The Process Abstraction

ICS332

Operating Systems

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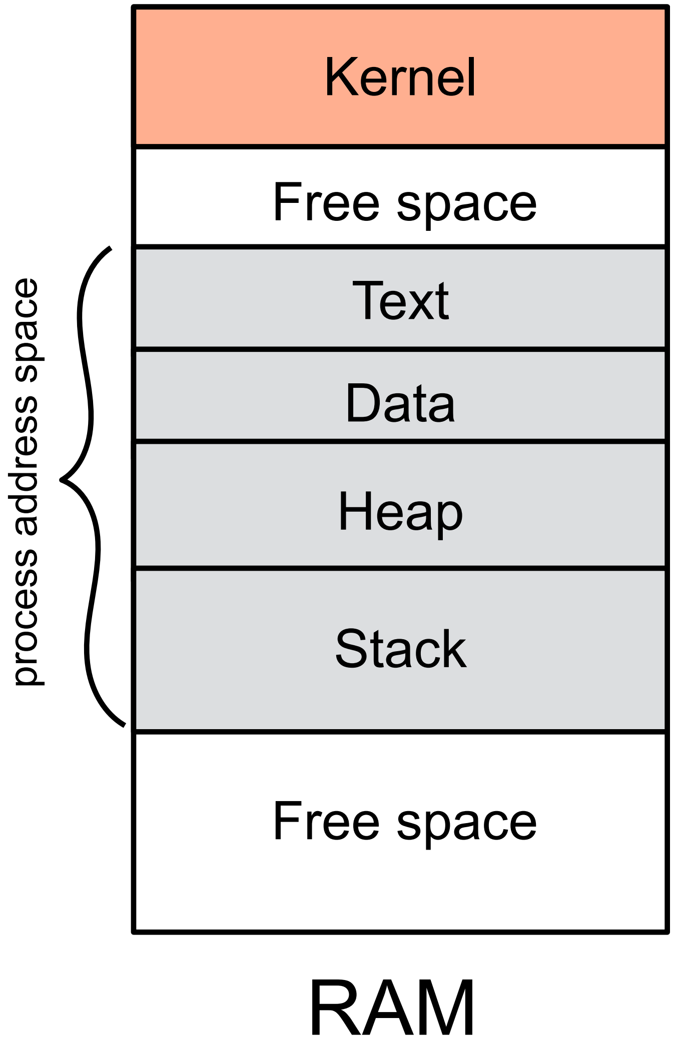
Definition

- A process is a program in execution
  - Program: passive entity (bytes stored on disk as an executable file)
  - Becomes a process when it is loaded into memory, at which point the fetch-decode-execute cycle can begin
  - The process abstraction is defined by the OS to virtualize the CPU
- Multiple processes can be associated to the same program
  - A user can start multiple instances of the same program (e.g., bash)
- Typically many processes run on a system
  - System processes (started by the OS to do “system things”)
  - User processes (started by users)
  - The terms “process” and “jobs” are used interchangeably in OS textbooks
- The set of locations that store bytes that a process can use/reference is called the process’ address space…

Process Address Space

- The code (also called text)
  - Binary instructions, loaded into RAM by the OS from an executable file
- The static data
  - The global variables and static local variables, which can be initialized (.data segment in x86 assembly) or not (.bss segment in x86 assembly)
- The content of all registers
  - They represent the state of the CPU in the current fetch-decode-execute cycle
  - This includes the program counter (PC)
- The heap
  - The zone of RAM in which new data can be be dynamically allocated (using malloc, new, etc.)
- The runtime stack
  - The zone of RAM for all bookkeeping related to method/procedure/function calls (more in the next slides)
- The page table
  - Let's not talk about it now and leave it for later…

Process Address Space



- The OS can be configured to limit parts of a process' address space
  - On UNIX-like systems you can find out what some limits are (all in KB):
    - **`ulimit -d`** (data + heap)
    - **`ulimit -s`** (stack size)
    - **`ulimit -m`** (maximum Resident Set Size)
  - These limits can be changed system-wide using the **`ulimit`** command
  - They can also be changed by the process itself using the **`setrlimit()`** system call
  - Let's see what limits are on my server…
- When running a Java program you can specify some limits
  - **`java -Xmx512m -Xss1m`** …
  - 512 MiB maximum heap size, 1MiB maximum stack size

The Heap

- New (i.e., dynamically allocated) bytes (objects, arrays, etc.) are allocated on the Heap (**`malloc()`** in C, **`new`** in Java/C++/C#, implicit in Python, etc.)
- Can be handled by a memory manager (e.g., the JVM, a library, the Python interpreter) but ultimately it is the OS that provides dynamic memory allocation
  - There is a system call that says “please OS, give me XX more bytes”
- At some point you will get an Out Of Memory error if you keep dynamically allocating memory
- On my Linux box (not Docker), let’s write a simple C program that calls **`malloc()`** 10,000 times for 1 byte and look at the addresses returned…

The Heap: what we observed

- When calling **`malloc()`** for 1 byte, the space used is actually more than 1 byte!
  - In our case addresses were 32 bytes apart, so we "wasted" 31 bytes for each **`malloc()`**!!
- Calling **`malloc()`**, say, 10,000 times for 1 byte "wastes" memory when compared to calling **`malloc()`** 1 time for 10,000 bytes
- This is due to the implementation of the OS's "memory allocator"
  - It needs to store meta-data about the chunk of memory allocated so that later it knows what to do when **`free()`** is called
  - It will often allocate memory at addresses that are multiple of some small power of 2
- Let's now **`strace`** this program we just wrote and see what the "give me more memory!" system call is…

The `brk` syscall

- The “give me more memory!” system call is **`brk()`**
- The man page for **`brk()`** shows that it is used to extent the heap up to some address that is beyond the current “end of the heap” address
  - **`brk(NULL)`** “asks” where the data+heap ends
- Weirdly, although our programs calls **`malloc()`** a lot, it calls **`brk()`** only a few times
- This is an optimization:
  - A call to **`malloc()`** can get more memory than asked
  - Subsequent calls to **`malloc()`** just grab some of that extra memory without any syscall at all! (less overhead, more speed)
- So when calling **`malloc(1)`**, memory footprint can grow by a lot more than 1 byte!
- Let’s figure out how much memory, in KiB, is allocated by a “first” call to **`malloc()`**
  - Anybody has some idea how we can do this?

The Heap: what we found out

- What we likely just did:
  - Count the number of **`malloc()`** calls between two calls to **`break()`**
  - Multiply that number of calls by 32
  - Divide by 1024
  - And that's the number of KiB we get the "first time" we call **`malloc(1)`**

- Of course are a little bit more complicated than that… isn't everything in the OS?

The Runtime Stack

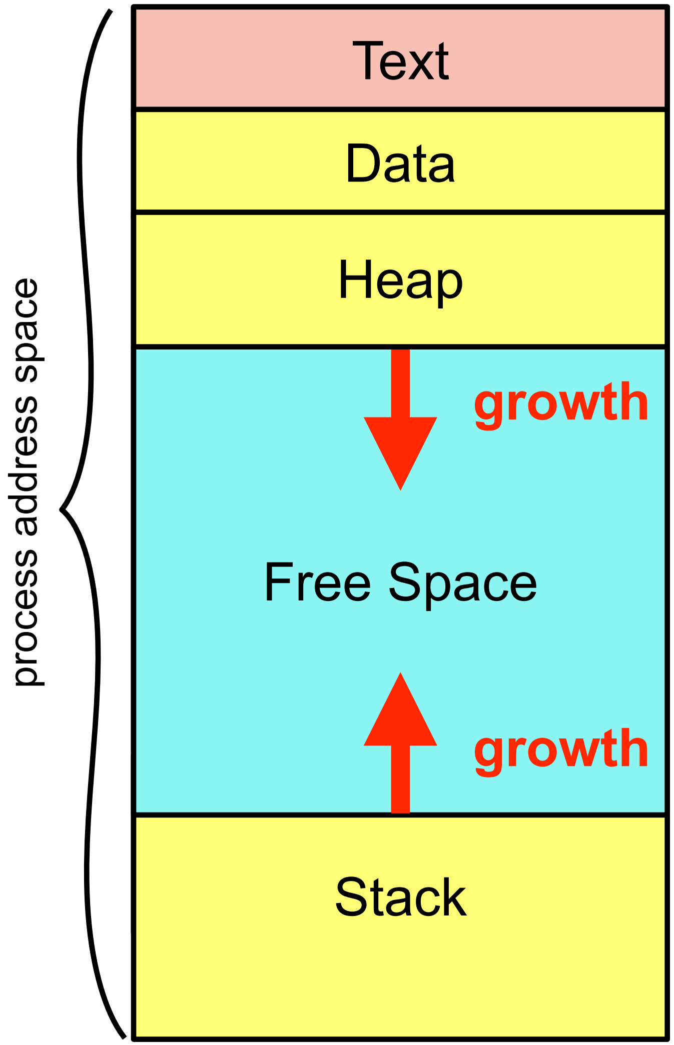
- Each process has in RAM a stack (a last-in-first-out data structure) where items can be pushed or popped
- It is used to manage method/procedure/function calls and returns
- On each call, an activation record is pushed onto the stack to do all the bookkeeping necessary for placing/returning from the call
  - It contains parameters, return address, local variables, saved register values
- The code to manage the stack is generated by compilers/ interpreters
  - In ICS 312 we learn all the details
- The stack size is limited
  - But configurable upon process creation
- Going over that limit is called a Stack Overflow
  - Happens, for instance, with a deep (or infinite) recursion

The Kernel Stack

- The code in the kernel uses functions, and therefore it must have a stack to call these functions
- But, to save space, the kernel's stack is very small (16KiB!!)
- Therefore, when writing functions in the kernel, these functions cannot allocate a lot on the stack
  - Not many parameters, not many local variables, no deep call sequences, and definitely no recursion

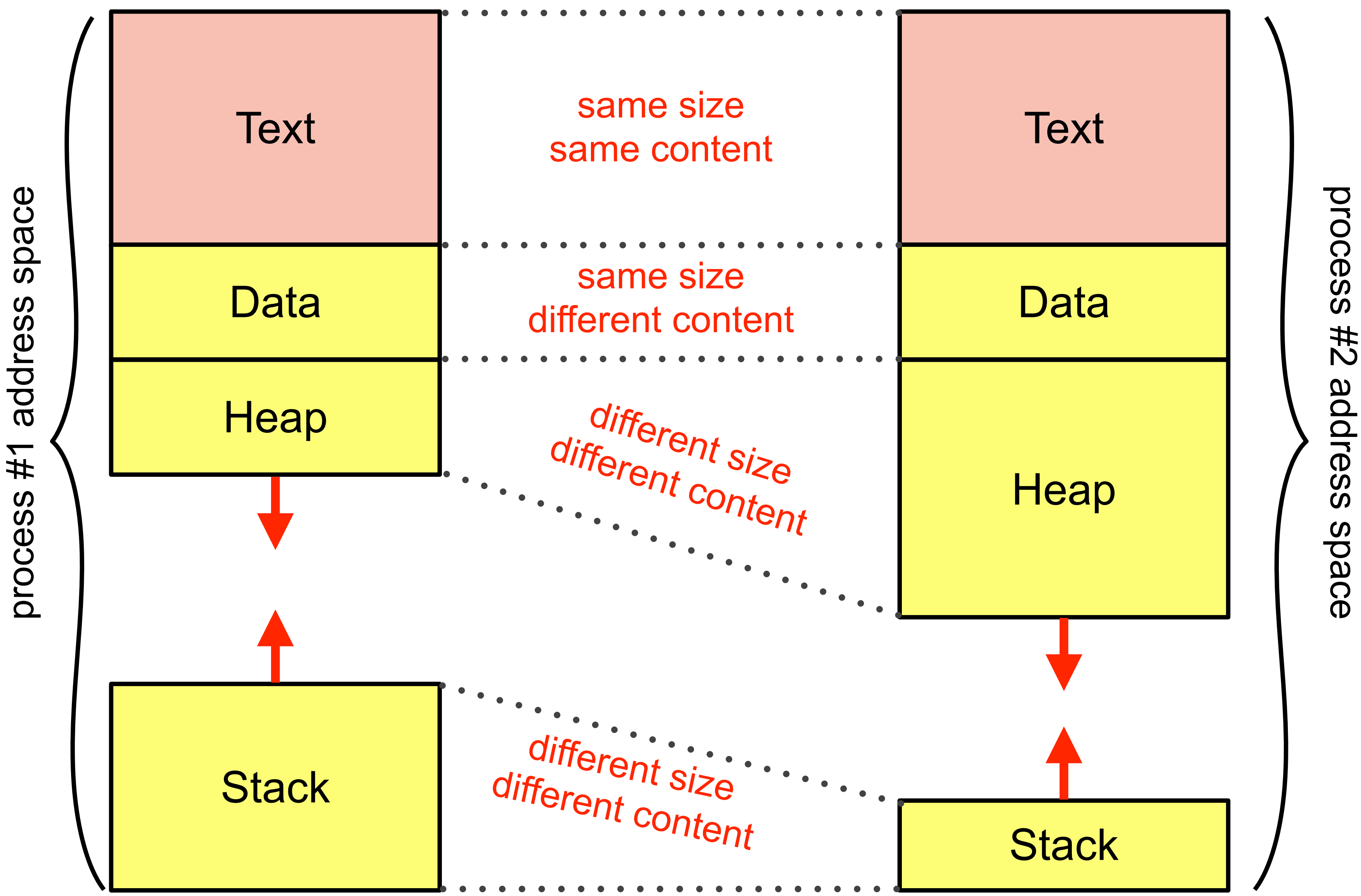
- This is one of the differences between user-level development and kernel-level development
  - Recall others, like the fact that kernel code cannot use standard libraries, because standard libraries use system calls, which are implemented in the kernel (chicken and egg problem)
  - e.g., you can't use `printf` when writing kernel code

Logical Address Space



- Typical depiction of a process' address space
  - The heap grows toward high addresses
  - The stack grows toward low addresses
  - If they collide you've run out of memory
- This is the logical view of a process' address space (i.e., virtualization of memory)
- Let us easily experience this logical view by writing a C program that prints text, data, heap and stack addresses on Linux…
- But this is **not at all** what things look like in physical memory
  - Because of "paging", which we'll talk about much later in the semester
  - And because that "free space" (in blue) would be a total waste if the program doesn't need additional stack/heap space!

Two Processes / One Program Example



Process Life Cycle

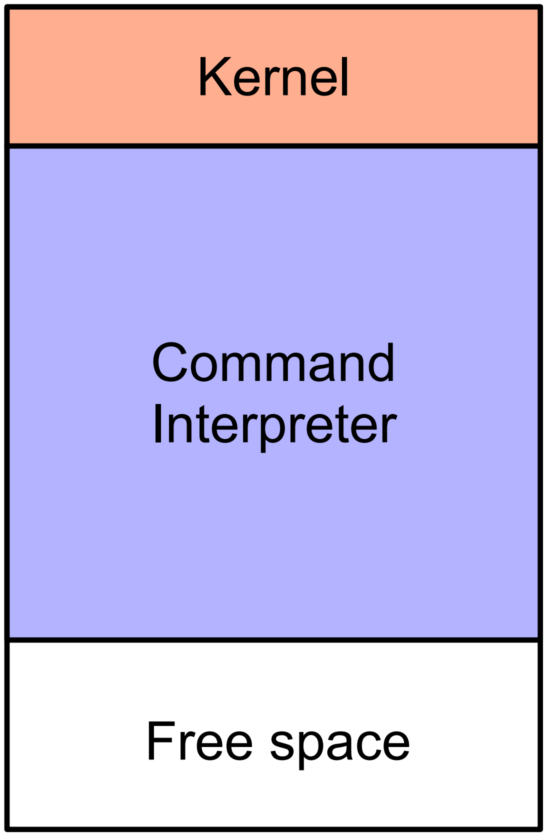
- Each process goes through a lifecycle
- This term (in computer science) means that:
  - There is a finite number of possible states
  - There are allowed transitions between some states
  - These transitions happen when some event occurs

- Before we look at the current process file cycle, let's go back in time to so-called "single-tasking OSes"…

Single-Tasking Ones

- OSes used to be single-tasking: only one process could be in memory at a time
- MS-DOS is the (last commercial?) most well-known example
  - A command interpreter is loaded upon boot
  - When a program needs to execute, no new process is created
  - Instead the program's code is loaded in memory by the command interpreter, **which overwrites part of itself with it!**
    - Done to cope with a very small RAM back in the days
  - The instruction pointer is set to the 1st instruction of the program
  - The small left-over portion of the interpreter resumes after the program terminates
  - This small portion reloads the full code of the interpreter from disk back into memory
  - The full interpreter is resumed

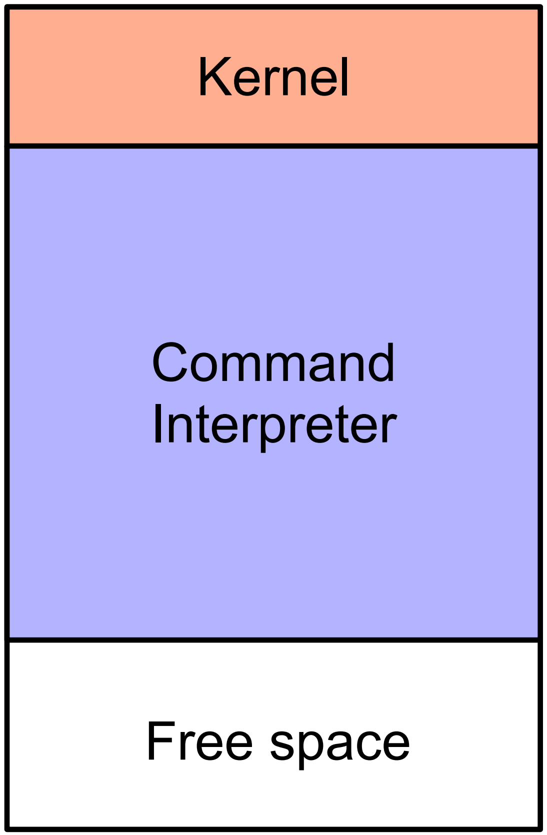
Single-Tasking with MS-DOS



Idle

Full command interpreter

Single-Tasking with MS-DOS



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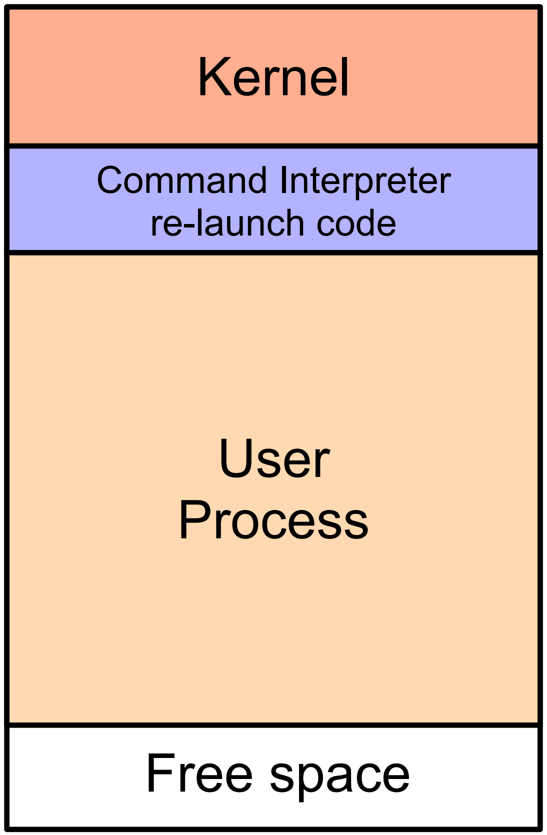
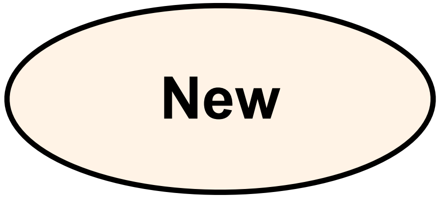


Running a program
Reduced command interpreter

Single-Tasking Process Lifecycle

- The process lifecycle was very simple:



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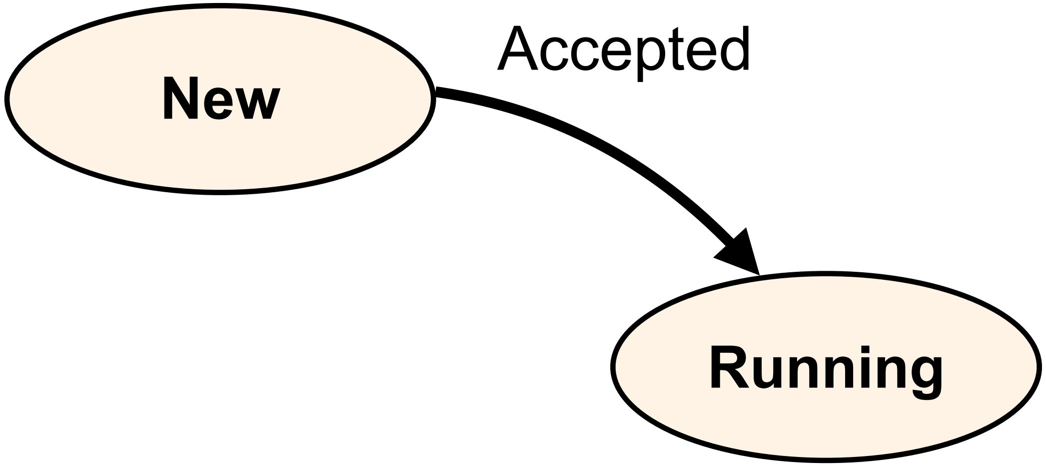

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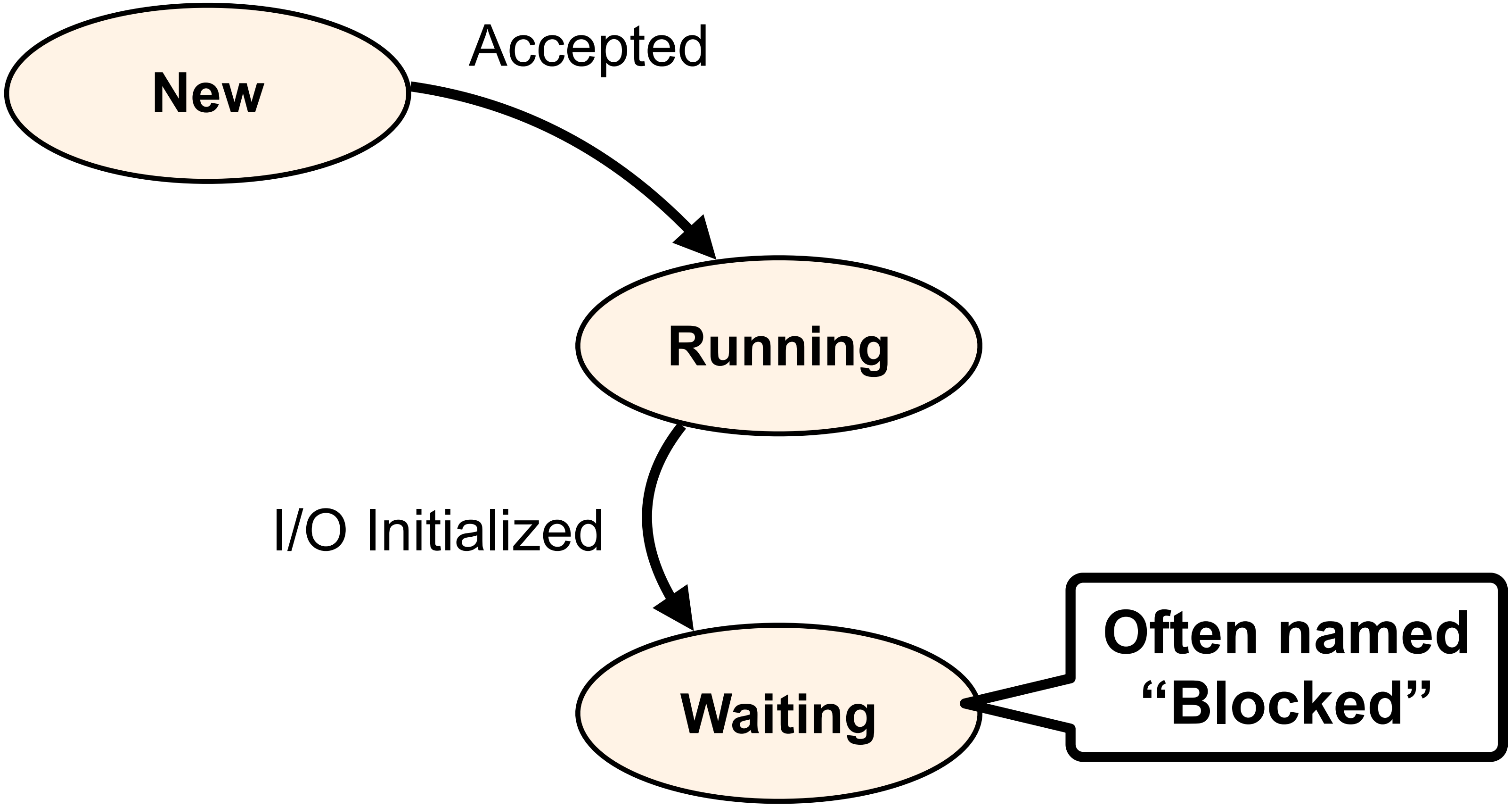

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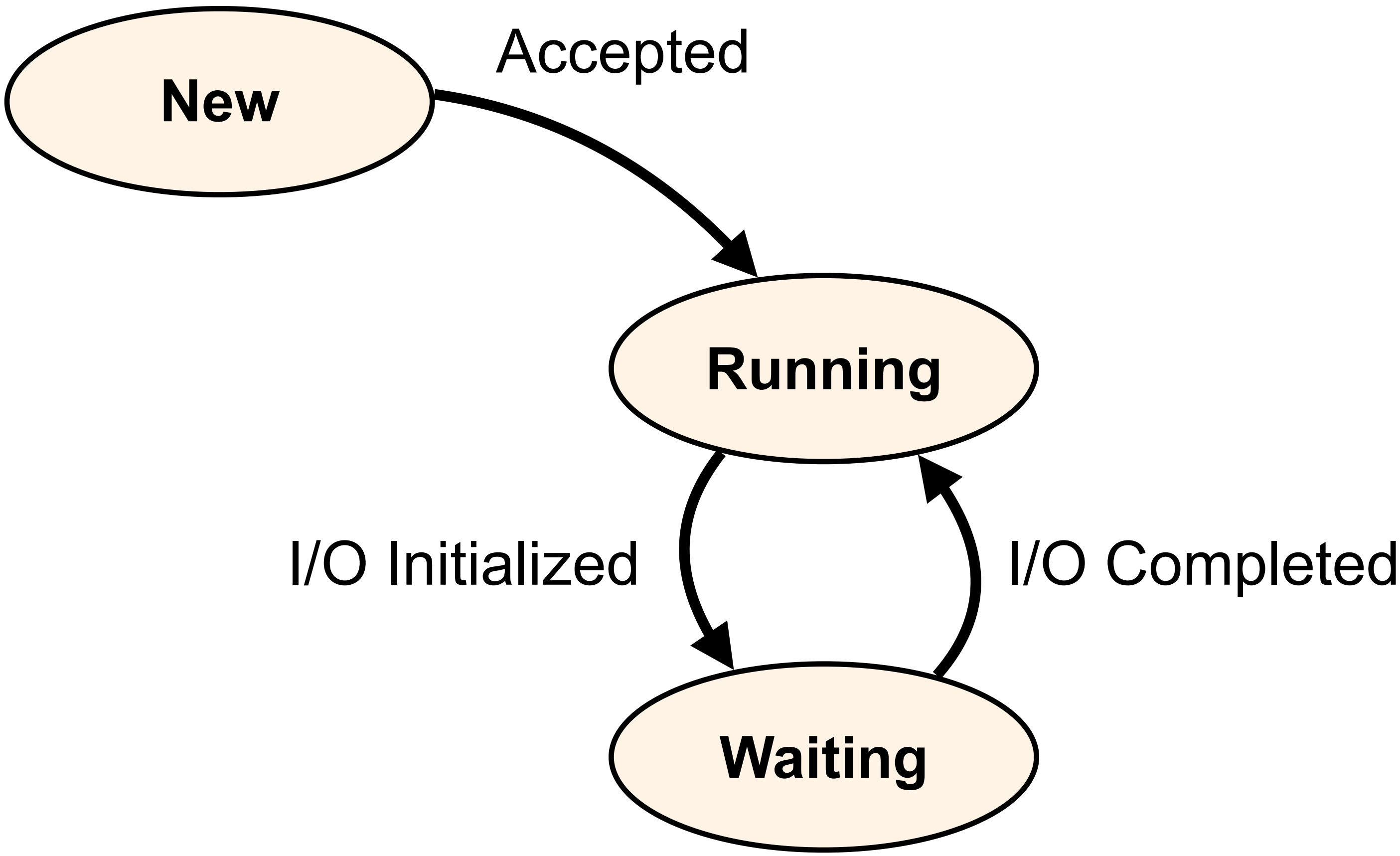

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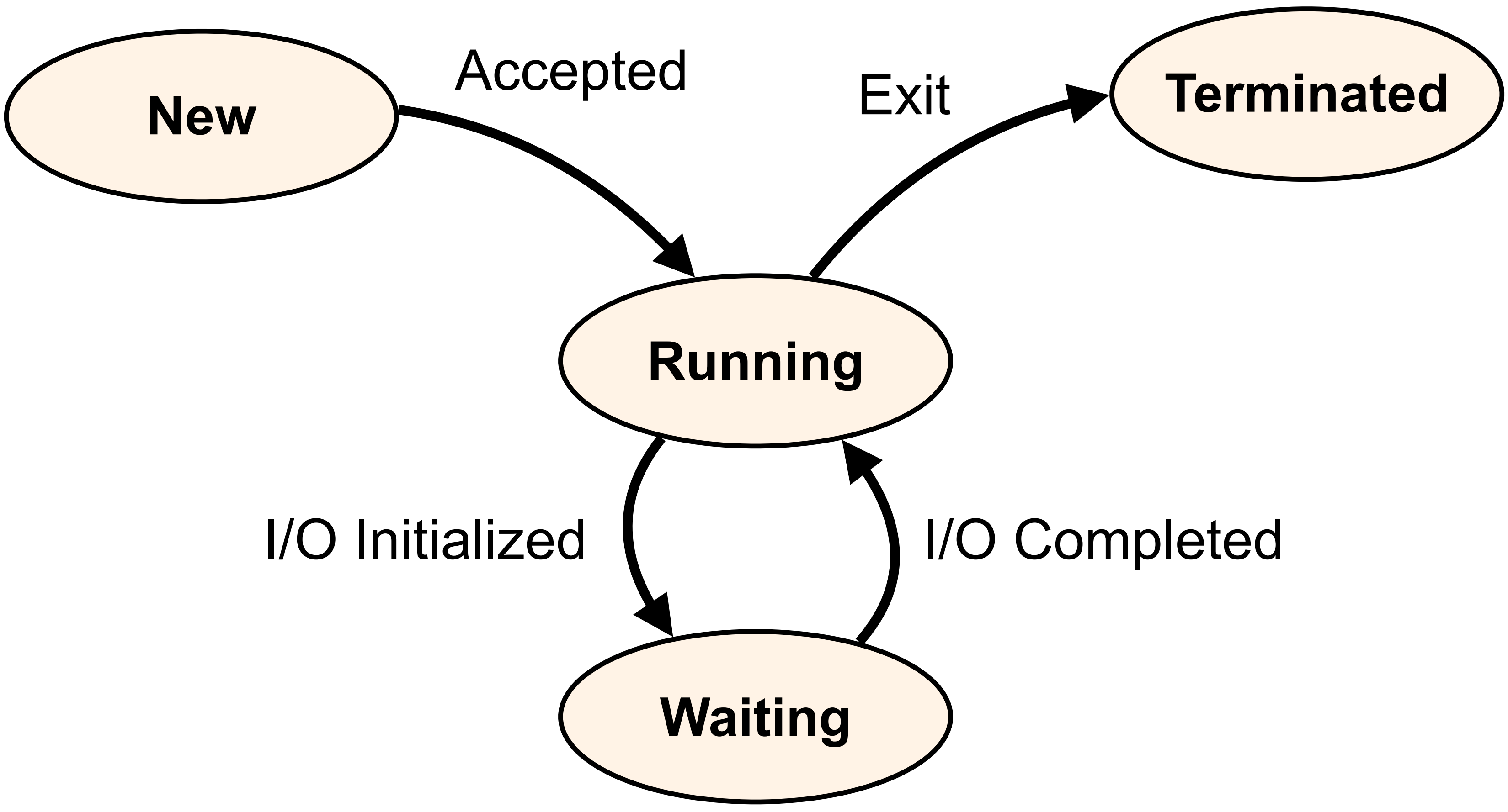

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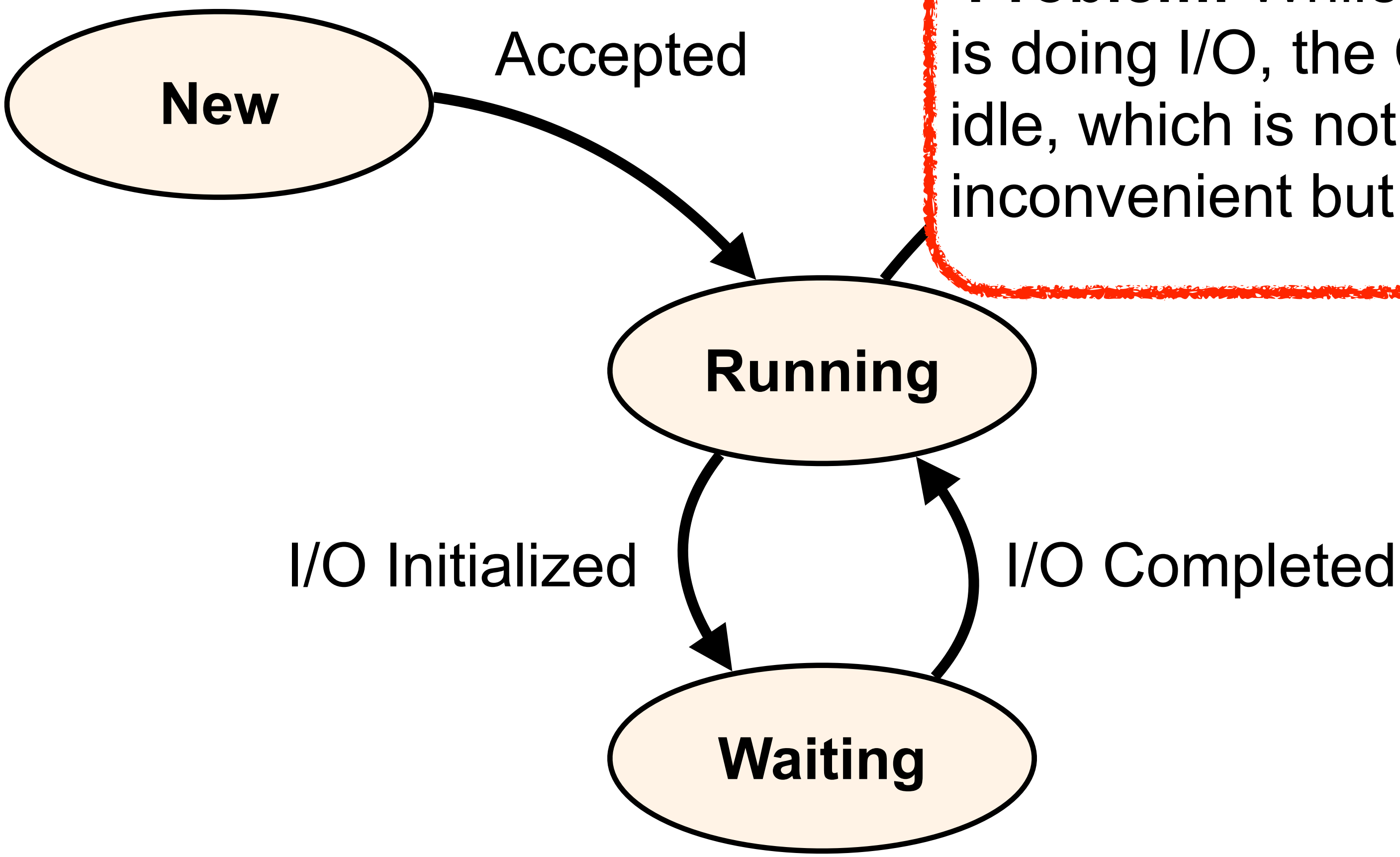
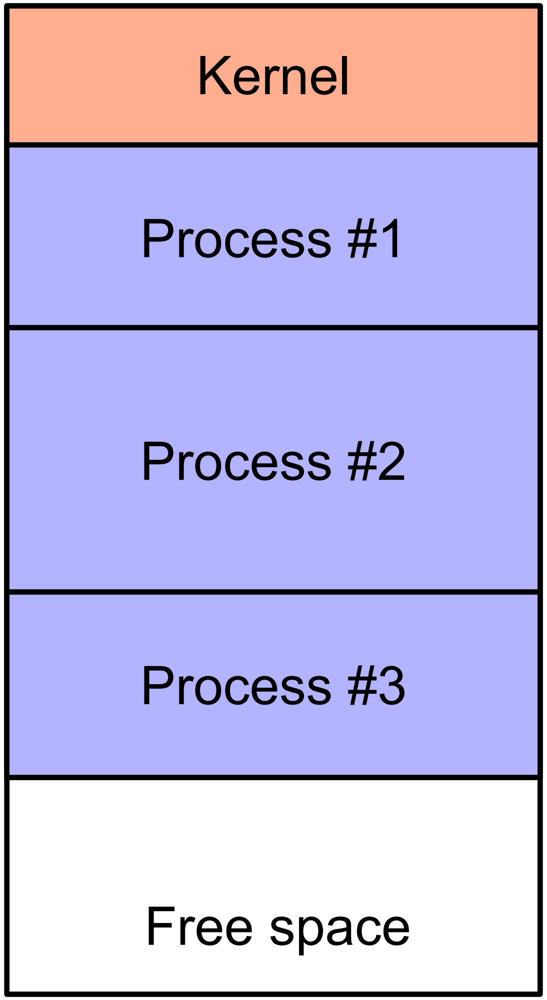


Problem: While a process is doing I/O, the CPU is idle, which is not only inconvenient but a waste

Multi-Tasking (aka Multiprogramming)

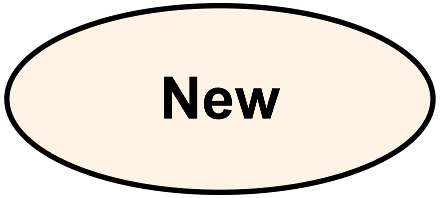


- In modern OSes, multiple processes can be in RAM at the same time
  - Each with its own address space
  - While it's running, a process thinks it's alone on the machine (it doesn't see anything outside of its address space)
- There is a system call to create a new process that any process can place (to create a "child" process)
- When a process terminates, its RAM space is reclaimed by the OS
- Therefore, a process can be ready to run but not running because another process is currently running on the CPU
- **The lifecycle needs a new state!**

The Ready State

- A process can be ready to run but not currently running: it's in the ready state
- It is the job of the OS to select one of the ready processes whenever the CPU becomes idle
  - This is part of what's called "scheduling"
- This is how the OS virtualizes the CPU, so that each process has the illusion it is the only one using the CPU
- We have a more complicated lifecycle…

Process Lifecycle



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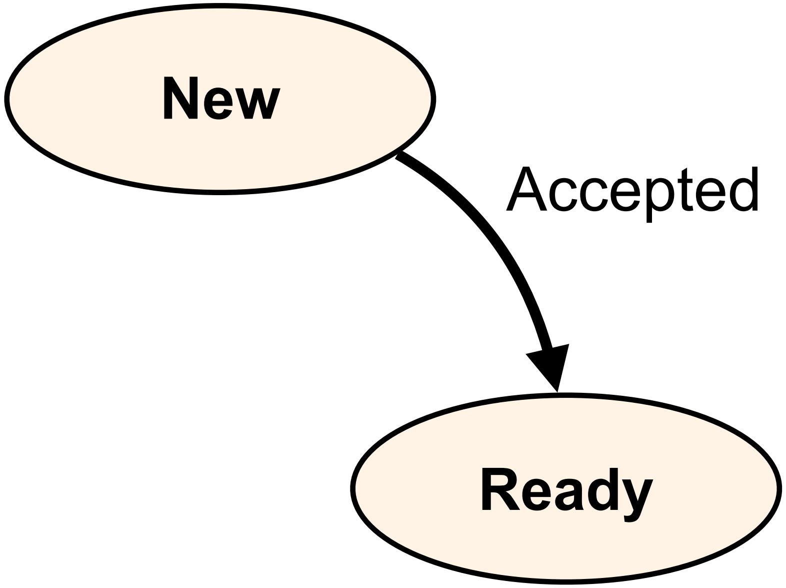

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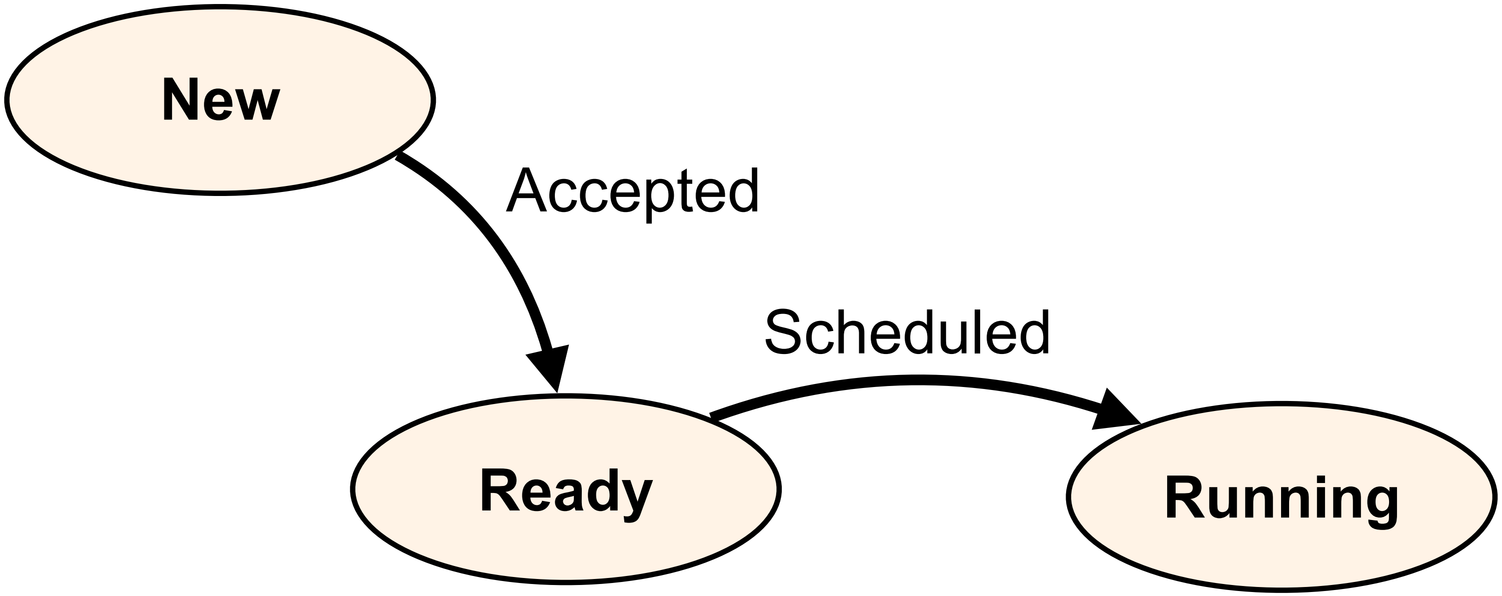

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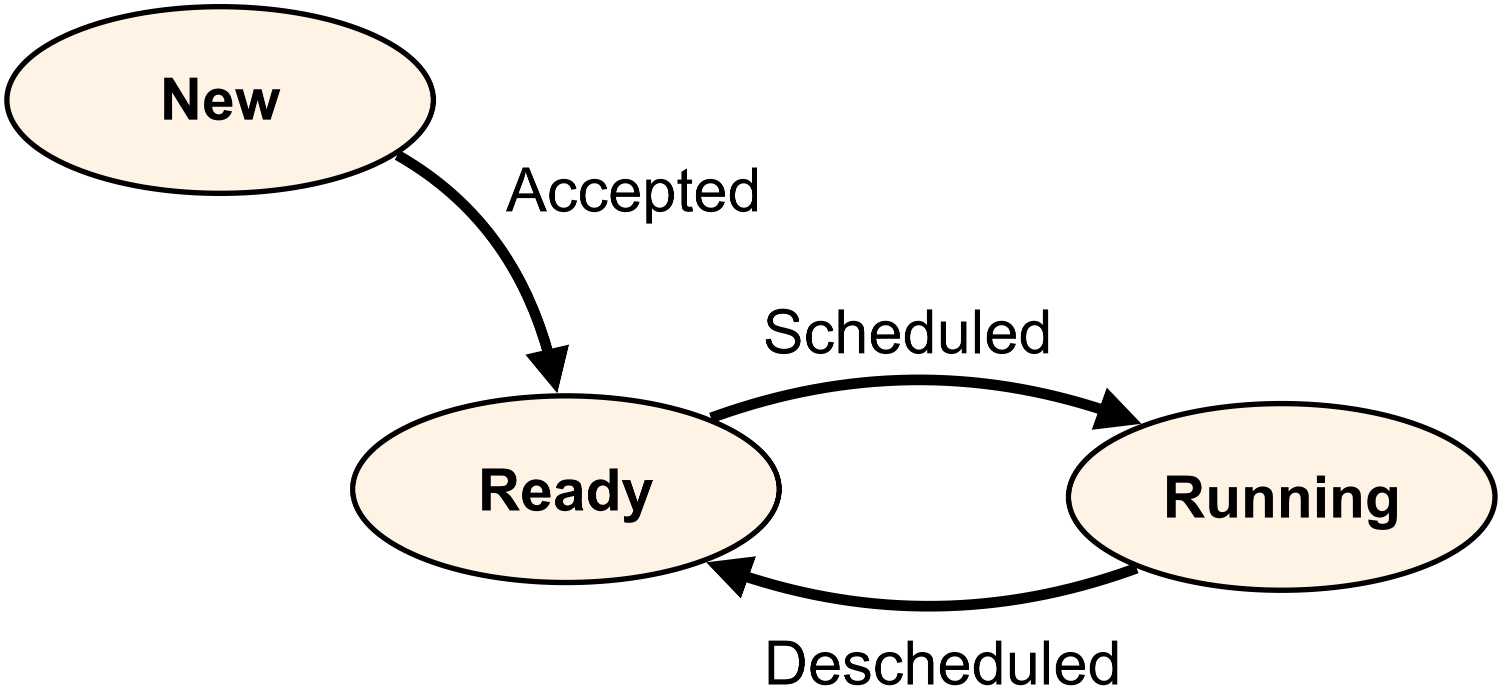

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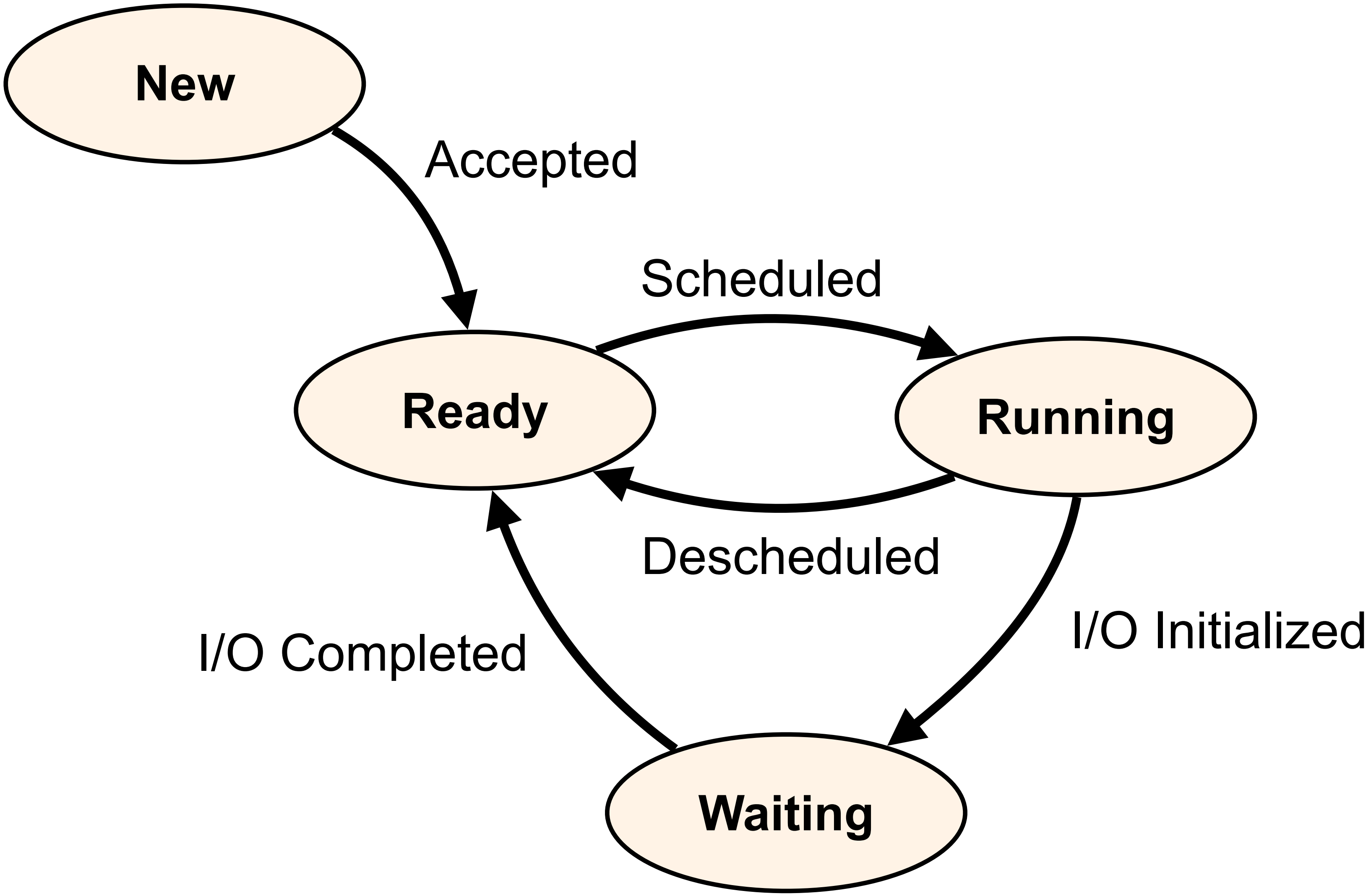

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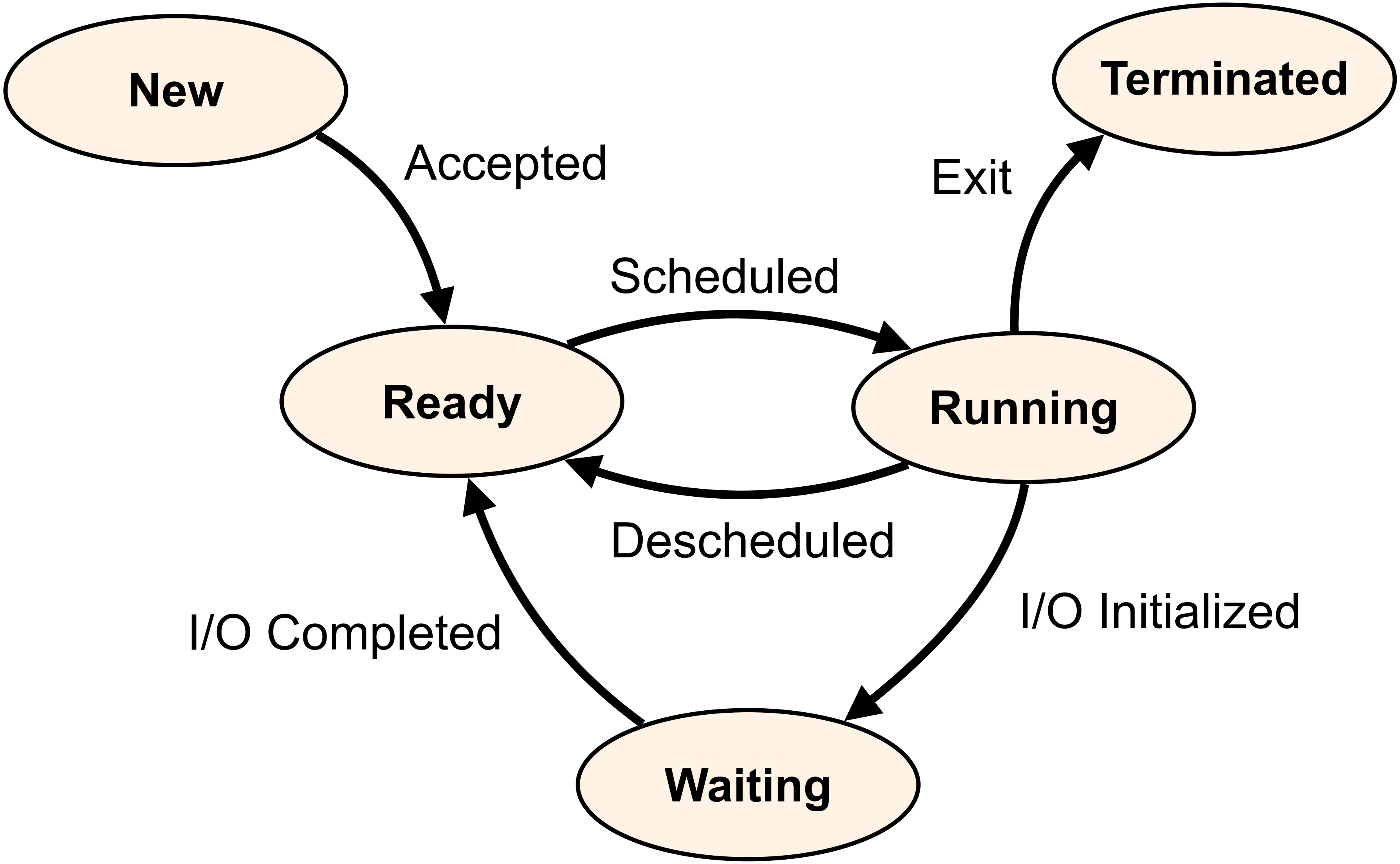

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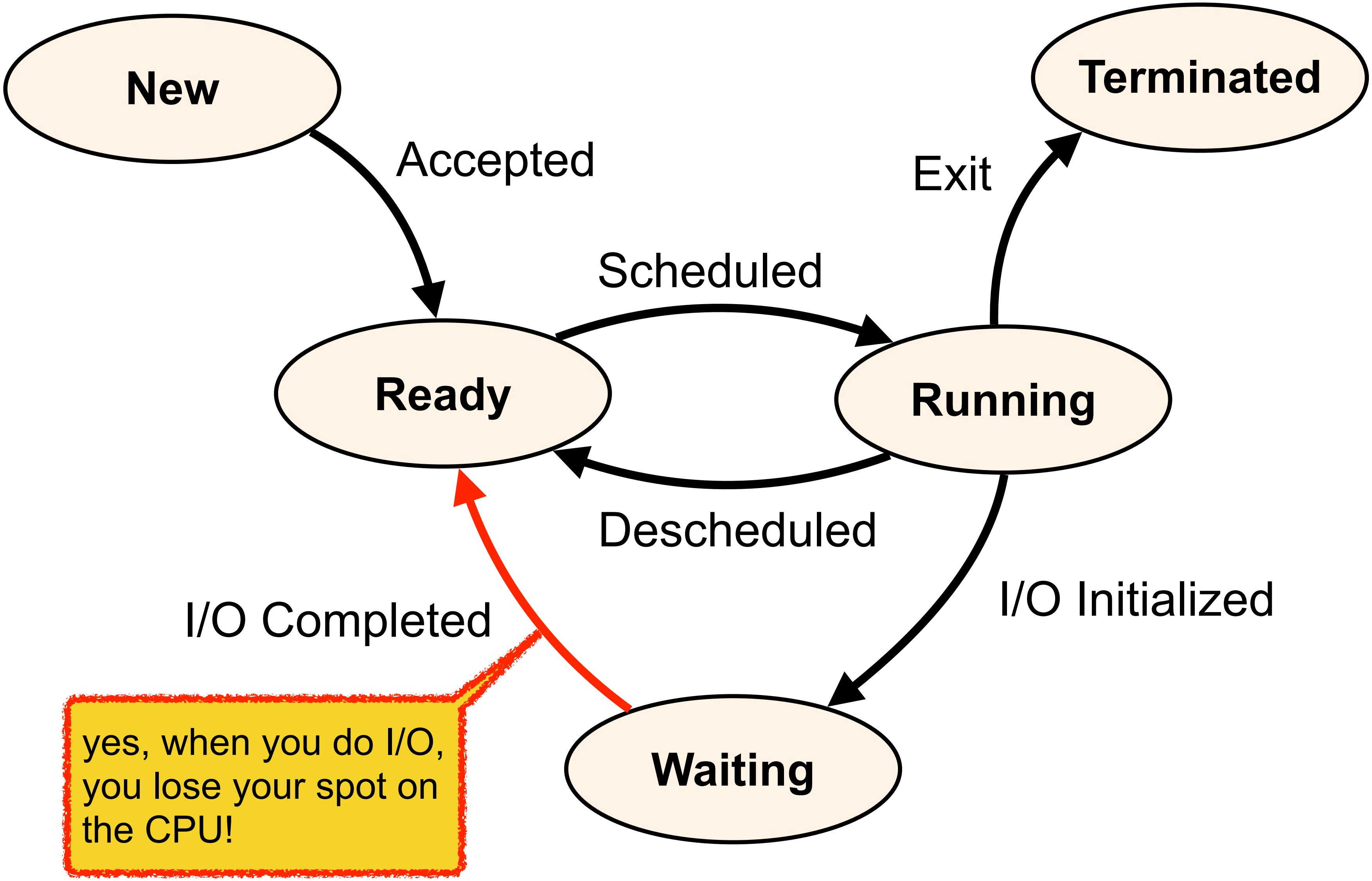
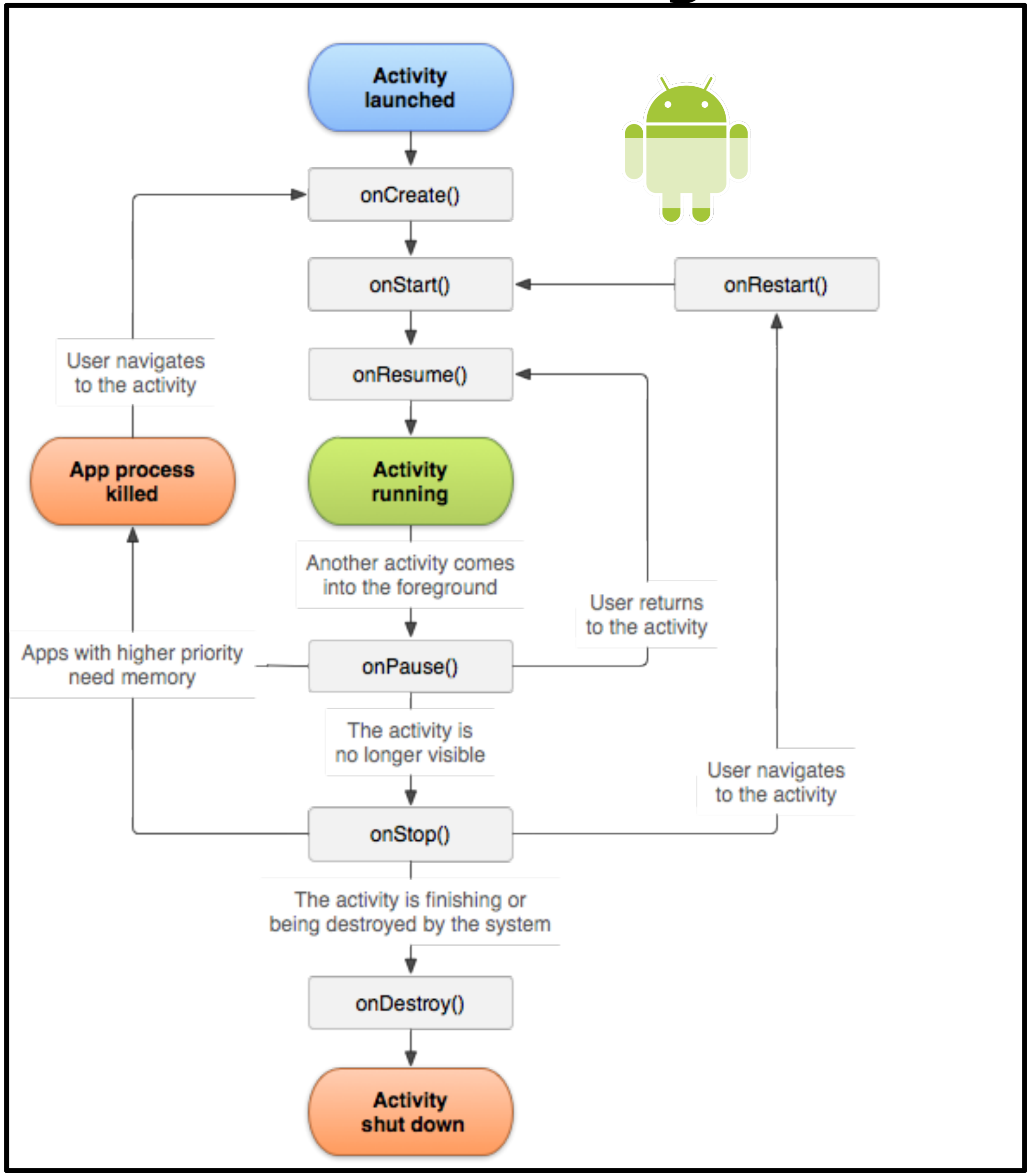


Process Lifecycle

It's important that you have this diagram in mind

The narrative is straightforward: just practice drawing this diagram by telling yourself the story, not by memorizing it!

Other Lifecycles



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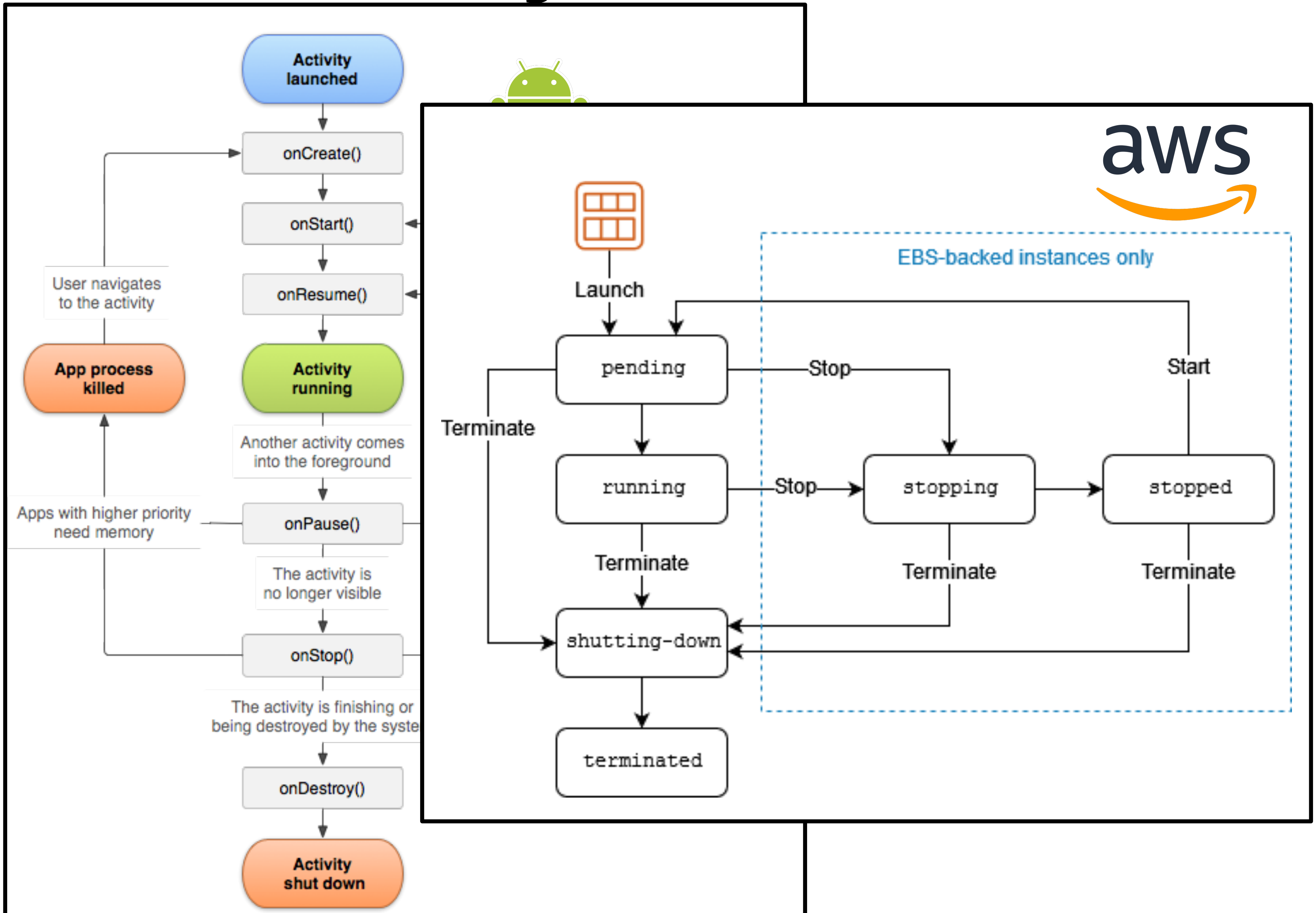

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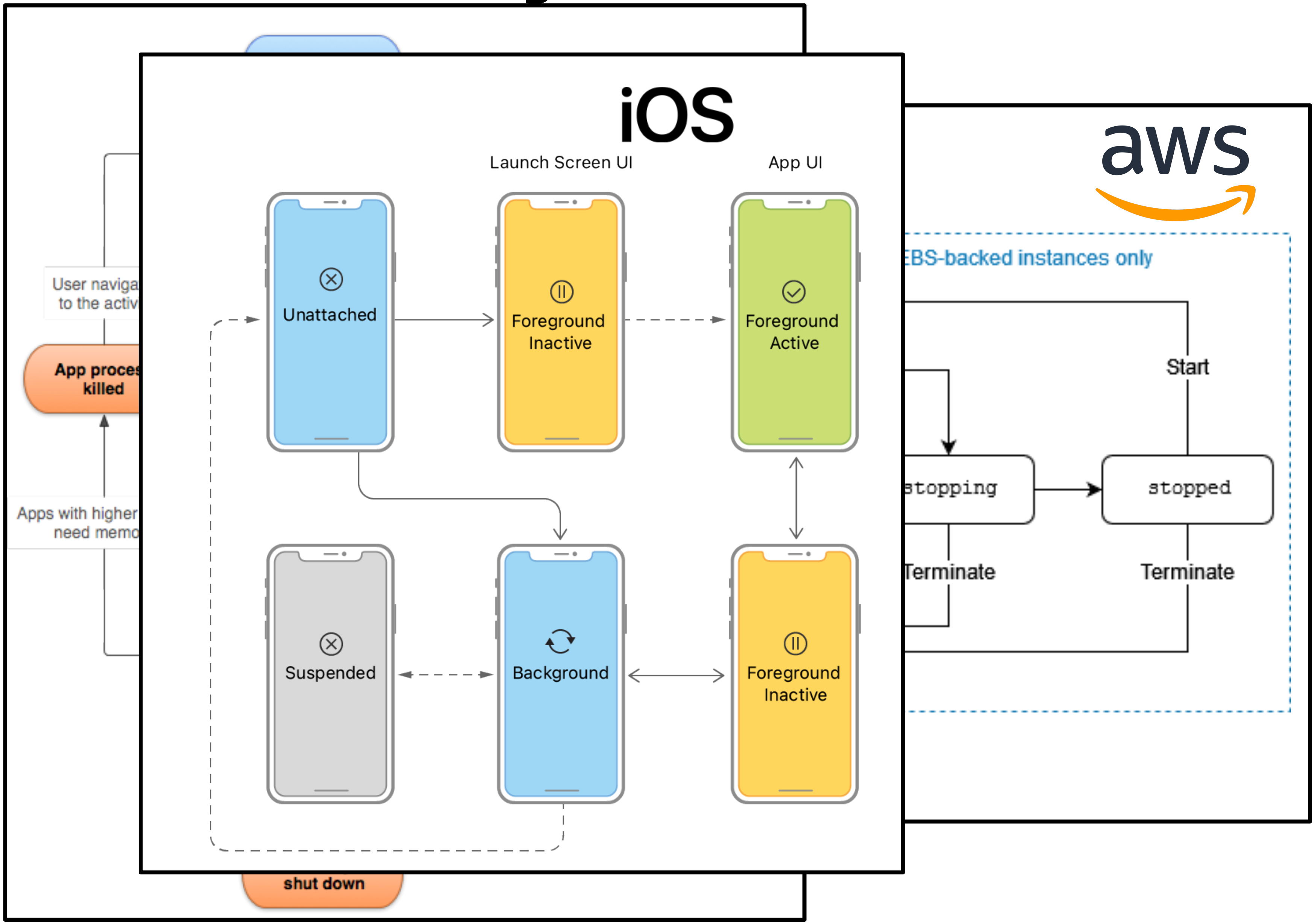

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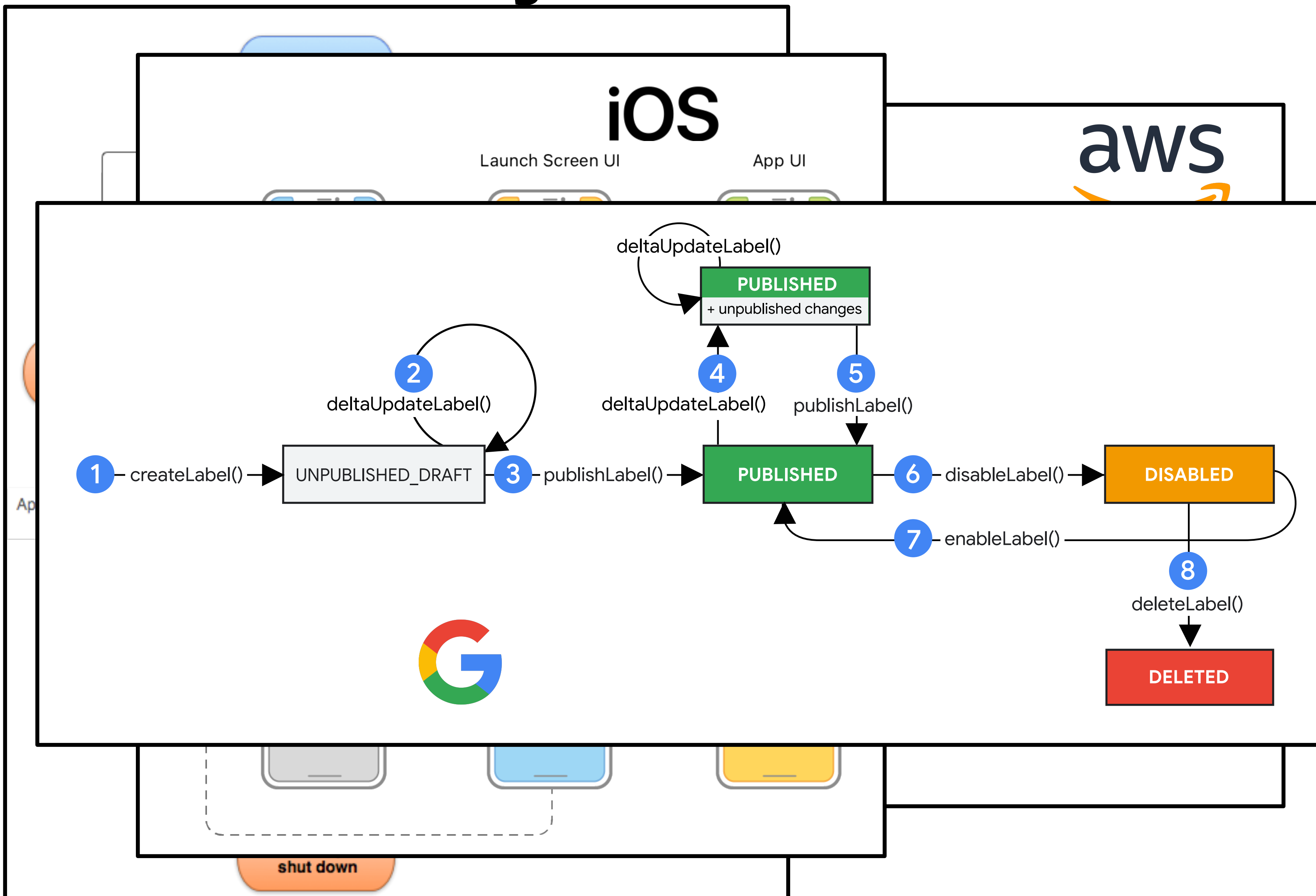

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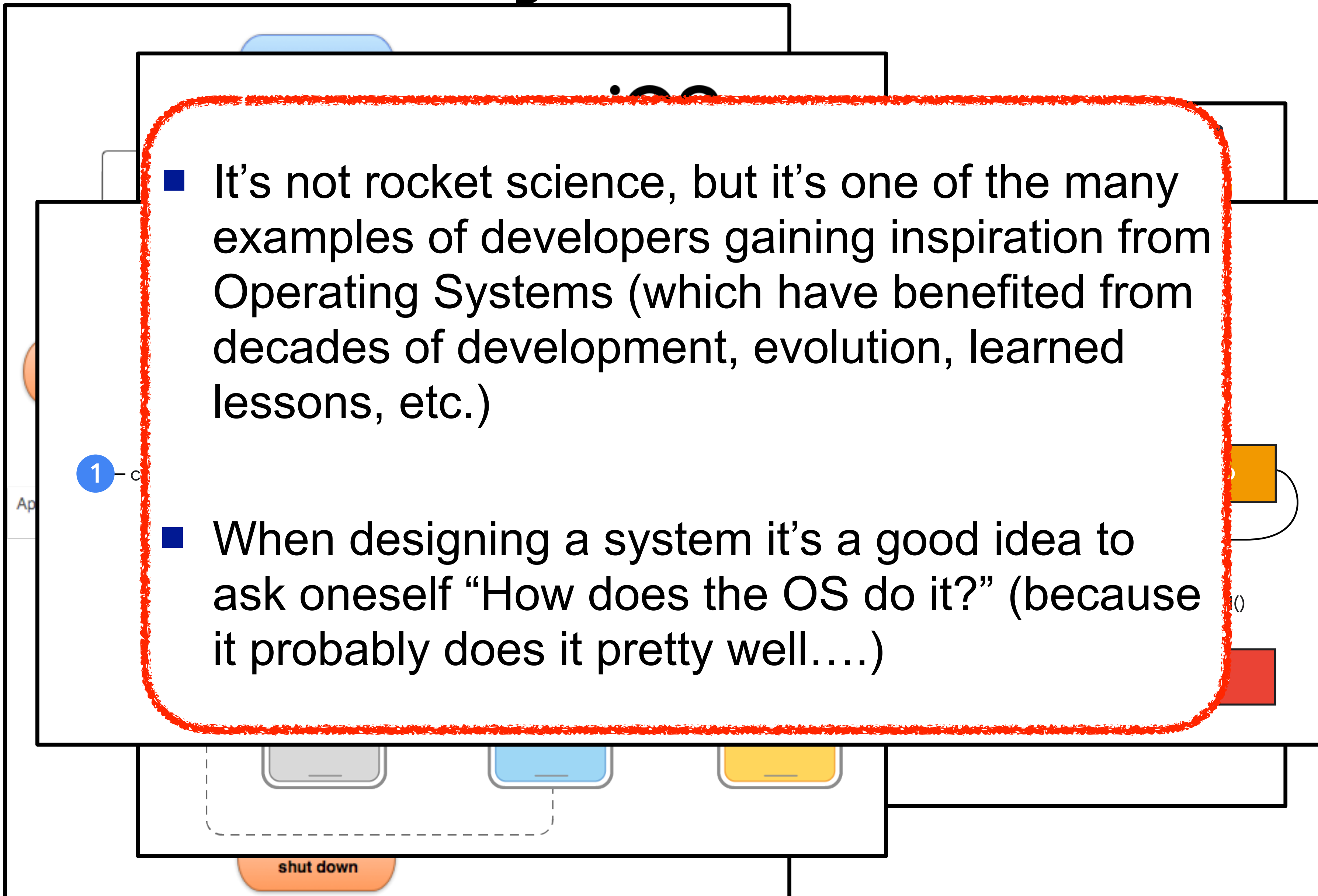

- It’s not rocket science, but it’s one of the many examples of developers gaining inspiration from Operating Systems (which have benefited from decades of development, evolution, learned lessons, etc.)
- When designing a system it’s a good idea to ask oneself “How does the OS do it?” (because it probably does it pretty well….)

Process Control Block

- The OS uses a data structure to keep track of each process
- This structure is called the Process Control Block (PCB) and contains:
  - Process state
  - Process ID (aka PID)
  - User ID
  - Saved Register Values (include PC)
  - CPU-scheduling information (see “Scheduling” Module)
  - Memory-management information (see “Main Memory” and “Virtual Memory” modules)
  - Accounting information (amount of hardware resources used so far)
  - I/O Status Info (e.g., for open files)
  - … and a lot of other useful things
- Let’s look at Figure 4.5 in OSTEP (for the Educational xv6 kernel)
- Let’s look at the **`task_struct`** data structure in **`/usr/src/linux-headers-6.8.0-79/include/linux/sched.h`** (on our Docker image)

The Process Table

- The OS has in memory (in the Kernel space) one PCB per process
  - A new PCB is created each time a new process is created
  - A PCB is destroyed each time a process terminates
- The OS keeps a “list” of PCBs: the Process Table
- Because Kernel size (i.e., its memory footprint) is bounded, so is the Process Table
- Therefore, the Process Table can fill up!
- If you (or your program) keeps creating new processes, at some point, the process creation will fail
  - One of the many ways in which a system can become unusable
  - Because at that point you can’t even start a new Shell, since the Shell is a process!
- Anybody has heard of the “fork bomb” term?
- Let’s find out the max number of possible processes on our Docker container…
  - **`cat /proc/sys/kernel/threads-max`**

Main Takeways

- Processes are running programs
- Multiple processes co-exist in RAM
  - The old single-tasking MSDOS case
- The concept of a process address space
  - Code/text, heap, data, stack
- The Process Control Block
- The Process Table
- The Process lifecycle

- Onward to the Process API....

Conclusion

- We have all necessary concepts for processes here
- But how do programs actually create/manage processes?
- Onward to the Process API....