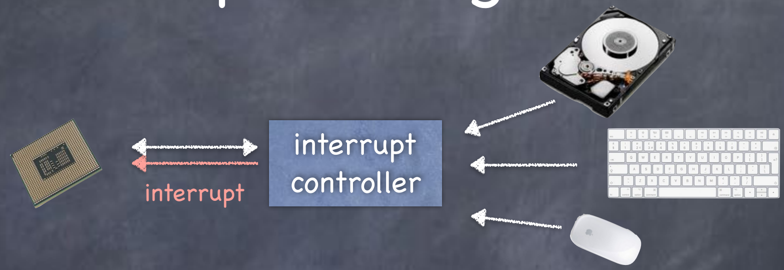
III. Timer Interrupts

- Hardware timer
  - can be set to expire after specified delay (time or instructions)
  - when it does, control is passed back to the kernel
- Other interrupts (e.g. I/O completion) also give control to kernel

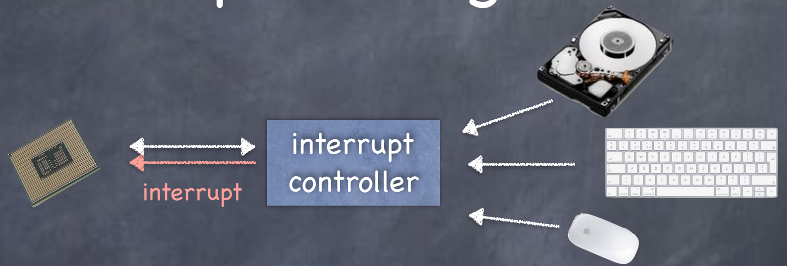
Interrupt Management



Interrupt controllers implements interrupt priorities:

- Interrupts include descriptor of interrupting device
- Priority selector circuit examines all interrupting devices, reports highest level to the CPU
- Controller can also buffer interrupts coming from different devices
  - more on this later...

Interrupt Management



Maskable interrupts

- can be turned off by the CPU for critical processing

Nonmaskable interrupts

- indicate serious errors (power out warning, unrecoverable memory error, etc.)

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

Interrupt Handling

- Two objectives
  - handle the interrupt and remove the cause
  - restore what was running before the interrupt
    - state may have been modified on purpose
- Two "actors" in handling the interrupt
  - the hardware goes first
  - the kernel code takes control by running the interrupt handler

A Tale of Two Stack Pointers

- Interrupt is a program: it needs a stack!
  - so, each process has two stacks pointers:
    - one when running in kernel mode
    - another when running in user mode
- Why not using the user-level stack pointer?
  - user SP may be badly aligned or pointing to non writable memory
  - user stack may not be large enough, and may spill to overwrite important data
  - security:
    - kernel could leave sensitive data on stack
    - pointing SP to kernel address could corrupt kernel

Handling Interrupts: HW

- On interrupt, hardware:
  - sets supervisor mode (if not set already)
  - disable (masks) interrupts
  - pushes PC, SP, and PSW of user program on interrupt stack
  - sets PC to point to the first instruction of the appropriate interrupt handler
    - depends on interrupt type
    - interrupt handler specified in interrupt vector loaded at boot time

(partially privileged)

kernel mode bit	interrupts enabled bit	Condition codes

Interrupt Vector

Interrupt Vector
I/O interrupt handler
System Call handler
Page fault handler
...

Handling Interrupts: SW

- We are now running the interrupt handler!
  - IH first pushes the registers' contents on the interrupt stack (part of the PCB)
    - need registers to run the IH
    - only saves necessary registers (that's why done in SW, not HW)

Typical Interrupt Handler Code

```
HandleInterruptX:
  PUSH %Rn     }
    ...        }  only need to save registers not
  PUSH %R1     }  saved by the handler function
  CALL _handleX
  POP %R1      }
    ...        }  restore the registers saved above
  POP %Rn      }
  RETURN_FROM_INTERRUPT
```

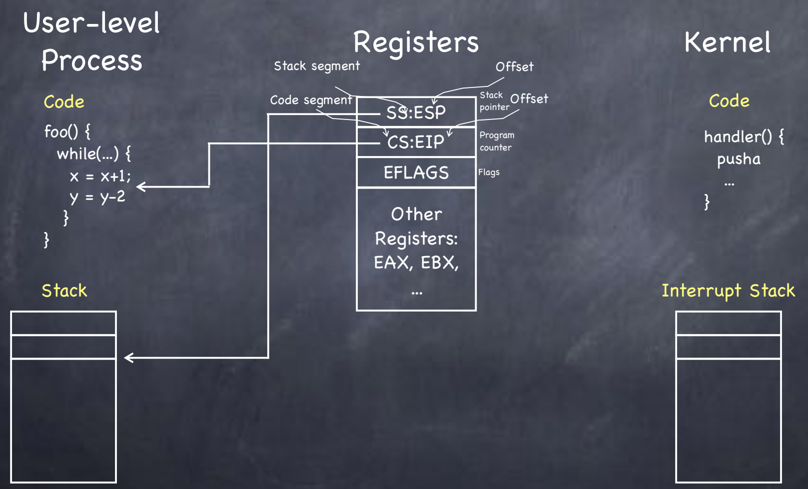
Returning from an Interrupt

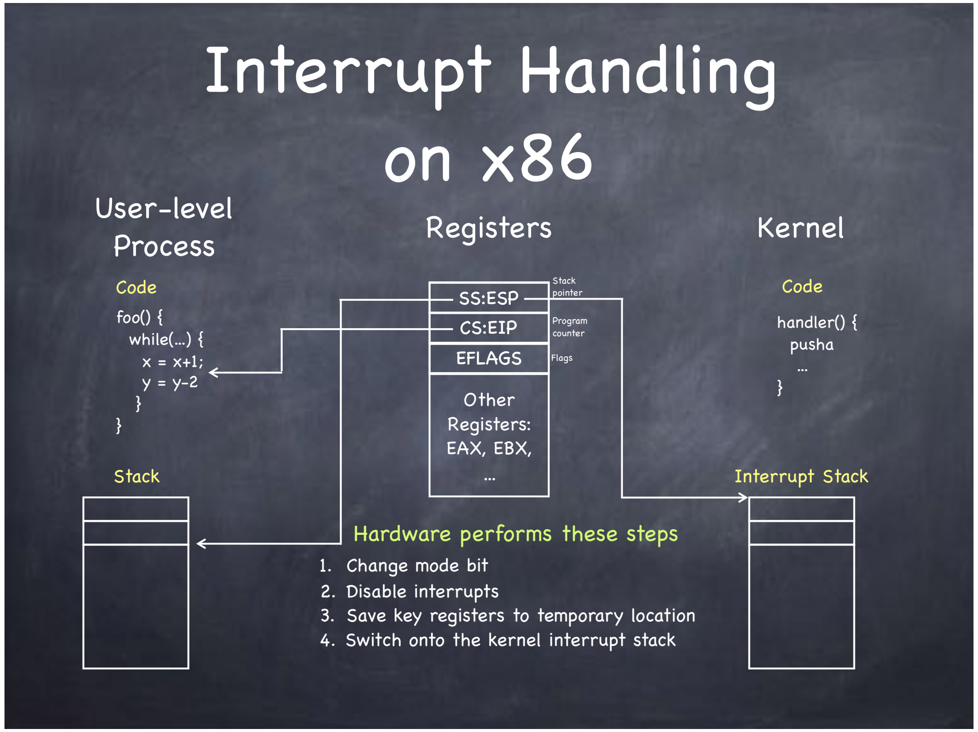
- Hardware pops PC, SP, PSW
- Depending on content of PSW
  - switch to user mode
  - enable interrupts
- From exception and system call, increment PC on return (we don't want to execute again the same instruction)
  - on exception, handler changes PC at the base of the stack
  - on system call, increment is done by hw when saving user level state

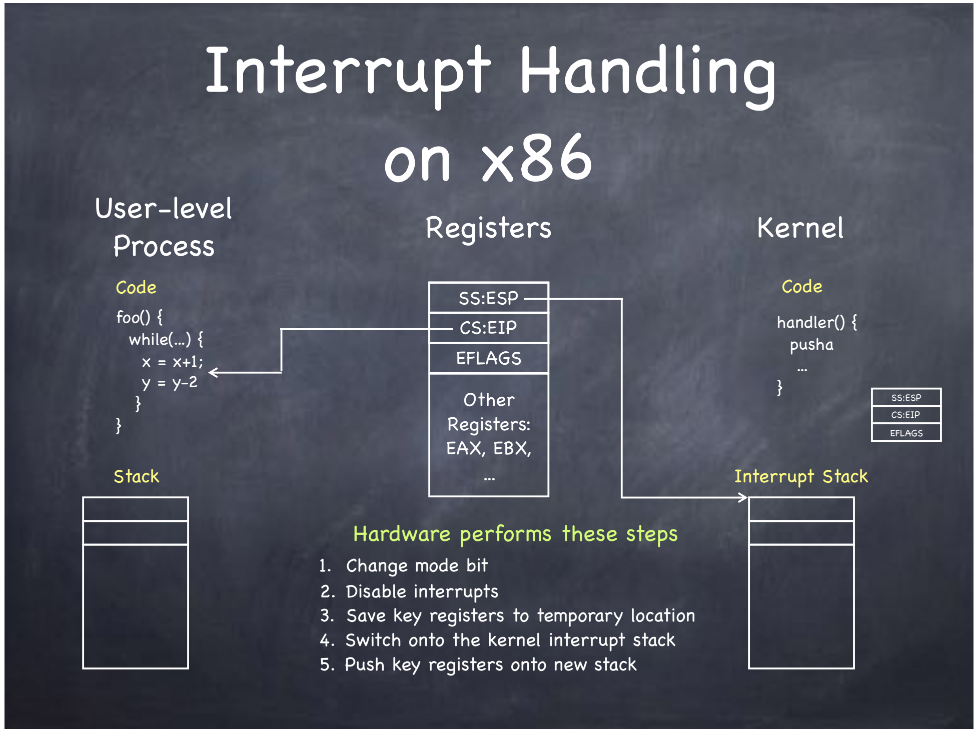
Starting a new process: the recipe

1. Allocate & initialize PCB
2. Setup initial page table (to initialize a new address space)
3. Load program intro address space
4. Allocate user-level and kernel-level stacks.
5. Copy arguments (if any) to the base of the user-level stack
6. Simulate an interrupt
   a) push initial PC, user SP
   b) push PSW (supervisor mode off, interrupts enabled)
7. Clear all other registers
8. RETURN_FROM_INTERRUPT

Interrupt Handling on x86




Interrupt Handling on x86
User-level Process
Registers
Kernel
Code
foo() {
while(...) {
x = x+1;
y = y-2
}
}
SS:ESP
Stack pointer
CS:EIP
Program counter
EFLAGS
Flags
Other Registers: EAX, EBX, ...
Code
handler() {
pusha
...
}
Stack
Interrupt Stack
Hardware performs these steps
1. Change mode bit
2. Disable interrupts
3. Save key registers to temporary location
4. Switch onto the kernel interrupt stack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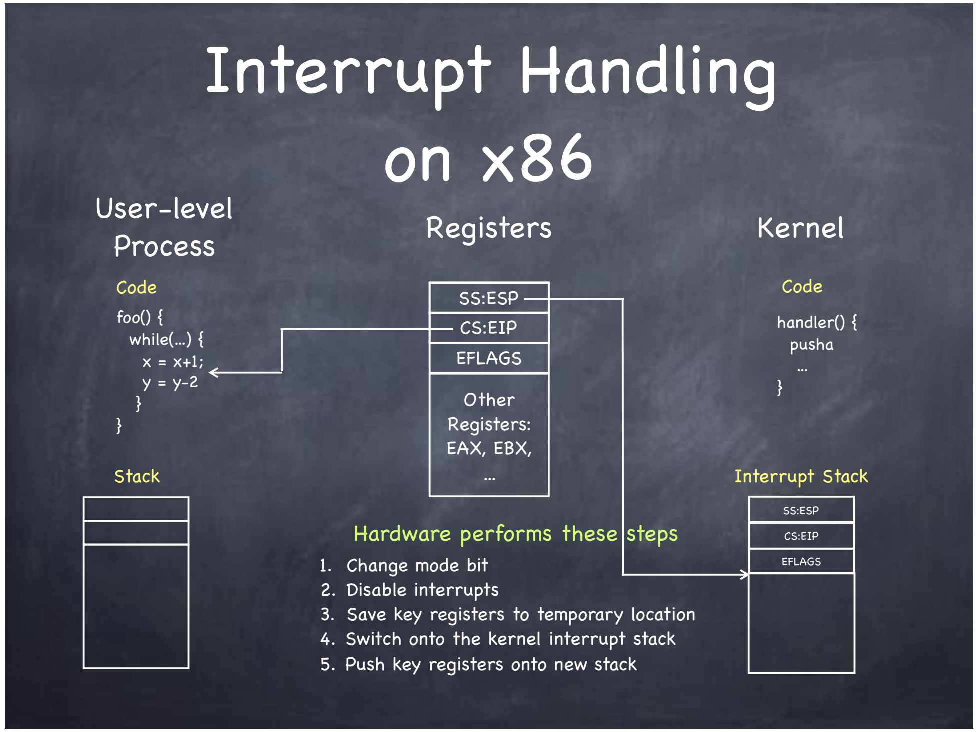
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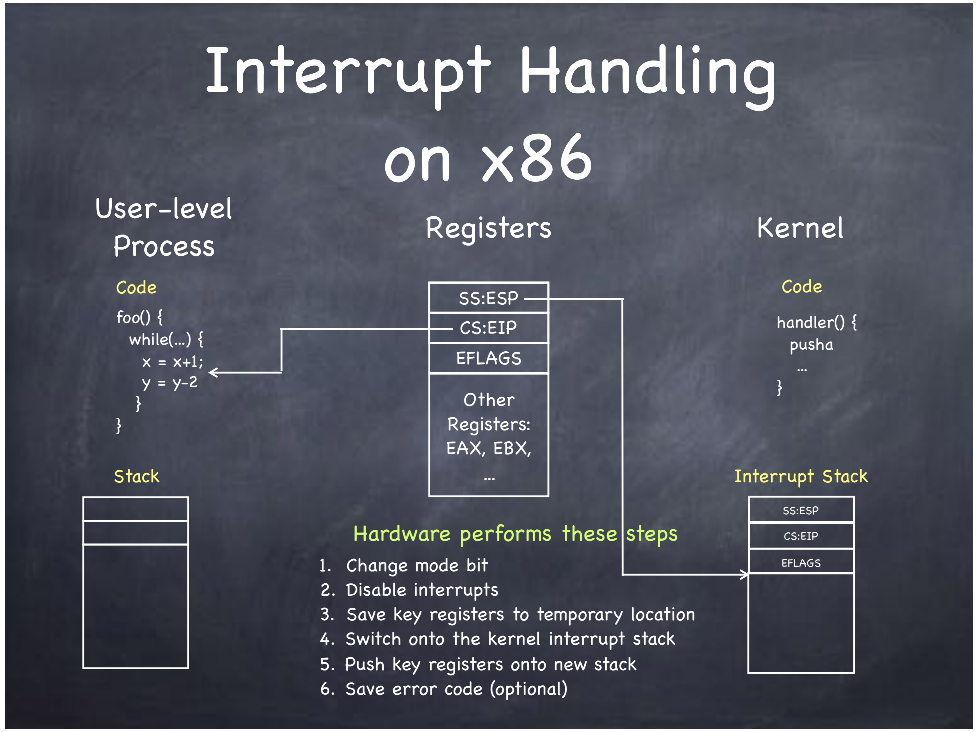
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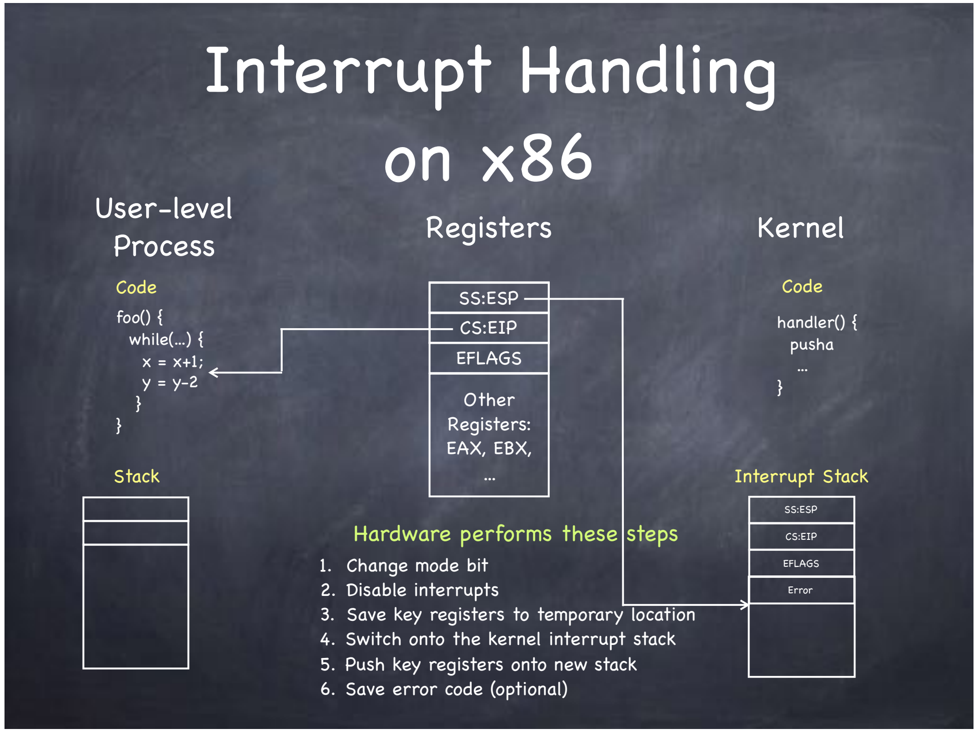

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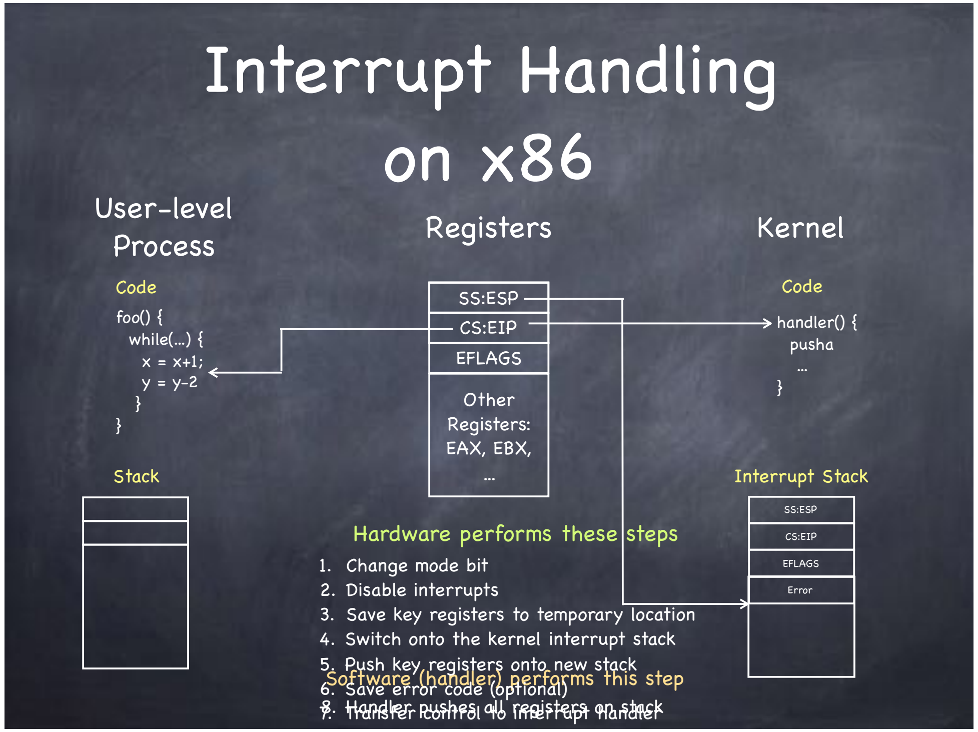

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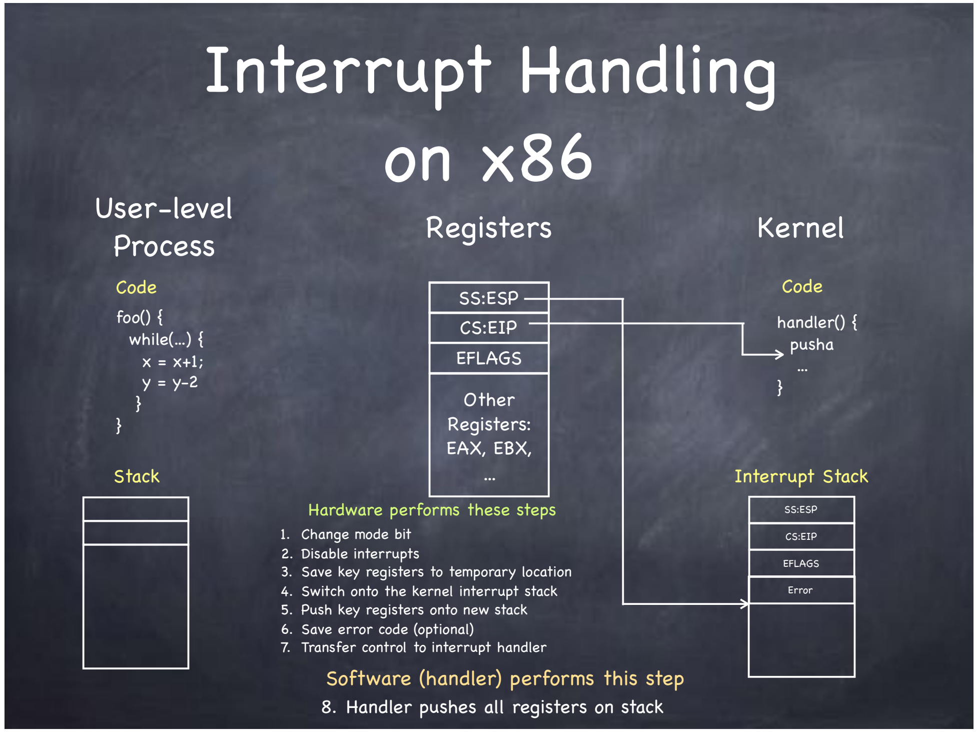
7. Transfer control to interrupt handler
Software (handler) performs this step
8. Handler pushes all registers on stack



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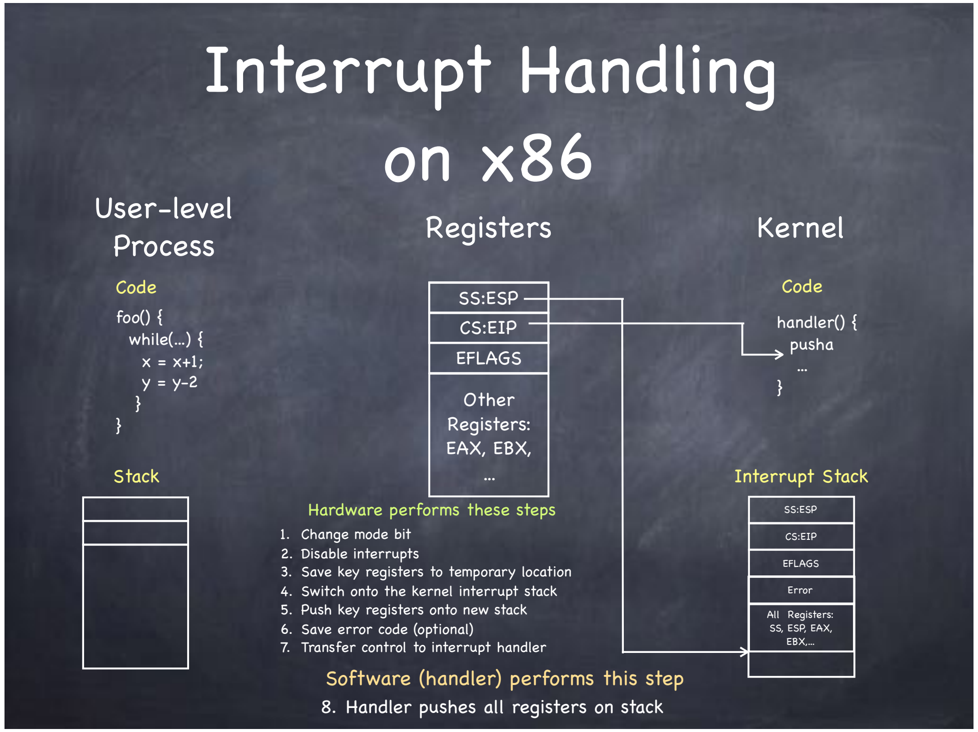

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Interrupt Safety

- Kernel should disable device interrupts as little as possible
  - interrupts are best serviced quickly
- Thus, device interrupts are often disabled selectively
  - e.g., clock interrupts enabled during disk interrupt handling
- This leads to potential "race conditions"
  - system's behavior depends on timing of uncontrollable events

Interrupt Race Example

- Disk interrupt handler enqueues a task to be executed after a particular time
  - while clock interrupts are enabled
- Clock interrupt handler checks queue for tasks to be executed
  - may remove tasks from the queue
- Clock interrupt may happen during enqueue

Concurrent access to a shared data structure (the queue!)

Making code interrupt-safe

- Make sure interrupts are disabled while accessing mutable data!
- But don't we have locks?
  - Consider

```
void function ()
{
  lock(mtx);
  /* code */
  unlock(mtx);
}
```

Is `function` thread-safe?

Operates correctly when accessed simultaneously by multiple threads

To make it so, grab a lock

Is function interrupt-safe?

Operates correctly when called again (re-entered) before it completes

To make it so, disable interrupts

Example of Interrupt-Safe Code

```
void enqueue(struct task *task) {
  int level = interrupt_disable();
  /* update queue */
  interrupt_restore(level);
}
```

- Why not simply re-enable interrupts?
  - Say we did. What if then we call enqueue from code that expects interrupts to be disabled?
    - Oops...
  - Instead, remember interrupt level at time of call; when done, restore that level

Many Standard C Functions are not Interrupt-Safe

- Pure system calls are interrupt-safe
  - e.g., read(), write(), etc.
- Functions that don't use global data are interrupt-safe
  - e.g., strlen(), strcpy(), etc.
- malloc(), free (), and printf() are not interrupt-safe
  - must disable interrupts before using it in an interrupt handler
  - and you may not want to anyway (printf() is huge!)

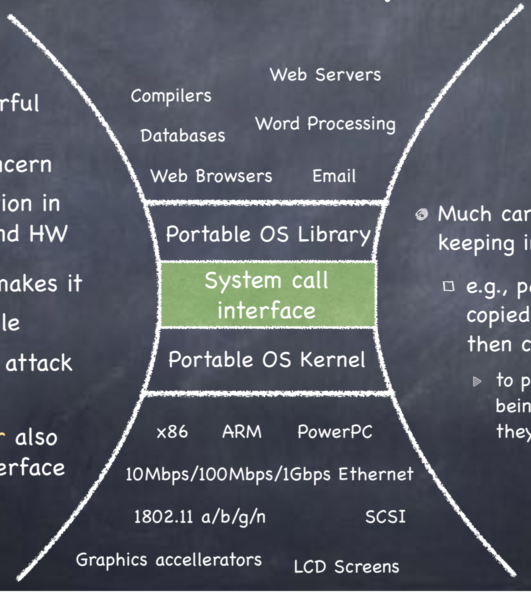
But they are all thread-safe!

System calls

- Programming interface to the services the OS provides:
  - read input/write to screen
  - create/read/write/delete files
  - create new processes
  - send/receive network packets
  - get the time / set alarms
  - terminate current process
  - ...

The Skinny

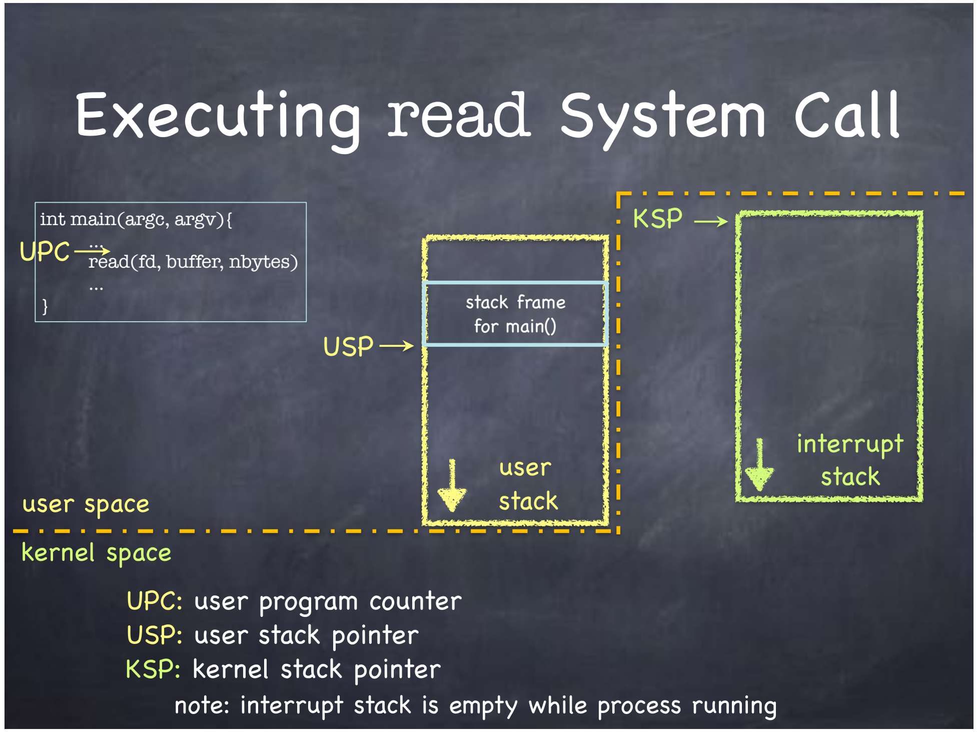
- Simple and powerful interface allows separation of concern
  - Eases innovation in user space and HW
- "Narrow waist" makes it
  - highly portable
  - robust (small attack surface)
- Internet IP layer also offers skinny interface

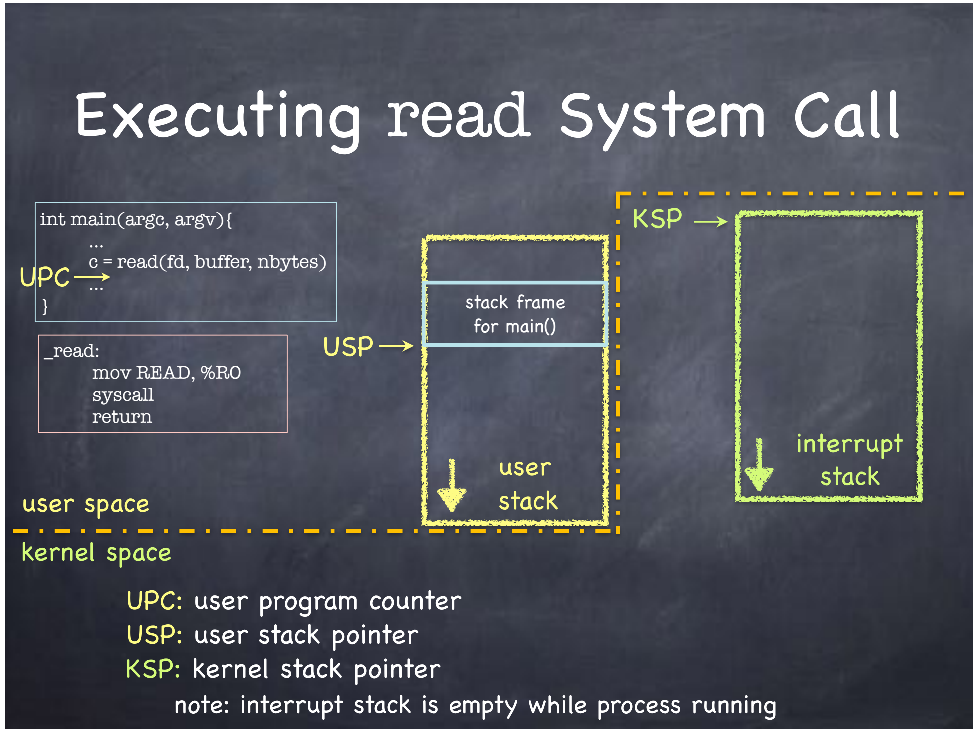


- Much care spent in keeping interface secure
  - e.g., parameters first copied to kernel space, then checked
    - to prevent them from being changed after they are checked!

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


Executing read System Call
int main(argc, argv){
...
read(fd, buffer, nbytes)
...
}
UPC
USP
stack frame
for main()
user
stack
KSP
interrupt
stack
user space
kernel space
UPC: user program counter
USP: user stack pointer
KSP: kernel stack pointer
note: interrupt stack is empty while process running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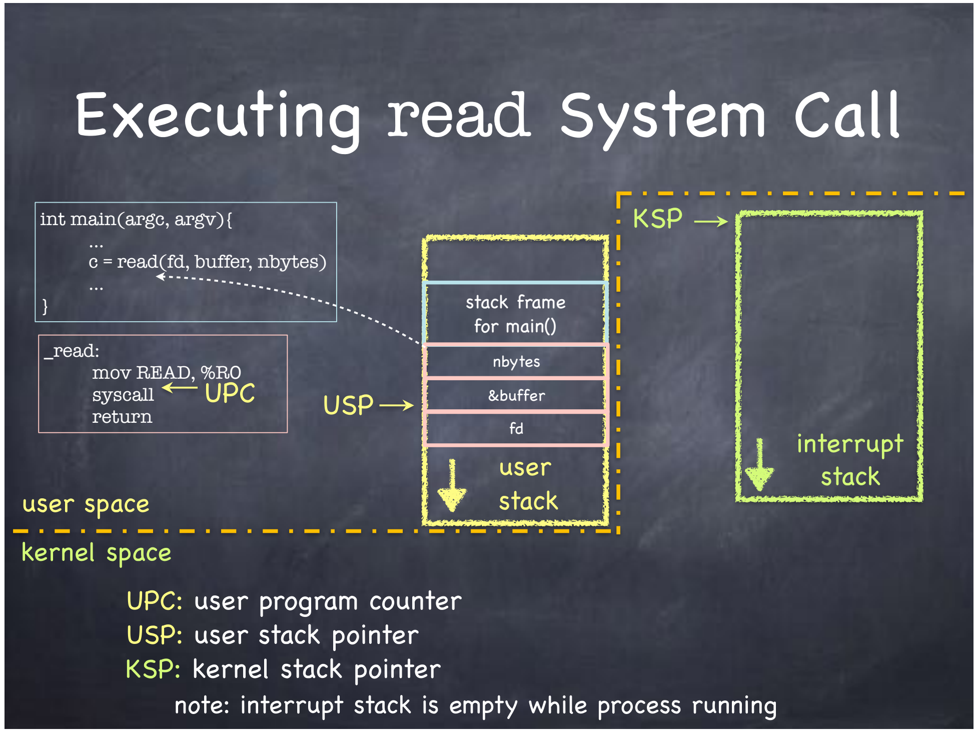
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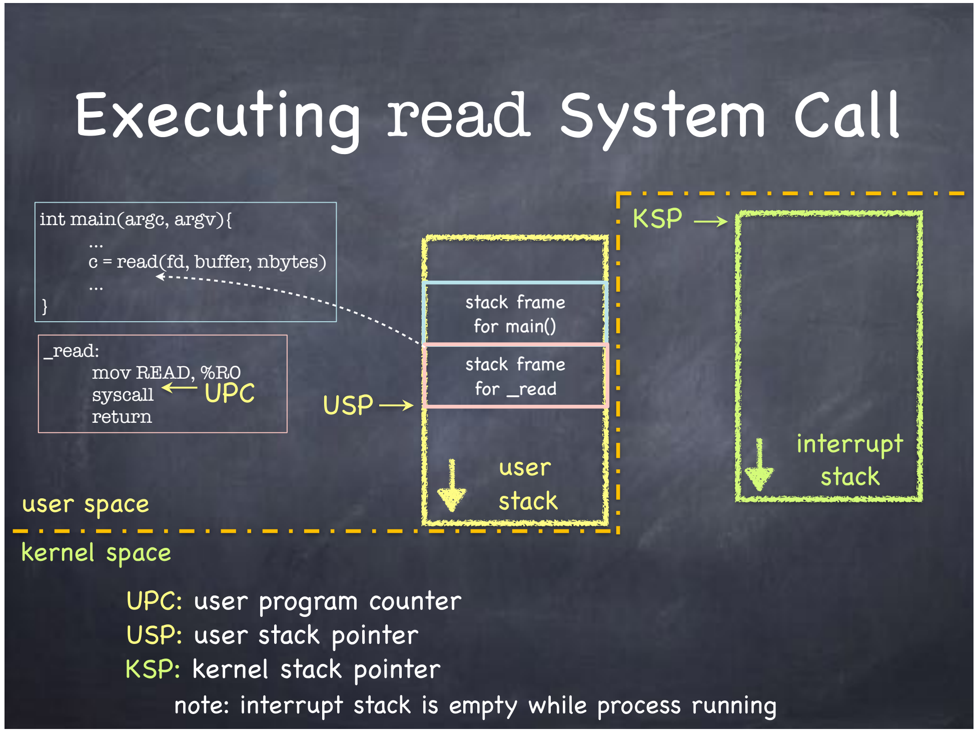
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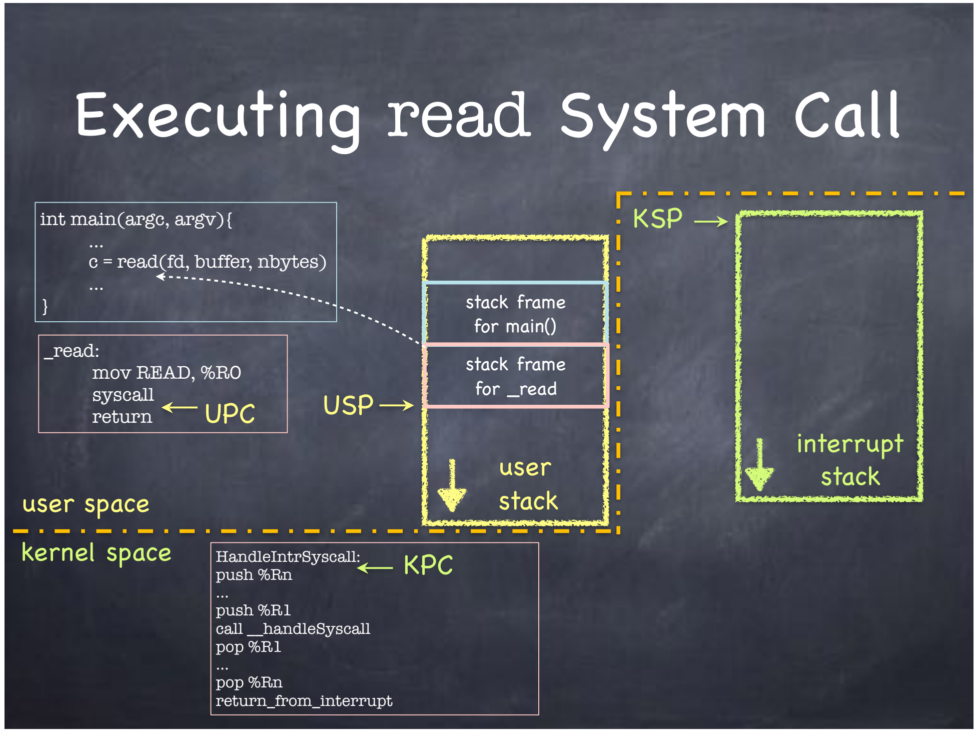
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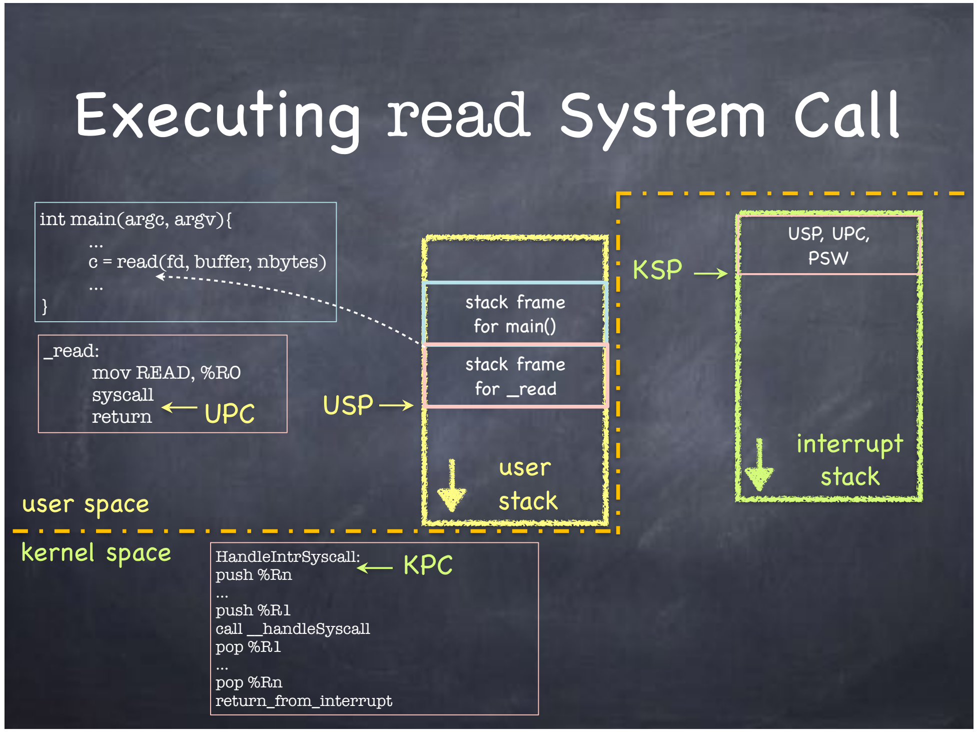
HandleIntrSyscall:
push %Rn
...
push %R1
call __handleSyscall
pop %R1
...
pop %Rn
return_from_interrupt
KPC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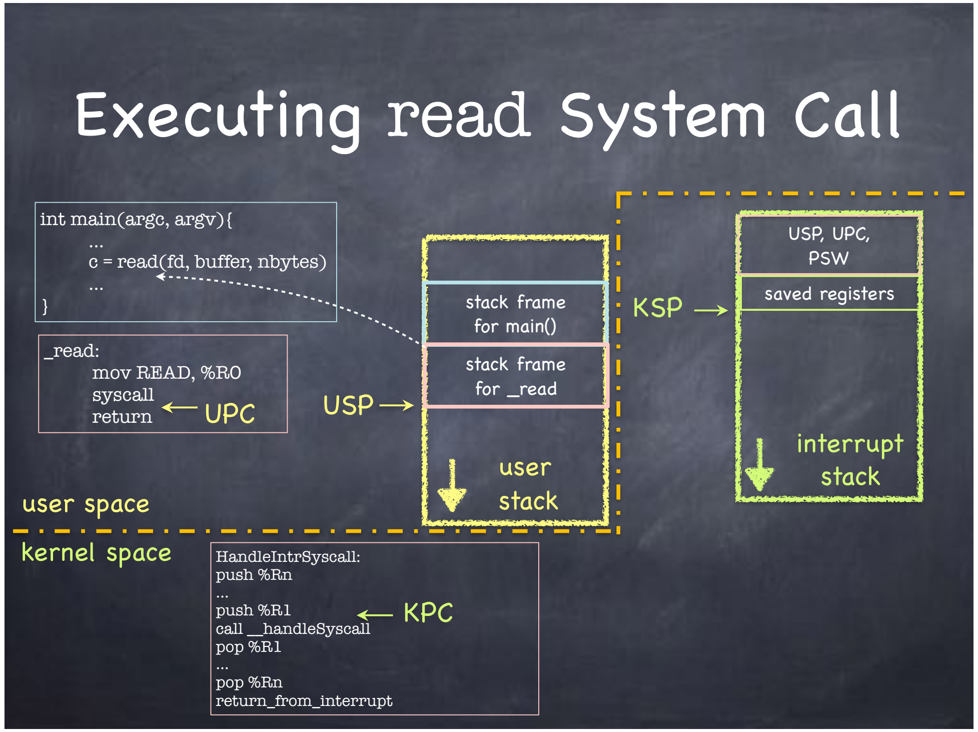
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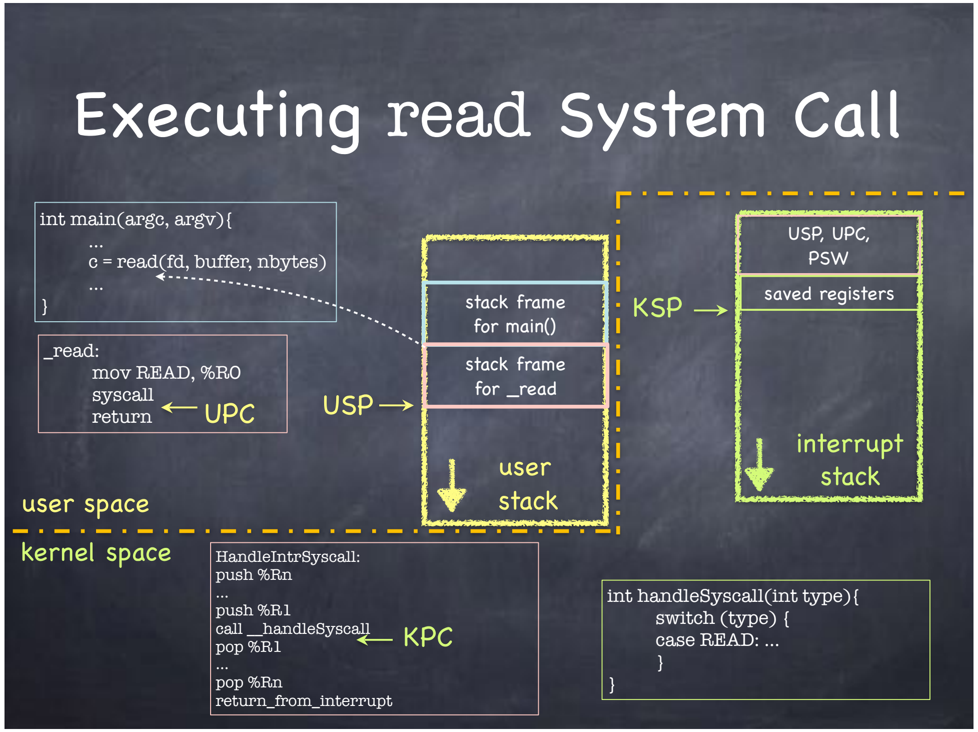
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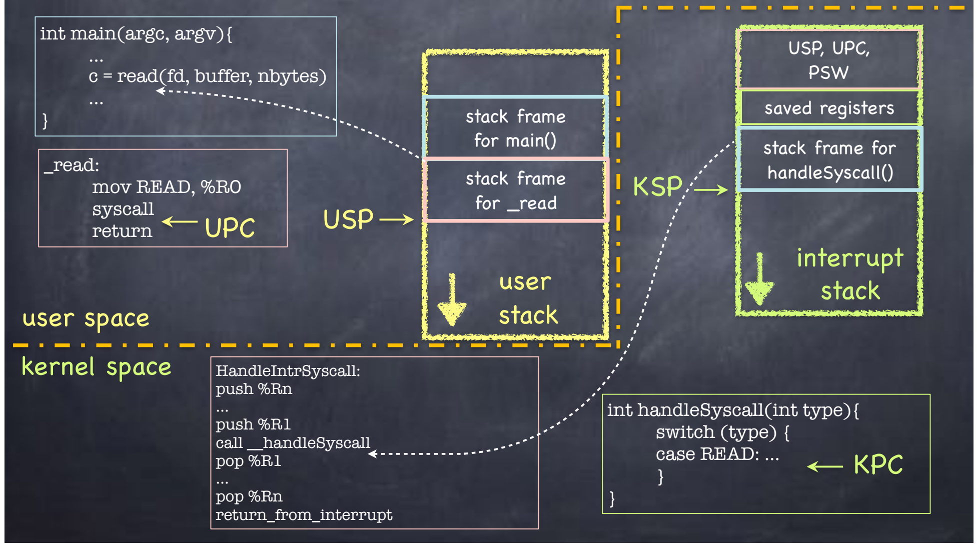
KPC
int handleSyscall(int type){
switch (type) {
case READ: ...
}
}

Executing read System Call



What if read needs to block?

- read may need to block if
  - It reads from a terminal
  - It reads from disk, and block is not in cache
  - It reads from a remote file server

We should run another process!