Mechanisms for entering the system

Yolanda Becerra Fontal
Juan José Costa Prats

Facultat d'Informàtica de Barcelona (FIB)
Universitat Politècnica de Catalunya (UPC)
BarcelonaTech

2024-2025 QP

Content

- Introduction
- Mechanisms for entering the system
  - Initialization
  - Management
  - Example
- Procedure for entering the system
- Procedure to exit from system
- Exceptions
- Interrupts
- System calls
- Summary

Content

- **Introduction**
- Mechanisms for entering the system
  - Initialization
  - Management
  - Example
- Procedure for entering the system
- Procedure to exit from system
- Exceptions
- Interrupts
- System calls
- Summary

Introduction

- OS implements access to machine resources
  - Isolate users from low-level machine-dependent code
  - Group common code for all users: save disk space
  - Implement resource allocation policies
    - Arbitrate the usage of the machine resources in multi-user and multiprogrammed environments
  - Prevent machine and other users from user damage
    - Some instructions can not be executed by user codes: I/O instructions, halt,…

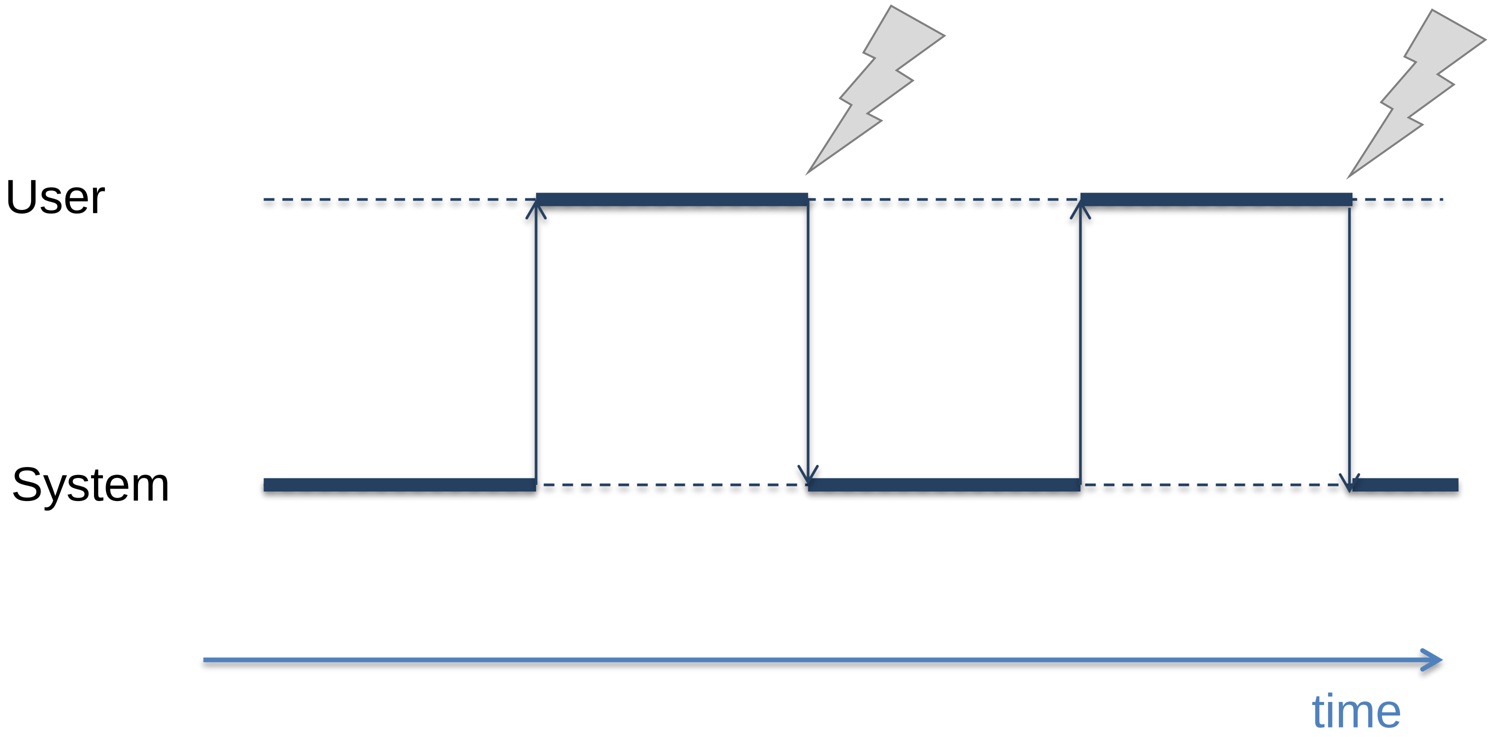
Privilege levels (I)

- Requirement:
  - Prevent users from direct access to resources
    - Ask the OS for services
- Privilege instructions
  - Instructions that only can execute the OS
  - HW support is needed
  - When a privilege instruction is executed, the hw checks if it is executing system code
    - If not → exception
- How to distinguish user code from system code?
  - Privilege levels
    - At least 2 different levels
    - System execution mode vs User execution mode
  - Intel defines 4 different privilege levels.

Privilege levels (II)

- How to scale privileges?
  - Intel offers interrupts
    - Interrupt Driven Operating System
  - When an interrupt/exception happens
    - Hw changes the current privilege level and enables the execution of privilege instructions
  - When the interrupt/exception management ends
    - Hw changes the current privilege level to disable the execution of privilege instructions

Interrupt driven OS



Content

- Introduction
- **Mechanisms for entering the system**
  - Initialization
  - Management
  - Example
- Procedure for entering the system
- Procedure to exit from system
- Exceptions
- Interrupts
- System calls
- Summary

Mechanisms for entering the system

- Exceptions
  - **Synchronous**, produced by the **CPU** control unit after terminating the execution of an instruction
- Interrupts
  - **Asynchronous**, produced by **other hardware devices** at arbitrary times
- System calls
  - **Synchronous**: **assembly instruction** to cause it
    - Trap (in Pentium: INT, sysenter…)
  - Mechanism to request OS services
- All of them are managed through the **interrupts vector**
  - New arquitectures implement a fast system call mechanism that skip the interrupts vector: sysenter instruction

Interrupts Vector

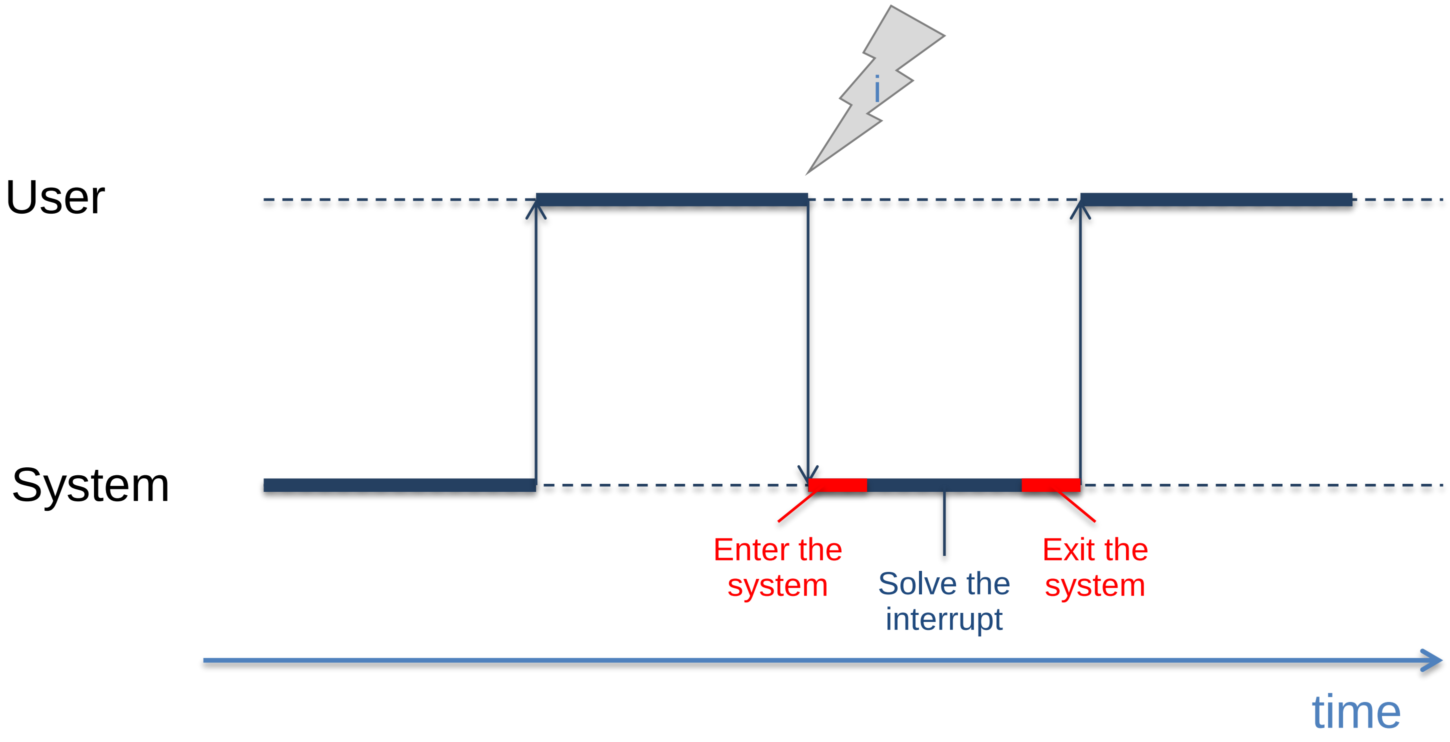
Mechanisms for entering the system

- Pentium
  - IDT: Interrupt Descriptor Table: 256 entries
- Three groups of entries, one for each kind of event:
  - 0 - 31: Exceptions (32)
  - 32 - 47: Masked interrupts (16)
  - 48 - 255: Software interrupts (Traps) (208)

Initialization

- Each entry in the IDT, identifying an interrupt number, has:
  - A code address
    - Entry point to the routine's code to be executed
  - A privilege level
    - The minimum needed to execute the previous code

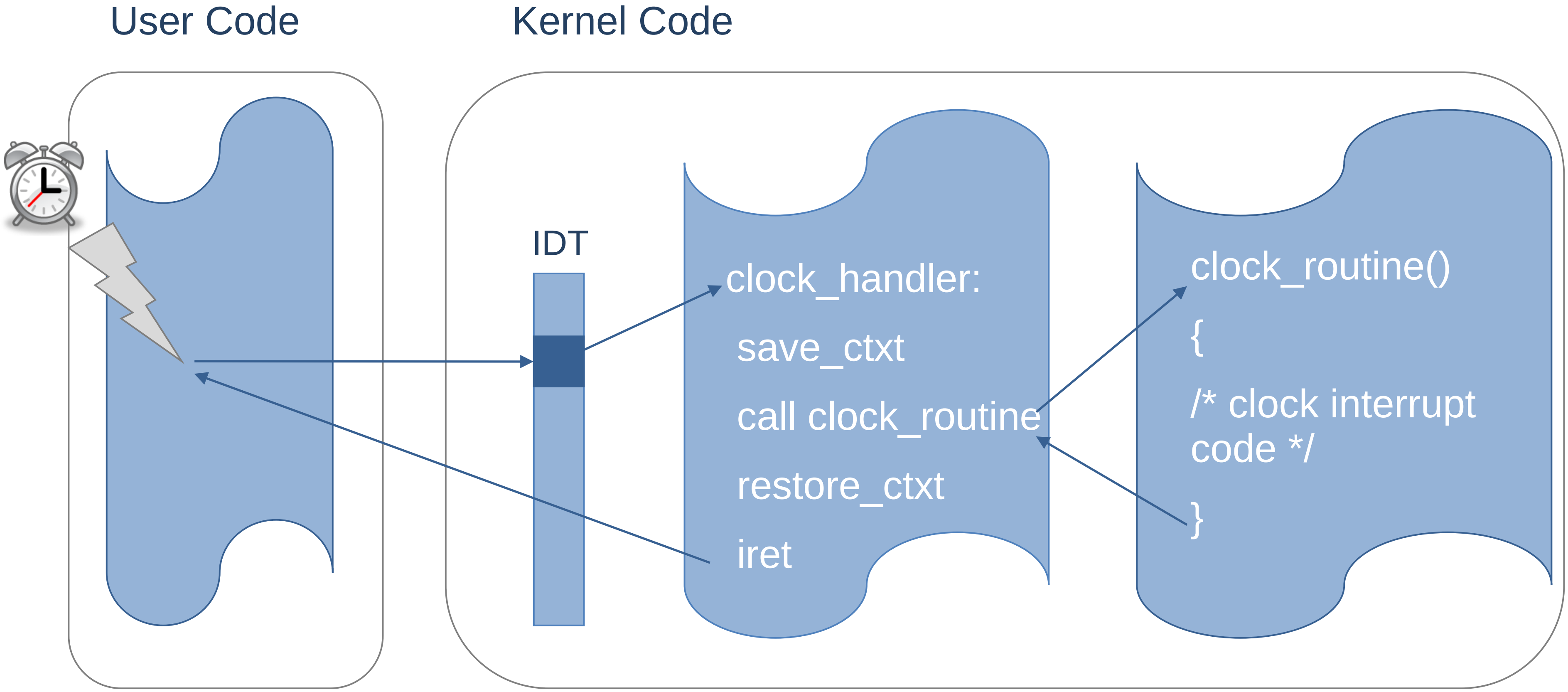
Management code



Management Code

- It could be done in a single routine
  - Divided in two parts: hw context mgmt + solve int.
- Hw context mgmt
  - Entry point handler
  - Basic hardware context management (save & restore)
  - Assembly code
  - Call to a Interrupt Service Routine
- Solve interrupt
  - Interrupt Service Routine
  - High level code (C for example)
  - Specific algorithm for each interrupt

Example: clock interrupt behavior



```
clock_handler:
  save_ctxt
  call clock_routine
  restore_ctxt
  iret
```

```
clock_routine()
{
/* clock interrupt
code */
}
```

Content

- Introduction
- Mechanisms for entering the system
  - Initialization
  - Management
  - Example
- **Procedure for entering the system**
- Procedure to exit from system
- Exceptions
- Interrupts
- System calls
- Summary

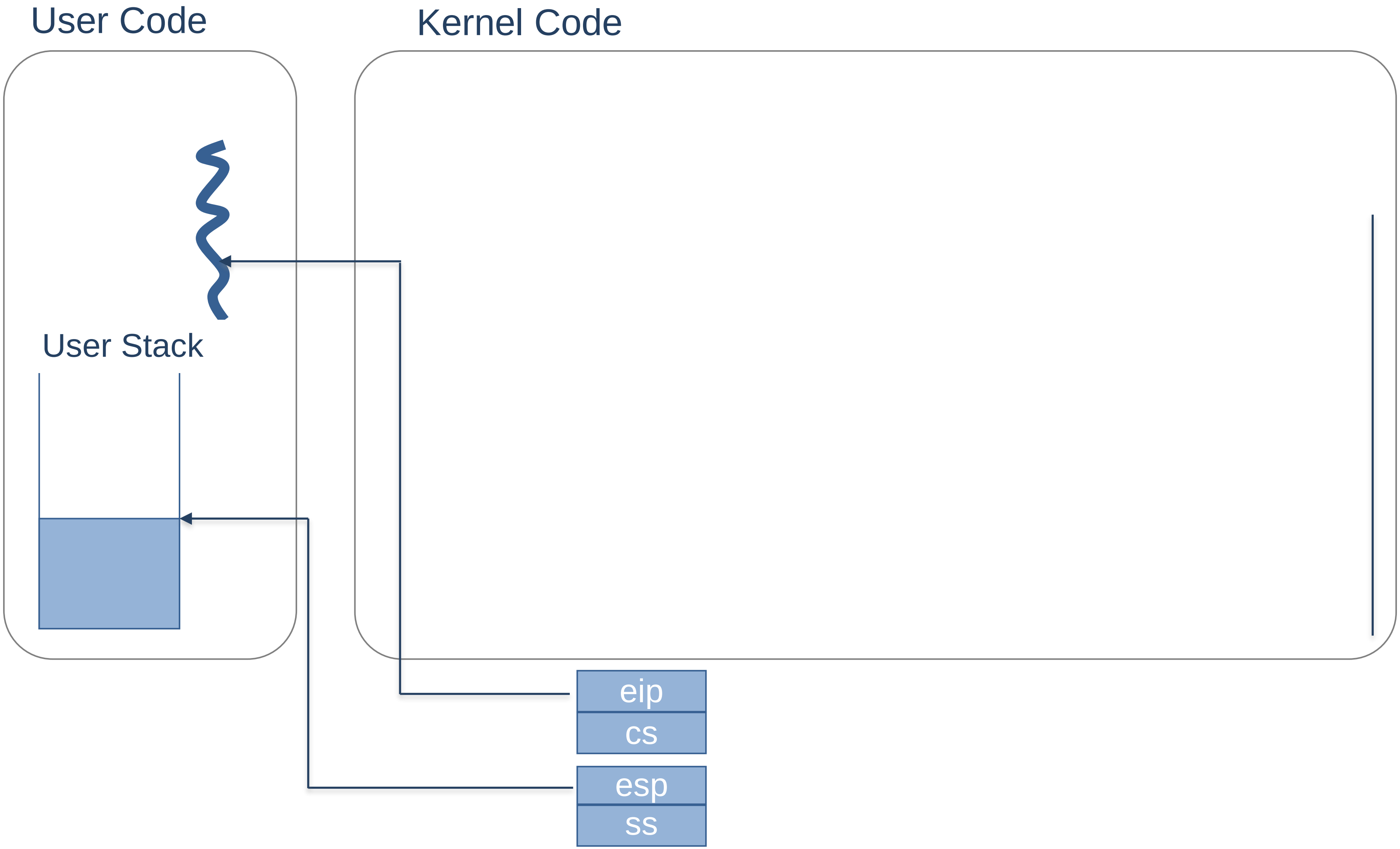
Procedure for entering the system

- Switch to protected execution mode
  - User Mode → Kernel Mode
- Save hardware context: CPU registers
  - ss, esp, psw, cs i eip
  - General purpose registers
- Execute service routine

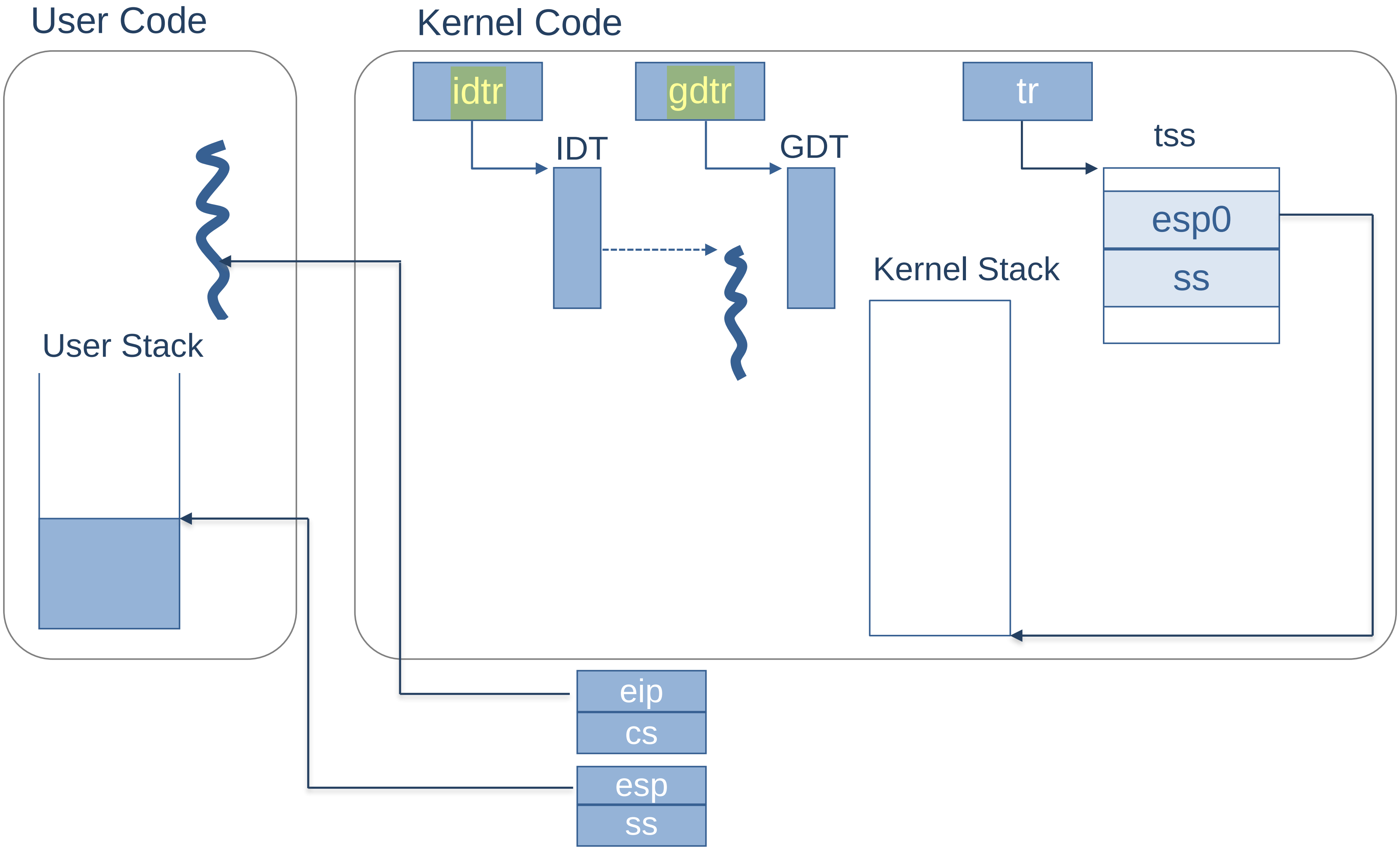
HW

handler

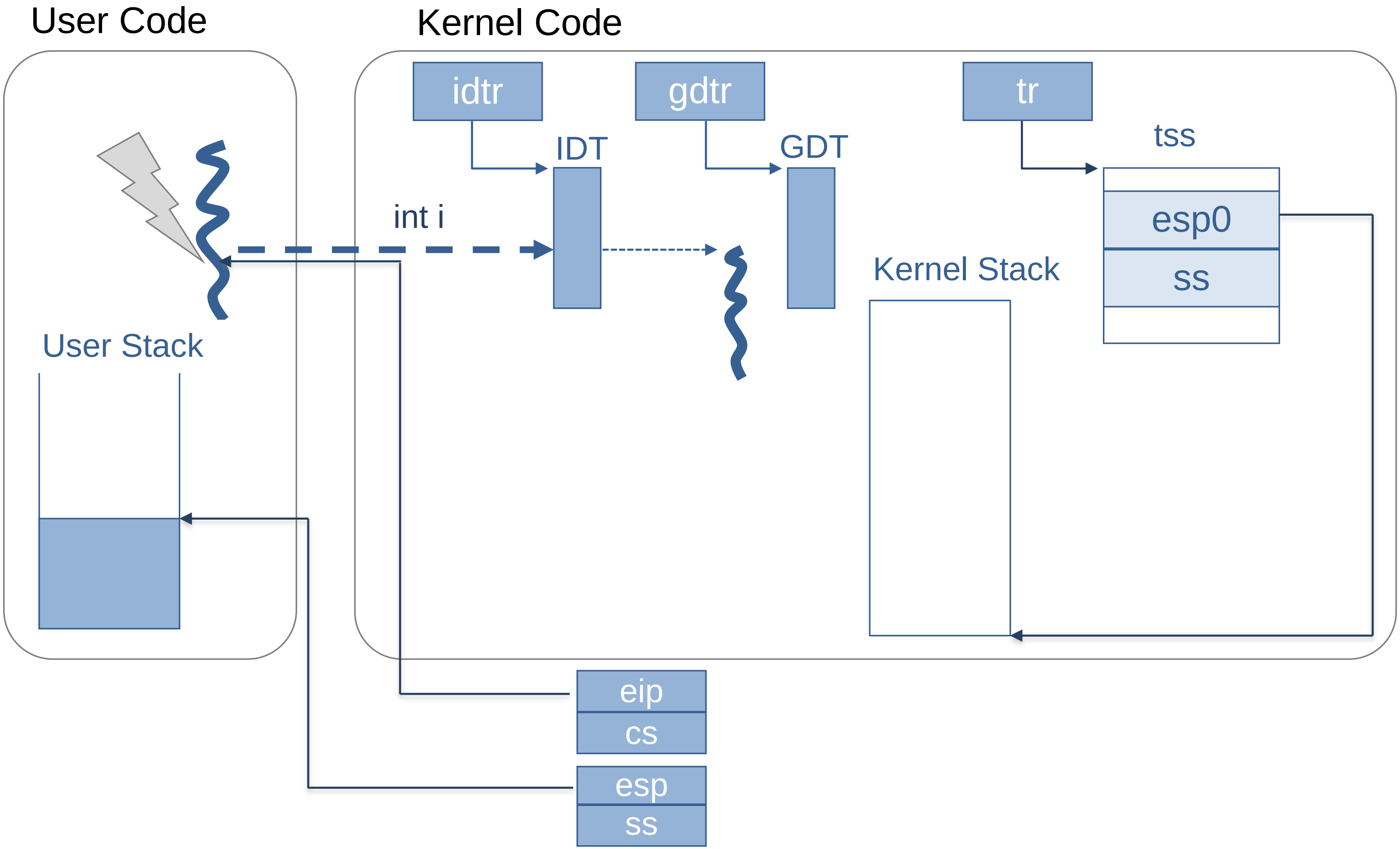
Procedure for entering the system



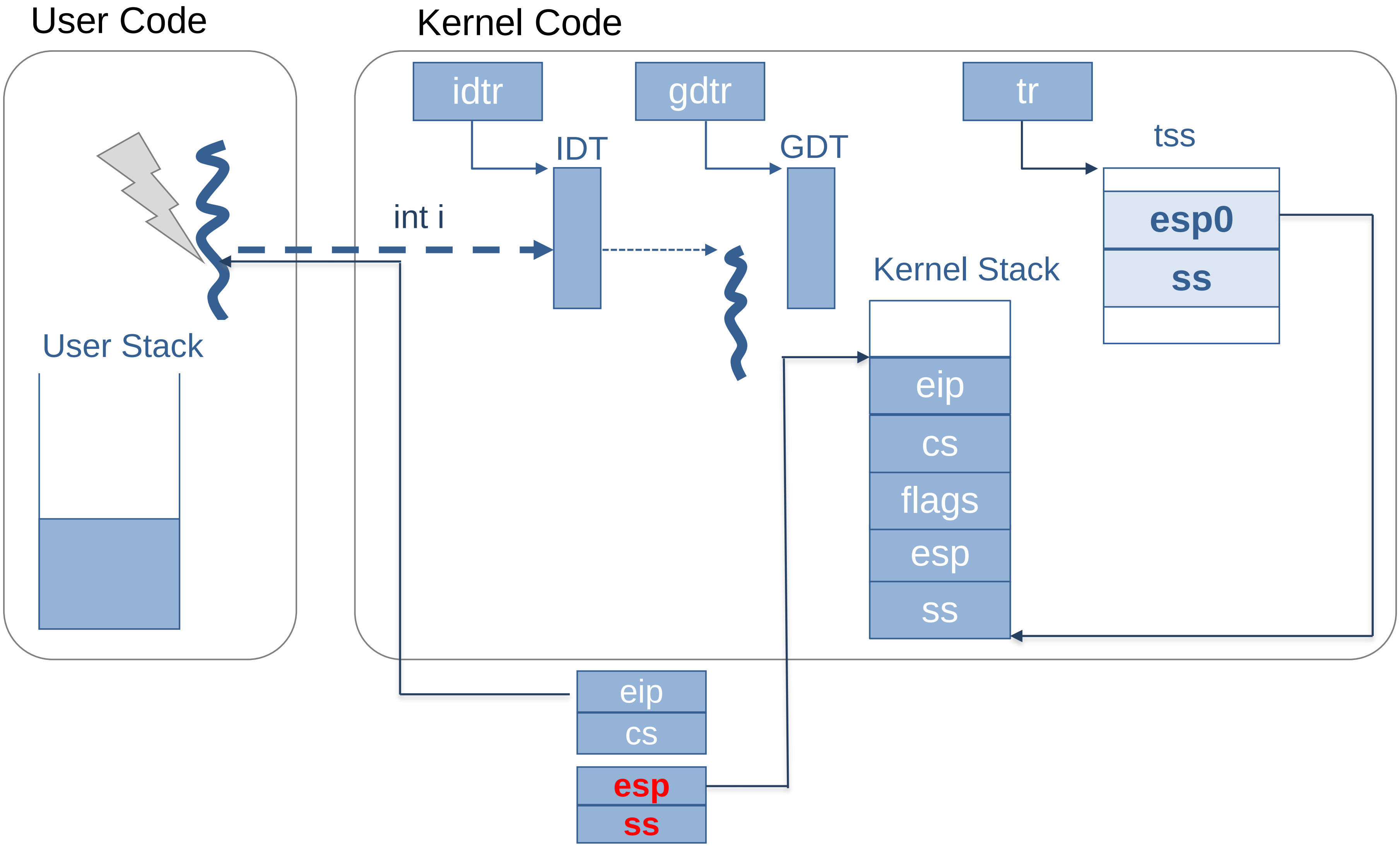
Procedure for entering the system



Procedure for entering the system

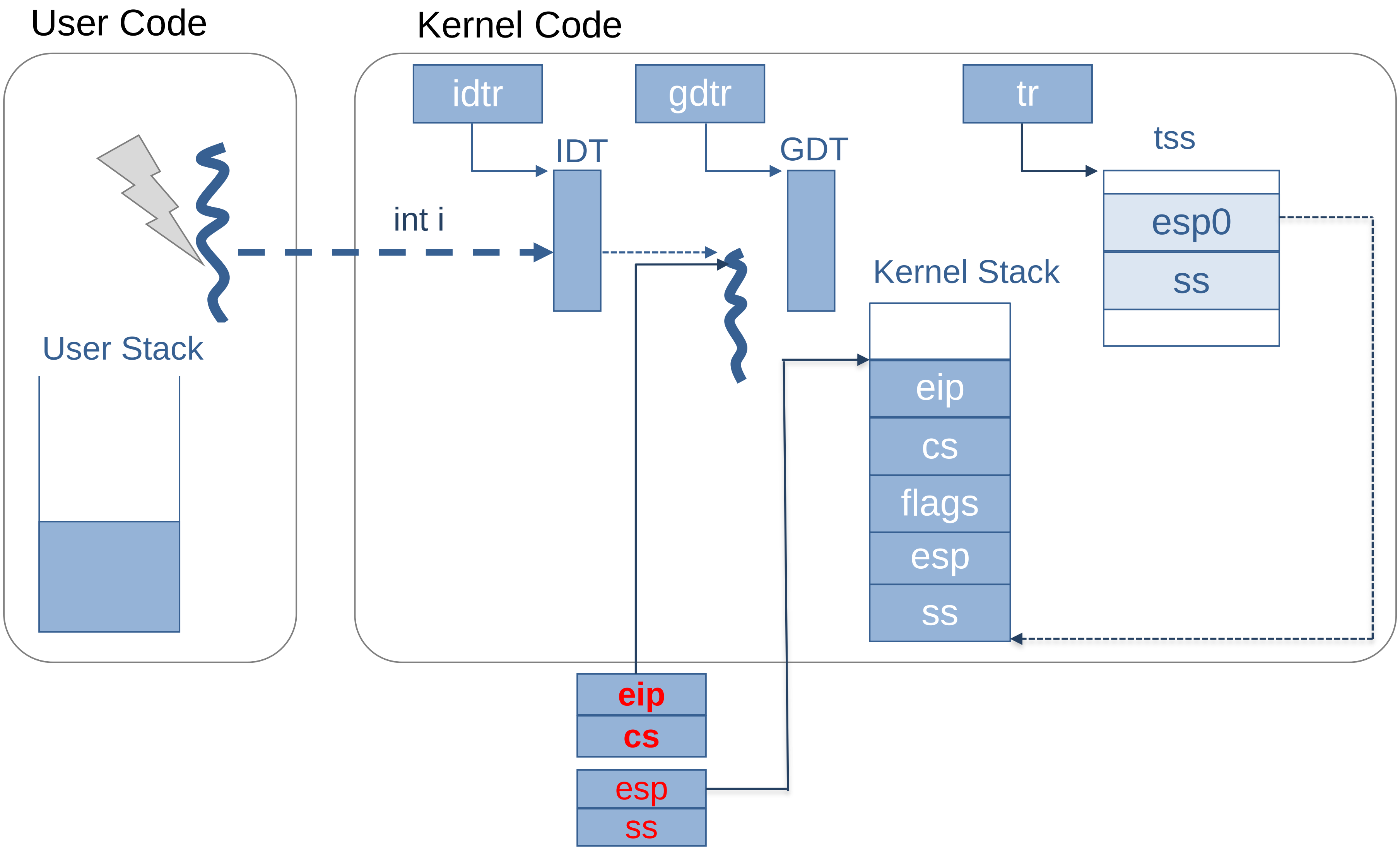


Procedure for entering the system



Procedure for entering the system

Procedure for entering the system



Content

- Introduction
- Mechanisms for entering the system
  - Initialization
  - Management
  - Example
- Procedure for entering the system
- **Procedure to exit from system**
- Exceptions
- Interrupts
- System calls
- Summary

Procedure to exit the system

- Restore HW context
  - General purpose registers
  - ss, esp, flags, cs, eip
- Switch execution mode
  - Kernel mode → User mode

handler

HW (iret instruction)

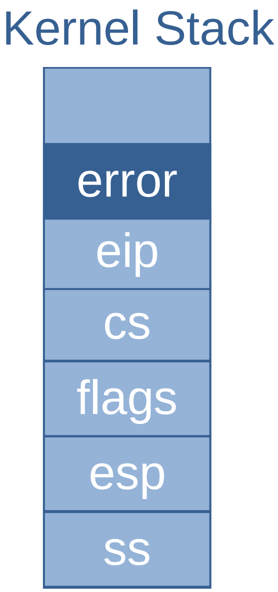
Procedure to exit the system

Content

- Introduction
- Mechanisms for entering the system
  - Initialization
  - Management
  - Example
- Procedure for entering the system
- Procedure to exit from system
- **Exceptions**
- Interrupts
- System calls
- Summary

Exceptions: Stack layout

- There are some exceptions that push a parameter of 4 bytes (a hardware error code) to the kernel stack after entering the system:



Exception: IDT

# IDT	Exception	Error Code
0	Divide Error	
1	Debug Exception	
2	NMI Interrupt	
3	Breakpoint	
4	Overflow	
5	BOUND Range Exceeded	
6	Invalid Opcode (Undefined Opcode)	
7	Device Not Available (No Math Coprocessor)	
8	Double Fault	✓
9	Coprocessor Segment Overrun (reserved)	
10	Invalid TSS	✓
11	Segment Not Present	✓
12	Stack-Segment Fault	✓
13	General Protection	✓
14	Page Fault	✓
15	*(Intel reserved. Do not use.)*	
16	x87 FPU Floating-Point Error (Math Fault)	
17	Alignment Check	✓
18	Machine Check	
19	SIMD Floating-Point Exception	
20	Virtualization Exception	
21-31	(Intel reserved. Do not use.)	

Exception´s handler

- Save hardware context
- Call exception service routine
- Restore hardware context
- Remove error code (if present) from kernel stack
- Return to user (iret)

Content

- Introduction
- Mechanisms for entering the system
  - Initialization
  - Management
  - Example
- Procedure for entering the system
- Procedure to exit from system
- Exceptions
- **Interrupts**
- System calls
- Summary

Interrupt´s handler

- Similar to exception, but:
  - No hardware error code in kernel stack
  - It is necessary to notify the interrupt controller when the interrupt management finishes
    - Meaning that a new interrupt can be processed
    - End Of Interrupt (EOI)

Content

- Introduction
- Mechanisms for entering the system
  - Initialization
  - Management
  - Example
- Procedure for entering the system
- Procedure to exit from system
- Exceptions
- Interrupts
- **System calls**
- Summary

Handling system calls

- Why cannot be invoked like a regular user function?
- Which is the mechanism to identify the system call?
- How to pass parameters to the kernel?
- How to get results from the kernel?

System calls: invocation and identification

- Assembly instruction that causes a software generated interrupt
  - **int** assembly instruction (*int idt_entry*)
  - Alternative: **sysenter** assembly instruction: fast system call mechanism
- An entry point per syscalls?
  - Limitation for the potential number of syscalls
- A single entry point is used for all system calls
  - int
    - 0x80 for Linux
    - 0x2e for Windows
  - sysenter
    - system call handler @ is kept on a control register: SYSENTER_EIP_MSR
- And an extra parameter (EAX) to identify the requested service
- A table is used to translate the user service request to a kernel function to execute

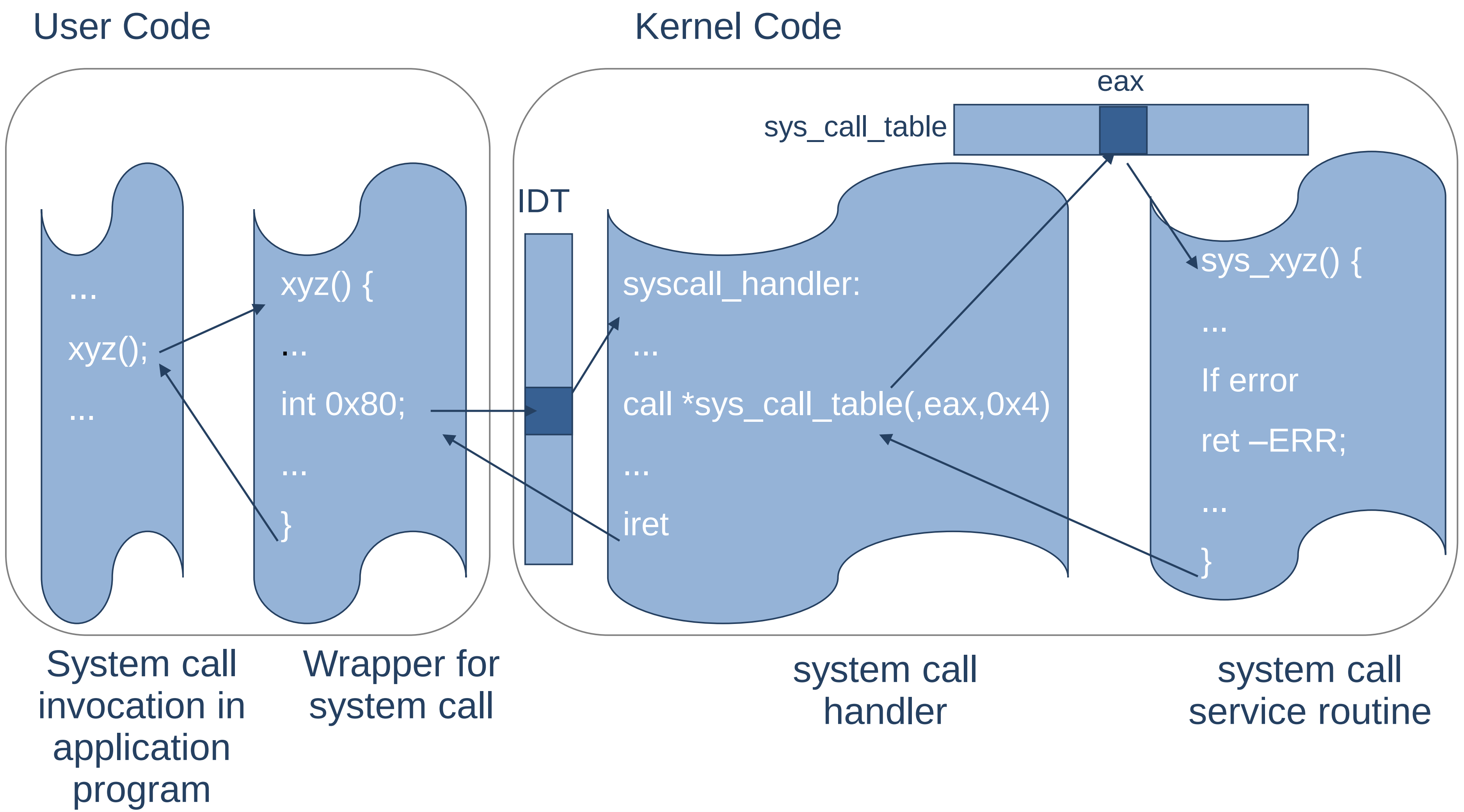
System calls: parameters and results

- Parameter passing: Stack is NOT shared
  - Linux: syscall handler expects parameters in the registers
    - (first parameter) ebx, ecx, edx, esi, edi, ebp
    - Copy parameters from user stack
  - Windows: Use a register to pass a pointer to parameters
    - EBX
- Returning results:
  - EAX register: contains error code

System call wrappers

- System must provide the users with an easy and portable way to use them
  - New layer: wrappers
    - wrap all the gory details in a simple function call
- Wrapper responsibilities
  - Invoke the system call handler
    - Responsible for parameter passing
    - Identify the system call requested
    - Generate the trap
  - Return the result to the user code
    - Use errno variable to codify type of error and returns -1 to users

System call mechanism overview



System calls

Fast System calls: sysenter/sysexit

- Avoid interrupt mechanism
- Avoid privilege check → Always user to sys
- 3 control registers initialized at boot time
  - SYSENTER_CS_MSR: contains kernel cs selector
  - SYSENTER_EIP_MSR: contains kernel entry point
  - SYSENTER_ESP_MSR: points to the TSS base @
    - NOT USED AS STACK!
    - used to load ESP with the TSS´s field esp0
    - avoid modifications in the task_switch code

modifications to wrapper

- vsyscall_page
  - Shared page: linked with system library
  - elf code:
    - defines kernel_vsyscall function
      - if sysenter is not available: int 0x80 + ret
      - else

```
pushl %ecx
pushl %edx
pushl %ebp
movl %esp, %ebp
sysenter
....
```

    - defines SYSENTER_RETURN

```
popl %ebp
popl %edx
popl %ecx
ret
```

sysenter

- change to system mode
- loads cs ←SYSENTER_CS_MSR
- loads eip ← SYSENTER_EIP_MSR
- loads esp ← SYSENTER_ESP_MSR
- loads ss ← CS + 8
  - – Stack segment must be defined at this position
    - (not a problem)

kernel entry point

- Trick: Change to real stack
  - At entry point ESP contains TSS base address
  - Load ESP ← TSS.esp0
- Configure kernel stack like the interrupt mechanism

```
pushl USER_DS
pushl %ebp
pushfl
pushl USER_CS
pushl $SYSENTER_RETURN
….
```

- And the rest as before (SAVE_ALL, check eax…)

exit

- after RESTORE_ALL
  - EDX ← EIP user (it is in the stack)
  - ECX ← ESP user (it is in the stack)
  - sysexit
    - change mode
    - change stack
    - returns to user code (vsyscall_page: SYSENTER_RETURN)

System call handler

- Save hardware context and prepare parameters for the service routine
  - Linux: stores registers with system call parameters at the top of the kernel stack
  - Windows: copy parameters from the address stored in ebx to the top of the kernel stack
- Execute system call service routine
  - Error checking: system calls identifiers
  - Using system_call_table
- Update kernel context with the system call result
- Restore hardware context
- Return to user

System calls service routines

- Check parameters
  - User code is NOT reliable
    - System MUST validate ALL data provided by users
- Access the process address space (if needed)
- Specific system call code algorithm

Content

- Introduction
- Mechanisms for entering the system
  - Initialization
  - Management
  - Example
- Procedure for entering the system
- Procedure to exit from system
- Exceptions
- Interrupts
- System calls
- **Summary**

Interrupt Handling Summary

- Save user context
- Restore system context
- Retrieve user parameters [if needed]
- Identify service [if needed]
- Execute service
- Return result [if needed]
- Restore user context

Summary

References

- [1] Understanding Linux Kernel 3rd ed. Chapter 4 Interrupts and Exceptions.
- [2] Understanding Linux Kernel 3rd ed. Chapter 9 System Calls.
- [3] Intel® 64 and IA-32 architectures software developer's manual volume 3: System programming guide. Chapter 6.
- [4] Intel® 64 and IA-32 architectures software developer's manual volume volume 2: Instruction set reference. sysenter, sysexit