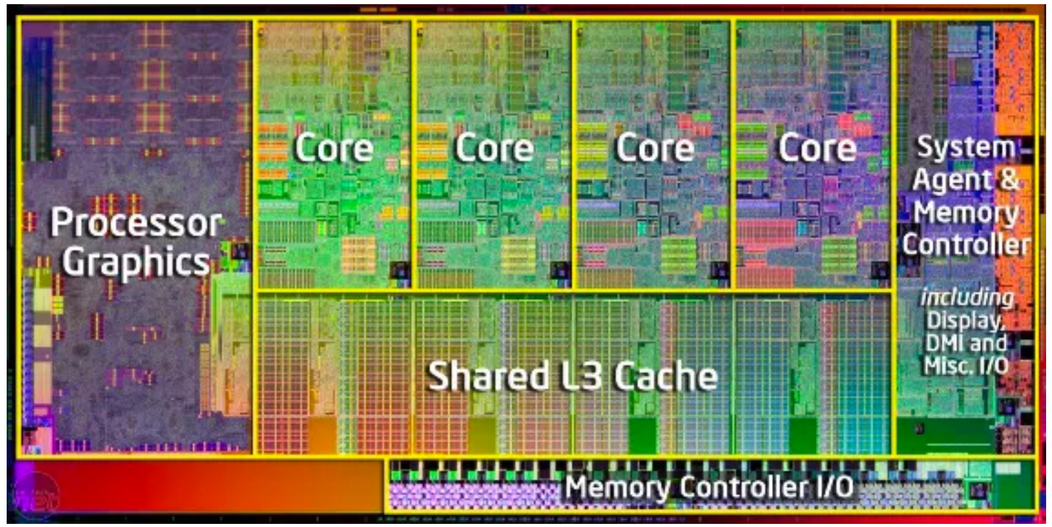
Process	Arrival Time	Start Time	Completion Time	Response Time	Turnaround Time
P1	0	0	20	0	20
P2	0	5	60	5	60
P3	0	10	30	10	30
			Avg:	5	36.7

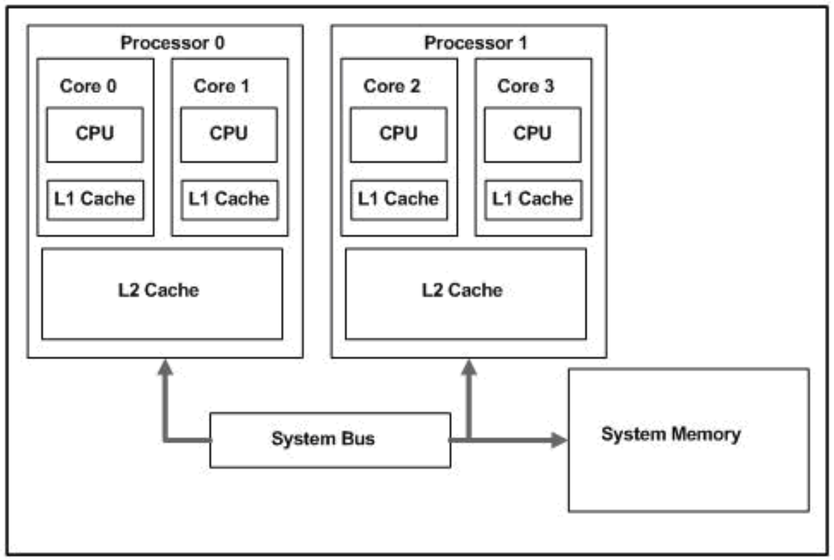
(SJF Avg: 10 & 30; SCTF Avg: 0 & 26.7)

- 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





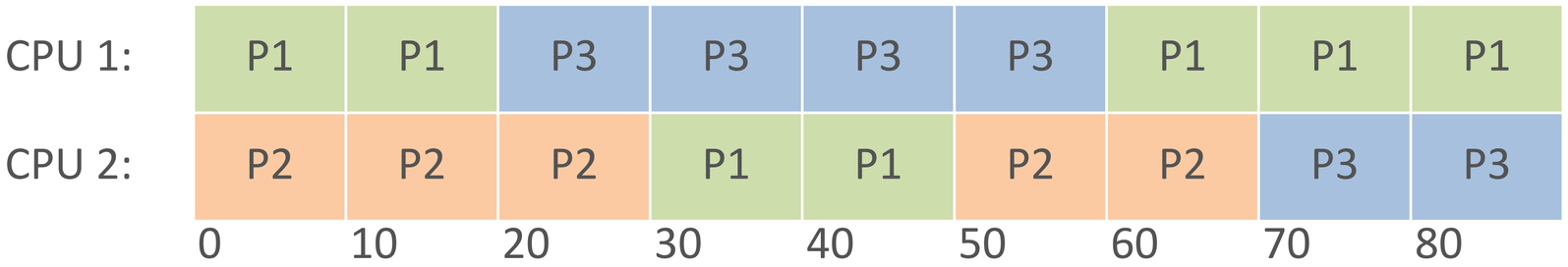
Thread v.s. process

- **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:



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.

Peer Instruction Activity

(Switch slides)