[537] Virtual Machine Monitors

Chapter 101 (appendix)

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10/08/14

Virtual Machines

Goal: run an OS over an OS

Who has done this?

Why might it be useful?

Virtual Machines

Goal: run an OS (guest) over an OS (host)

Who has done this?

Why might it be useful?

Motivation

Functionality: want Linux programs on Mac OS X

Consolidation: avoid light utilization

Cloud computing: fast scalability

Testing/Development: for example, xv6

Virtualization Software

Desktop: VMware, VirtualBox

Cloud: Amazon ec2, Microsoft Azure, DigitalOcean

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Demos…

Needs

An OS expects to run on **raw hardware**.

Need to give illusion to OS of private ownership of H/W.

Didn't we already virtualize H/W? How is this different?

Process Virtualization

We have done two things:
- given **illusion** of private resources
- provided more **friendly interface**

The interface (what **processes** see/use):
- virtual memory (w/ holes)
- most instructions (but not lidt, etc)
- most registers (but not cr3, etc)
- syscalls, files, etc

Process Virtualization

We have done two things:
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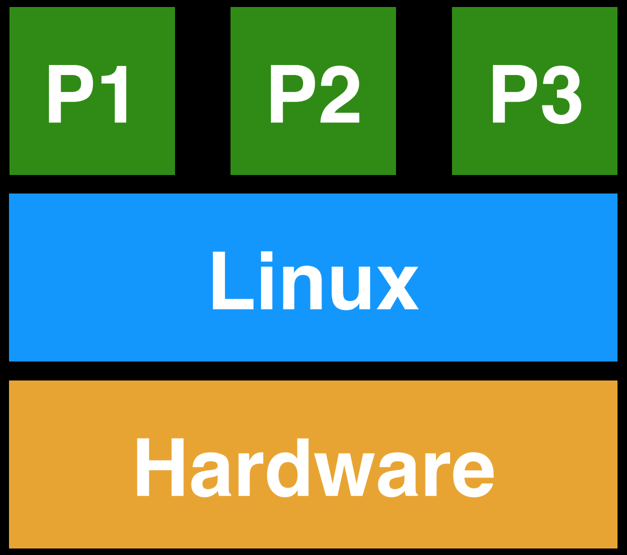
- virtual memory (w/ holes)
- most instructions (but not lidt, etc)
- most registers (but not cr3, etc)
- syscalls, files, etc

Machine Virtualization

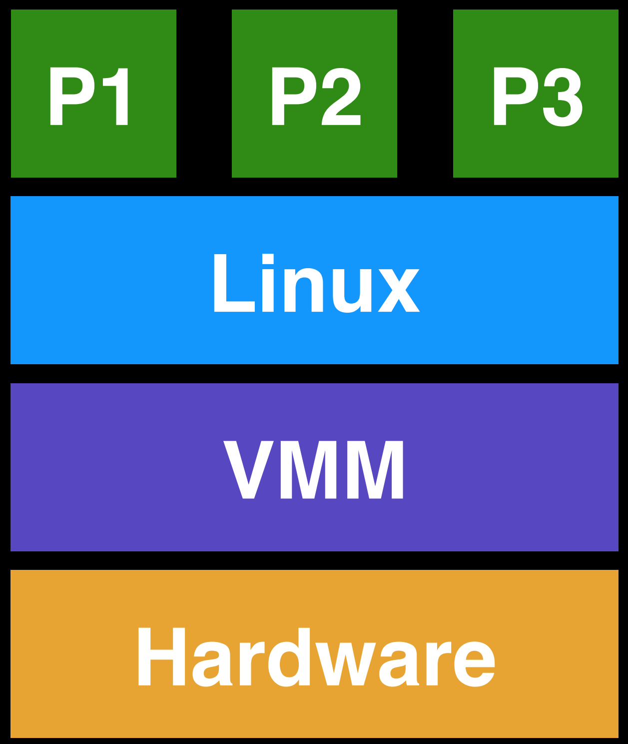
We have done two things:
- given **illusion** of private resources
- ~~provided more **friendly interface**~~ (get rid of this)

The interface (what **guest OS's** see/use):
- "physical" memory (no holes), PT management
- **all** instructions (even dangerous ones!)
- **all** registers
- "physical" devices, interrupts, disks, etc

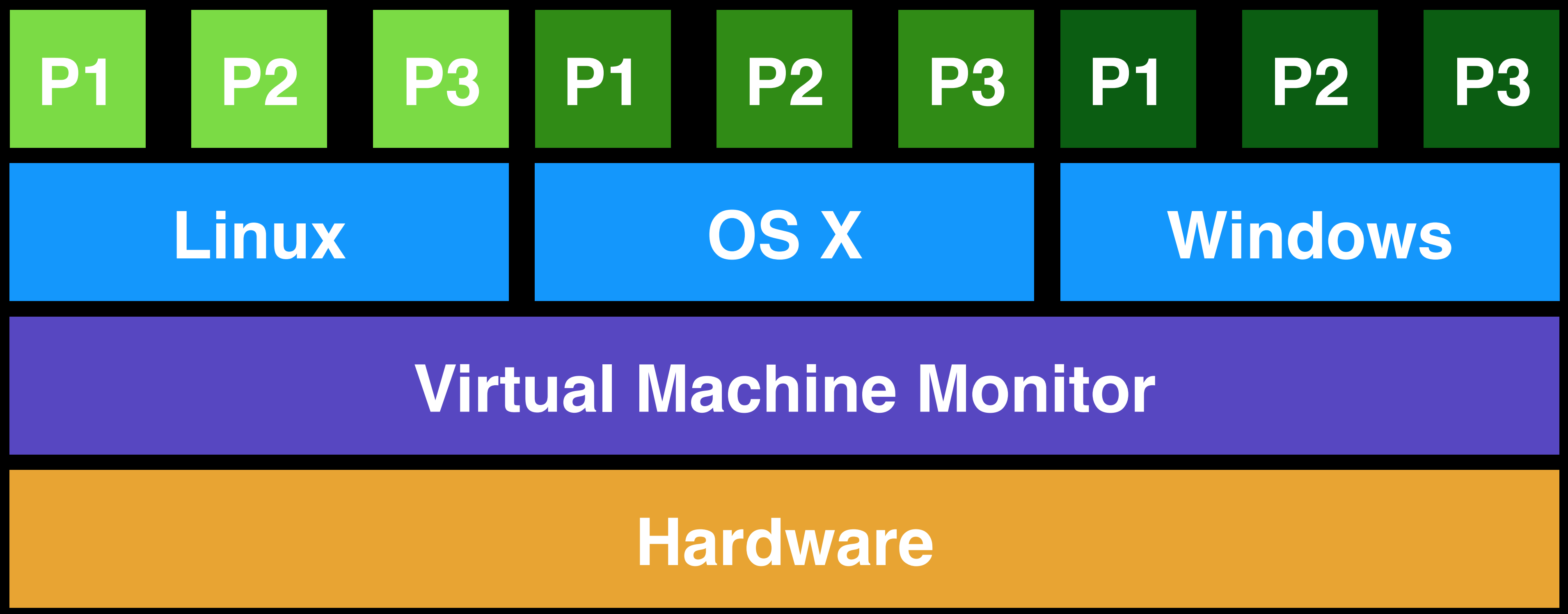
Before



Now



Now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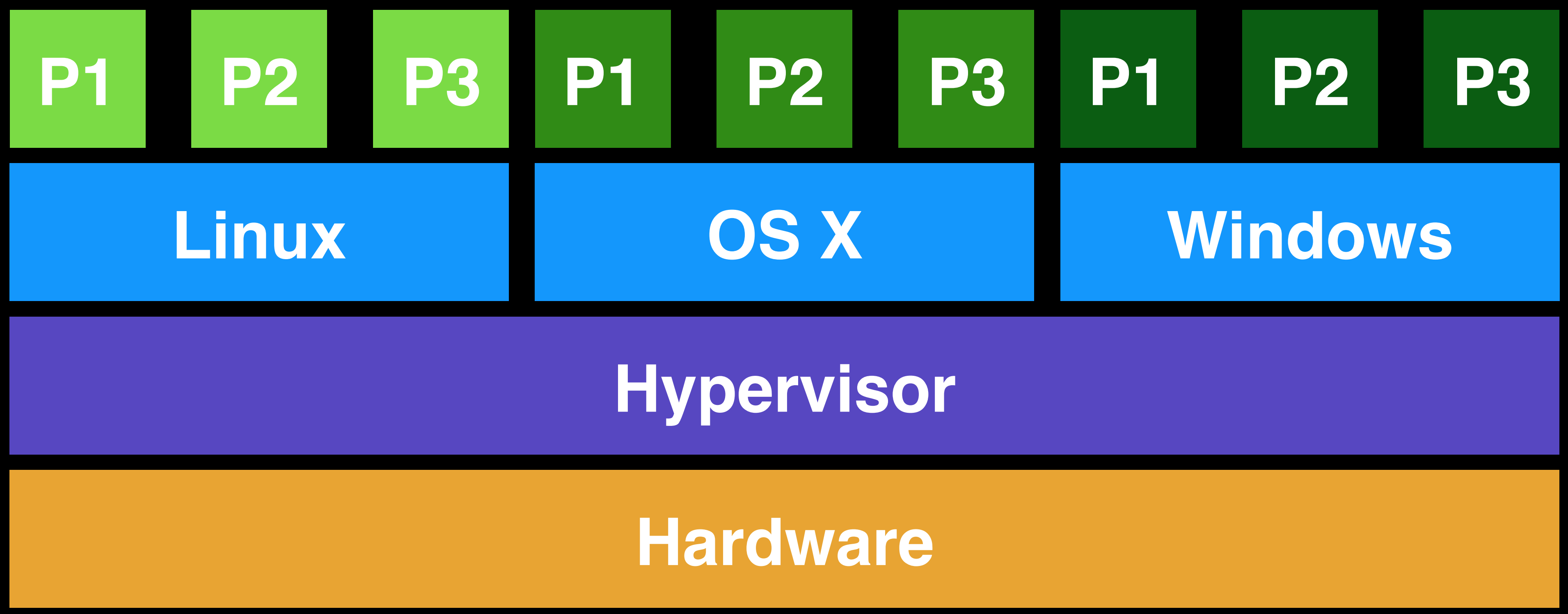
Linux
OS X
Windows
Virtual Machine Monitor
Hardware

Now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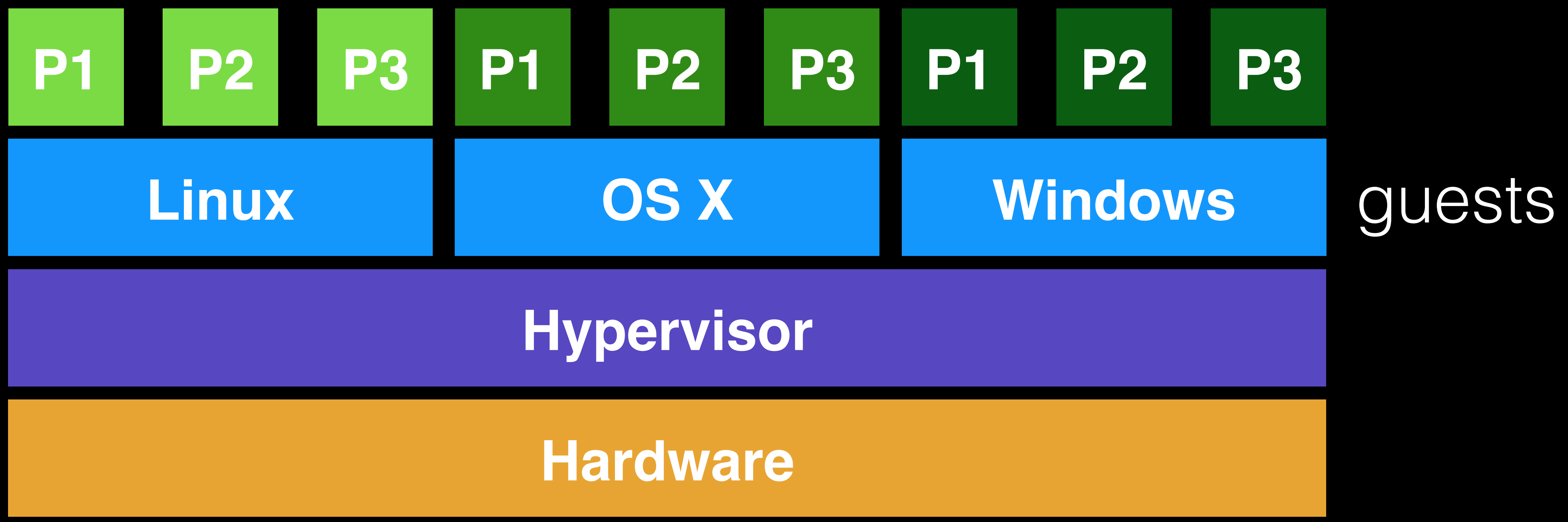
Linux
OS X
Windows
Hypervisor
Hardware

Now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P3
Linux
OS X
Windows
guests
Hypervisor
Hardware

Approach 1

Write a **simulator**.

For example:
- big array for “physical” memory
- run over OS instructions, call function for each

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Problems?

Approach 1

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Problems? (performance)
Solution?

Approach 1

Write a **simulator**.

For example:
- big array for "physical" memory
- run over OS instructions, call function for each

Problems? (performance)
Solution? Limited Direct Execution!

Approach 2: Limited Direct Execution

Hypervisor runs in kernel mode and can do anything.

Processes and guest OS's run in user mode when they don't need to do anything privileged.

LDE is like baby proofing!

Process/Guest Privilege

Process: how do processes correctly do privileged ops?

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Guest: why can't guest OS's do the same?

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Process/Guest Privilege

Process: how do processes correctly do privileged ops?

Guest: why can't guest OS's do the same?

Process: What should an OS do when a process tries to call something like `lidt`?

Guest: What should a hypervisor do when a guest OS tries to call something like `lidt`?

Virtual CPU

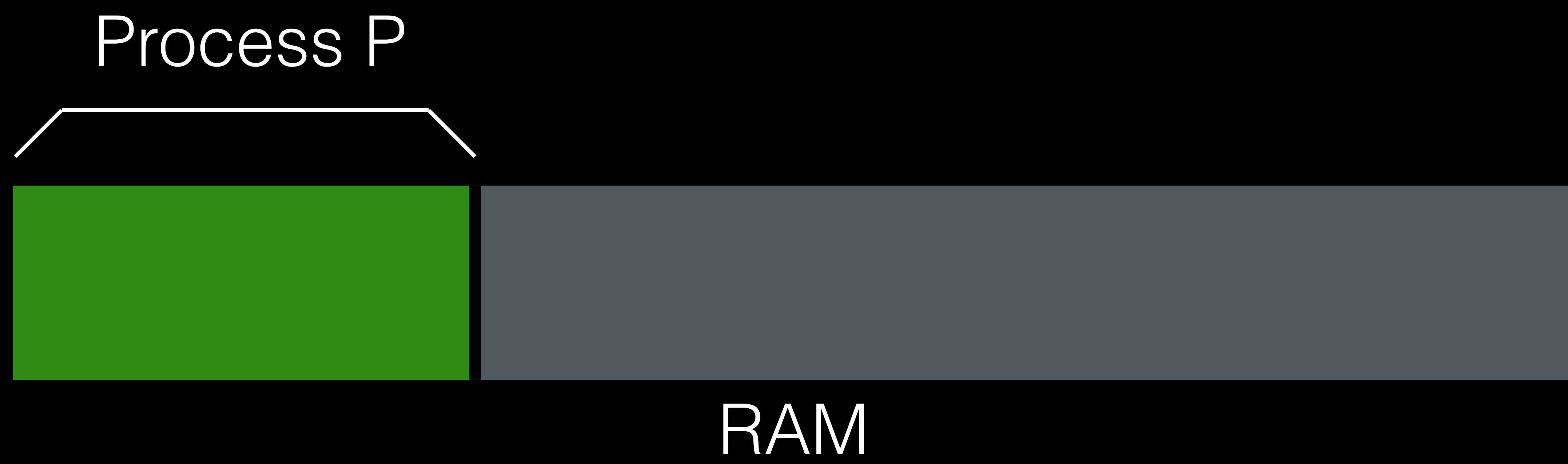
Example

How to emulate an `lidt` call.

Example

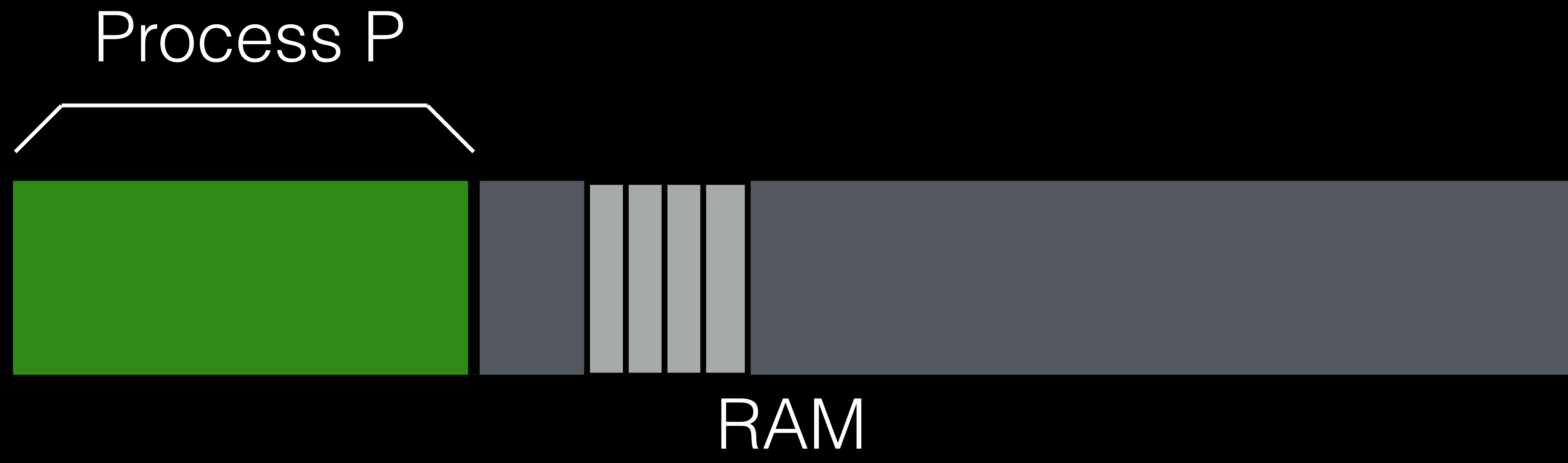
How to emulate an `lidt` call.

Review IDT table…




```
movl $6, %eax;    int $64
```

```
struct gatedesc idt[256]     (trap.c)
```

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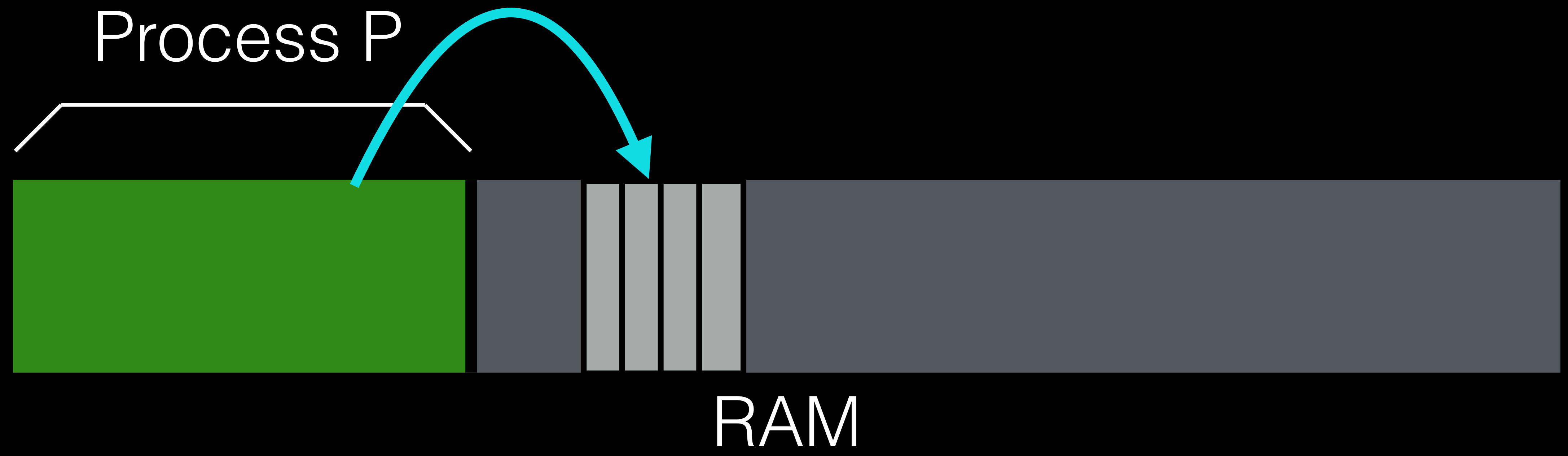
trap-table index
for syscalls

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trap-table index
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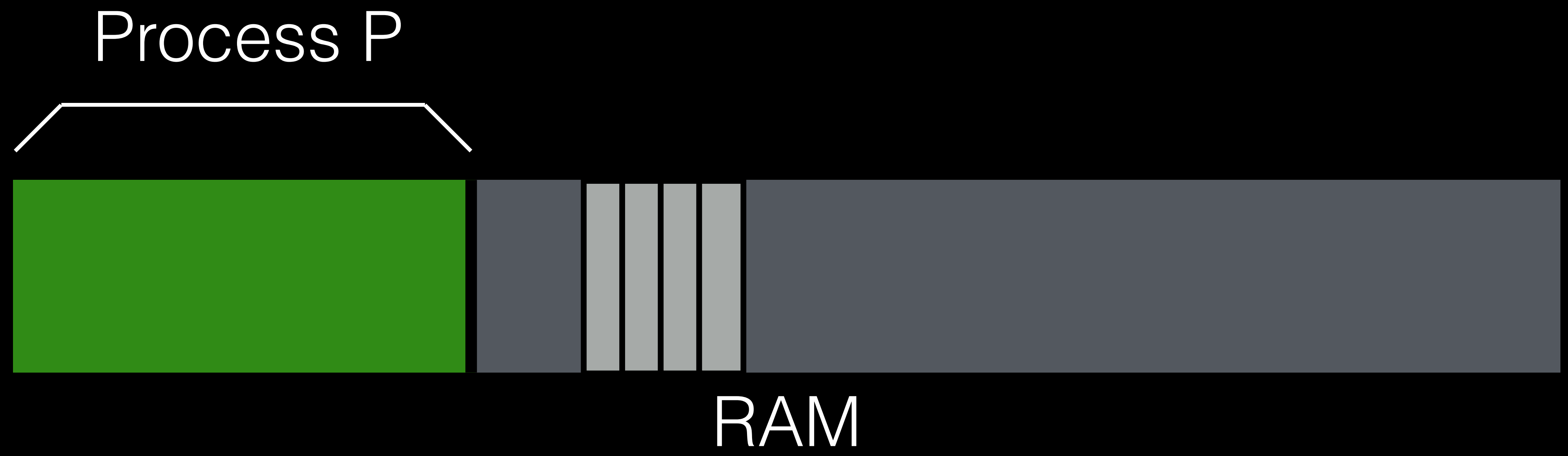
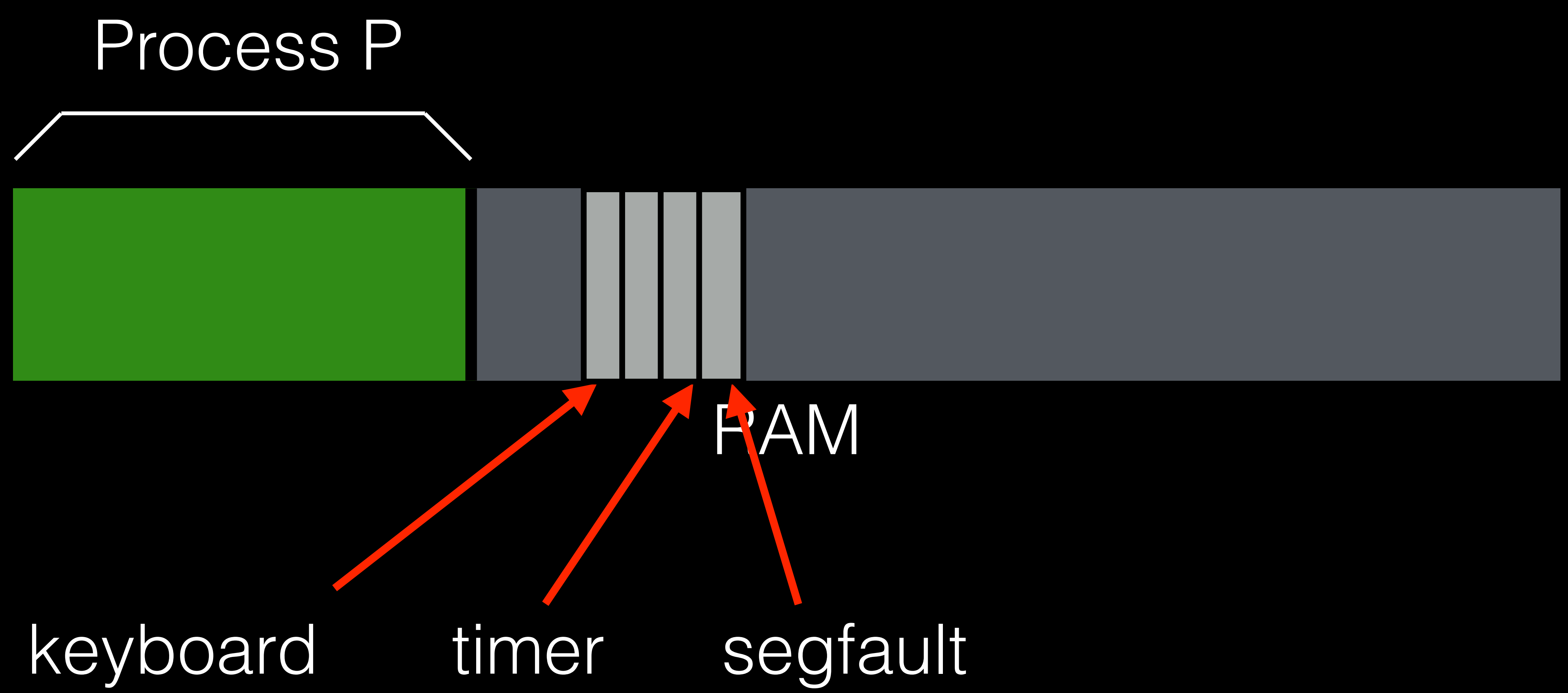

Process P
RAM


Process P
RAM
keyboard
timer
segfault

Example

How to emulate an `lidt` call.

Review IDT table…

Example

How to emulate an `lidt` call.

Review IDT table…

Bootup of VMM and guest OS.


VMM
H/W
Guest OS
time
Memory:

VMM	H/W	Guest OS
create table		

time

Memory:

VMM	H/W	Guest OS
create table		
lidt		

time

Memory:

VMM	H/W	Guest OS
create table		
lidt		
switch to guest		

time

Memory:

VMM	**H/W**	**Guest OS**
create table		
lidt		
switch to guest		
	user mode	

time

Memory:

VMM	H/W	Guest OS
create table		
lidt		
switch to guest		
	user mode	
		create table

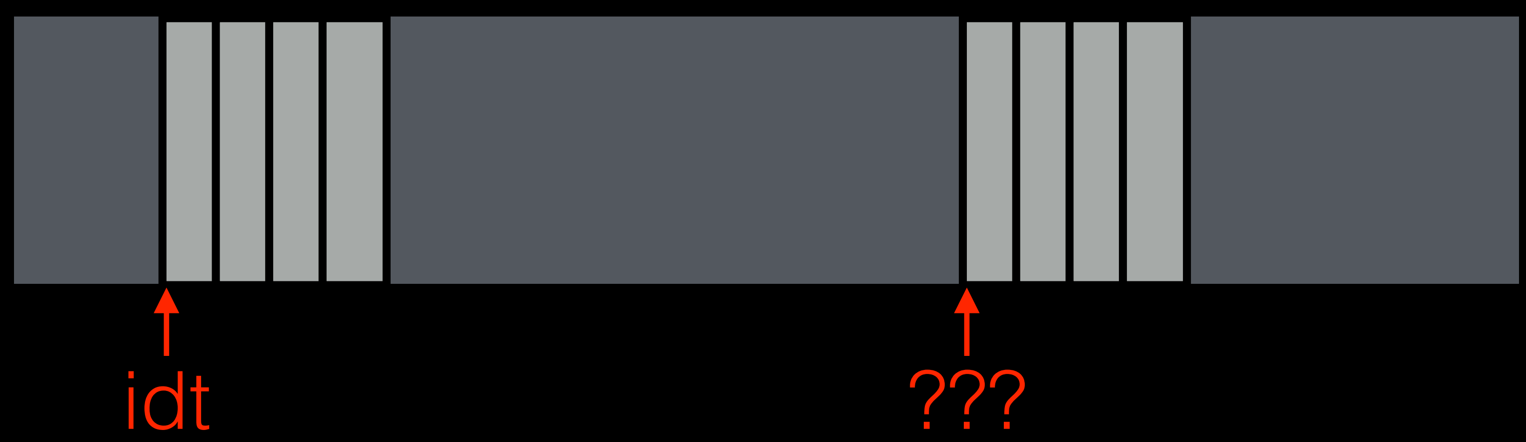
time

Memory:

VMM	H/W	Guest OS
create table		
lidt		
switch to guest		
	user mode	
		create table
		lidt

time

Memory:



VMM	H/W	Guest OS
create table		
lidt		
switch to guest		
	user mode	
		create table
		lidt

time

Memory:

VMM	H/W	Guest OS
create table		
lidt		
switch to guest		
	user mode	
		create table
		lidt
	kernel mode	

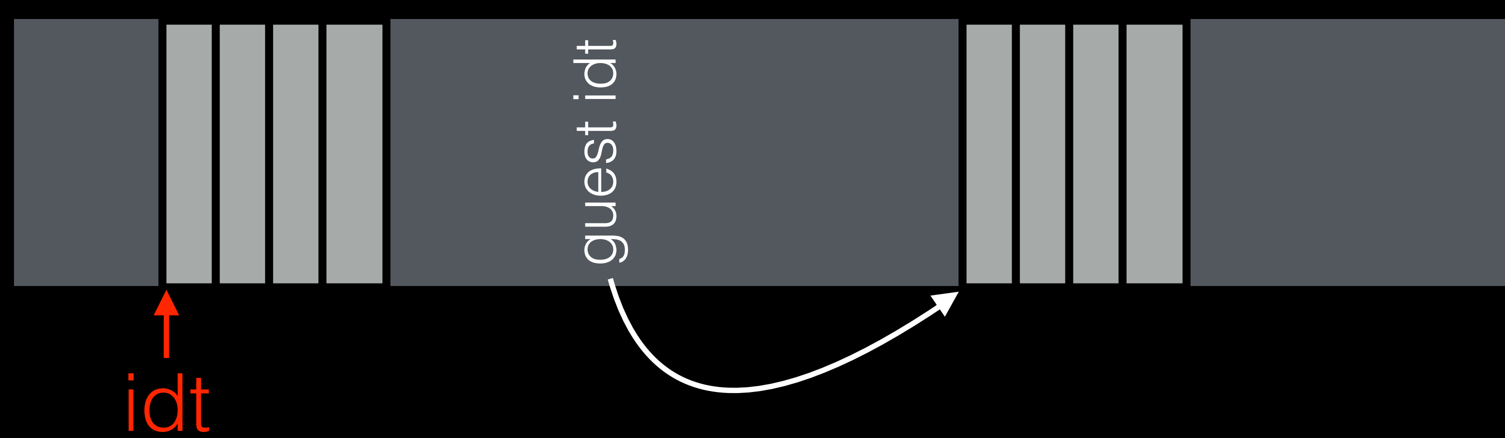
time

Memory:

VMM	H/W	Guest OS
create table		
lidt		
switch to guest		
	user mode	
		create table
		lidt
	kernel mode	
store guest idt addr		

time

Memory:



VMM	H/W	Guest OS
create table		
lidt		
switch to guest		
	user mode	
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time

Memory:

VMM	H/W	Guest OS
create table		
lidt		
switch to guest		
	user mode	
		create table
		lidt
	kernel mode	
store guest idt addr		

time

Memory:

vmm timer

guest timer

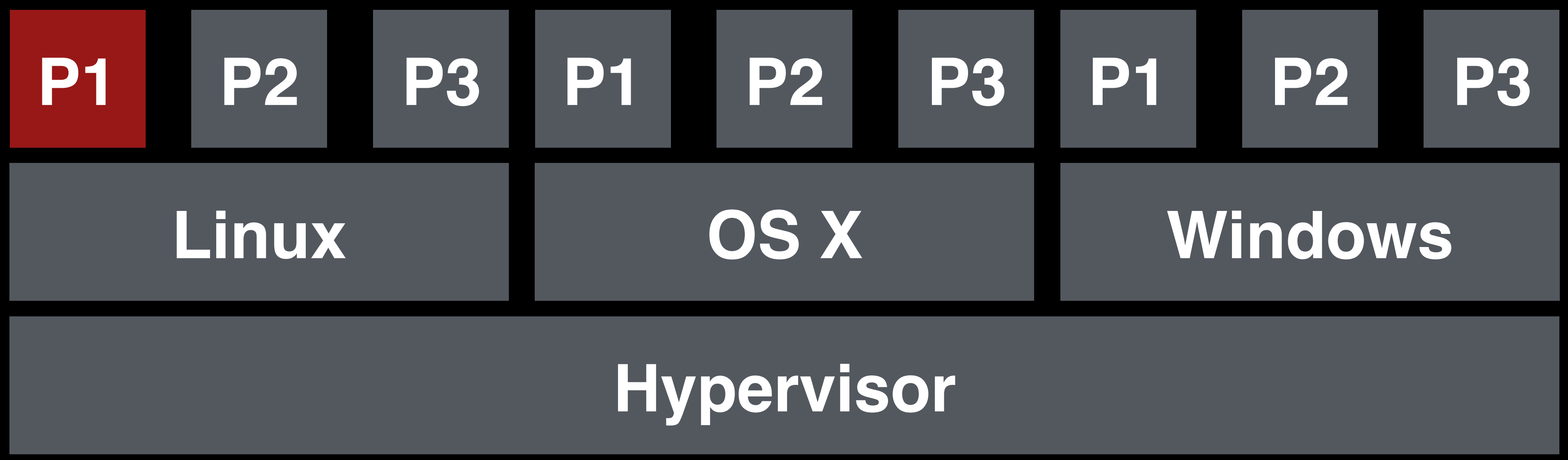
Timer Interrupt Handlers

Host Trap Handler

```
tick() {
   if (…) {
      switch OS;
   } else {
      call OS tick;
   }
}
```

Guest OS Trap Handler

```
tick() {
   maybe switch process;
   return-from-trap;
}
```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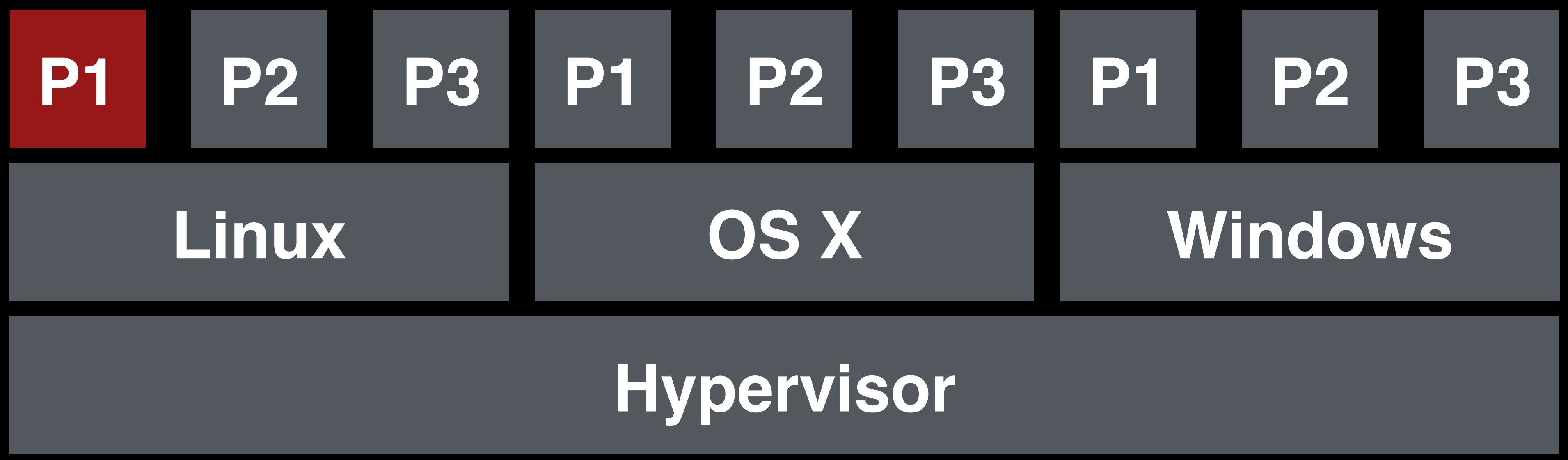
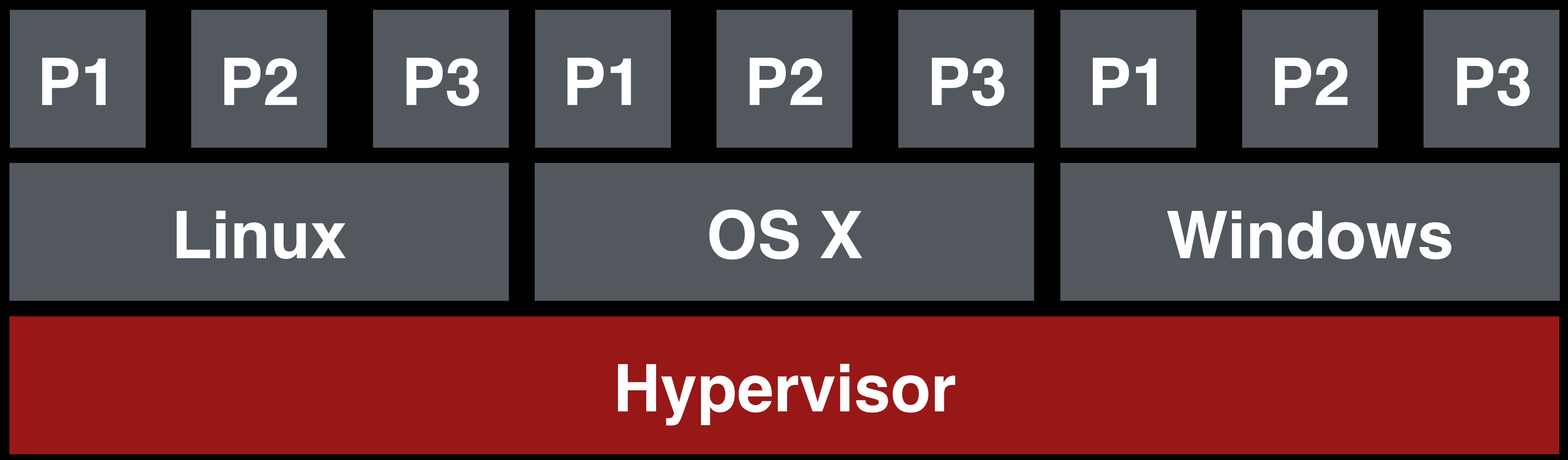
Linux
OS X
Windows
Hypervisor

timer interrupt!

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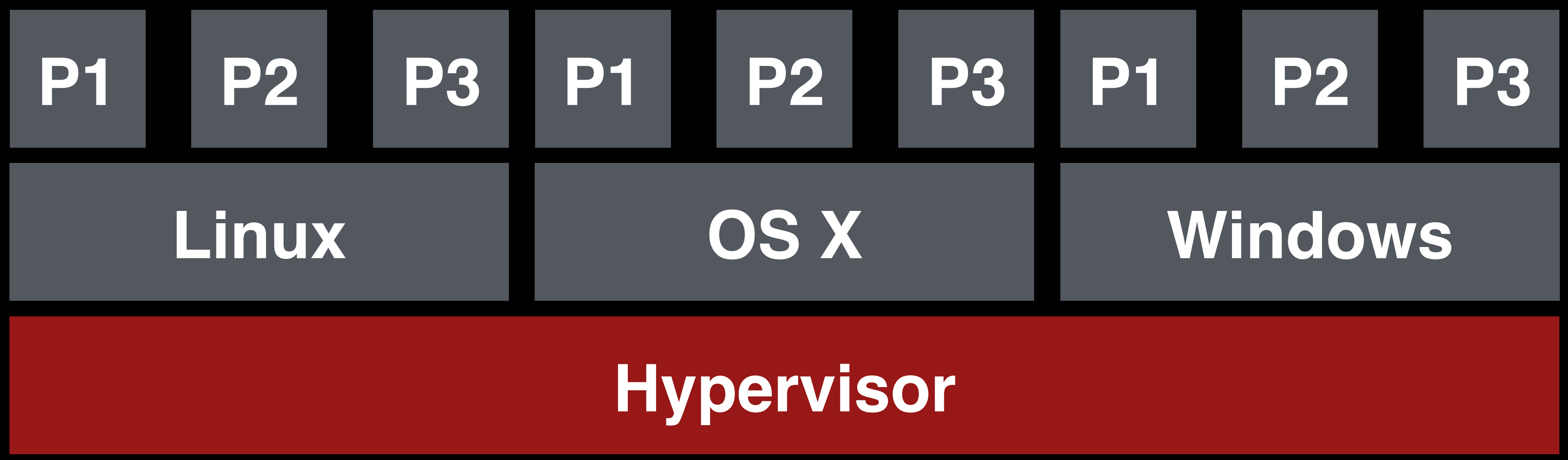
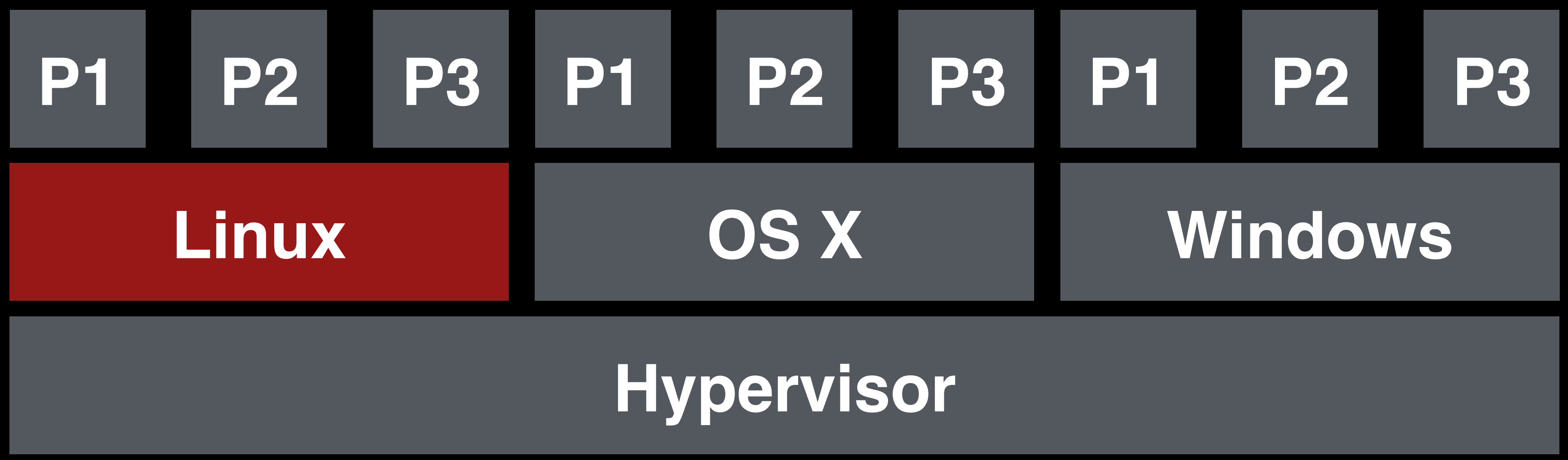
Windows
Hypervisor

Hypervisor decides to keep running Linux

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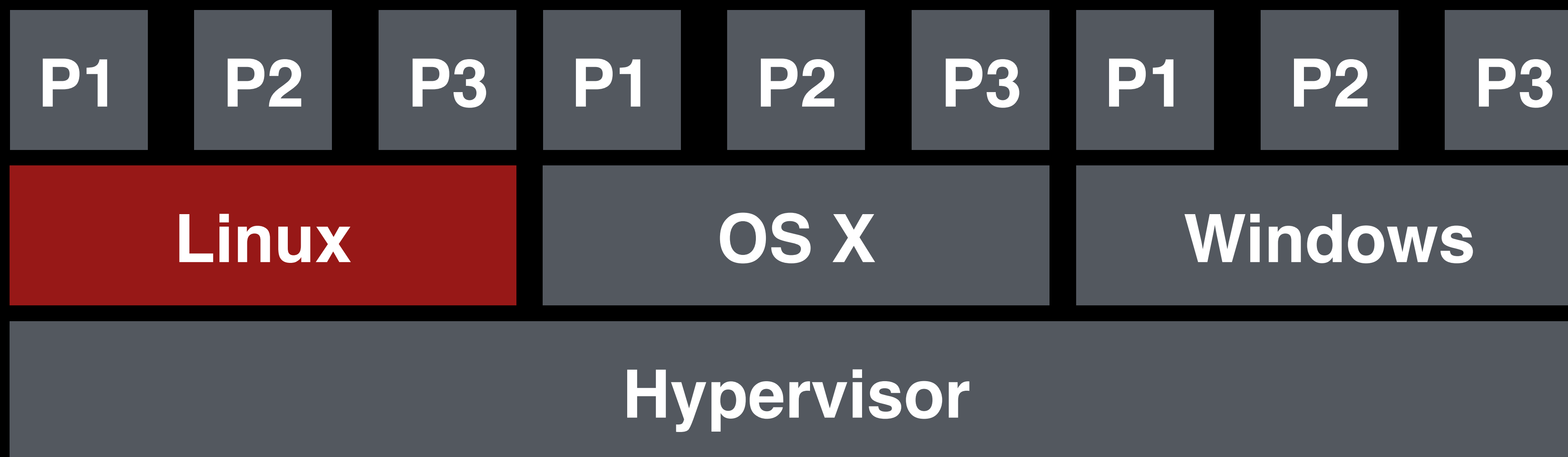
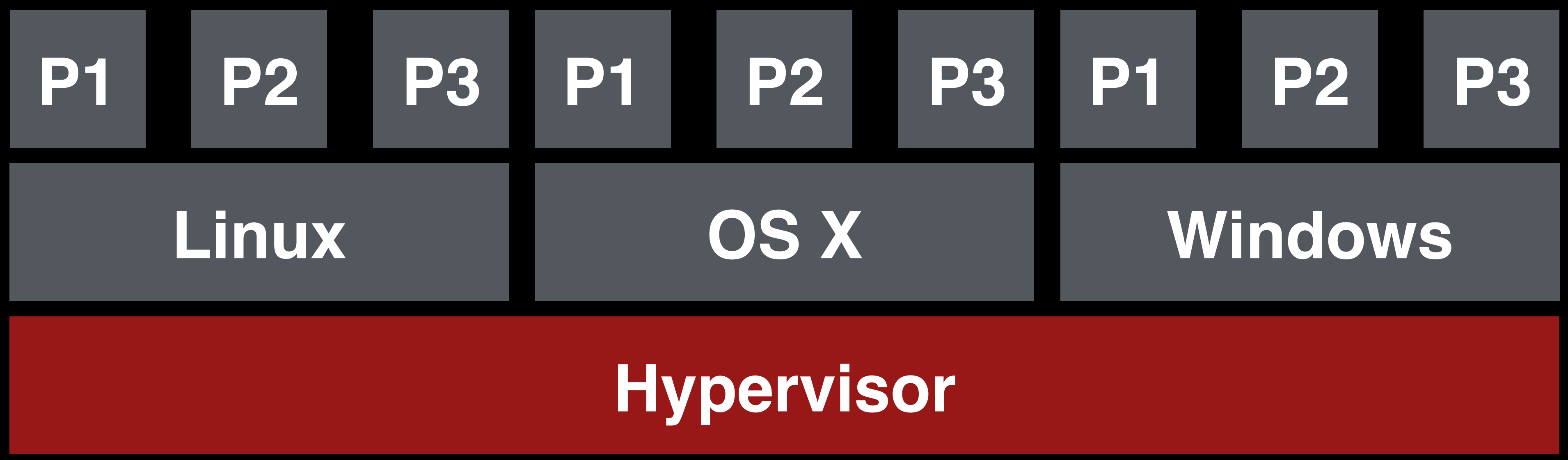
Hypervisor

Linux tries to return-from-trap to P2,
H/W intercepts and switches to Hypervisor.

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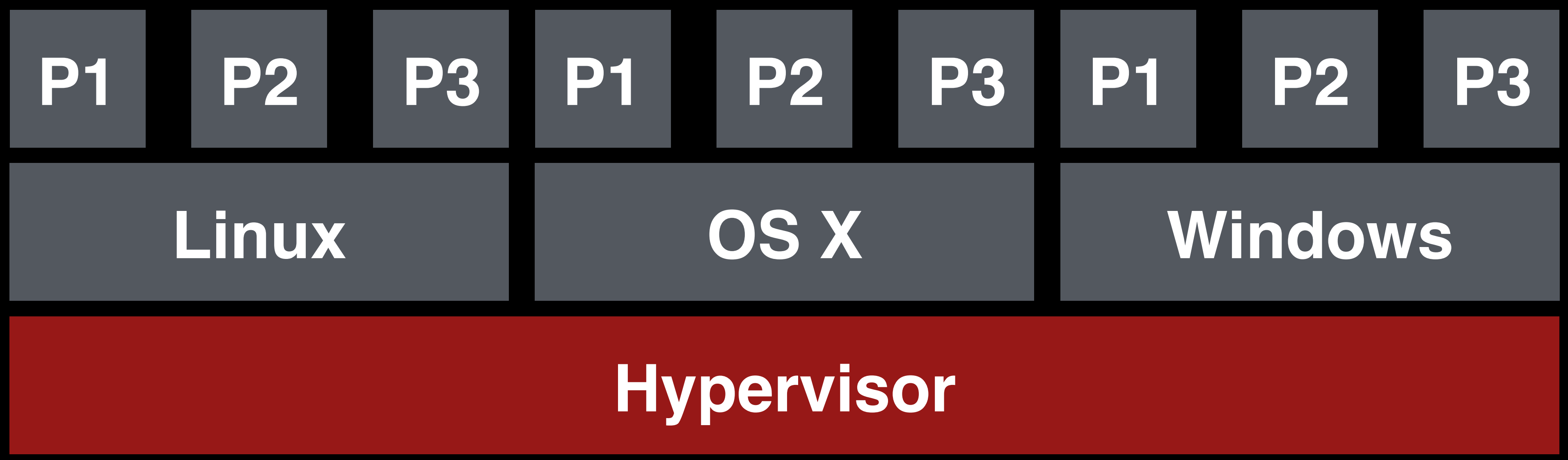
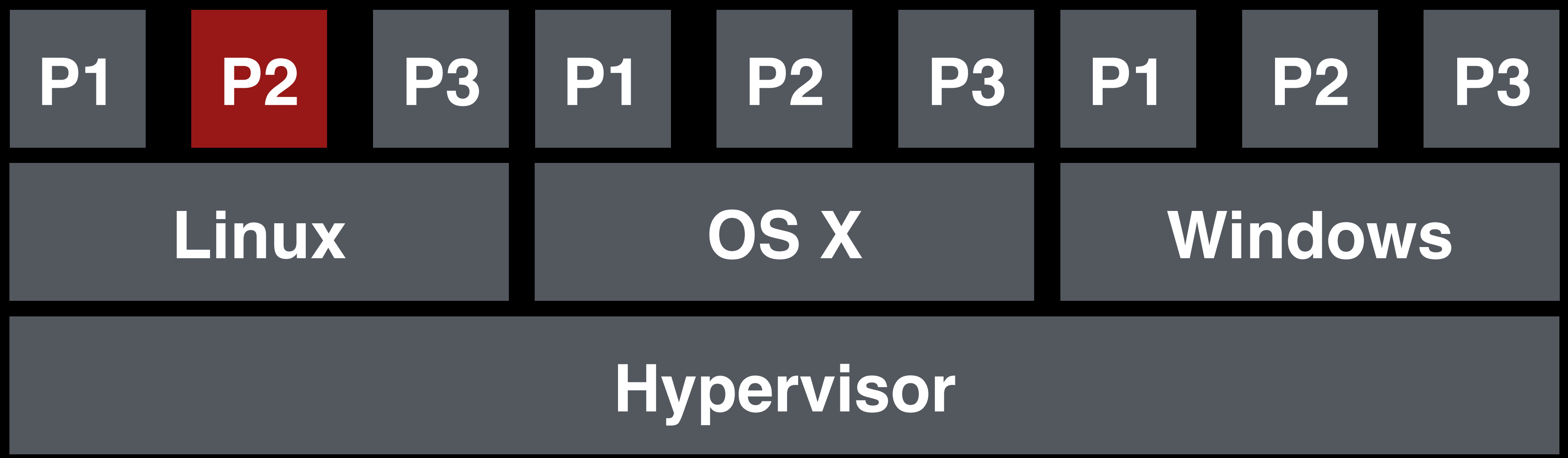
Linux
OS X
Windows
Hypervisor

Hypervisor switches to P2 for Linux.

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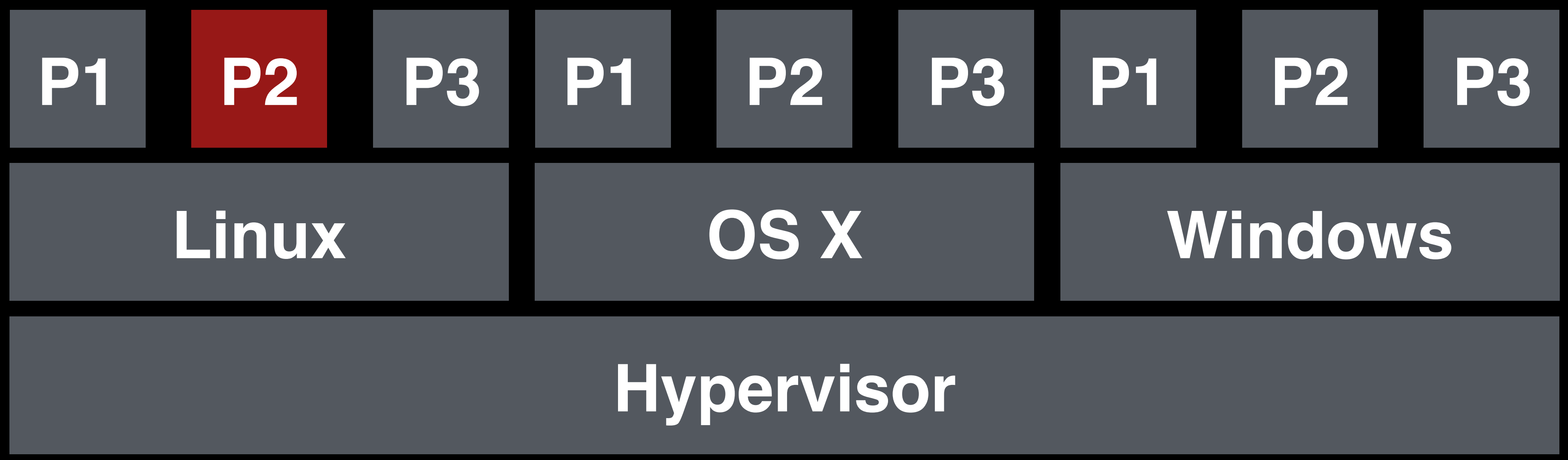
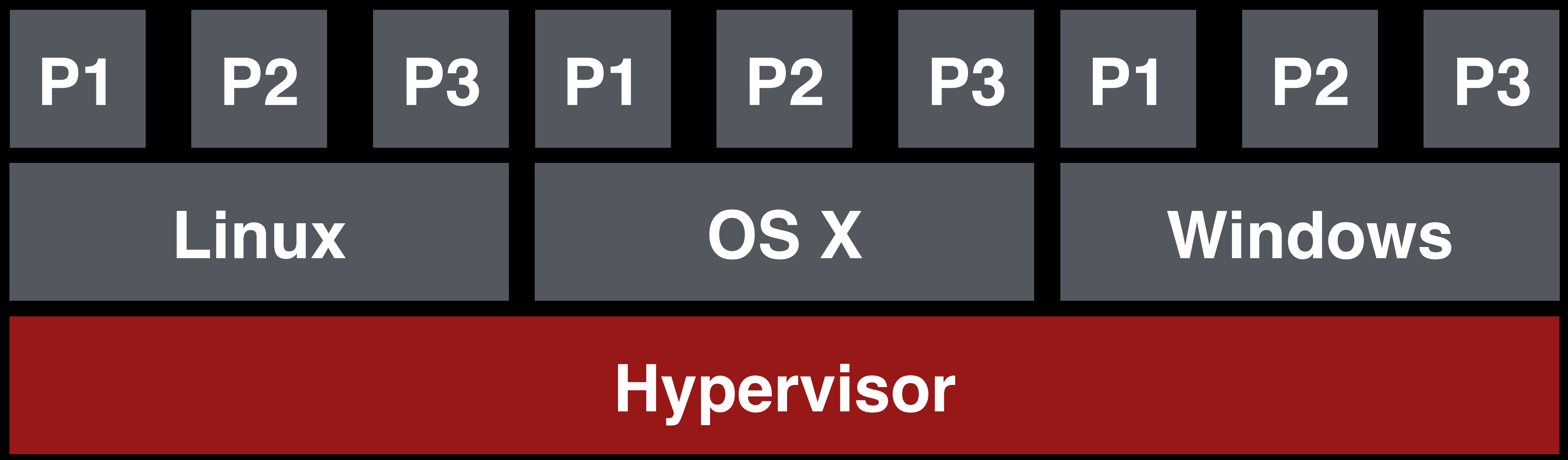
Linux
OS X
Windows
Hypervisor

timer interrupt!

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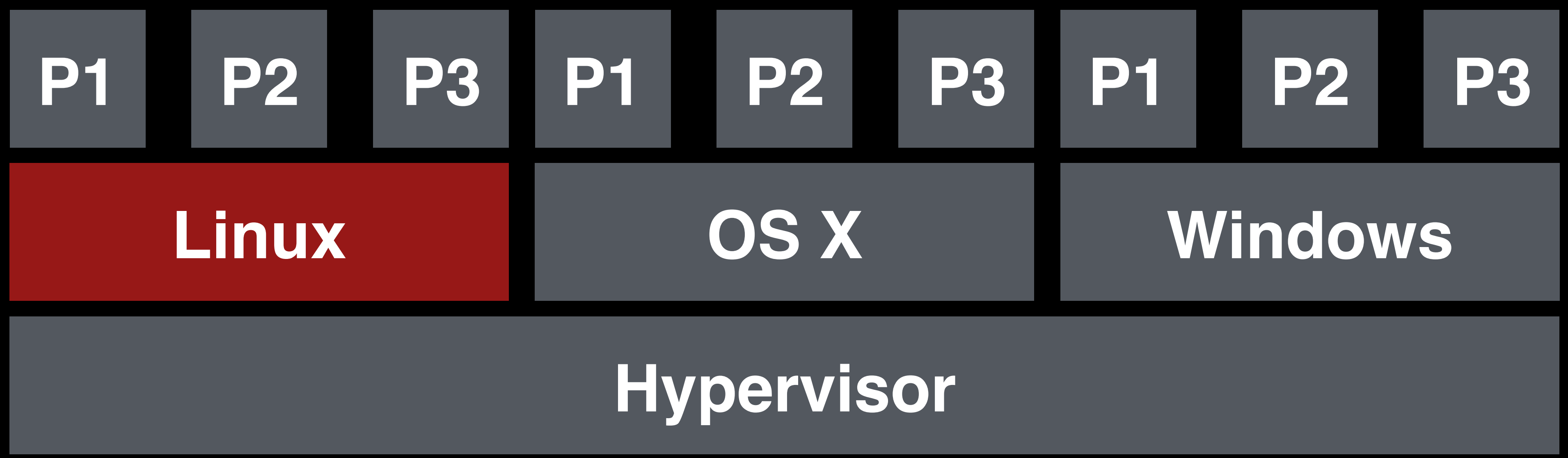
OS X
Windows
Hypervisor



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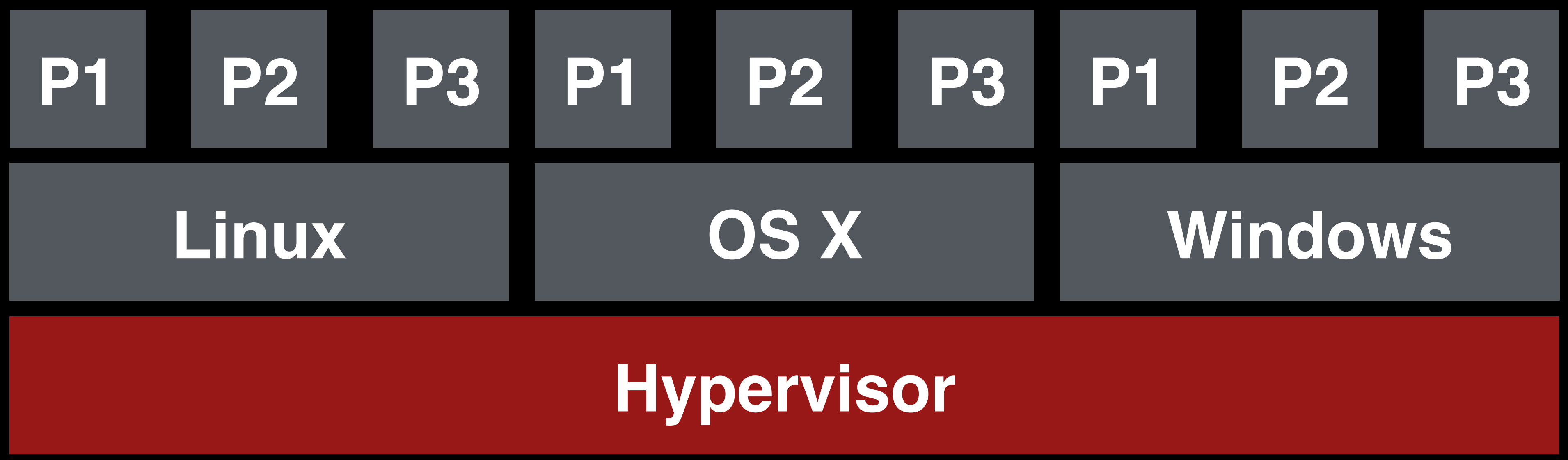
Hypervisor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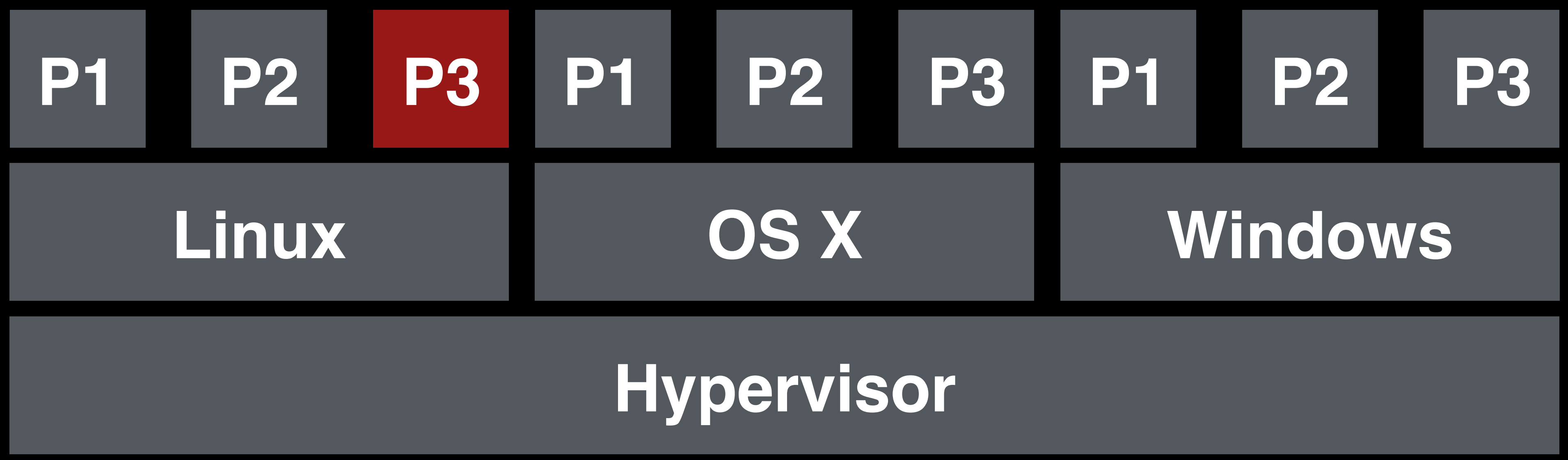
Hypervisor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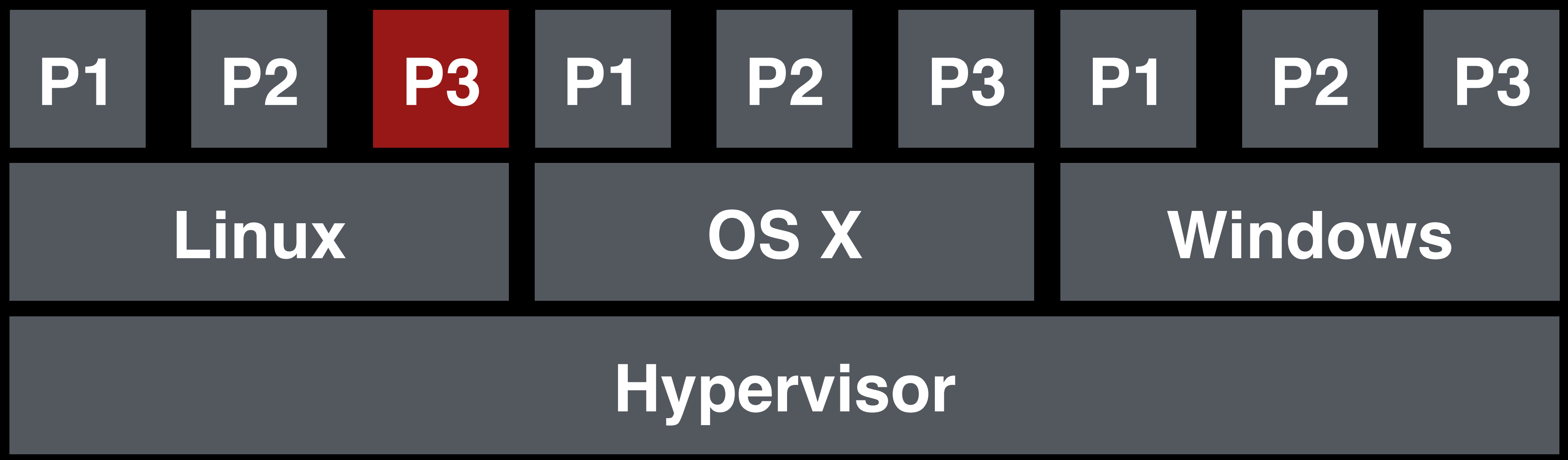
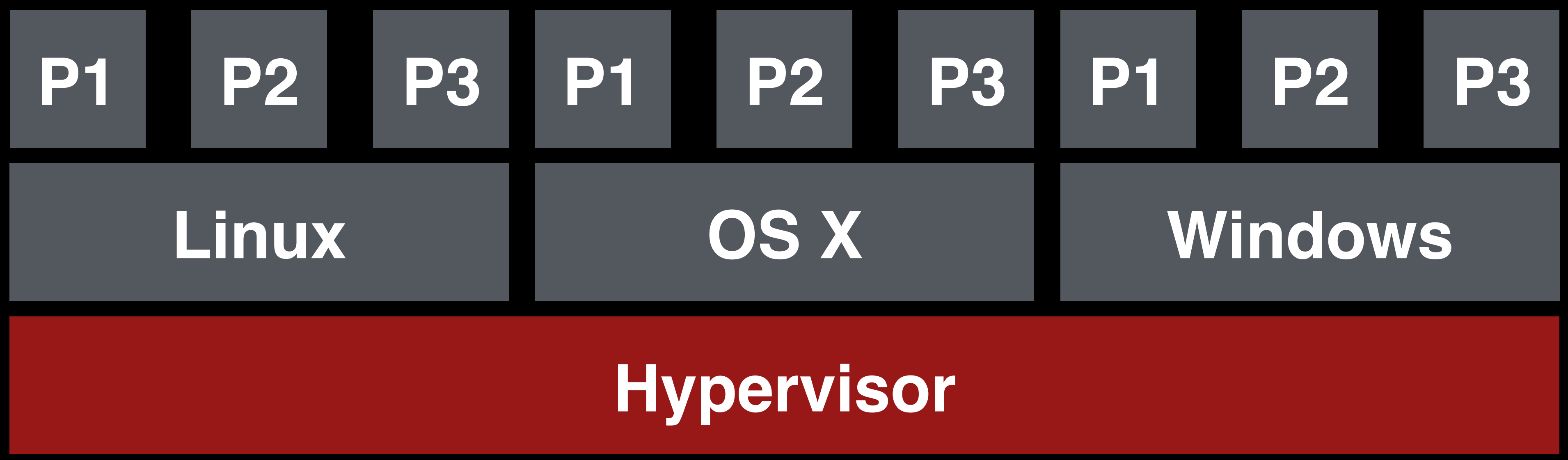
Linux
OS X
Windows
Hypervisor

timer interrupt!

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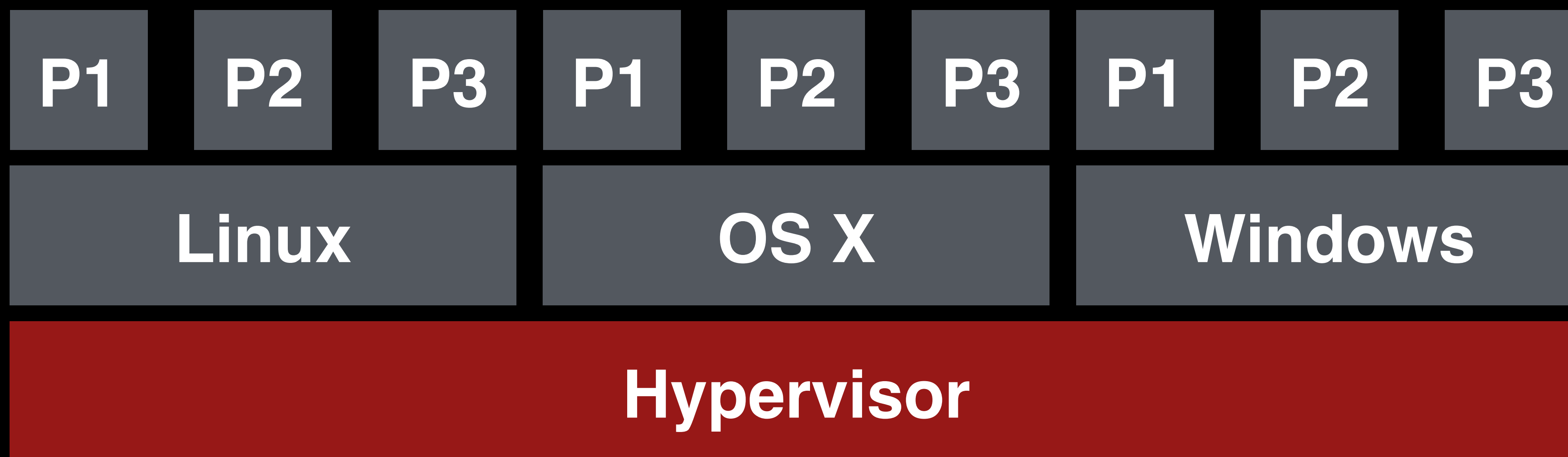
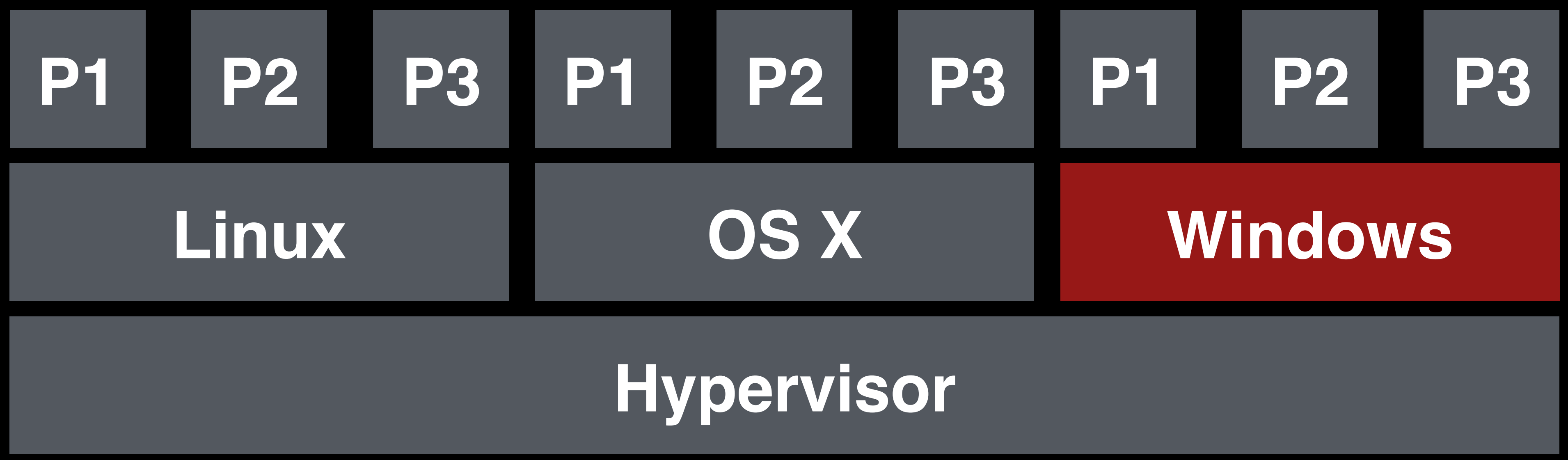
Linux
OS X
Windows
Hypervisor

Hypervisor decides to switch to Windows.

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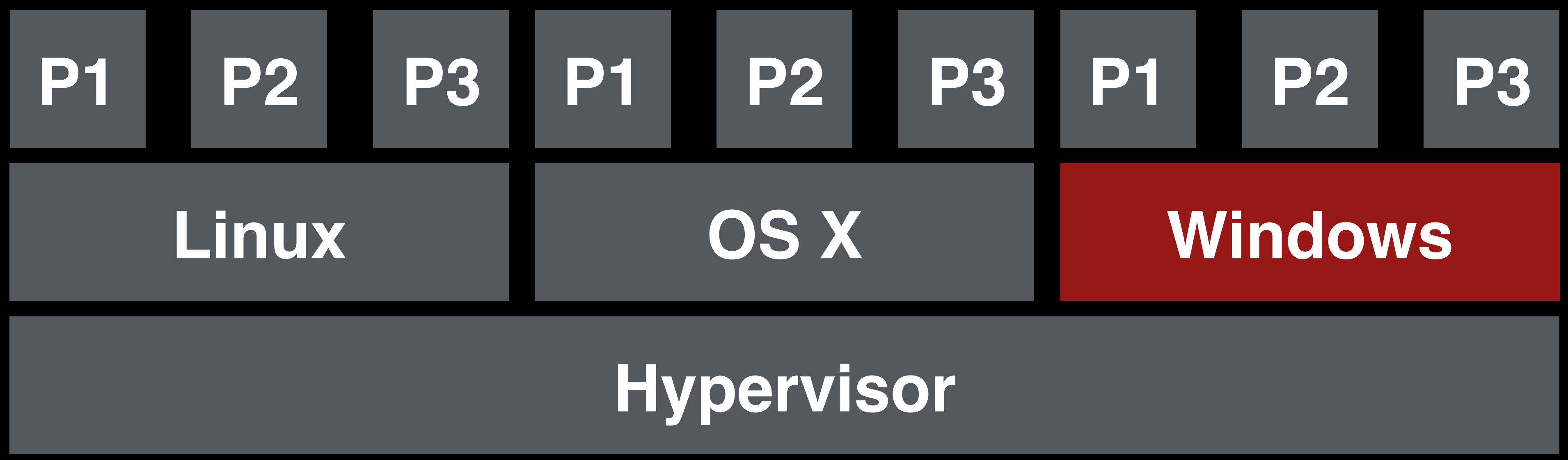
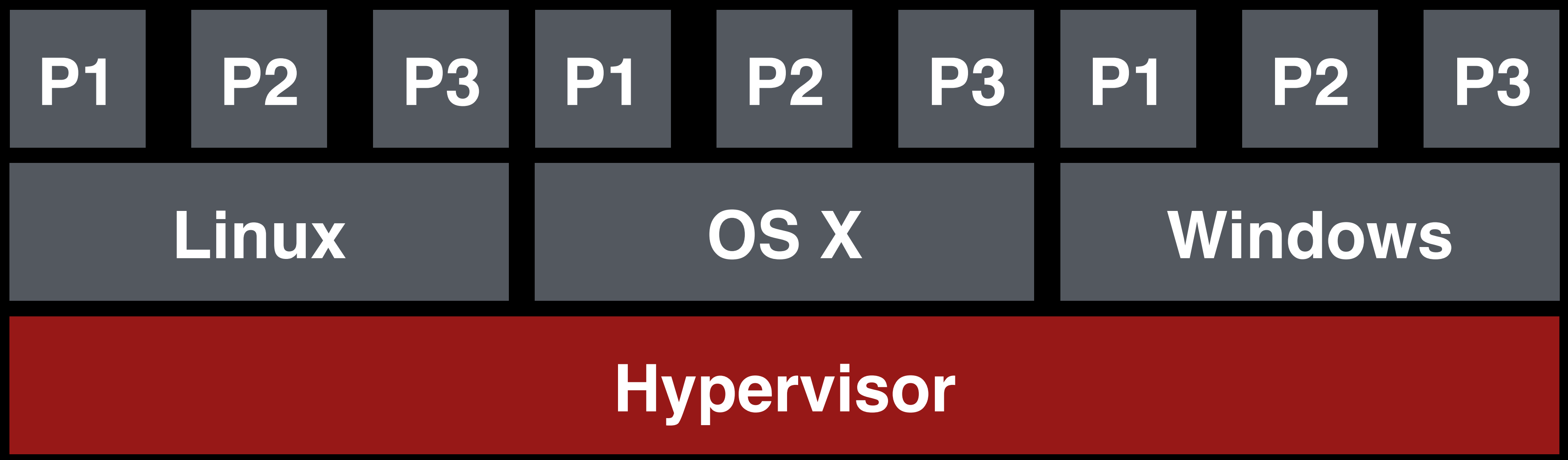
Linux
OS X
Windows
Hypervisor

Windows tries to return-from-trap to P2,
H/W intercepts and switches to Hypervisor.





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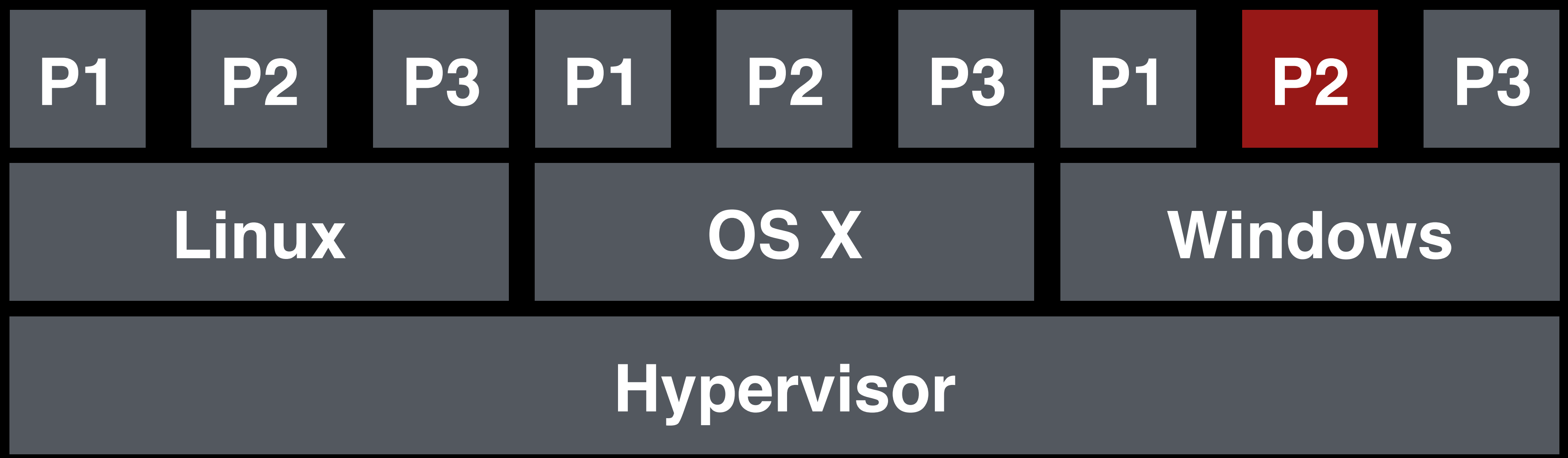
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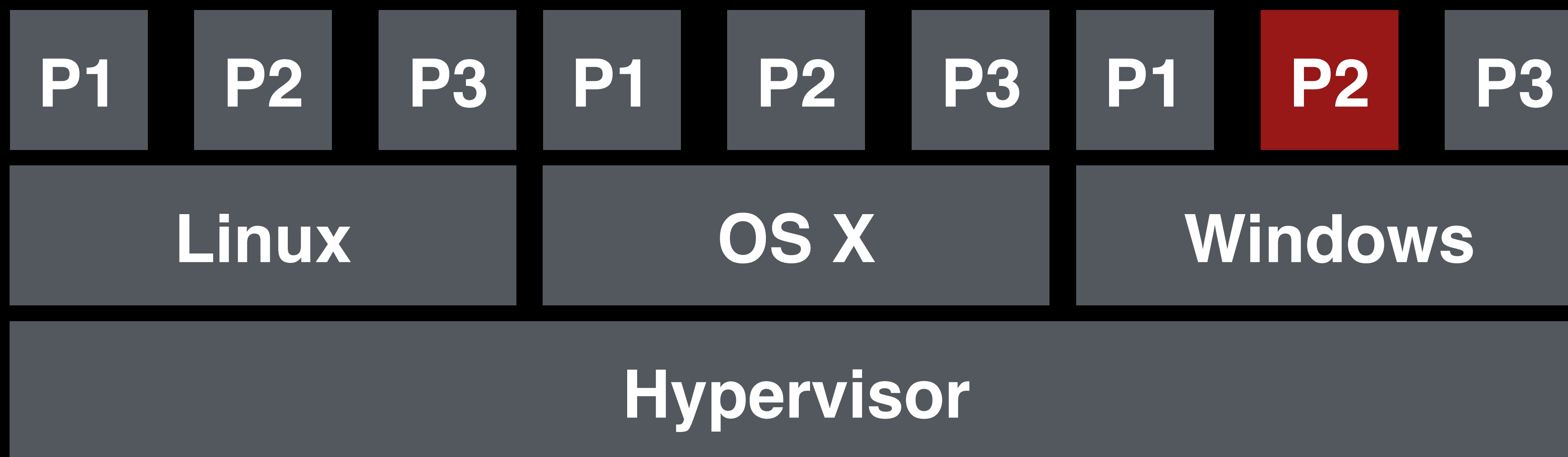
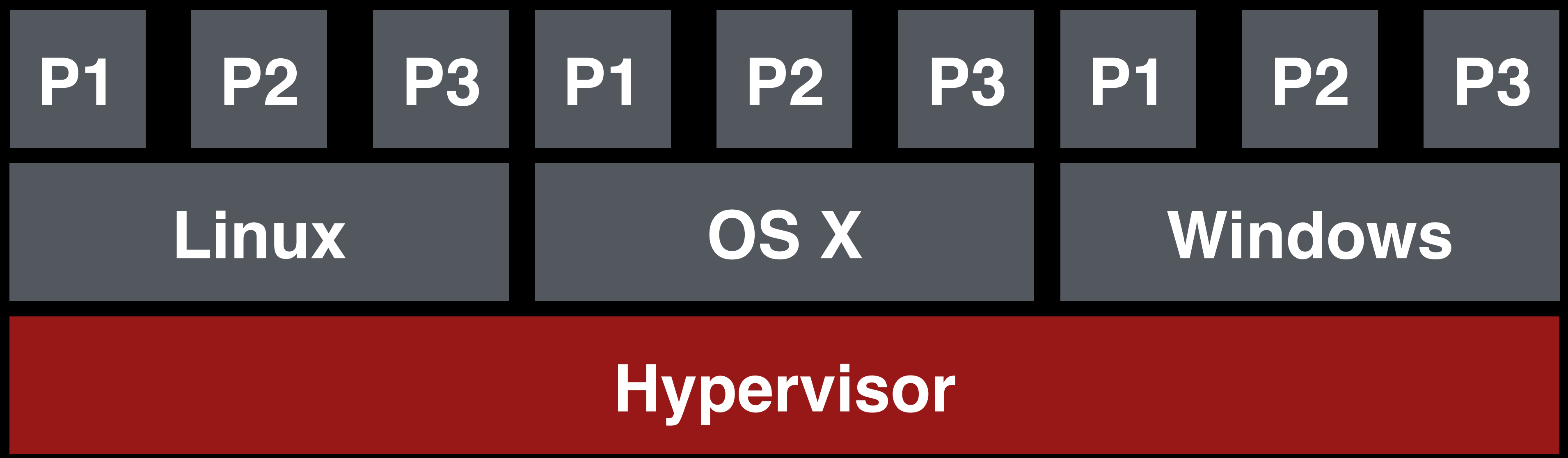
Windows
Hypervisor

timer interrupt!

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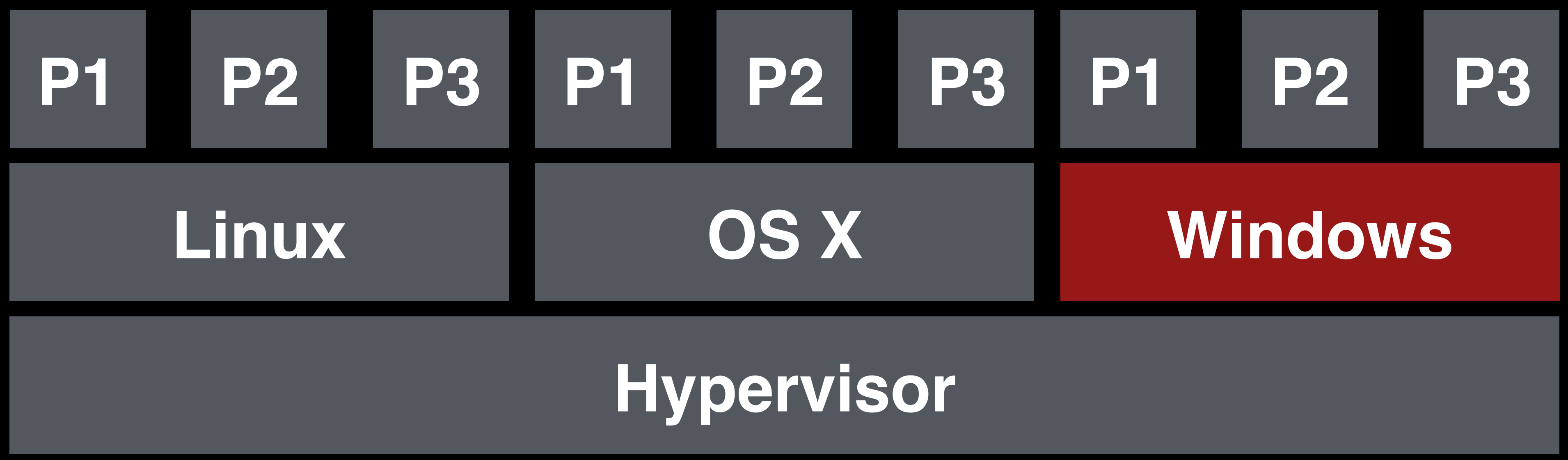
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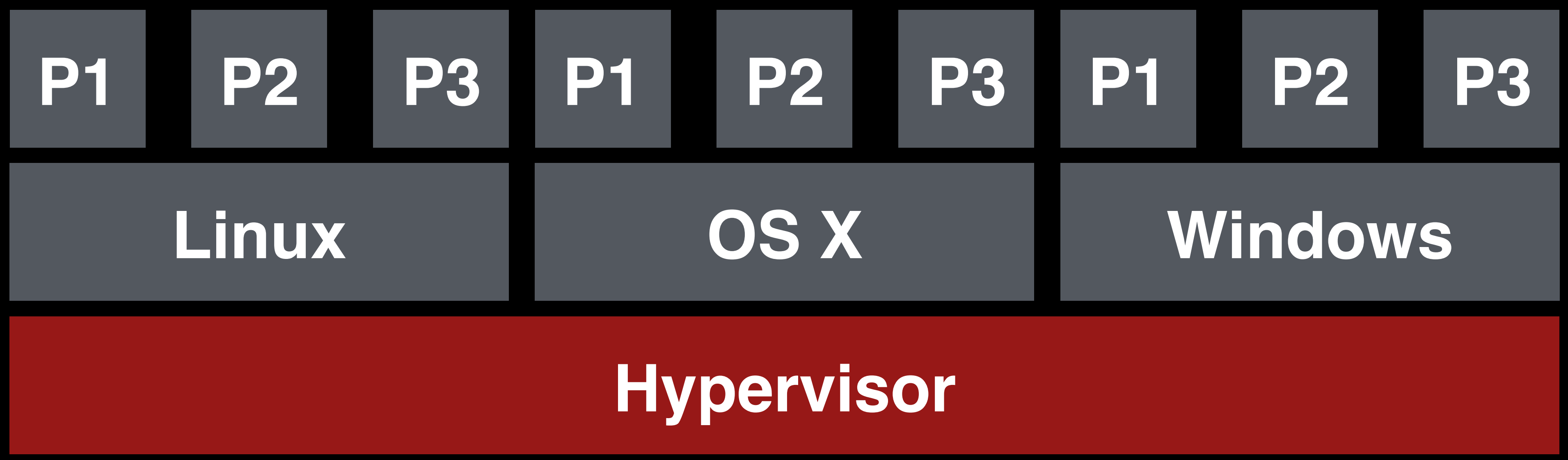
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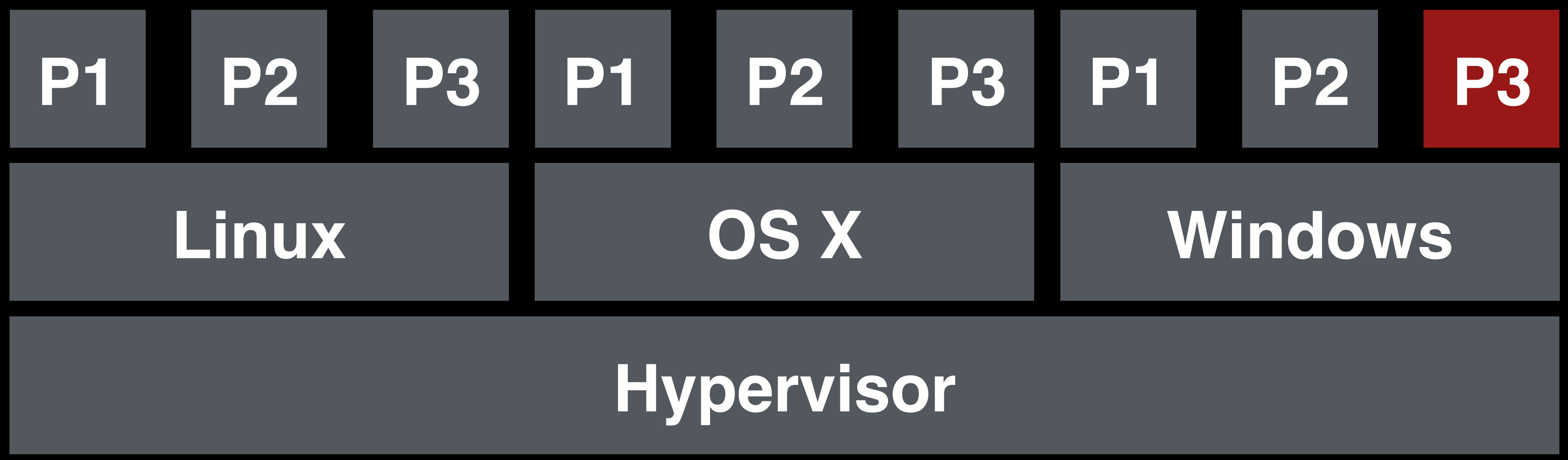
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Example

How to emulate an `lidt` call.

Review IDT table…

Bootup of VMM and guest OS.

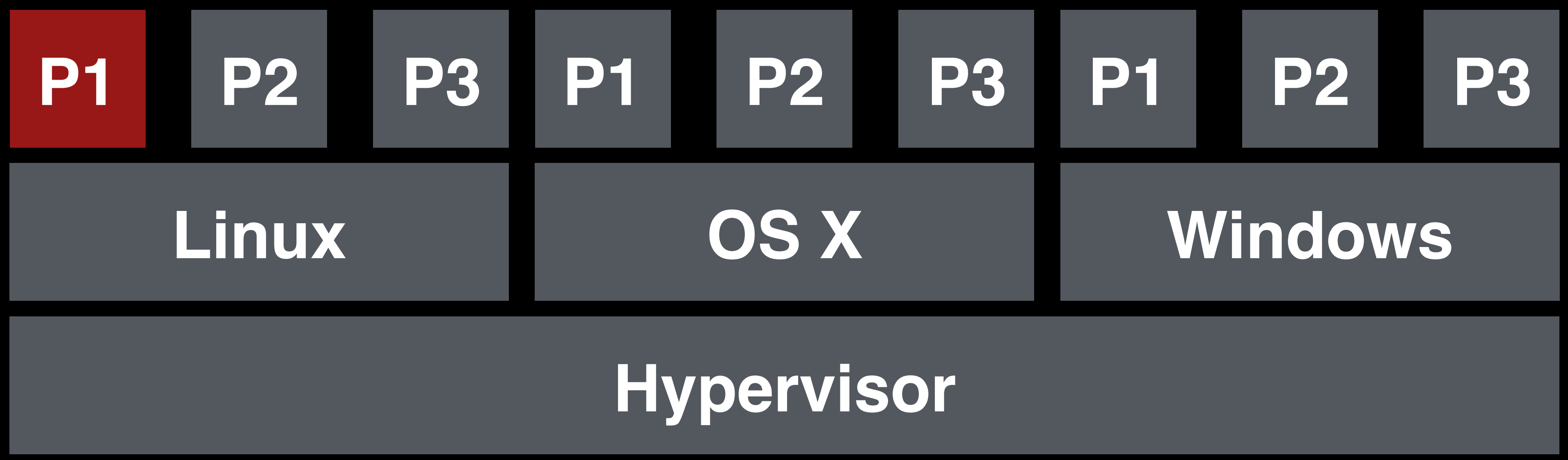
Example

How to emulate an `lidt` call.

Review IDT table…

Bootup of VMM and guest OS.

What if process in guest calls `lidt`?


P1
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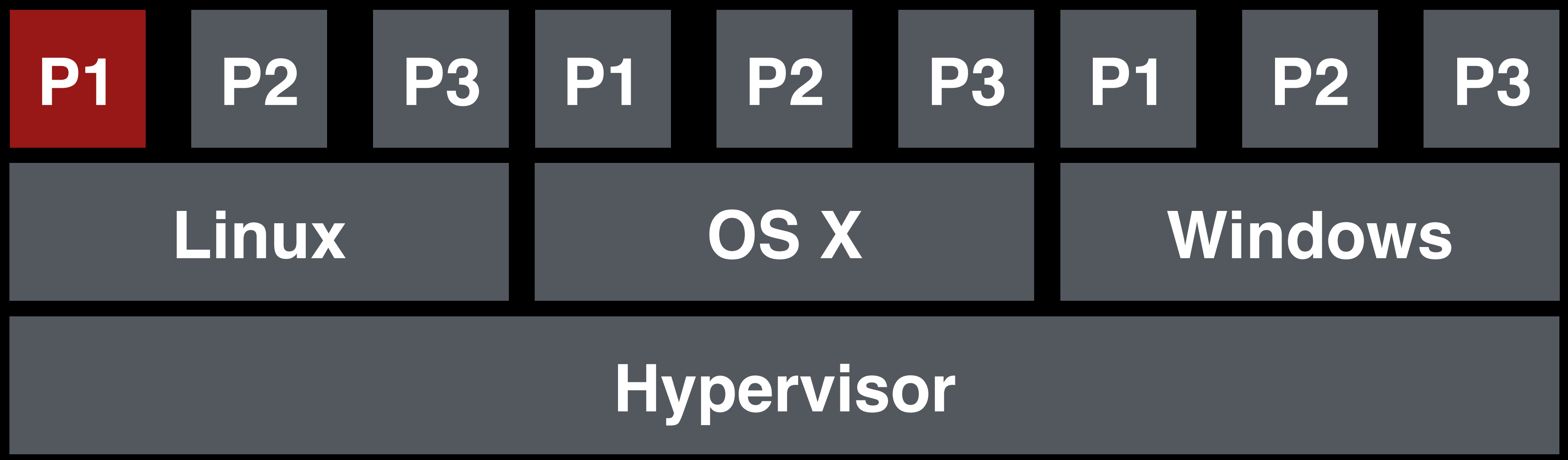
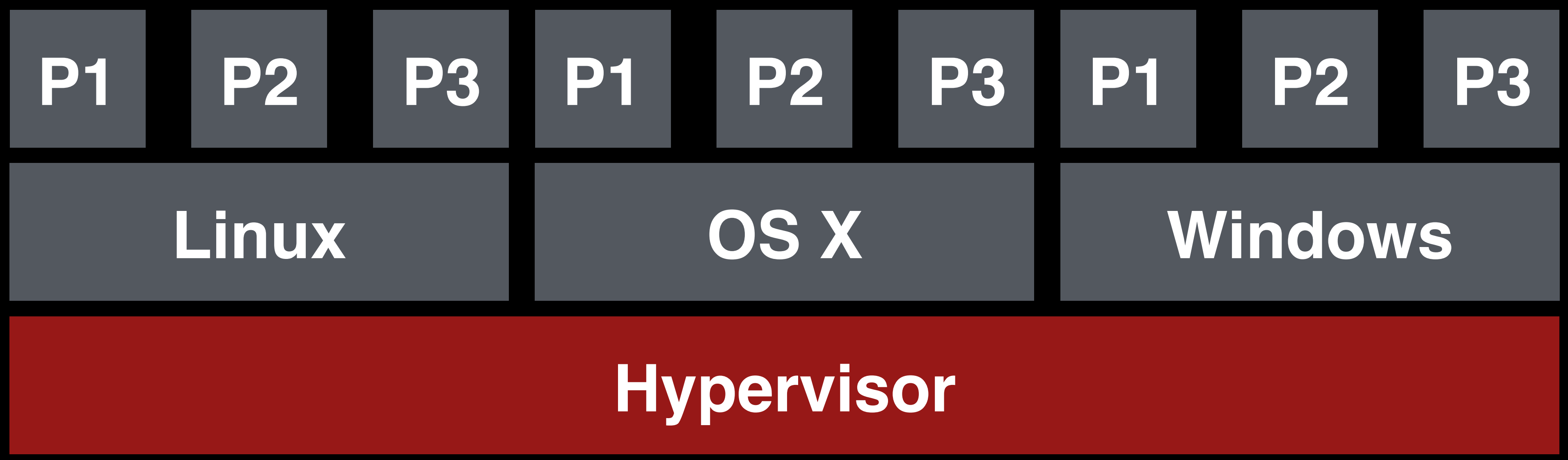
P1 calls lidt!

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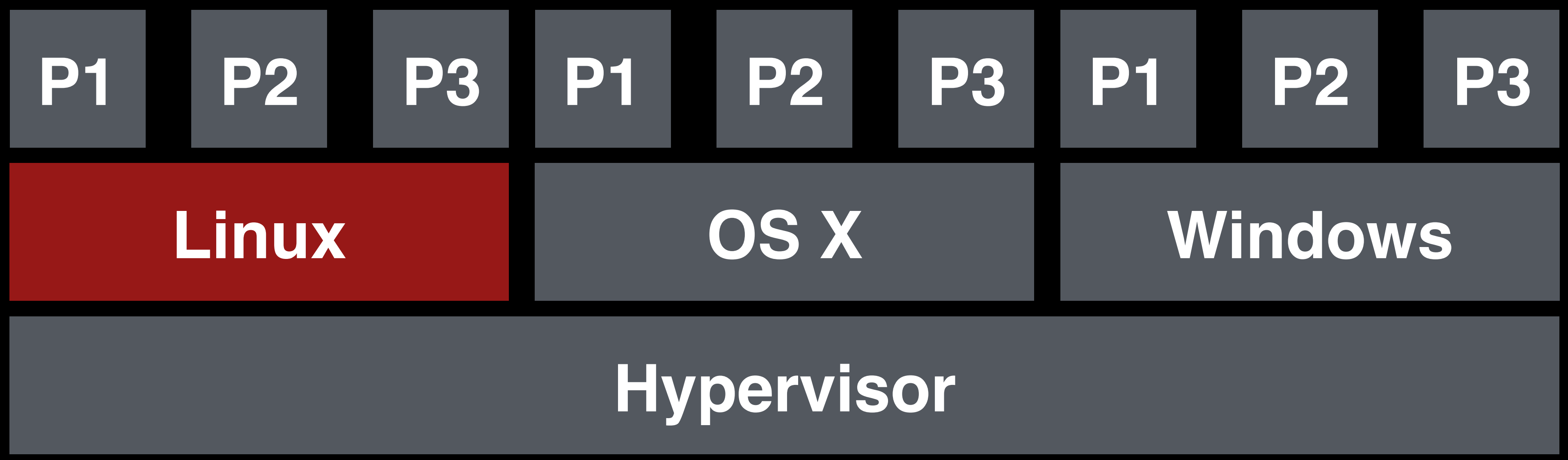
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Linux
OS X
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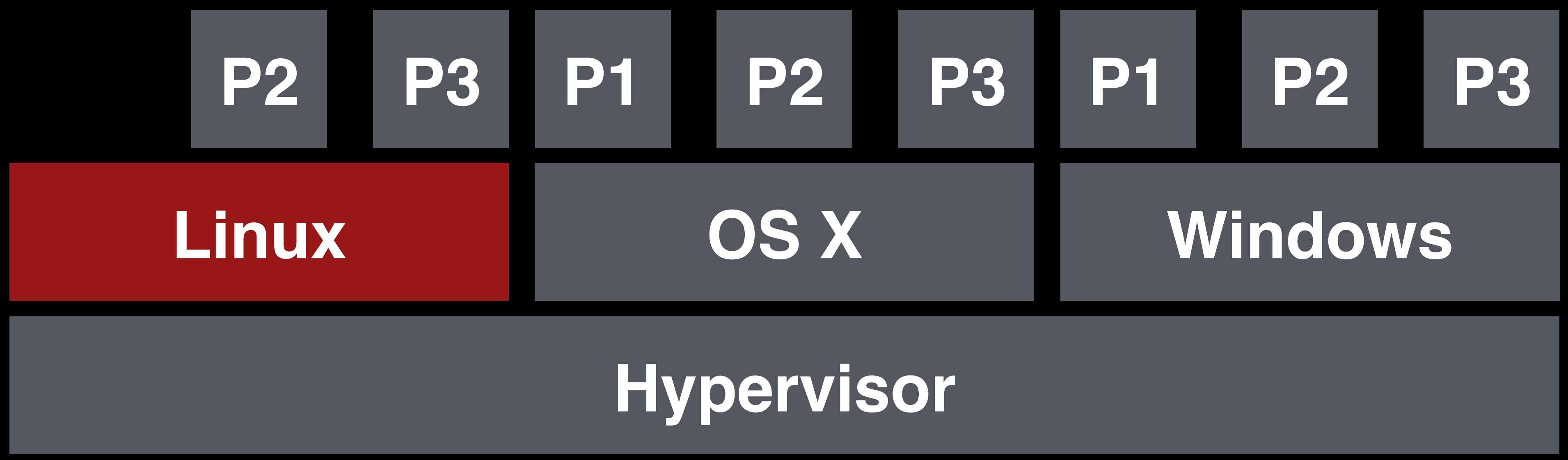
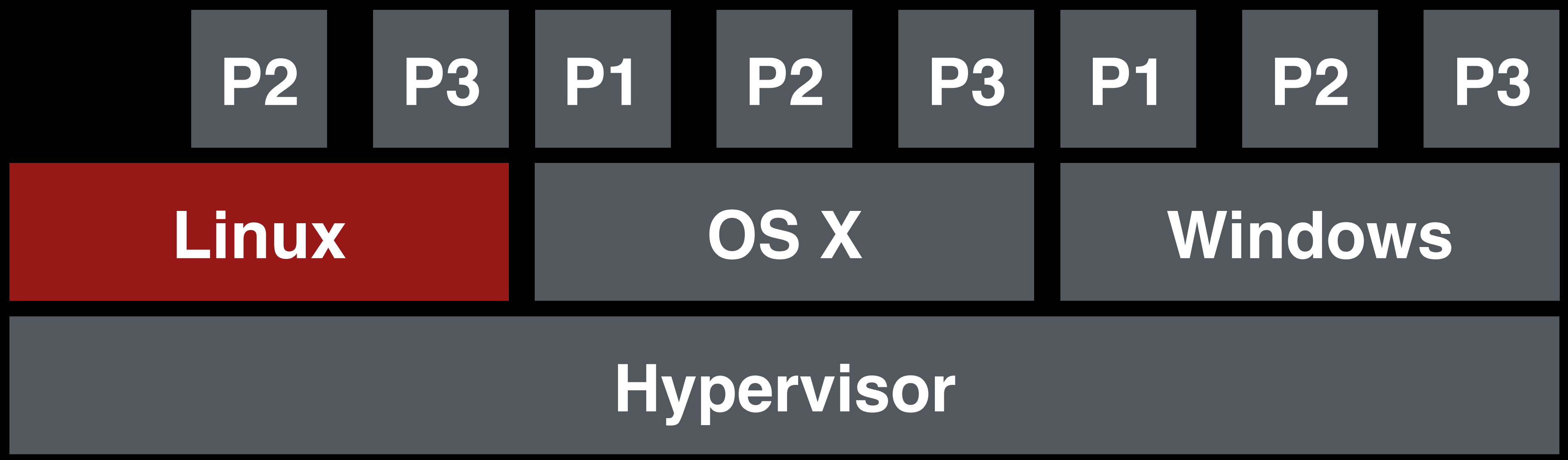
Linux kills P1. Privileged?




P2
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P1
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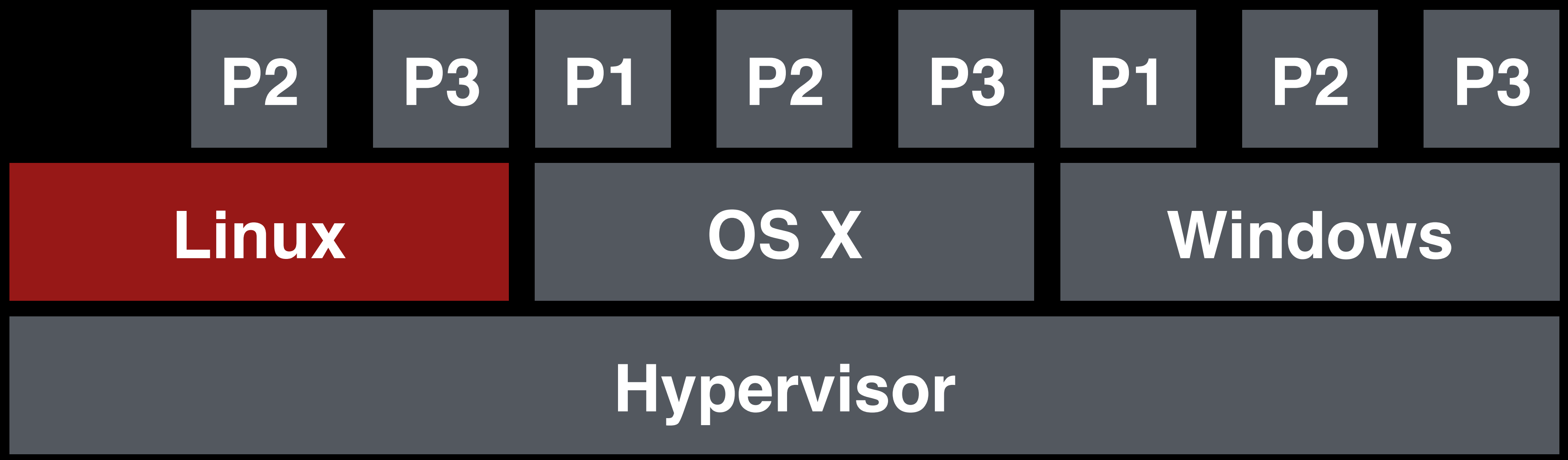
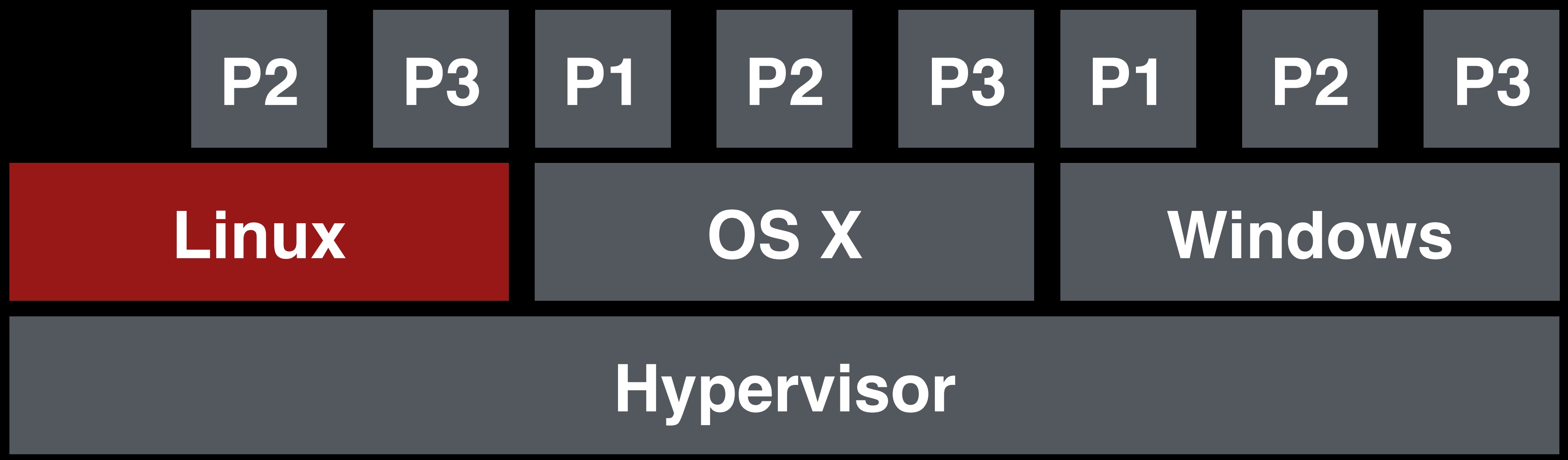
P1
P2
P3
Linux
OS X
Windows
Hypervisor

Linux tries to return-from-trap to P2. Privileged?

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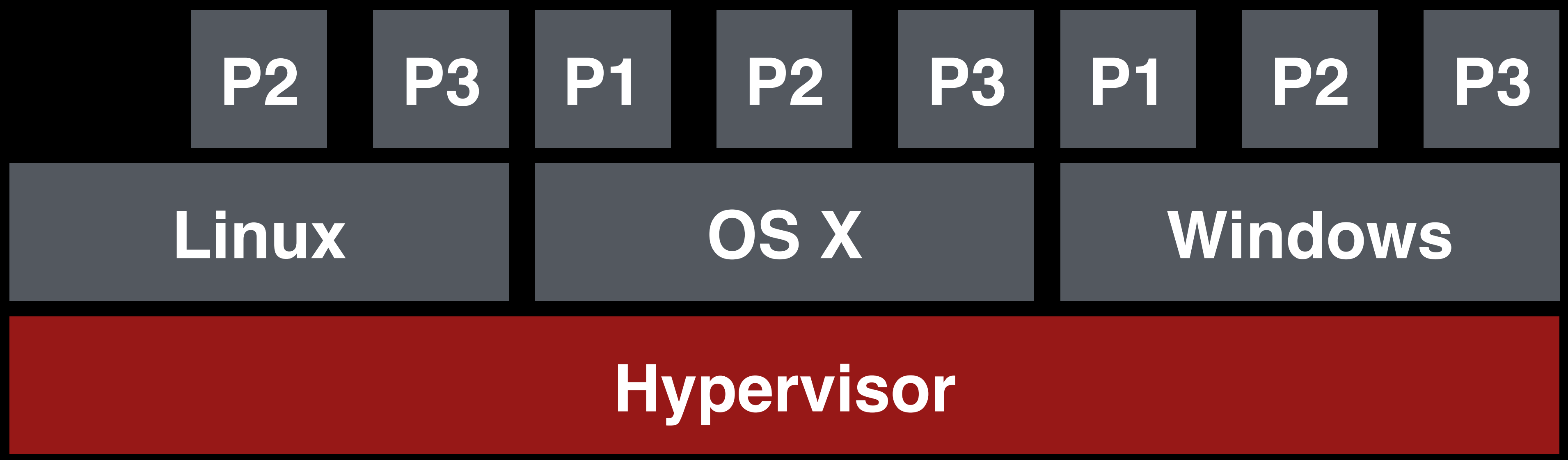
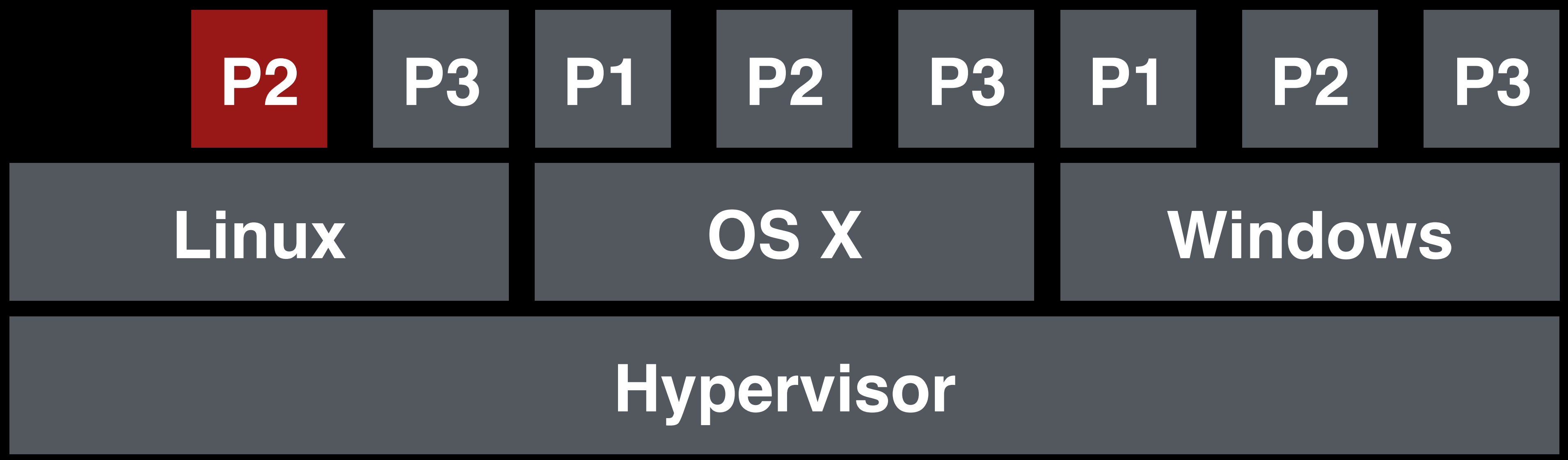
Windows
Hypervisor


P2
P3
P1
P2
P3
P1
P2
P3
Linux
OS X
Windows
Hypervisor


P2
P3
P1
P2
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P2
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System Calls

System calls must also have the VMM in the middle…

Process	Guest OS	VMM
system call: trap to OS		

time

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		process trapped: call os Trap handler (at reduced privilege)

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		OS tried return-from-trap: do real return-from-trap
resume execution: (@PC after trap)		

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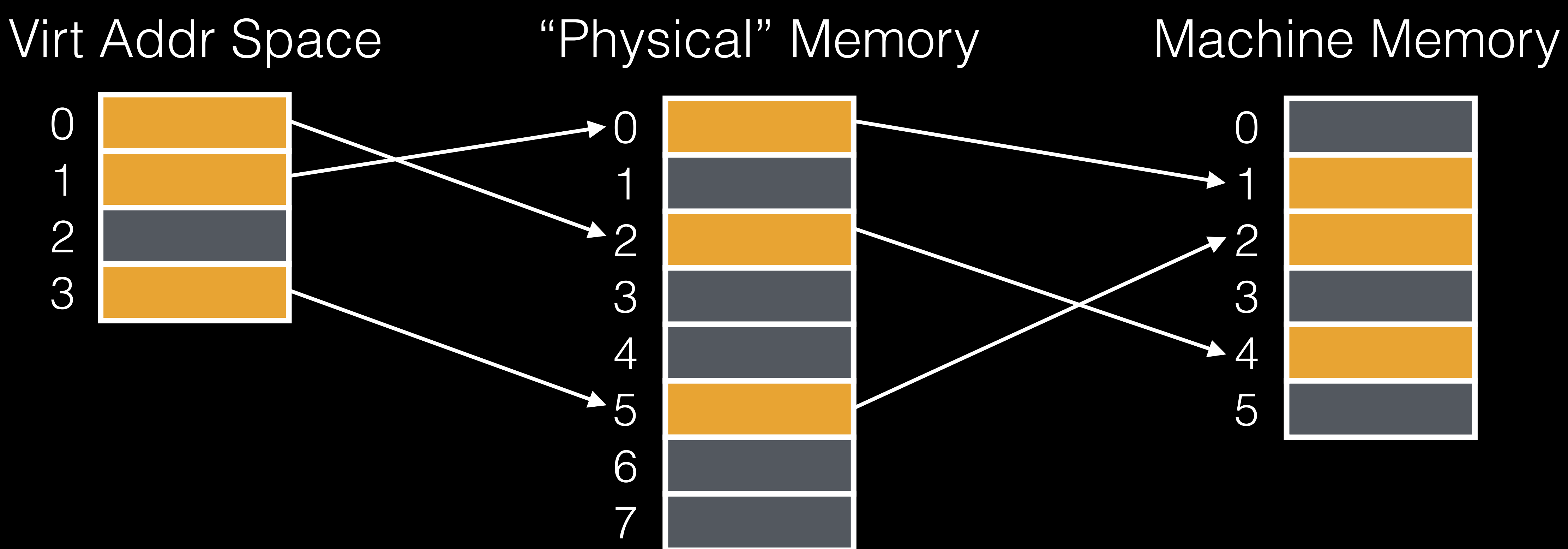
Virtual Memory

How to get more pages?

Process: asks politely, with `sbrk` or mmap `syscall`

OS: just uses it!

VMM needs to intercept such usage. How?
(assume software-managed TLB)

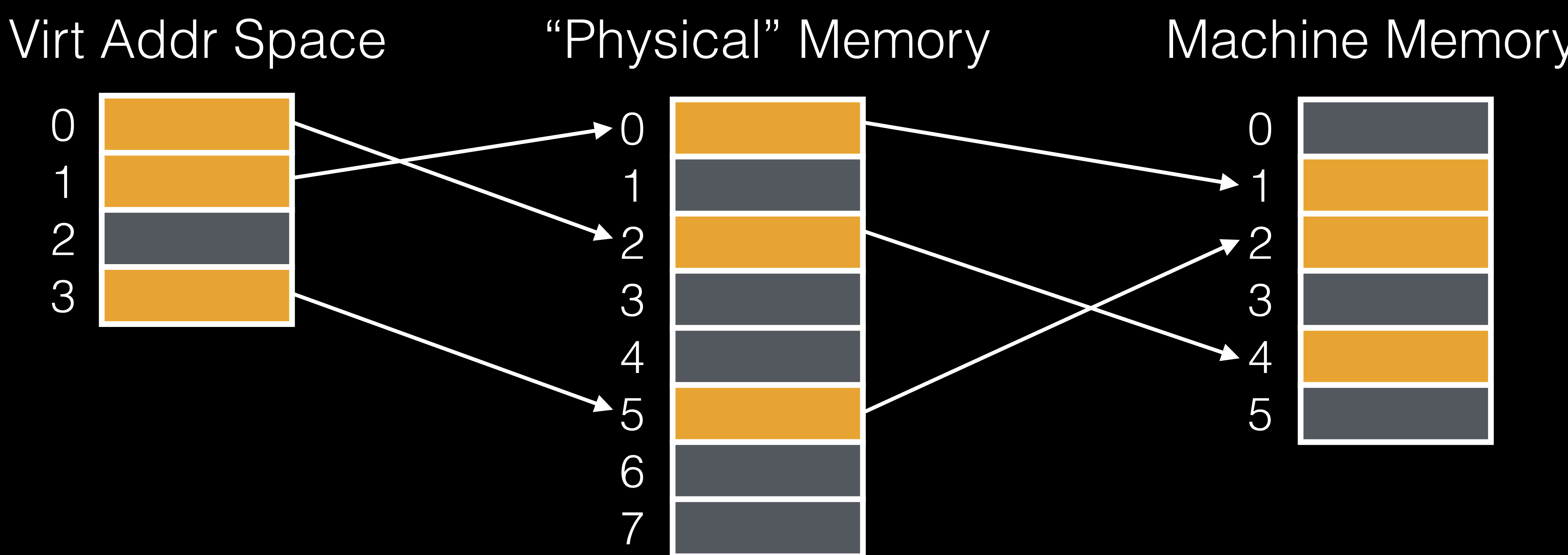

Virt Addr Space
"Physical" Memory
Machine Memory
0
1
2
3
0
1
2
3
4
5
6
7
0
1
2
3
4
5

OS Page Table

VPN 0 => PFN 2
VPN 1 => PFN 0
VPN 3 => PFN 5

VMM Page Table

PFN 0 => MFN 1
PFN 2 => MFN 4
PFN 5 => MFN 2



OS Page Table	VMM Page Table
VPN 0 => PFN 2	PFN 0 => MFN 1
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Strategy: store VPN => MFN mapping in TLB.

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Strategy: store VPN => MFN mapping in TLB.

- OS tries to insert VPN => PFN to TLB
- VMM intercepts it, looks up in its PT, inserts VPN => MFN

Examples…

OS Page Table	VMM Page Table
VPN 0 => PFN 2	PFN 0 => MFN 1
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Examples…
Timeline…

Process	Guest OS	VMM

time

Process	Guest OS	VMM
Mem load		
TLB miss: trap		

time

Process	**Guest OS**	**VMM**
Mem load		
TLB miss: trap		
		Call OS TLB handler (reducing privilege)

time

Process	Guest OS	VMM
Mem load TLB miss: trap		
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	Extract VPN from VA. Do page table lookup. Get PFN, update TLB	

time

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		Unprivileged code trying to update TLB! Tried to install **VPN-to-PFN**. Insert **VPN-to-MFN**. Jump back to OS.

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time

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		Return from trap.
resume execution: (@PC of instruction)		

Problems

Information Gap

OS's were not built to run on top of a VMM.
(less true than it used to be)

H/W interface does not give VMM enough info about guest OS.

In particular, is the OS using all its resources?

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Examples of waste from xv6…

Waste 1 (proc.c)

```
void scheduler(void) {
  struct proc *p;
  for(;;){
    // Enable interrupts on this processor.
    sti();
    // Loop over process table looking for process to run.
    acquire(&ptable.lock);
    for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
      if(p->state != RUNNABLE)
        continue;
      ...
    }
    release(&ptable.lock);
  }
}
```

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How does the VMM know to give CPU to another OS?

Waste 2 (kalloc.c)

```
struct {
  struct spinlock lock;
  struct run *freelist;
} kmem;
// first address after kernel loaded from ELF file
extern char end[];

// Initialize free list of physical pages.
void kinit(void) {
  char *p;

  initlock(&kmem.lock, "kmem");
  p = (char*)PGROUNDUP((uint)end);
  for(; p + PGSIZE <= (char*)PHYSTOP; p += PGSIZE)
    kfree(p);
}
```

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How does the VMM know to give pages to another OS?

Waste 3 (vm.c)

```
// Allocate page tables and physical memory to grow process.
// Returns new size or 0 on error.
int allocuvm(pde_t *pgdir, uint oldsz, uint newsz) {
  char *mem;
  uint a;
  a = PGROUNDUP(oldsz);
  for(; a < newsz; a += PGSIZE){
    mem = kalloc();
    memset(mem, 0, PGSIZE);
    mappages(pgdir, (char*)a, PGSIZE, PADDR(mem), PTE_W|PTE_U);
  }
  return newsz;
}
```

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  }
  return newsz;
}
```

How does OS know page is already zeroed?

Summary

VM's have overheads.

The existing H/W interface is restrictive.

New opportunities for sharing often outweigh the disadvantages, as utilization is improved.

More fun…

The Turtles Project: Design and Implementation of Nested Virtualization