Operating Systems
Lecture 6

Process life cycle
CPU Scheduling

Announcements

- **HW1 is out**
  - A lot of "cool" problems
  - Goal: deeper understanding of all concepts covered so far
- **Note on academic integrity**
  - I take it VERY seriously
  - If any indication of cheating
    - Both the copy-er, and the copy-ee are responsible
    - I reserve the right to invite you to an oral test

Homework may feel hard: start early!

Context for today's lecture

- **A lot of "algorithms"**
  - Scheduling is an algorithmic problem
  - With some interesting OS bits ...
- **Focus on understanding tradeoffs**
  - No algorithm will be perfect for every scenario
  - If you understand tradeoffs
    - You'll be able to choose the "right" one

I don't expect you to learn these by heart

Recall: Types of Interrupts

Exceptions

- process missteps (e.g. division by zero)
- attempt to perform a privileged instruction
  - sometime on purpose! (breakpoints)
- synchronous/non-maskable

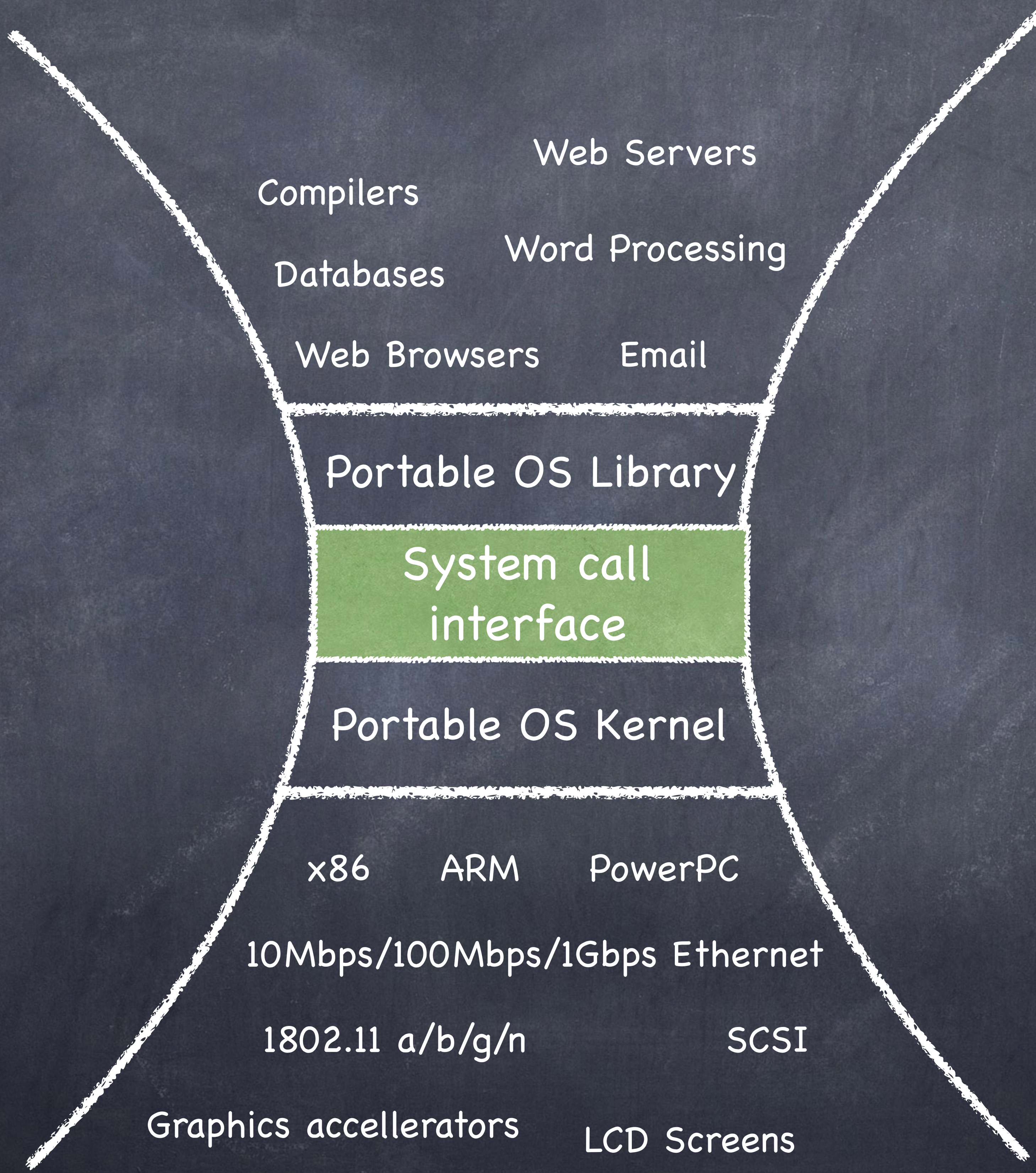
System calls/traps

- user program requests OS service
- synchronous/non-maskable

Interrupts

- HW device requires OS service
  - timer, I/O device, interprocessor
- asynchronous/maskable

Recall: The Narrow Waist



Recall: Executing a System Call

- Process:
  - Calls system call function in library
  - Places arguments in registers and/or pushes them onto user stack
  - Places syscall type in a dedicated register
  - Executes syscall machine instruction
- Kernel
  - Executes syscall interrupt handler
  - Places result in dedicated register
  - Executes RETURN_FROM_INTERRUPT
- Process:
  - Executes RETURN_FROM_FUNCTION

Signals (Virtualized Interrupts)

Signals (Virtualized Interrupts)

Just a taste...

Asynchronous notifications in user space

ID	Name	Default Action	Corresponding Event
2	SIGINT	Terminate	Interrupt (e.g., CTRL-C from keyboard)
9	SIGKILL	Terminate	Kill program (cannot override or ignore)
14	SIGALRM	Terminate	Timer signal
17	SIGCHLD	Ignore	Child stopped or terminated
20	SIGSTP	Stop until SIGCONT	Stop signal from terminal (e.g., CTRL-Z from keyboard)

Receiving a Signal

- Each signal prompts one of these default actions
  - terminate the process
  - ignore the signal
  - terminate the process and dump core
  - stop the process
  - continue process if stopped
- Signal can be caught by executing a user-level function called signal handler
  - similar to exception handler invoked in response to an asynchronous interrupt

Context switch

How to Yield/Wait?

- Must switch from executing the current process to executing some other READY process
  - Current process: RUNNING → READY
  - Next process: READY → RUNNING

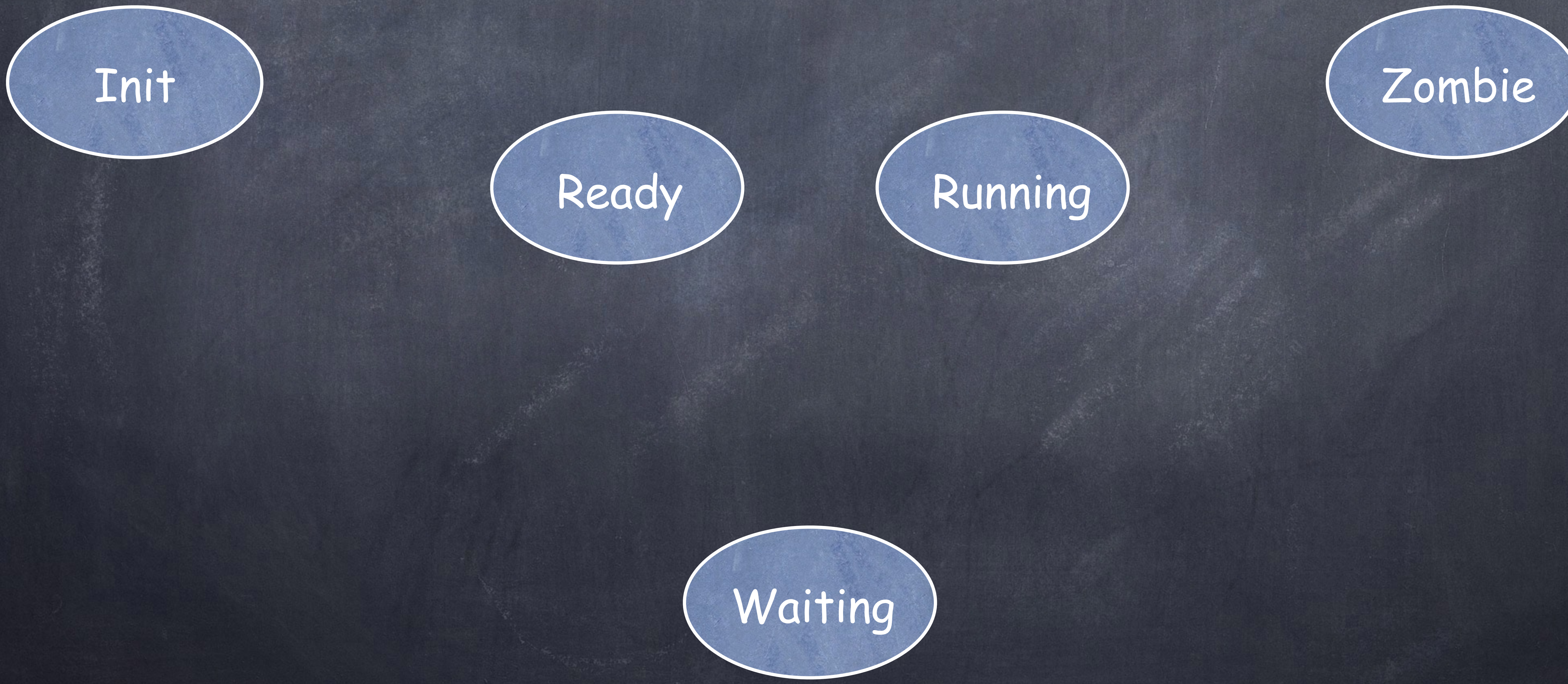
1. Save kernel registers of Current on its interrupt stack
2. Save kernel Stack pointer of Current in its PCB
3. Restore kernel Stack pointer of Next from its PCB
4. Restore kernel registers of Next from its interrupt stack

Three Flavors of Context Switching

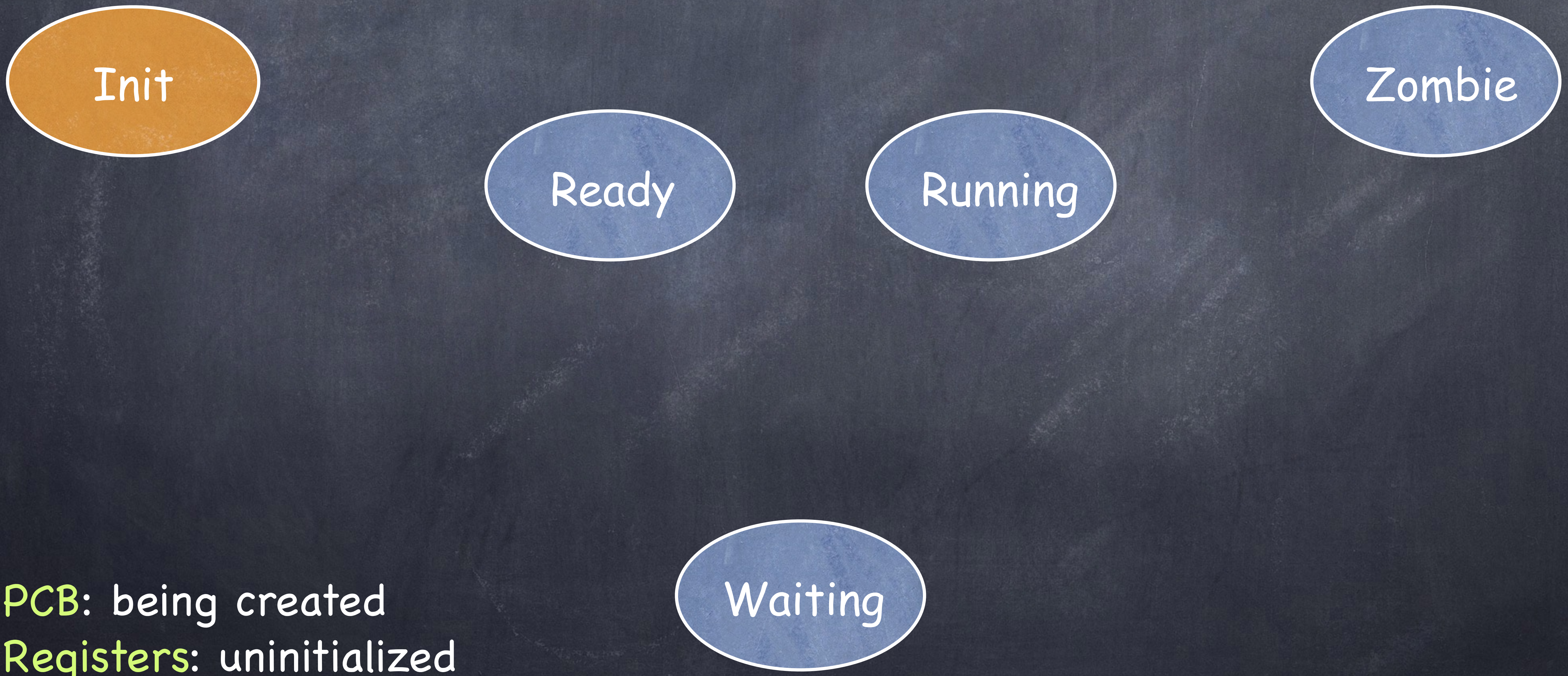
- Interrupt: from user to kernel space
  - on system call, exception, or interrupt
  - Stack switch: P_x user stack $\rightarrow P_x$ interrupt stack
- Yield: between two processes, inside kernel
  - from one PCB/interrupt stack to another
  - Stack switch: P_x interrupt stack $\rightarrow$ P_y interrupt stack
- Return from interrupt: from kernel to user space
  - with the homonymous instruction
  - Stack switch: P_x interrupt stack $\rightarrow P_x$ user stack

We are now ready
to understand
the life cycle of a Process

Process Life Cycle

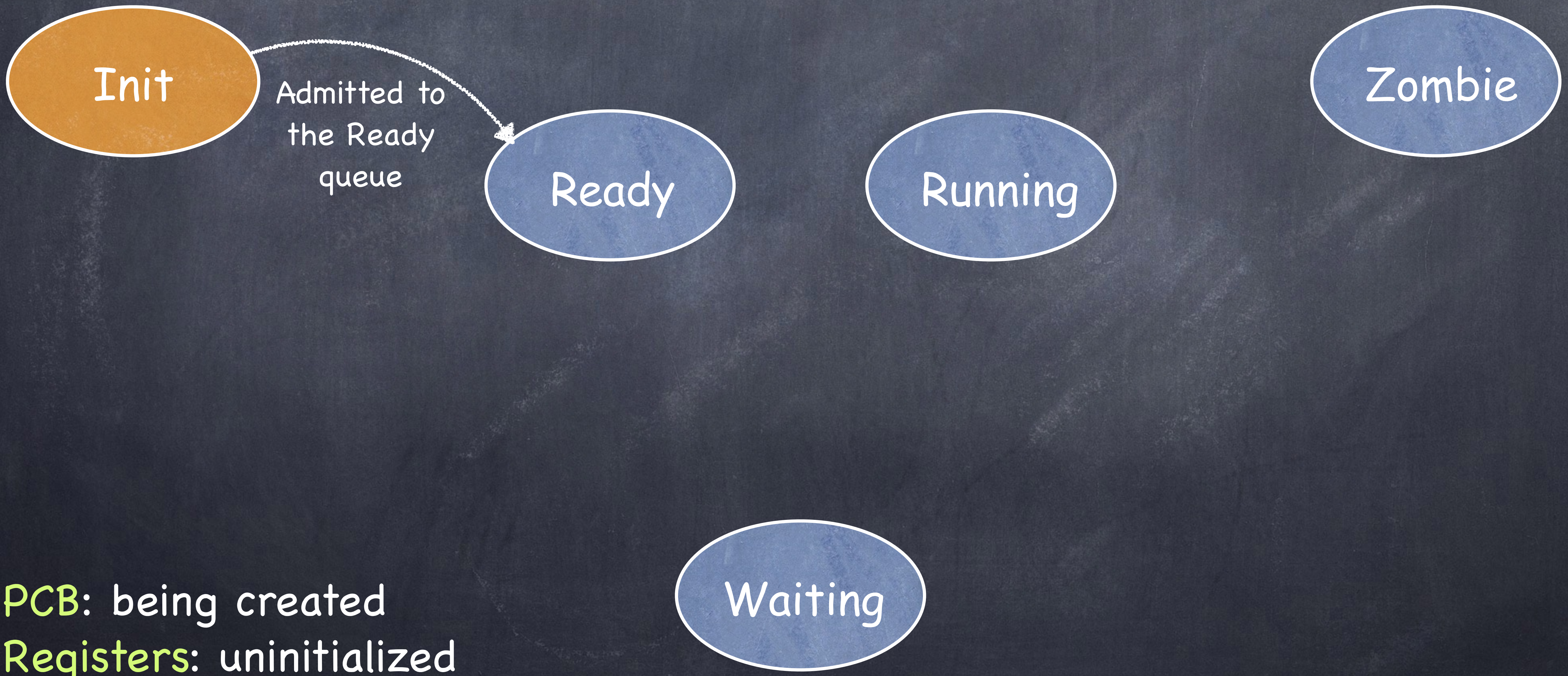


Process Life Cycle



PCB: being created
Registers: uninitialized

Process Life Cycle



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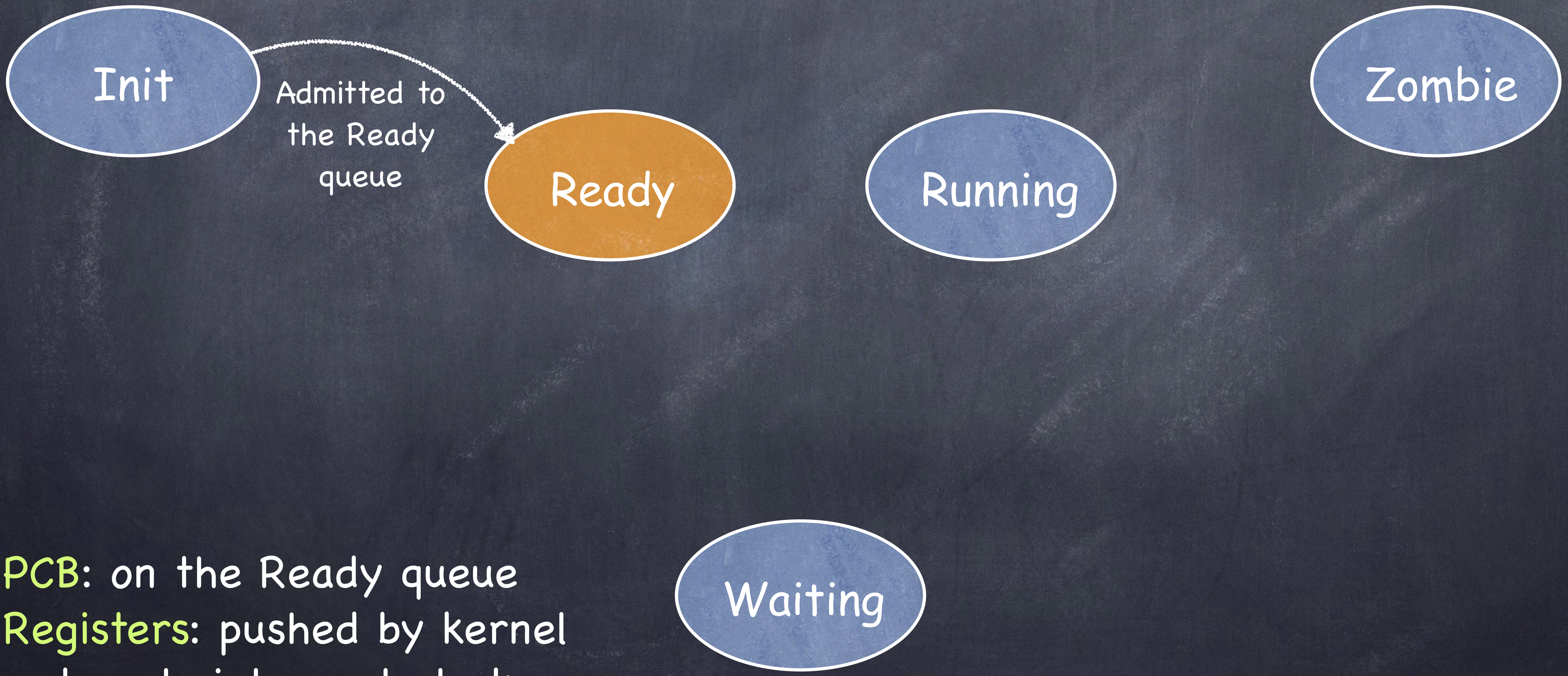
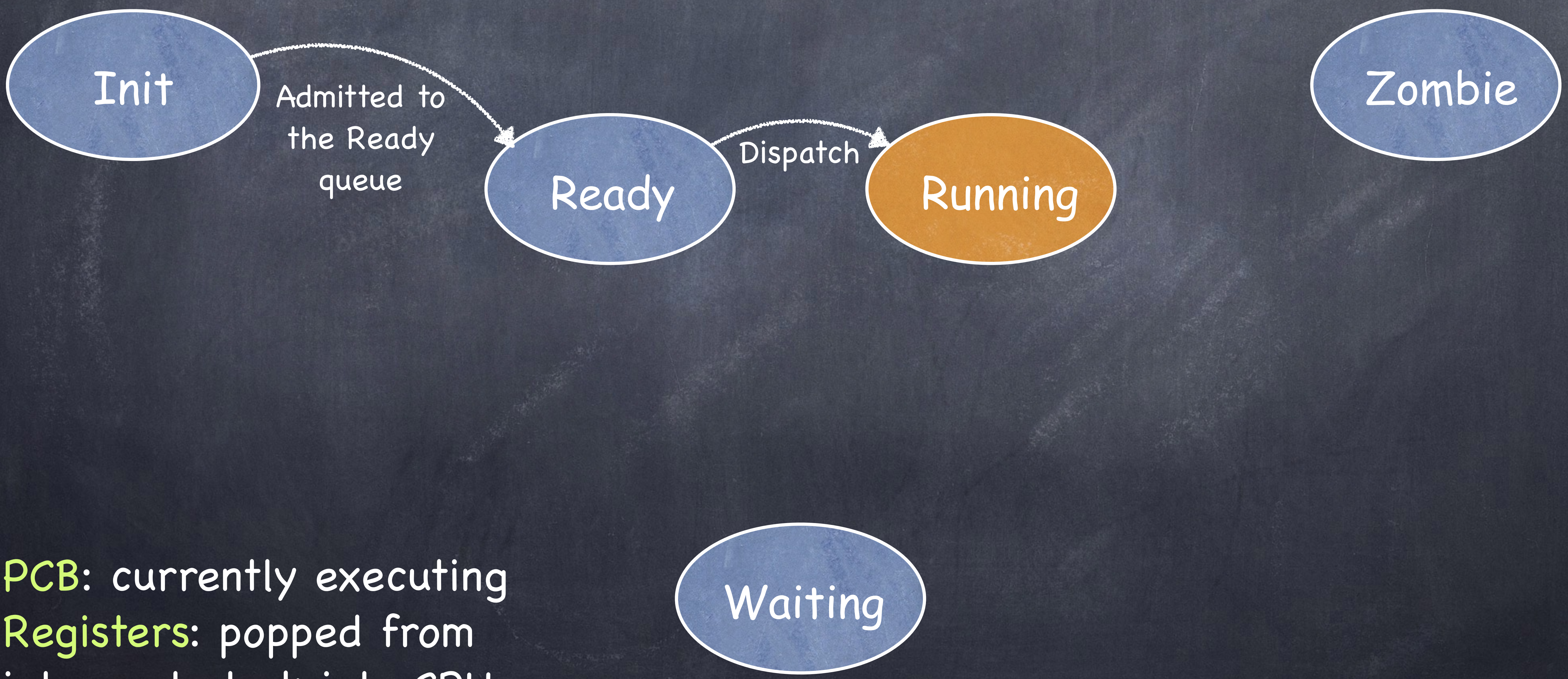
Process Life Cycle



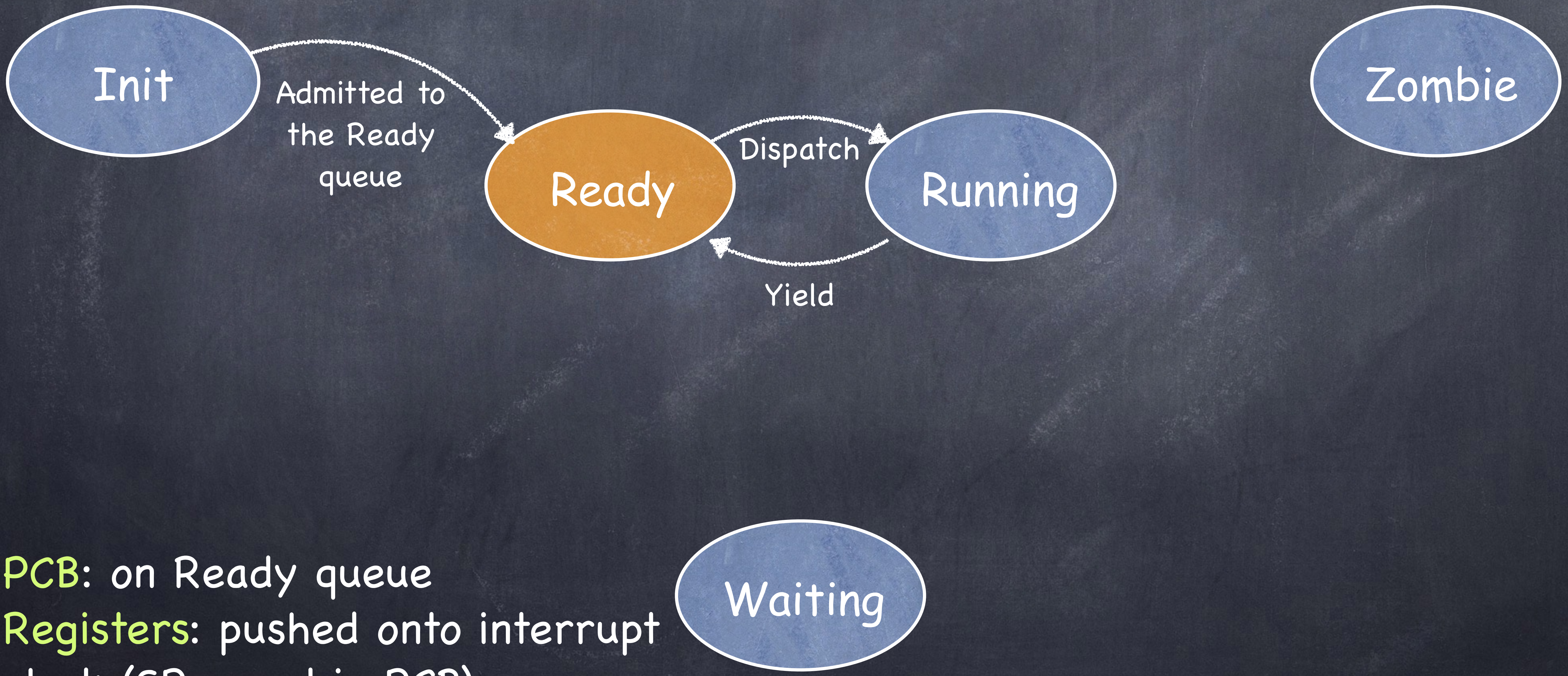
PCB: on the Ready queue
Registers: pushed by kernel code onto interrupt stack

Process Life Cycle



PCB: currently executing
Registers: popped from interrupt stack into CPU

Process Life Cycle

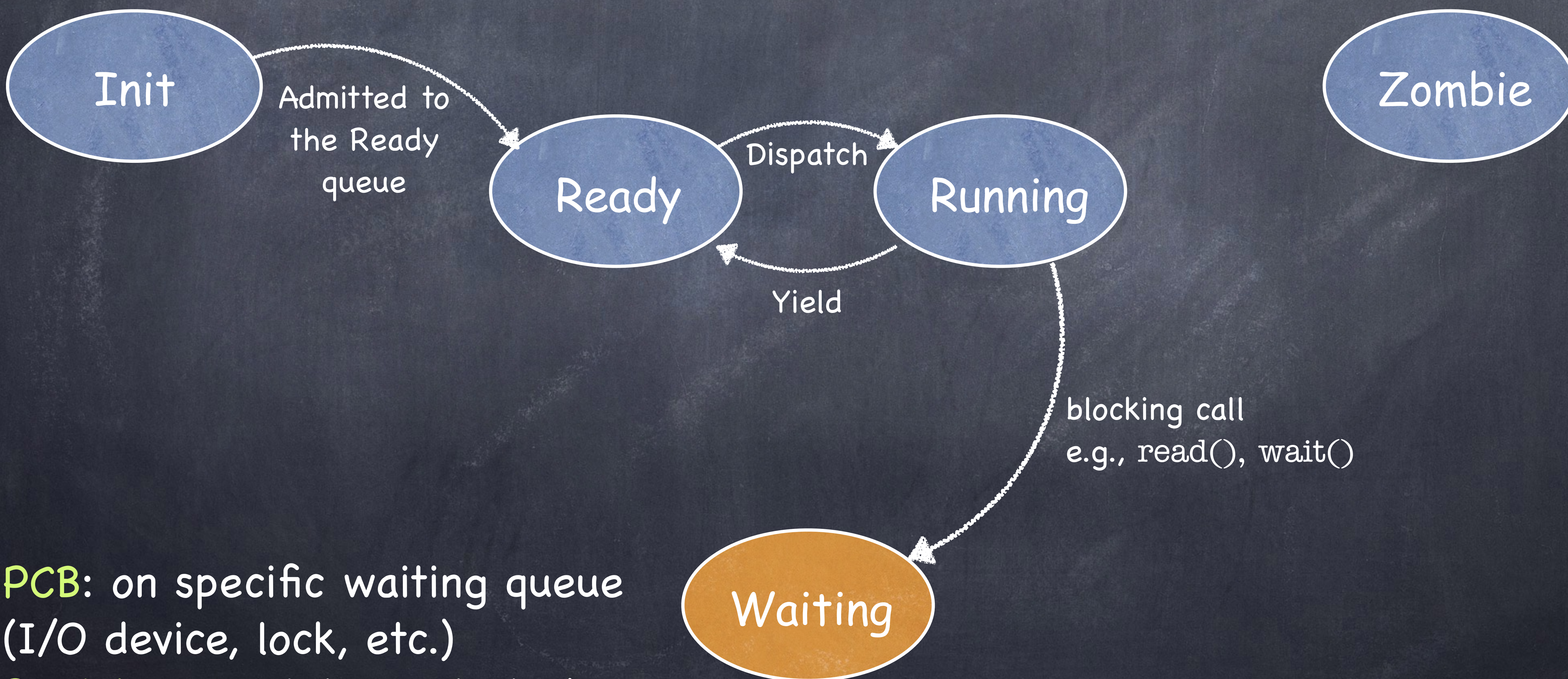


PCB: on Ready queue
Registers: pushed onto interrupt stack (SP saved in PCB)

Process Life Cycle

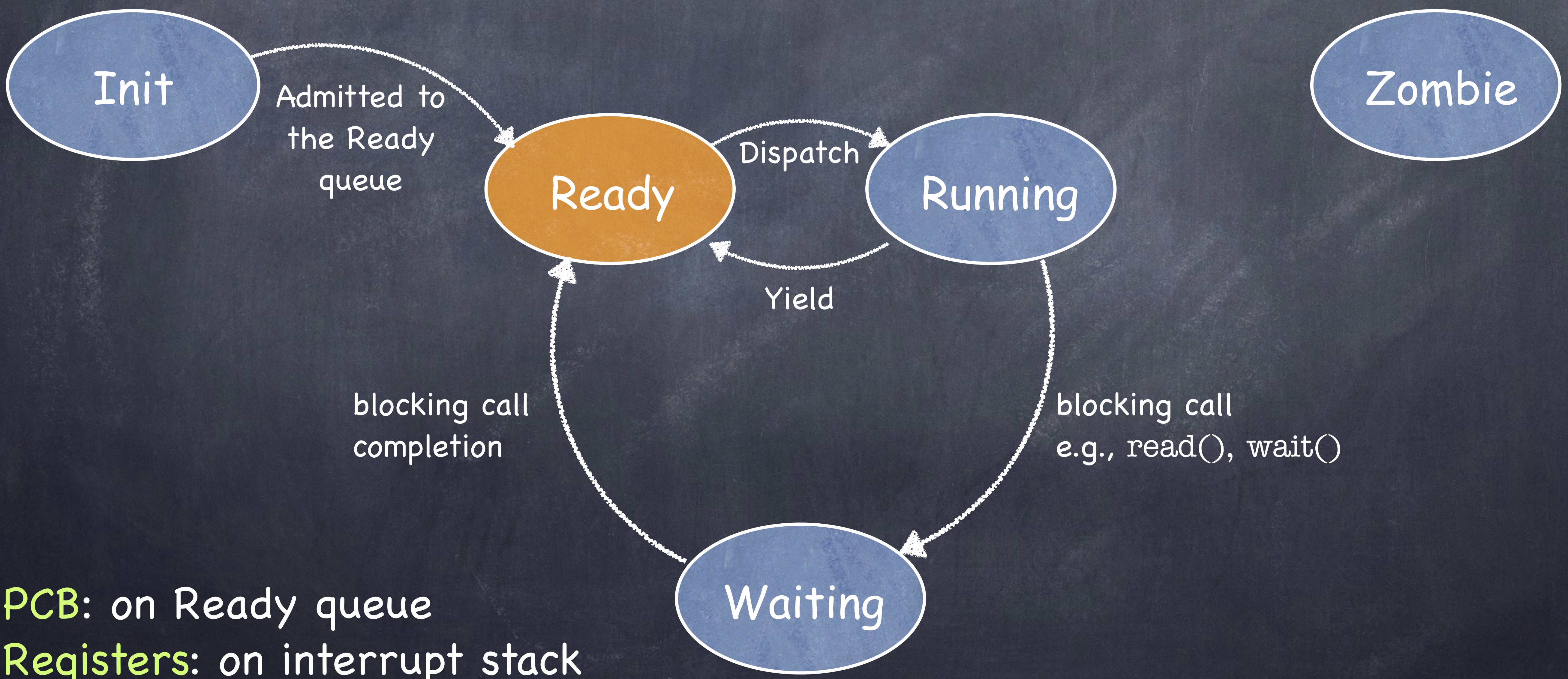
PCB: currently executing
Registers: SP restored from PCB; others restored from stack

Process Life Cycle



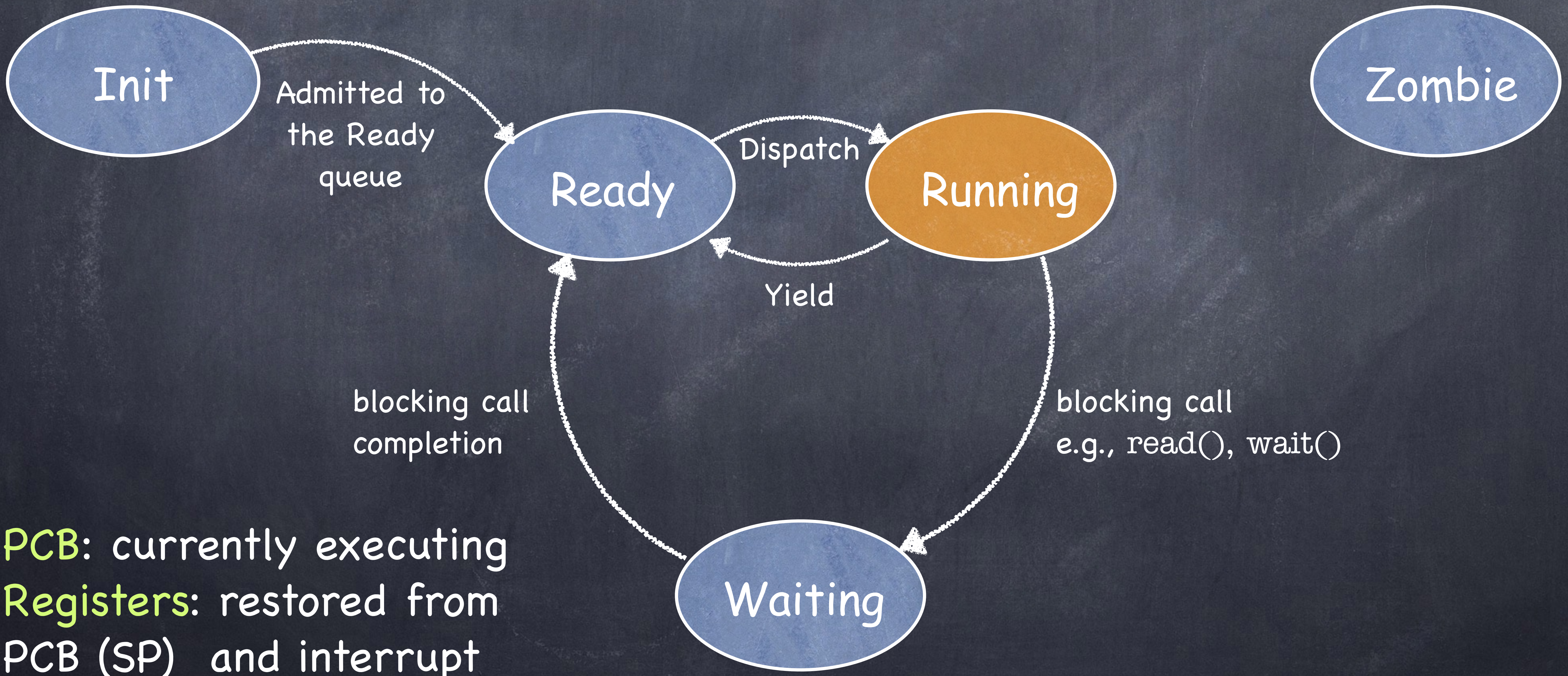
PCB: on specific waiting queue (I/O device, lock, etc.)
Registers: on interrupt stack

Process Life Cycle



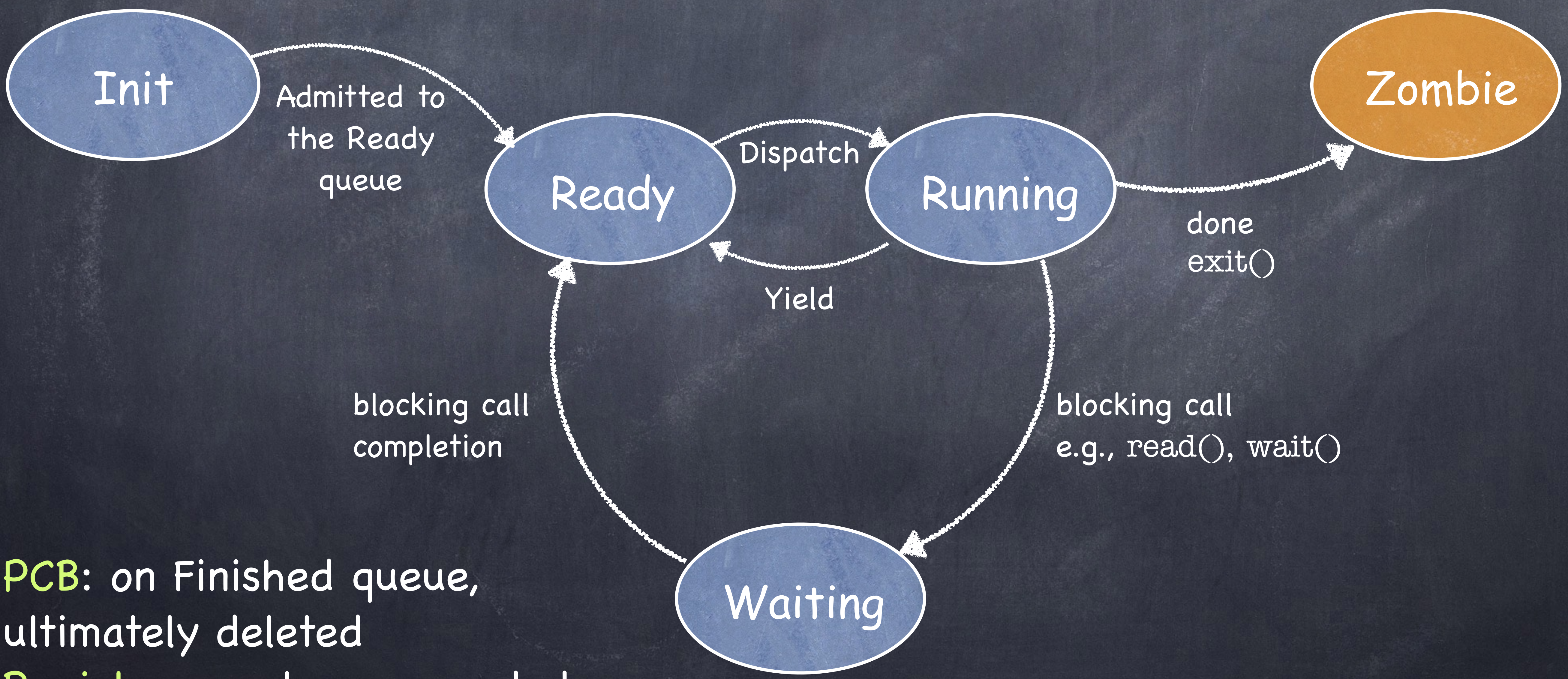
PCB: on Ready queue
Registers: on interrupt stack

Process Life Cycle



PCB: currently executing
Registers: restored from PCB (SP) and interrupt stack into CPU

Process Life Cycle



PCB: on Finished queue, ultimately deleted
Registers: no longer needed

CPU scheduling

Mechanism and Policy

- Mechanism
  - enables a functionality
- Policy
  - determines how that funtionality should be used

Mechanisms should not determine policies!

Kernel Operation (conceptual, simplified)

Initialize devices

Initialize "first process"

while (TRUE) {

- while device interrupts pending
  - handle device interrupts
- while system calls pending
  - handle system calls
- if run queue is non-empty
  - select a runnable process and switch to it
- otherwise
  - wait for device interrupt

}

CPU Scheduling

The Problem

- You are the cook at the State Street Diner
  - Customers enter and place orders 24 hours a day
  - Dishes take varying amounts of time to prepare
- What are your goals?
  - Minimize average turnaround time?
  - Minimize maximum turnaround time?
- Which strategy achieves your goal?

Context matters!

- What if instead you are:
  - Google, serving millions of users?
  - the head nurse managing the waiting room of an emergency room
  - a student who has to do homework in various classes, hang out with other students, eat, and (occasionally) sleep

Schedulers in the OS

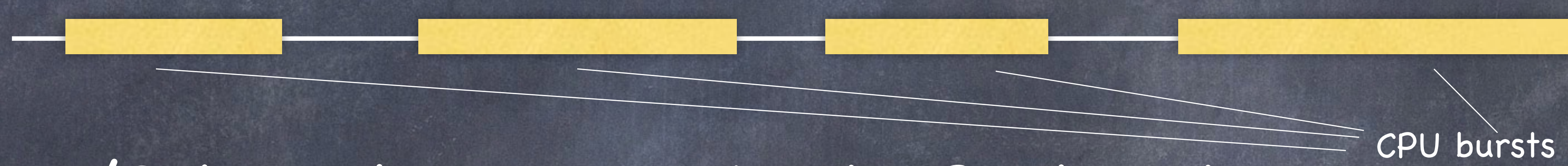
- CPU scheduler selects next process to run from the ready queue
- Disk scheduler selects next read/write operation
- Network scheduler selects next packet to send or process
- Page Replacement scheduler selects page to evict

Scheduling processes

- OS keeps PCBs on different queues
  - Ready processes are on ready queue - OS chooses one to dispatch
  - Processes waiting for I/O are on appropriate device queue
  - Processes waiting on a condition are on an appropriate condition variable queue
- OS regulates PCB migration during life cycle of corresponding process

Why scheduling is challenging

- Processes are not created equal!
  - CPU-bound process: long CPU bursts
    - mp3 encoding, compilation, scientific applications



  - I/O-bound process: short CPU bursts
    - index a file system, browse small web pages

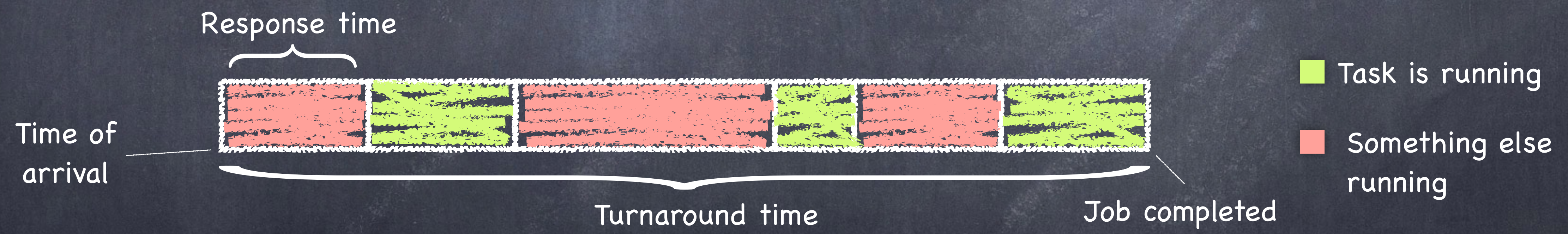
- Problem?
  - don't know process type before running it
  - Process behavior can change over time

Job Characteristics

- Job: A task that needs a period of CPU time
  - A user request: e.g., mouse click, web request, shell command…
- Defined by:
  - Arrival time
    - When the job was first submitted
  - Execution time
    - Time needed to run the task in isolation
  - Deadline
    - By when the task must have completed (e.g. for videos, car brakes…)

Metrics

- Response time
  - How long between job's arrival and first time job runs?
- Total waiting time
  - How much time on ready queue but not running?
    - sum of "red" intervals below
- Execution time: sum of "green" intervals



- Turnaround time: "red" + "green"
  - Time between a job's arrival and its completion
- Throughput: jobs completed/unit of time

Other Concerns

- Fairness: Who get the resources?
  - Equitable division of resources
- Starvation: How bad can it get?
  - Lack of progress by some job
- Overhead: How much useless work?
  - Time wasted switching between jobs
- Predictability: How consistent?
  - Low variance in response time for repeated requests

The Perfect Scheduler

- Minimizes response time and turnaround time for each job
- Maximizes overall throughput
- Maximizes resource utilization ("work conserving")
- Meets all deadlines
- Is fair: everyone makes progress, no one starves
- Has zero overhead

Alas, no such scheduler exists...

When does the Scheduler Run?

- Non-preemptive
  - job runs until it voluntarily yields the CPU
    - process blocks on an event (e.g., I/O or P(sem))
    - process explicitly yields
    - process terminates
- Preemptive
  - all of the above, plus timer and other interrupts
    - when processes can't be trusted
  - incurs some context switching overhead

Context switch overhead

- Cost of saving registers
- Cost of scheduler determining which process to run next
- Cost of restoring register
- Cost of flushing caches
  - L1, L2, L3, TLB

Basic Scheduling Algorithms

- FIFO (First In First Out)
- SJF (Shortest Job First)
- EDF (Earliest Deadline First)
  - preemptive
- Round Robin
  - preemptive
- Shortest Remaining Time First (SRTF)
  - preemptive

FIFO

- Jobs J_1, J_2, J_3 with compute time 12, 3, 3
  - Job arrival J_1, J_2, J_3

Average Turnaround Time: (12+15+18)/3 = 15

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  - Job arrival J_1, J_2, J_3

Average Turnaround Time: (12+15+18)/3 = 15

  - Job arrival J_2, J_3, J_1

Average Turnaround Time: (3+6+18)/3 = 9

Average turnaround time very sensitive to arrival time!

FIFO Roundup

Simple
Low overhead
No starvation

Average turnaround time very sensitive to arrival time

Not responsive to interactive tasks

How to minimize average turnaround time?

SJF: Shortest Job First

- Schedule jobs in order of estimated completion time

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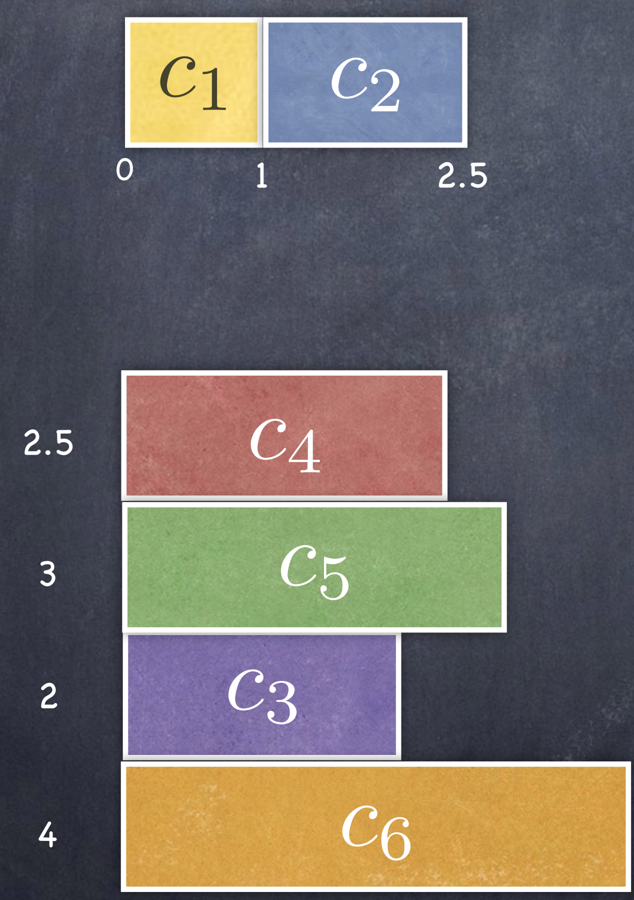
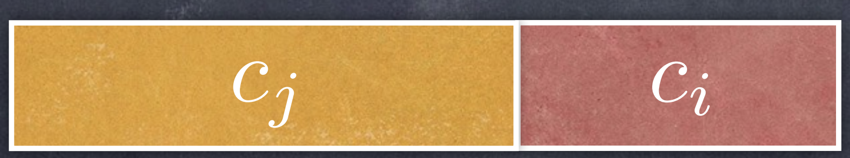


SJF: Shortest Job First

- Schedule jobs in order of estimated completion time

- Average Turnaround time (att): 39/6 = 6.5
- Would a different schedule produce a lower turnaround time?

Consider



where $c_i < c_j$

att = $(c_j + (c_i + c_j))/2$

SJF: Shortest Job First

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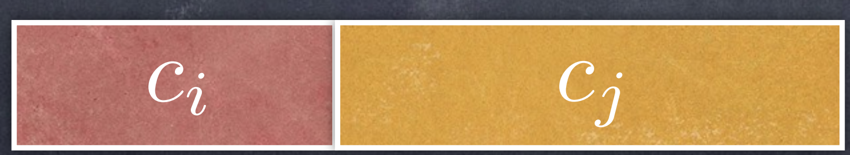
Consider 

where $c_i < c_j$

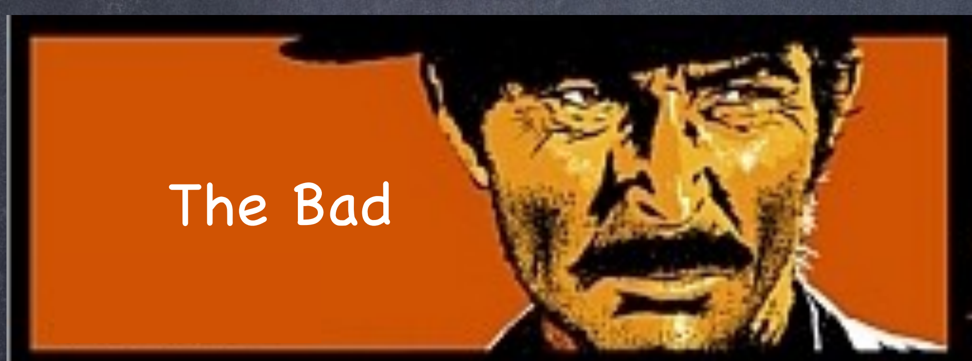
 $<$ 

att = $(c_i + (c_i + c_j))/2$

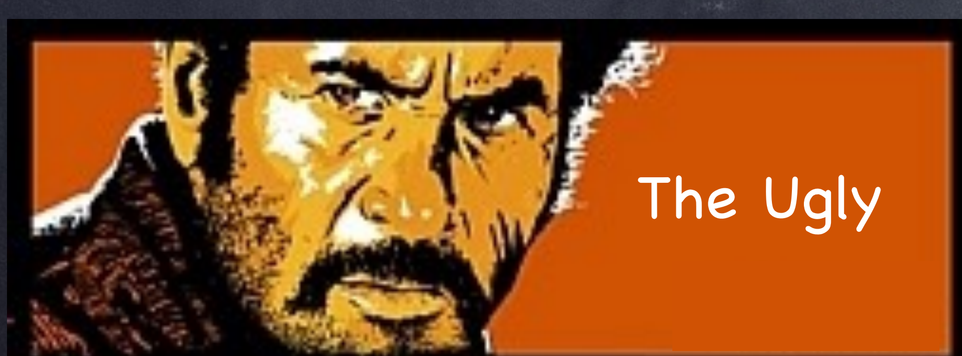
att = $(c_j + (c_i + c_j))/2$

SJF Roundup

Optimal average turnaround time



Need to estimate execution time



Can starve long jobs

Earliest Deadline First (EDF)

- Schedule in order of earliest deadline
- If a schedule exists that meets all deadlines, then EDF will generate that schedule!
  - does not even need to know the execution times of the jobs

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..but only if tasks only need the processor!

EDF Roundup

Meets deadlines if possible (but...)

Free of starvation

Does not optimize other metrics

Cannot decide when to run jobs without deadlines

Round Robin

- Each process is allowed to run for a quantum
- Context is switched (at the latest) at the end of the quantum — preemption!
- Next job to run is the one that hasn't run for the longest amount of time
- What is a good quantum size?
  - Too long, and it morphs into FIFO
  - Too short, and much time lost context switching
  - Typical quantum: about 100X cost of context switch (~100ms vs. << 1ms)

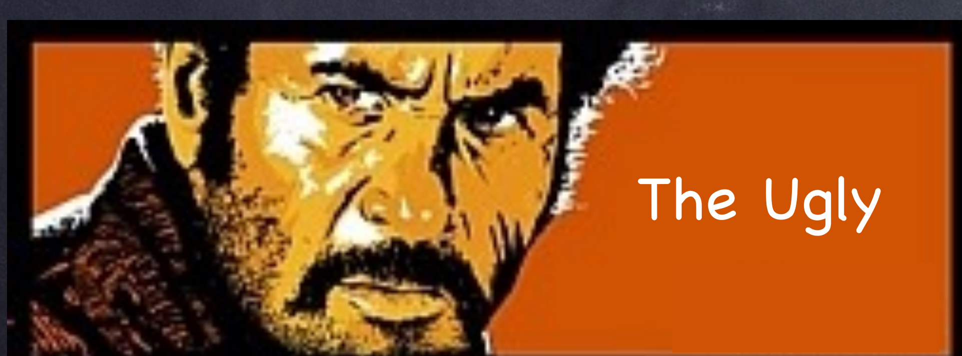
Round Robin Roundup

No starvation

Can reduce response time

Overhead of context switching

Mix of I/O and CPU bound



Particularly bad average turnaround for simultaneous, equal length jobs

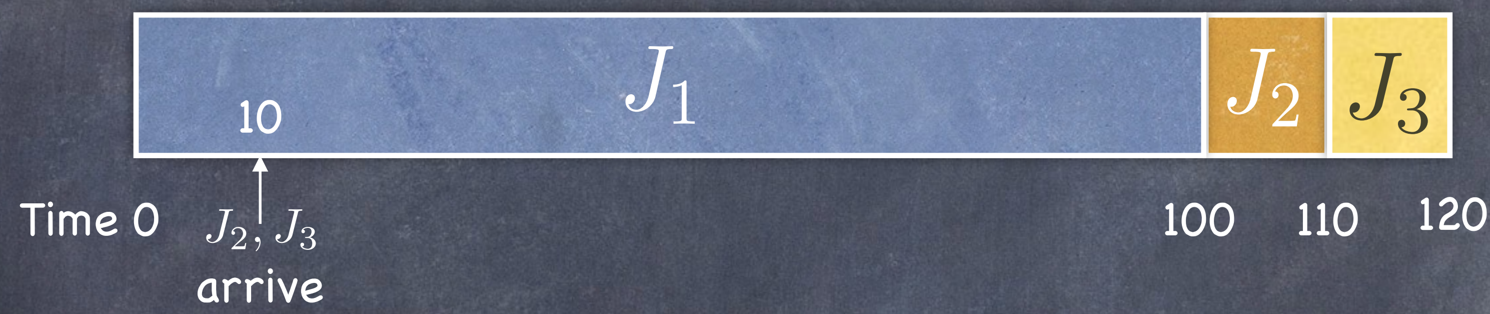
SJF

- J_1 arrives at time 0; J_2, J_3 arrive at time 10

Average Turnaround Time:
100+(110-10)+(120 -10)/3
= 103.33

SJF + Preemption

- J_1 arrives at time 0; J_2, J_3 arrive at time 10



Average Turnaround Time:
100+(110-10)+(120 -10)/3
= 103.33

- With a preemptive scheduler — SRTF

Shortest Remaining Time First

At end of each quantum, scheduler selects job with the least remaining time to run next

- Often same job is selected, avoiding a context switch...
- ...but new short jobs see improved response time

Average Turnaround Time:
(120-0)+(20-10)+(30-10)/3
= 50

SRTF Roundup

Good response time and turnaround time of I/O bound processes

Bad turnaround time and response time for CPU bound processes

Need estimate of execution for each job

Starvation

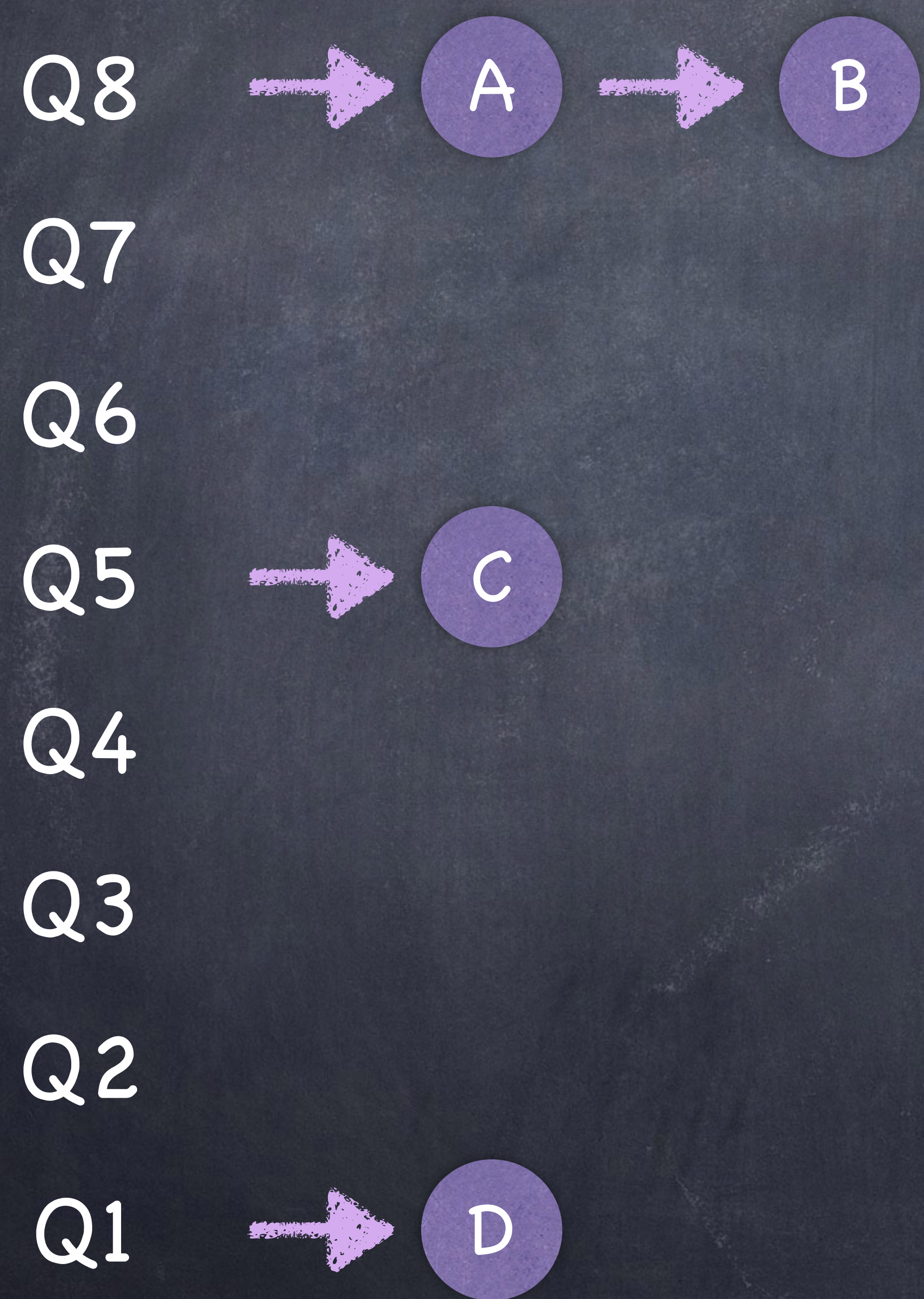
Priority Scheduling

- Assign a number (priority) to each job and schedule jobs in priority order
- Reduces to SRTF when using as priority the estimate of the execution time
- To avoid starvation
  - change job's priority with time (aging)
  - select jobs randomly, weighted by priority

Multi-level Feedback Queue (MFQ)

- Scheduler learns characteristics of the jobs it is managing
  - Uses the past to predict the future
- Favors jobs that used little CPU…
  - …but can adapt when the job changes its pattern of CPU usage

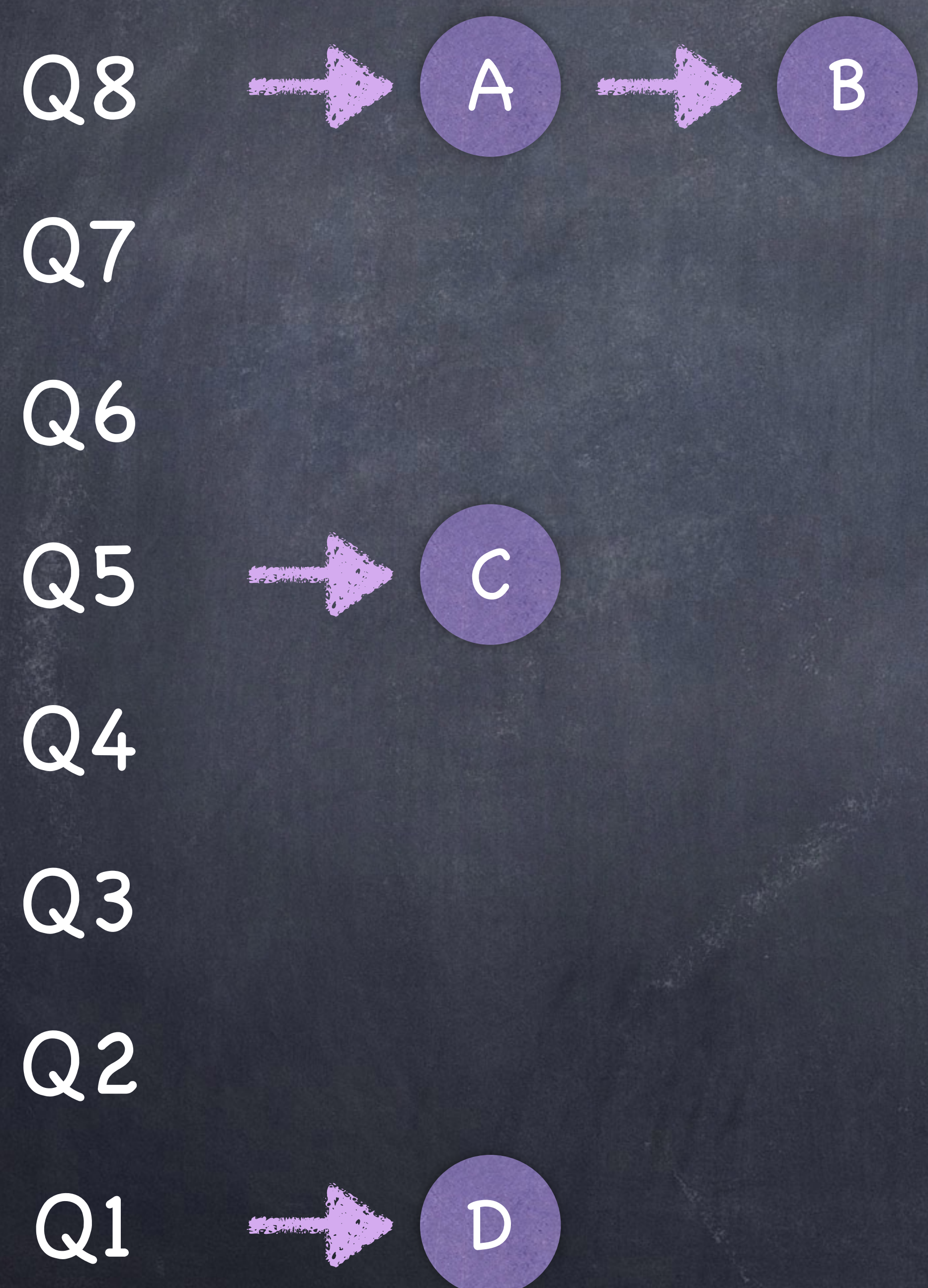
The Basic Structure



- Queues correspond to different priority levels
  - higher is better
- Scheduler runs job in queue i if no other job in higher queues
- Each queue runs RR
- Parameter:
  - how many queues?

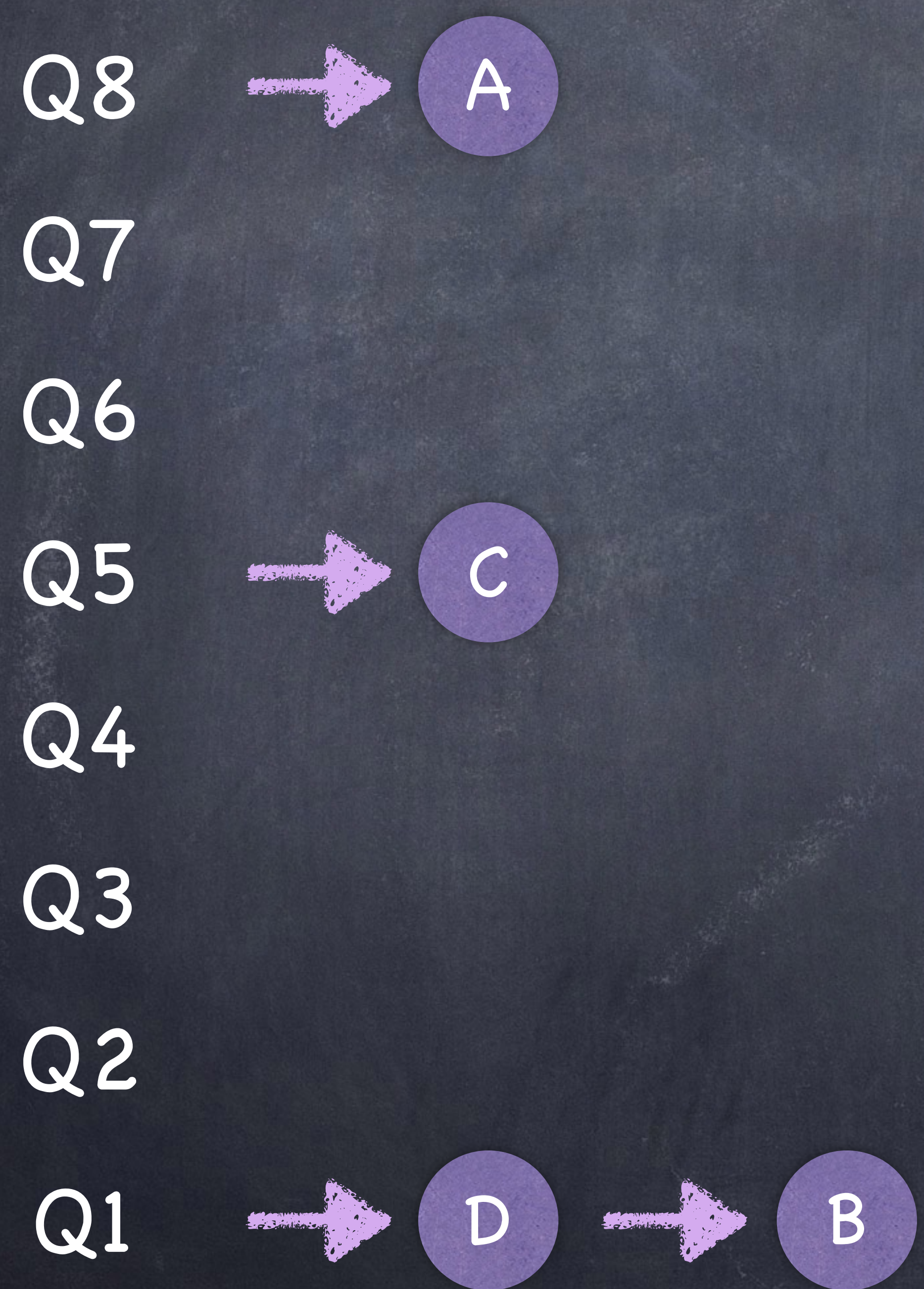
How are jobs assigned to a queue?

Moving down



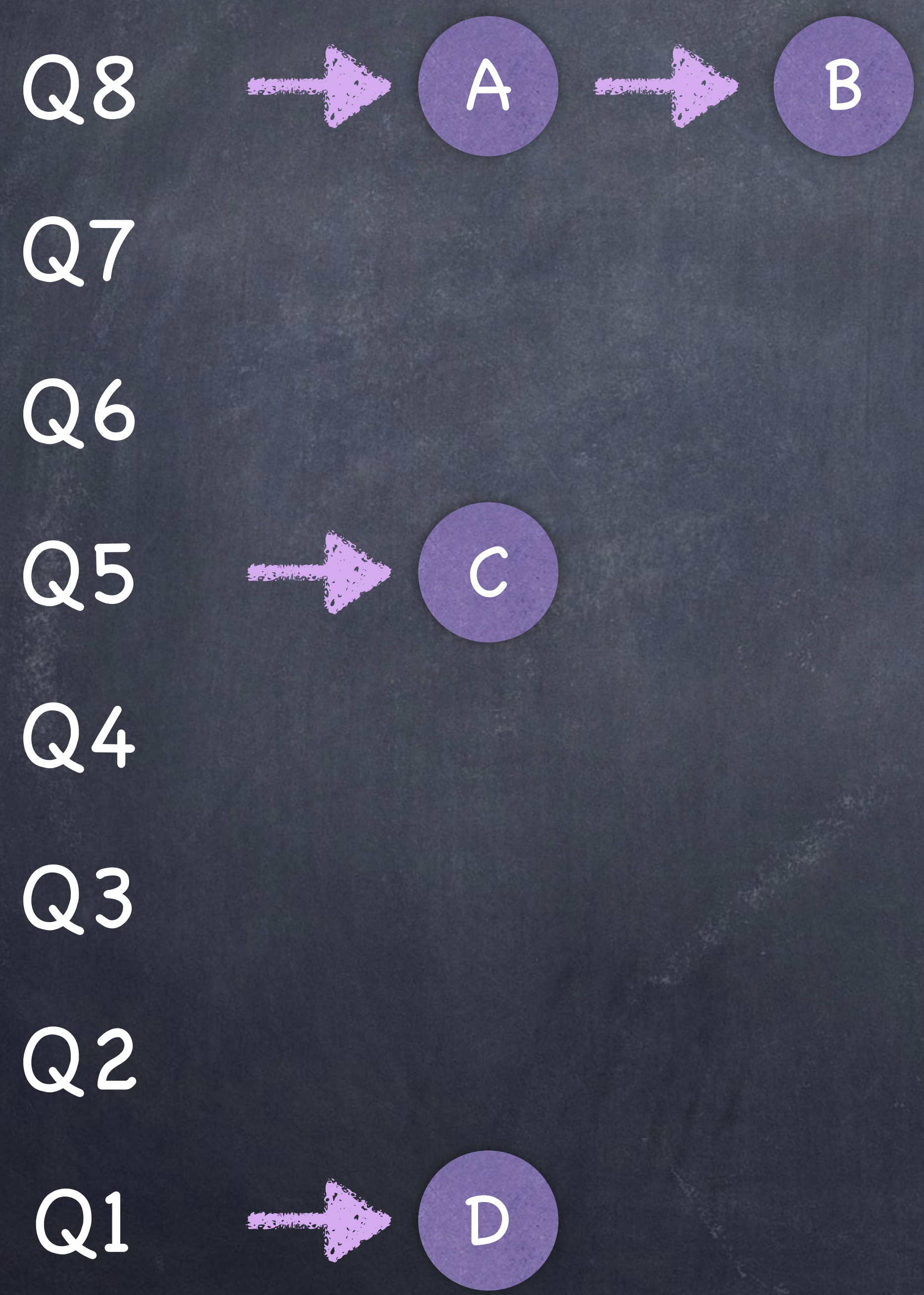
- Job starts at the top level
- If it uses full quantum before giving up CPU, moves down
- Otherwise, it stays where it is
- What about I/O?
  - Job with frequent I/O will not finish its quantum and stay at the same level
- Parameter
  - quantum size for each queue

Moving Up



- A job's behavior can change
  - After a CPU-bound interval, process may become I/O bound
- Must allow jobs to climb up the priority ladder…
  - As simple as periodically placing all jobs in the top queue, until they percolate down again
- Parameter
  - time before jobs are moved up

Sneeeeakyyy…



- Say that I have a job that requires a lot of CPU
  - Start at the top queue
  - If I finish my quantum, I'll be demoted…

  - …just give up the CPU before my quantum expires!
- Better accounting
  - fix a job's time budget at each level, no matter how it is used

Linux's "Completely Fair Scheduler" (CFS)

- Let "Spent Execution Time" (SET) to be the amount of time that a process has been executing
- Scheduler selects process with lowest SET
- Let △ be some time (typically, 50ms or so)
- Let N be the number of processes on the run queue
- Process runs for △/N time
    - there is a minimum value too
- If it uses up this quantum, reinsert into the queue
    - SET += △/N
- Computing of elapsed SET can be weighed by priority value
- Processes that move to a waiting queue, upon returning to the READY queue have SET initialized to the minimum SET of any process on the READY queue

CPU scheduling

- **Many possible "algorithms"**
  - Scheduling is an algorithmic problem
  - With some interesting OS bits …
- **Knowing tradeoffs is important**
  - No algorithm will be perfect for every scenario
  - If you understand tradeoffs
    - You'll be able to choose the "right" one

I don't expect you to learn these by heart