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
```

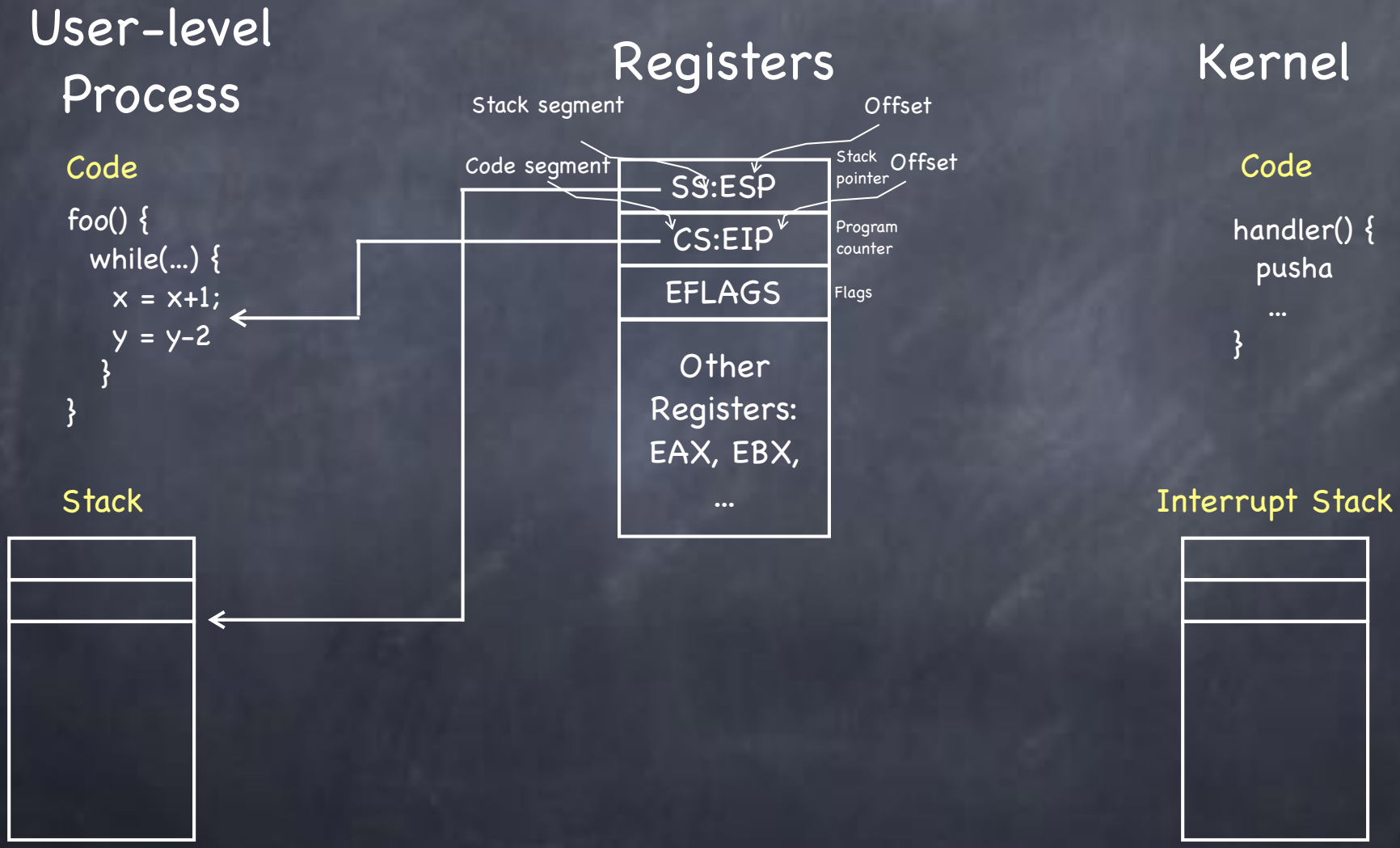
Returning from an Interrupt

- Hardware pops PC, SP, PSW
- Depending on content of PSW
  - switch to user mode
  - enable interrupts
- From exception and system call, may 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

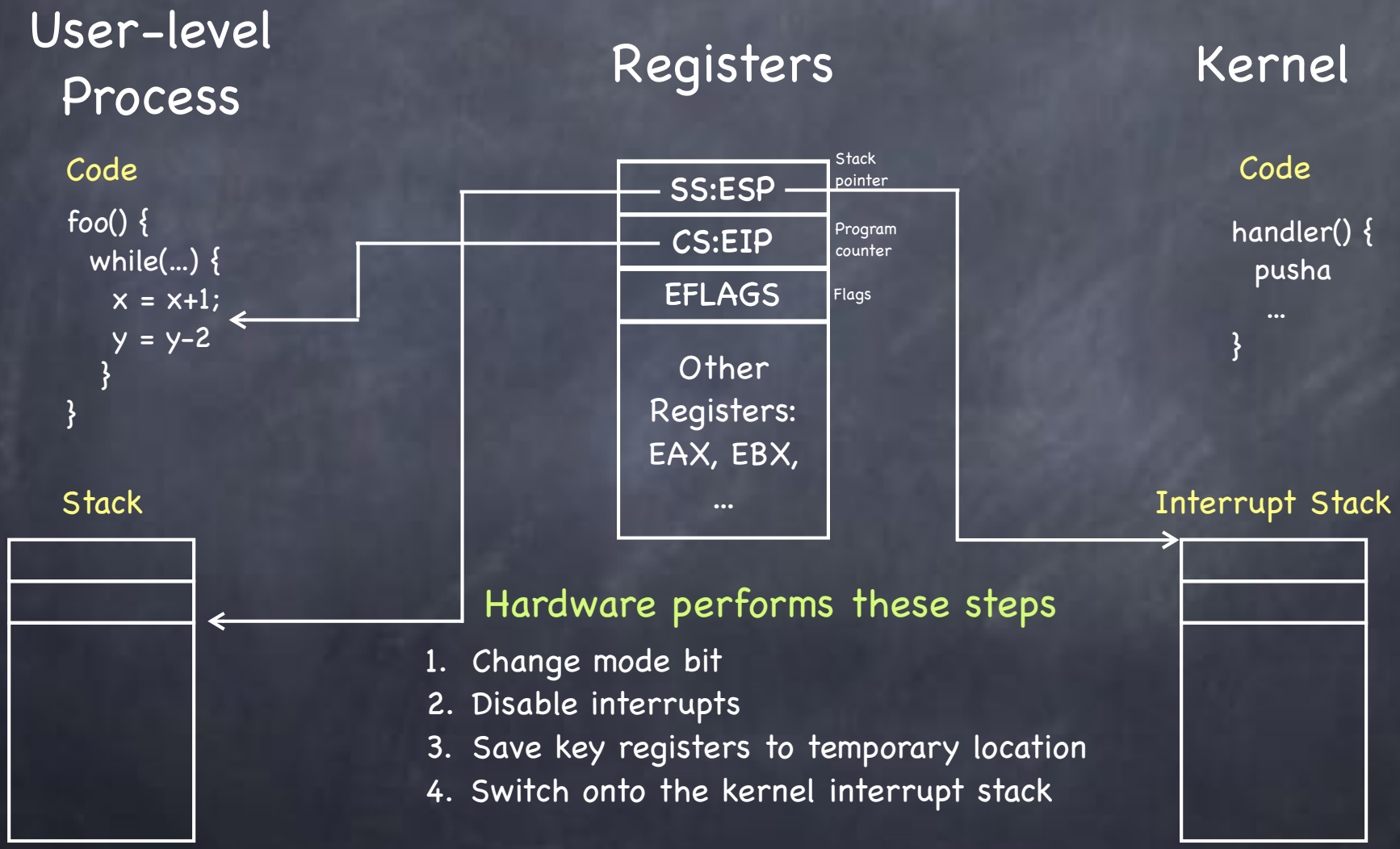
Starting a new process: a recipe

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 on kernel stack initial PC, user SP
   b) push PSW (supervisor mode off, interrupts enabled)
7. Clear all other registers
8. RETURN_FROM_INTERRUPT

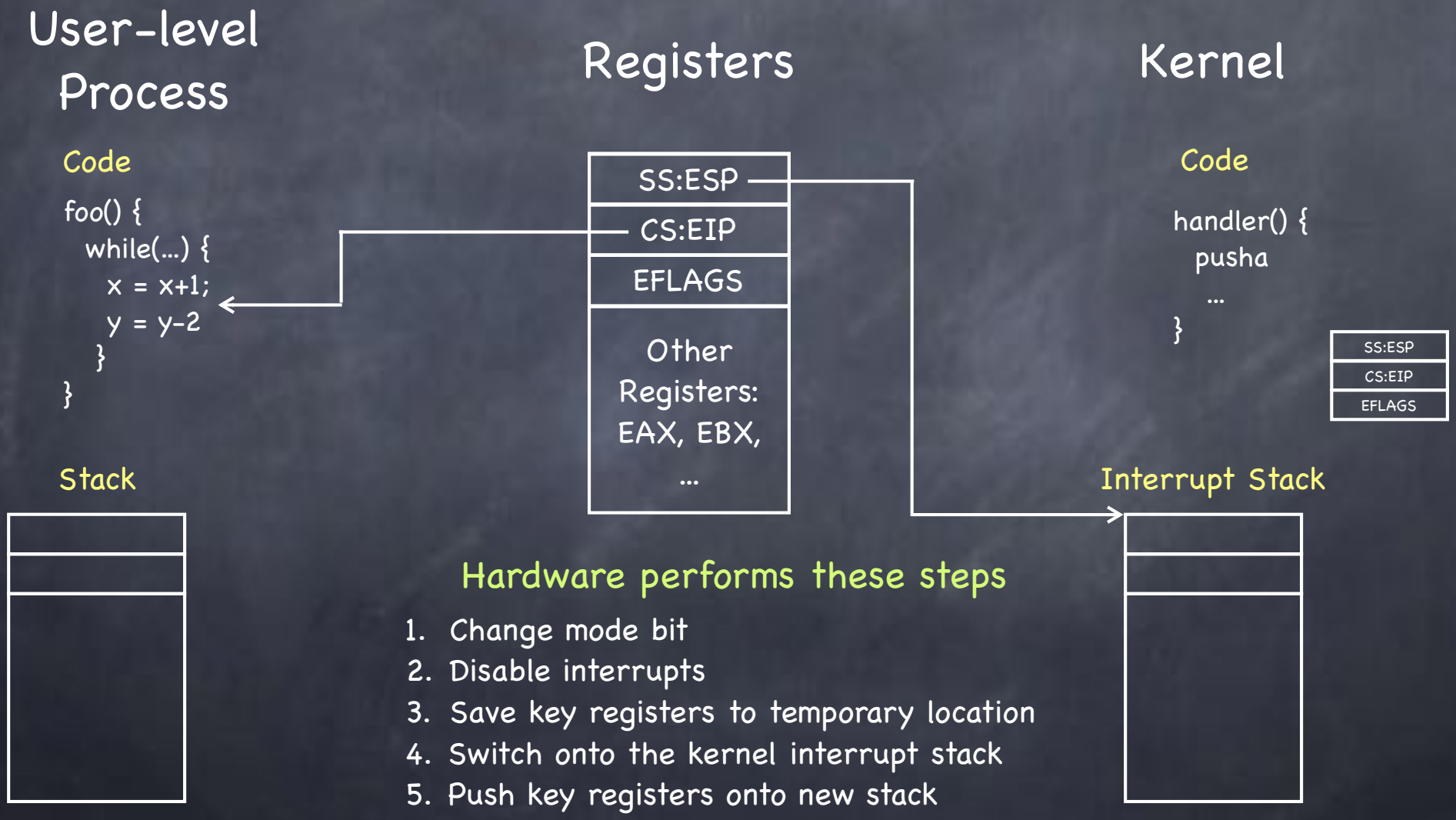
Interrupt Handling on x86



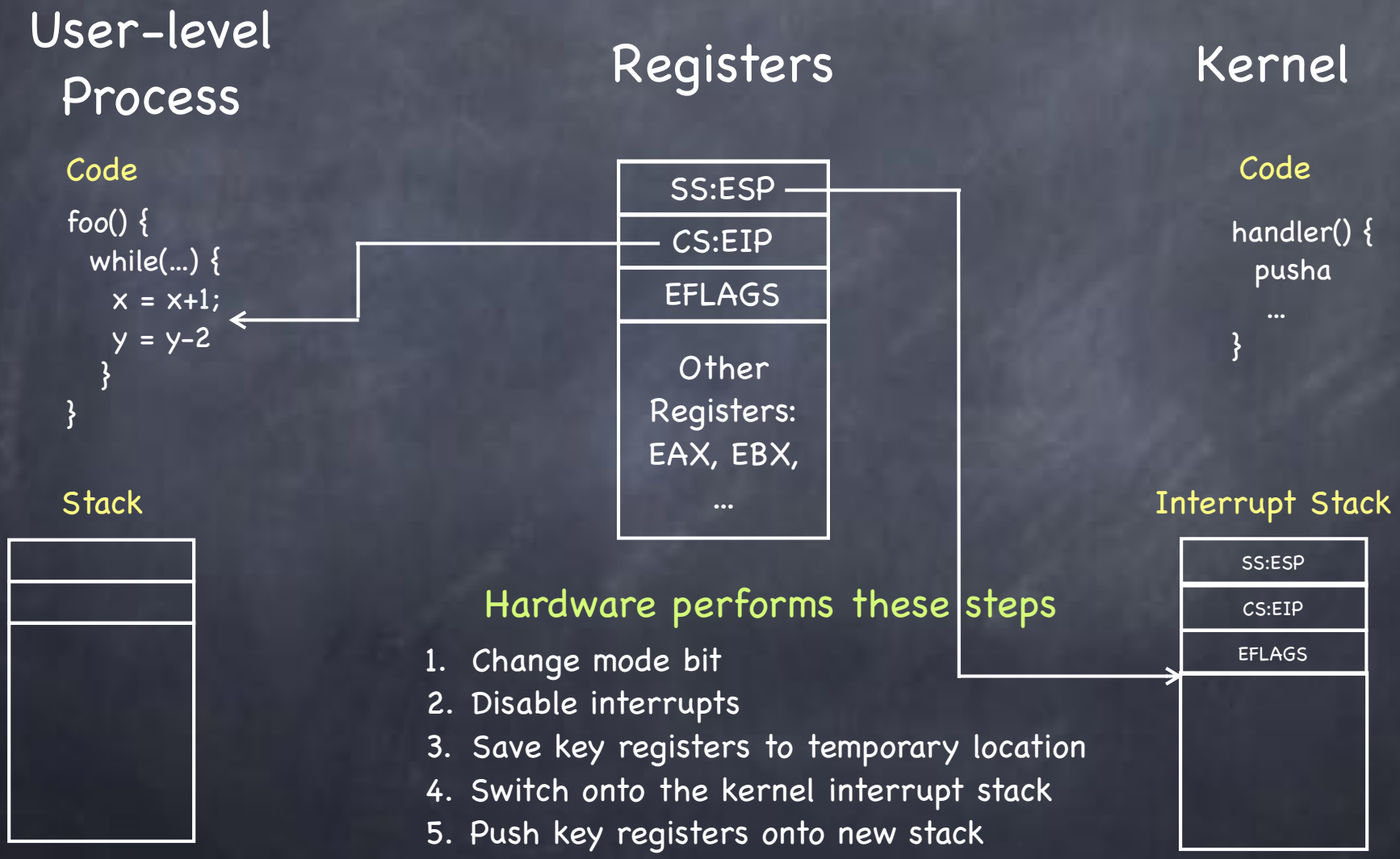
Interrupt Handling on x86



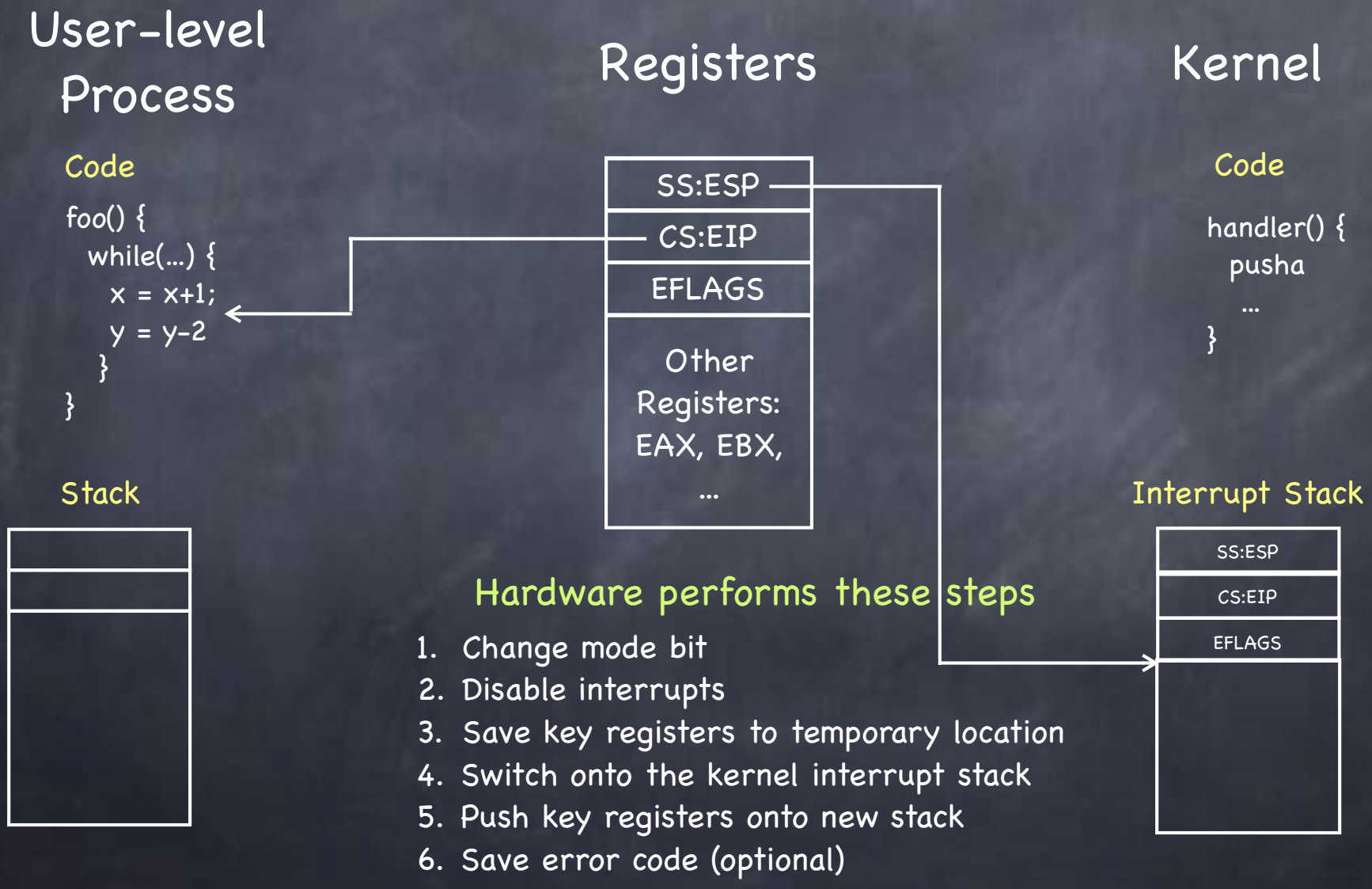
Interrupt Handling on x86



Interrupt Handling on x86



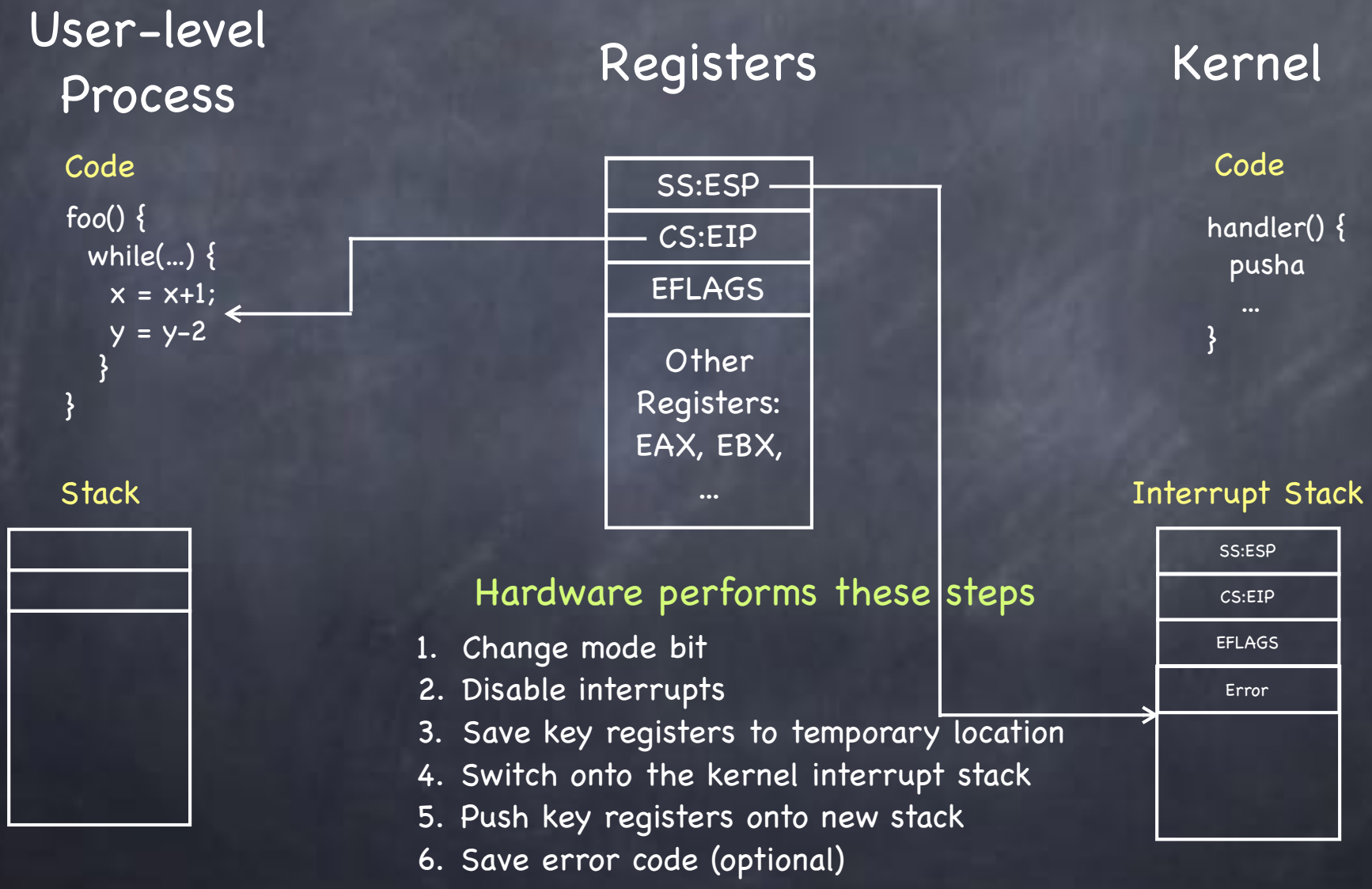
Interrupt Handling on x86



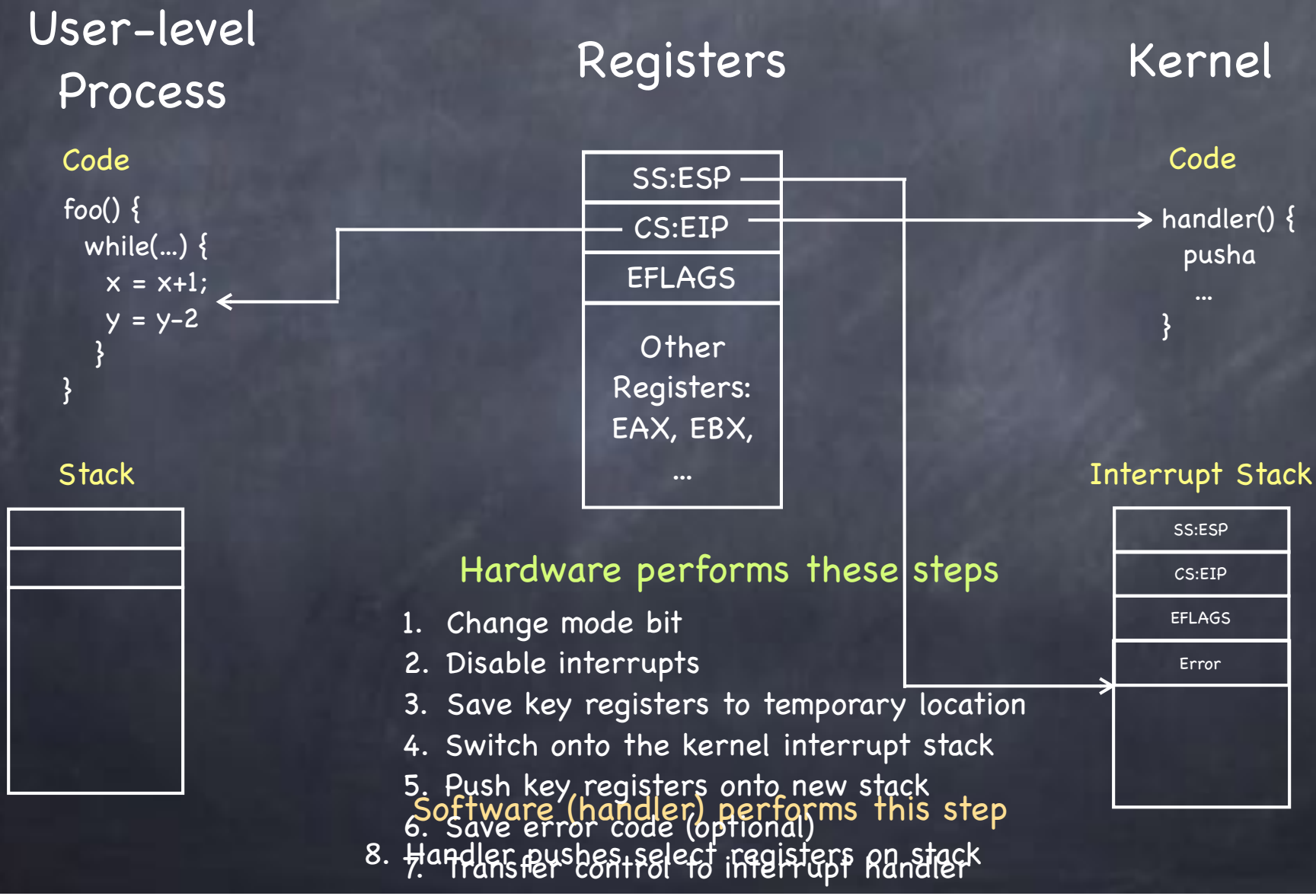
Hardware performs these steps

1. Change mode bit
2. Disable interrupts
3. Save key registers to temporary location
4. Switch onto the kernel interrupt stack
5. Push key registers onto new stack
6. Save error code (optional)

Interrupt Handling on x86



Interrupt Handling on x86



Interrupt Handling on x86

User-level Process

Code

```
foo() {
  while(...) {
    x = x+1;
    y = y-2
  }
}
```

Stack

Registers

Kernel

Code

```
handler() {
  pusha
  ...
}
```

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
5. Push key registers onto new stack
6. Save error code (optional)
7. Transfer control to interrupt handler

Software (handler) performs this step

8. Handler pushes select registers on stack

Interrupt Handling on x86

User-level Process

Code

```
foo() {
  while(...) {
    x = x+1;
    y = y-2
  }
}
```

Stack

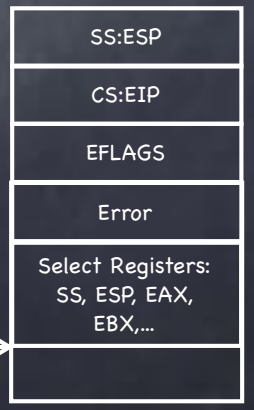
Registers

Kernel

Code

```
handler() {
  pusha
  ...
}
```

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
5. Push key registers onto new stack
6. Save error code (optional)
7. Transfer control to interrupt handler

Software (handler) performs this step

8. Handler pushes select registers on stack

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 asynchronous (and thus uncontrollable) events

Interrupt Race Example

- Disk interrupt handler enqueues a task to be executed after a particular time
  - while keeping clock interrupts 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

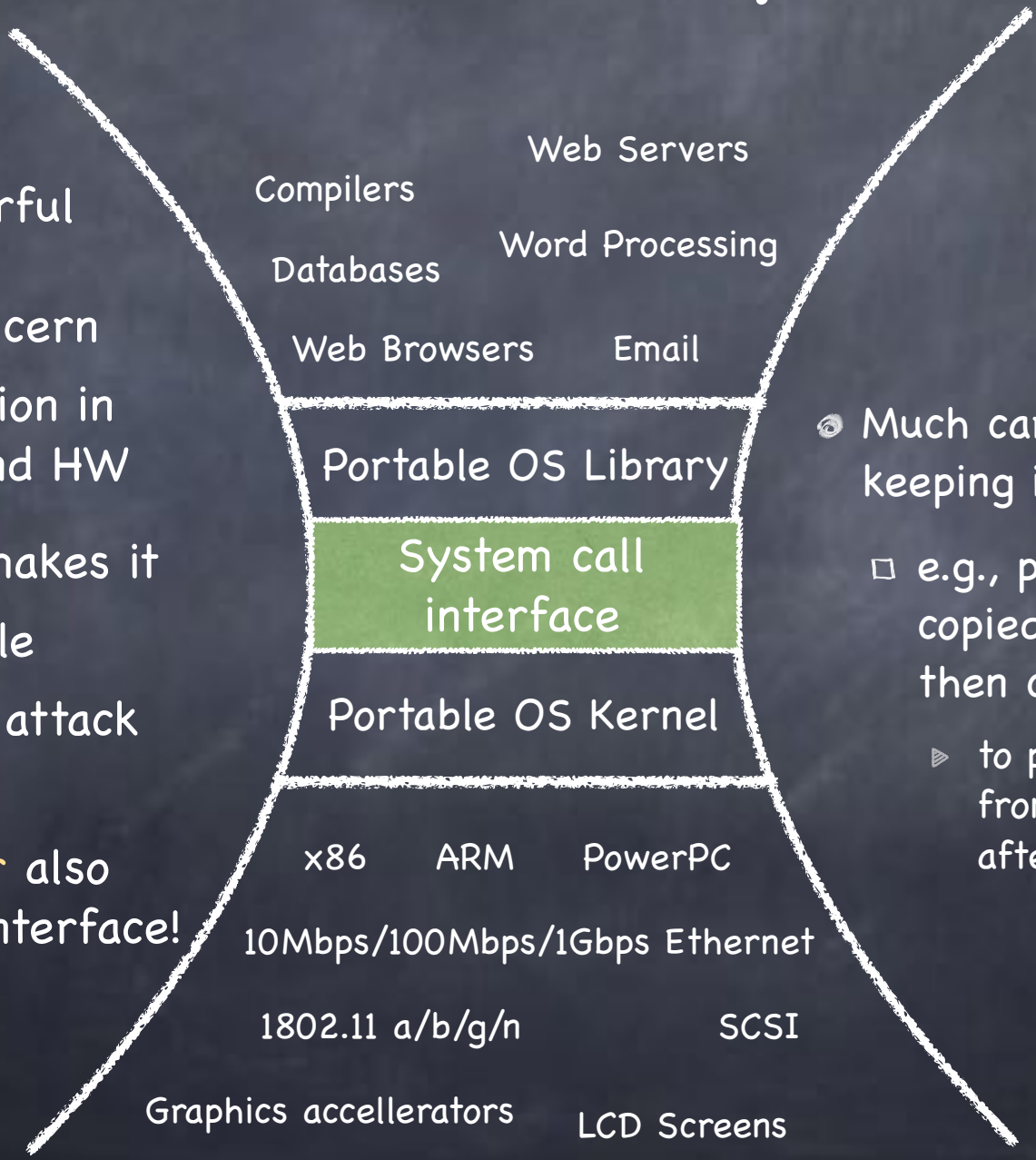
- Pure system calls are interrupt-safe
  - e.g., read(), write(), etc.
- Functions that don't use global data are interrupt-safe
  - e.g., strlen(), strcpy(), etc.
- malloc(), free (), and printf() are not interrupt-safe
  - must disable interrupts before using them in an interrupt handler
  - and you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

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 a skinny interface!

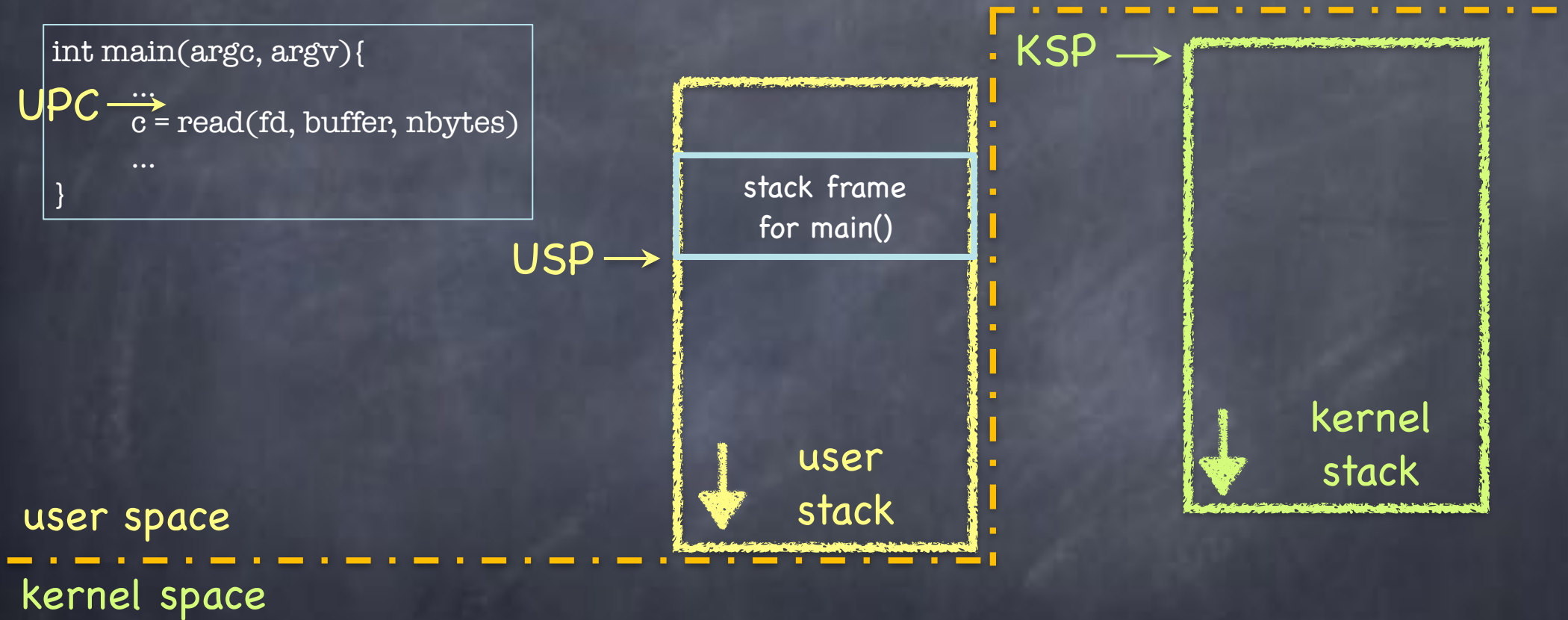


- Much care spent in keeping interface secure
  - e.g., parameters first copied to kernel space, then checked
    - to prevent user program from changing them after they are checked!

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

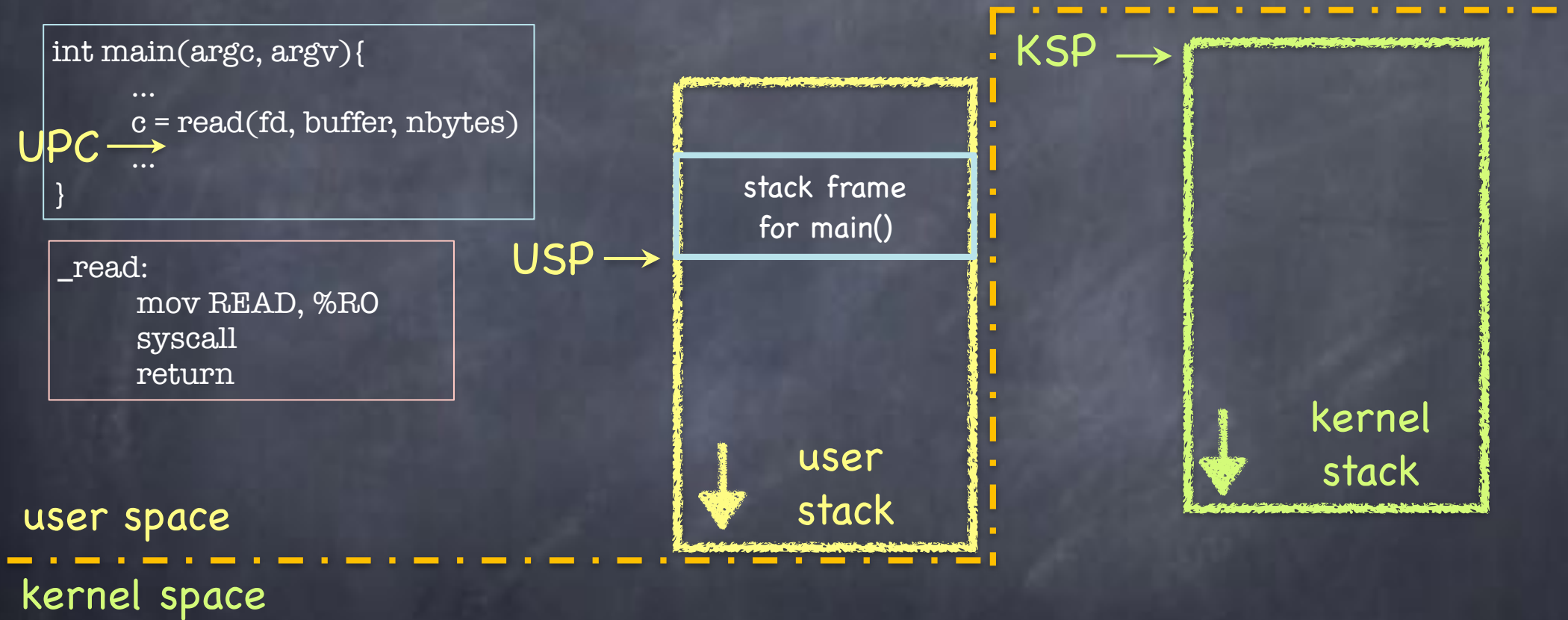
Executing read System Call



UPC: user program counter KPC: kernel program counter
USP: user stack pointer
KSP: kernel stack pointer

note: kernel stack is empty while process running

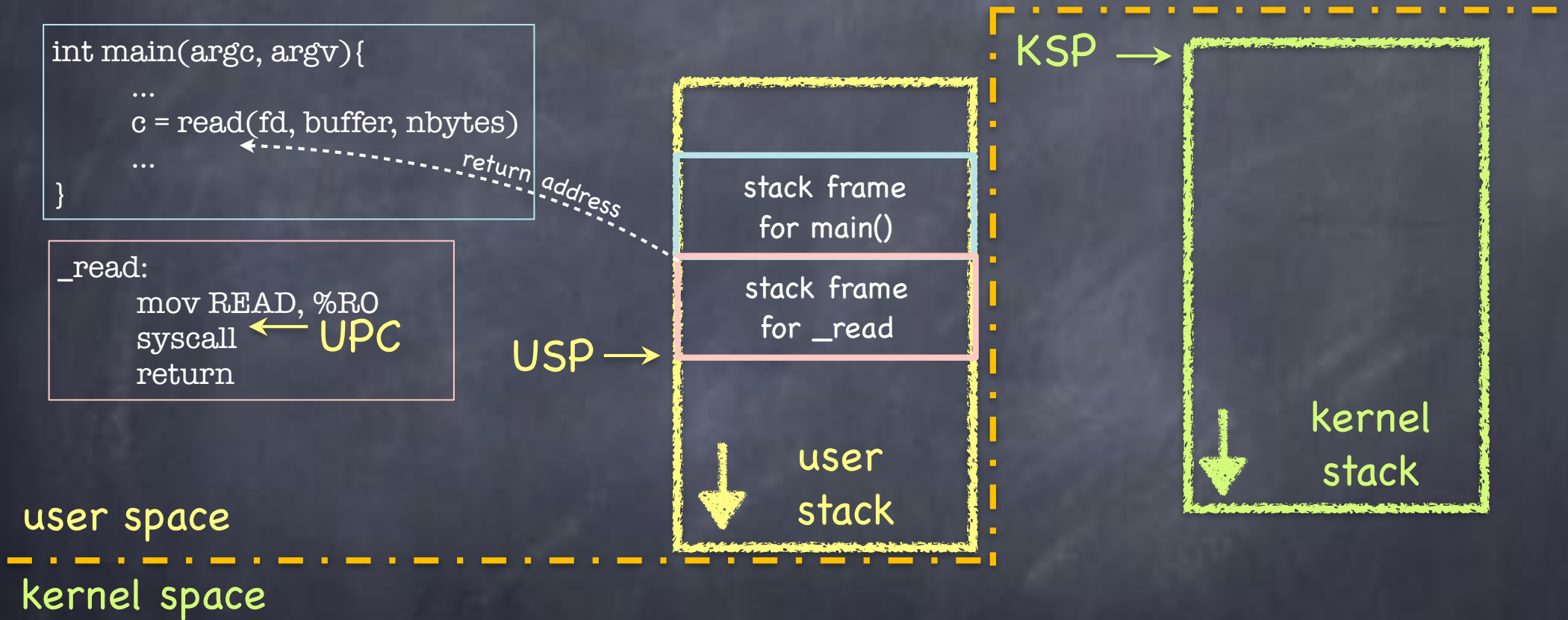
Executing read System Call



UPC: user program counter KPC: kernel program counter
USP: user stack pointer
KSP: kernel stack pointer

note: kernel stack is empty while process running

Executing read System Call



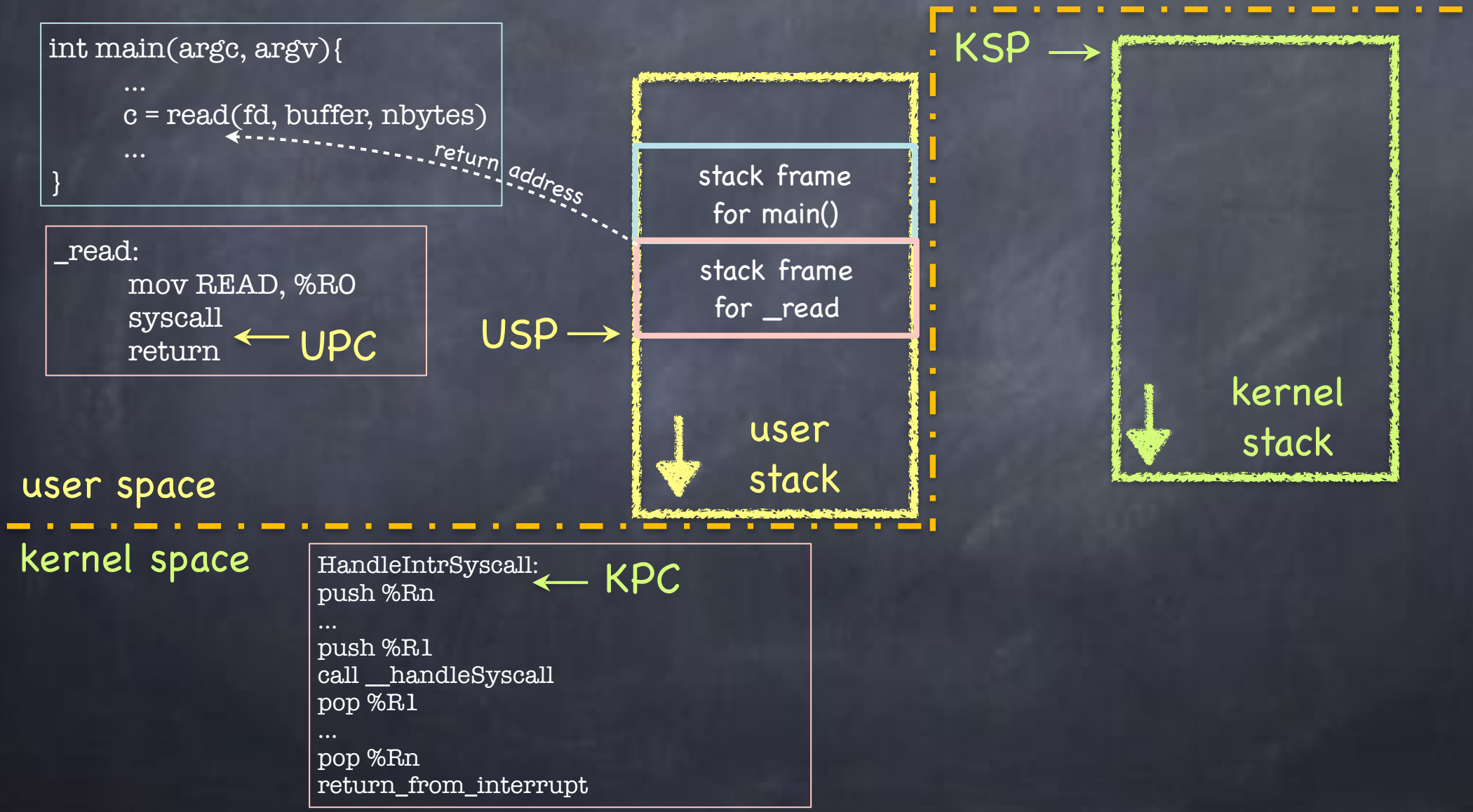
UPC: user program counter KPC: kernel program counter

USP: user stack pointer

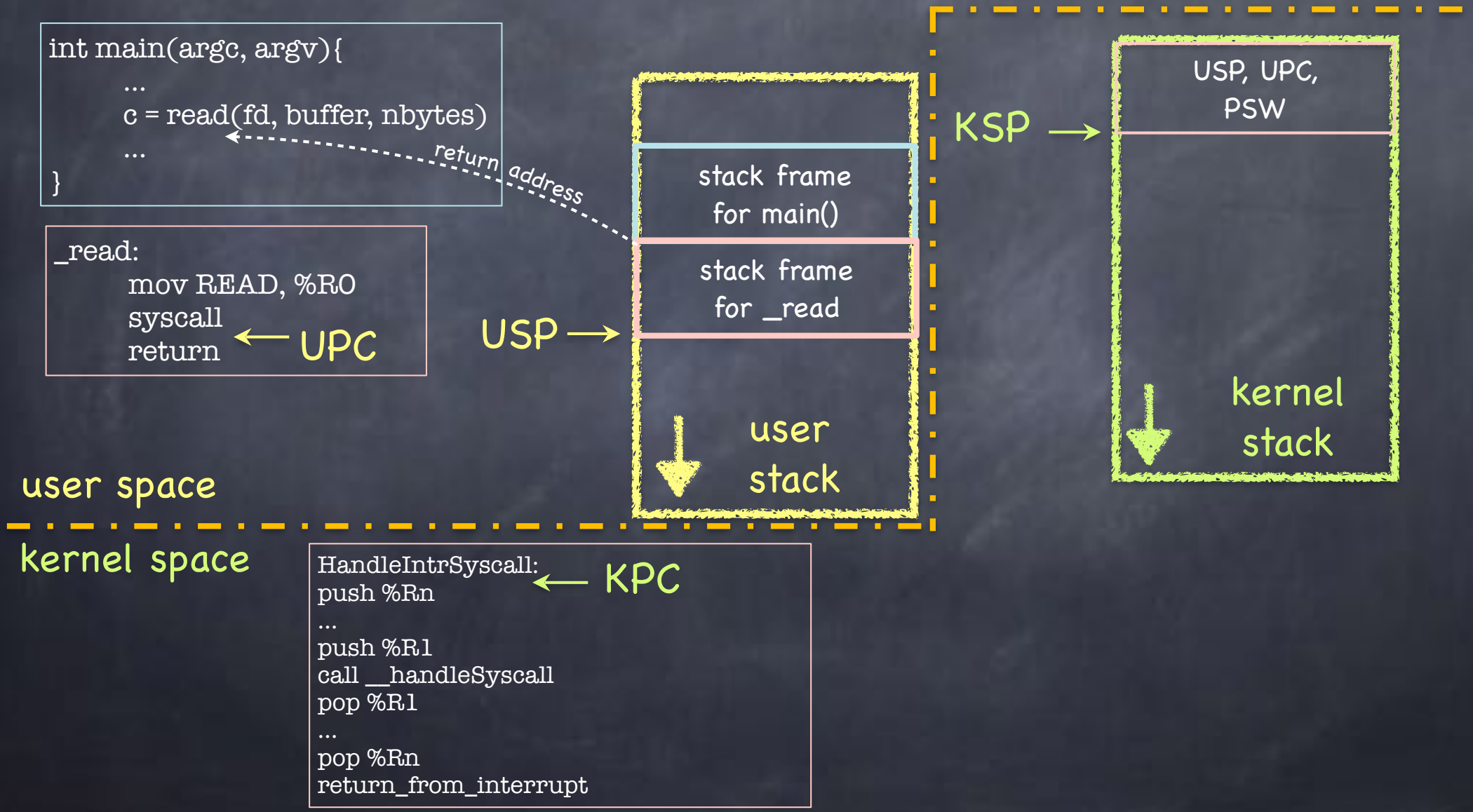
KSP: kernel stack pointer

note: kernel stack is empty while process running

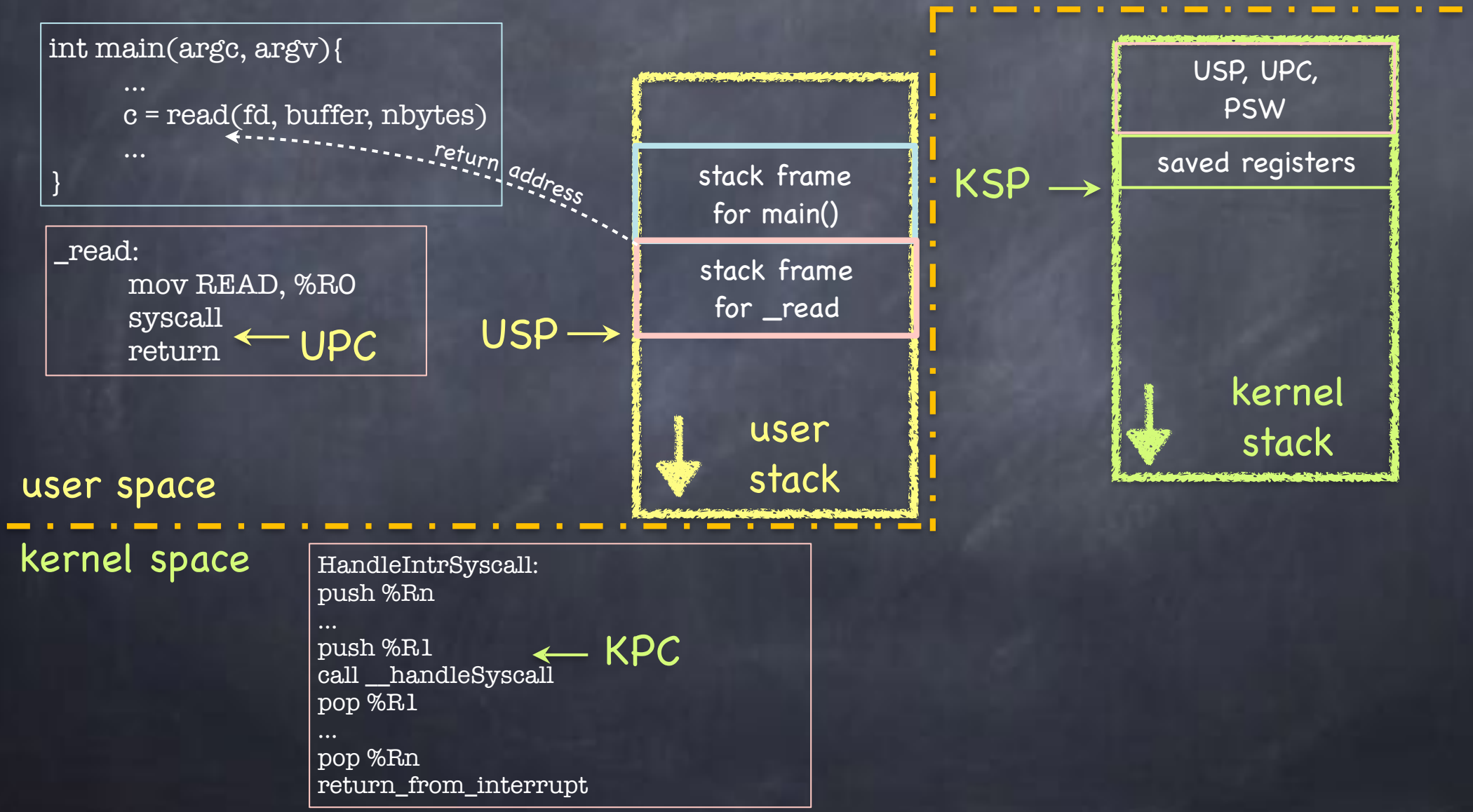
Executing read System Call



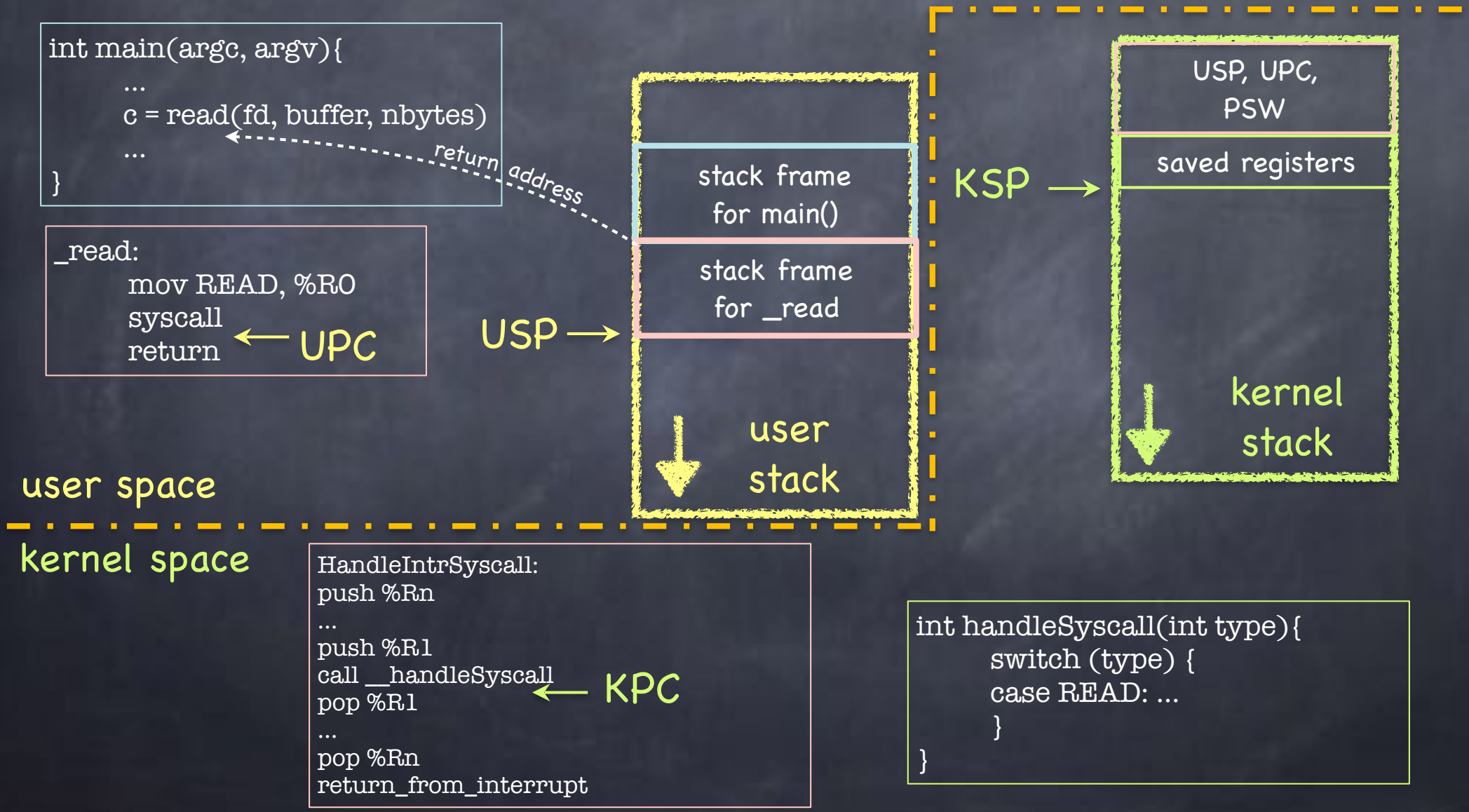
Executing read System Call



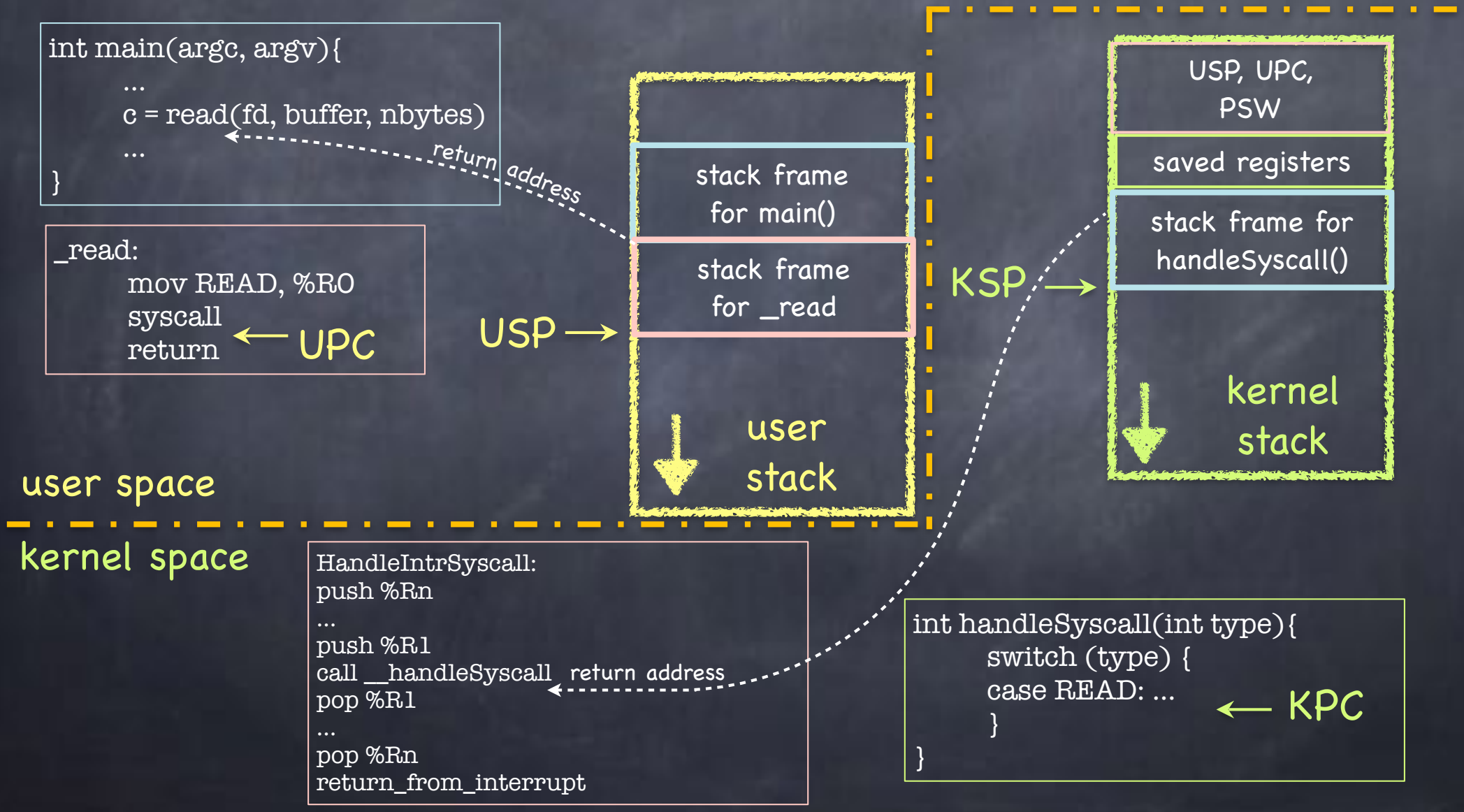
Executing read System Call



Executing read System Call



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!

How to run multiple processes