CS444/544
Operating Systems II

Lecture 8

User/Kernel Context Switch

4/29/2024

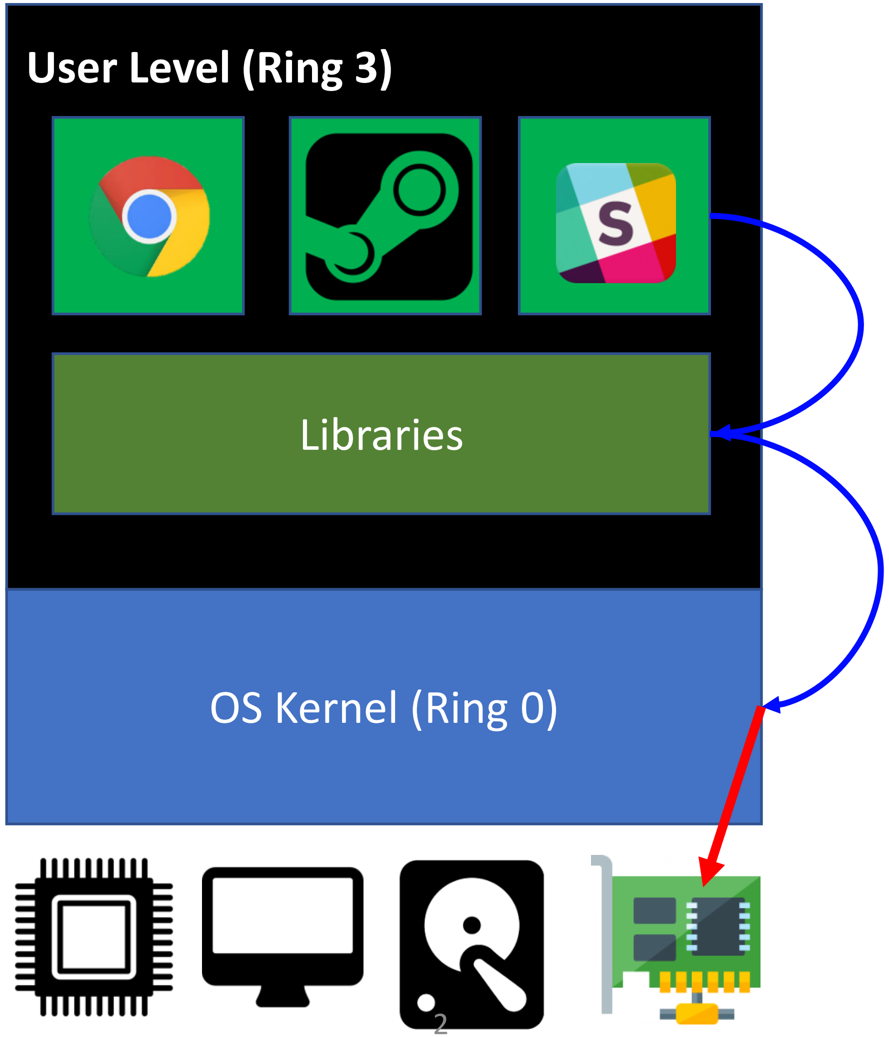
Acknowledgement: Slides drawn heavily from Yeongjin Jiang

Oregon State University

Today’s Topic

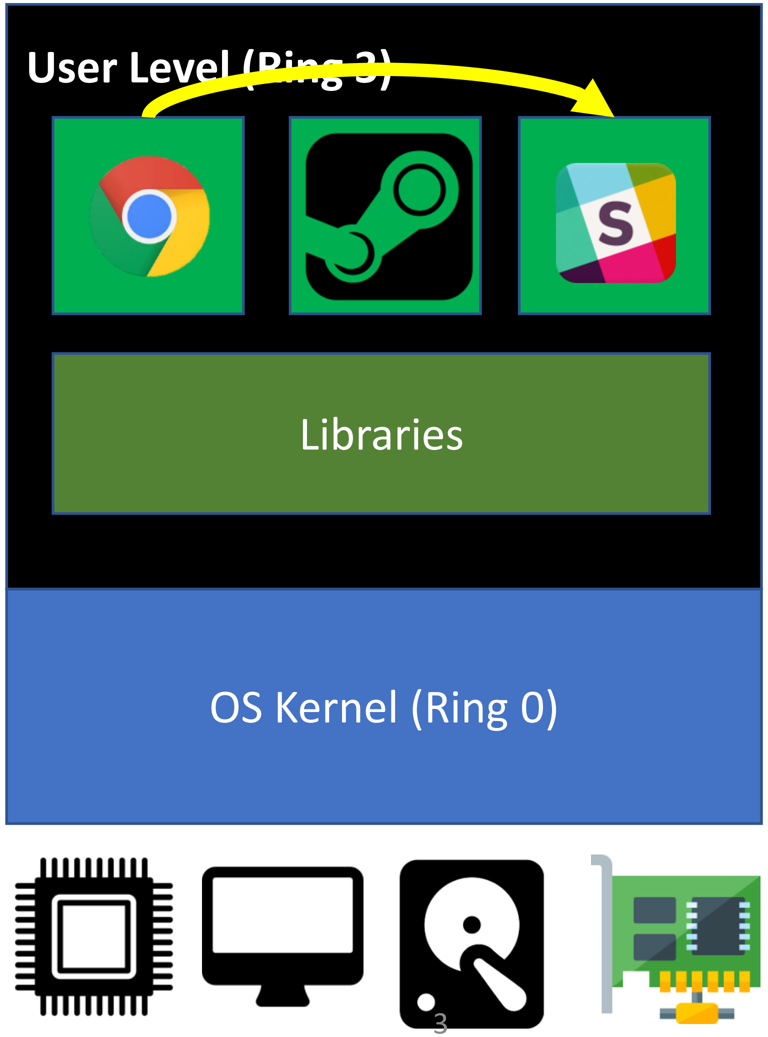
- User/Kernel Space Switch
  - How does the OS kernel run a program in Ring 3 (user level)?
  - How does the OS kernel take back the execution to Ring 0 (kernel)?

- System call
  - How could a user level program let OS serve for them?



Today’s Topic

- Process Context Switch
  - How could our CPU run multiple applications at the same time?
- 3 design candidates
  - Not switching
  - Co-operative Multitasking
  - Preemptive Multitasking

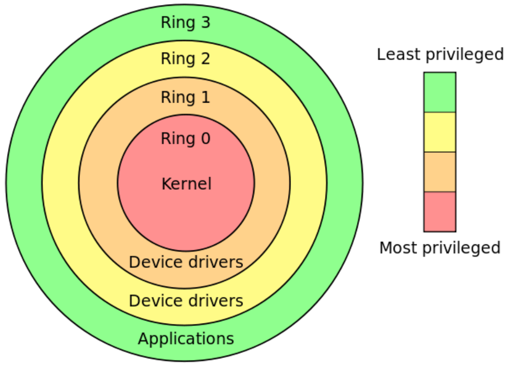


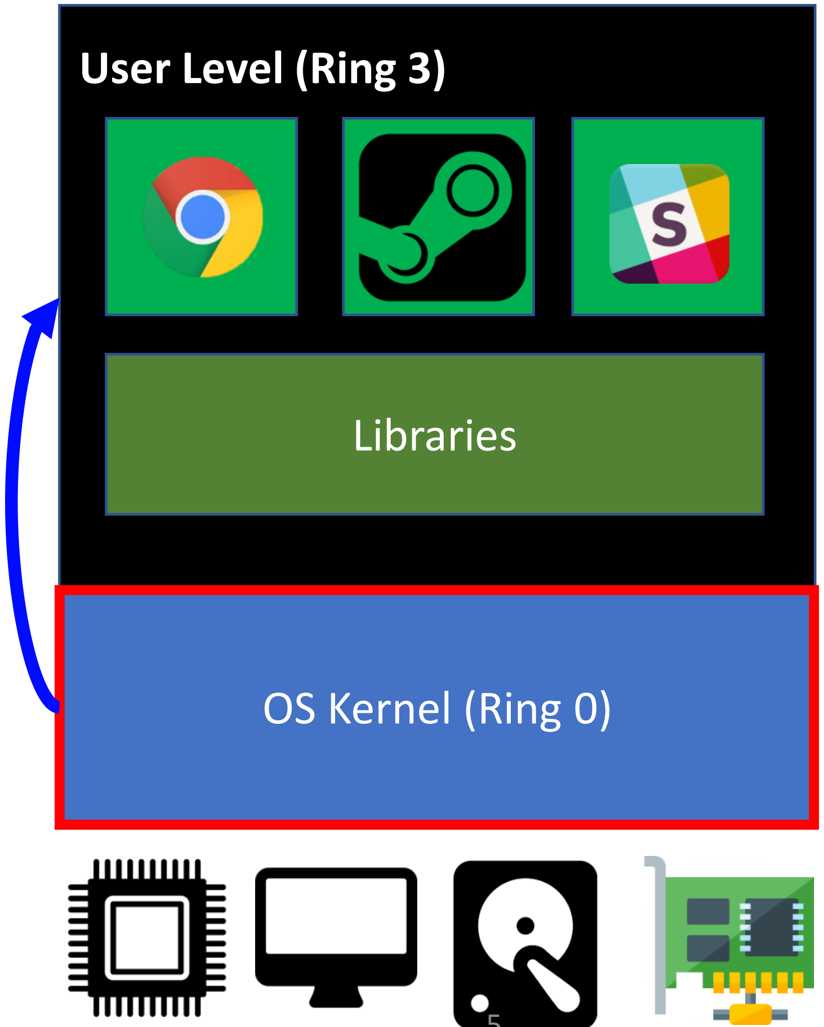
Today’s Topic

- User/Kernel Space Switch
  - Interrupt
  - System calls
  - Fault / Exceptions

Kernel (Ring 0)

- Runs with the highest privilege level (Ring 0)
- Configures system (devices, memory, etc.)
- Manages hardware resources
  - Disk, memory, network, video, keyboard, etc.
- Manages other jobs
  - Processes and threads
- Serves as trusted computing base (TCB)
  - Set privilege
  - Restrict other jobs from doing something bad..



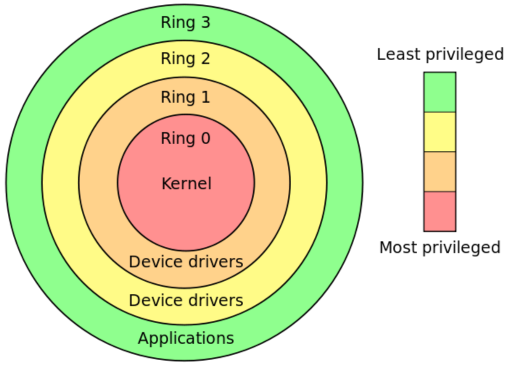


User Level (Ring 3)

Libraries

OS Kernel (Ring 0)

User (Ring 3)



Ring 3

Ring 2

Ring 1

Ring 0

Kernel

Device drivers

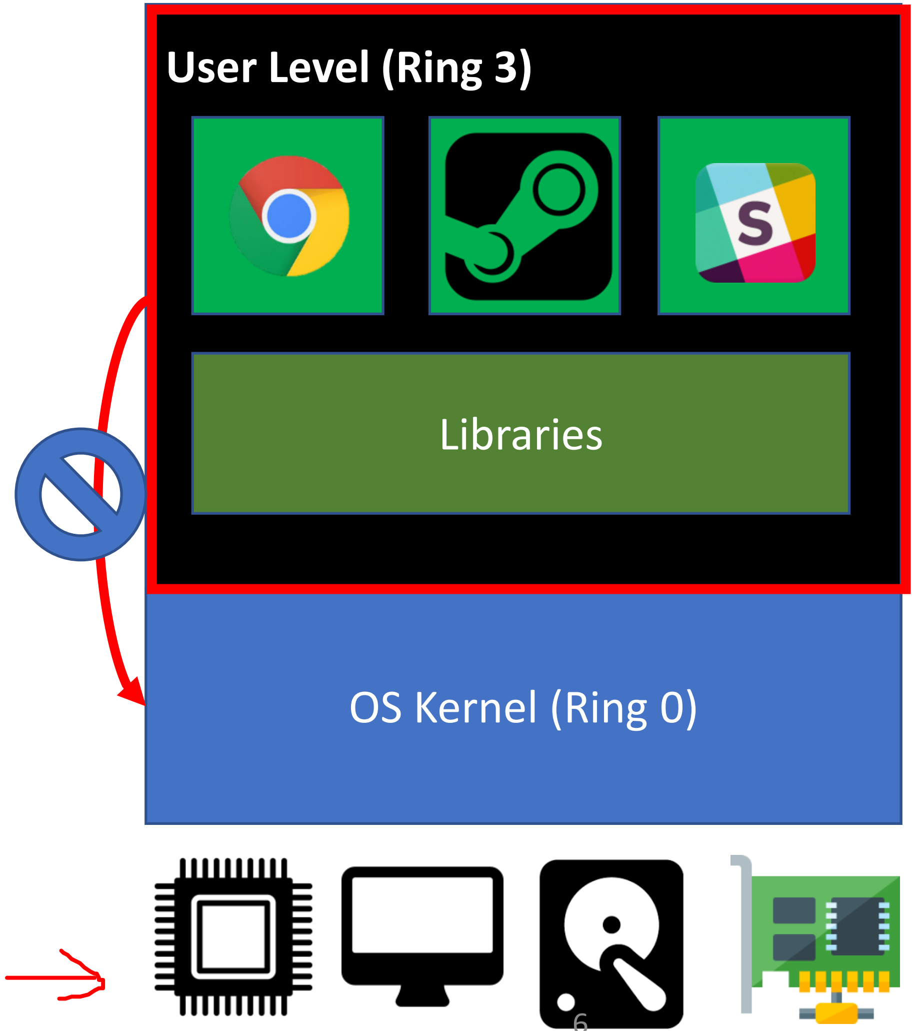
Device drivers

Applications

Least privileged

Most privileged

- Runs with a restricted privilege (Ring 3)
  - The privilege level for running an application…
- Most of regular applications runs in this level
- Cannot access kernel memory
  - Can only access pages set with PTE_U
- Cannot talk directly to hardware devices
  - Kernel must mediate the access

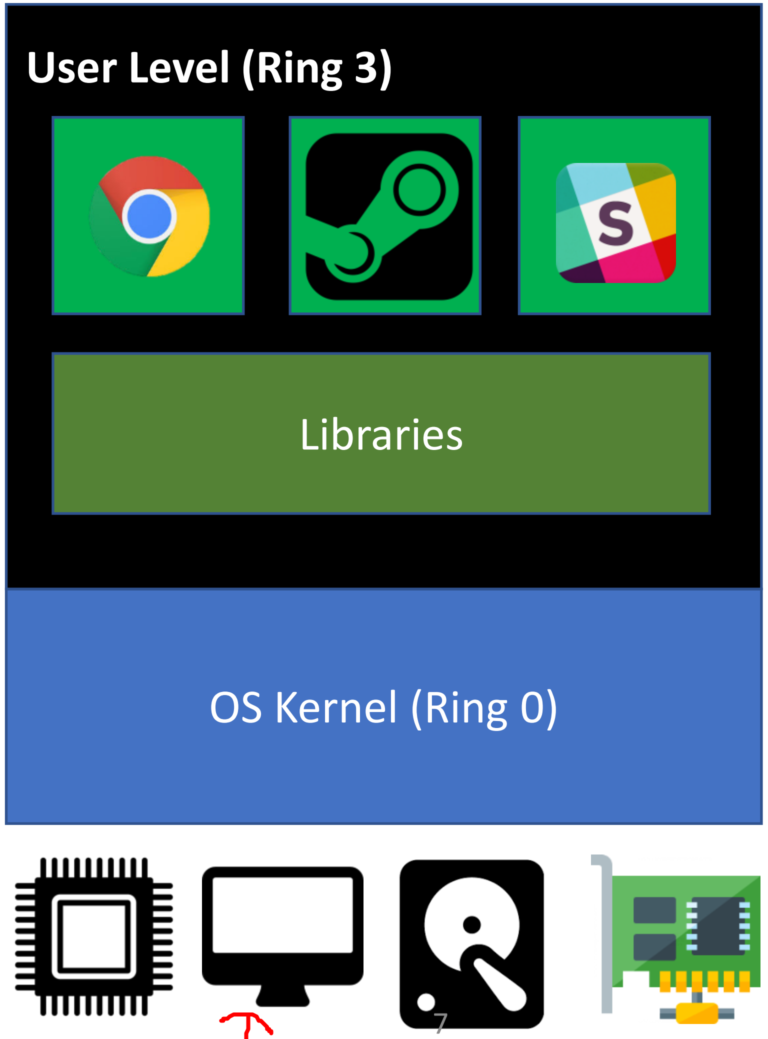


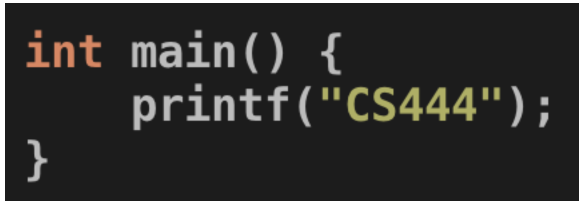
User Level (Ring 3)

Libraries

OS Kernel (Ring 0)

A High-level Overview of User/Kernel Execution





```
int main() {
    printf("CS444");
}
```

A High-level Overview of User/Kernel Execution

printf("CS444")

A library call in ring 3

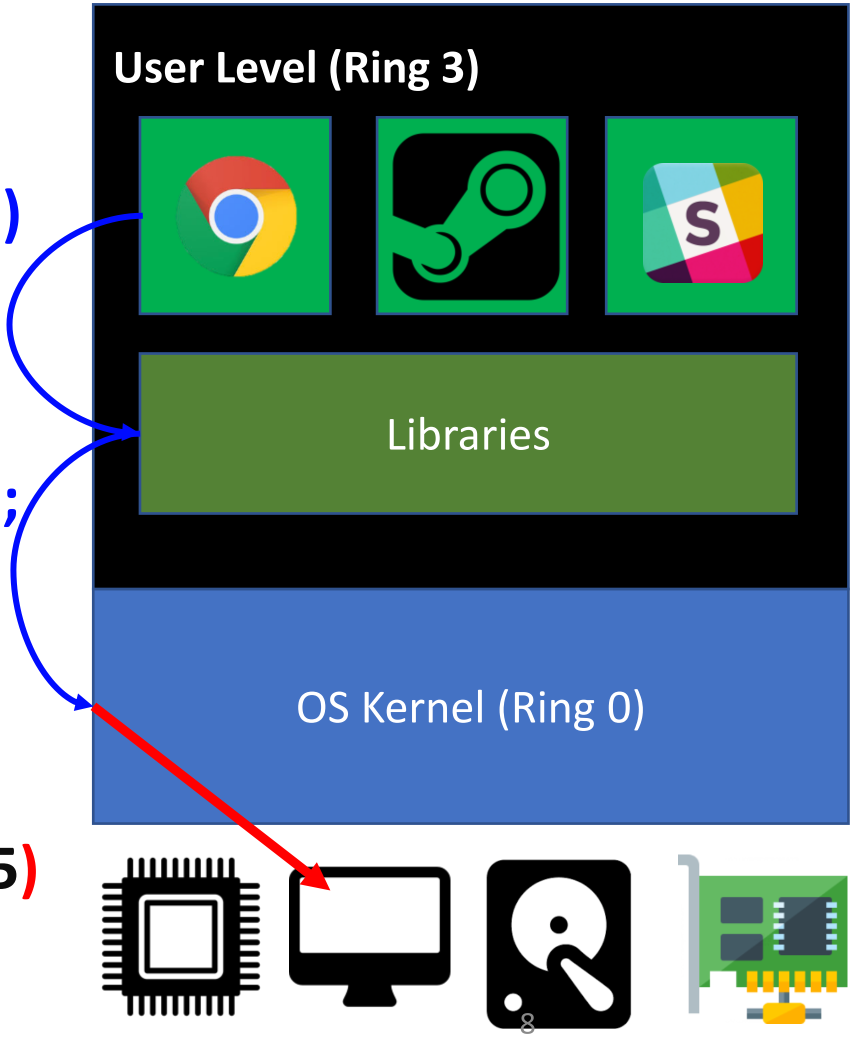
sys_write(1, "CS444", 5);

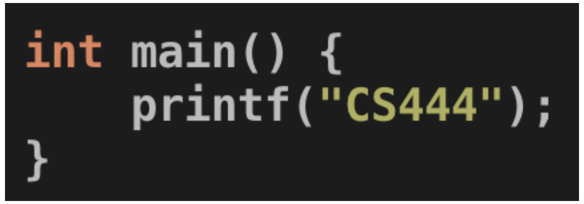
A system call, **From ring 3**

Interrupt!, switch from ring3 to ring0

A kernel function

do_sys_write(1, "CS444", 5)





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A High-level Overview of User/Kernel Execution

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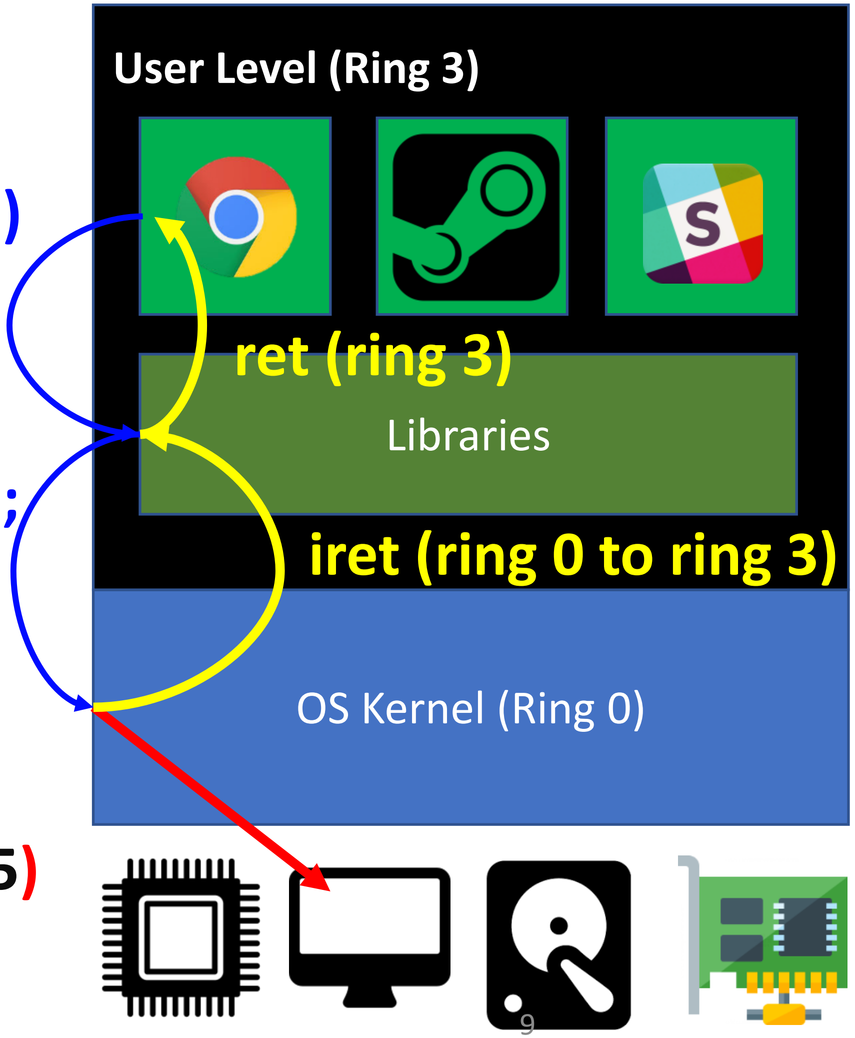


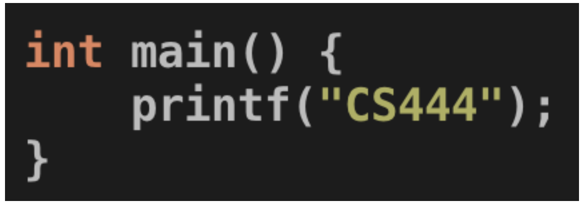
User Level (Ring 3)

ret (ring 3)

Libraries

iret (ring 0 to ring 3)

OS Kernel (Ring 0)

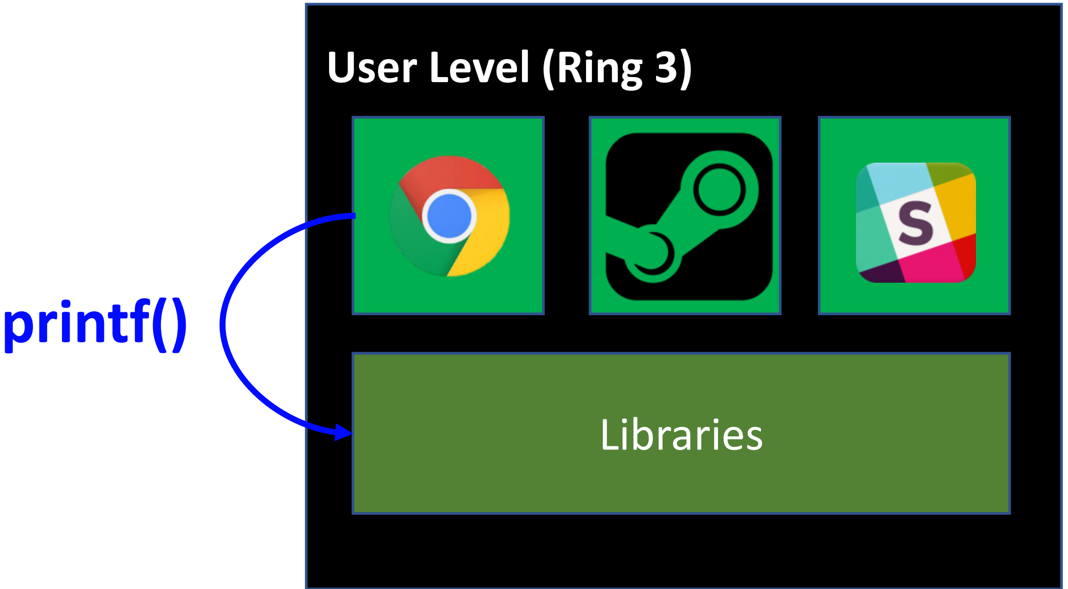


```
int main() {
    printf("CS444");
}
```

A Library Call

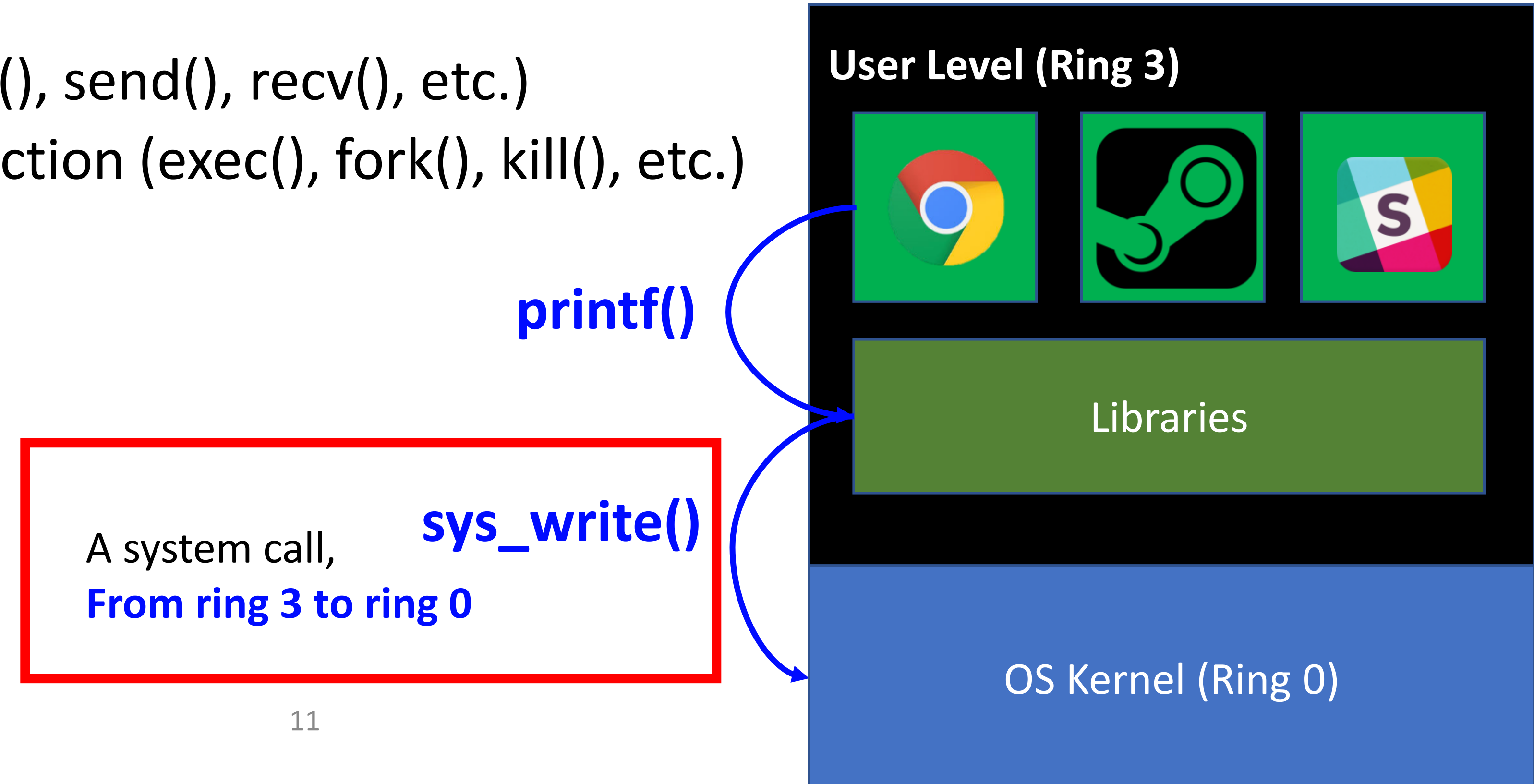
- A function call within the application’s memory space
- All regular C/C++ API calls are library calls
  - fwrite(), printf(), time(), srand(), etc.
  - Calls that you did not implement but prepared by others (in ring 3)
- From Ring 3 to Ring 3

A library call in ring 3



A System Call

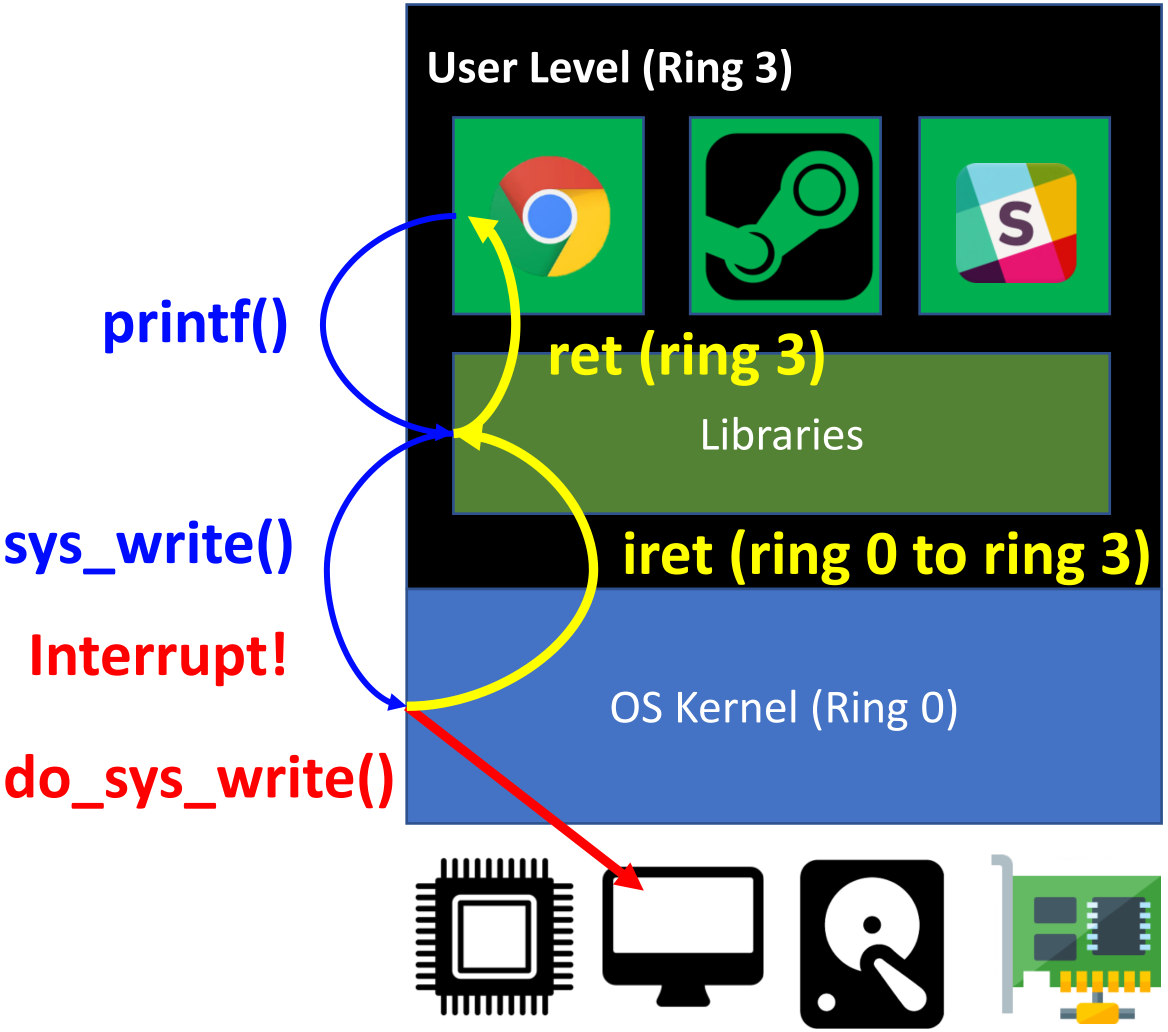
- A function call from applications that request OS to do something special for them
- System APIs
  - I/O access (read(), write(), send(), recv(), etc.)
  - Process creation, destruction (exec(), fork(), kill(), etc.)
  - Other hardware access..
- From Ring 3 to Ring 0



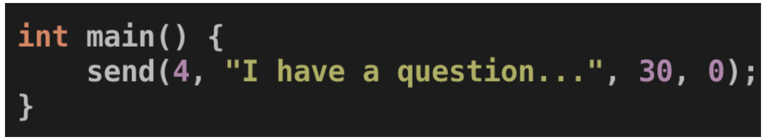
A system call,
From ring 3 to ring 0

Returning from a Call

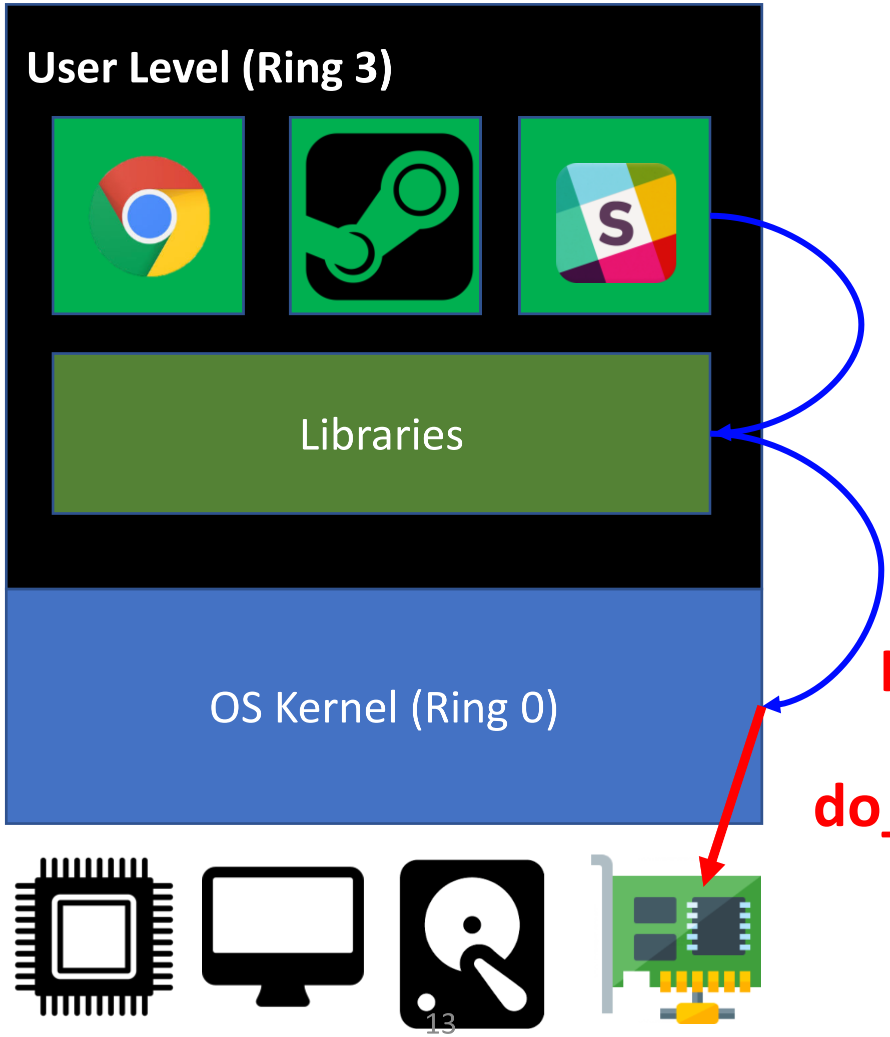
- Returning from a Library Call
  - `ret`
  - No ring switch (ring 3 -> ring 3)
- Returning from a System Call
  - `iret` (interrupt return)
  - Ring switch happens (ring 0 -> ring 3)



A High-level Overview of User/Kernel Execution



```
int main() {
    send(4, "I have a question...", 30, 0);
}
```



User Level (Ring 3)

Libraries

OS Kernel (Ring 0)

send()

A library call in ring 3

sys_send()

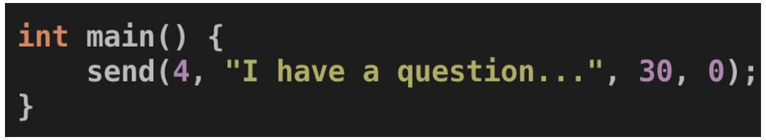
A system call,

From ring 3 to ring 0

Interrupt!

do_sys_send()

A High-level Overview of User/Kernel Execution



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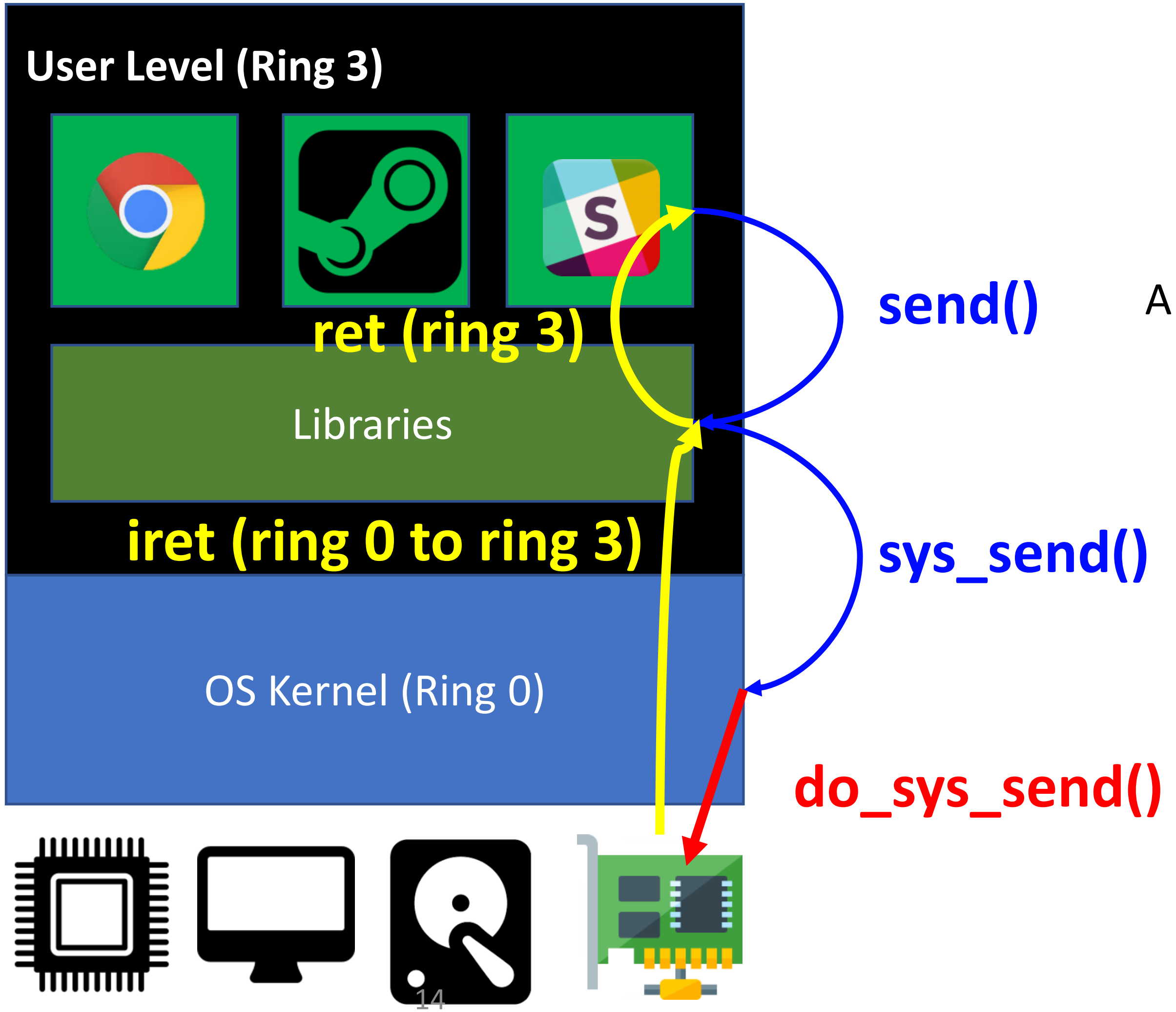


User Level (Ring 3)

Libraries

OS Kernel (Ring 0)

ret (ring 3)

iret (ring 0 to ring 3)

send()

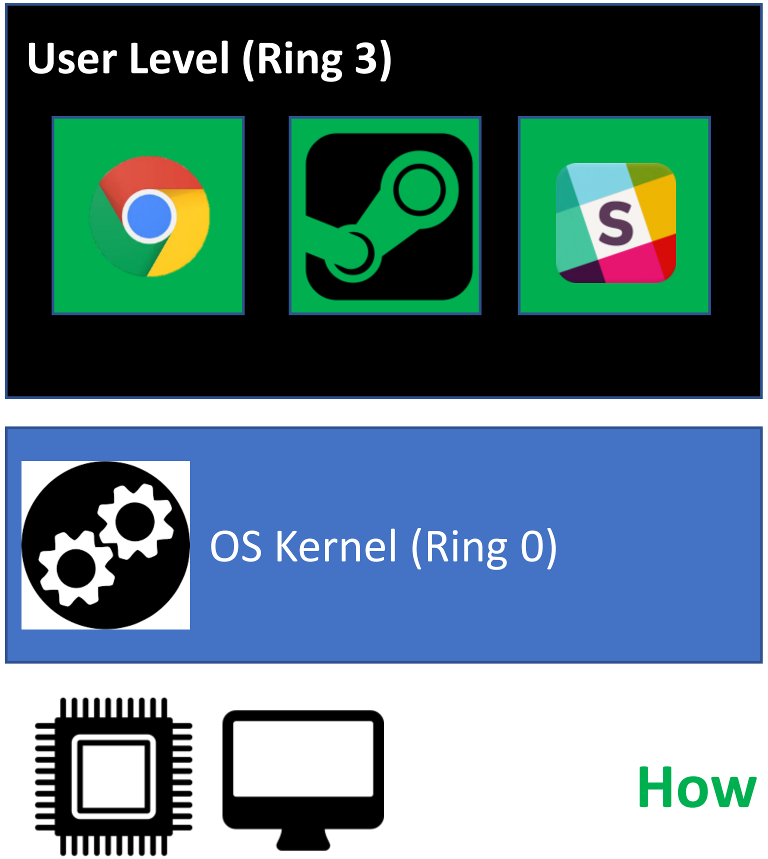
sys_send()

do_sys_send()

A library call in ring 3

A system call,
From ring 3 to ring 0

How does Kernel Execute an Application?



User Level (Ring 3)

OS Kernel (Ring 0)

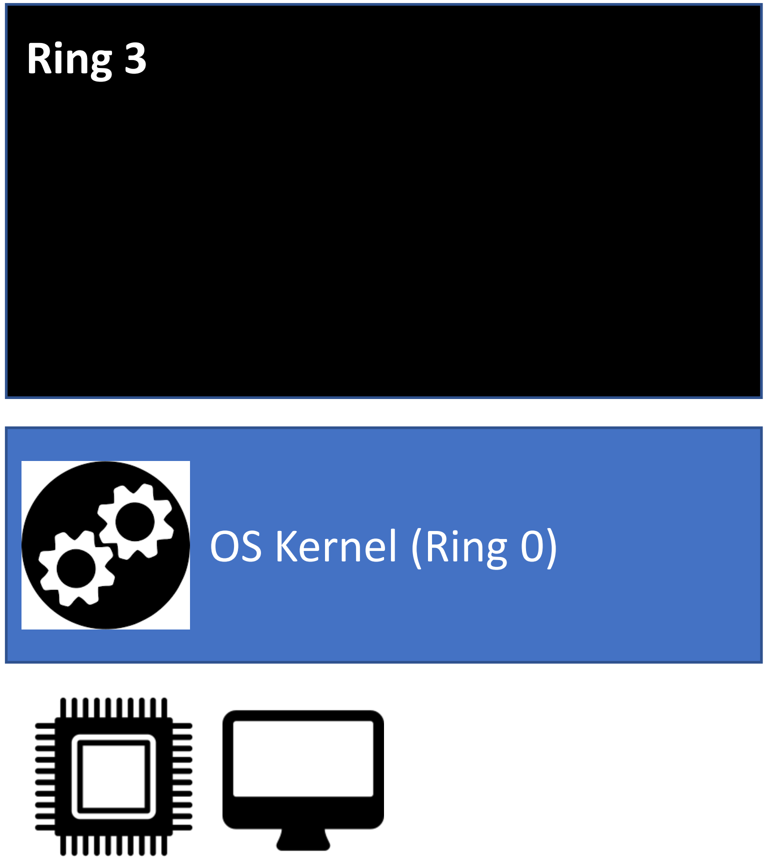
Lab1: Booting

Lab2: Set VM

Lab3: Set kernel/user env

How does an OS run an application?

How does Kernel Execute an Application?

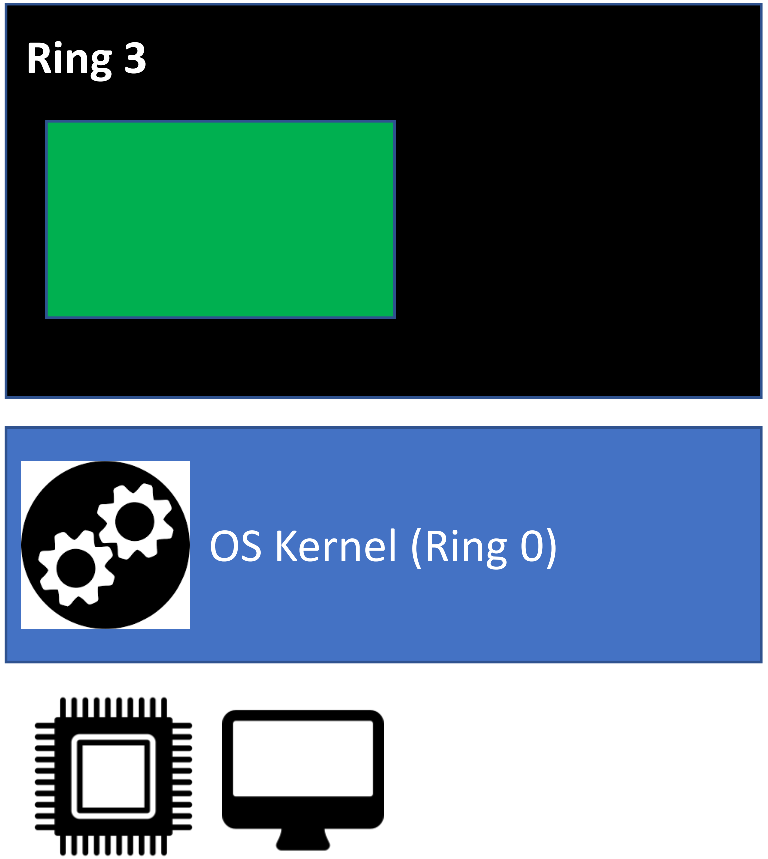


Ring 3

OS Kernel (Ring 0)

How does Kernel Execute an Application?

1. Prepare a process,
an environment for running
an application



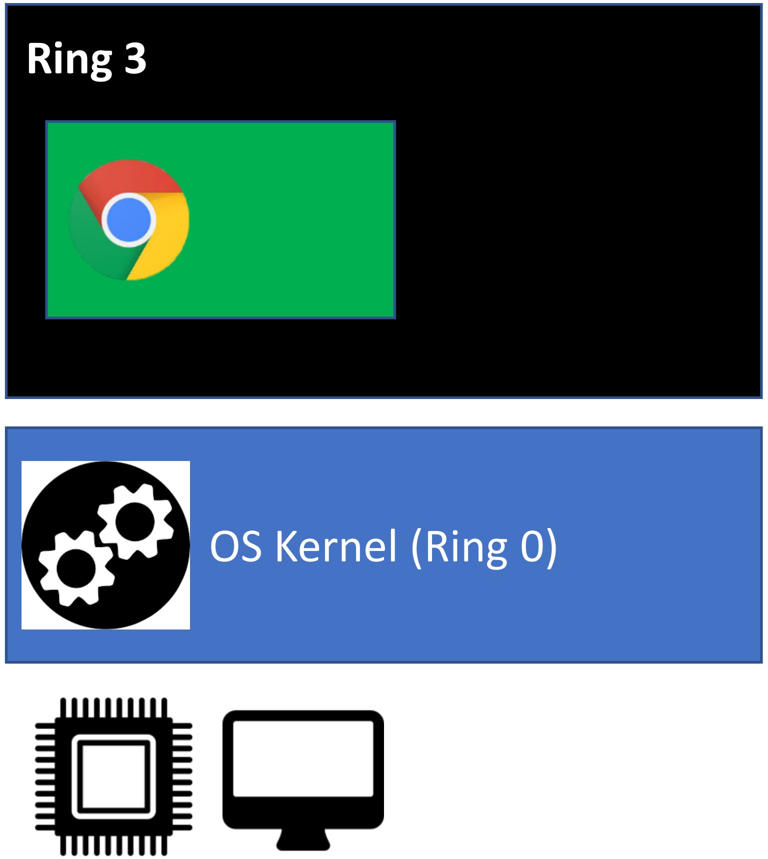
Assign a separated
Virtual Memory Space

New page directory
New page table
Etc..

How does Kernel Execute an Application?

1. Prepare a process,
an environment for running
an application

2. Put an application!
load code!

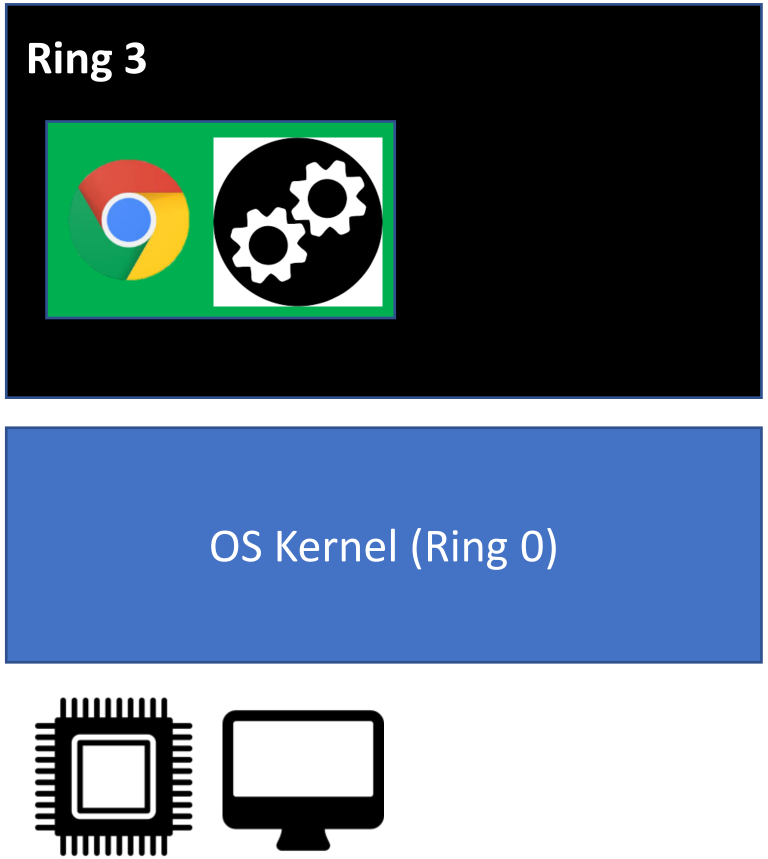


How does Kernel Execute an Application?

1. Prepare a process, an environment for running an application

2. Put an application! load code!

3. Execute!

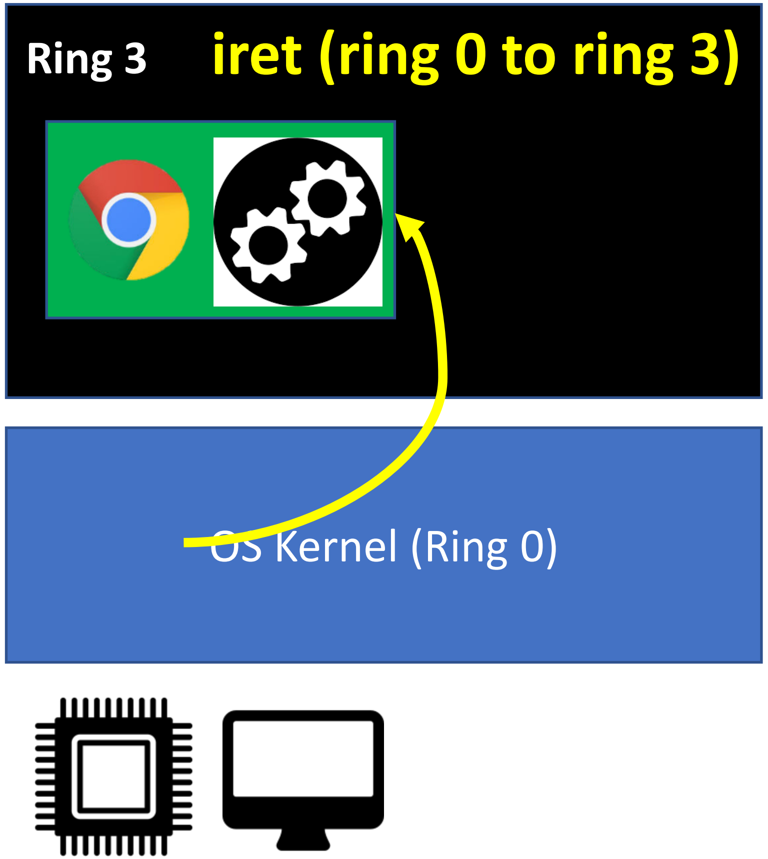


How does Kernel Execute an Application?

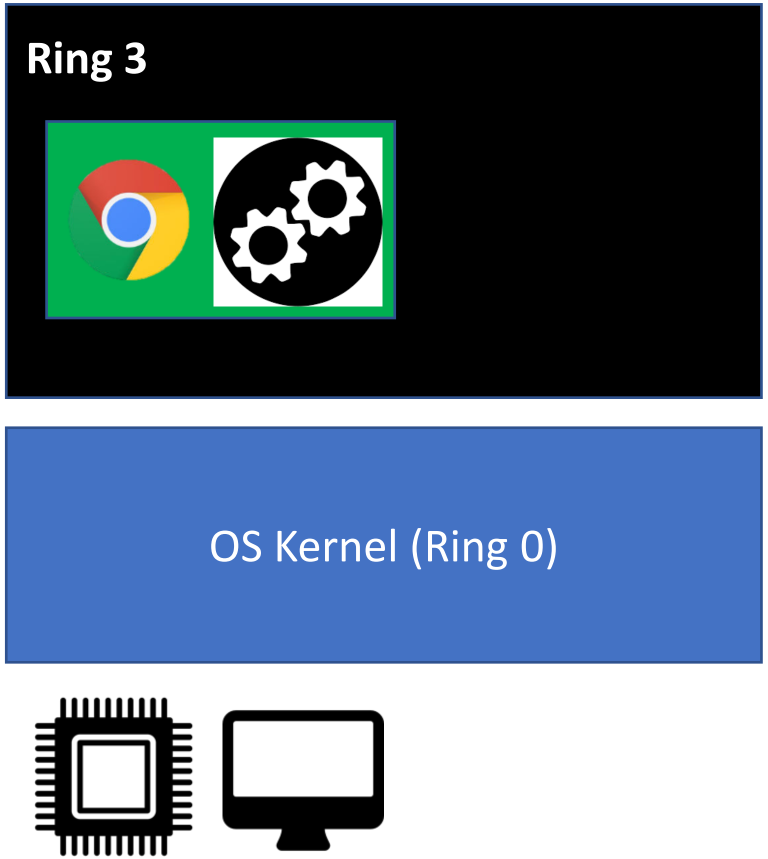
1. **Prepare a process, an environment for running an application**

2. **Put an application! load code!**

3. **Execute!**



How does Kernel Get the Execution Back?



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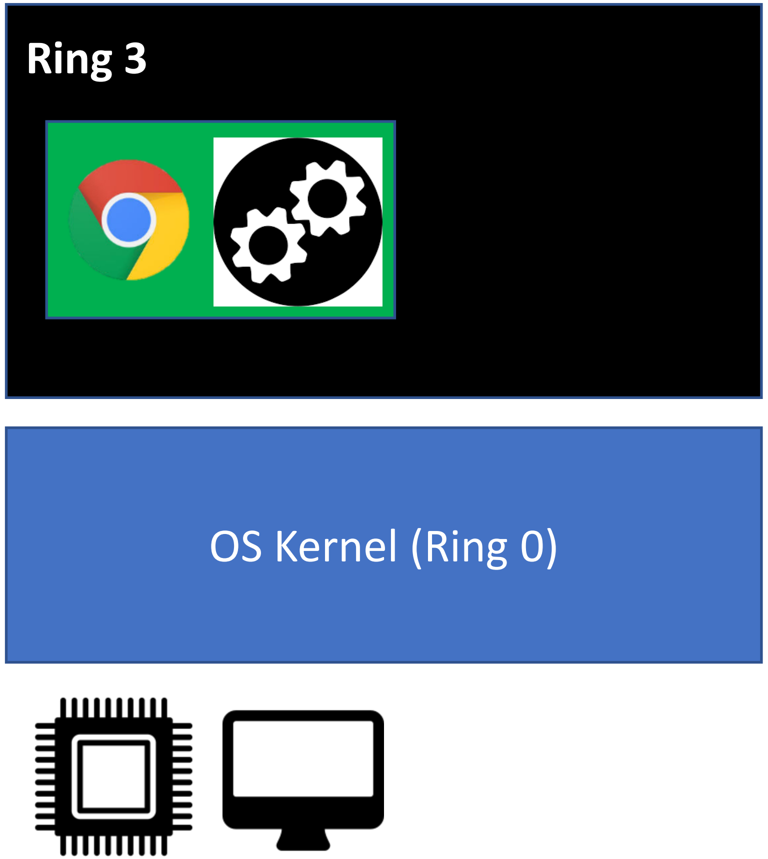
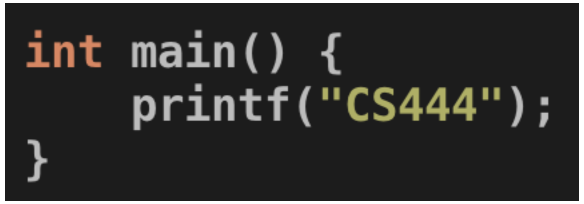


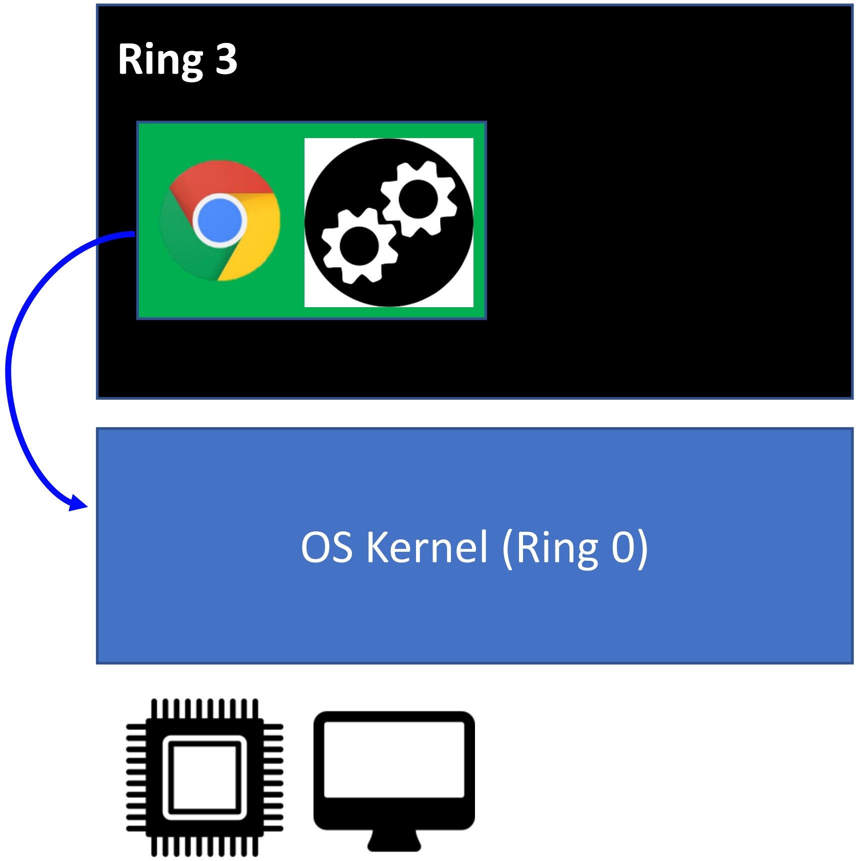


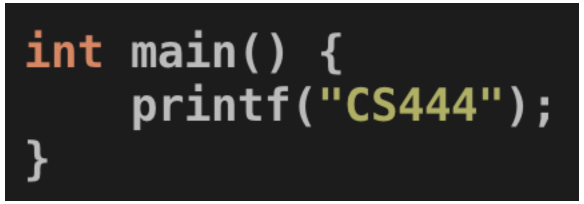
```
int main() {
    printf("CS444");
}
```

How does Kernel Get the Execution Back?

System call!

sys_write()





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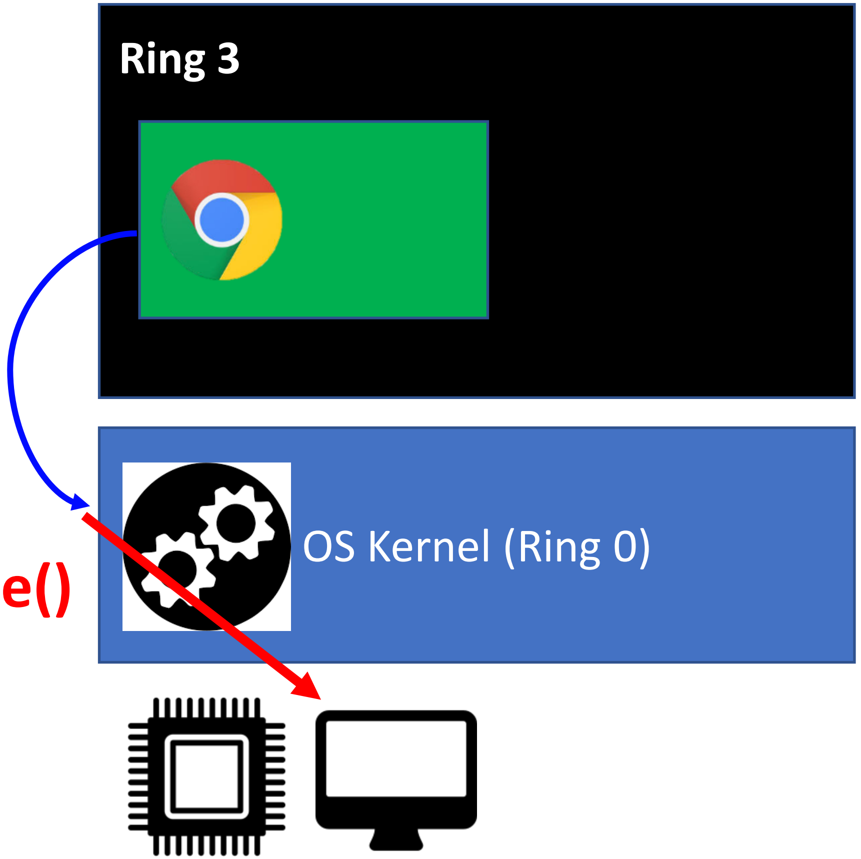
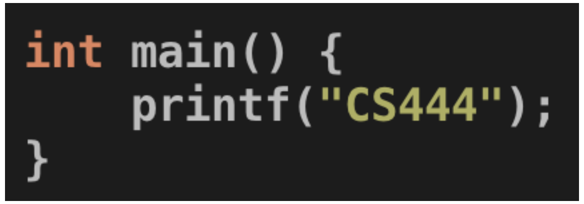
How does Kernel Get the Execution Back?

System call!

sys_write()

do_sys_write()





```
int main() {
    printf("CS444");
}
```

Is System Call the Only Way to Execute in Kernel?

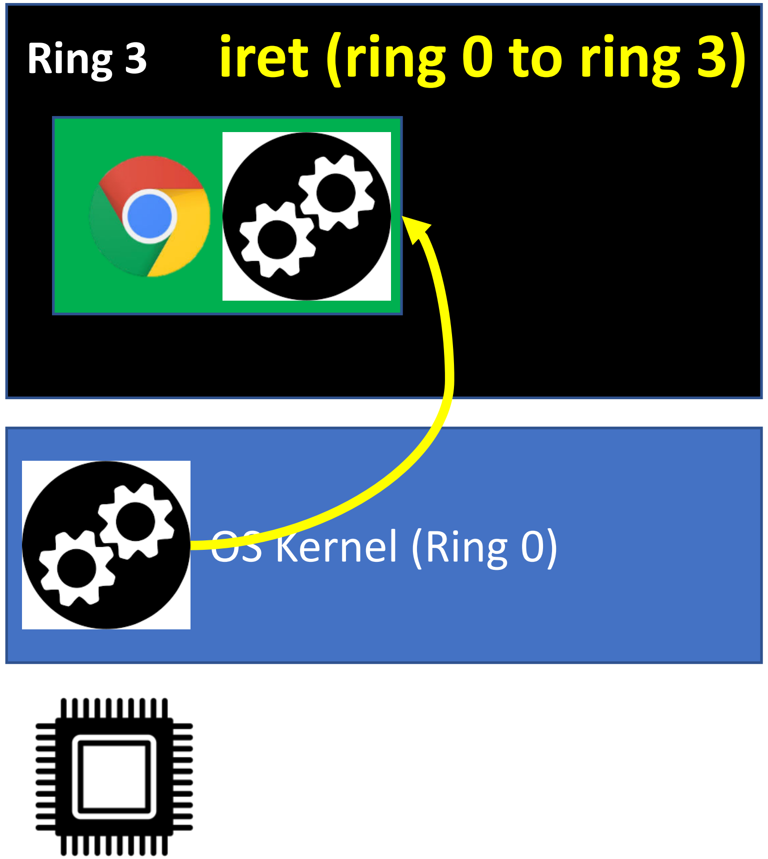
- No
  - In such a case, we have lots of problems..
  - E.g., kernel waits until an application runs a system call
  - What if an application never calls a system call????

- We have the following ways to switch
  - System call (ring 3 -> ring 0)
  - Interrupt (usually runs in ring 0, sometimes runs in ring 3)
  - Fault/Exception (runs in ring 0)

User Execution Strawman 1

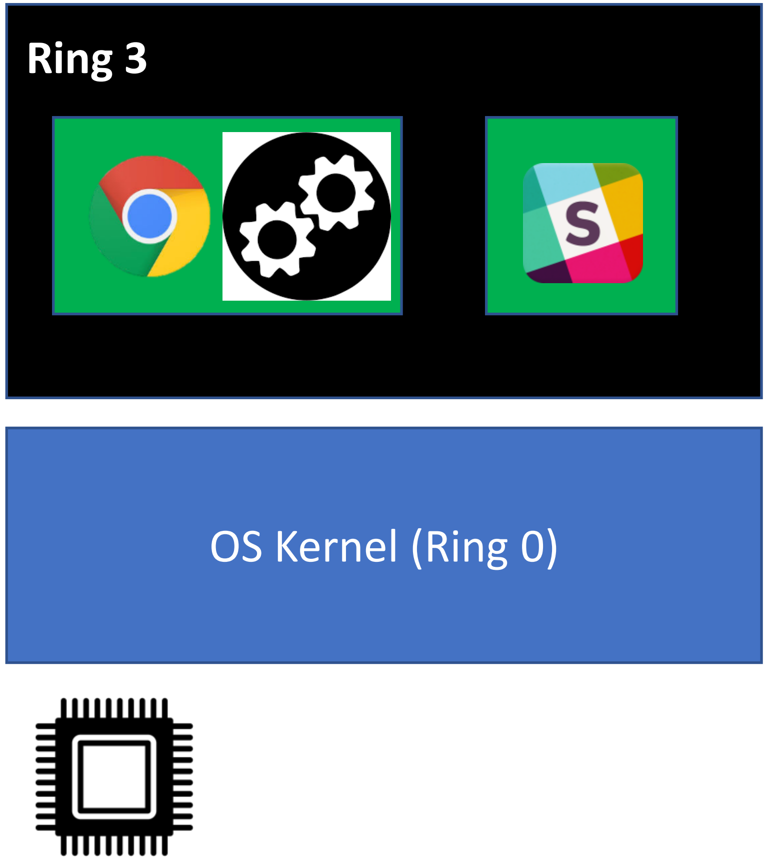
- Just run user application

- Seems OK, but…



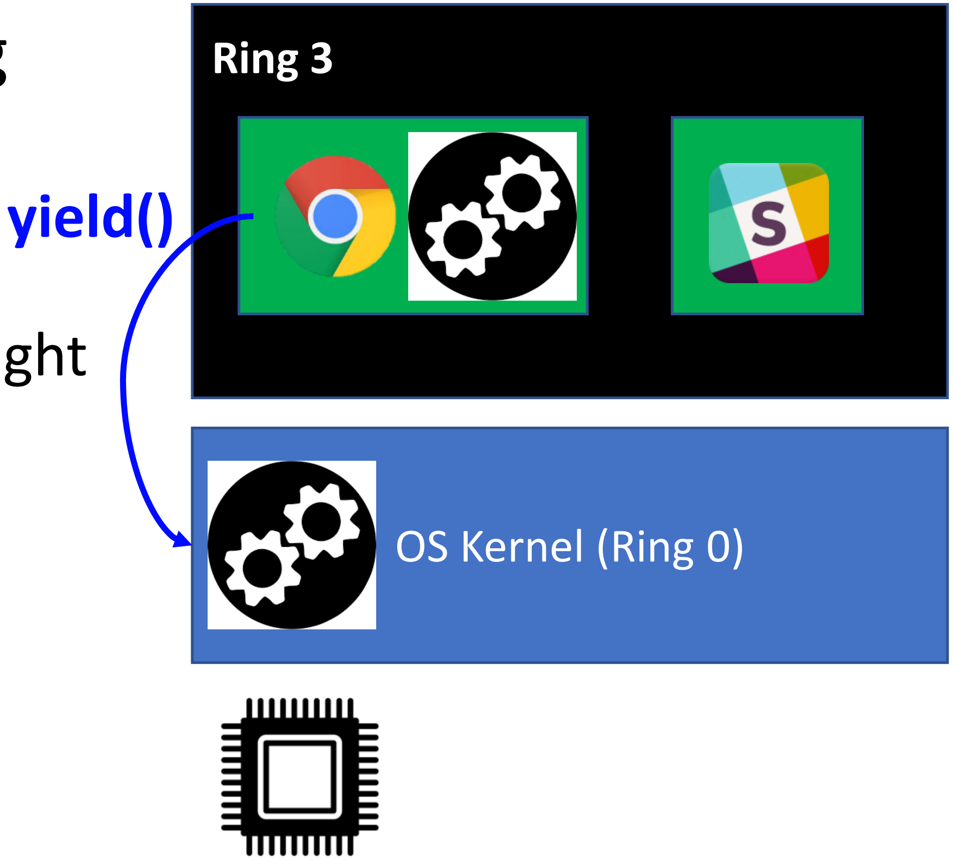
User Execution Strawman 1’

- Just run user application
- What happens if we run 2 applications at the same time?
- How can we switch execution?



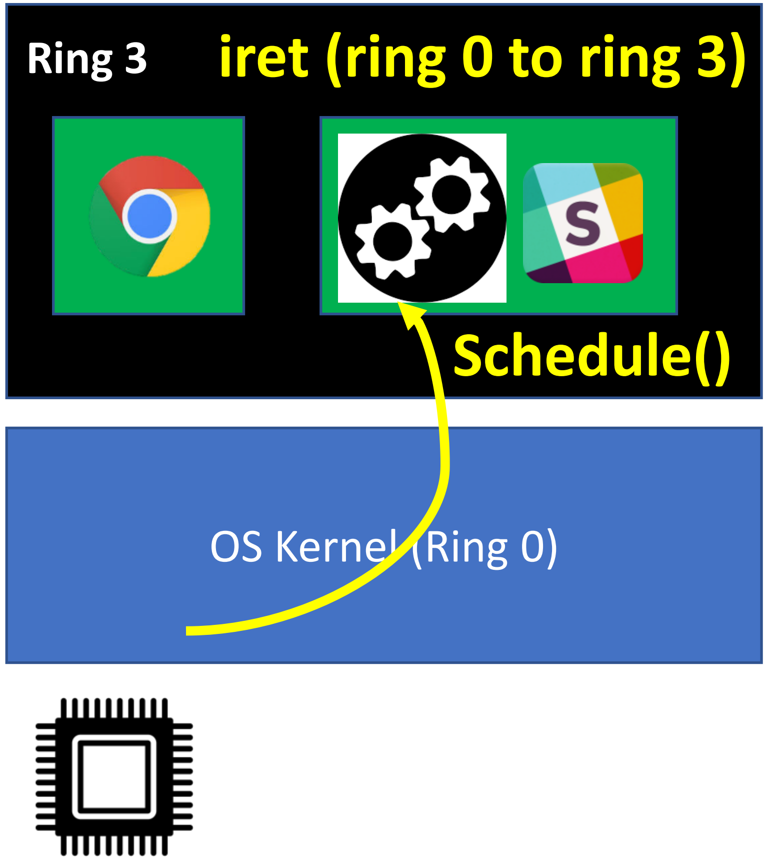
User Execution Strawman 2

- Co-operative Multitasking
- Yield()
  - Surrender the execution right when a process finishes / pauses its execution



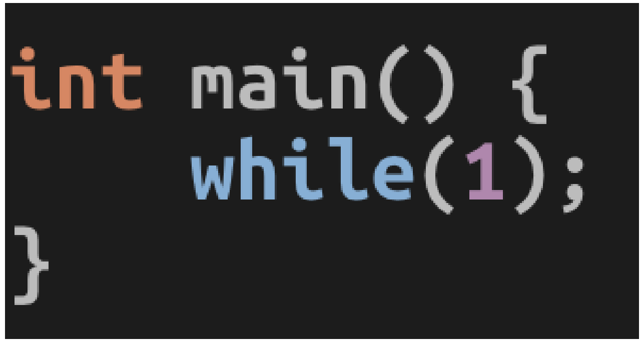
User Execution Strawman 2

- Co-operative Multitasking
- Yield()
  - Surrender the execution right when a process finishes / pauses its execution
- Schedule()
  - Execute a different process..



User Execution Strawman 2’

- What if a process runs

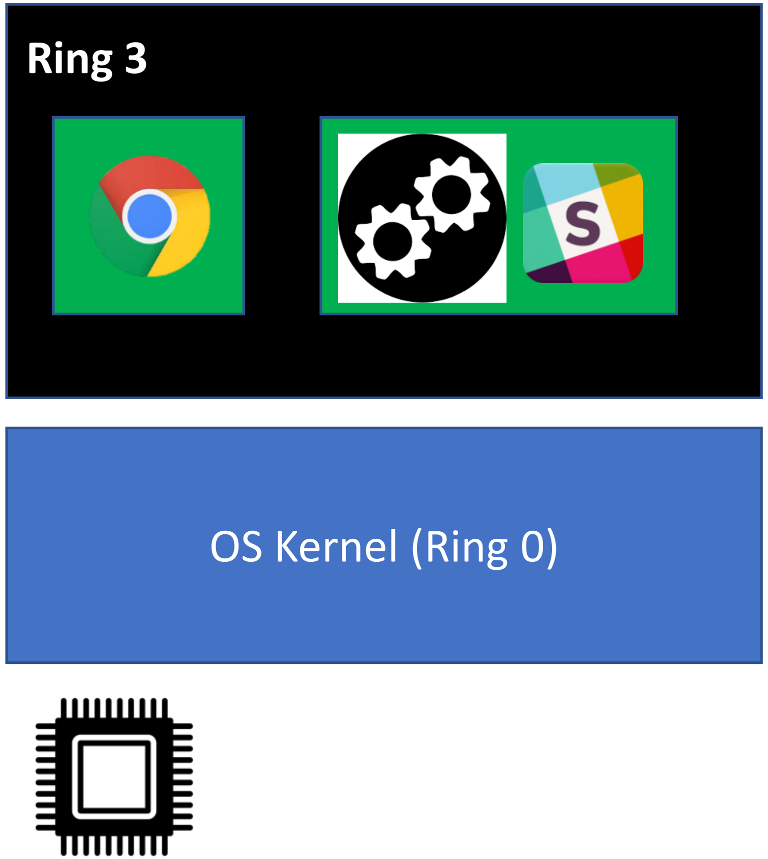


```
int main() {
    while(1);
}
```

Too long

No such yield()

Much wait



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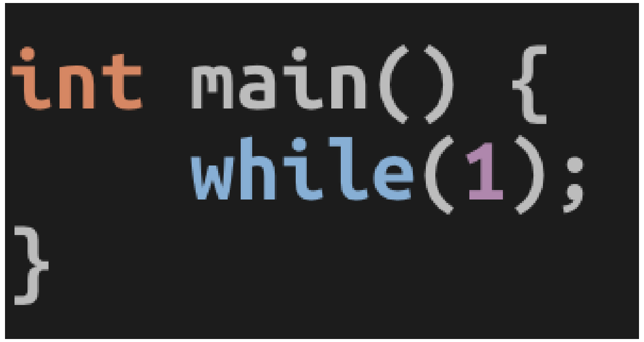


```
int main() {
    while(1);
}
```

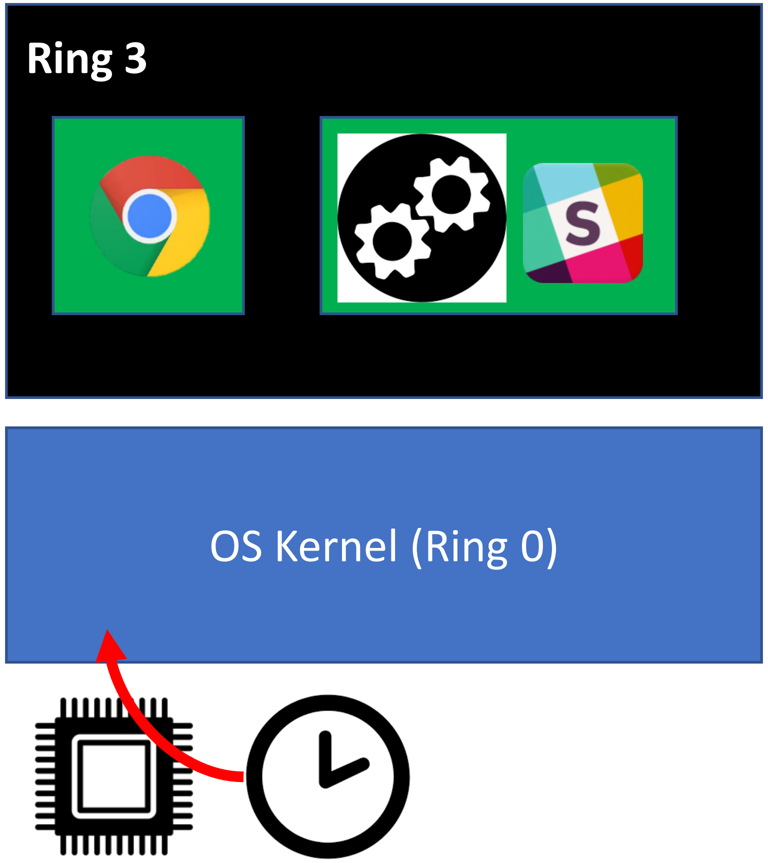
Too long

User Execution Strawman 3

After 1ms

- Preemptive Multitasking (Lab 4)

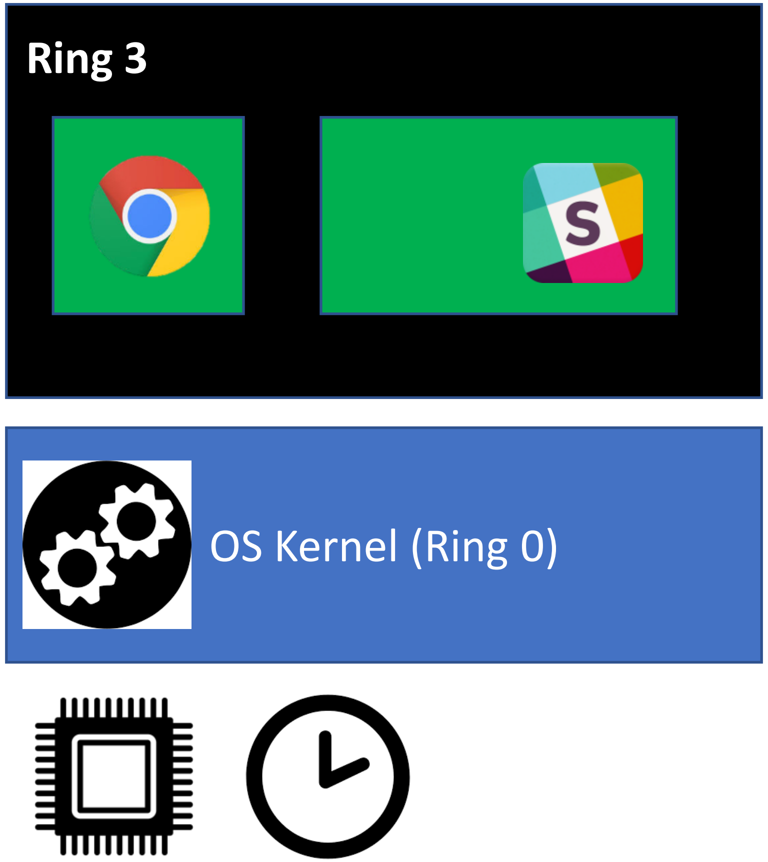
- CPU generates an interrupt to force execution at kernel after some time quantum
  - E.g., 1000Hz, on each 1ms..



Timer interrupt!

User Execution Strawman 3

- Preemptive Multitasking (Lab 4)
- CPU generates an interrupt to force execution at kernel after some time quantum
  - E.g., 1000Hz, on each 1ms..
- Guaranteed execution in kernel
  - Let kernel mediate resource contention



User Execution Strawman 3

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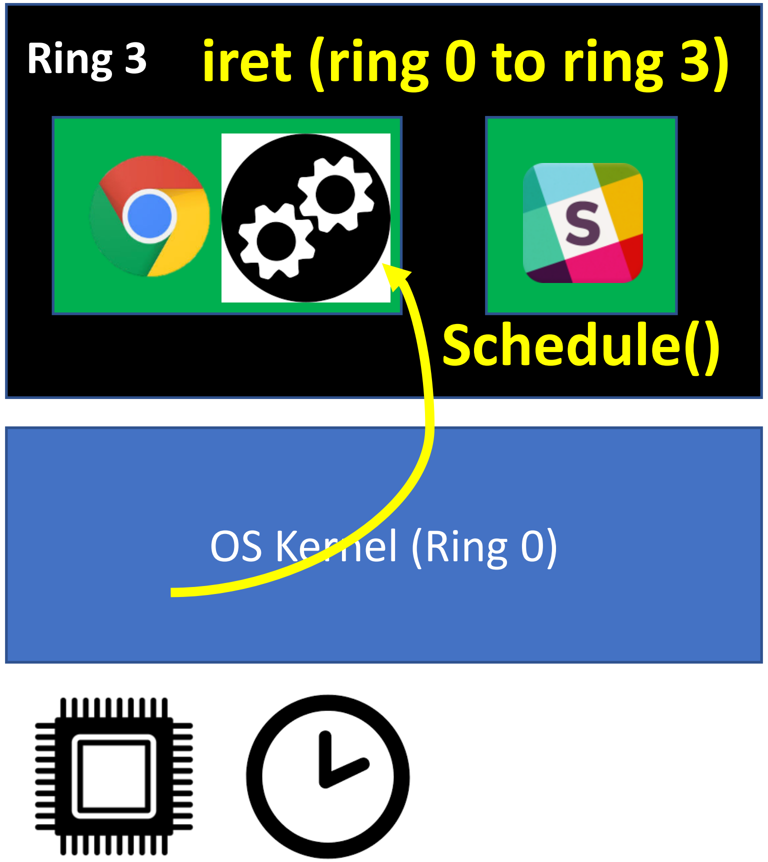
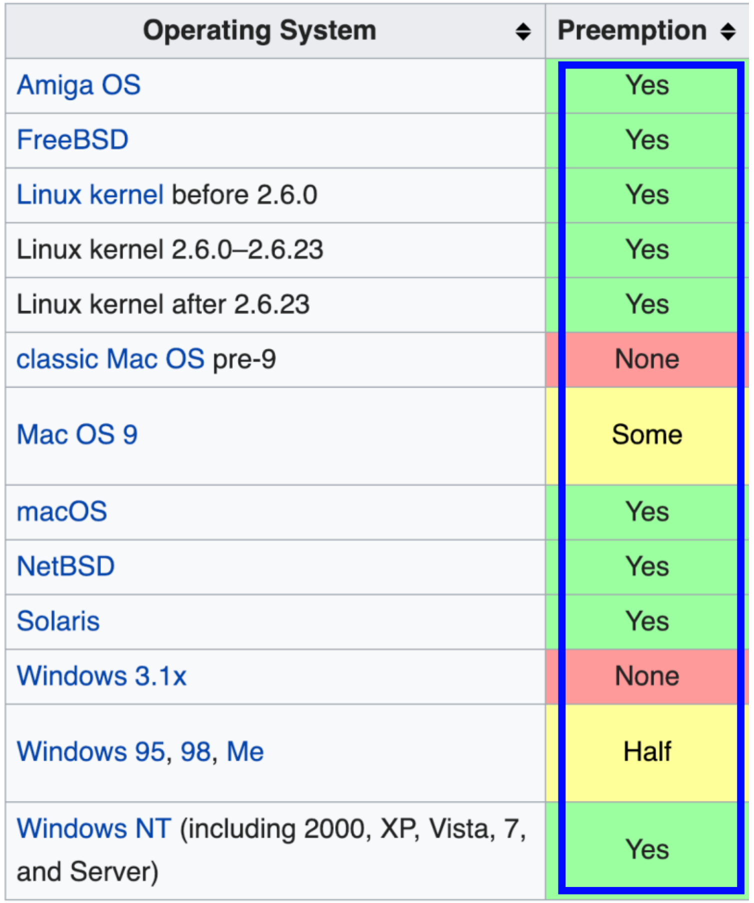


How are Popular OSes doing?

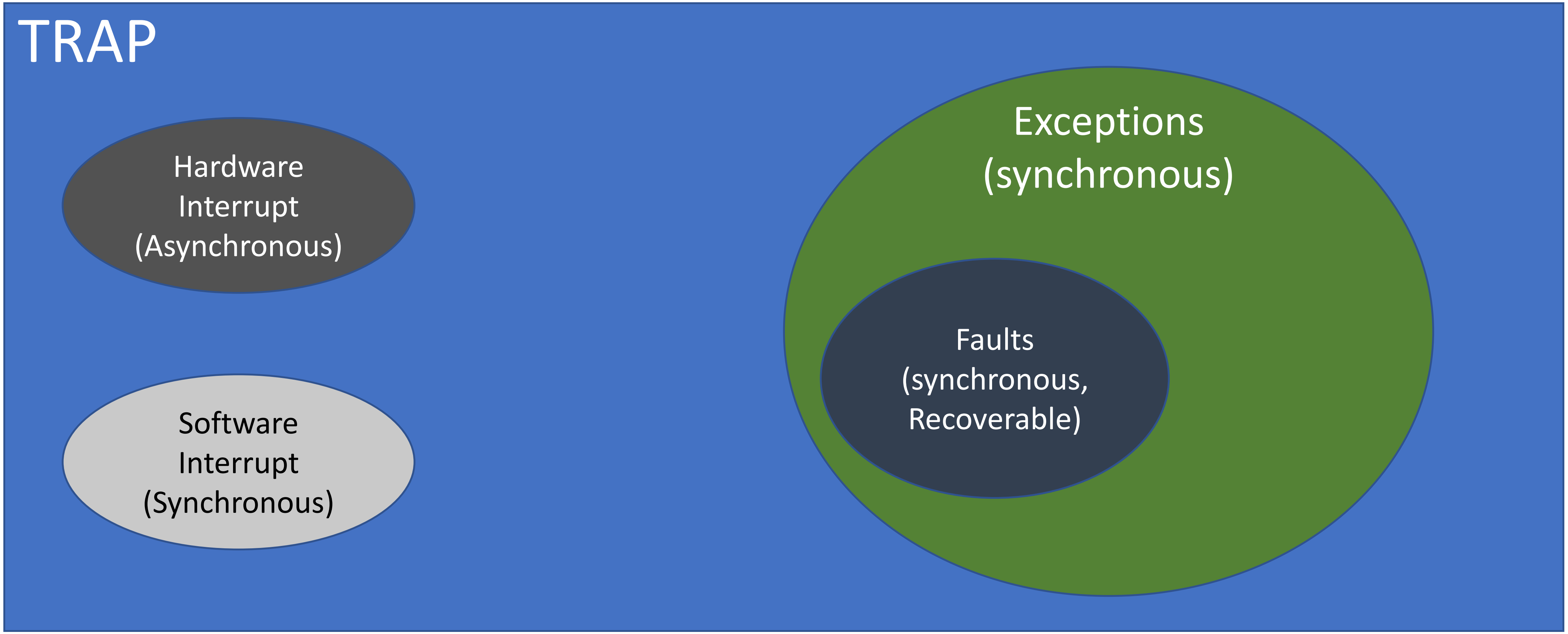


Operating System	Preemption
Amiga OS	Yes
FreeBSD	Yes
Linux kernel before 2.6.0	Yes
Linux kernel 2.6.0–2.6.23	Yes
Linux kernel after 2.6.23	Yes
classic Mac OS pre-9	None
Mac OS 9	Some
macOS	Yes
NetBSD	Yes
Solaris	Yes
Windows 3.1x	None
Windows 95, 98, Me	Half
Windows NT (including 2000, XP, Vista, 7, and Server)	Yes

Trap: Interrupt/Faults/Exception

- Trap
  - An event that forces CPU to execute (some) code in kernel
  - Will run trap handler
- Interrupts
  - Hardware interrupt
  - System call (software interrupt)
- Faults
  - An error that OS may recover and continue execution (e.g., page fault)
- Exception
  - An error that OS cannot recover and must stop the current execution (e.g., divide by zero)
- Many others, please refer to the Intel Manual
  - Chapter 6 of volume 3A

Trap Summary


TRAP
Hardware Interrupt (Asynchronous)
Software Interrupt (Synchronous)
Exceptions (synchronous)
Faults (synchronous, Recoverable)

Hardware Interrupt

- A way of hardware interacting with CPU

- Example: a network device
  - NIC: *"Hey, CPU, I have received a packet for the OS, so please wake up the OS to handle the data"*
  - CPU: call the interrupt handler for network device in ring 0 (set by the OS)

- Asynchronous (can happen at any time of execution)
  - It's a request from a hardware, so it comes at any time of CPU's execution
- Read
  - https://en.wikipedia.org/wiki/Intel_8259
  - https://en.wikipedia.org/wiki/Advanced_Programmable_Interrupt_Controller

Software Interrupt

- A software method to run code in ring 0 (e.g., int $\overset{48}{\underline{\texttt{\$0x30}}}$)
    - Telling CPU that ”Please run the interrupt handler at 0x30”

- Synchronous (caused by running an instruction, e.g., `int $0x30`)

- System call
    - int $0x30 ← system call in JOS

Exceptions/Faults

- Exceptions
  - An error caused by the current execution (may or may not be recovered)
  - Examples of non-recoverable exception (cannot continue the execution)
    - Triple fault
    - Divide by zero
    - Breakpoint
- Fault
  - An error caused by the current execution that may be recovered and continue the execution
  - Examples
    - Page fault
    - Double fault

- Synchronous (an execution of an instruction can generate this)
  - E.g., divide by 0

Handling Interrupt/Exceptions

- Set an Interrupt Descriptor Table (IDT)

Interrupt Number	Code address
0 (Divide error)	0xf0130304
1 (Debug)	0xf0153333
2 (NMI, Non-maskable Interrupt)	0xf0183273
3 (Breakpoint)	0xf0223933
4 (Overflow)	0xf0333333
…	
8 (Double Fault)	0xf0222293
…	
14 (Page Fault)	0xf0133390
…	…
0x30 (syscall in JOS)	0xf0222222

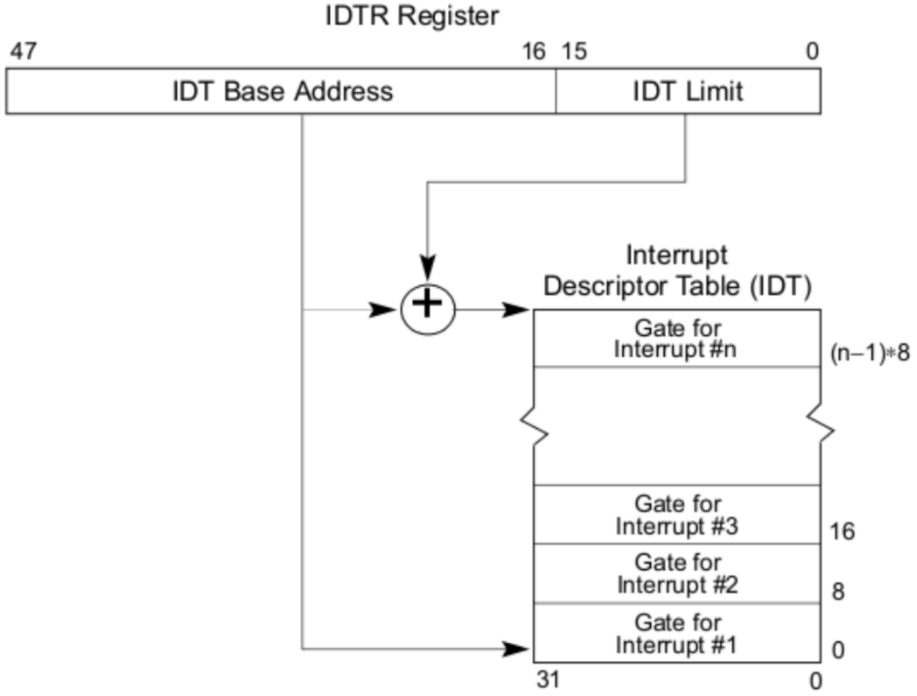


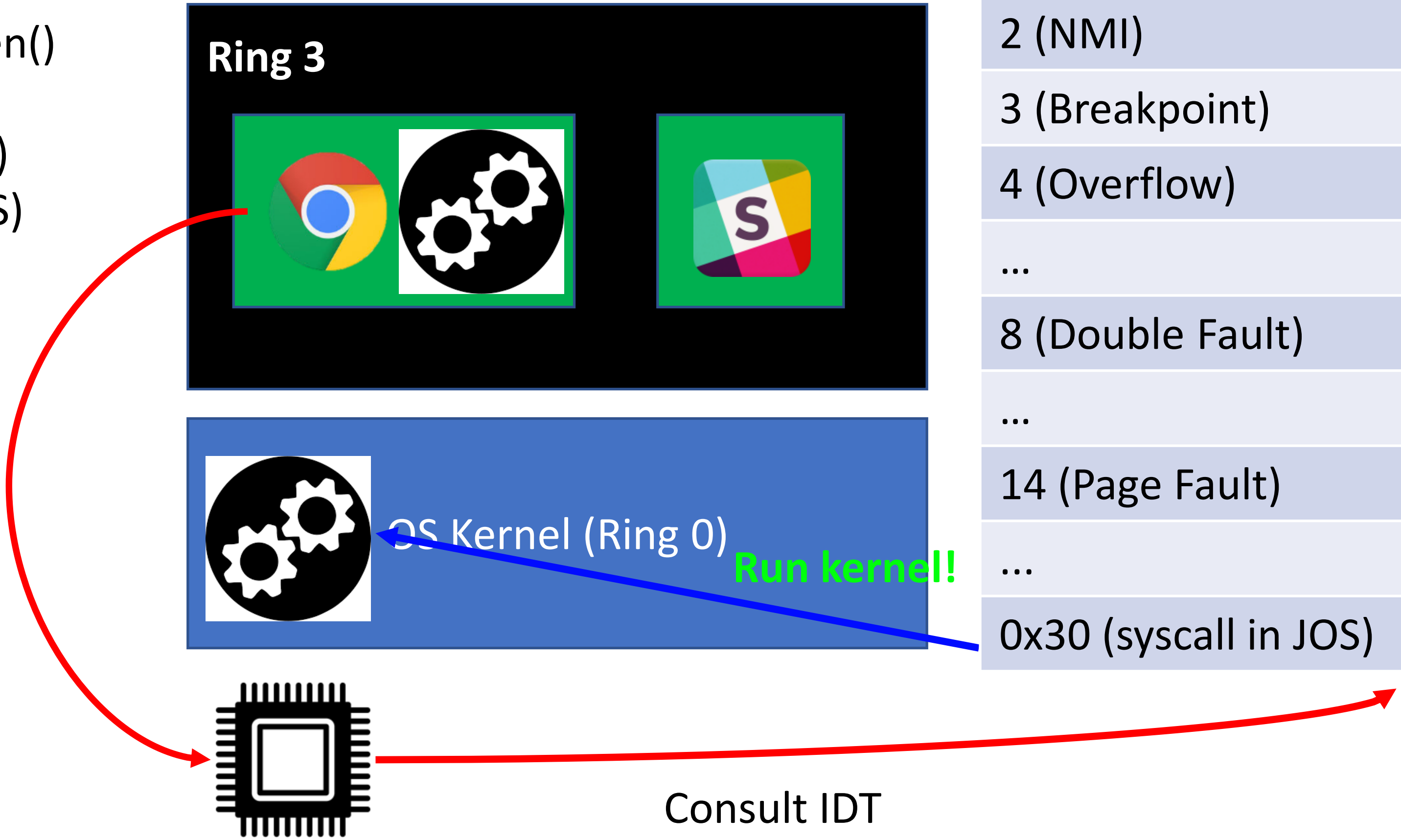
Figure 6-1. Relationship of the IDTR and IDT

Opening a file

App calls open()

Set arguments (fn, flag)
int $0x30 (syscall in JOS)

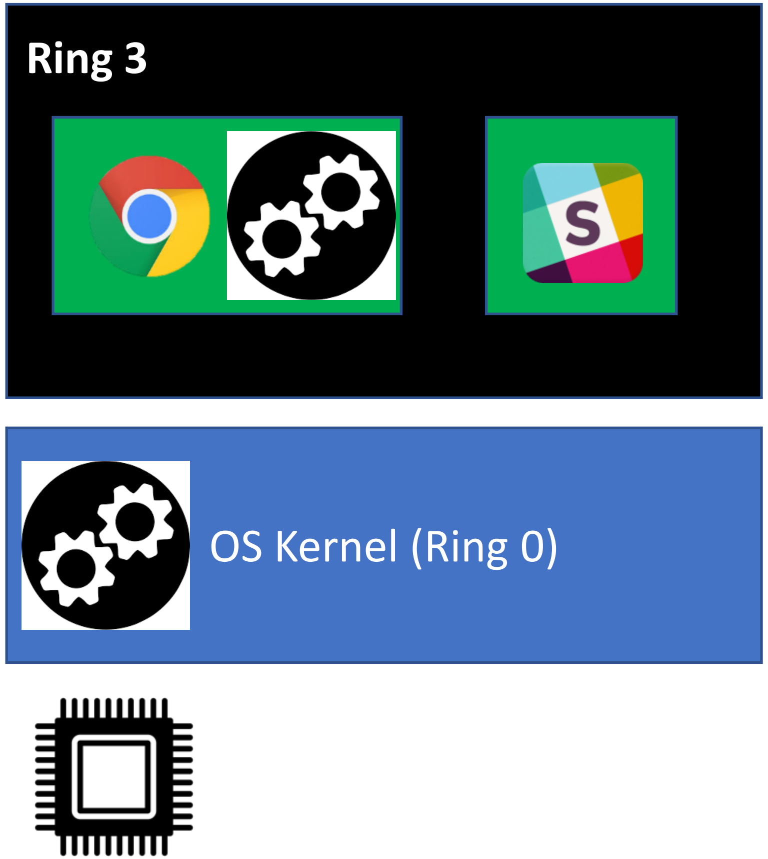
Interrupt!



Interrupt Number	Code address
0 (Divide error)	0xf0130304
1 (Debug)	0xf0153333
2 (NMI)	0xf0183273
3 (Breakpoint)	0xf0223933
4 (Overflow)	0xf0333333
…	
8 (Double Fault)	0xf0222293
…	
14 (Page Fault)	0xf0133390
…	…
0x30 (syscall in JOS)	0xf0222222

At the kernel (in running `open()`)

- Access arguments from Ring 3
  - Need to check its security…
- Access disk to open a file
  - Need to check permissions…
- Return a file descriptor
  - `iret`



Summary

- A user program can invoke a system call to ‘request’ the OS to run code in a higher privileged level, ring 0
  - System call, and it is a synchronous interrupt
- A hardware would like to talk to the CPU to tell that blocks of data is ready for the OS
  - Hardware interrupt, an asynchronous interrupt
- A program generated an error that is not recoverable, a triple fault
  - A non-recoverable exception, synchronous
- A program generated a page fault
  - Fault, because OS regards page fault as recoverable error, synchronous
  - (we will learn more about this in coming lectures)