Operating Systems: Process Management

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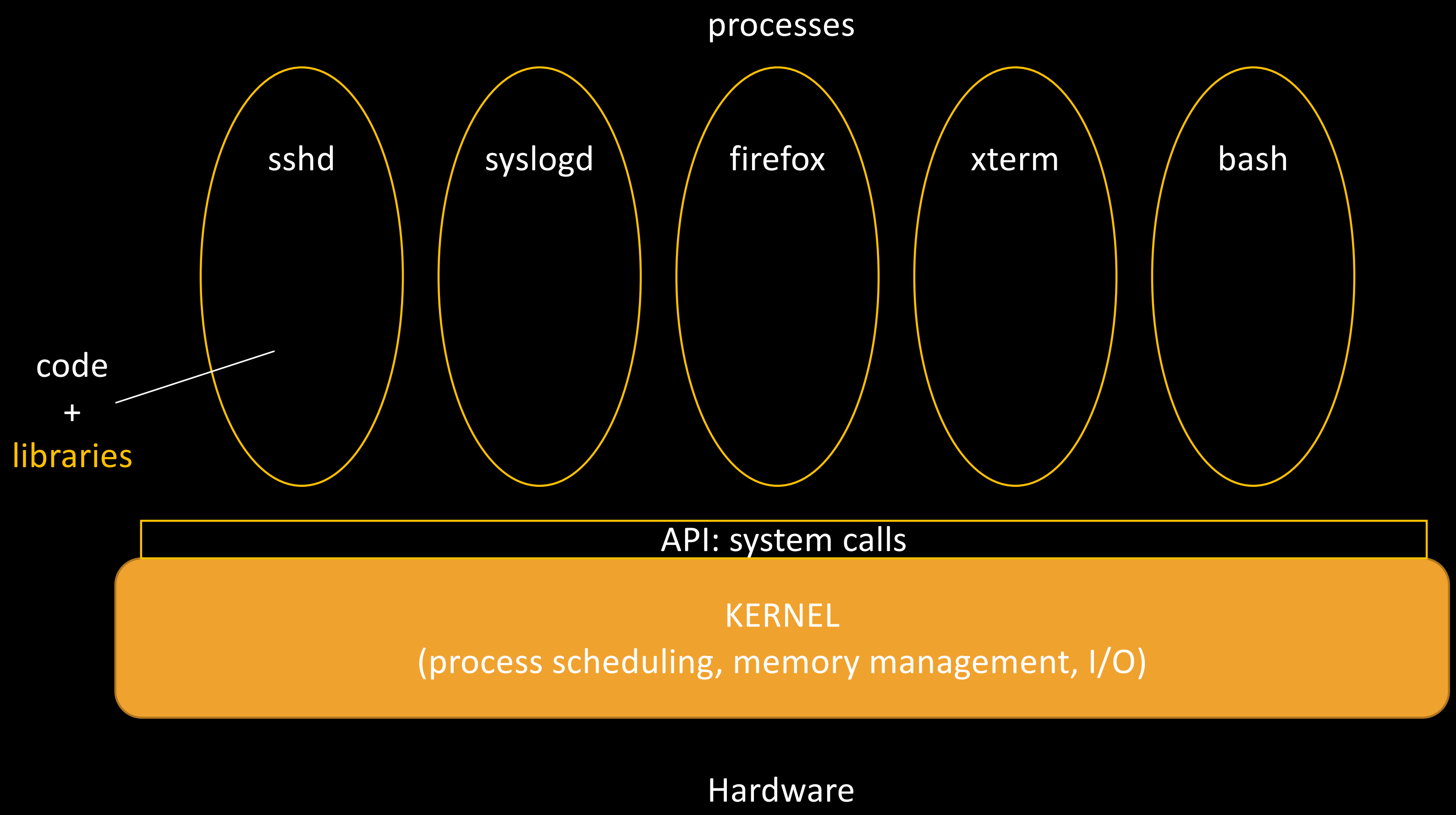
https://gforgeron.gitlab.io/se/

Structure of an OS



Processes

- Processes are lively instances of programs
  - Program = binary code stored on disk
  - Multiple processes can run the same program independently

- Process = Address Space + Execution Context
  - Address space
    - Set of visible memory addresses
      - Code, Data, Heap, Stack, Shared Libraries, etc.
  - Execution Context
    - Stack + content of processor registers

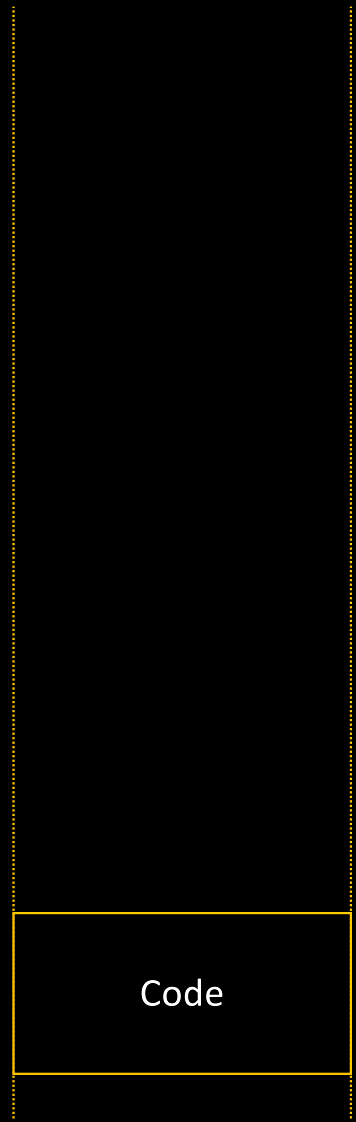
Address Space

- Typically composed of distinct memory regions
  - A region being a contiguous range of valid addresses

Address Space

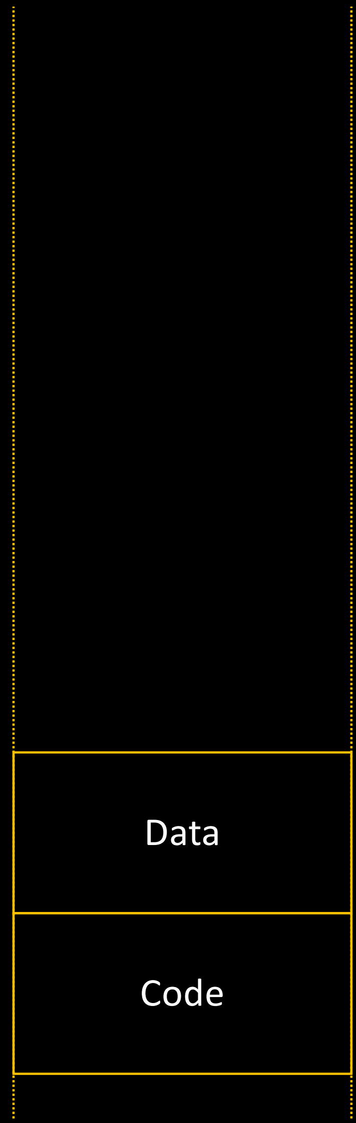
- Typically composed of the following regions
  - Code
    - (aka text segment)
    - Contains executable instructions
    - Usually, a read-only region

    - It also hosts constants
      - E.g. constant strings
        - “hello world!”



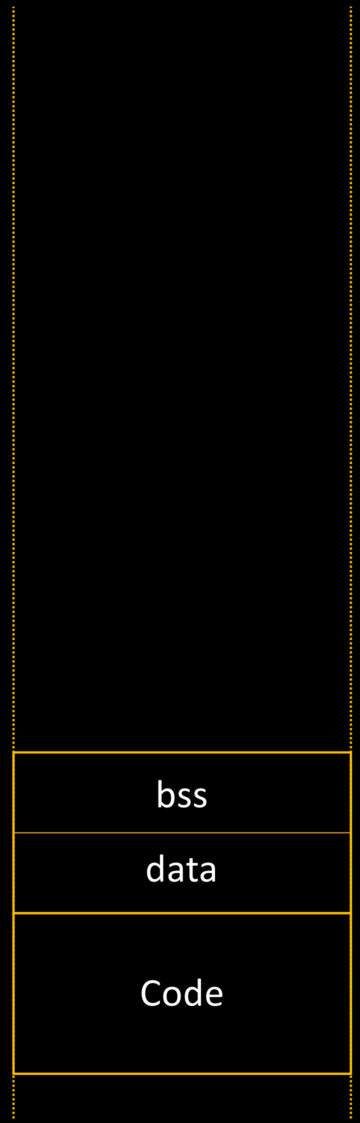
Address Space

- Typically composed of the following regions
  - Code
  - Data
    - Allocation of static variables
      - `int i;`



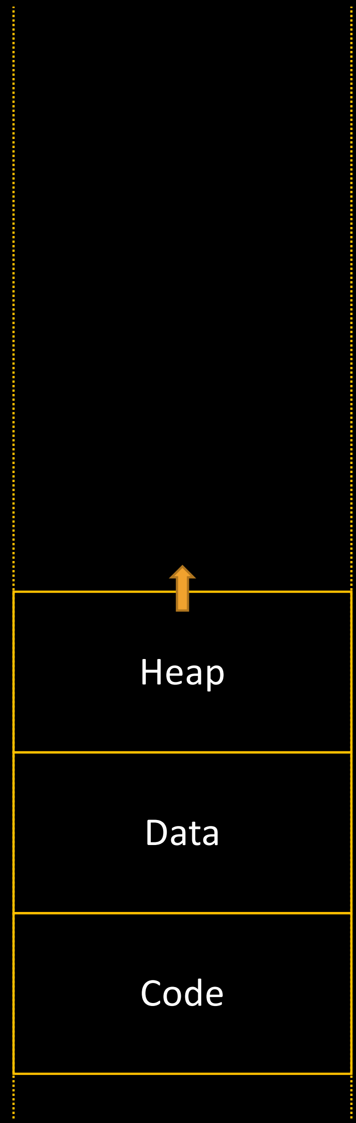
Address Space

- Typically composed of the following regions
  - Code
  - Data
    - Allocation of static variables
    - Actually two segments
      - Initialized data (data segment)
        - `float pi = 3.1415;`
        - Stored in object file
      - Uninitialized data (bss segment)
        - `int i;`
        - Only segment size is stored in object file



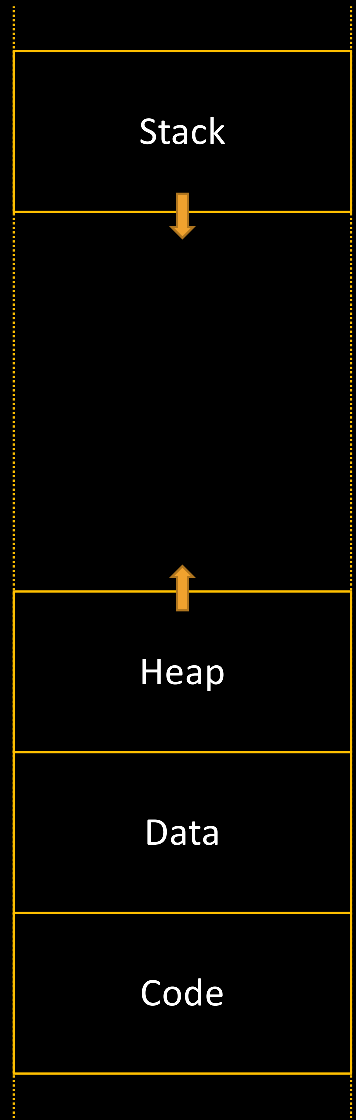
Address Space

- Typically composed of the following regions
  - Code
  - Data
  - Heap
    - Dynamic allocations
      - `malloc/free`
    - Managed by libc
      - Dynamic expansion
      - OS cannot (always) detect accesses outside malloc'ed buffers…



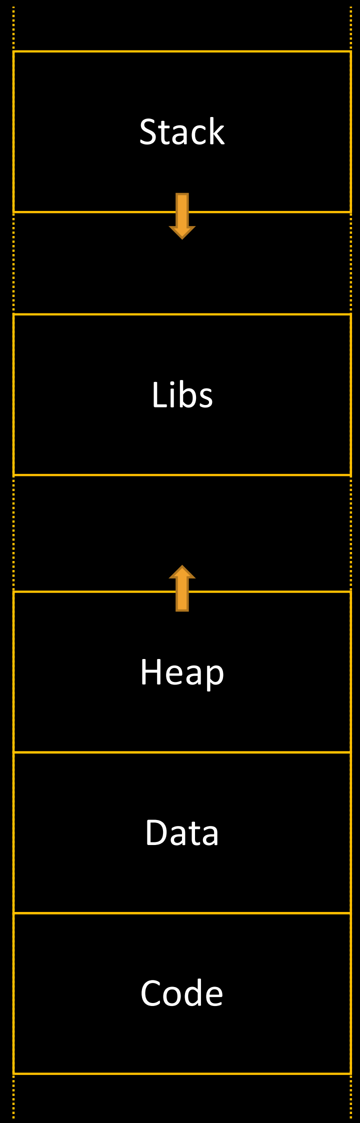
Address Space

- Typically composed of the following regions
  - Code
  - Data
  - Heap
  - Stack
    - Allocation of function parameters and local variables
    - Automatic growth
    - 8 MiB default limit under Linux



Address Space

- Typically composed of the following regions
  - Code
  - Data
  - Heap
  - Stack
  - Shared Libraries
    - libc, libm, libGL, etc.
    - Mapped on demand



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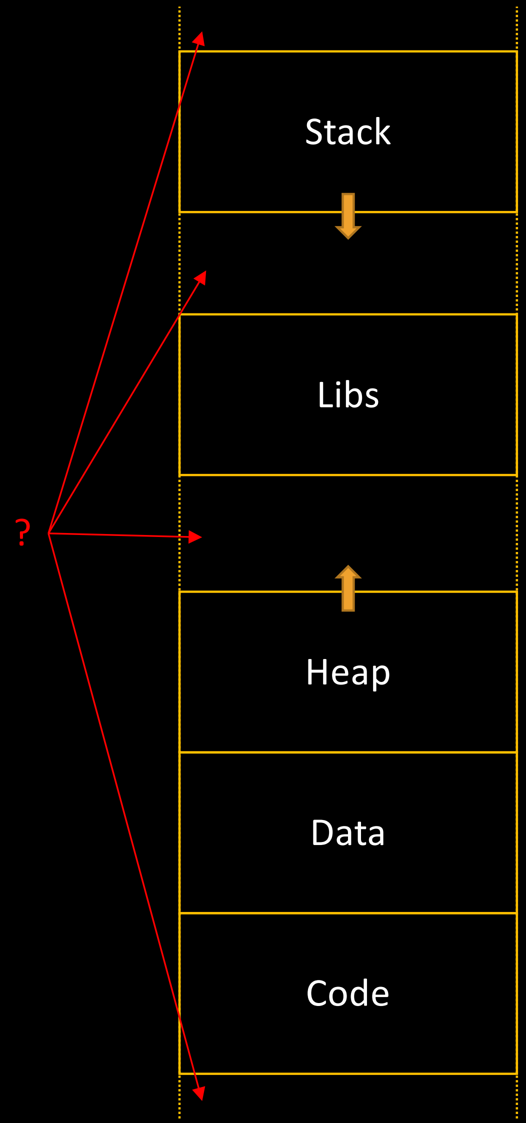

Address Space

- Typically composed of the following regions
  - Code
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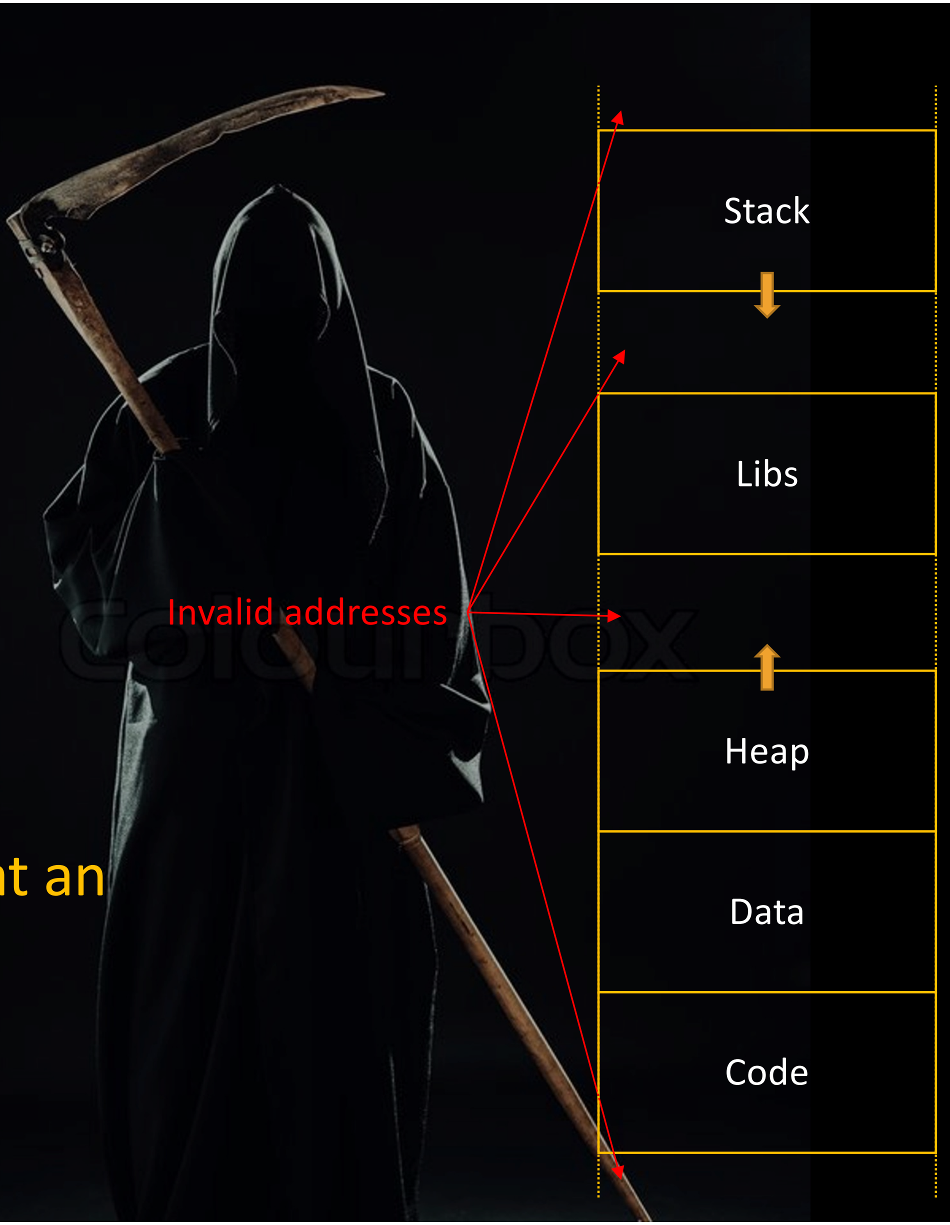
- Attempt to access memory at an invalid address leads to a Segmentation Fault



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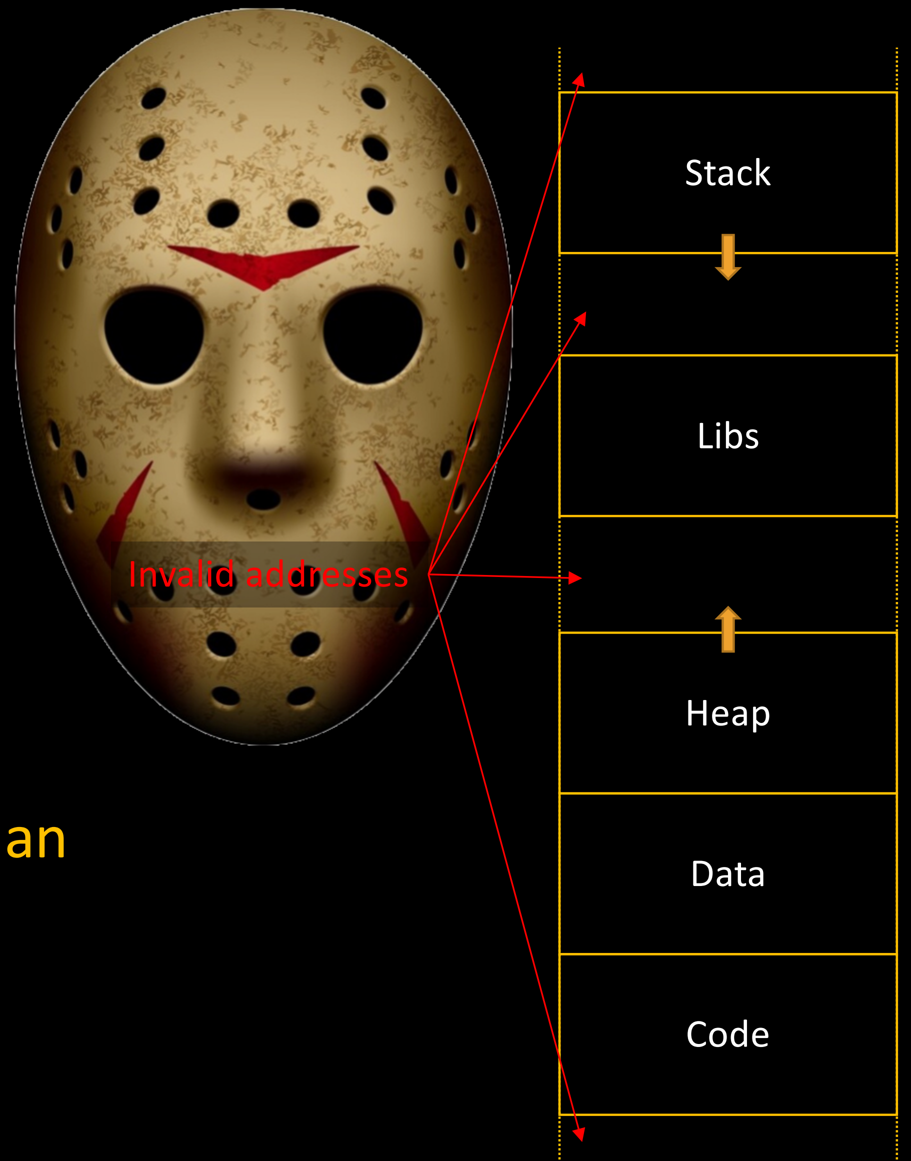
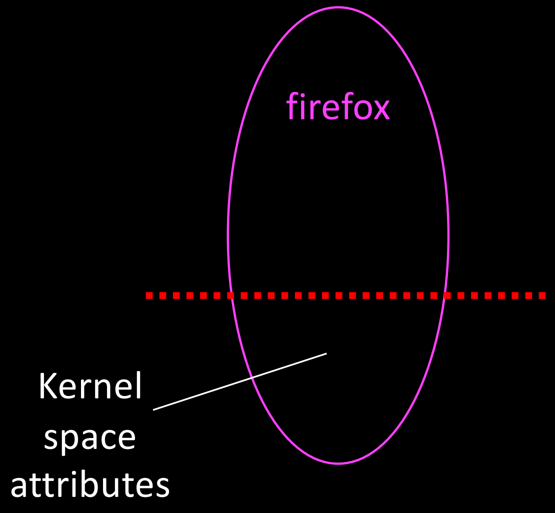


Inspecting Memory Regions under Linux

```
[jolicoeur] cat /proc/self/maps
    55ad0226e000-55ad02276000 r-xp 00000000 08:01 1573289                /bin/cat
    55ad02475000-55ad02476000 r--p 00007000 08:01 1573289                /bin/cat
    55ad02476000-55ad02477000 rw-p 00008000 08:01 1573289                /bin/cat
    55ad02c0d000-55ad02c2e000 rw-p 00000000 00:00 0                      [heap]
    7f9a1646b000-7f9a1669e000 r--p 00000000 08:01 7079259                /usr/lib/locale/locale-archive
    7f9a166a3000-7f9a16838000 r-xp 00000000 08:01 8131225                /lib/x86_64-linux-gnu/libc-2.24.so
    7f9a16838000-7f9a16a38000 ---p 00195000 08:01 8131225                /lib/x86_64-linux-gnu/libc-2.24.so
    7f9a16a38000-7f9a16a3c000 r--p 00195000 08:01 8131225                /lib/x86_64-linux-gnu/libc-2.24.so
    7f9a16a3c000-7f9a16a3e000 rw-p 00199000 08:01 8131225                /lib/x86_64-linux-gnu/libc-2.24.so
    7f9a16a43000-7f9a16a66000 r-xp 00000000 08:01 8128192                /lib/x86_64-linux-gnu/ld-2.24.so
    7f9a16c66000-7f9a16c67000 r--p 00023000 08:01 8128192                /lib/x86_64-linux-gnu/ld-2.24.so
    7f9a16c67000-7f9a16c68000 rw-p 00024000 08:01 8128192                /lib/x86_64-linux-gnu/ld-2.24.so
    7ffeaea77000-7ffeaea98000 rw-p 00000000 00:00 0                      [stack]
```

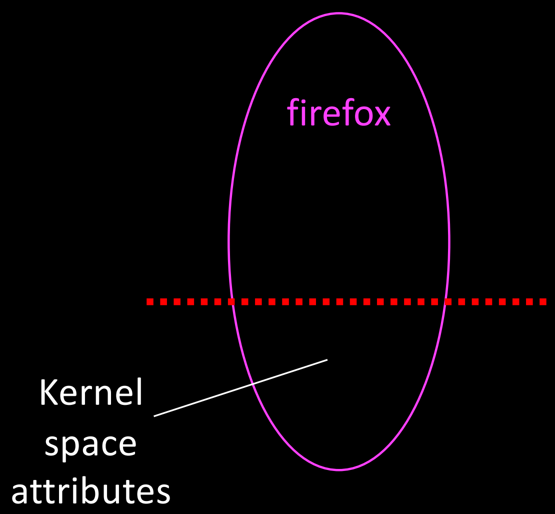
Process Attributes

- In addition to Address Space description, the kernel stores the following information about each process:
  - Process ID (pid)
  - Priority
  - User ID (real/effective)
  - File descriptor table
  - Signal handling table
  - Space for registers backup
  - Etc.

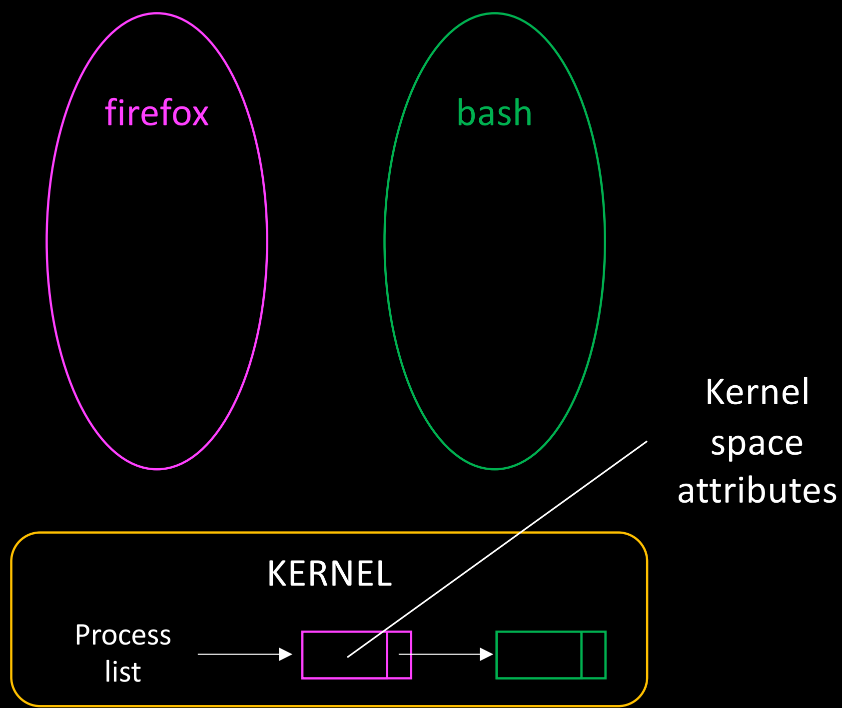


Process Attributes

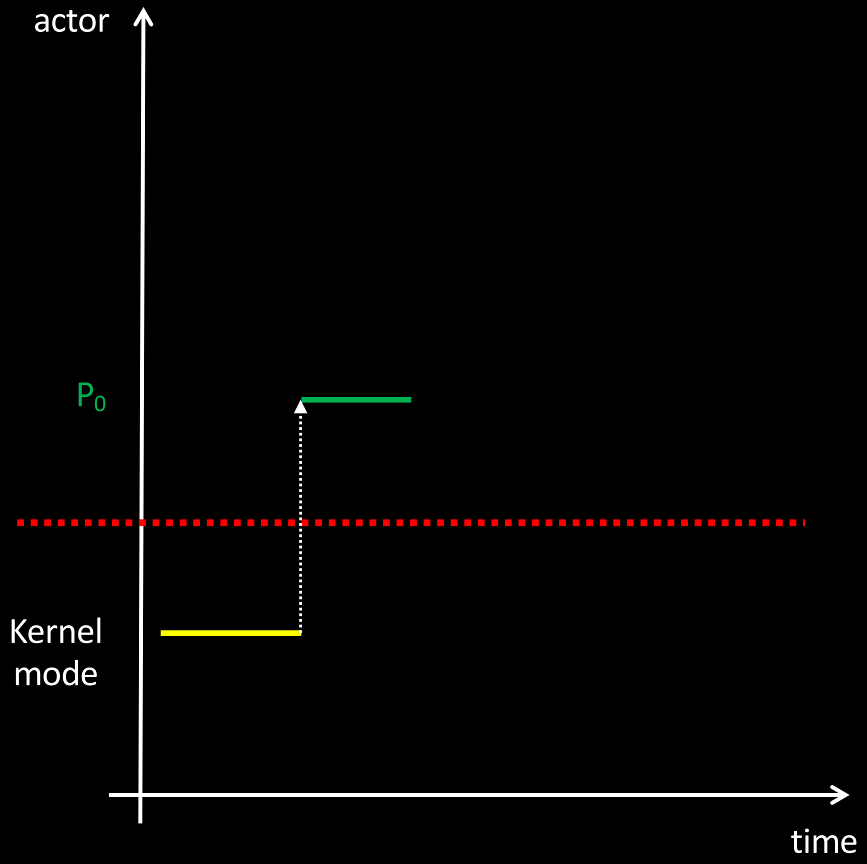
Processes can be represented this way:



But reality is (obviously) more like:

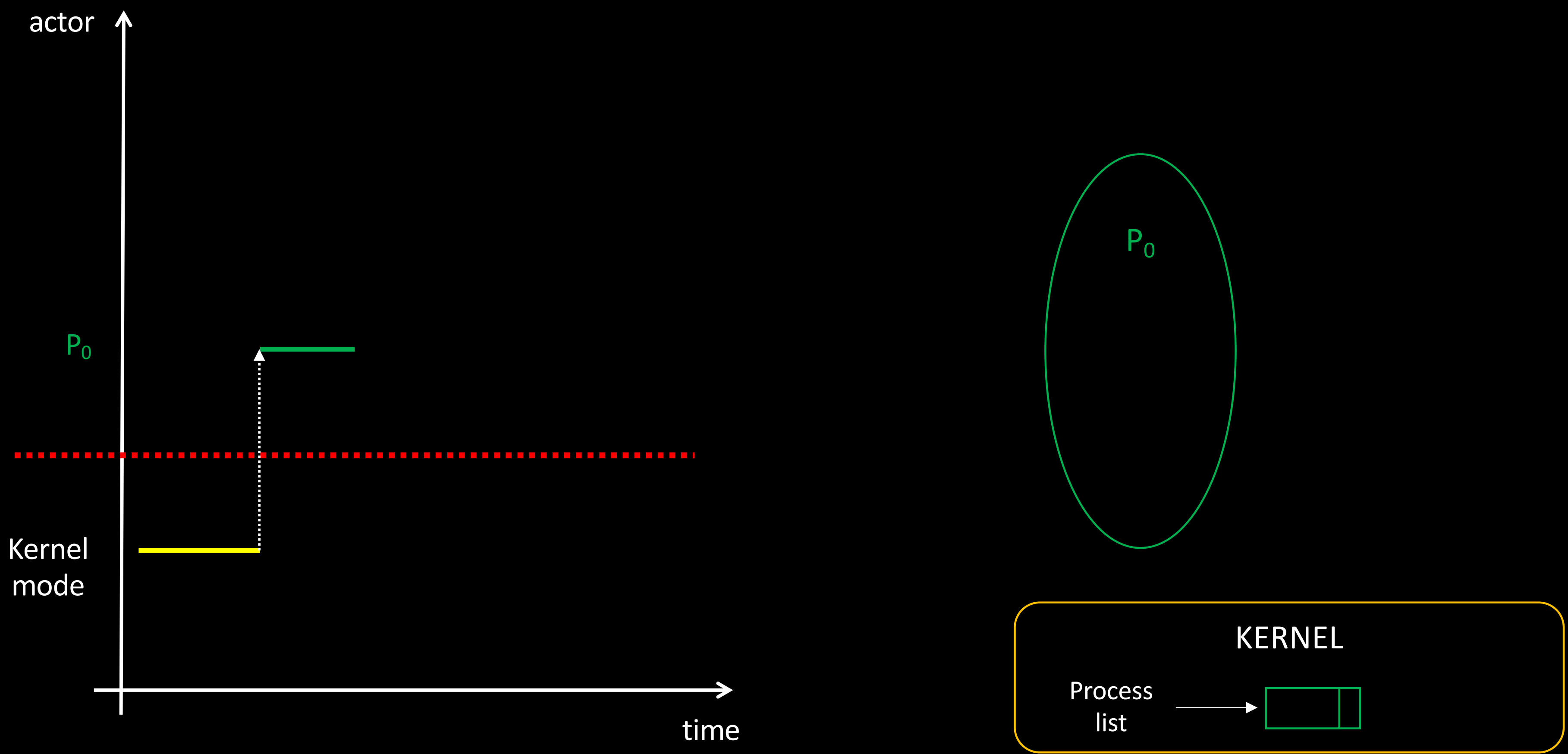


Process Creation



- The Kernel originally spawns one process (P_0)
  - This process will in turn create several processes (background DAEMONs)
    - Using a system call (what else?)

Process Creation



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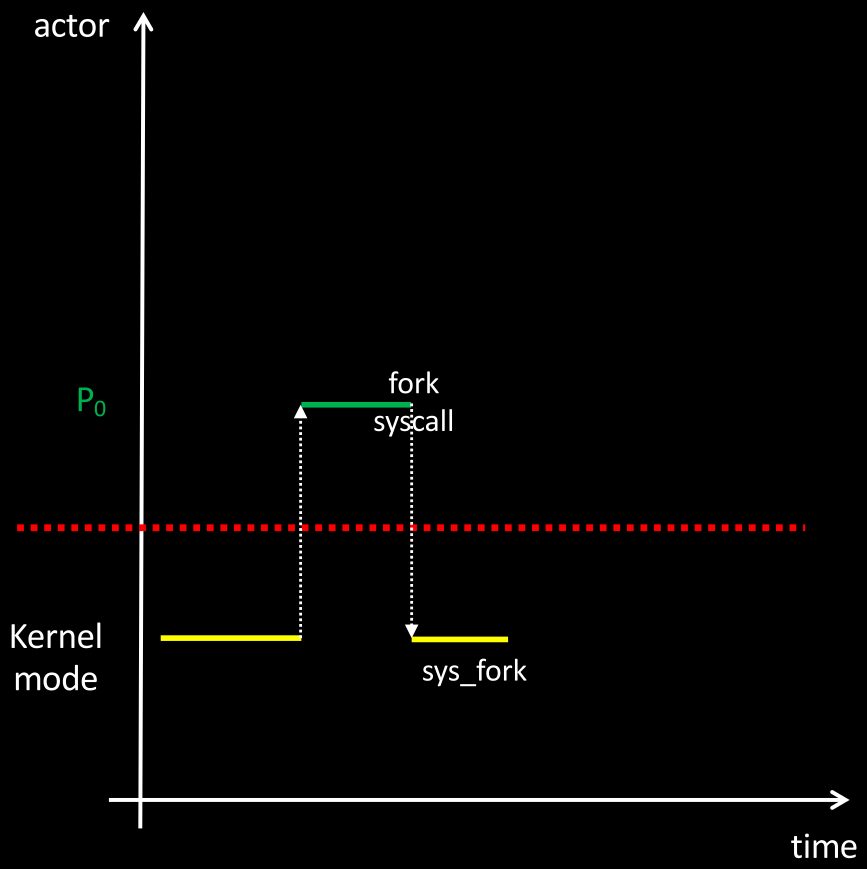

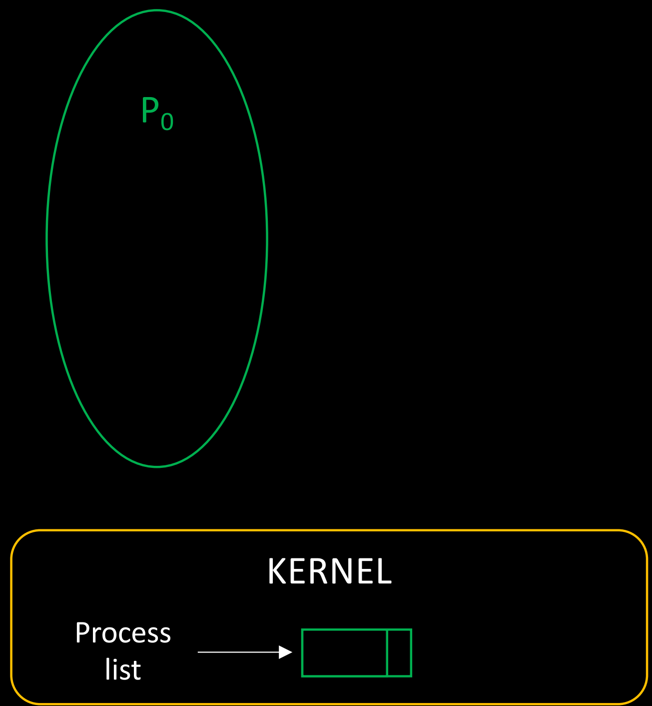

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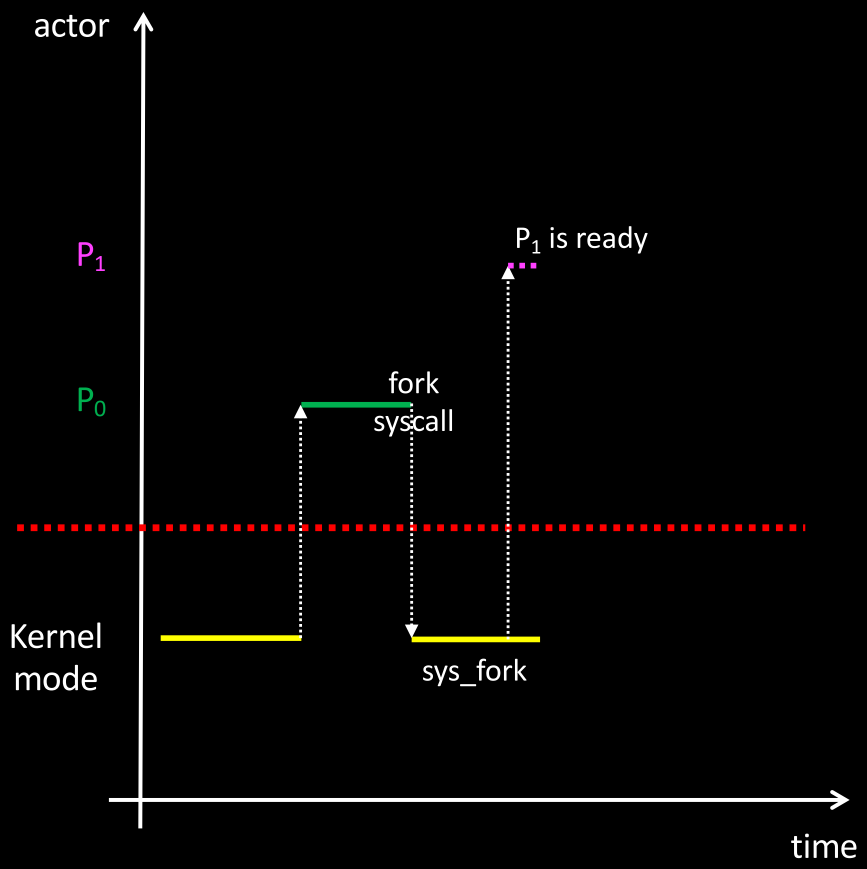

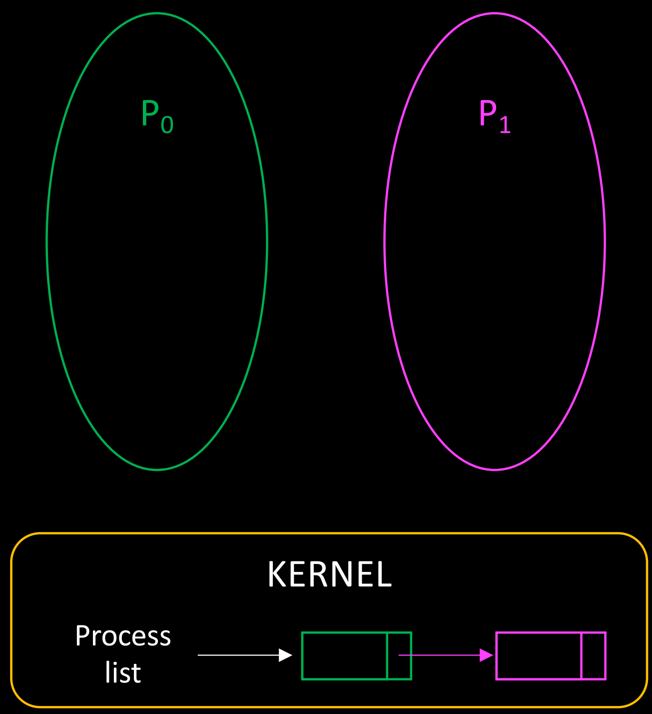

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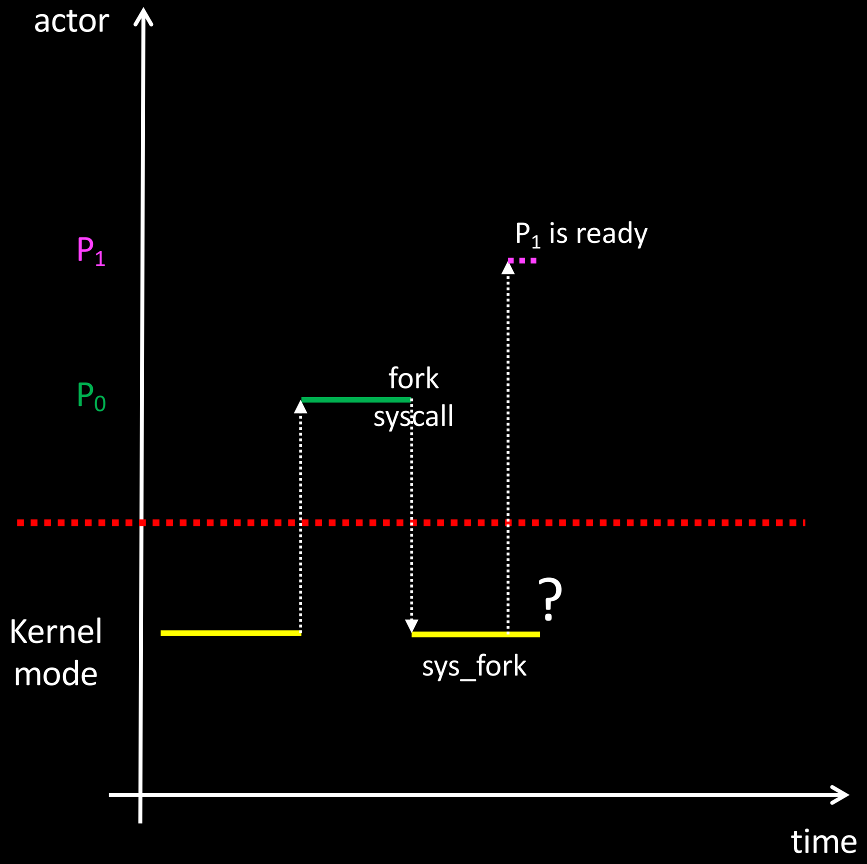

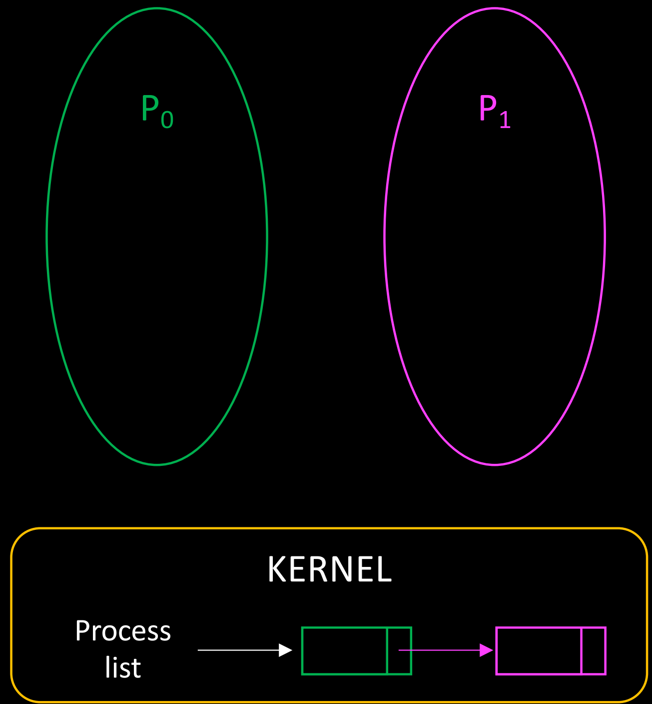

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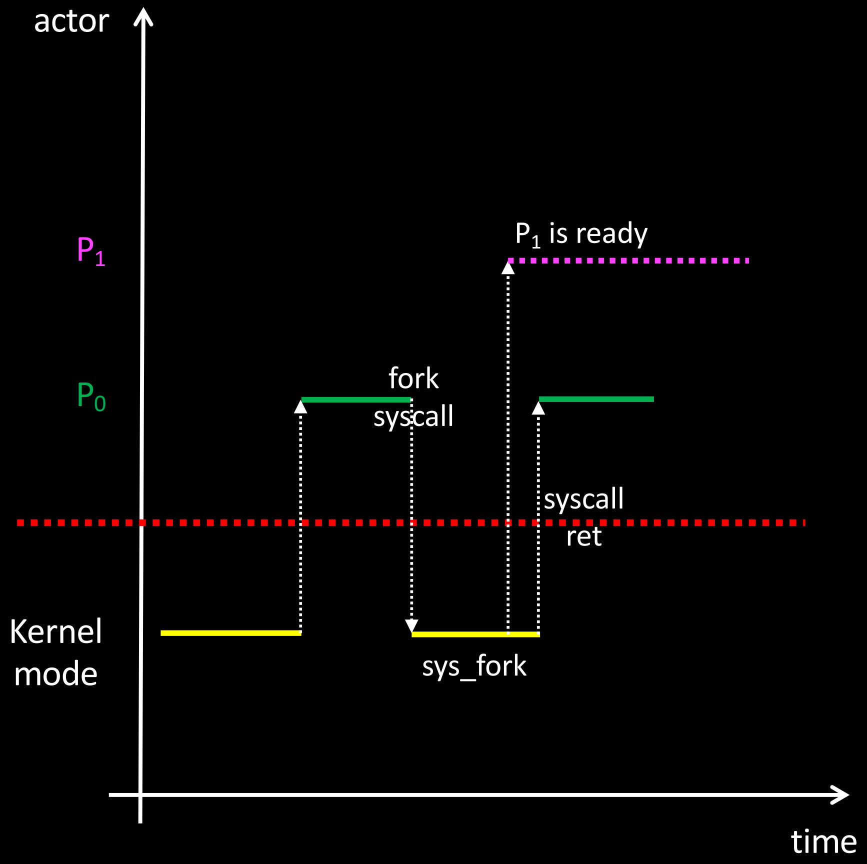

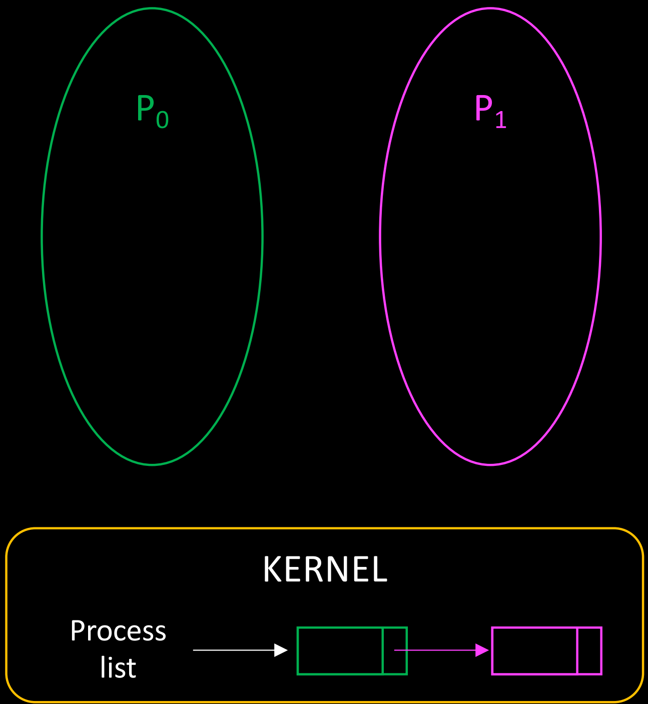

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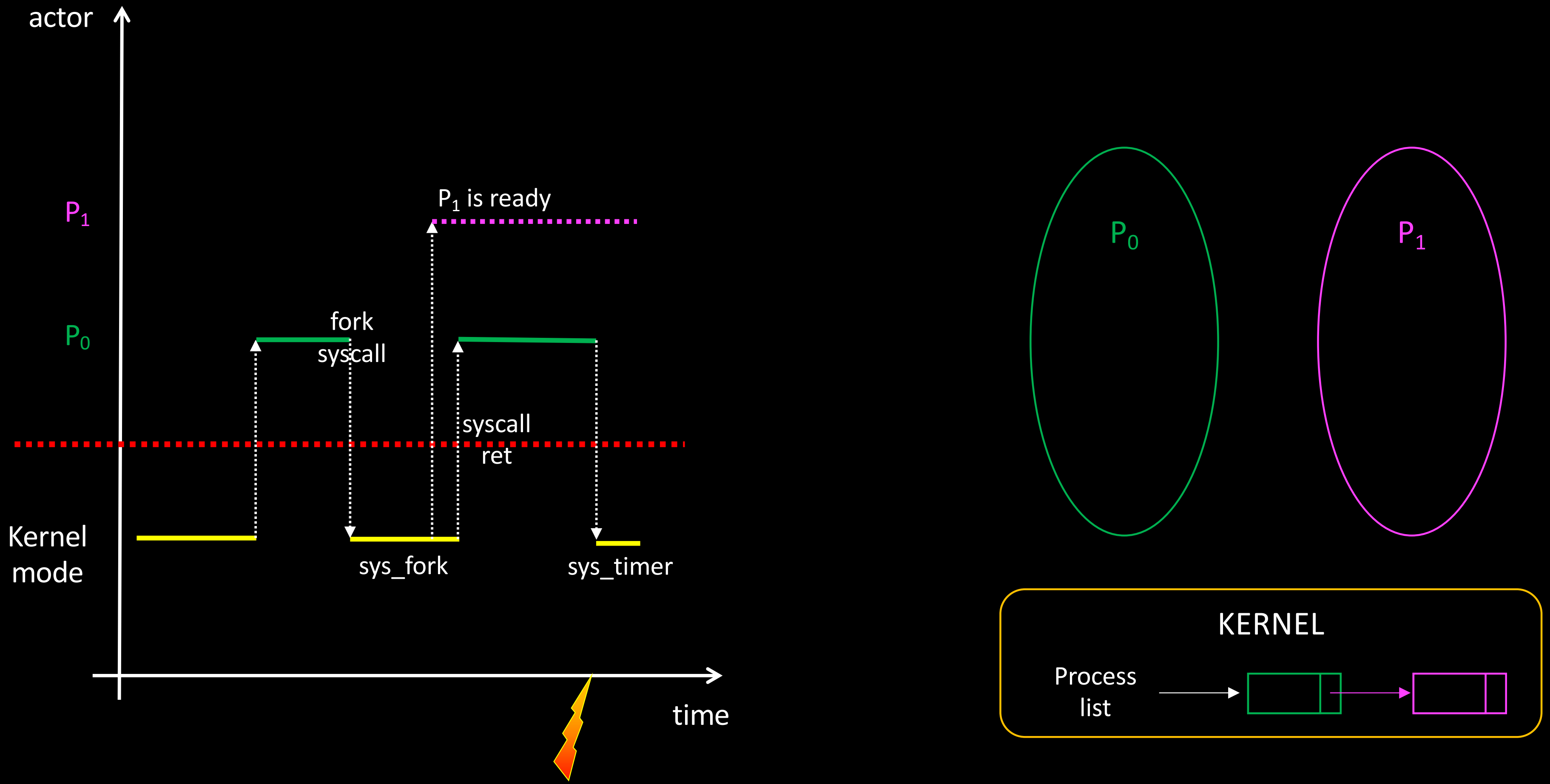
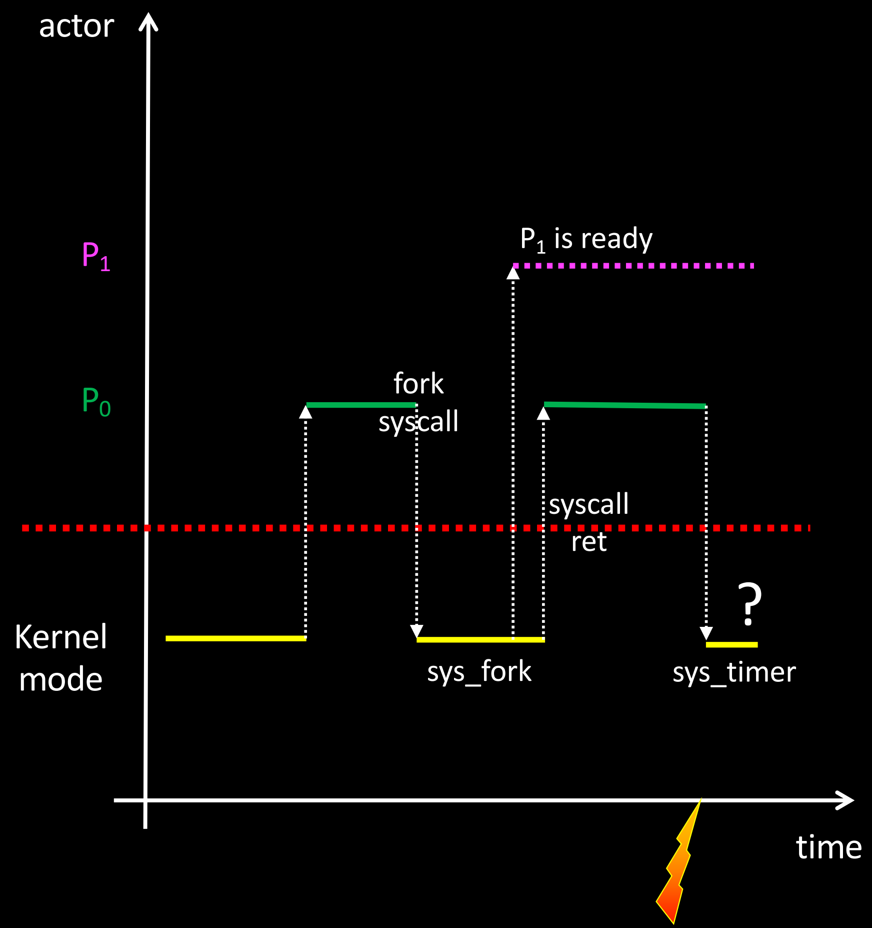


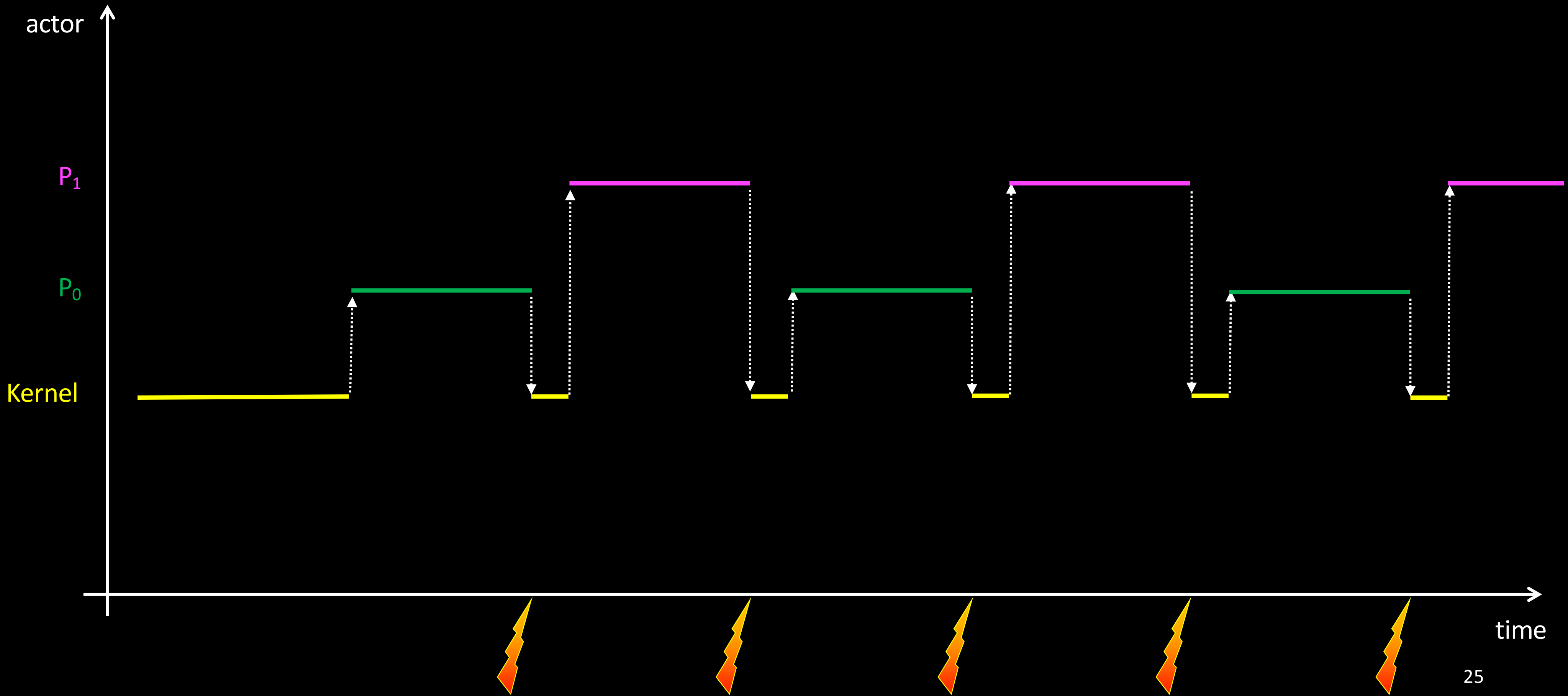
Process Scheduling



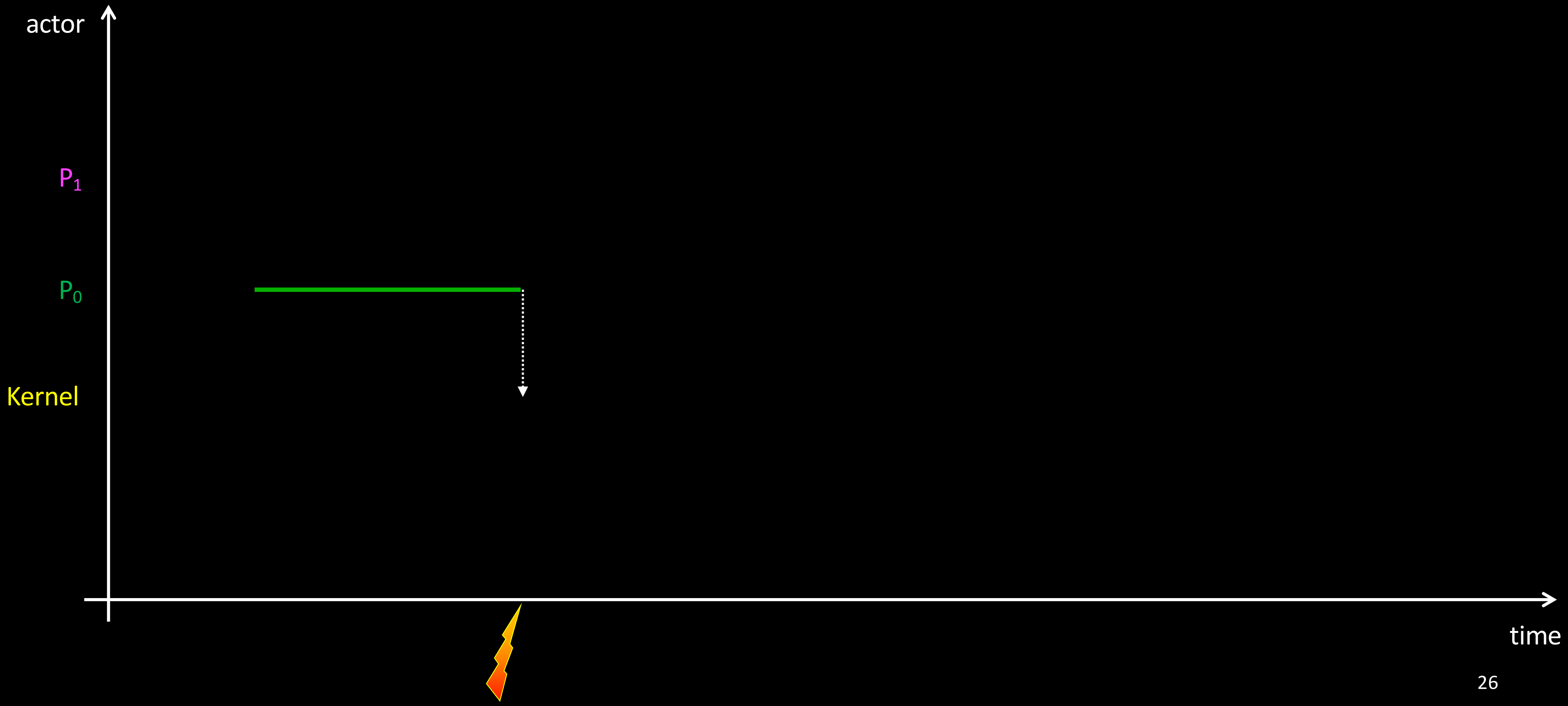
- At some point, the kernel must decide "which process should run now?"
  = Process Scheduling

- NB
  - A CPU executes one program at a time
  - There can be at most #CPU processes running simultaneously

Process Scheduling



Process Scheduling (close up)



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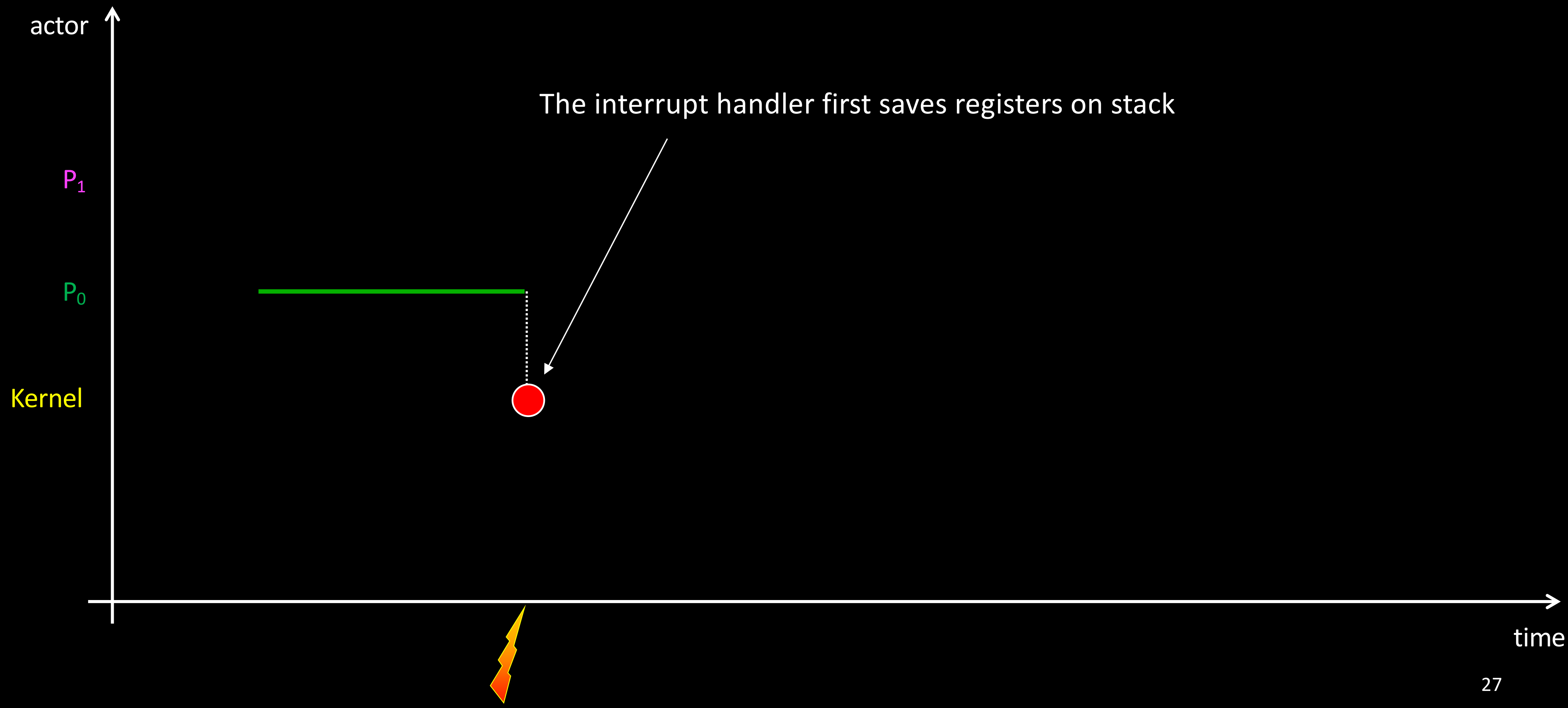

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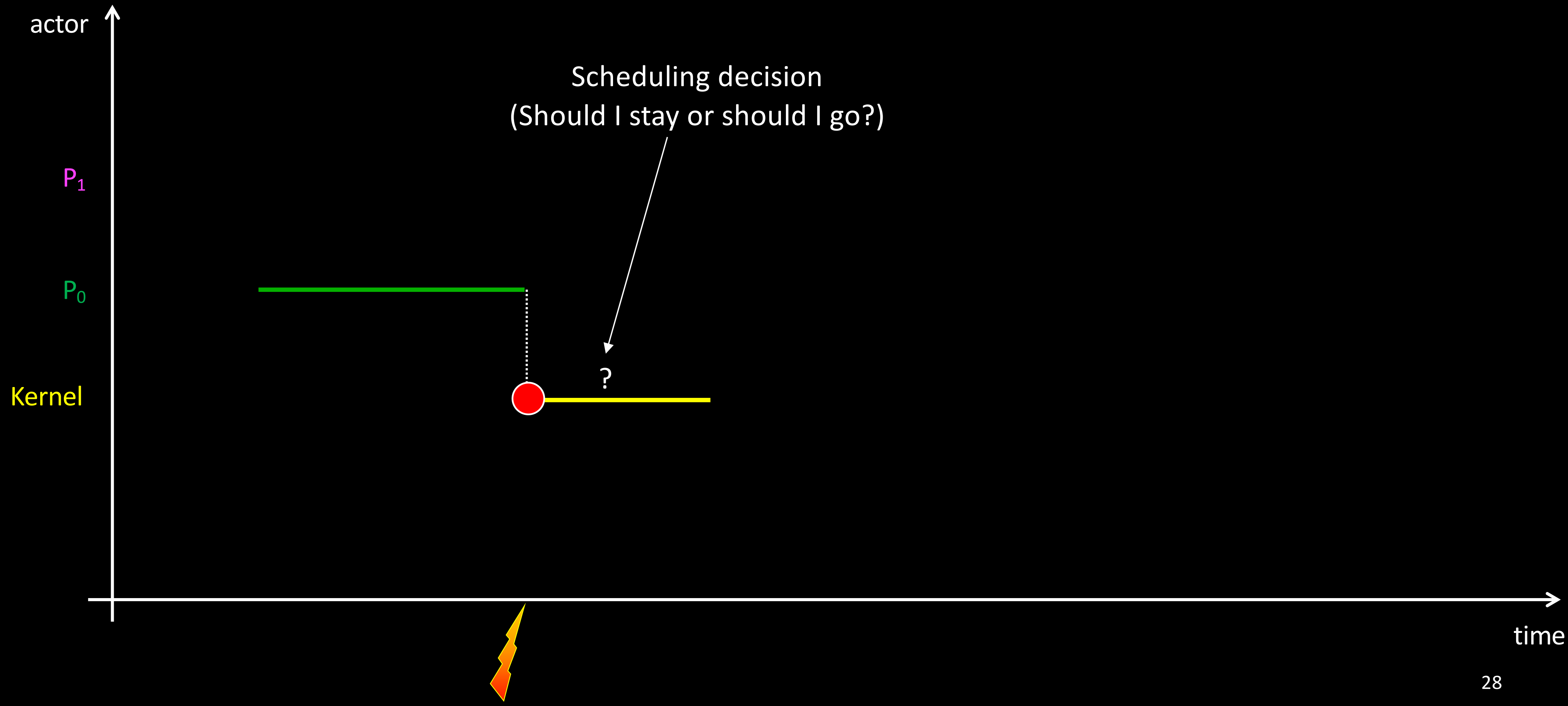

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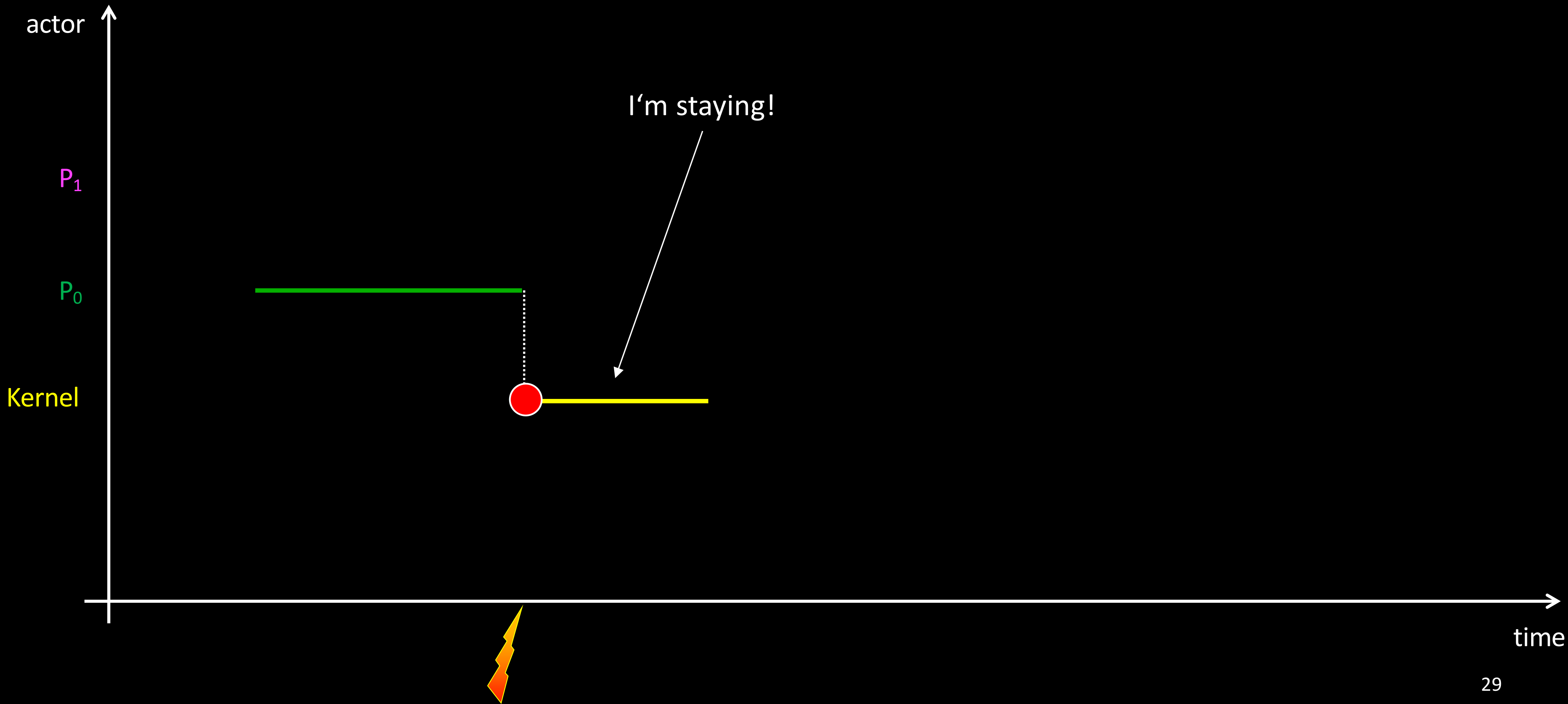

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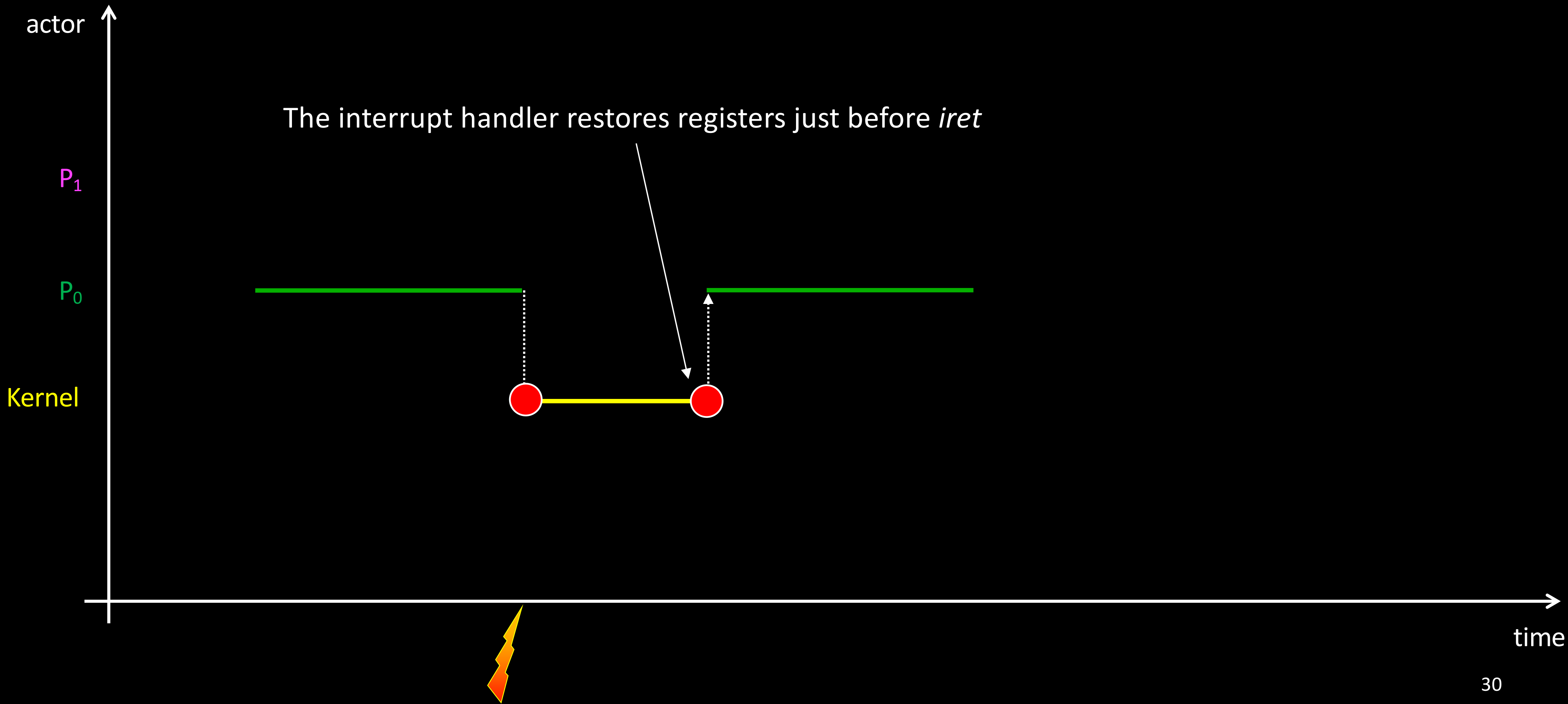

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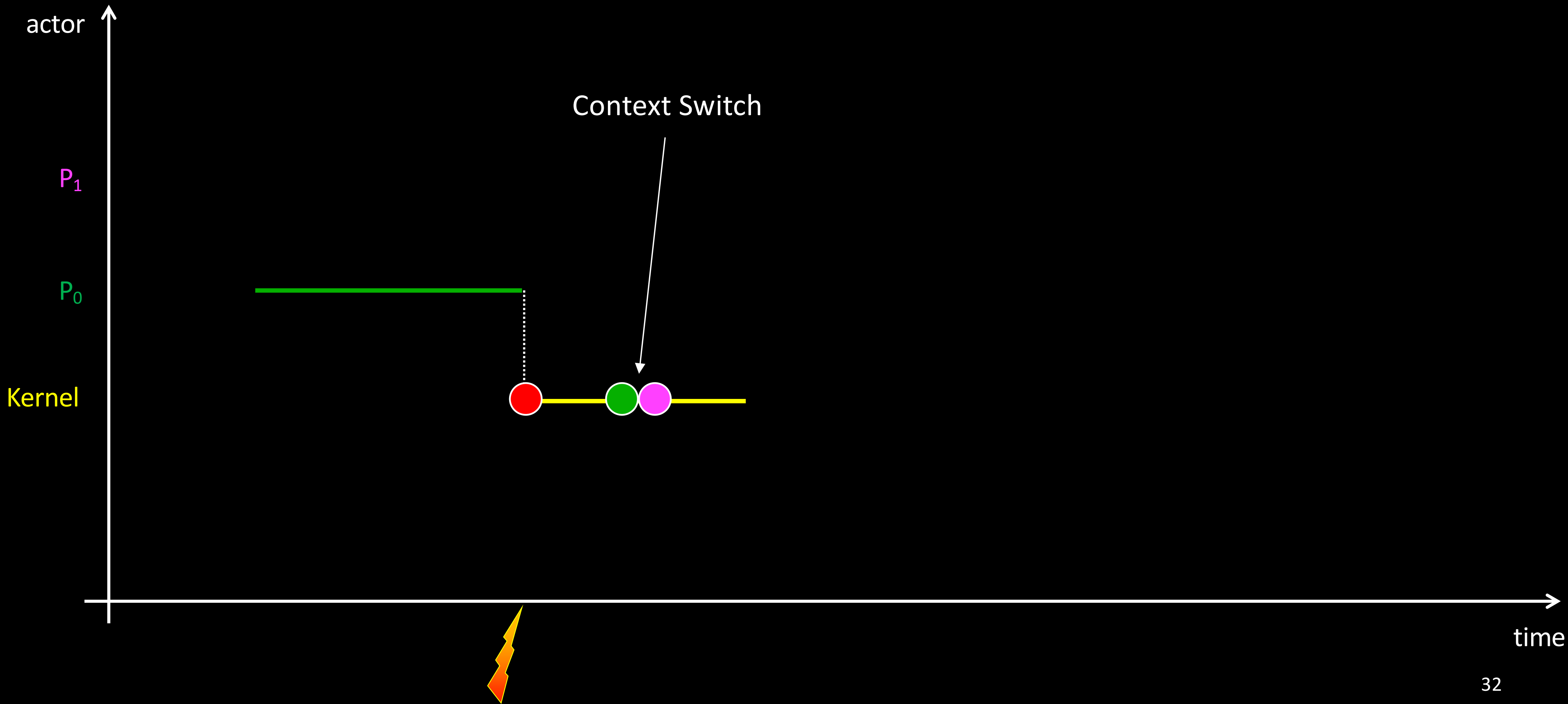

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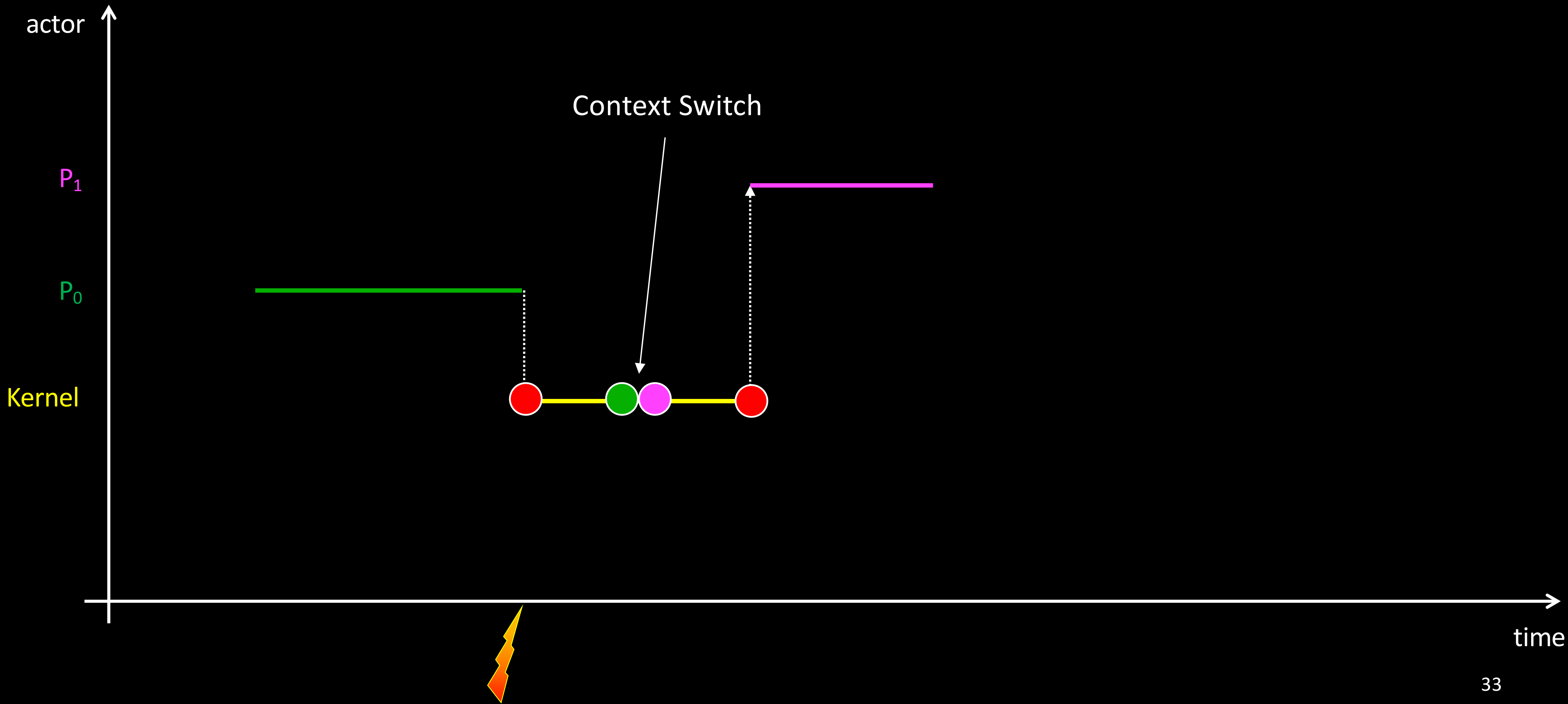


Context Switching

- switch_to (P_{prev}, P_{next})
  - Save P_{prev} registers
  - Restore P_{next} registers

  - P_{prev} becomes P_{next}
  - P_{next} resumes execution and returns from "one" `switch_to` call

  - P_{prev} will resume execution when some process will switch back to it

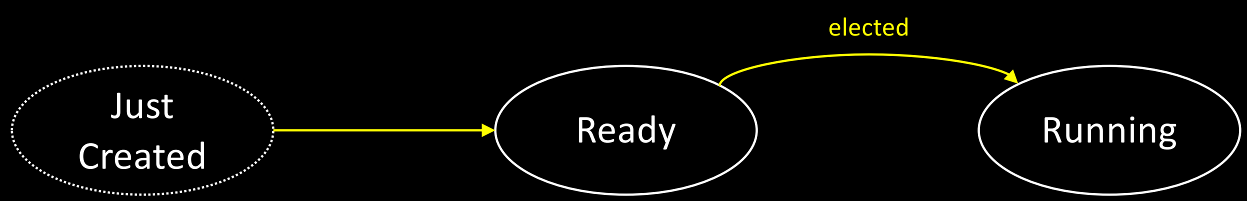
```
kernel_f()
{
  …
  switch_to (prev, next);
  …
}

kernel_g()
{
  …
  switch_to (prev, next);
  …
}
```

Process States

Just
Created

Process States

Process States



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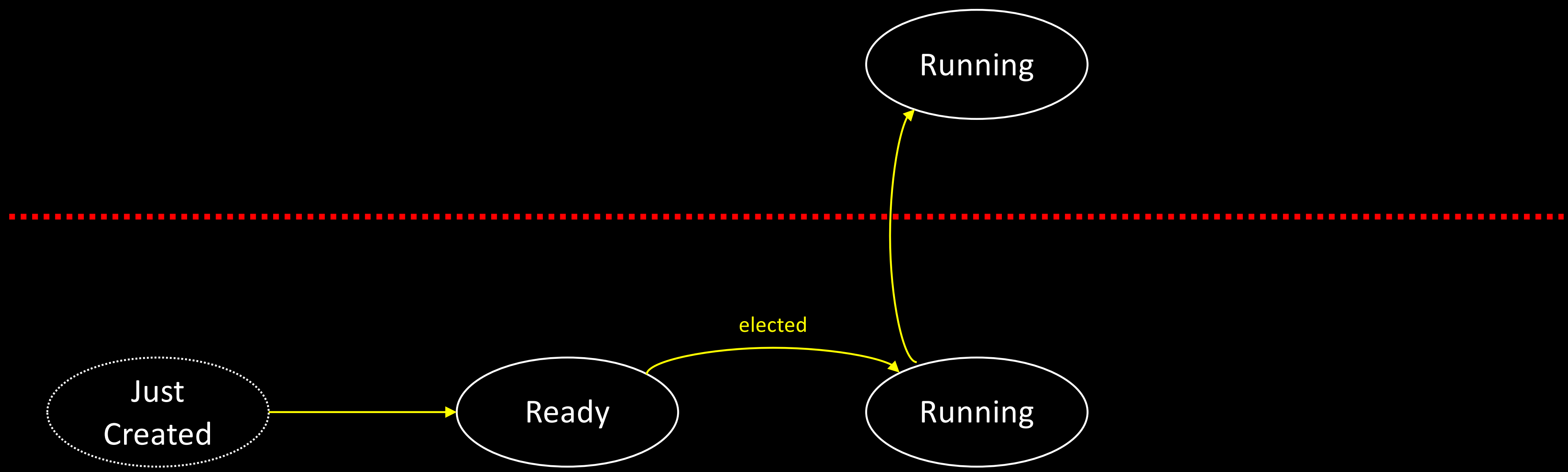

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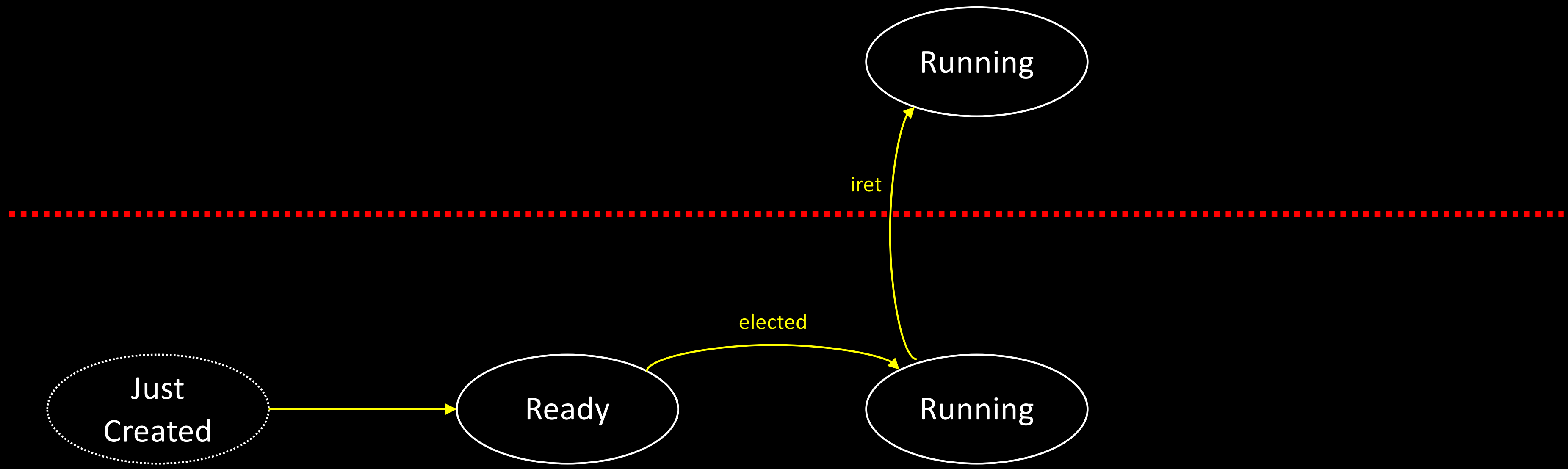

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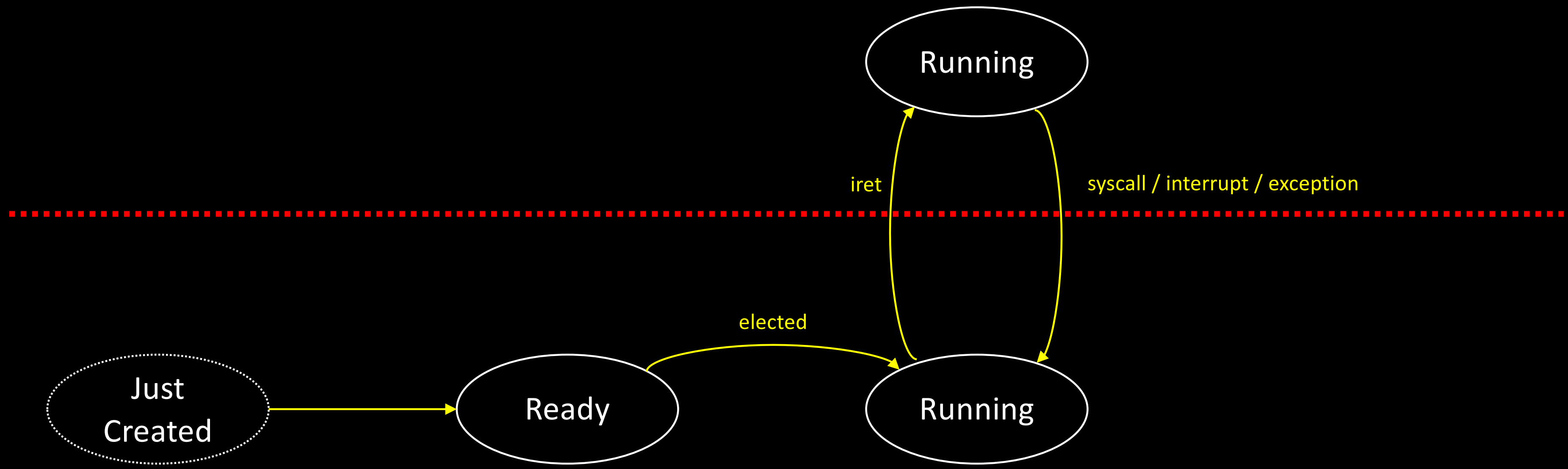

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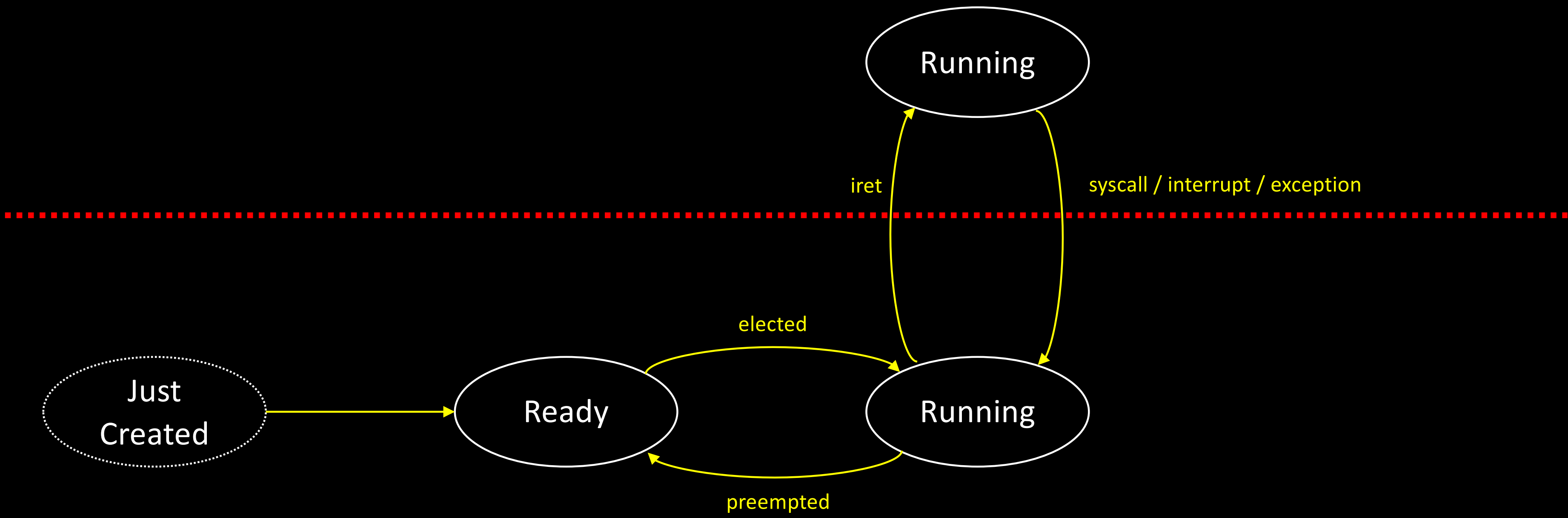

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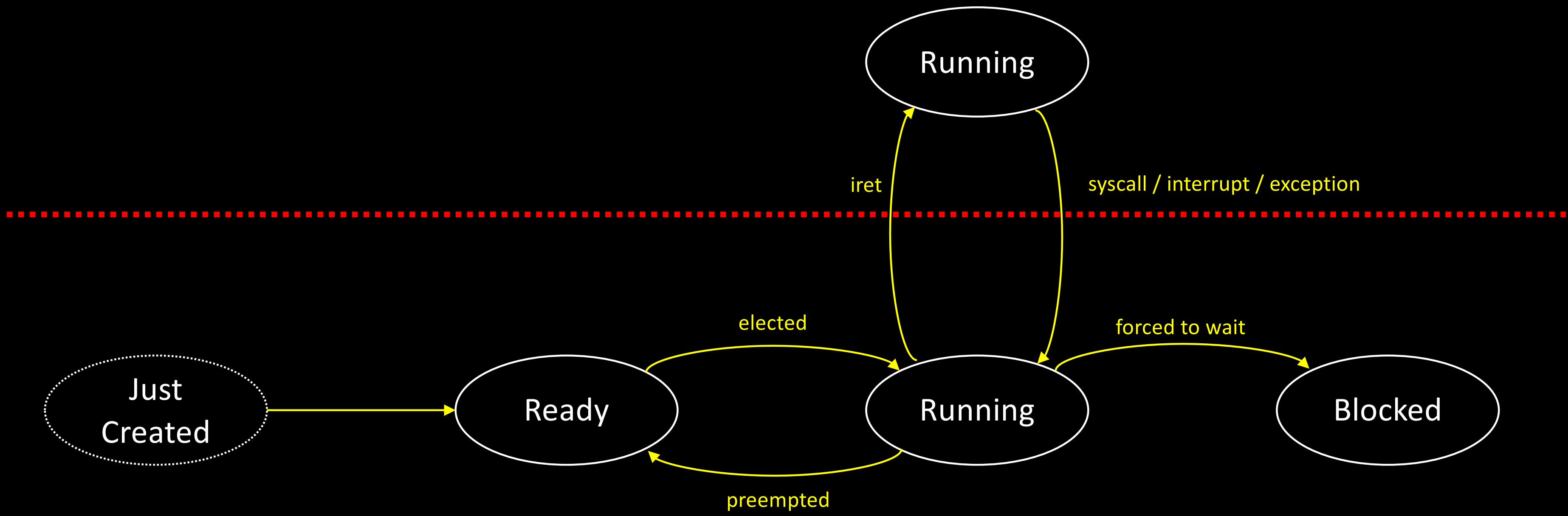

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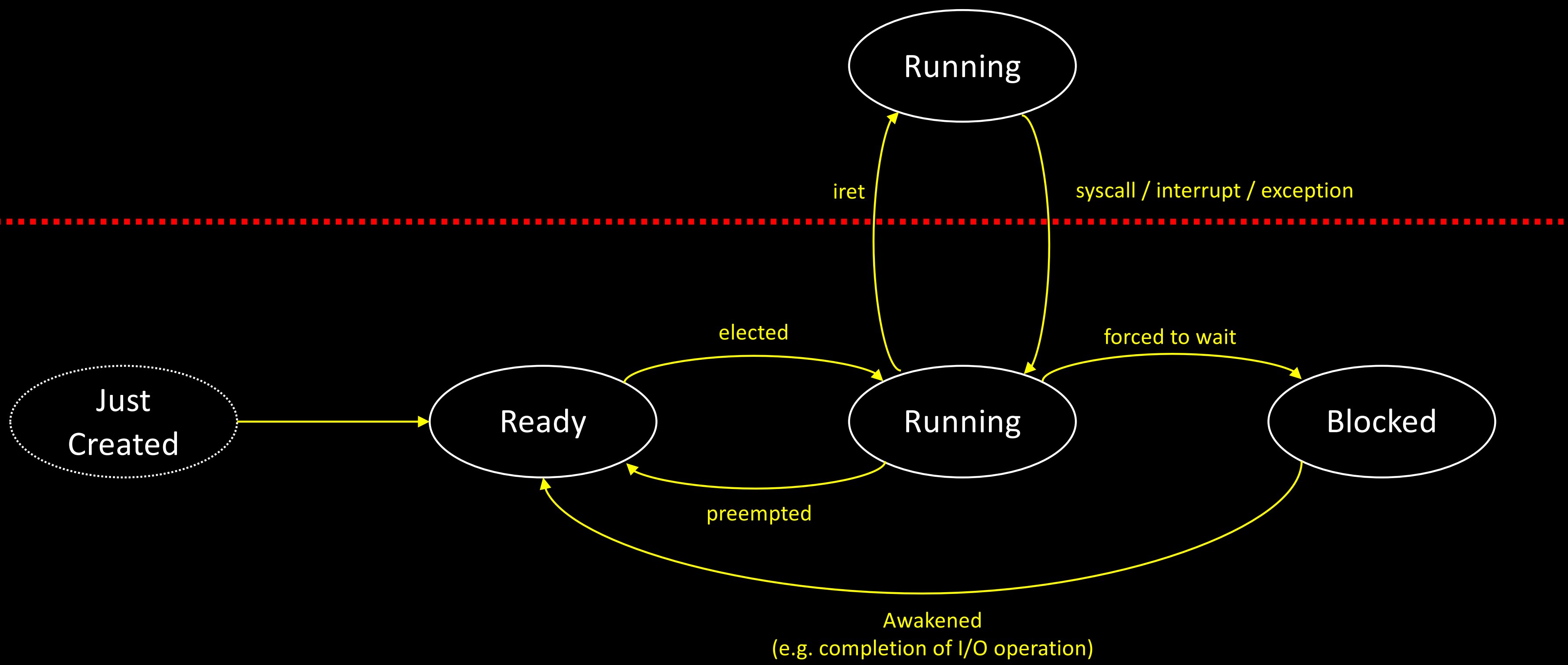

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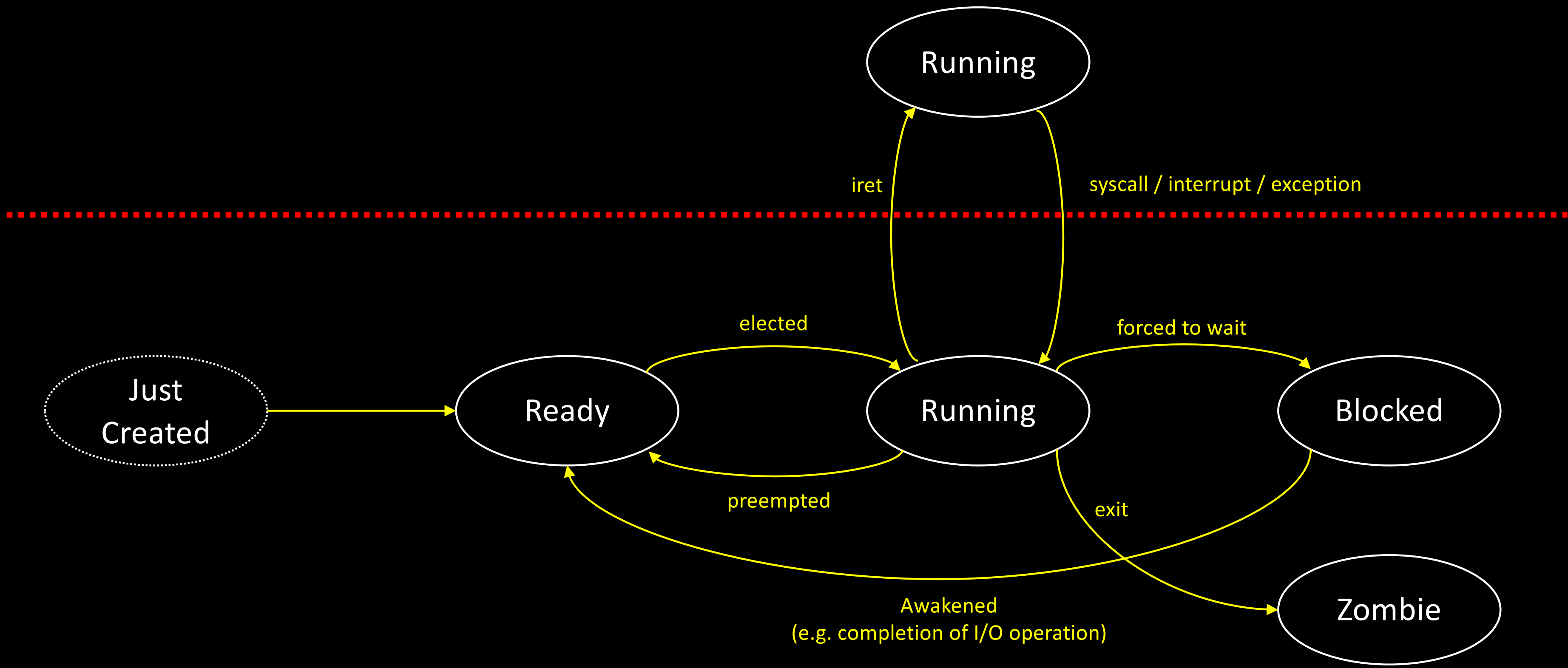
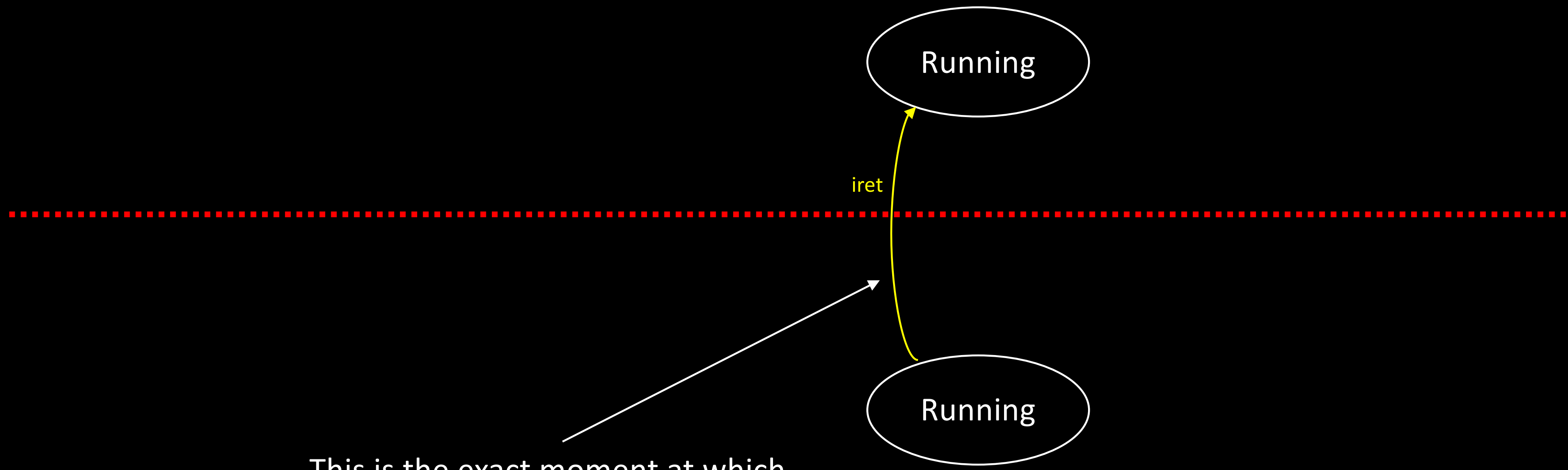
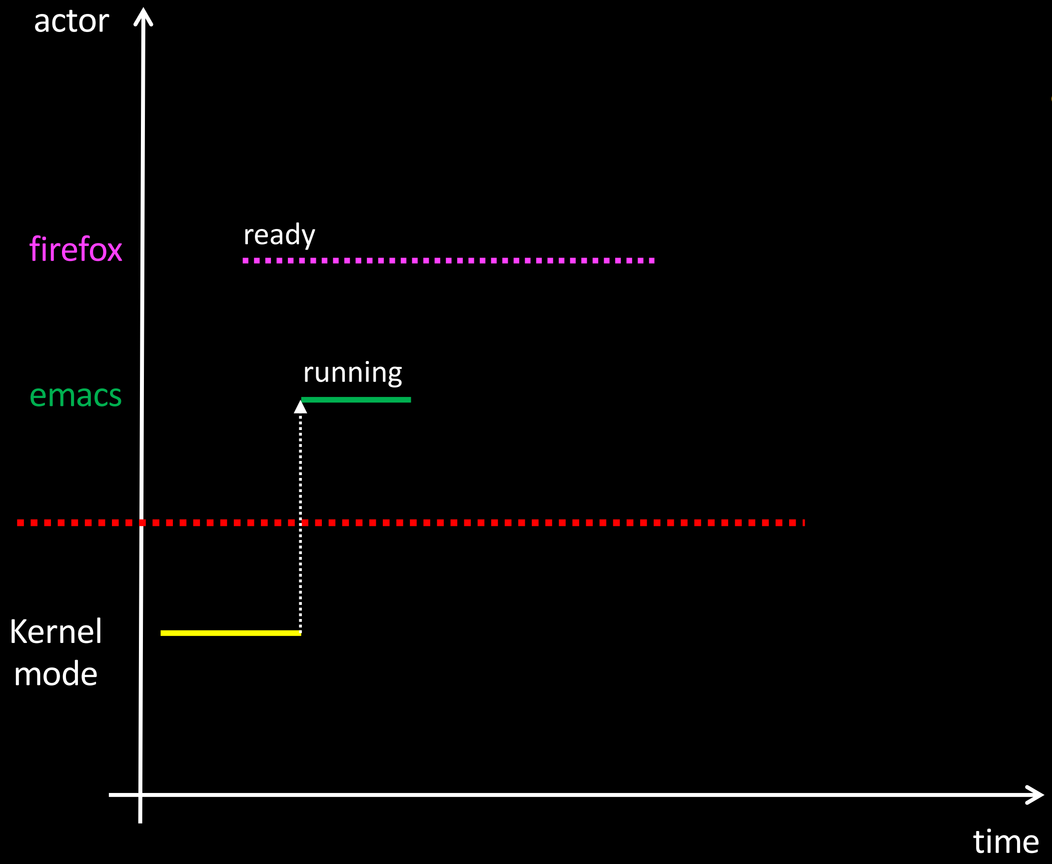


Oh, by the way…



This is the exact moment at which
pending signals are delivered

Handling of Blocking Calls



- Let's say emacs is running
  - Emacs spends its life
    - Waiting for keyboard input
    - Refreshing display

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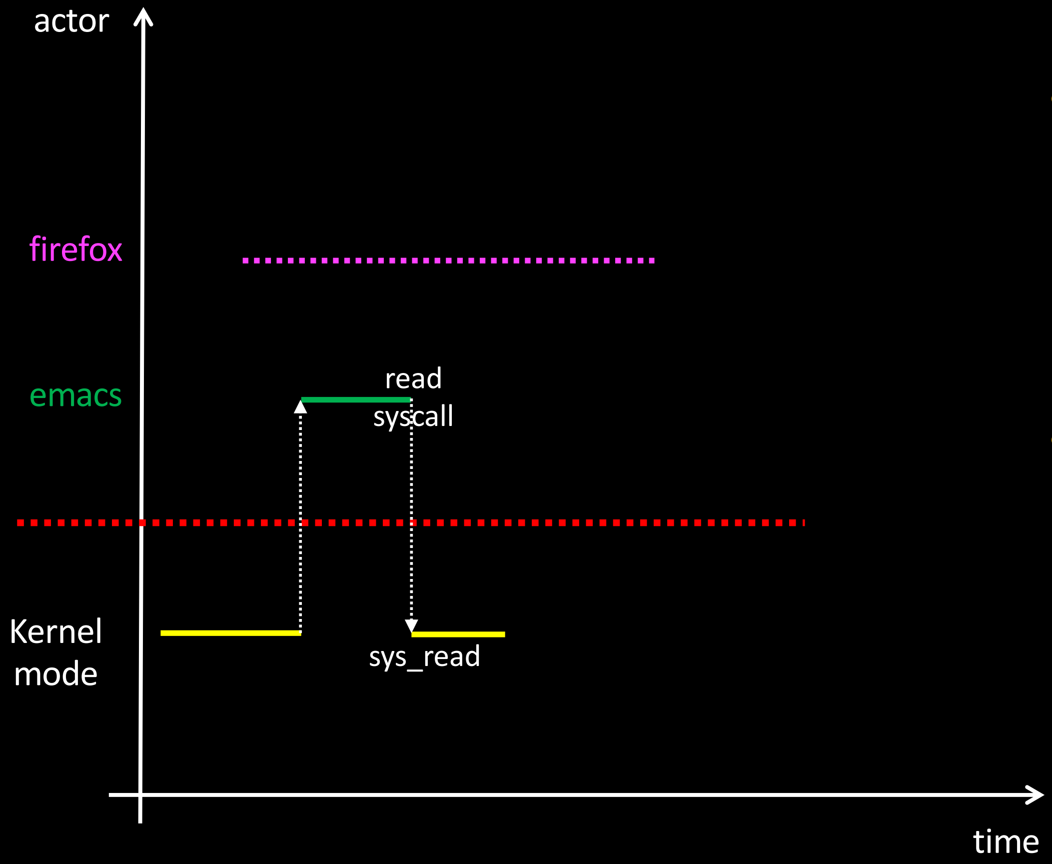

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- Waiting for keyboard input
  - `read` system call

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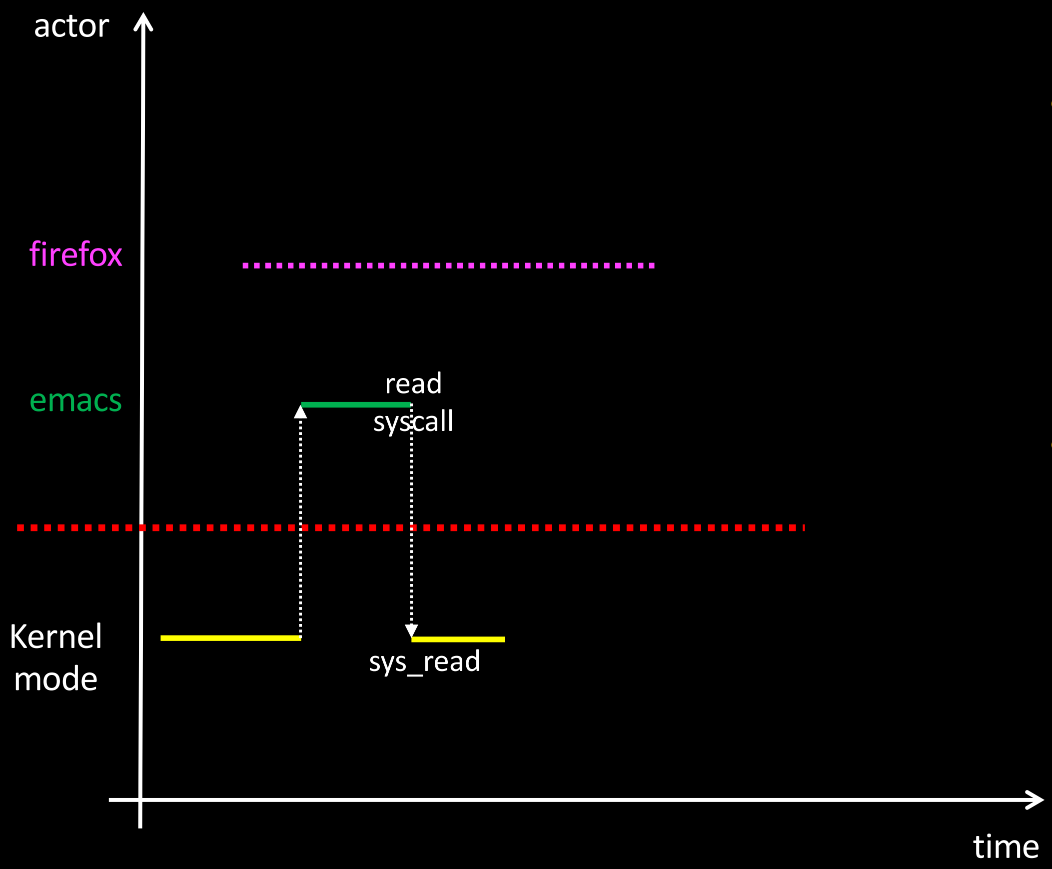

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  - `read` system call
  - Most of the time, keyboard buffer is empty

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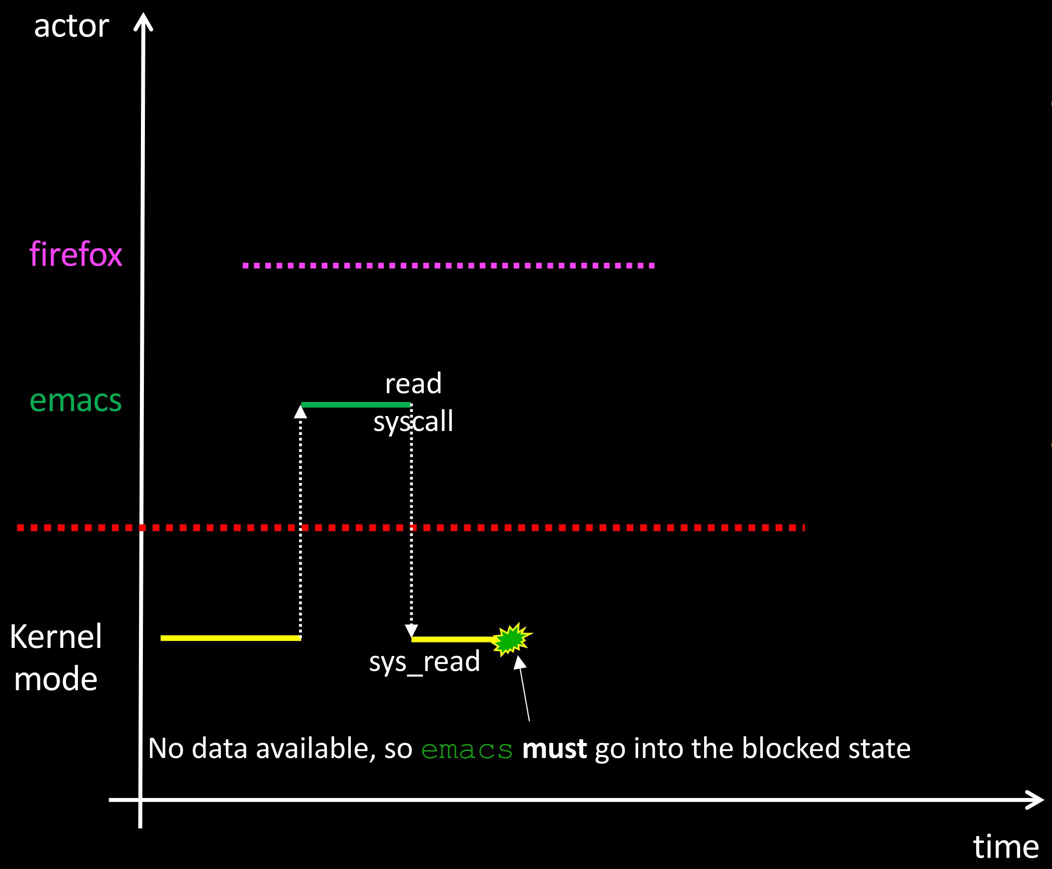

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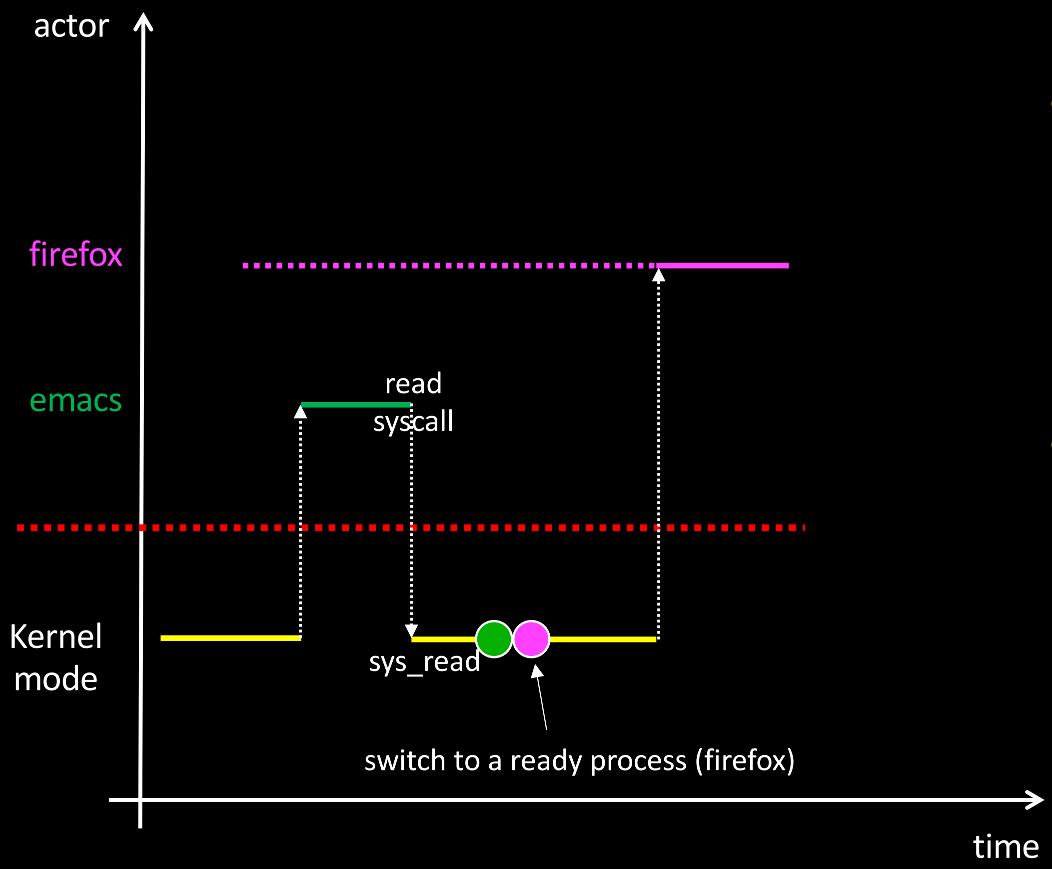

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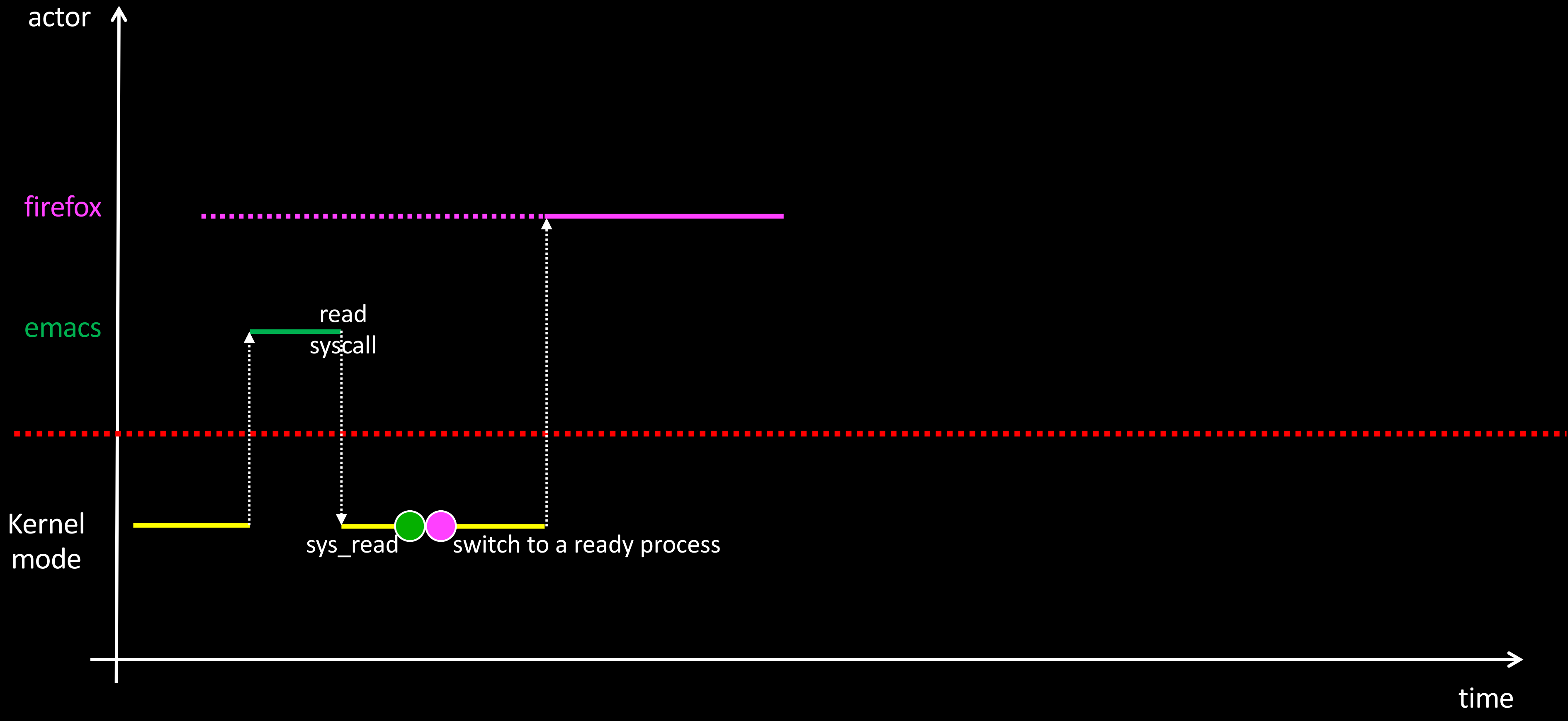

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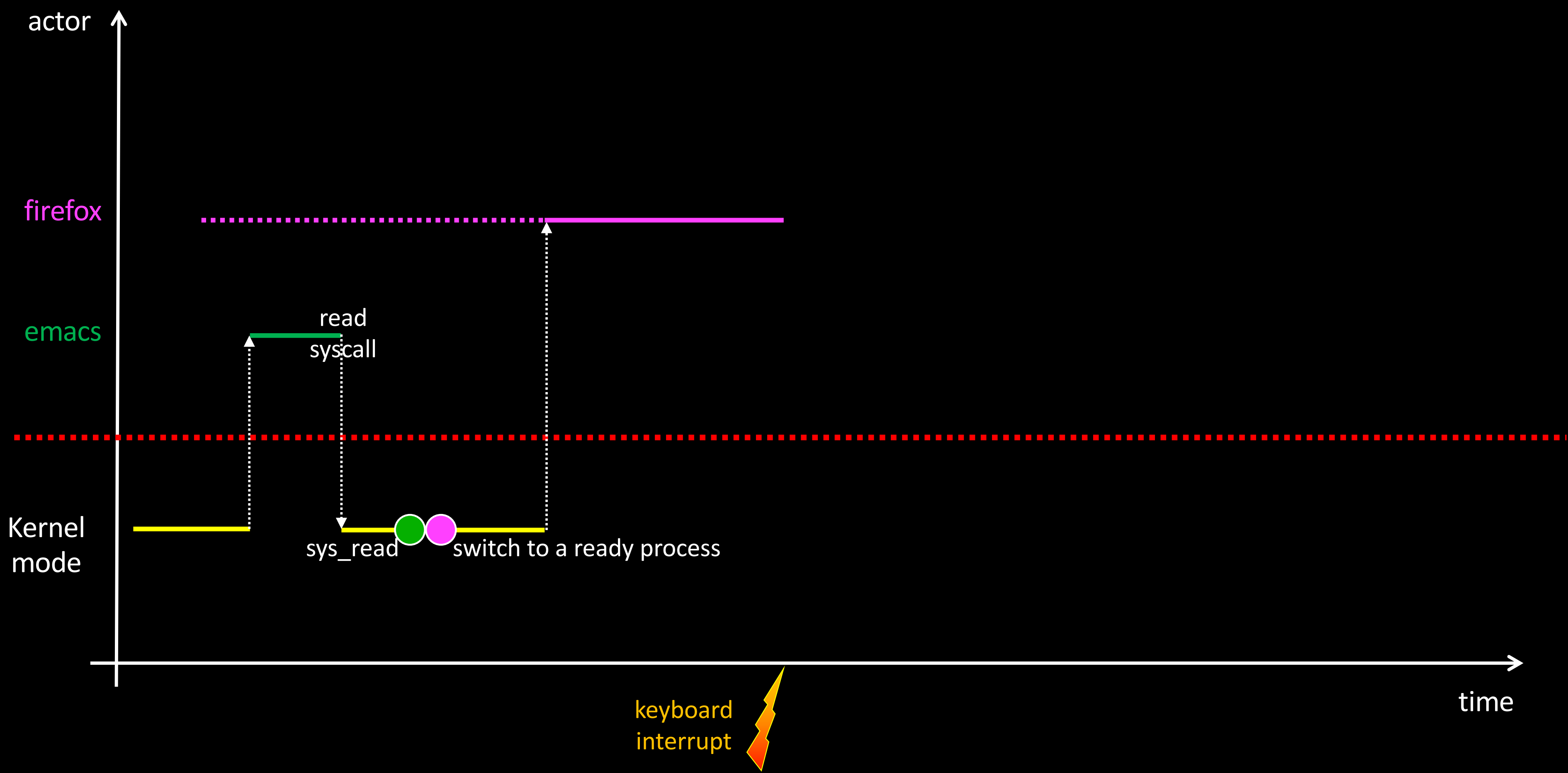

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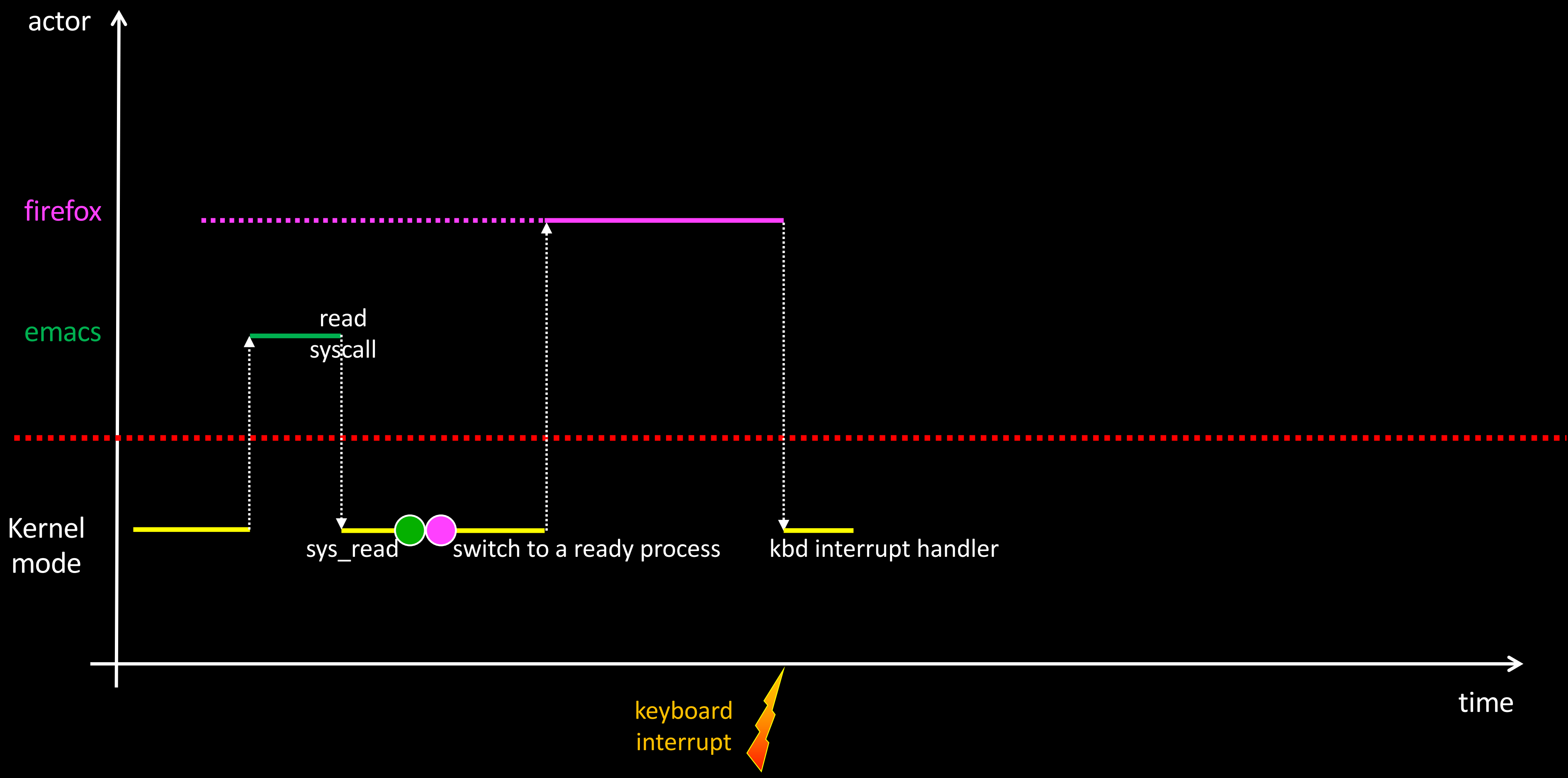

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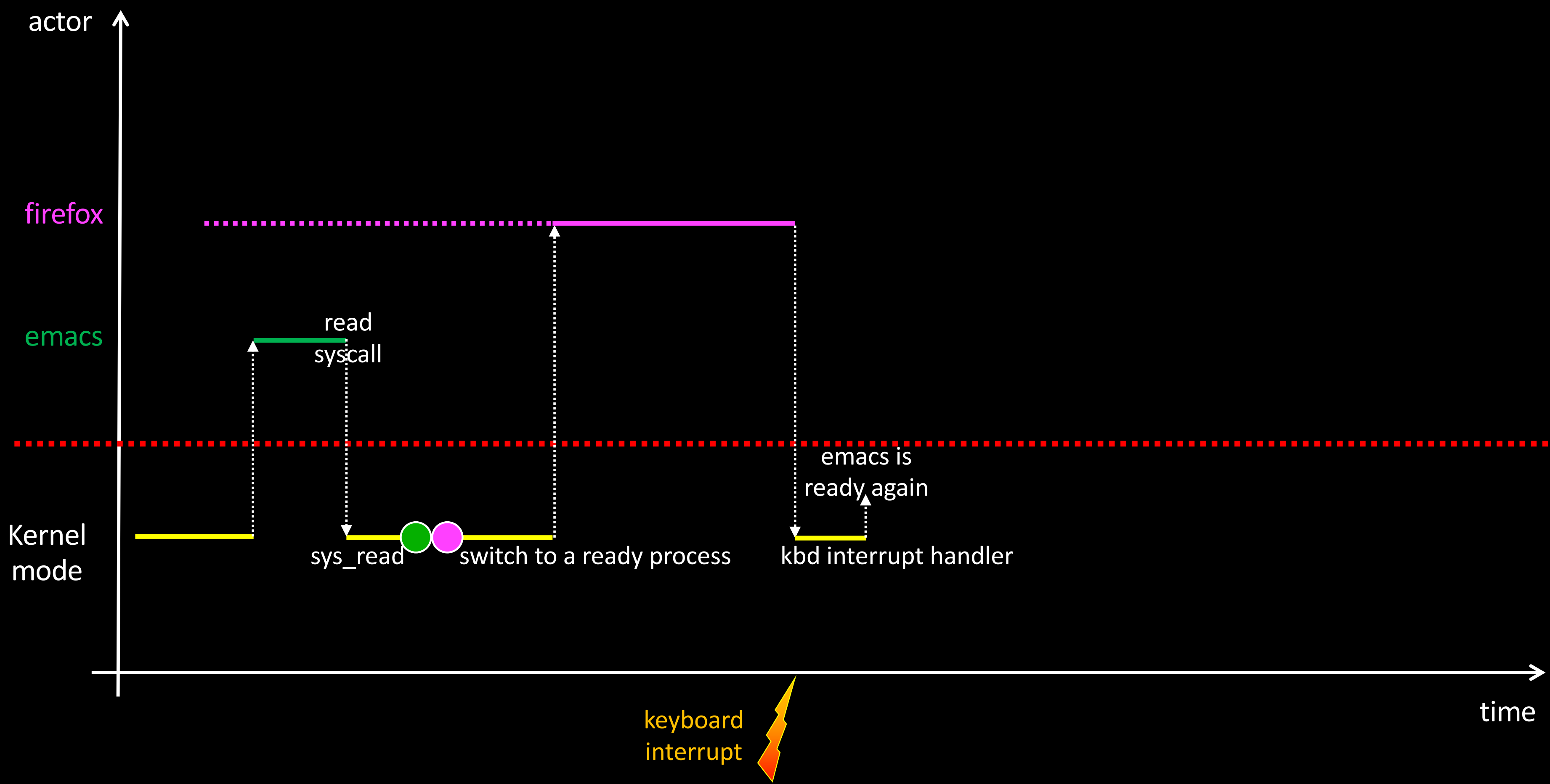

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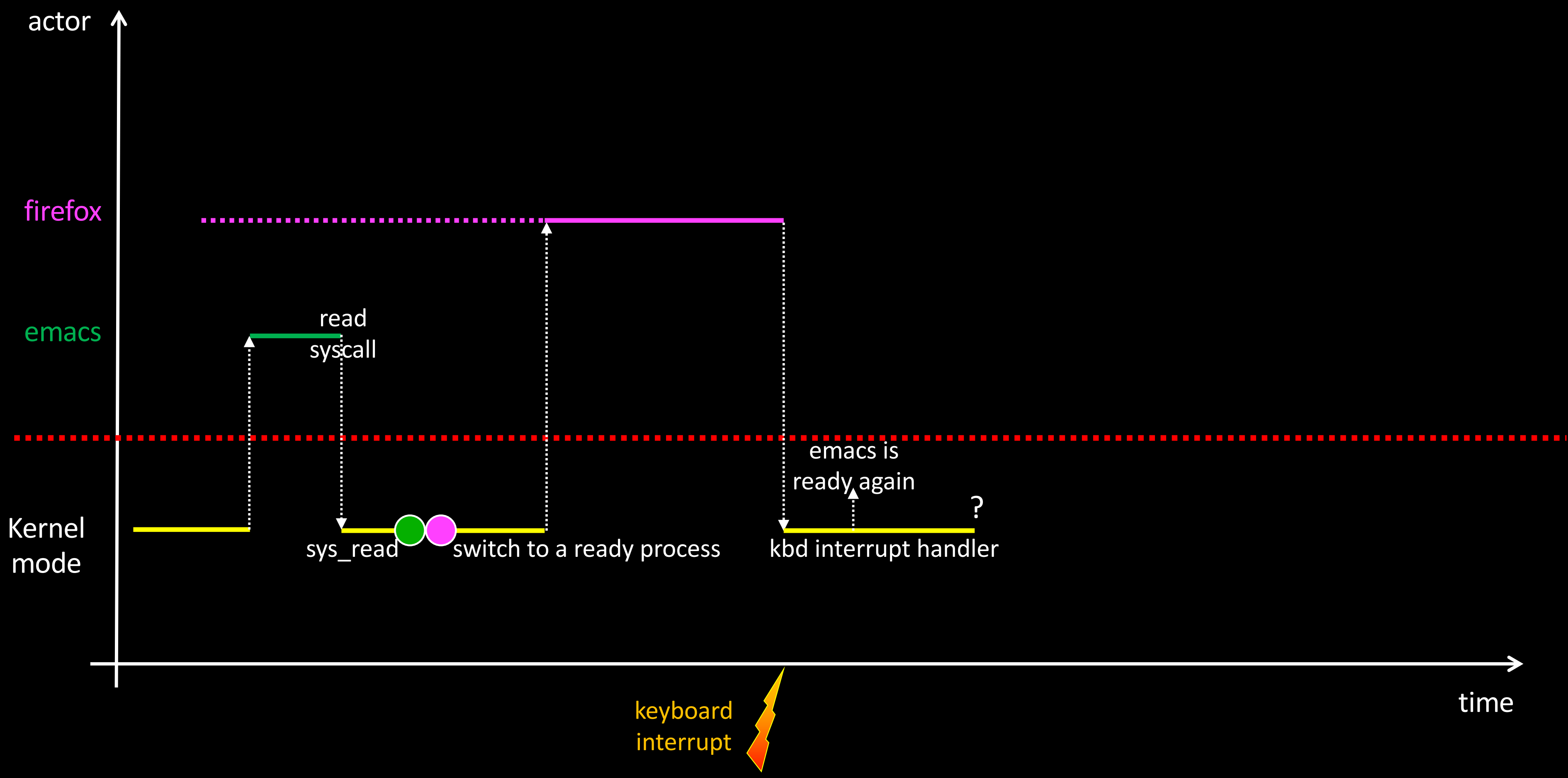

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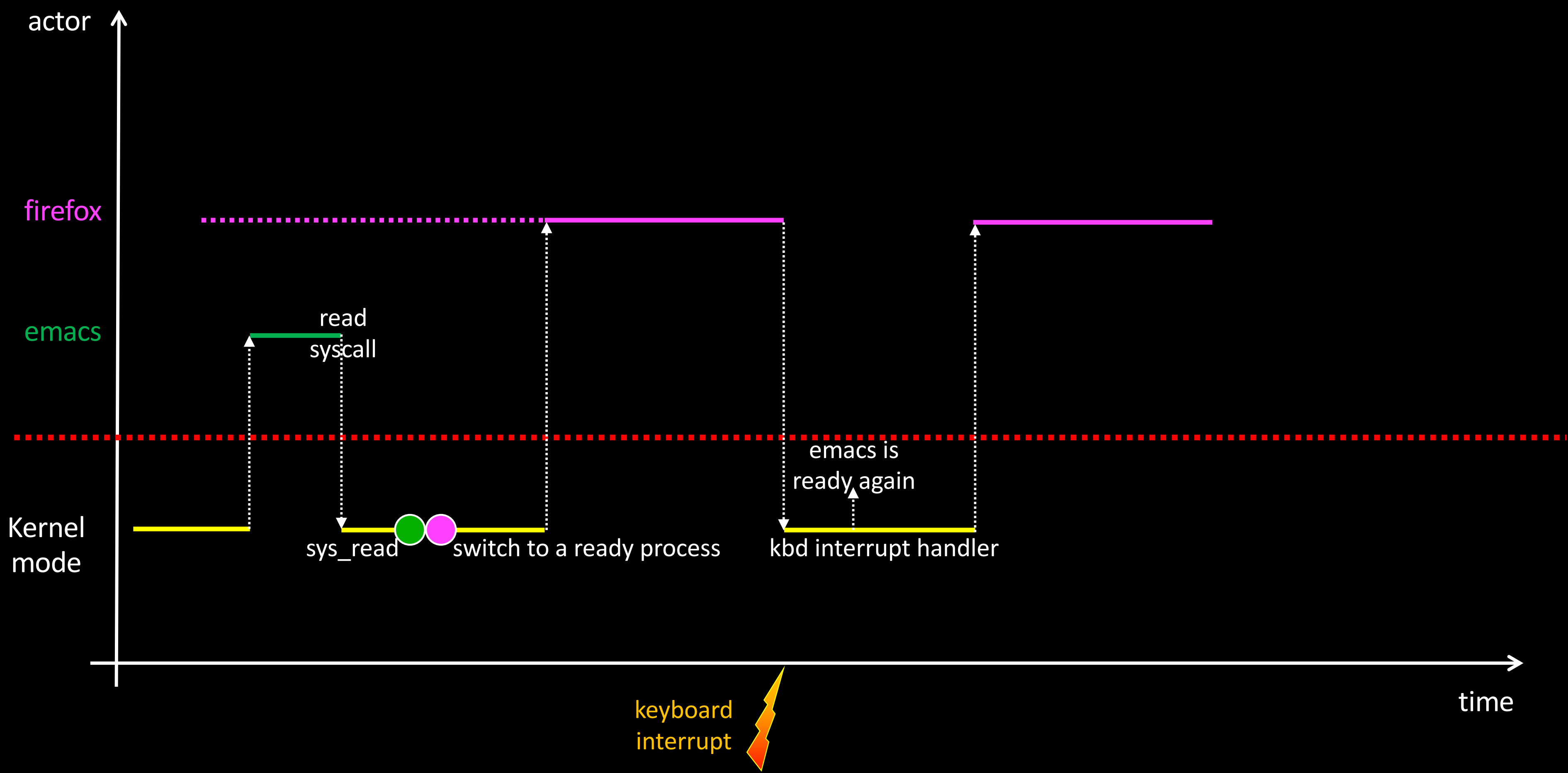

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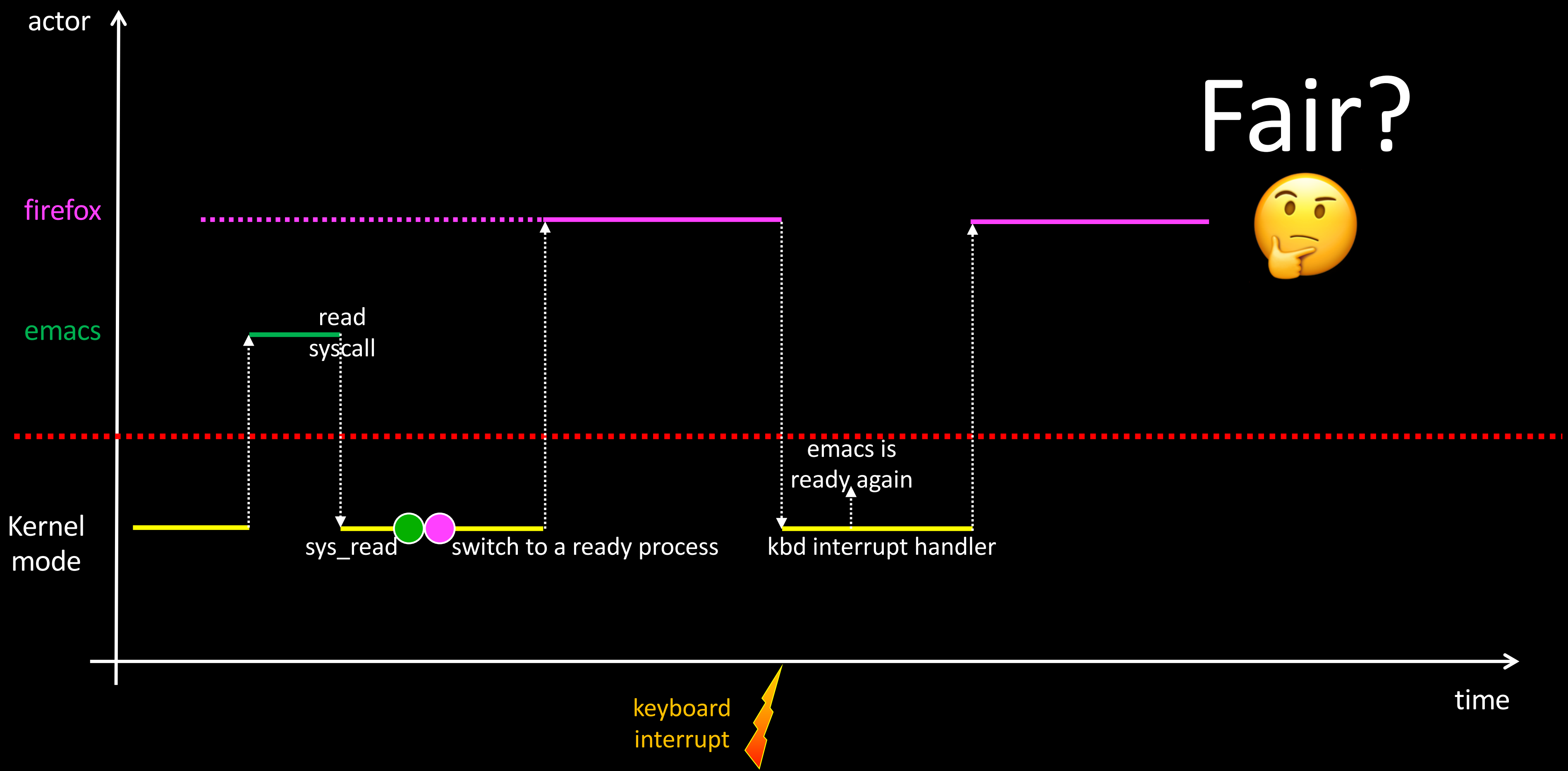


Scheduling

- General goal of a process scheduler
  - Optimize CPU usage and maximize user happiness
    - Each process has a fair access to the CPU
    - CPU is always running at 100%
    - Responsiveness of interactive processes is optimal
    - Completion time of long-running processes is minimal
    - Etc.
  - Satisfying these rules altogether is impossible
    - There is no such thing as a *Universal ~~Soldier~~ Scheduler*
    - Scheduling heavily depends on OS type
      - Interactive
      - Real-time
      - Batch server

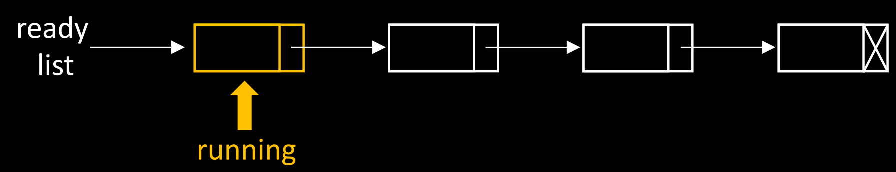
Scheduling in an interactive world

- Most critical property
  - Responsiveness of interactive processes is optimal
- Interactive processes
  - Processes reacting to I/O events
- Scheduling strategy
  - Scheduling algorithm
    - Election of next running process among the pool of ready ones
  - Places where the scheduling code is executed

The FIFO Scheduler

- Running process = head of ready list
    - Removed only when blocking or terminating
    - No periodic preemption

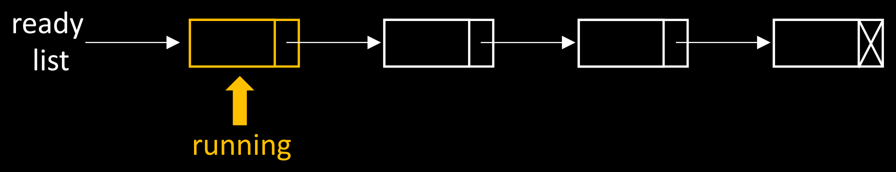
- Pros
    - ?
    - ?
- Cons
    - ?



The FIFO Scheduler

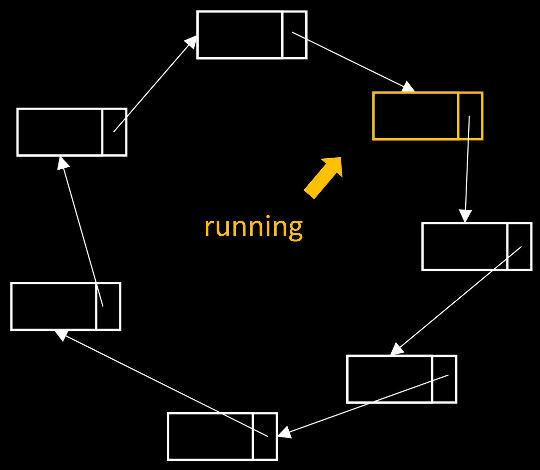
- Running process = head of ready list
  - Removed only when blocking or terminating
  - No periodic preemption

- Pros
  - Very small overhead
  - O(1) election algorithm
- Cons
  - Starvation



The Round-Robin Scheduler

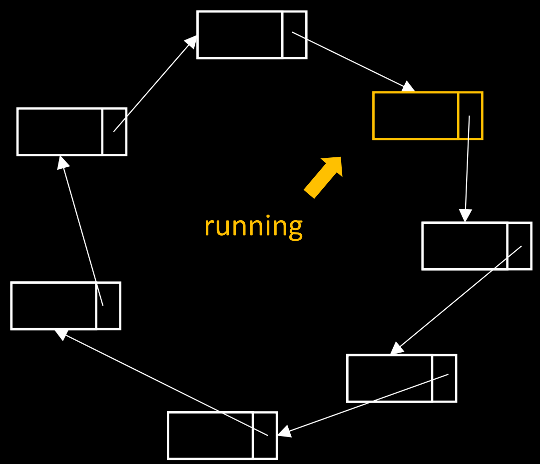
- FIFO + preemption
  - At each timer interrupt, the running process yields CPU to its successor



- Pros
  - ?
  - ?
- Cons
  - ?

The Round-Robin Scheduler

- FIFO + preemption
  - At each timer interrupt, the running process yields CPU to its successor
- Pros
  - No starvation
  - O(1) scheduler
- Cons
  - No priority

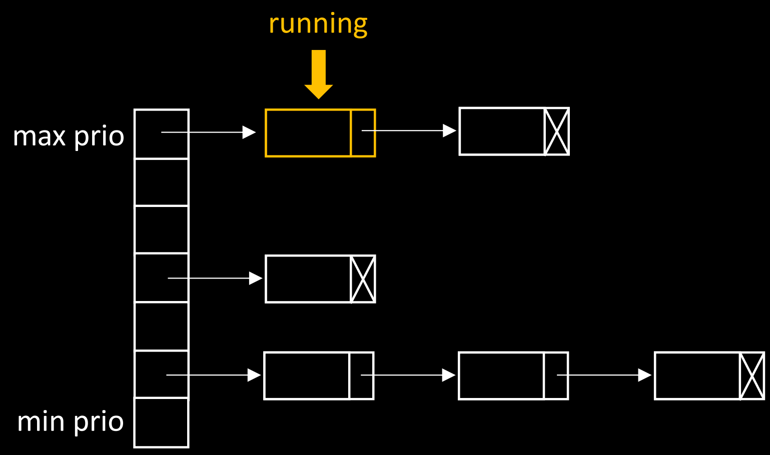


The (strict) Priority Scheduler

- Used in Real-time systems
- One FIFO list per priority level

- Running process = head of highest non-empty priority list

- Pros
  - O(#priorities) scheduler
- Cons
  - ?



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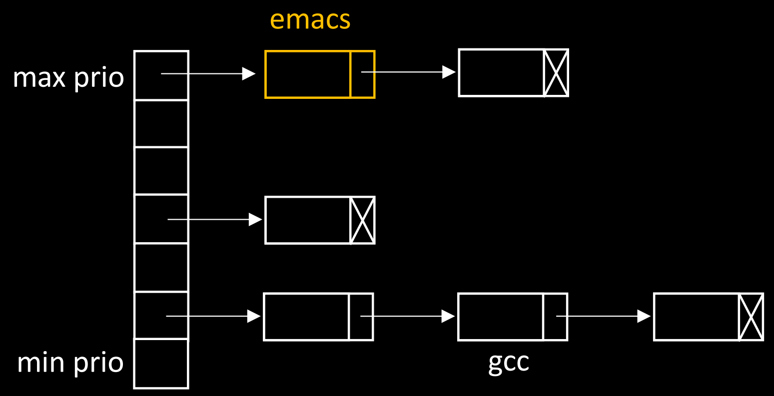
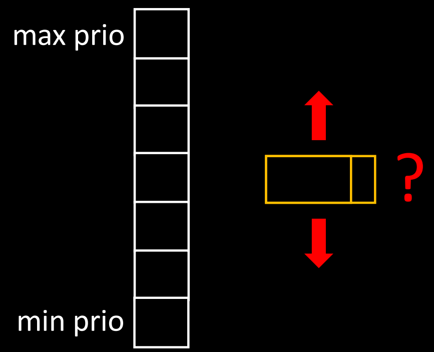
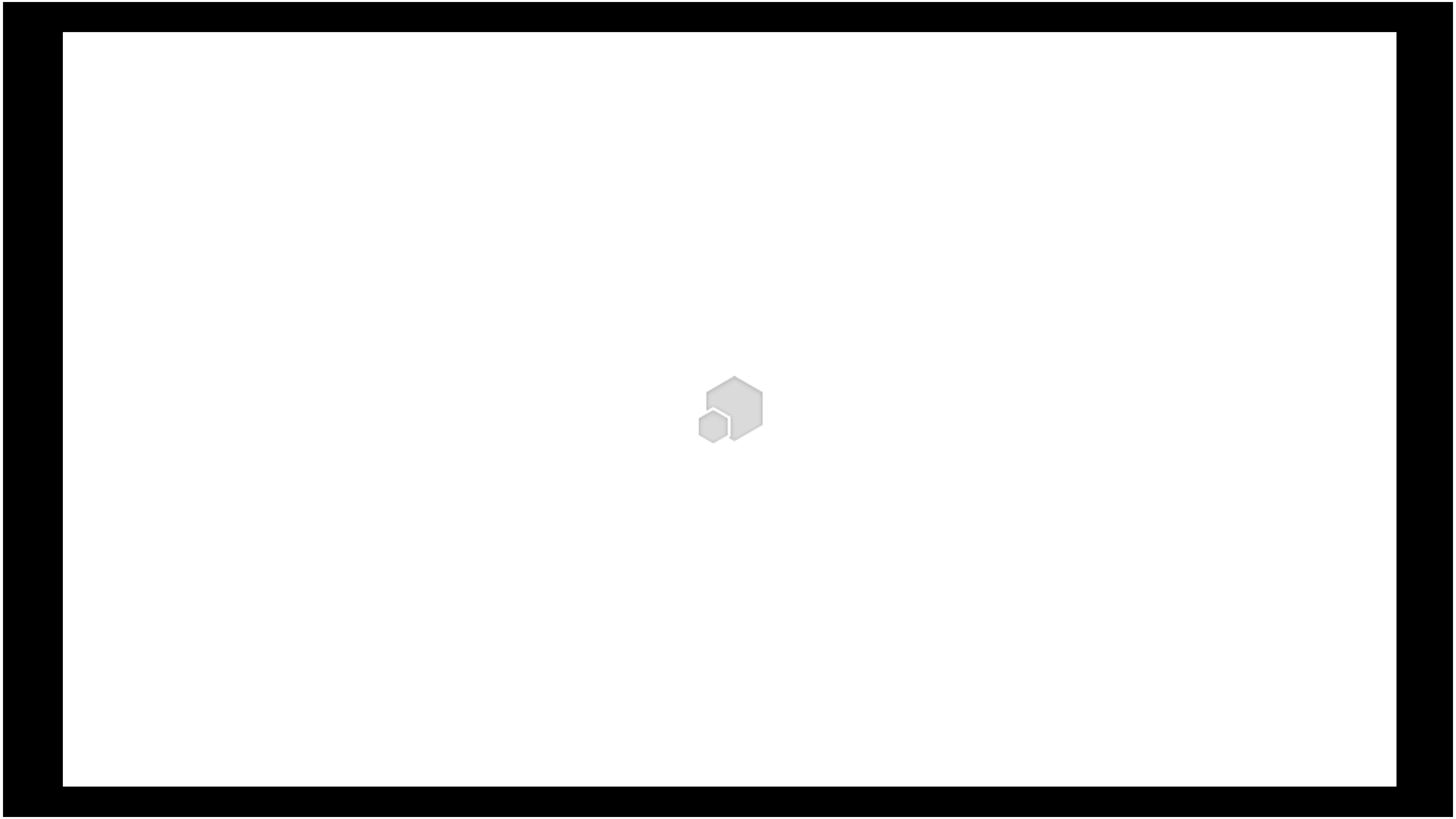


- Pros
  - O(#priorities) scheduler
- Cons
  - How to assign priorities to processes?

Assigning dynamic priorities to processes

- We'd like to assign higher priorities to "cool" processes
    - Which need to react quickly to events?
    - Which perform a lot of I/O?
    - Which won't use a full quantum of time (10ms) next time?





Assigning dynamic priorities to processes

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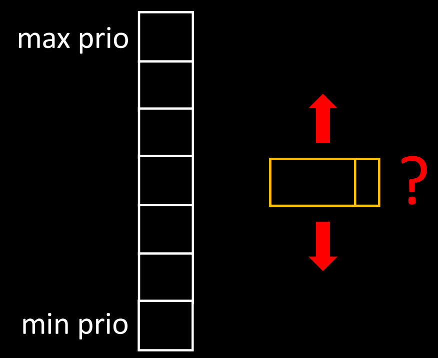
  - Which need to react quickly to events?
  - Which perform a lot of I/O?
  - Which won't use a full quantum of time (10ms) next time?

- How do we know?
  - People can change…
    - *"If I can change, and you can change, everybody can change!"*
      [Rocky Balboa, 1985]



Predicting the Future ?

Predicting the Future

- By looking at the past!
  - If a process kept behaving well so far…
    …it will probably do so next time we schedule it!

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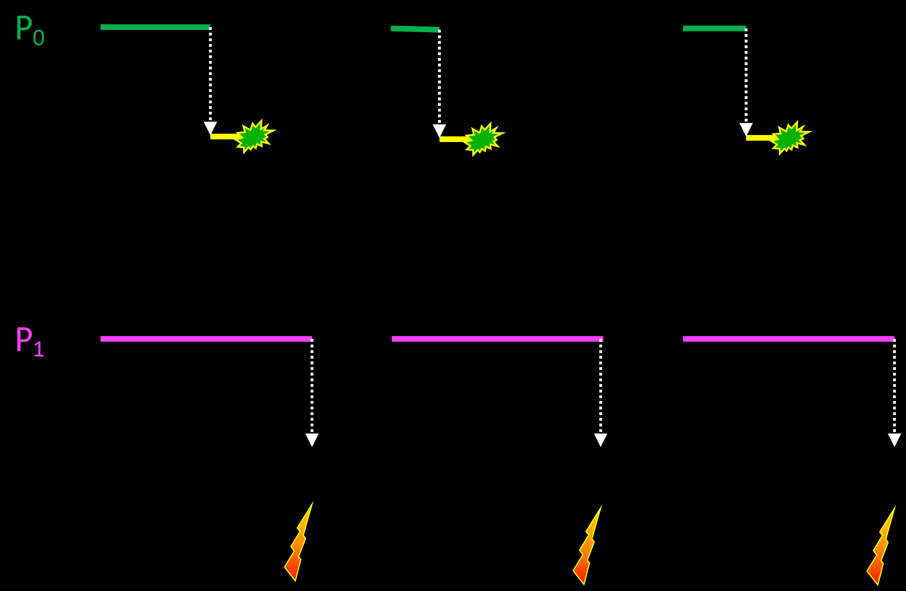
- P_0 looks more friendly than P_1



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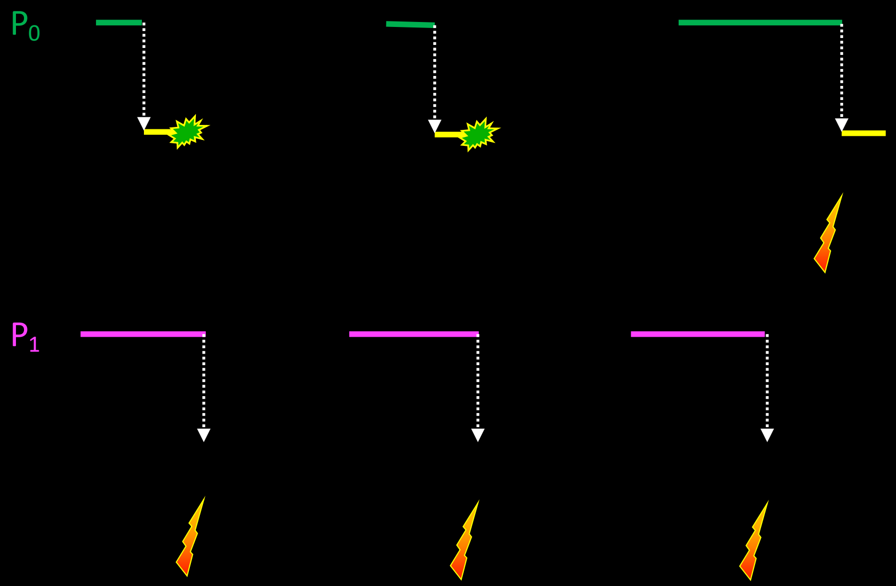
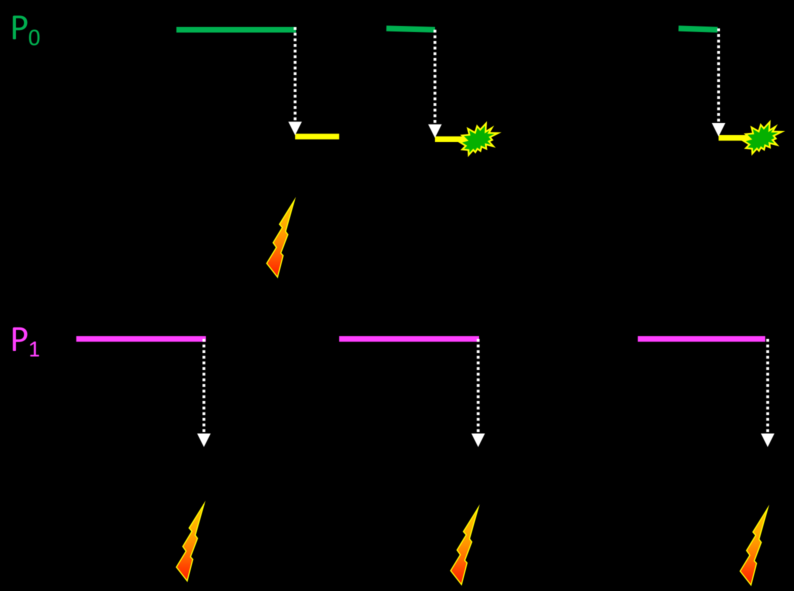


Predicting the Future

- By looking at the past!
  - If a process kept behaving well so far…
    …it will probably do so next time we schedule it!

- P_0 looks more friendly than P_1
  - Really?
  - Can we forgive P_0?



Estimating duration of the next quantum

- T_n: CPU utilization observed at step n
- E_n: estimation of the CPU utilization time at step n

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  - $E_n = \alpha(T_{n-1}) + (1 - \alpha)E_{n-1}$

Estimating duration of the next quantum

- T_n: CPU utilization observed at step n
- E_n: estimation of the CPU utilization time at step n
  - $E_n = \alpha(T_{n-1}) + (1-\alpha)E_{n-1}$

- $\alpha = 0$
  - Fixed, a priori estimation
- $\alpha = 1$
  - We only look at the last period
- $\alpha = \frac{1}{2}$
  - $E_1 = T_0$
  - $E_2 = \frac{1}{2}T_1 + \frac{1}{2}T_0$
  - $E_3 = \frac{1}{2}T_2 + \frac{1}{4}T_1 + \frac{1}{4}T_0$

From Estimation to Priority

- OK, we can predict how long each process will run next time it is scheduled
  - Which process do we choose?
- Try to maximize average happiness!
  - Think about queues at the supermarket!

From Estimation to Priority

- To maximize average happiness
  - We should minimize average waiting time
    - Schedule shortest jobs first!

From Estimation to Priority

- To maximize average happiness
  - We should minimize average waiting time
    - Schedule shortest jobs first!
- Priority should be inversely proportional to E_n
  - Interactive Operating Systems schedulers try, more or less, to follow this strategy

Strategy used in Linux 2.4.x kernels

- Credits are assigned to processes, based on their fixed priority
  - Sort of “*pocket money*”
- To run on the CPU, a process must spend money
  - No more money = no CPU
- At some point, no more ready processes have money left
  - The kernel restarts a new epoch and redistributes credits

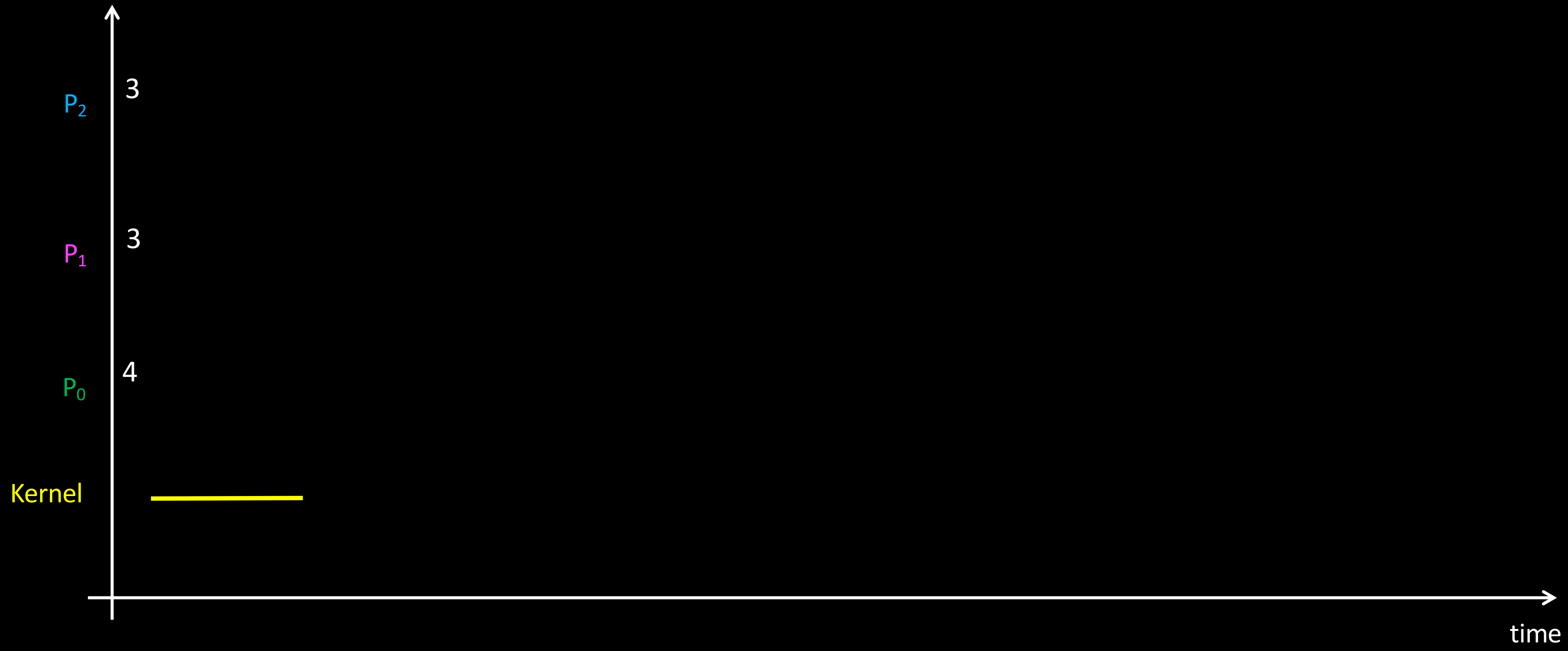
Strategy used in Linux 2.4.x kernels

- Credits are assigned to processes, based on their fixed priority
  - Let us take a concrete, simple example with 3 processes
  - Initially:
    - P_0 has 4 credits
    - P_1 has 3 credits
    - P_2 has 3 credits

Strategy used in Linux 2.4.x kernels

- Credits are assigned to processes, based on their fixed priority
  - Let us take a concrete, simple example with 3 processes
  - Initially:
    - P_0 has 4 credits
    - P_1 has 3 credits
    - P_2 has 3 credits
  - Rich people are usually privileged, aren't they?
    - So P_0 will be the next running process

Strategy used in Linux 2.4.x kernels



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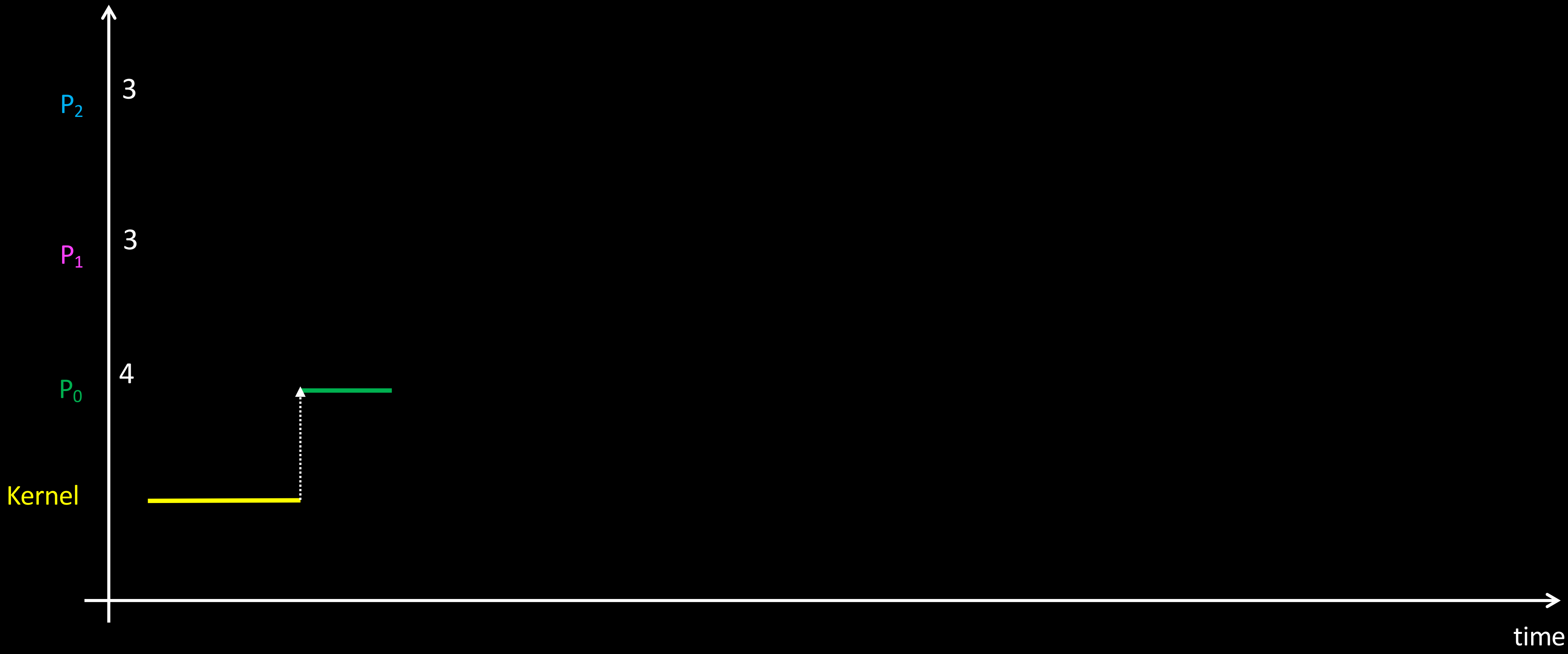

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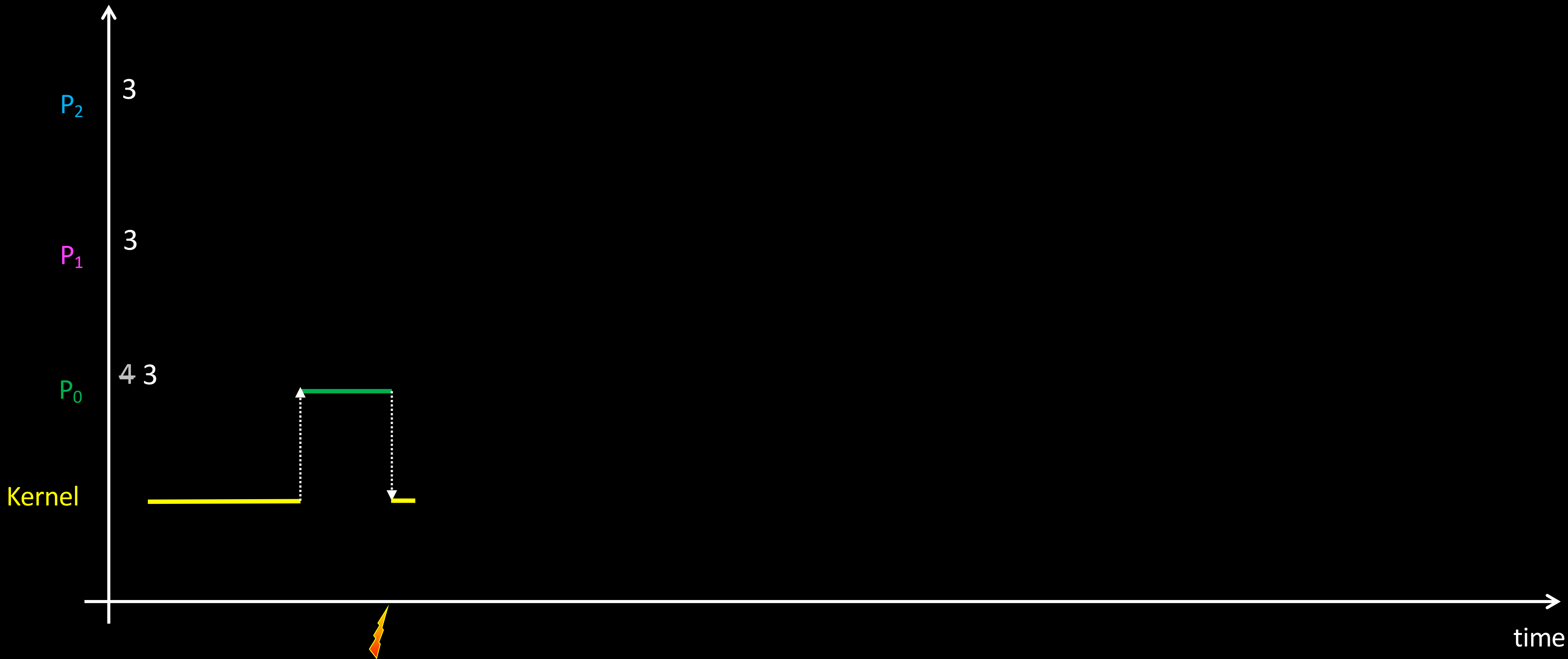

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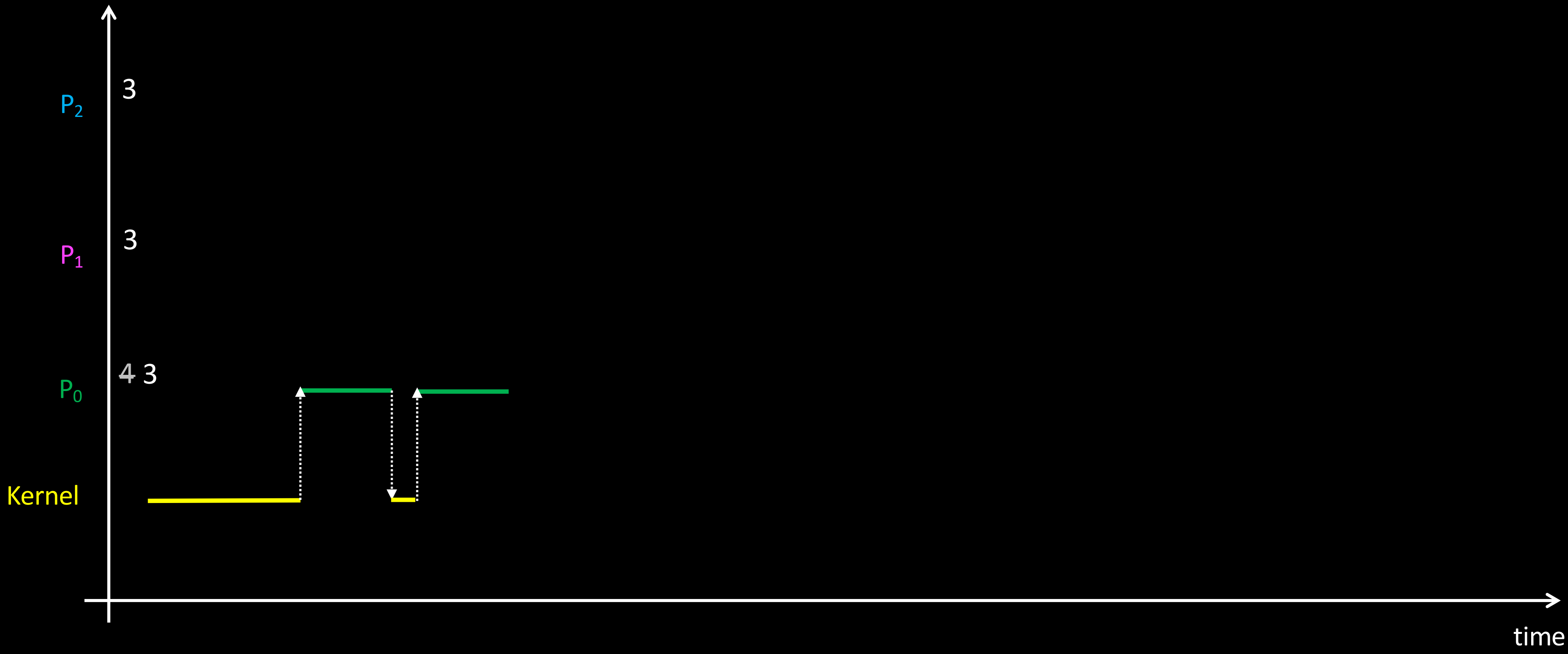

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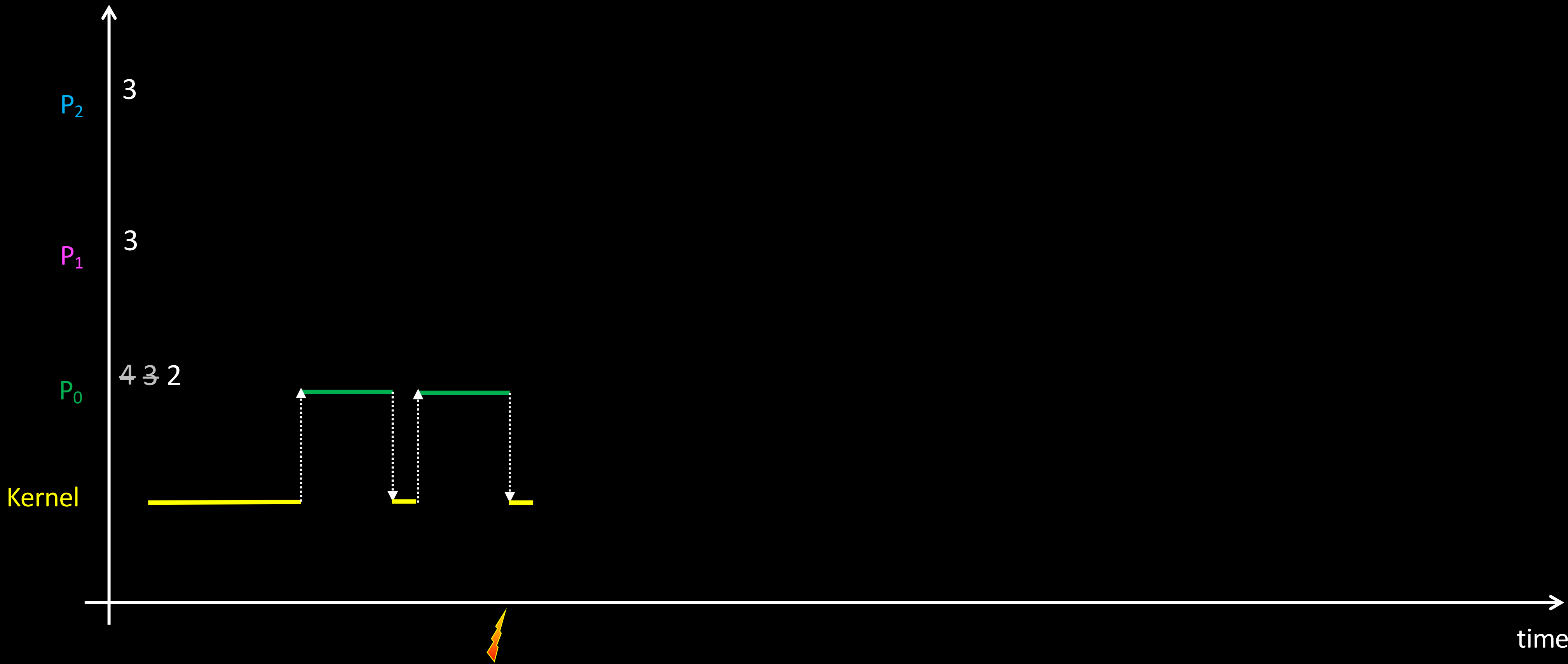

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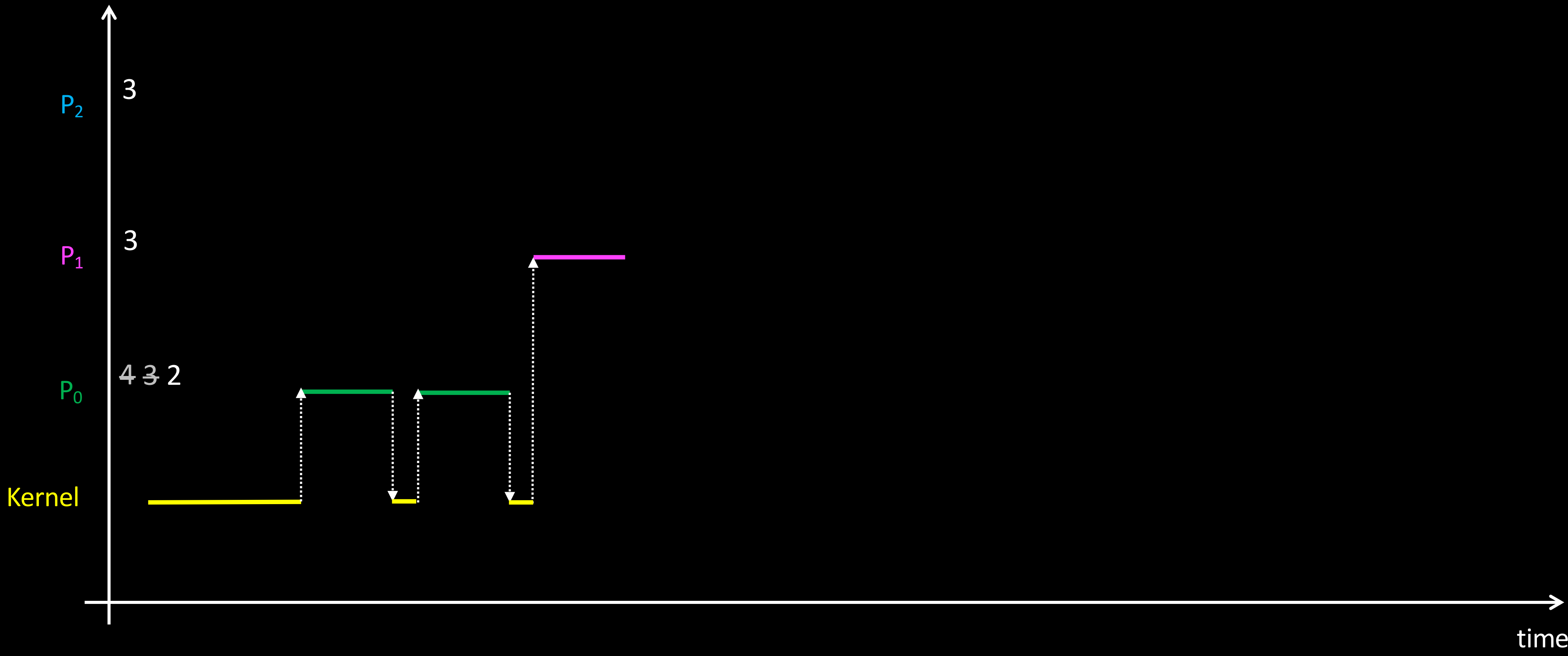

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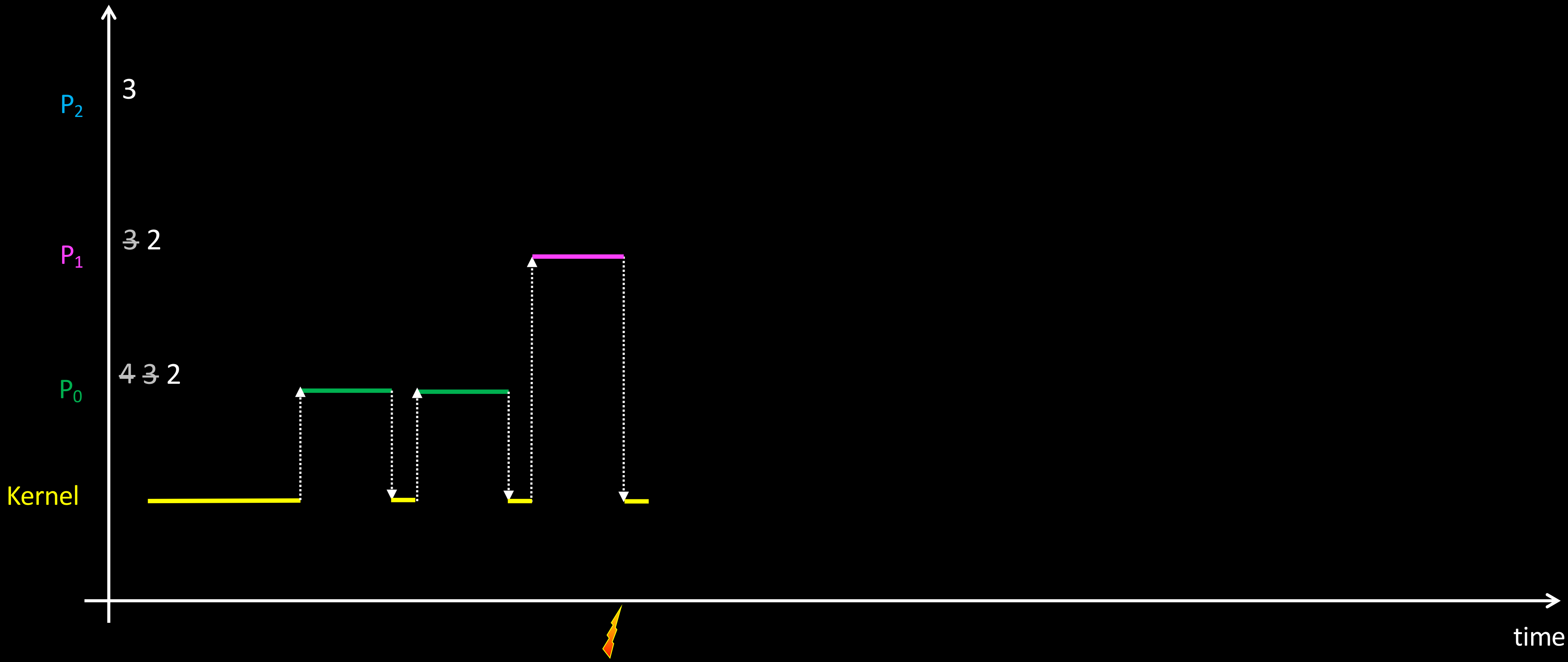

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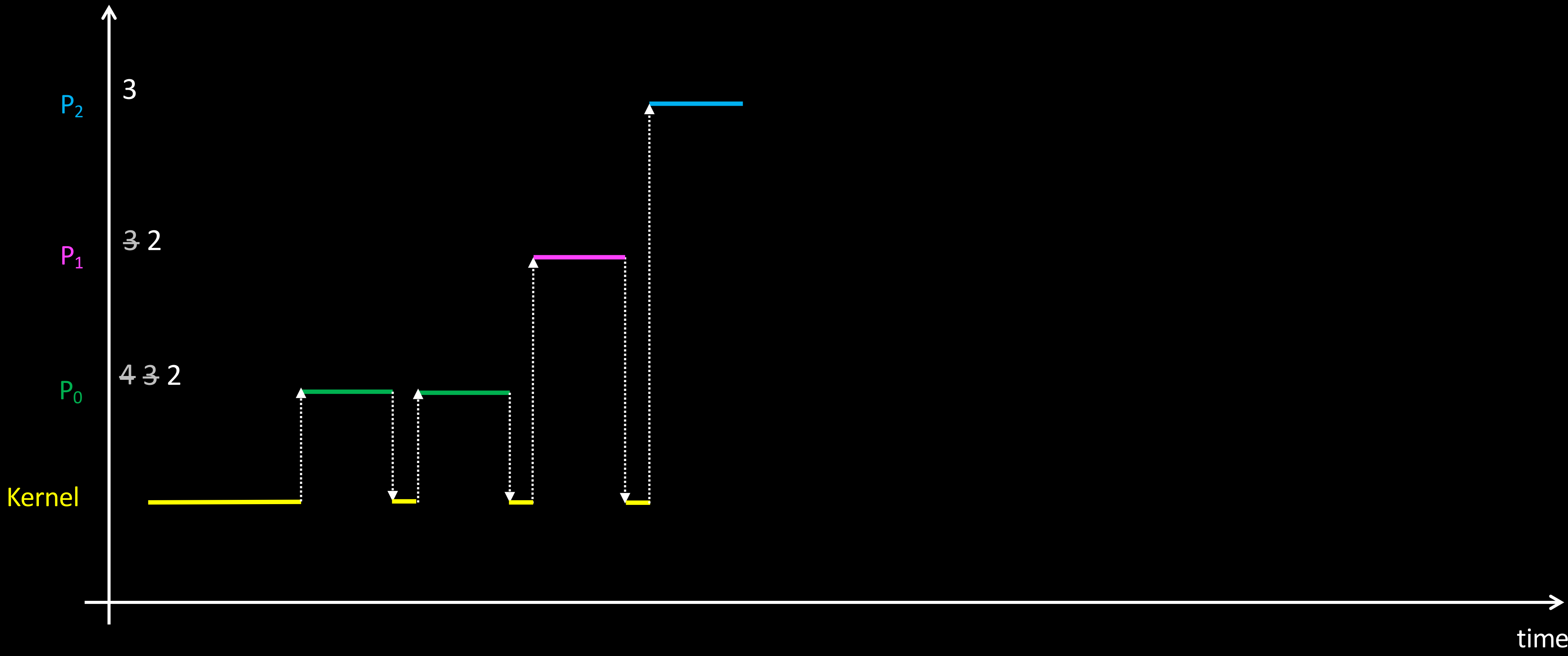

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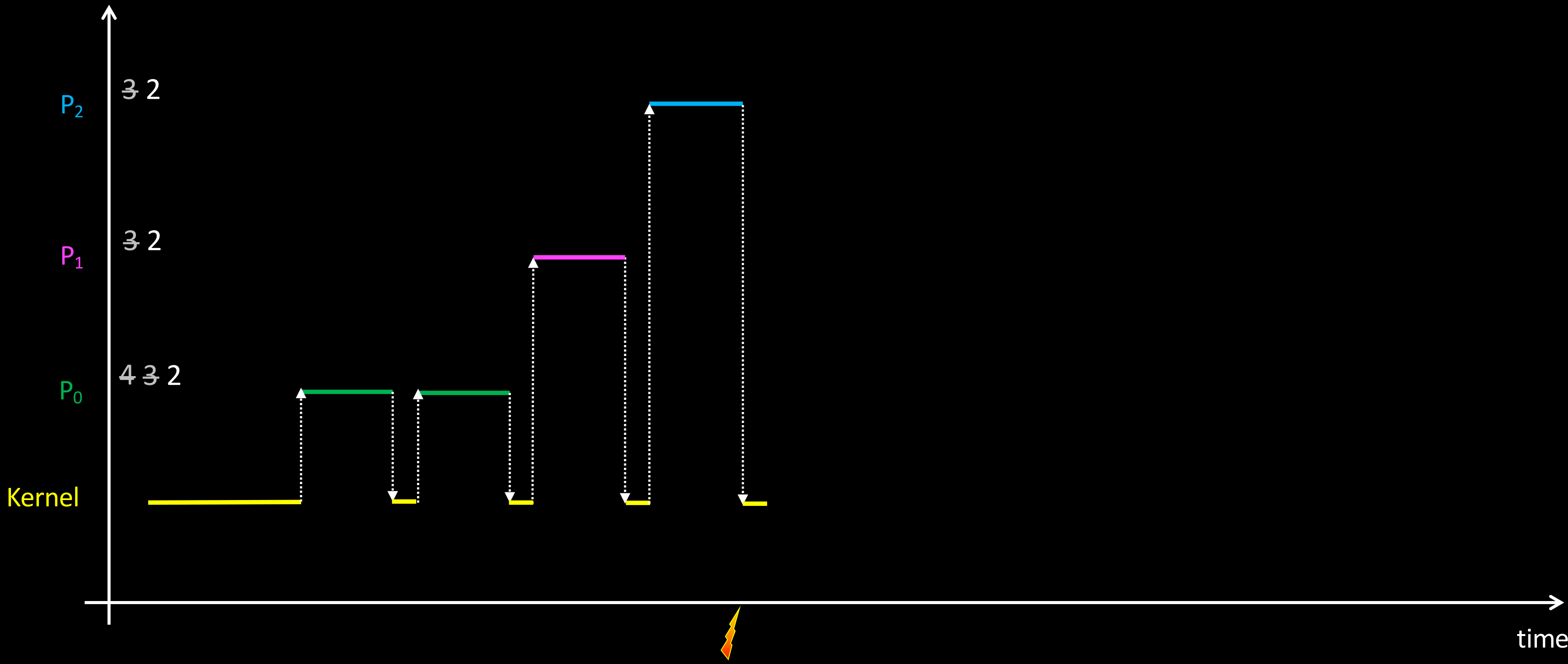

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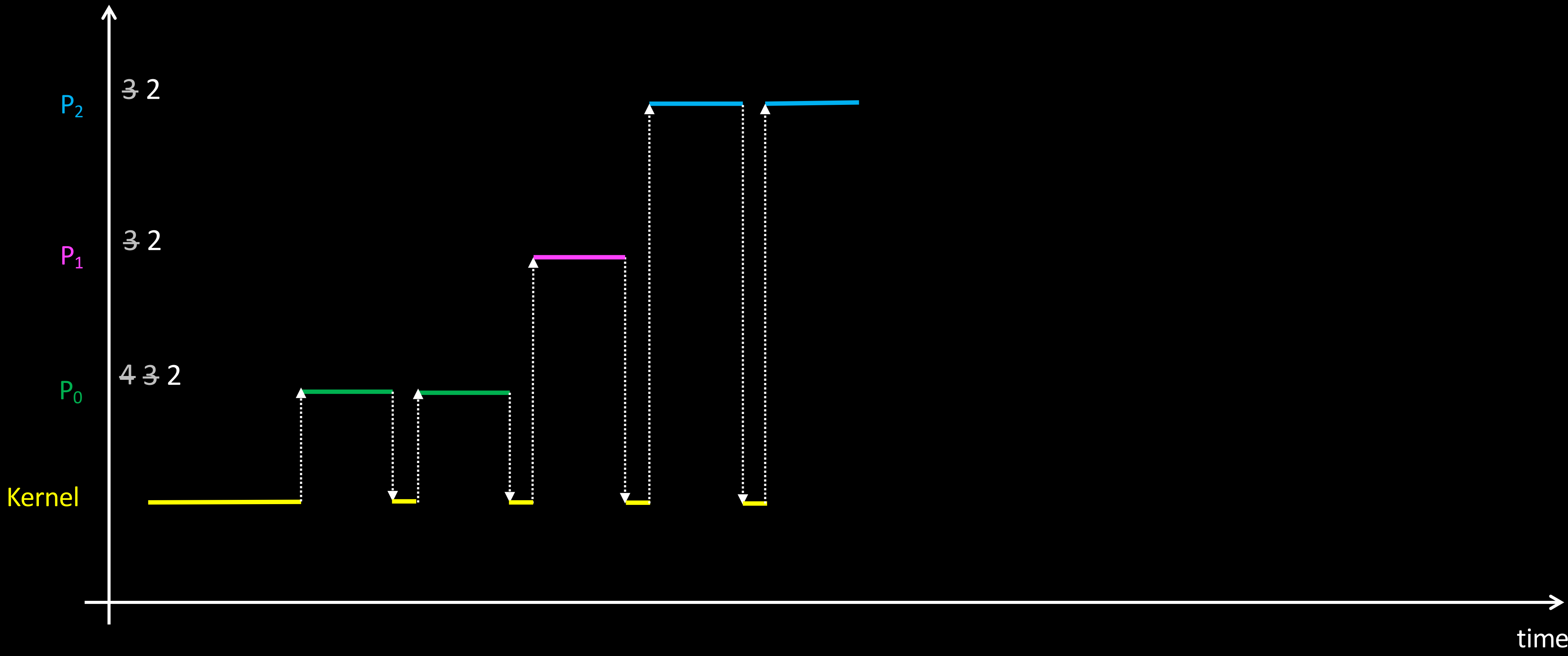

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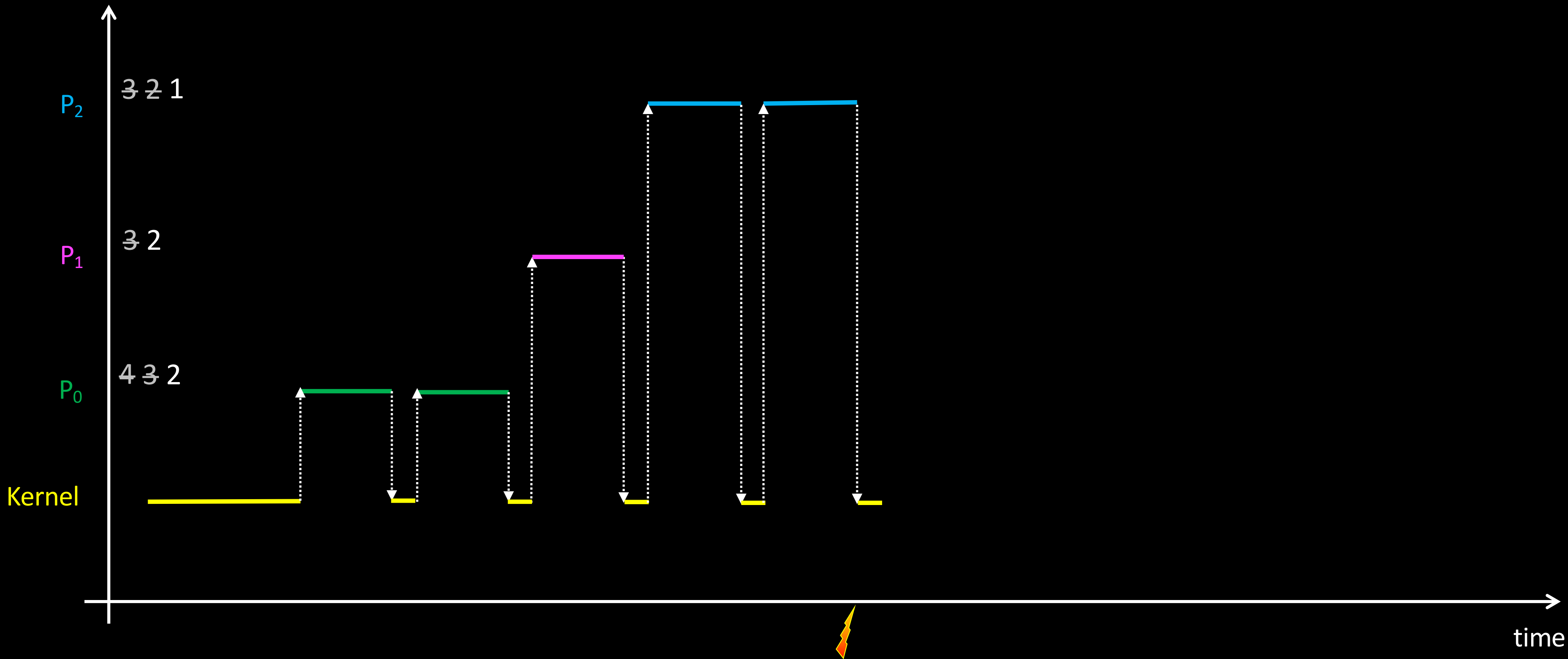

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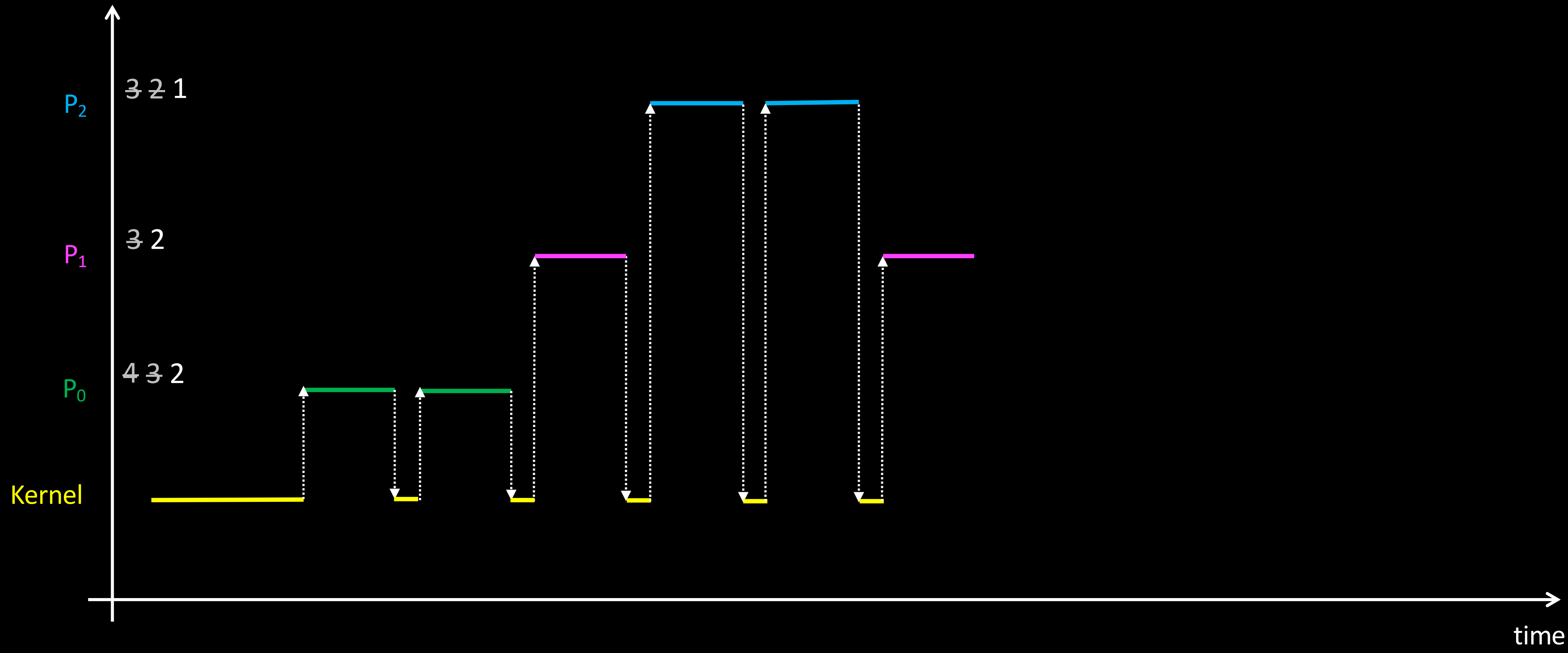

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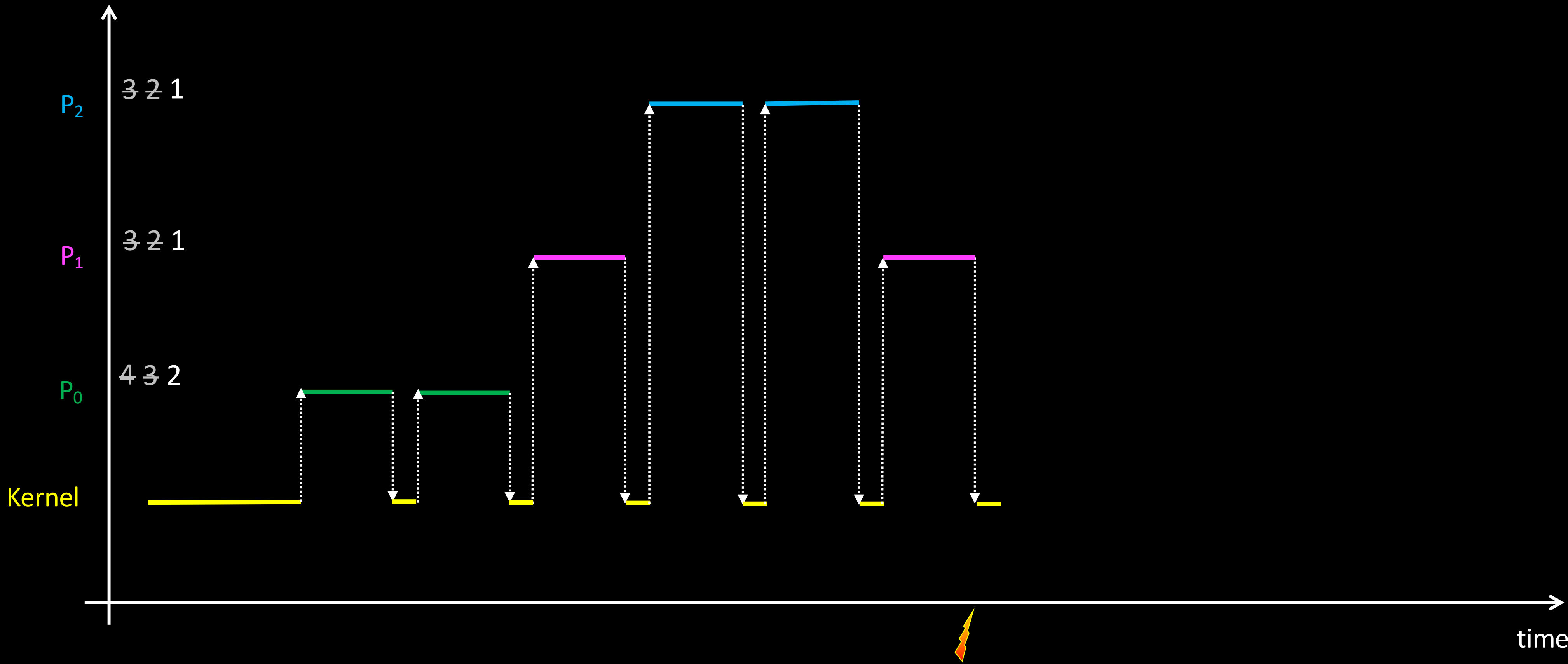

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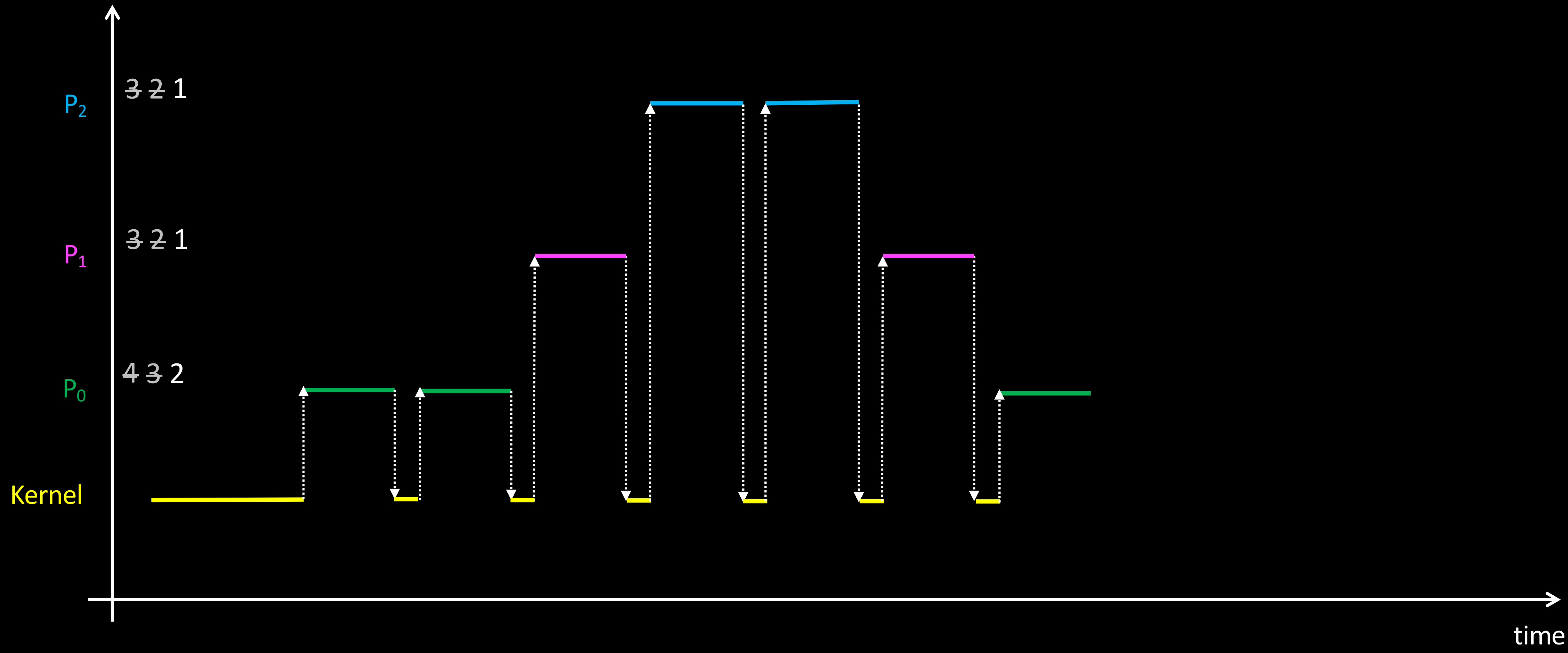

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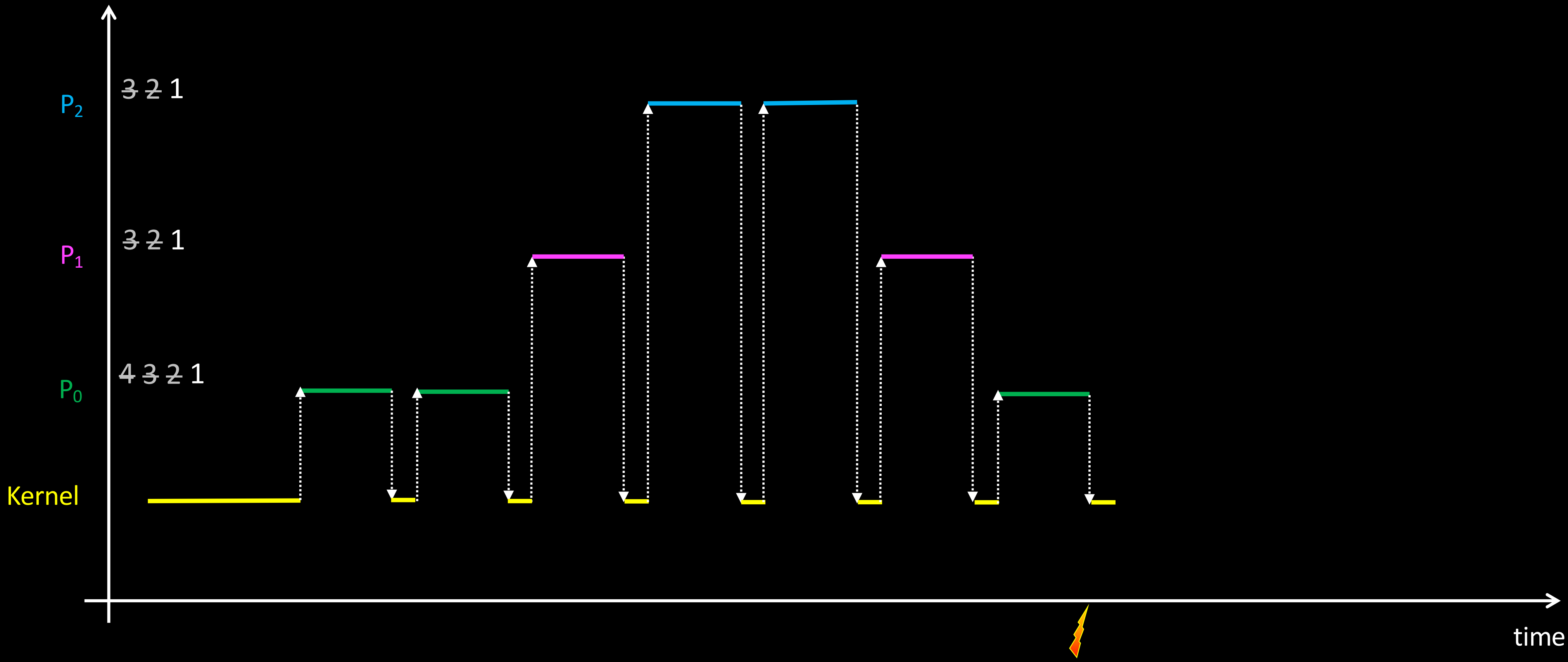

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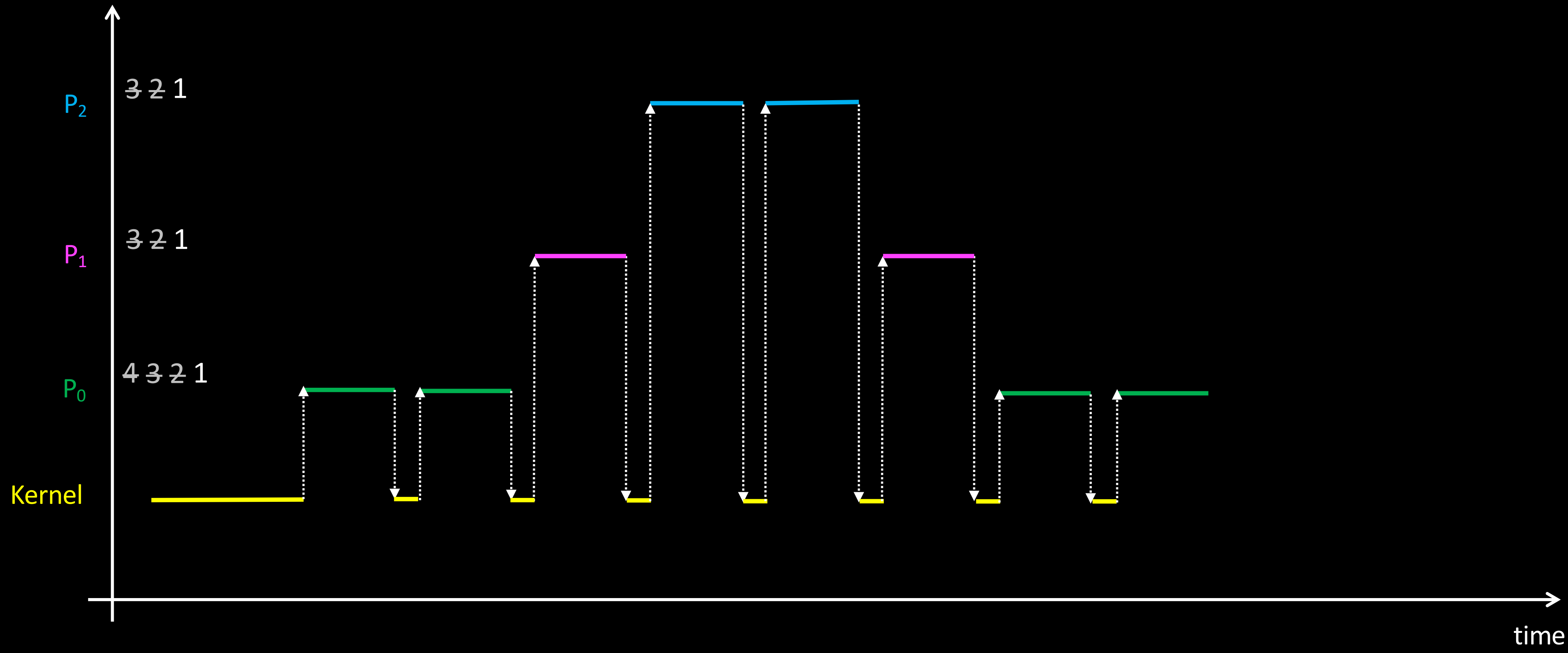

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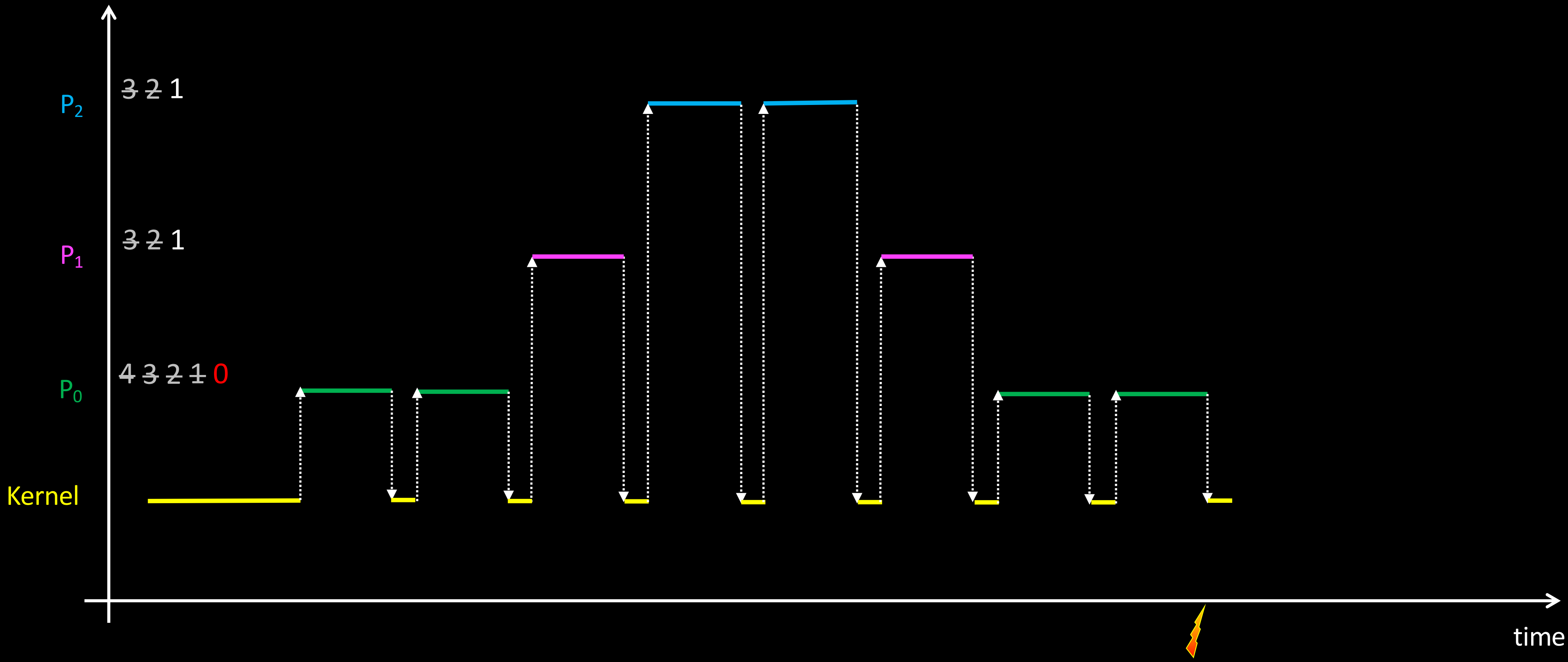

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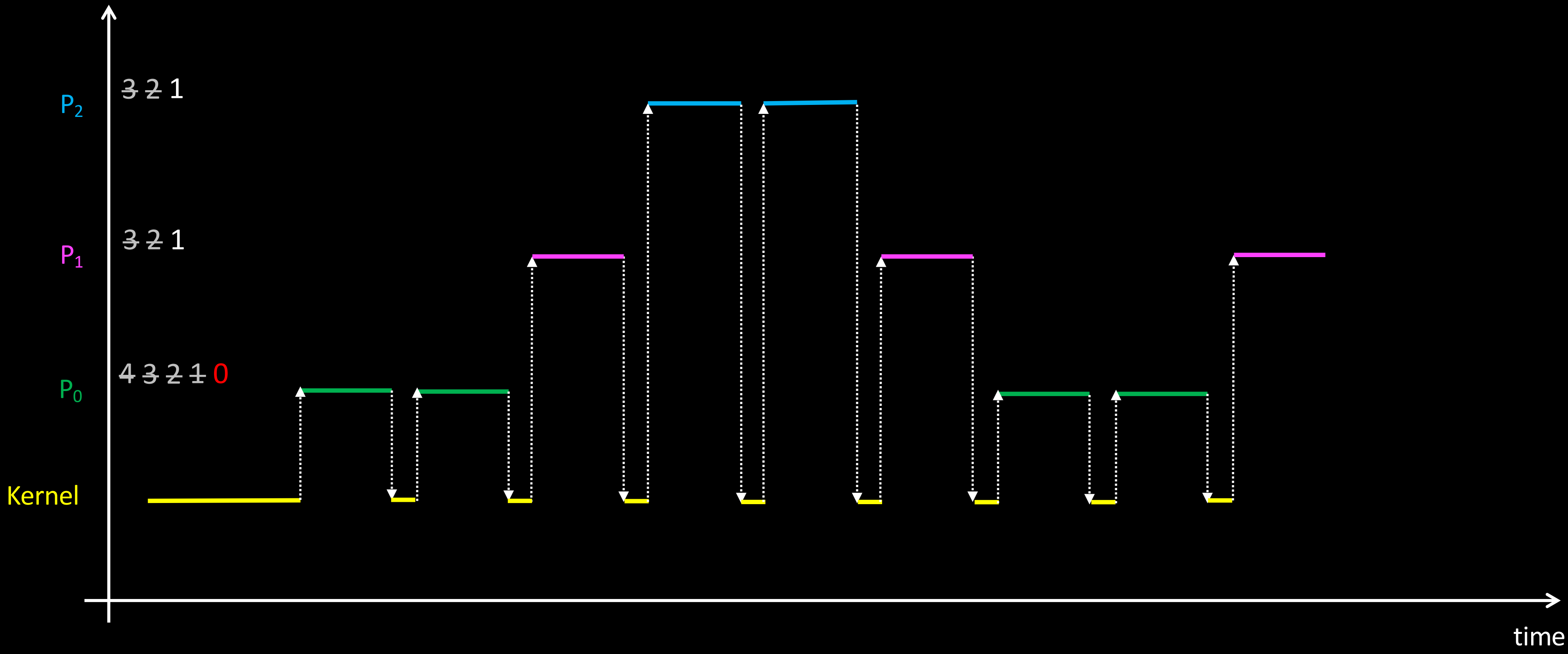

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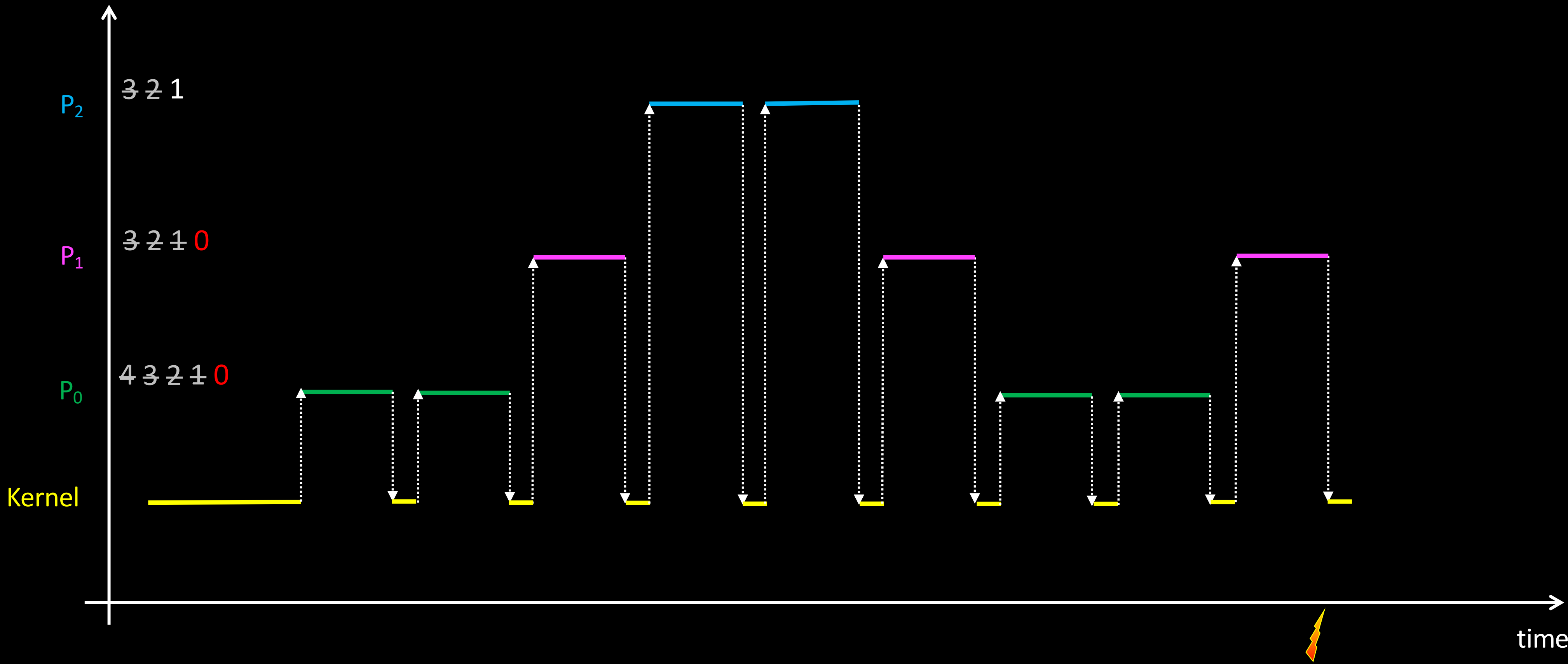

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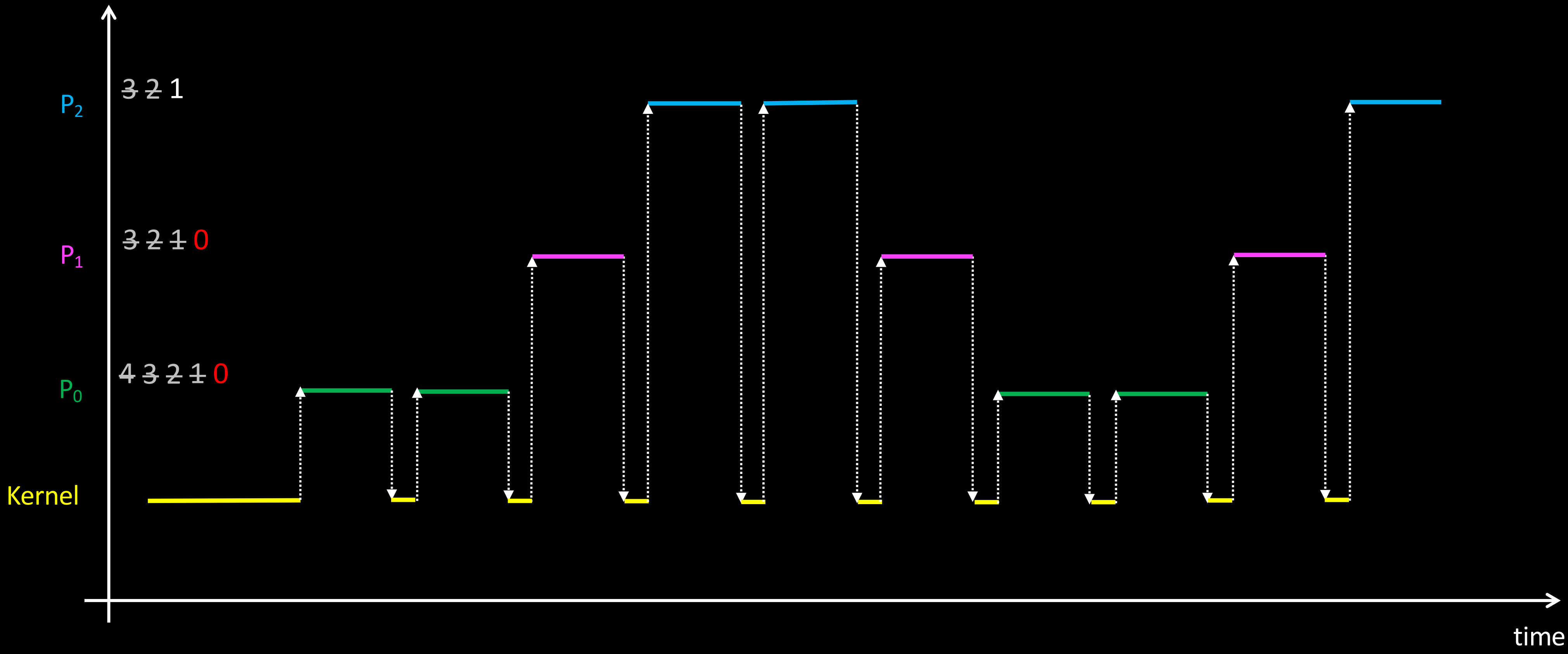

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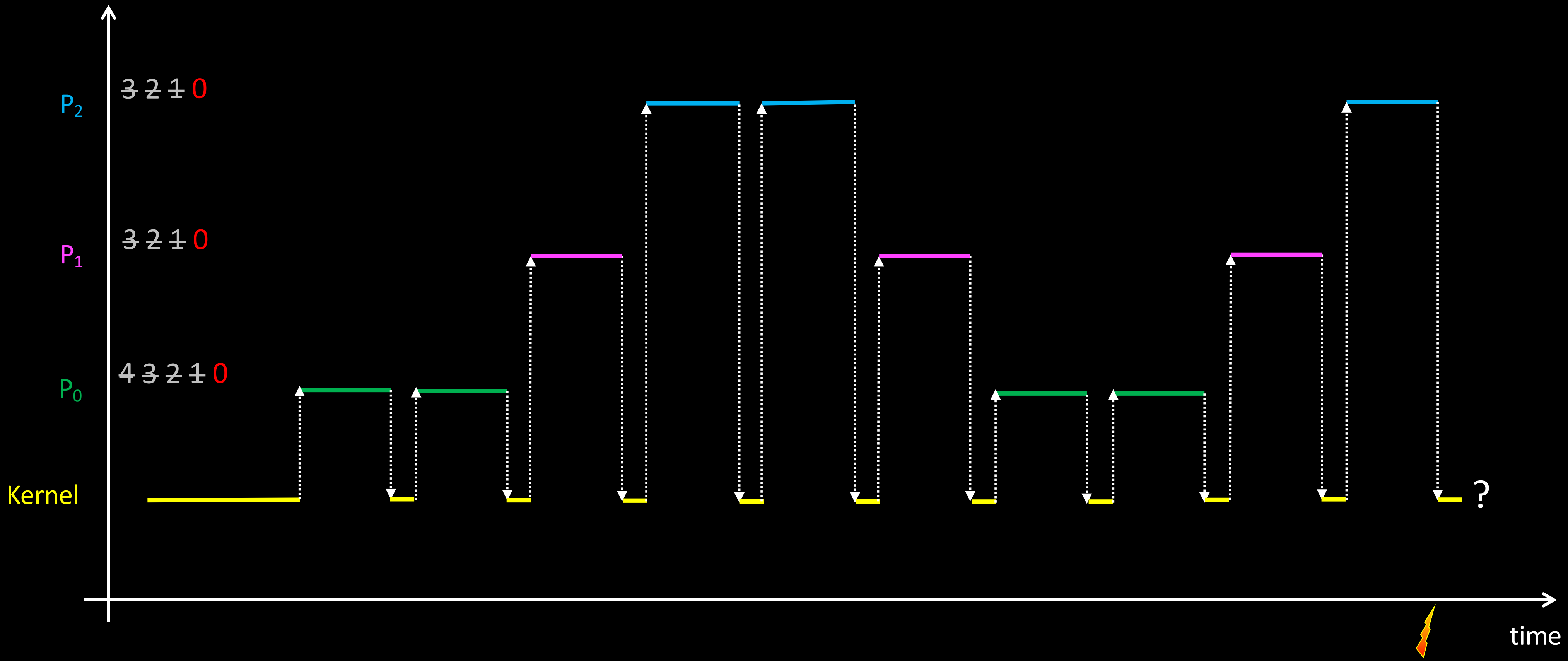

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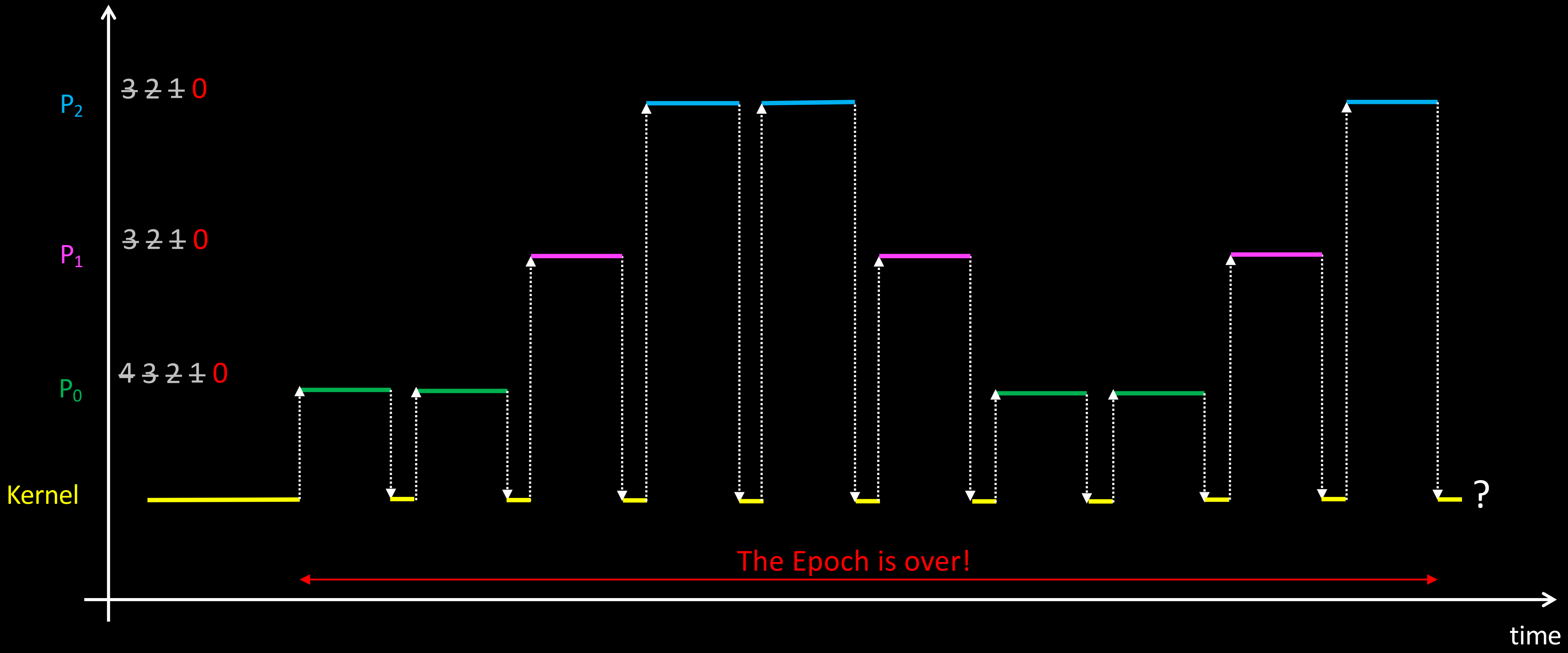

Strategy used in Linux 2.4.x kernels

- When all “ready processes” are short of credits, Linux starts a new Epoch
  - Money is credited back to all processes
  - The same way you give money to your kids every month…
    - Duration of an Epoch is unknown, though

Strategy used in Linux 2.4.x kernels

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- Uh, wait… Really?
  - What if a process did not spend all its credits?
    - In other words: one of your kids is secretly saving money…

Strategy used in Linux 2.4.x kernels

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Strategy used in Linux 2.4.x kernels

- To avoid infinite accumulation of credits
  - One solution is to introduce a tax!

- At the beginning of a new Epoch, each process receives
  - to_credits(priority) + remaining_credits/2

Strategy used in Linux 2.4.x kernels

- To avoid infinite accumulation of credits
  - One solution is to introduce a tax!

- At the beginning of a new Epoch, each process receives
  - to_credits(priority) + remaining_credits/2

- In the worst case, a process can accumulate
  - C
  - C + C/2
  - C + C/2 + C/4
  - C + C/2 + C/4 + C/8
  - C + C/2 + C/4 + C+8 + …

- Bounded by 2C

Strategy used in Linux 2.4.x kernels

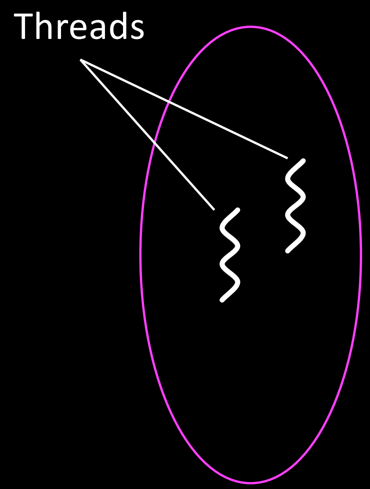
- We’re now ready to explore how this is implemented!

Scheduling on multicore machines

- Each core runs the scheduler asynchronously
  - Timer interrupts not necessarily synchronized
- The ready list can be
  - Shared by all cores
    - How to prevent multiple cores from choosing the same process simultaneously?
  - Distributed among cores
    - How to balance ready threads fairly? How often?
- Local scheduling decisions can require “reschedule” operations on other cores

Processes and Threads

- Threads = Execution context
- Process = Thread + Address Space
- Several threads can share the same address space



Process featuring 2 threads

Processes and Threads

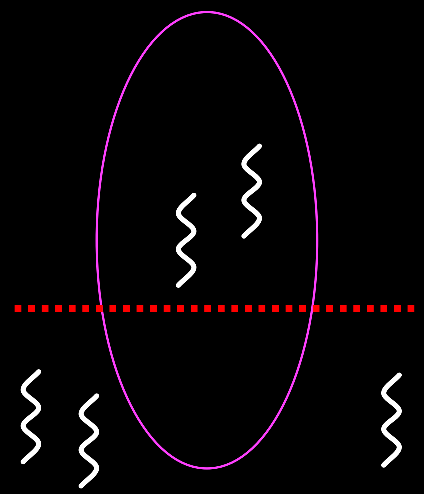
```c
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

int NBTHREADS = 1;

void *func (void *arg)
{
  printf ("Hello from %s\n", arg);

  return NULL;
}
```

```c
int main (int argc, char *argv[])
{
  pthread_t pid;

  pthread_create (&pid, NULL, func, “thread”);

  printf ("Hello from main\n");

  pthread_join (pid, NULL);

  return 0;
}
```

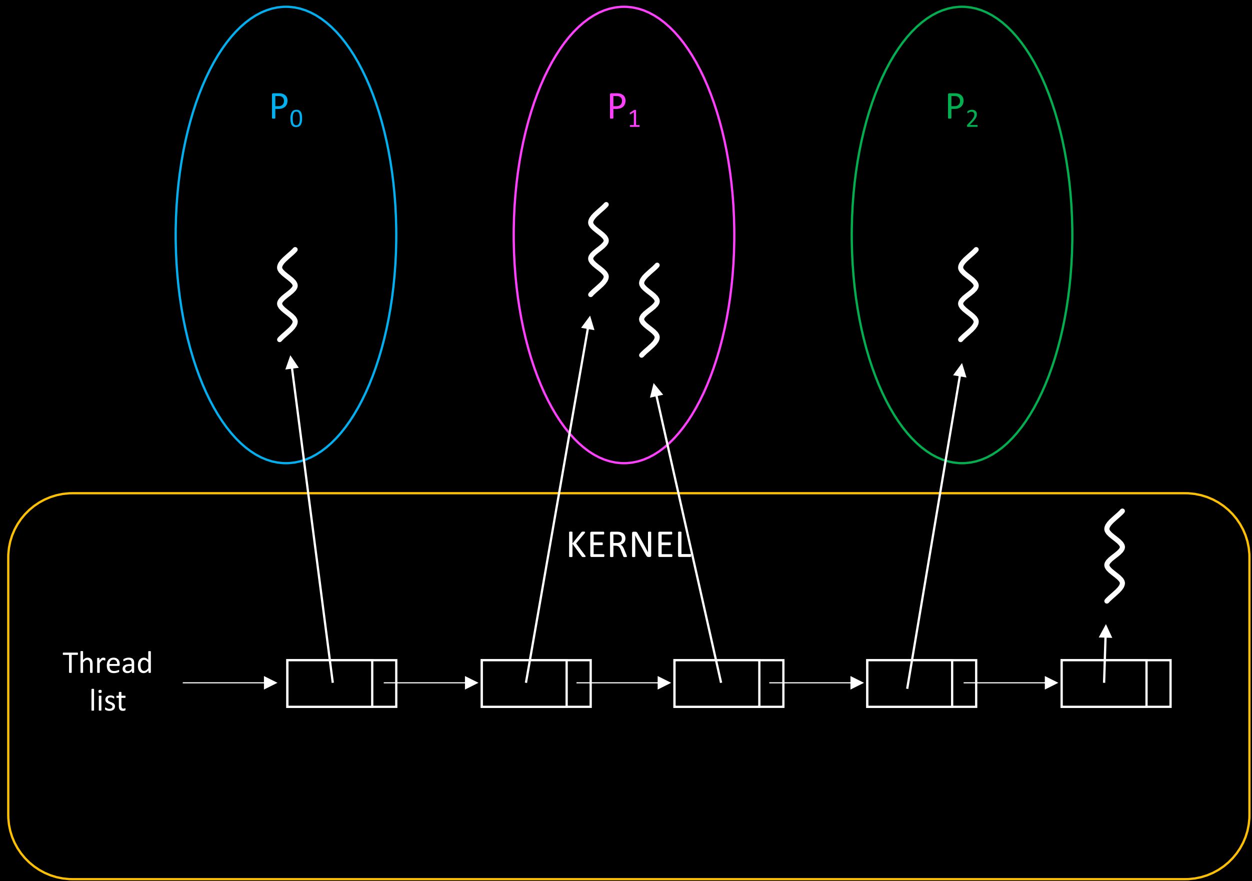
Processes and Threads

- Some (daemons) threads only run inside the kernel

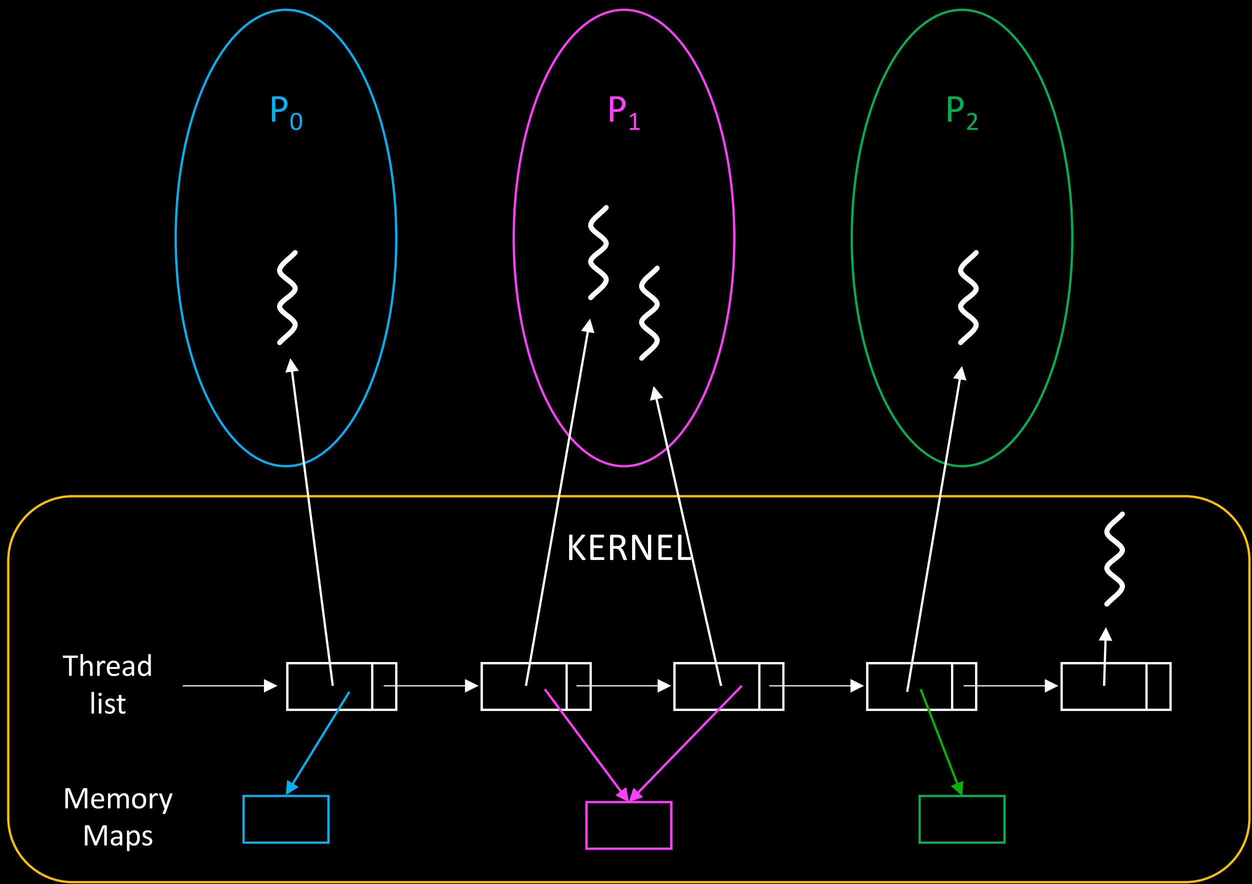
- Modern kernels manage only threads



Processes and Threads: the Big Picture



Processes and Threads: the Big Picture



Race conditions

- Threads can access the same data simultaneously
  - May lead to undefined behavior, data corruption, …
  - Think about
    - Linked lists, graphs, hash tables
    - Structures where several fields must be updated consistently
    - Or just integers…
- When executing kernel code, processes share data as well
  - So the kernel must enforce synchronization

Race conditions

```
volatile int n = 0;
```

```
for (int i = 0; i < 100; i++)
  n++;
```

```
for (int i = 0; i < 100; i++)
  n++;
```

pthread_join

```
printf ("n = %d\n", n);
```

$n = 200$?

Race conditions

```
volatile int n = 0;
```

```
for (int i = 0; i < 100; i++)
  n++;
```

```
for (int i = 0; i < 100; i++)
  n++;
```

pthread_join

```
printf ("n = %d\n", n);
```

$n \in [100,200]$?

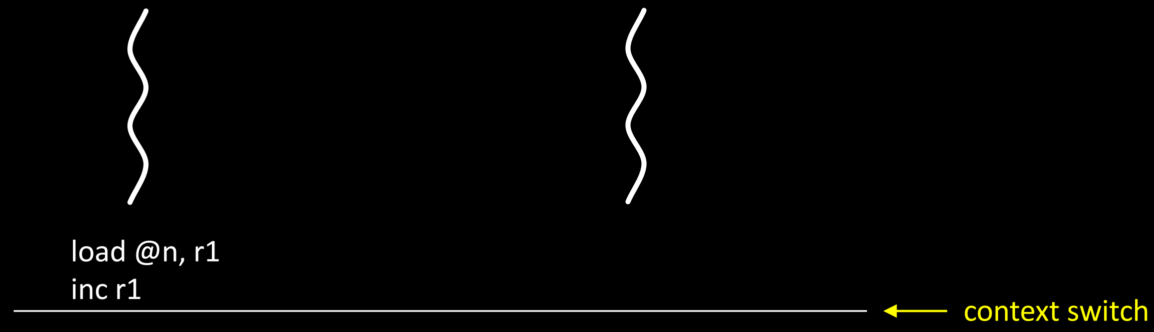
Possible scenario

	load @n, r1	; load from memory
n++ ⇔	inc r1	; increment register
	store r1, @n	; store in memory

n : 0

Possible scenario

n++ ⇔	load @n, r1	; load from memory
	inc r1	; increment register
	store r1, @n	; store in memory



n : 0

Possible scenario

n++ ⇔

```
load @n, r1      ; load from memory
inc r1           ; increment register
store r1, @n     ; store in memory
```

n : ~~0~~ 99

```
load @n, r1
inc r1
```

```
load @n, r1
inc r1
store r1, @n
...
```

99x

Possible scenario

n++ ⇔

```
load @n, r1      ; load from memory
inc r1           ; increment register
store r1, @n     ; store in memory
```

load @n, r1
inc r1

---

load @n, r1
inc r1
store r1, @n
...

} 99x

---

store r1, @n

---

n : ~~0 99~~ 1

Possible scenario

n++ ⇔

```
load @n, r1      ; load from memory
inc r1           ; increment register
store r1, @n     ; store in memory
```

n : ~~0 99~~ 1

load @n, r1 inc r1		
	load @n, r1 inc r1 store r1, @n …	99x
store r1, @n		
	load @n, r1 inc r1	

Possible scenario

```
        load @n, r1      ; load from memory
n++ ⇔  inc r1           ; increment register
        store r1, @n     ; store in memory
```

n : ~~0~~ ~~99~~ ~~1~~ 100

	load @n, r1 inc r1		
		load @n, r1 inc r1 store r1, @n …	99x
	store r1, @n		
		load @n, r1 inc r1	
99x	load @n, r1 inc r1 store r1, @n …		

Possible scenario

n++ ⇔	load @n, r1	; load from memory
	inc r1	; increment register
	store r1, @n	; store in memory

n : ~~0 99 1 100~~ 2

	load @n, r1 inc r1	
		load @n, r1 inc r1 store r1, @n … (99x)
	store r1, @n	
		load @n, r1 inc r1
99x	load @n, r1 inc r1 store r1, @n …	
		store r1, @n

Possible scenario

n++ ⇔
load @n, r1 ; load from memory
inc r1 ; increment register
store r1, @n ; store in memory

n : ~~0 99 1 100~~ 2

$n \in [2{,}200]$!

ad

load @n, r1
inc r1
store r1, @n
…
} 99x

store r1, n

load @n, r1
inc r1

99x {
load @n, r1
inc r1
store r1, @n
…

store r1, @n

Race conditions

- Even the simple ++ operator is not an *atomic* operation
  - So we must prevent multiple threads to execute this operation concurrently!

- To do so, we need synchronization tools
  - This is the topic of the fascinating next chapter! ☺

Additional resources available on http://gforgeron.gitlab.io/se/