Operating Systems: CPU Management

DS 5110: Big Data Systems (Spring 2023)

Lecture 2b

Yue Cheng

University of Virginia

CPU processors and architecture

Basics of CPU processors

- Hardware to execute instructions
  - Other processing units: GPU, TPU, FPGA, etc.
- Instruction Set Architecture (ISA)
  - Vocabulary of instructions of a processor

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A C program

↓ *Compile*

Program in assembly language

↓ *Assemble*

Machine code tied to ISA

↓ *Execute*

Run on processor

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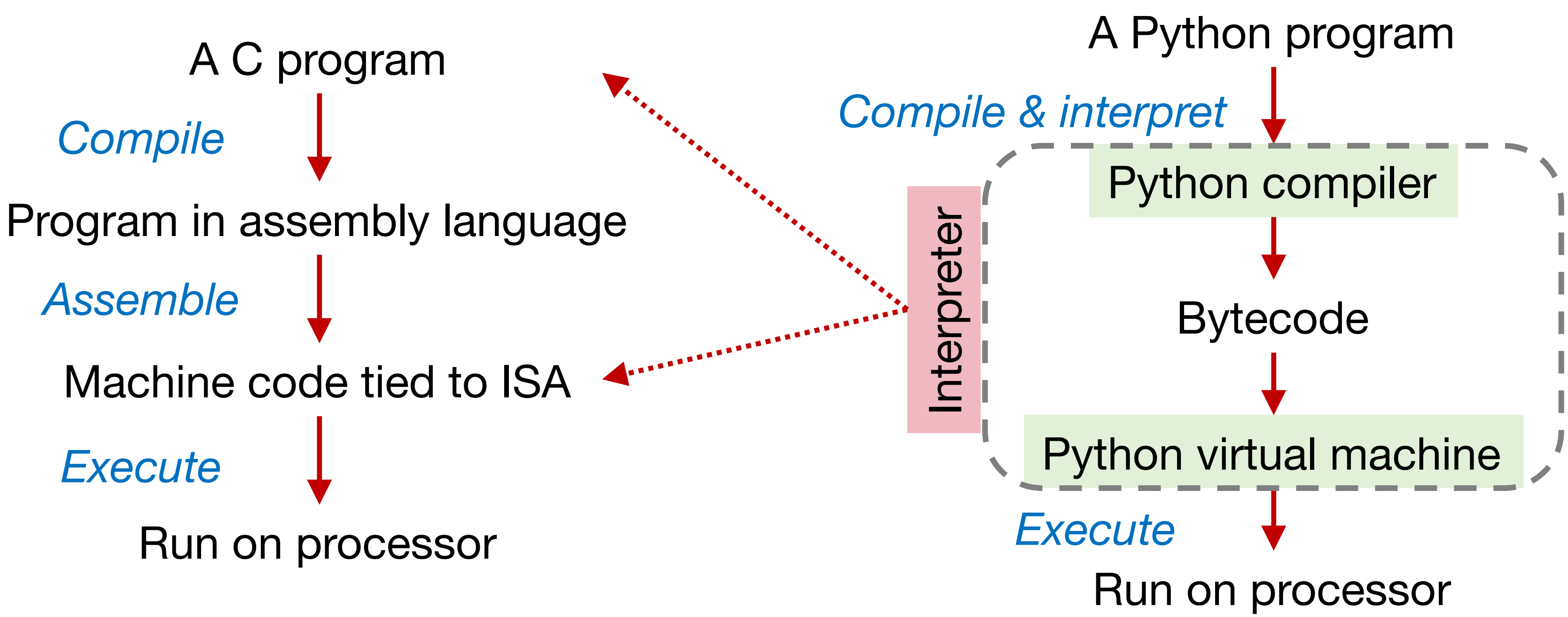
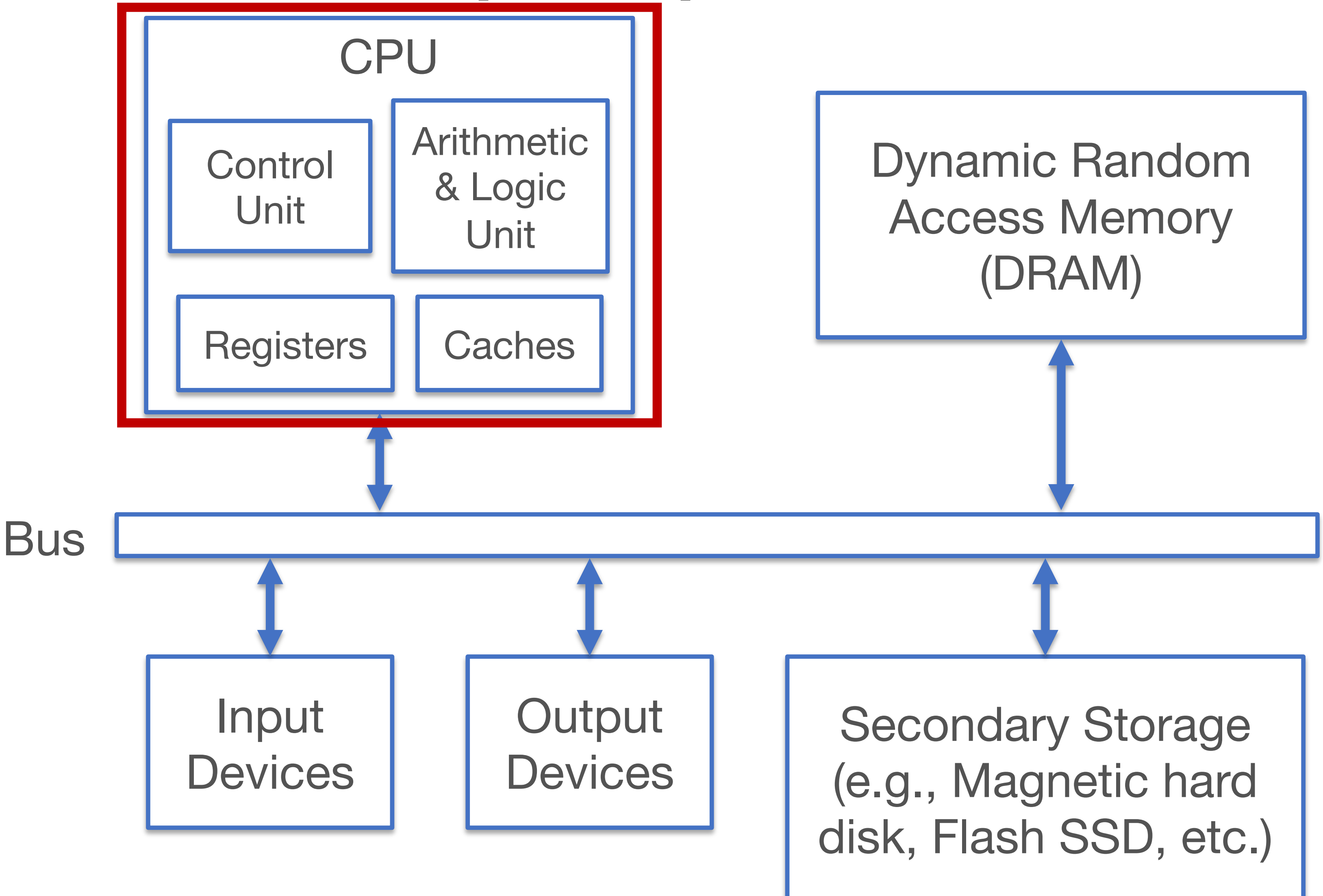


Abstract computer parts



How does a CPU execute machine code?

- Most common approach: load-store architecture
- **Registers:** Tiny local memory ("scratch space") on CPU into which instructions and data are copied
- ISA specifies bit length/format of machine code instructions
- ISA has several instructions to manipulate register contents

How does a CPU execute machine code?

- Type of ISA instructions to manipulate register contents
  - Memory access: `load` (copy bytes from a DRAM address to register); `store` (reverse)
  - Arithmetic & logic on data items in registers: add/multiple/etc.; bitwise ops; compare, etc.; handled by ALU
  - Control flow (branch, call, etc.): handled by CU
- **CPU caches:** Small CPU-local memory to buffer instructions and data

CPU performance

Or, how fast can a CPU execute a program?

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- Modern CPUs can run millions-billions of instructions per second
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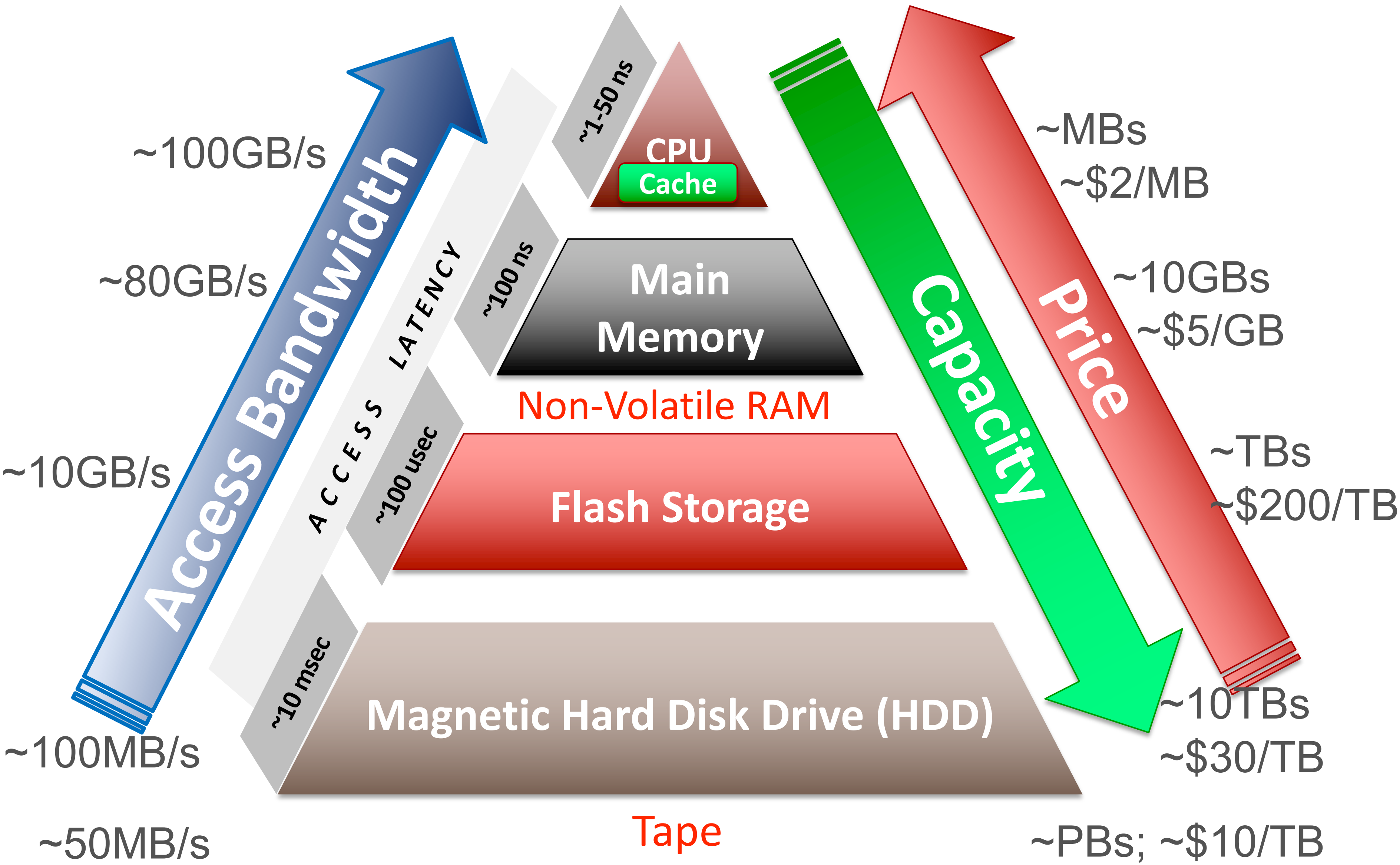
  - Memory access instructions stall the CPU: i.e., ALU & CU idle during DRAM-register transfer
  - Worse, data may not be in DRAM – wait for disk I/O!
  - So, actual runtime of a program may be orders-of-magnitude higher than what clock rate calculation suggests

Memory-storage hierarchy



*UCSD DSC 102: Systems for scalable analysis. Arun Kumar

Key principle: Optimizing use of CPU caches is critical for processor performance!

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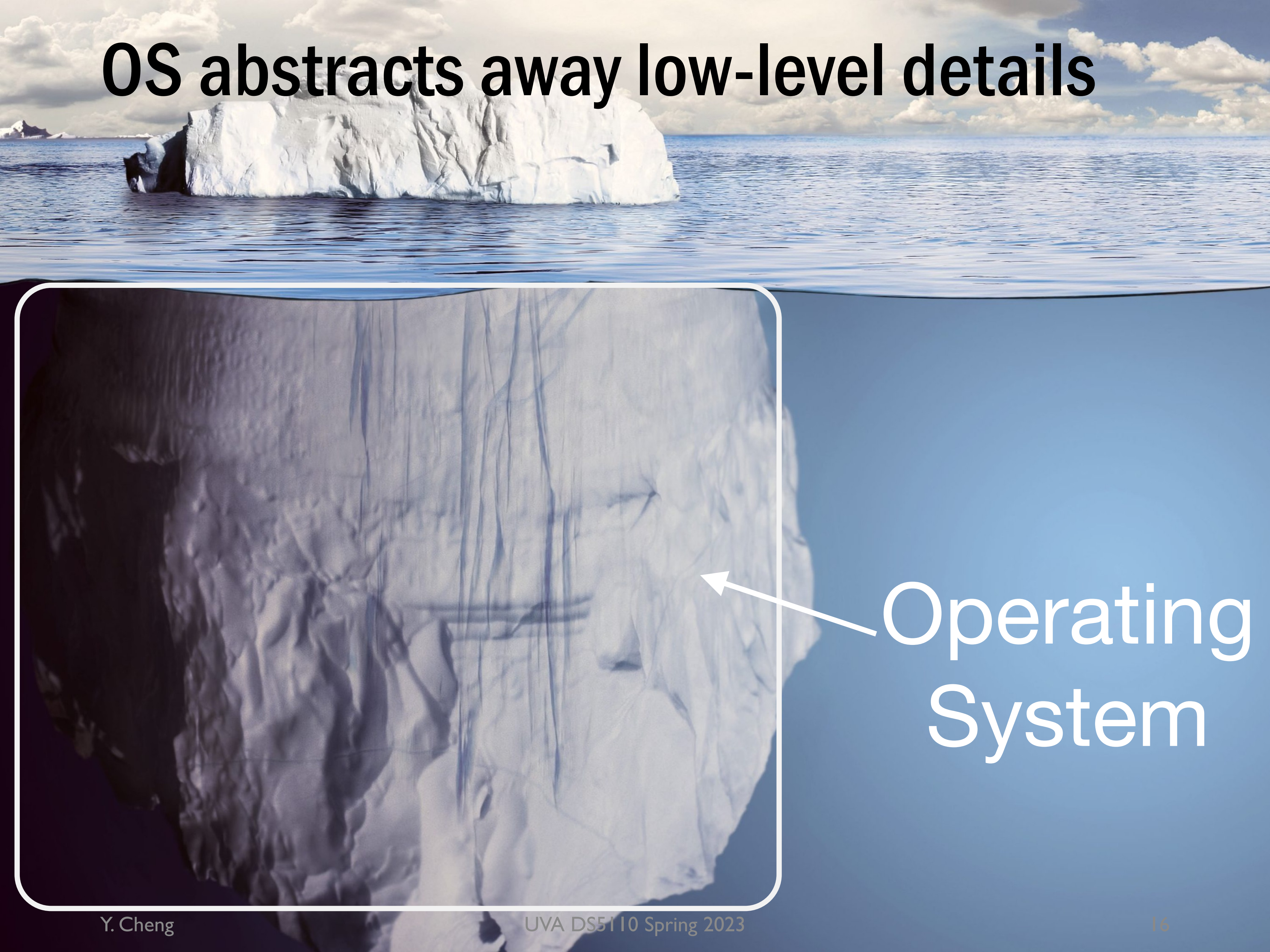
What is an OS?

What is an OS?

- OS manages resources
  - Memory, CPU, storage, network
  - Data (file systems, I/O)

- Provides low-level abstractions to applications
  - Files
  - Processes, threads
  - Virtual machines (VMs), containers
  - …

OS abstracts away low-level details



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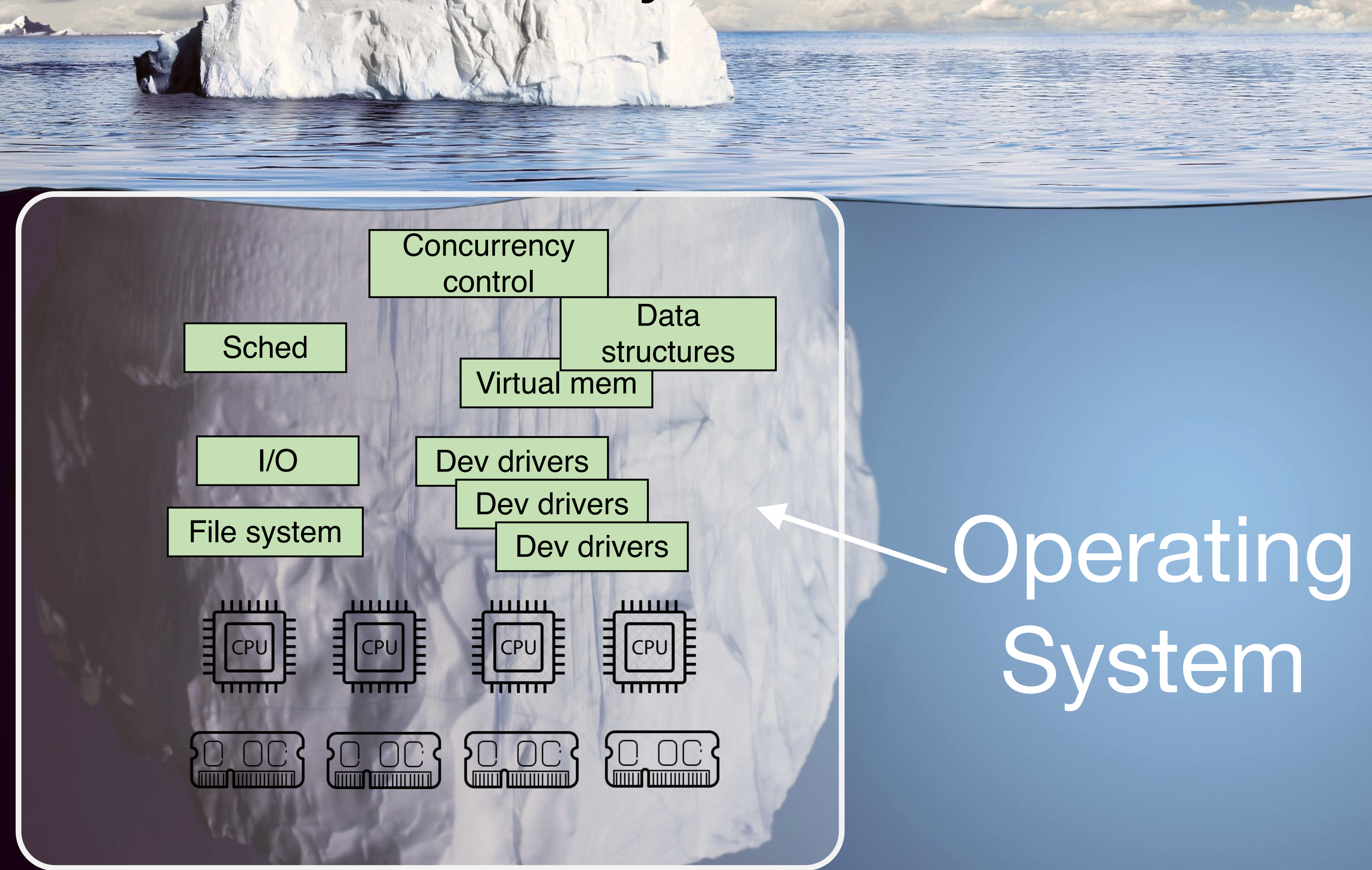

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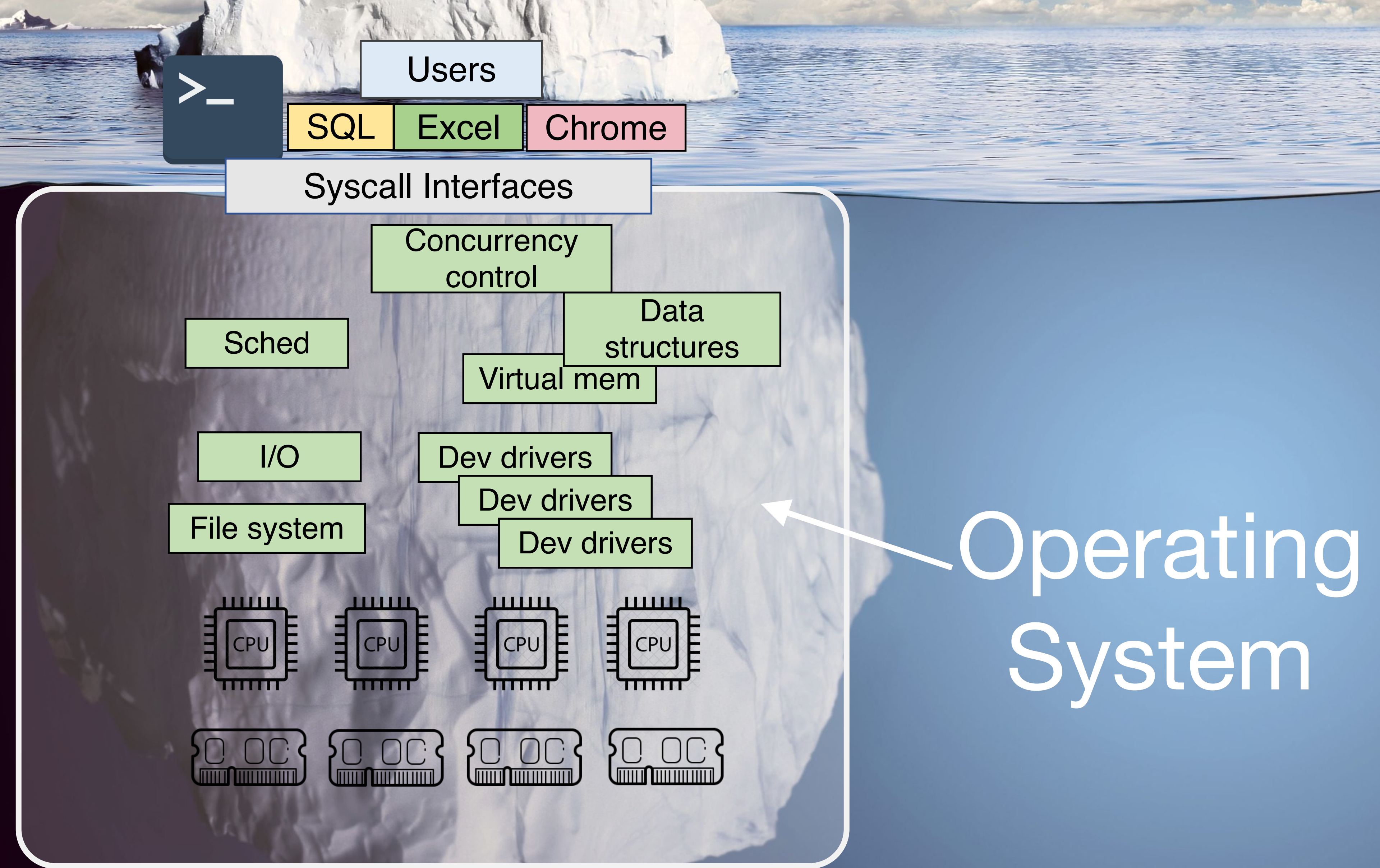

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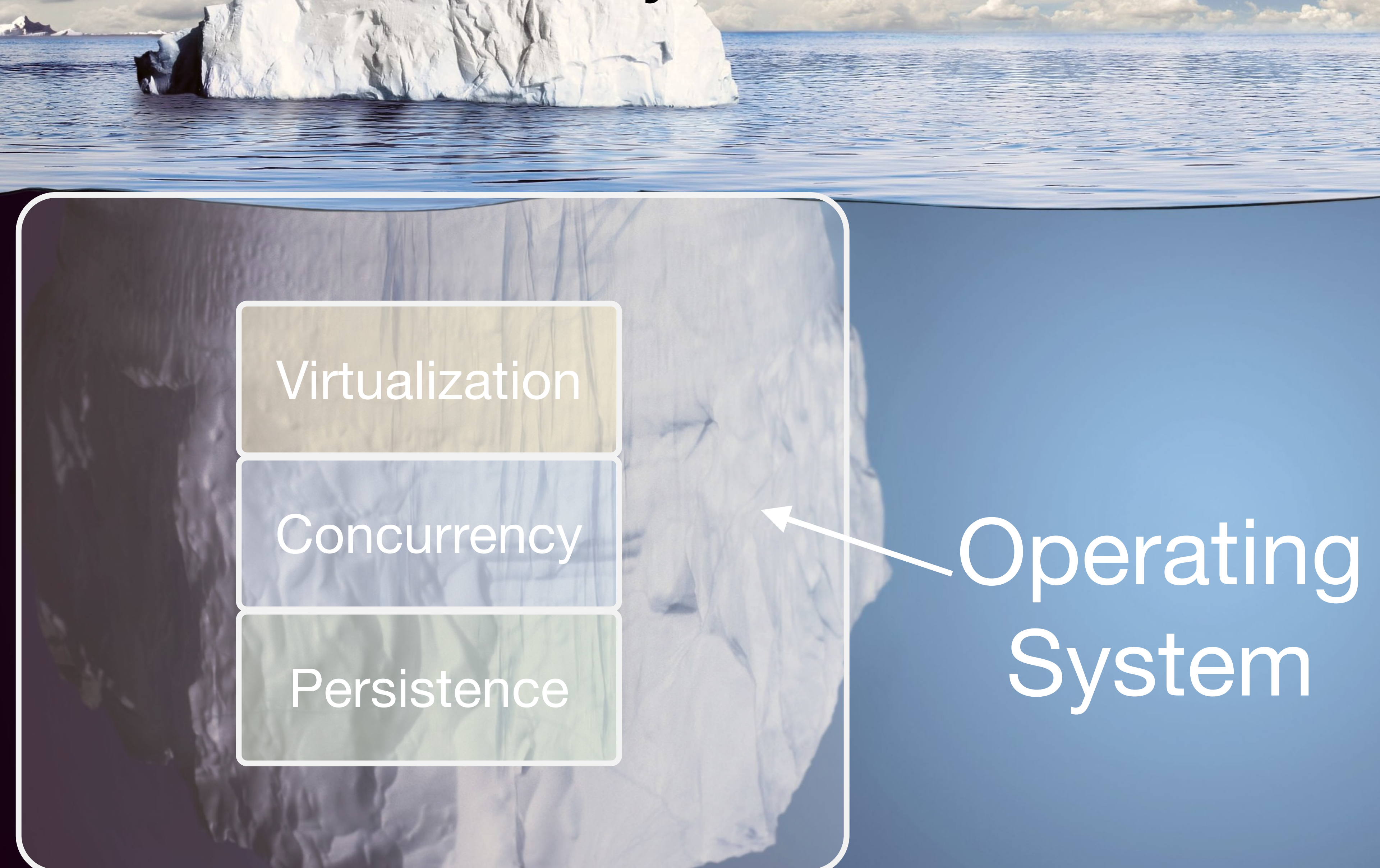

What happens when a program runs?

- A running program executes instructions
  1. The processor **fetches** an instruction from memory
  2. **Decode**: Understand which instruction it is
  3. **Execute**
  4. The processor moves on to **the next instruction** and so on

How does a running program interact with the OS?

- System calls allow a user application to tell the OS what to do
  - OS provides interfaces (APIs)
  - Hundreds of system calls (for Linux)
    - Run programs
    - Access memory
    - Access devices

Virtualization

- OS virtualizes physical resources
  - Gives illusion of private resources

Virtualizing the CPU

- OS creates and manages many virtual CPUs
  - Turning a single CPU into seemingly infinite number of CPUs
  - Allowing many programs to seemingly run at once (concurrently)

Virtualizing memory

- The physical memory is an array of bytes
- A program keeps (most of) its data in memory
  - Read memory (load): Access an address to fetch the data
  - Write memory (store): Store the data to a given address

Concurrency

- OS is juggling many things at once
  - First running one process, then another, and so forth

- Multi-threaded programs also have concurrency problem

Persistence

- Main memory (DRAM) is **volatile**
- How to persist data?
  - **Hardware**: I/O devices such as hard disk drives (HDDs)
  - **Software**: File systems

What is a process?

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- Programs are code (static entity)
- Processes are running programs

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

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- Programs are code (static entity)
- Processes are running programs

- **Q:** Why bother knowing process management in Data Science?
  - Everything in Data Science runs in a process
  - A large data system is multiple cooperating, running processes that execute user-submitted jobs/queries

What is in a process?

Process

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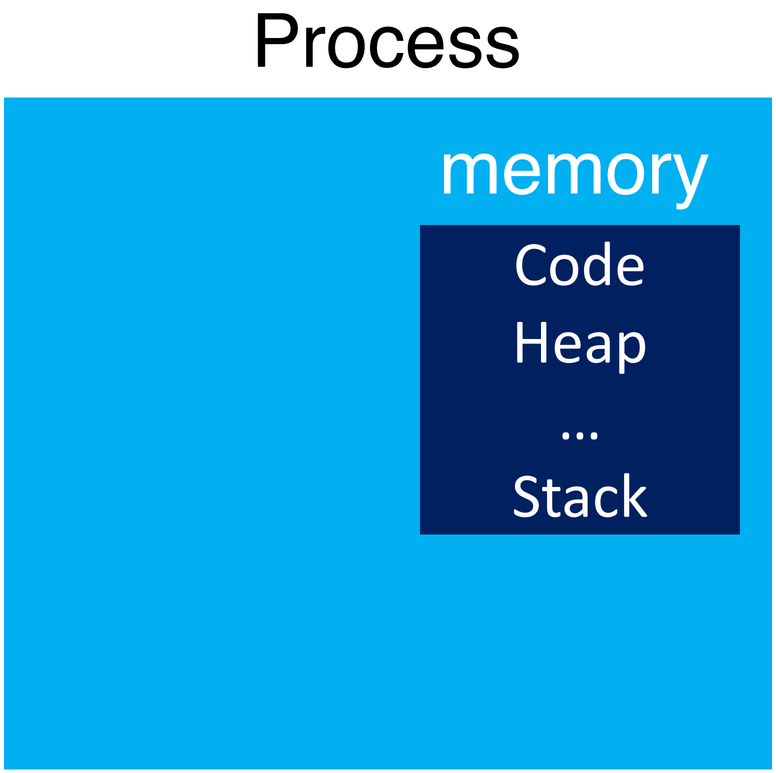

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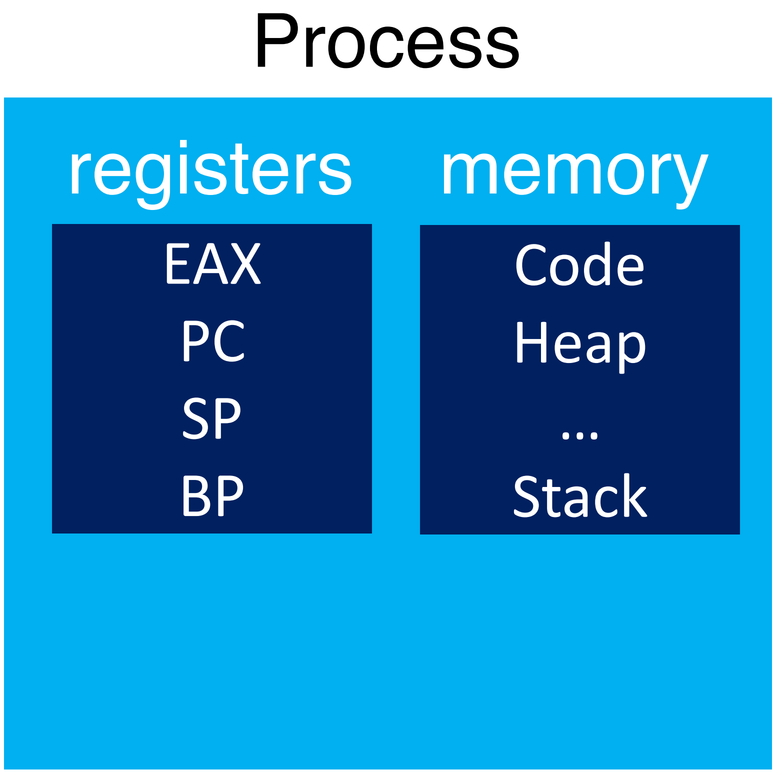

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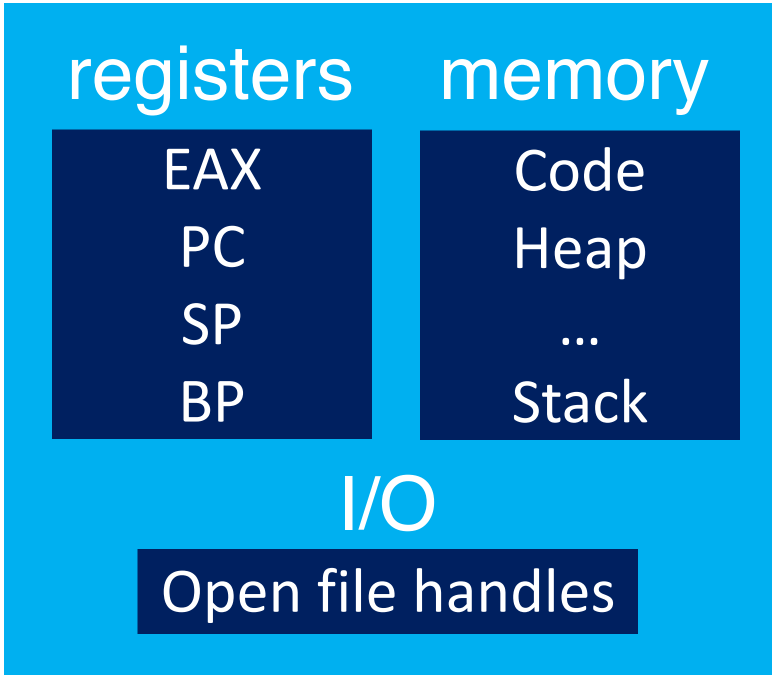
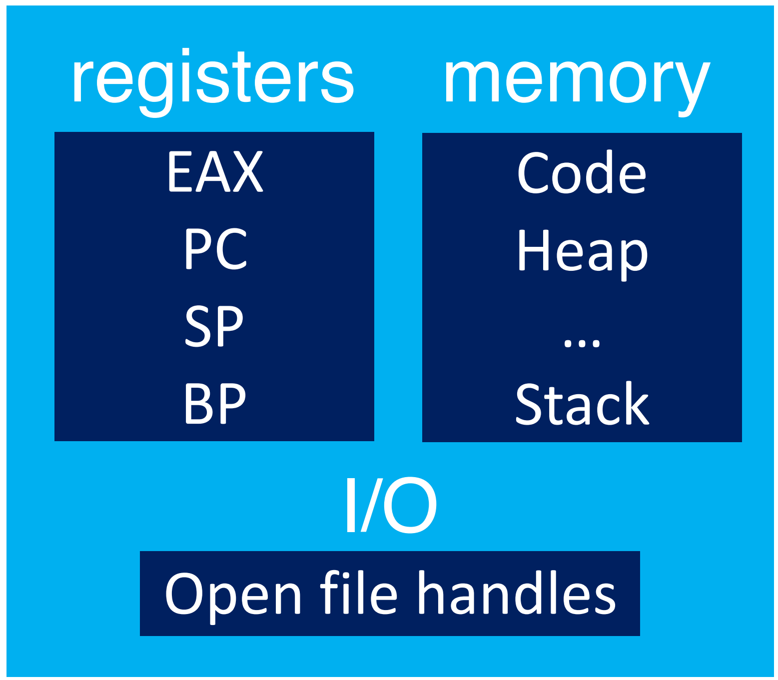
Process



What things change as a program runs?

What is in a process?

Process



What things change as a program runs?

Running program's internal state (runtime data)

Peeking inside

- Processes share code, but each has its own "context"
- CPU state
  - Instruction pointer (Program Counter)
  - Stack pointer
- Memory state
  - Set of memory addresses ("address space")
  - `cat /proc/<PID>/maps`
- Disk state
  - Set of file handles (file descriptors or fd)
  - `cat /proc/<PID>/fdinfo/*`

Is it not safe/secure for OS to hand off control of hardware to a process?

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- **Limited direct execution (LDE):** Low-level mechanism that implements the user-kernel space separation

- Usually let processes run with no OS involvement
- Limit what processes can do
- Offer privileged operations through well-defined channels with help of OS

Limited Direct Execution (LDE)

Limited Direct Execution (LDE)

Running program

LDE
mechanism

OS

Sharing (virtualizing) the CPU

How does OS share…

- CPU?
- Memory?
- Disk?

How does OS share…

- CPU? (a: time sharing)
- Memory? (a: space sharing)
- Disk? (a: space sharing)

How does OS share...

- CPU? (a: time sharing)

Today

- Memory? (a: space sharing)
- Disk? (a: space sharing)

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Goal: processes should **not** know they are sharing
(each process will get its own virtual CPU)

What to do with processes that are not running?

- A: Store context in OS structures

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- Context:
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  - Open file descriptors
  - State (sleeping, running, etc.)

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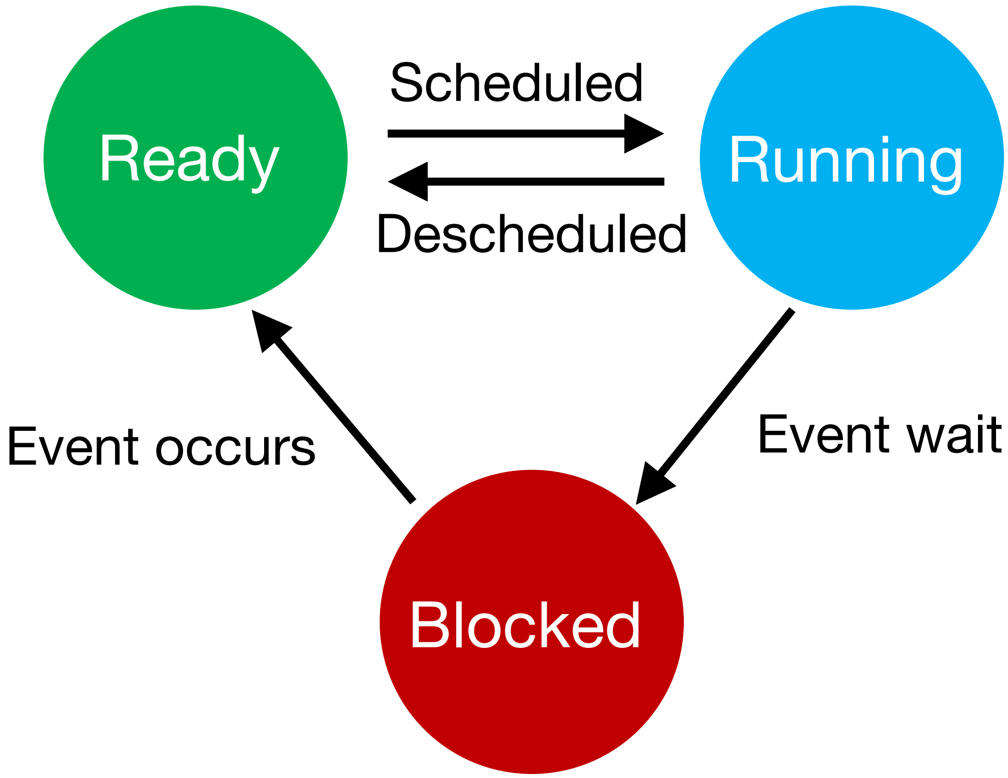
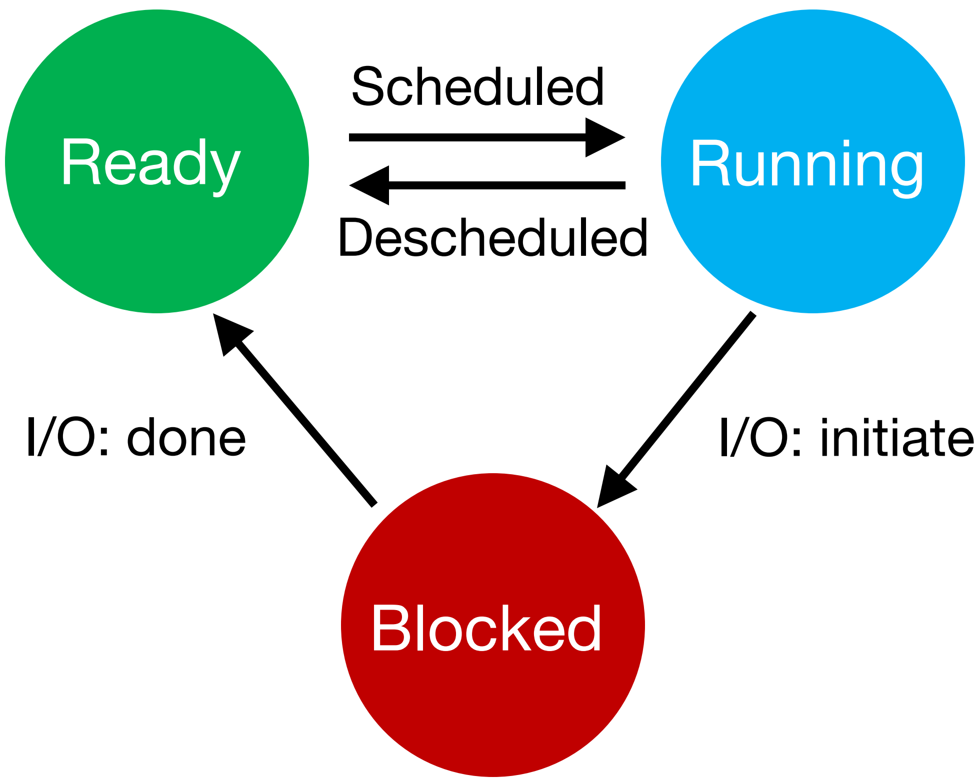
Program-specific runtime data

Process state transitions

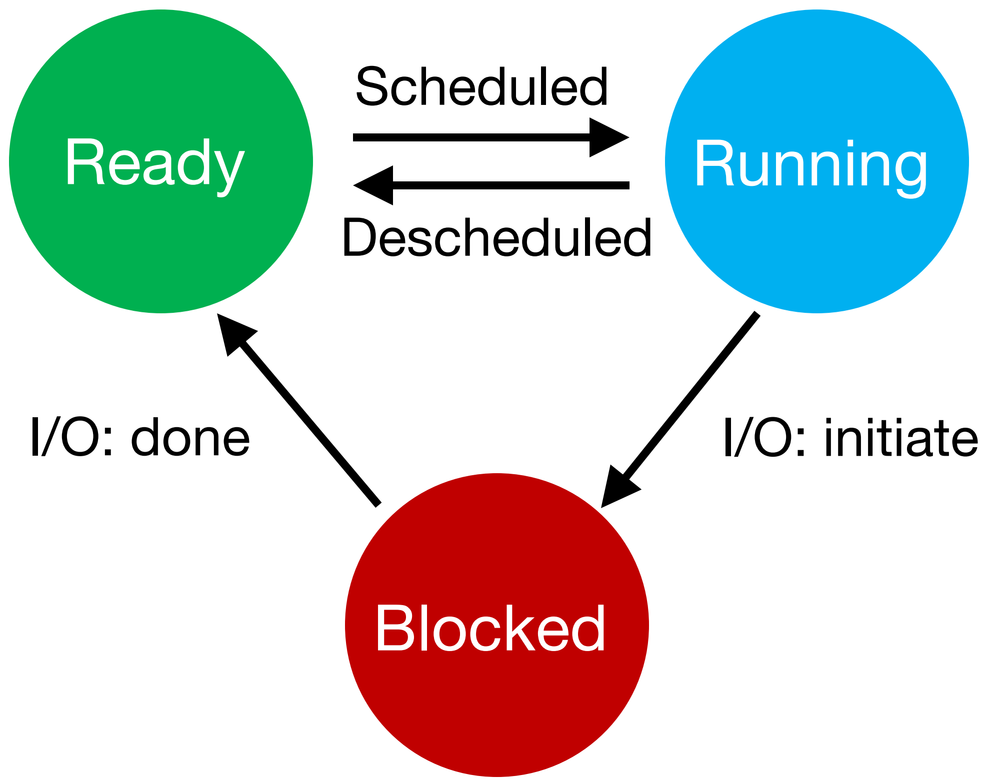


Process state transitions



On a Linux/Mac: View process state with "`ps xa`"

How to transition? (mechanism)
When to transition? (policy)



On a Linux/Mac: View process state with "`ps xa`"

CPU scheduling policies/algorithms

- **Problem to solve:** How to optimize the tradeoff b/w overall workload performance and fairness?
  - Given that the number of processes (applications) is way larger than that of the available CPU cores

- Processes get queued up and the CPU scheduler will select one in the ready queue for execution
- The scheduling policies may have tremendous effects on the system efficiency
  - Interactive systems: Responsiveness (latency)
  - General-purpose systems: Fairness in CPU usage

First-In, First-Out

Workload assumptions

1. Each job runs for the same amount of time

2. All jobs arrive at the same time

3. All jobs only use the CPU (no I/O)

4. The runtime of each job is known

FIFO

- First-In, First-Out: Run jobs in arrival order

Proc	Arrival time	Runtime
P1	~0	5
P2	~0	5
P3	~0	5

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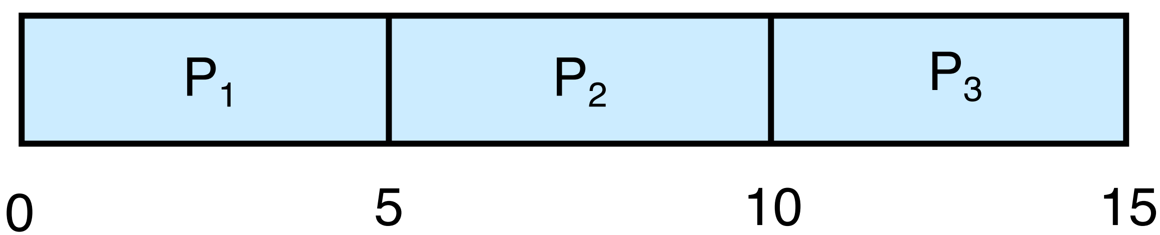
Gantt chart



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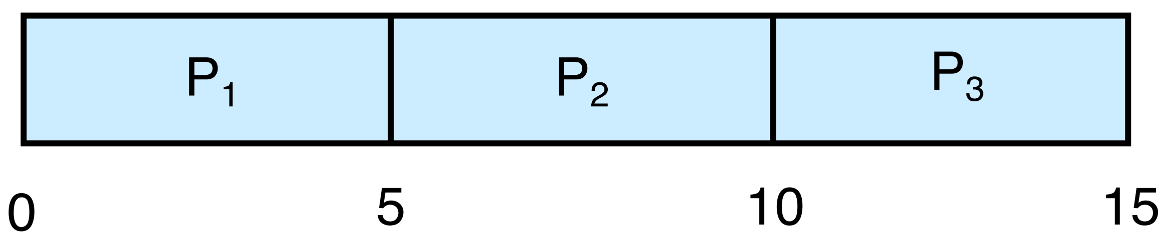

What is the average turnaround time?

Def: turnaround_time = completion_time – arrival_time

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Example: big first job

Proc	Arrival time	Runtime
P1	~0	80
P2	~0	5
P3	~0	5

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P2	~0	5
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What is the average turnaround time?

Average turnaround time: (80+85+90) / 3 = 85

Convoy effect!!

Better schedule?

Shortest Job First (SJF)

Passing the tractor

- New scheduler: SJF (Shortest Job First)

- Policy: When deciding which job to run, choose the one with the smallest runtime

Example: SJF

Proc	Arrival time	Runtime
P1	~0	80
P2	~0	5
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What is the average turnaround time with SJF?

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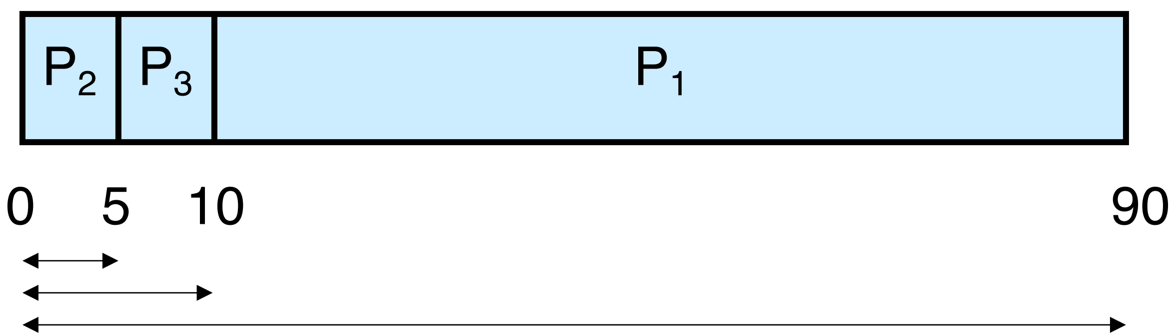

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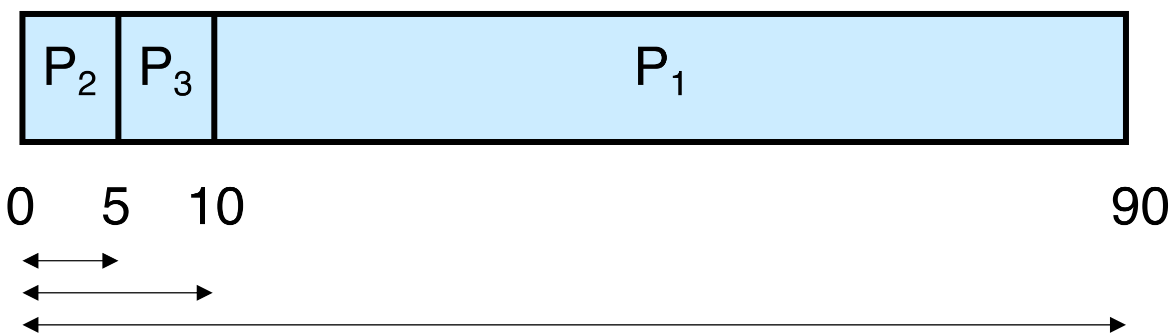

Average turnaround time: (5+10+90) / 3 = 35

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What if jobs arrive at different time?

Shortest Job First (arrival time)

Proc	Arrival time	Runtime
P1	~0	80
P2	~15	20
P3	~15	10

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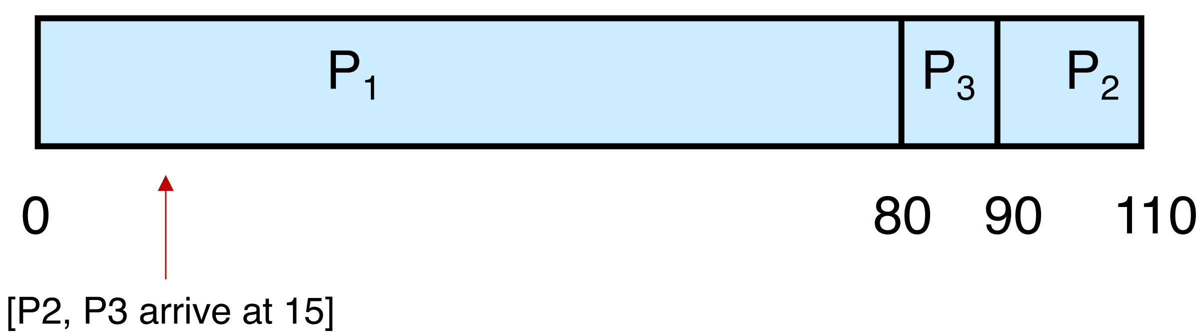

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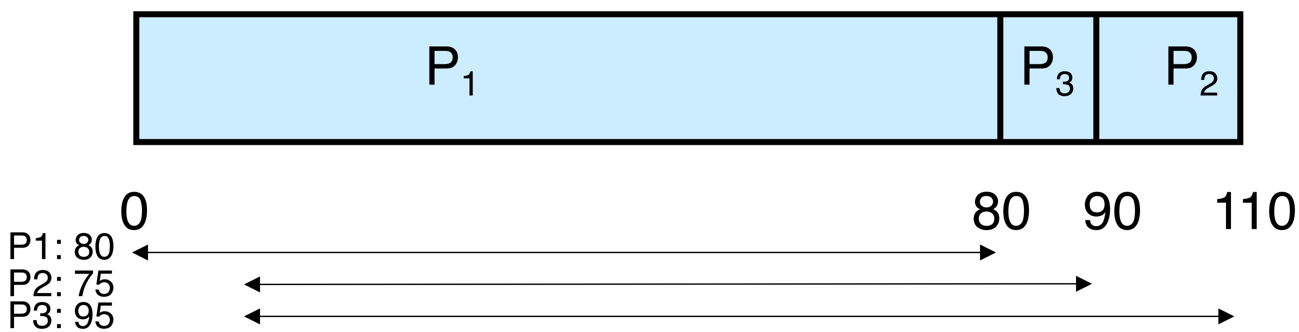


Average turnaround time: (80+75+95) / 3 = ~83.3

A preemptive scheduler

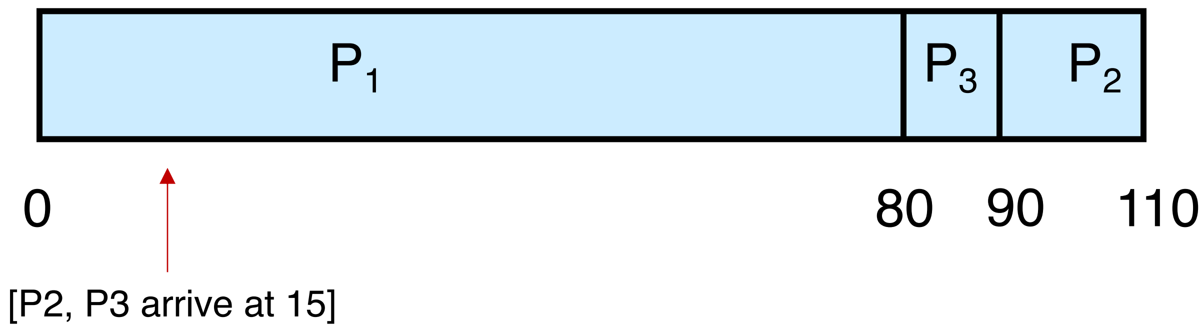
- Previous schedulers: FIFO and SJF are non-preemptive

- New scheduler:
  STCF (Shortest Time-to-Completion First)

- Policy: Switch jobs so we always run the one that will complete the quickest

SJF

Proc	Arrival time	Runtime
P1	~0	80
P2	**~15**	20
P3	**~15**	10



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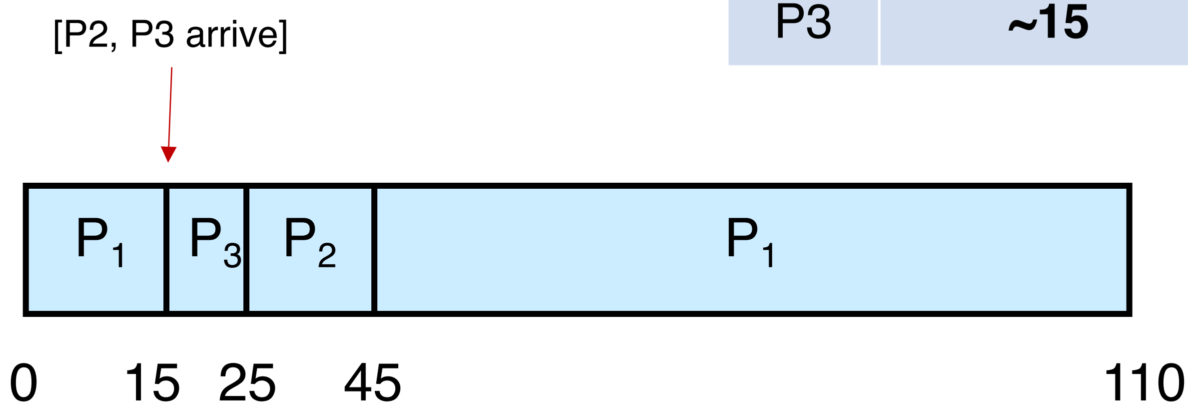

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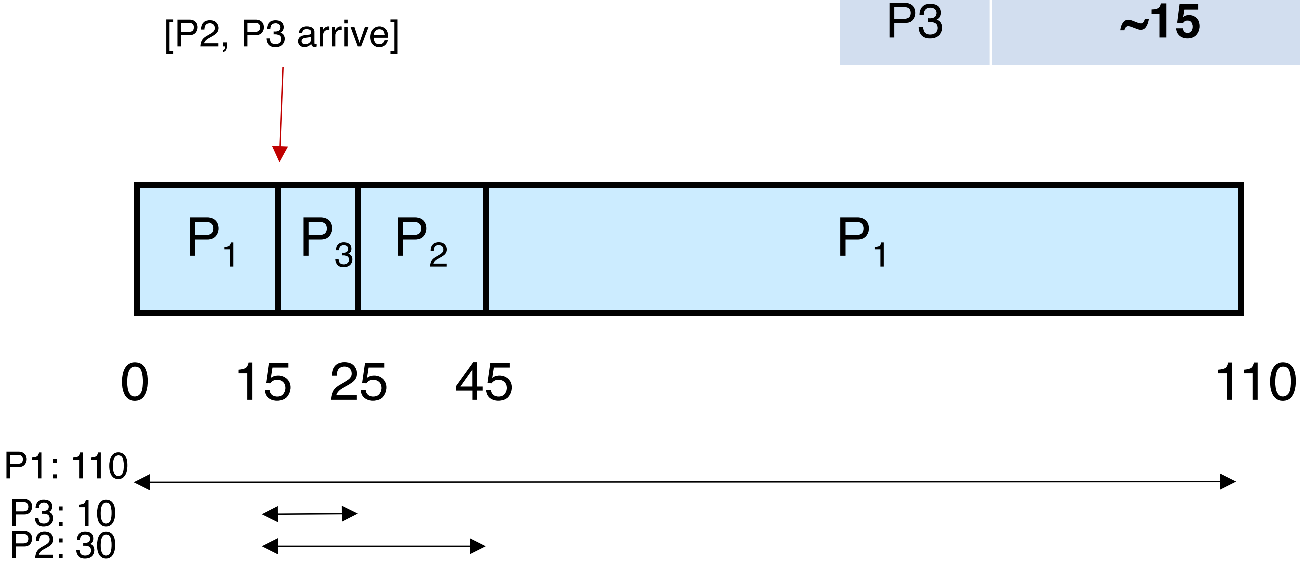

Average turnaround time: (110+30+10) / 3 = 50

Workload assumptions

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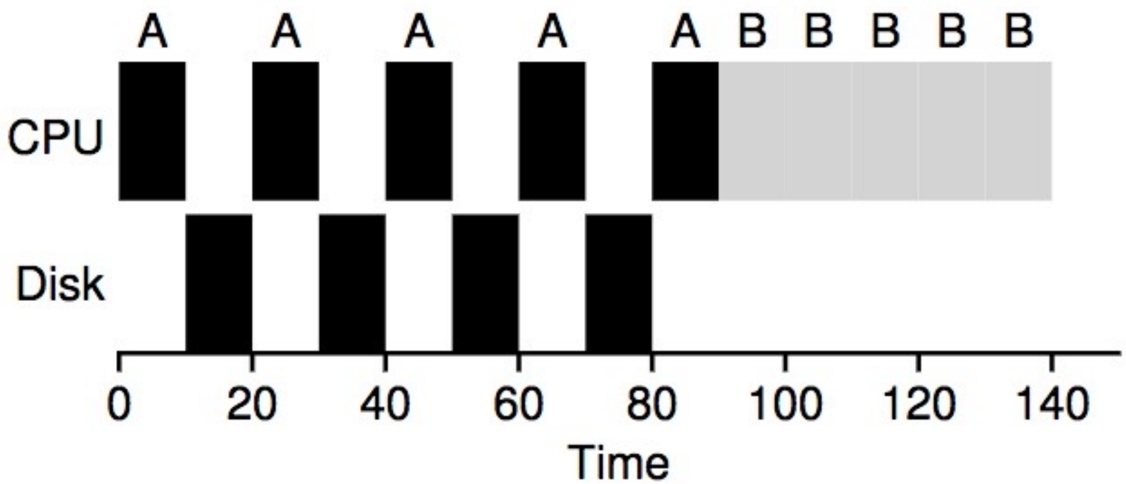
What if jobs do I/Os as well?

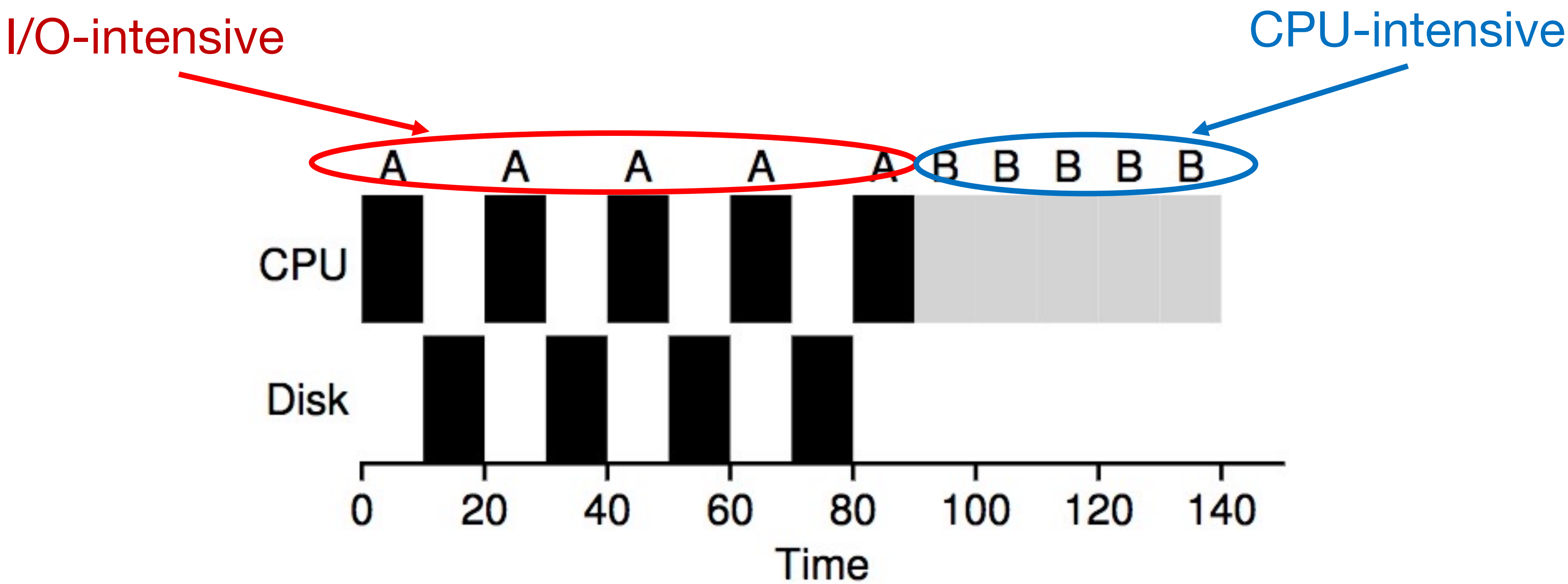
- No good if a program can only do pure CPU-intensive compute
- A common execution pattern of the typical big data applications (Hadoop, Spark, Dask)
  - Completes the CPU burst, performs I/O (e.g., read further CSV files from disk into DRAM), rejoins the ready queue and completes the second CPU bursts…

Not I/O Aware



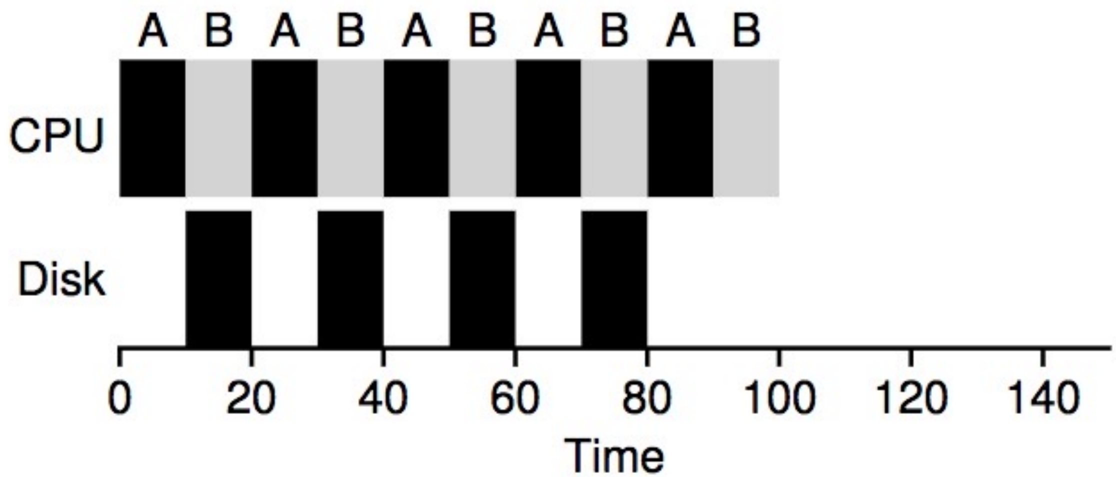
Poor use of resources

Not I/O Aware



Poor use of resources

I/O Aware (Overlap)

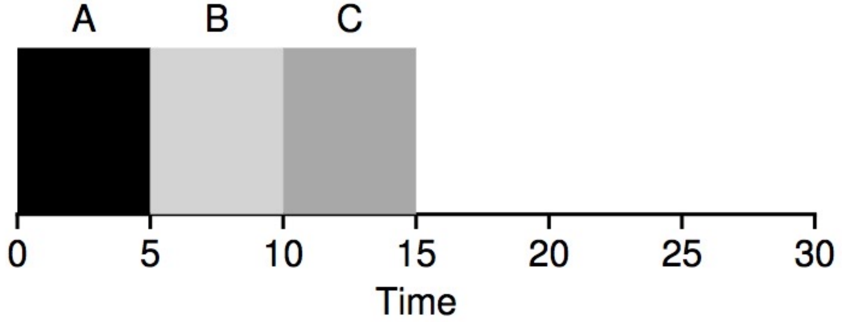


Overlap allows better use of resources!

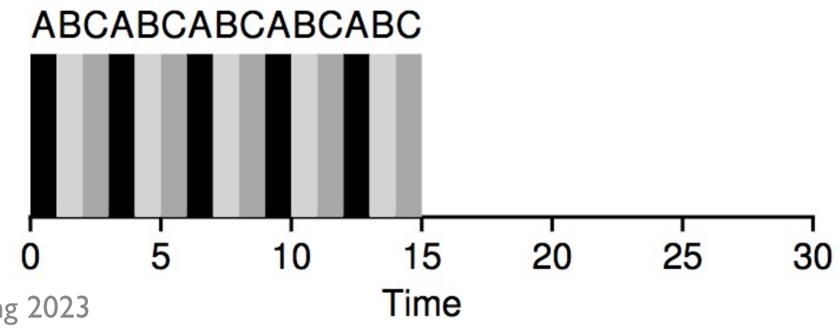
Round Robin (RR)

Process	Burst time
A	~5
B	~5
C	~5

- Each process gets a small unit of CPU time (time slice). After this time has elapsed, the process is preempted and added to the end of the ready queue
- SJF's average response time
  - (0 + 5 + 10) / 3 = 5



- RR's average response time (time slice = 1)
  - (0 + 1 + 2) / 3 = 1



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4. The runtime of each job is known ?

Why bother learning these low-level stuff in Data Science?

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	Job Title	Median Base Salary	Job Satisfaction	Job Openings	
#1	Enterprise Architect	$144,997	4.1/5	14,021	View Jobs
#2	Full Stack Engineer	$101,794	4.3/5	11,252	View Jobs
#3	Data Scientist	$120,000	4.1/5	10,071	View Jobs
#4	Devops Engineer	$120,095	4.2/5	8,548	View Jobs
#5	Strategy Manager	$140,000	4.2/5	6,977	View Jobs
#6	Machine Learning Engineer	$130,489	4.3/5	6,801	View Jobs

Why bother learning these low-level stuff in Data Science?

- Basics of computer organization
  - Digital representation of data
  - Machine architecture (ISA)
  - CPU and memory hierarchy

- Basics of operating systems
  - CPU management
  - Memory management
  - File system and data management