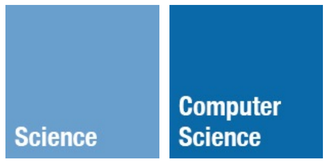
CPU Virtualization



CS 450: Operating Systems
Michael Lee <lee@iit.edu>

Agenda

- Central question: how to implement time-sharing?
  - While maintaining OS control & maximizing performance
- “Limited direct execution”
- Mechanics of context switches

Direct Execution

- OS loads process program/data/args into predefined location(s), then points PC at entry point (e.g., `main`)
- When program terminates (e.g., return from main), OS cleans up process footprint (data/metadata)

Direct Execution

- Problems:
  - No concurrency
  - Process is unchecked; can wreak havoc on system!

Limited Direct Execution

- Must prevent user from:
  - accessing arbitrary memory addresses
  - executing “dangerous” instructions
    - e.g., access to I/O and system registers

province of VM (later)

focus on this first

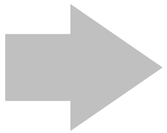
Recall: kernel vs. user mode

- Privileged instructions can only be executed in kernel mode
  - (what happens when user attempts to run?)
- On x86: CPL flag in CS register — 0 = kernel, 3 = user
- After system boot, OS switches to user mode before ceding control to process

System Calls

- When user needs to perform I/O, invoke kernel-mode OS functions via system calls
  - e.g., `printf(…)` → `write(…)`
- Looks like a regular function call, but isn't!

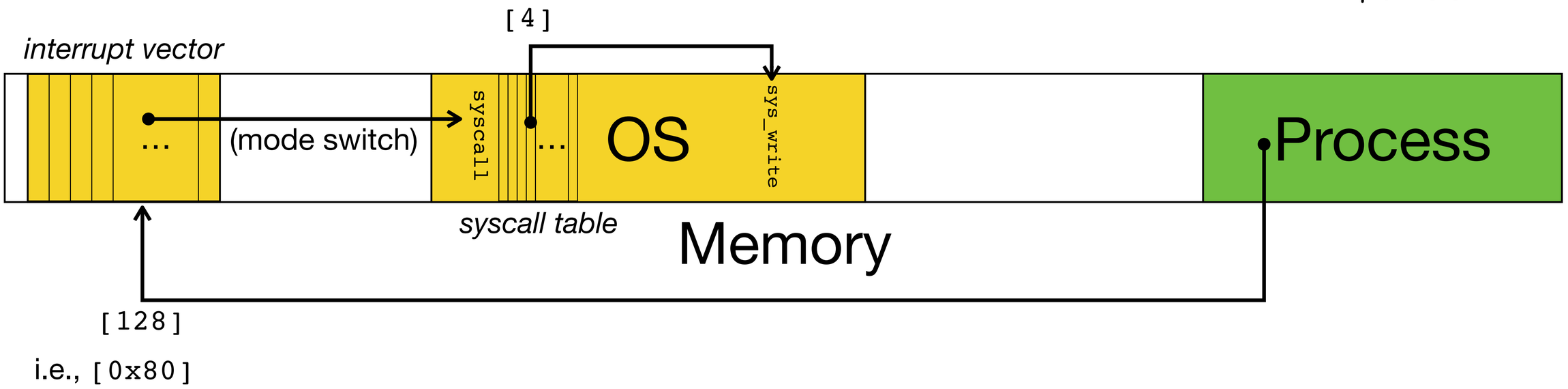
```
char *str = "hello world";
int len = strlen(str);
write(1, str, len);
...
```



```
movl len, %edx
movl str, %ecx
movl $1,  %ebx
movl $4,  %eax # syscall num
int  $0x80     # trap instr
...
```

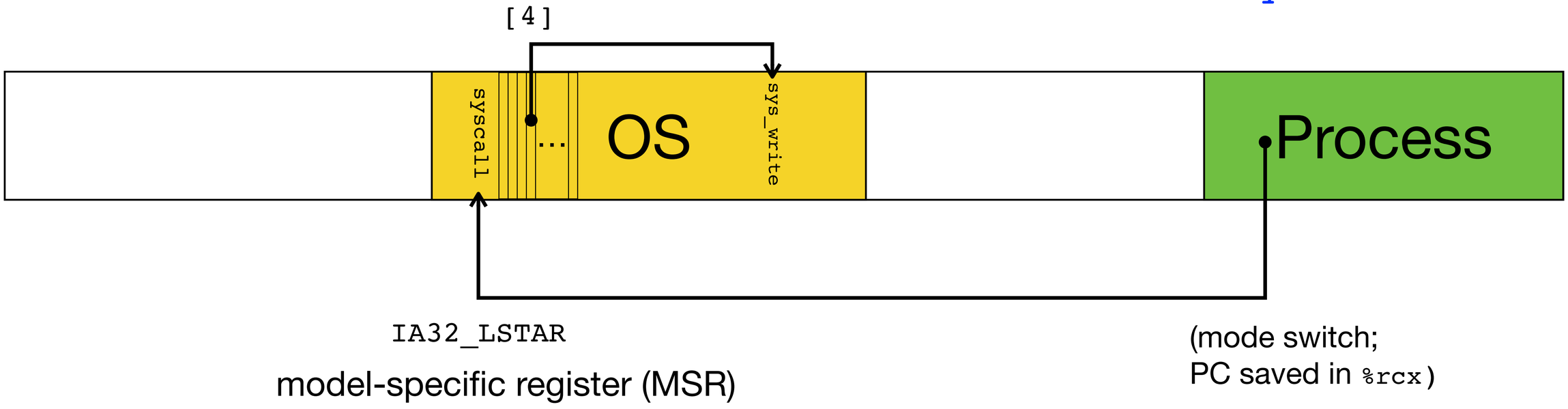
Trap Mechanism

```
movl $4, %eax
int  $0x80
```



- x86-64 adds `syscall` instruction — avoids trap mechanism
  - much faster! (software interrupts are expensive)
  - but traps still used for other things

```
movq $4, %rax
syscall
```



General Interrupt Mechanism

`IDTR` (base address register) — populated by privileged `lidtr` instruction

0-31
reserved for
CPU-generated

32-255
software configurable
(for sw/hw interrupts)

(not all can be triggered from user mode!)

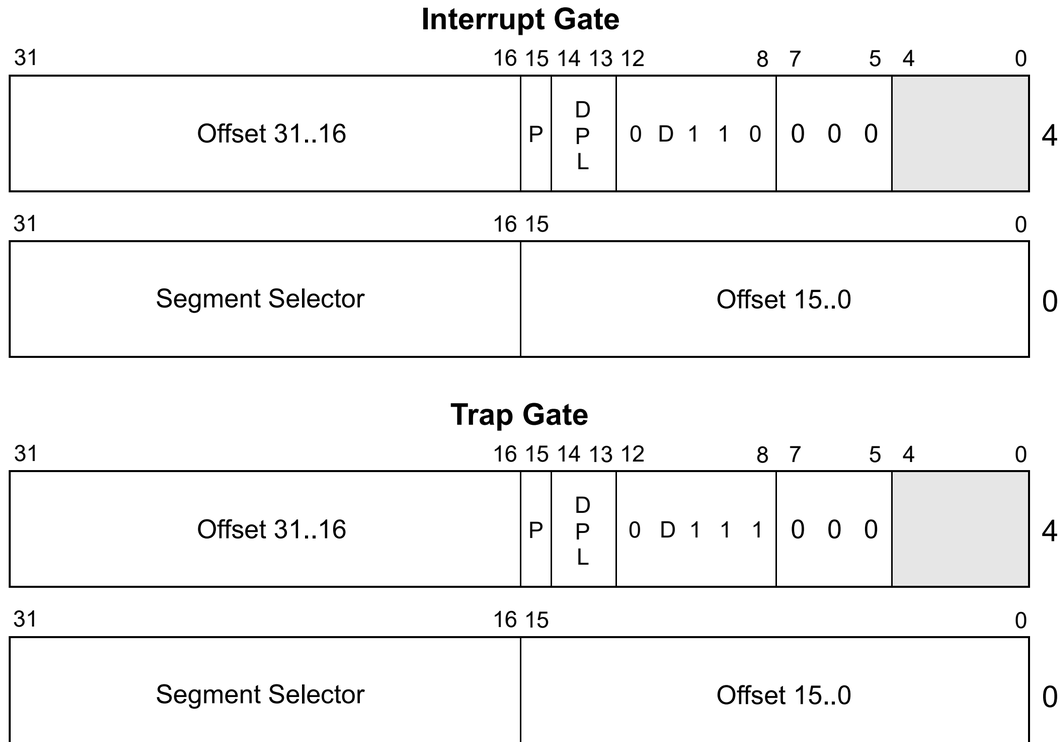
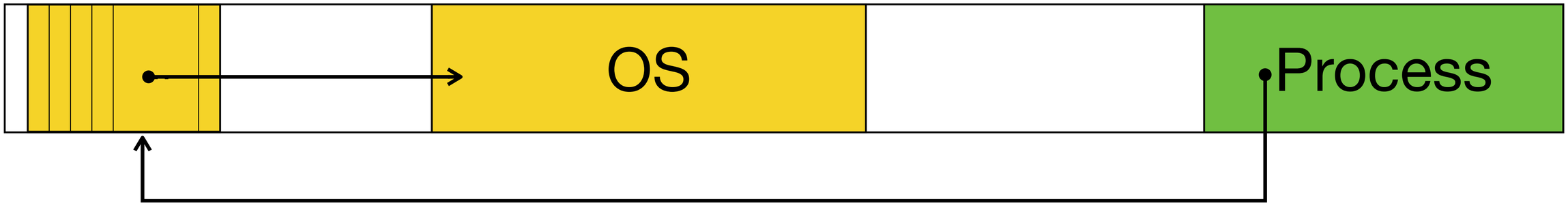


Figure 6-2. IDT Gate Descriptors

from Intel 64 and IA-32 Software Developer's Manual, Volume 3

- Problem: when transitioning to OS code, process state may be lost (e.g., PC, SP, etc.)
  - Should save in case we return to process after servicing trap



Saving Process State

- Hardware automatically saves current context during trap
  - Where?
    - On *kernel stack* — automatically activated on mode switch
- Every process has its own separate kernel stack — used to keep track of kernel state (e.g., while handling I/O)

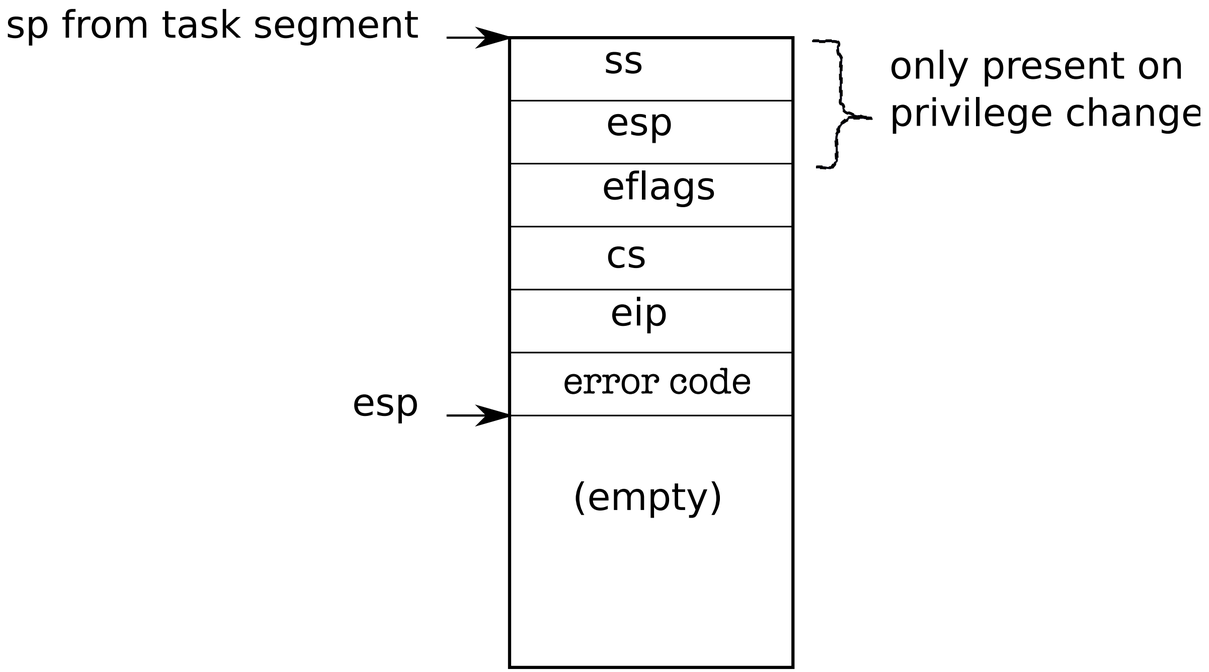
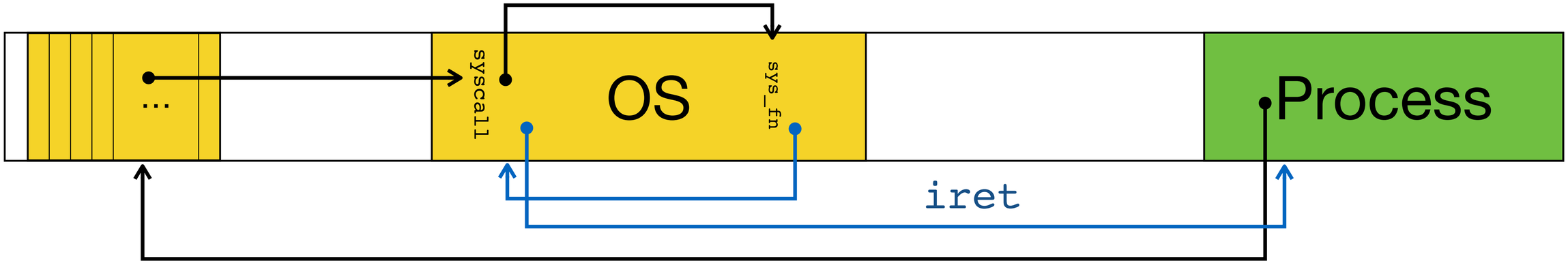


Figure 3-1. Kernel stack after an int instruction.

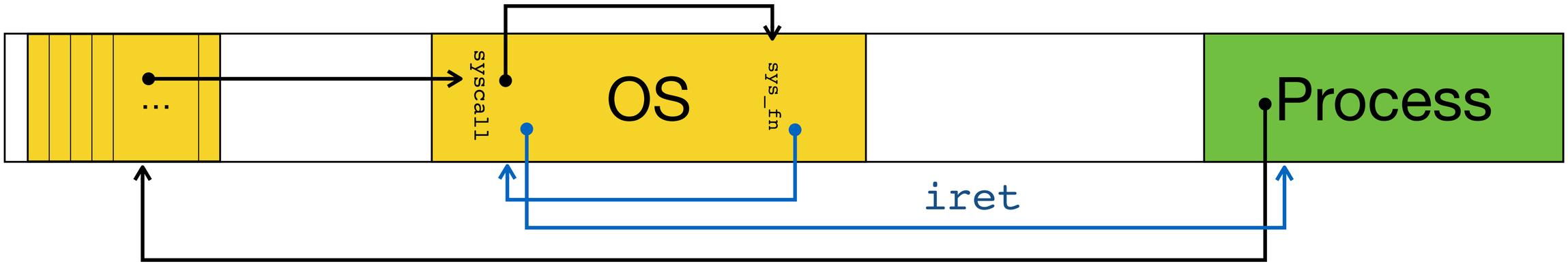
from xv6 commentary

Restoring Process State

- “return from trap” instruction: `iret` — pops and restores *trap frame* and returns to process in user mode



(On x86-64, `sysret` instead; loads PC from `%rcx`)



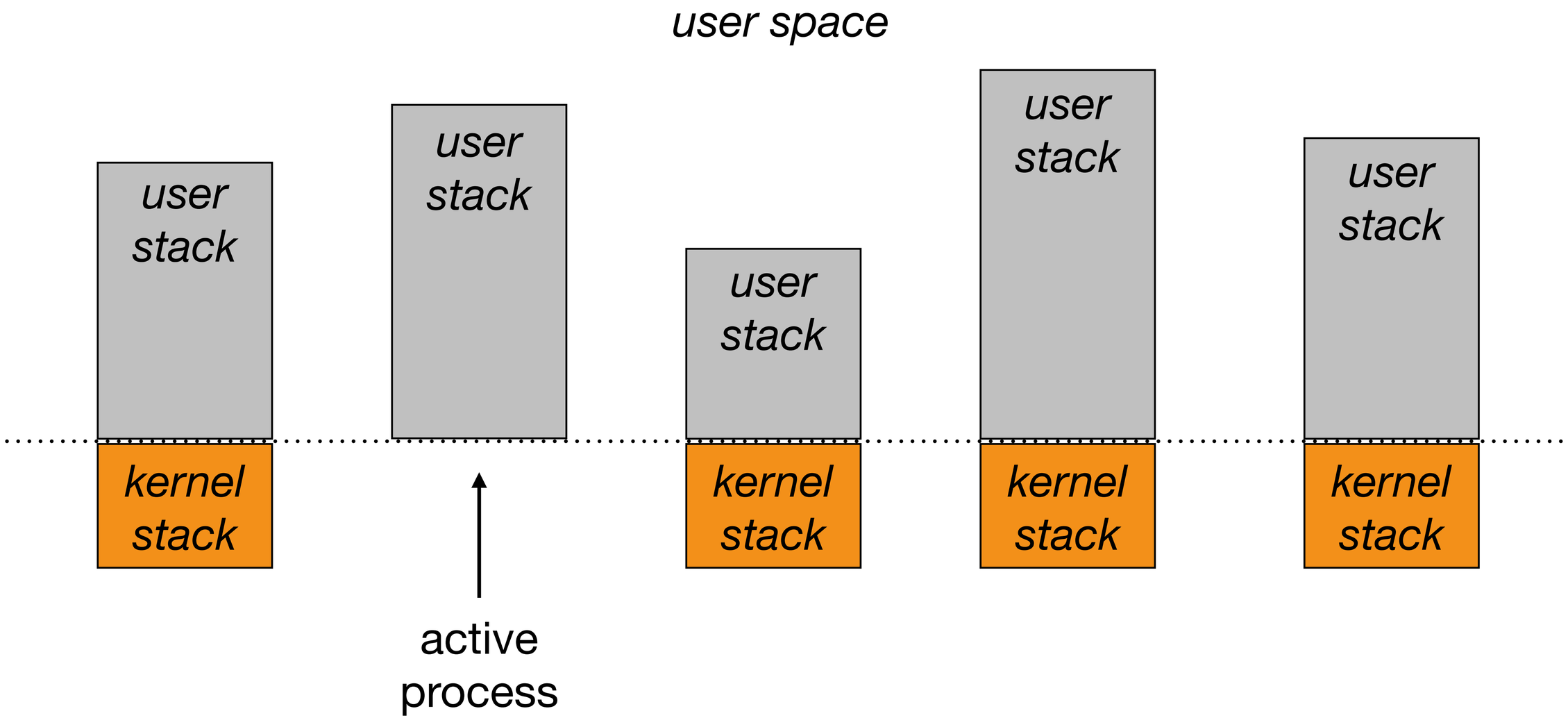
- Do we always immediately return to trapping process?
  - No! (Why not?)
    - Process may be blocked (due to I/O request)
    - Scheduling decision

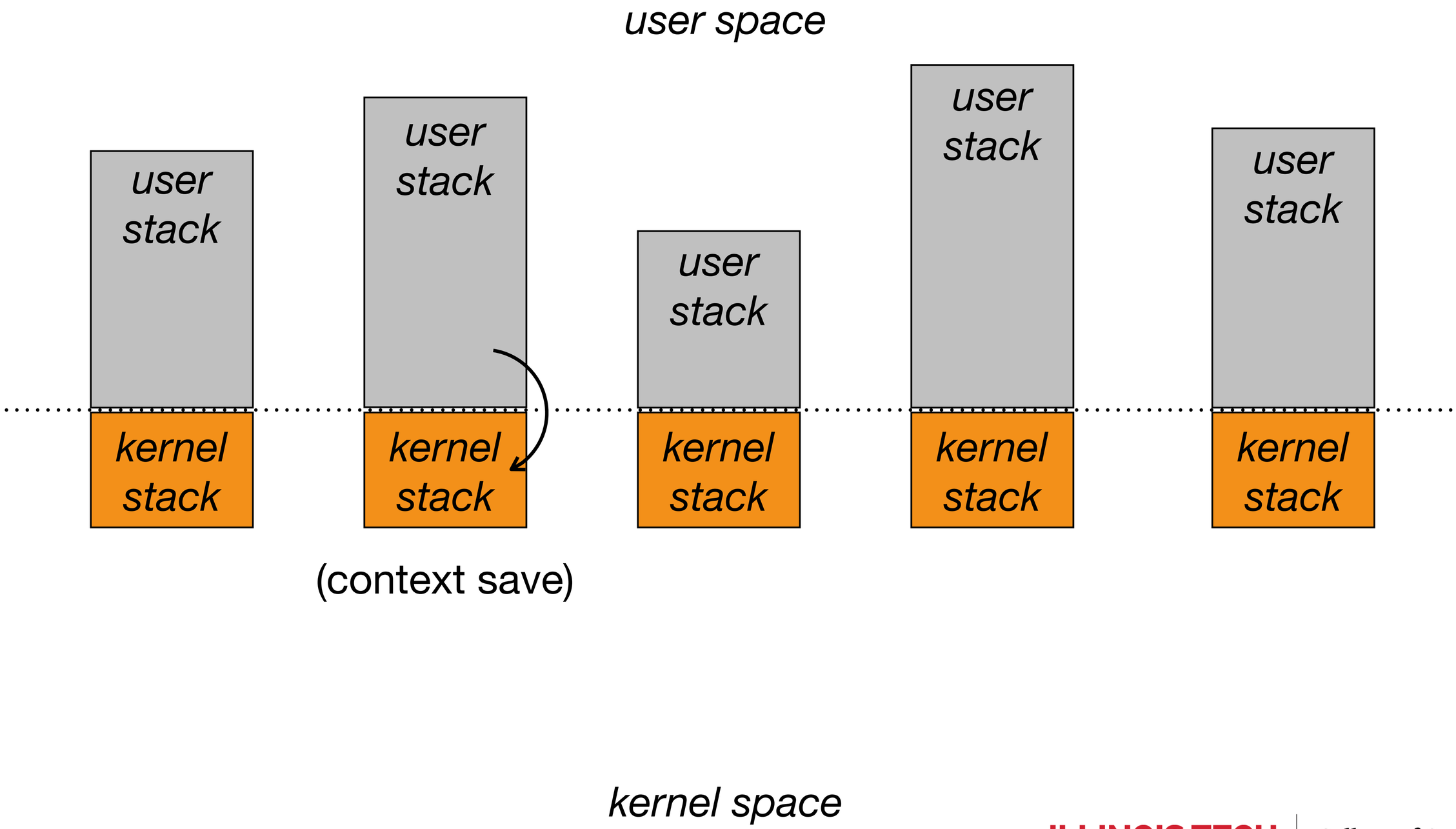
Context Switch

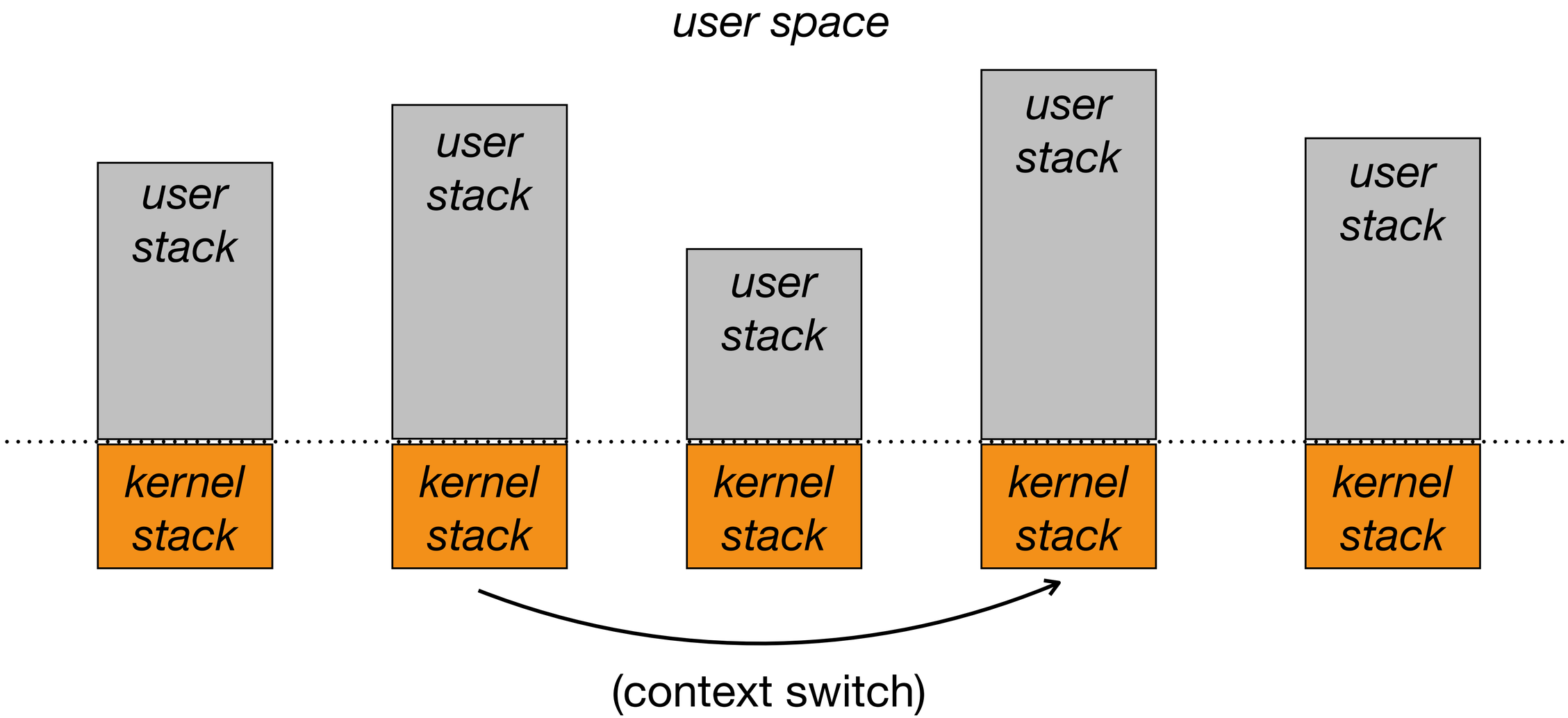
1. Trap to kernel; save trap frame on kernel stack
2. Save outgoing process context on kernel stack
3. Switch to different kernel stack
4. Restore incoming process context from kernel stack
5. `iret` (restore trap frame from kernel stack)

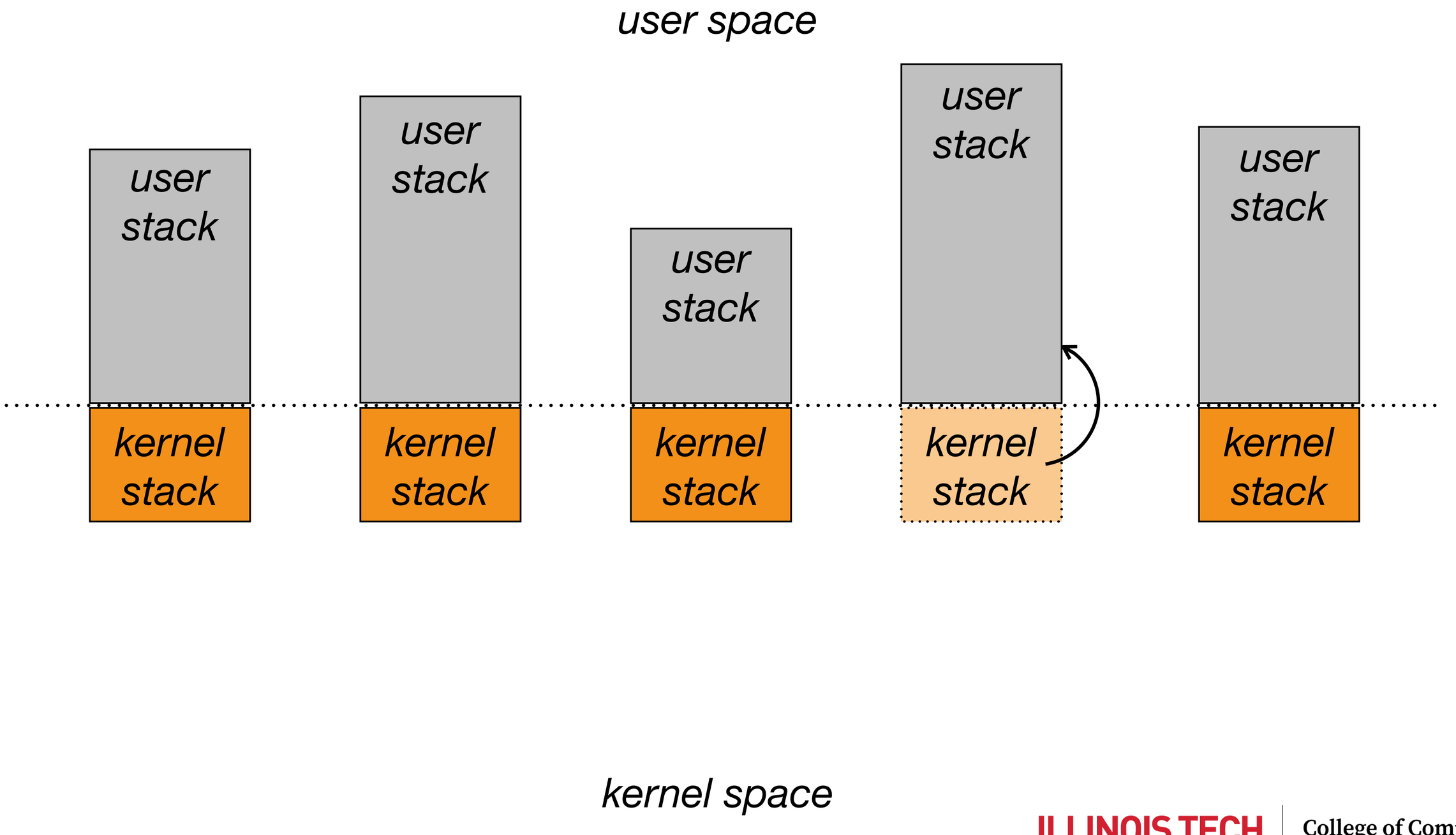
```
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-saved registers
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-saved registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```

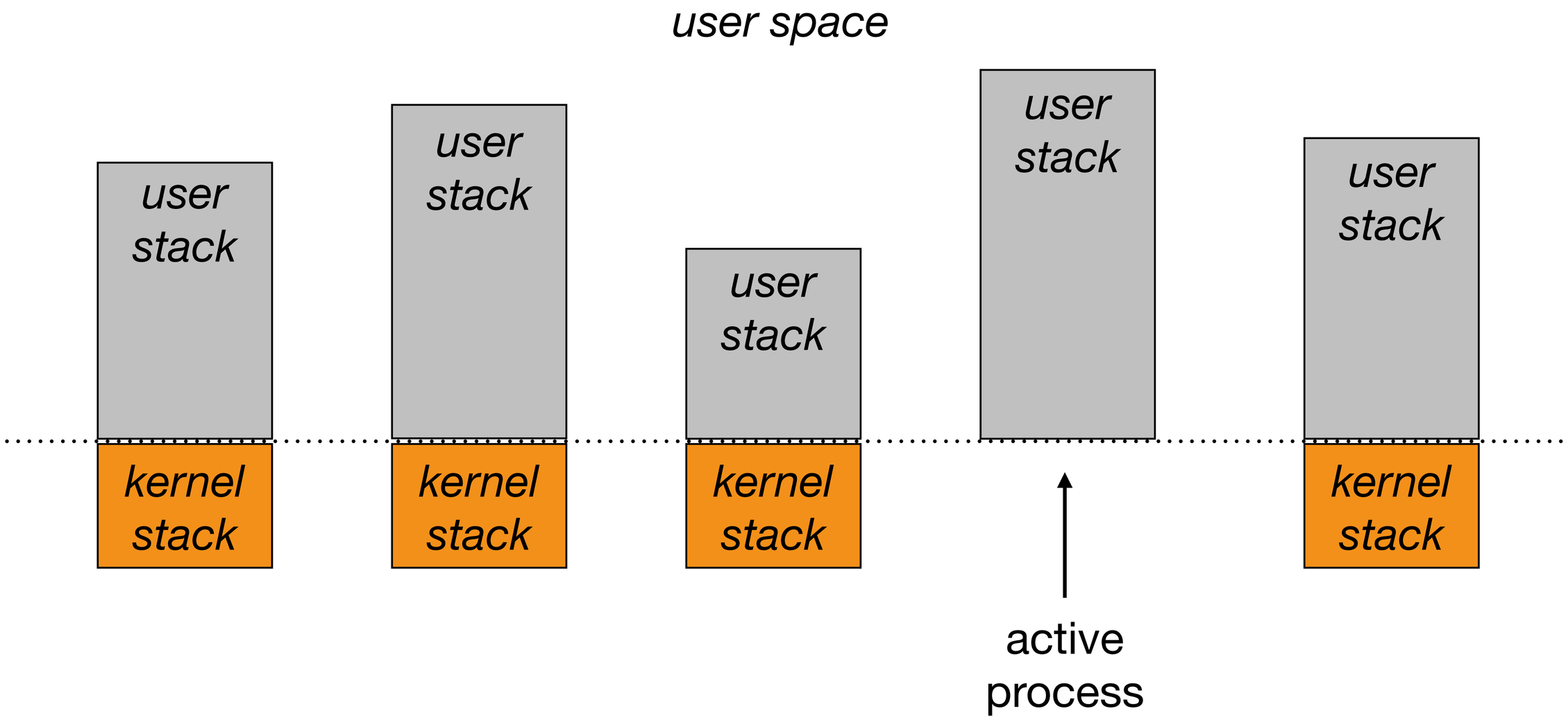
```
trapret:
  popal
  popl %gs
  popl %fs
  popl %es
  popl %ds
  addl $0x8, %esp
  iret
```


user space
user stack
user stack
user stack
user stack
user stack
kernel stack
kernel stack
kernel stack
kernel stack
kernel stack
active process
kernel space


user space
user stack
user stack
user stack
user stack
user stack
kernel stack
kernel stack
kernel stack
kernel stack
kernel stack
(context save)
kernel space


user space
user stack
user stack
user stack
user stack
user stack
kernel stack
kernel stack
kernel stack
kernel stack
kernel stack
(context switch)
kernel space


user space
user stack
user stack
user stack
user stack
user stack
kernel stack
kernel stack
kernel stack
kernel stack
kernel stack
kernel space


user space
user stack
user stack
user stack
user stack
user stack
kernel stack
kernel stack
kernel stack
kernel stack
kernel stack
active process
kernel space

Cooperative Multitasking, done!

- aka non-preemptive multitasking
- Only context switch on trap to OS that results in:
  - process termination
  - process blocking
- Can also add “yield” system call to voluntarily cede control

Preemptive Multitasking

- Must guarantee that OS regains control periodically
- Hardware assistance: schedule periodic *clock interrupt* at fixed time intervals (e.g., 1ms)
    - Decide whether to perform context switch after some number of intervals (typically ~100ms)

Decision = *Policy*

- Context switch is merely a mechanism
  - Carried out by low level *dispatcher*
- *When* to carry out context switch is decided by the *scheduler*
  - Scheduling policies/algorithms, coming up!