Interrupts

ECE 469, Feb 11

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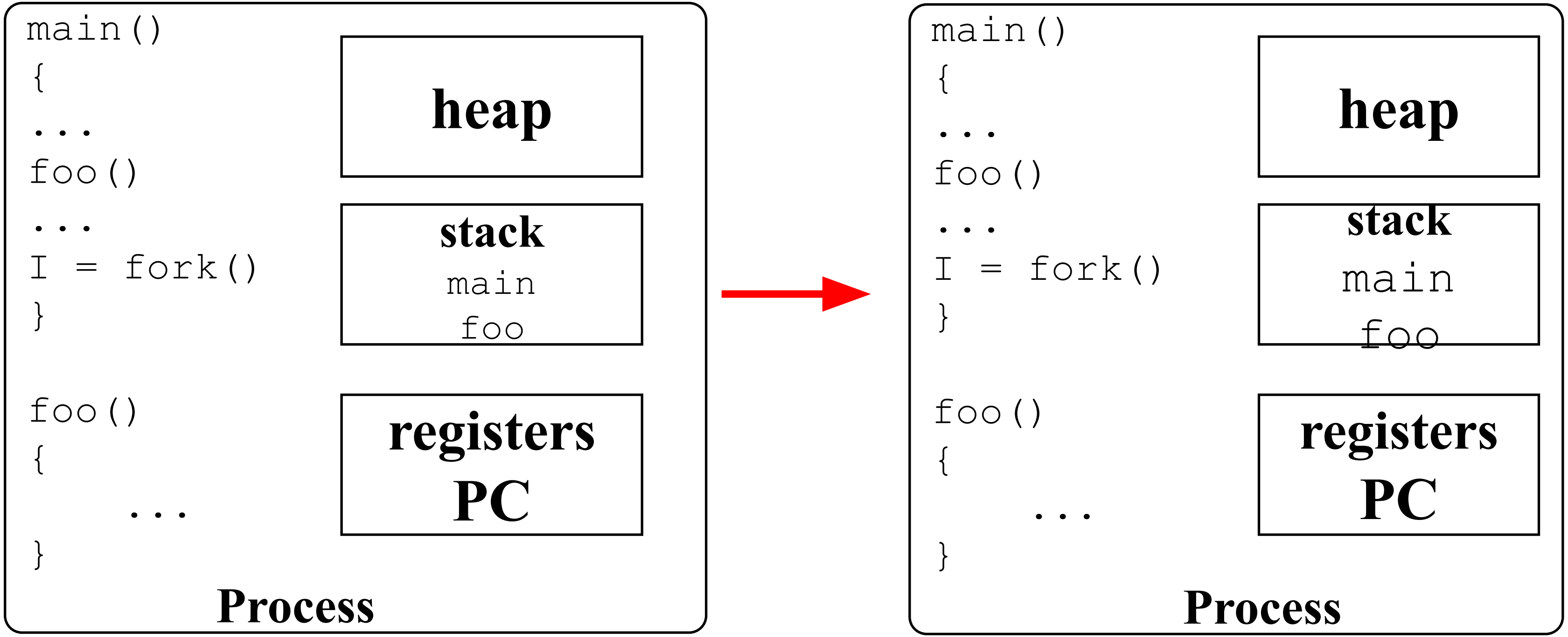
Recap: OS Process API

- 4 system calls related to process creation/termination:
  - Process Creation:
    - fork/clone – create a copy of this process
    - exec – replace this process with this program
  - Wait for completion:
    - wait – wait for child process to finish
  - Terminate a process:
    - kill - send a signal (to terminate) a process

Recap: fork

fork causes OS creates a copy of the calling process:

- Why?
- How can we disambiguate between new process and the calling process?



```
main()
{
...
foo()
...
I = fork()
}

foo()
{
    ...
}
```

```
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{
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foo()
...
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foo()
{
    ...
}
```
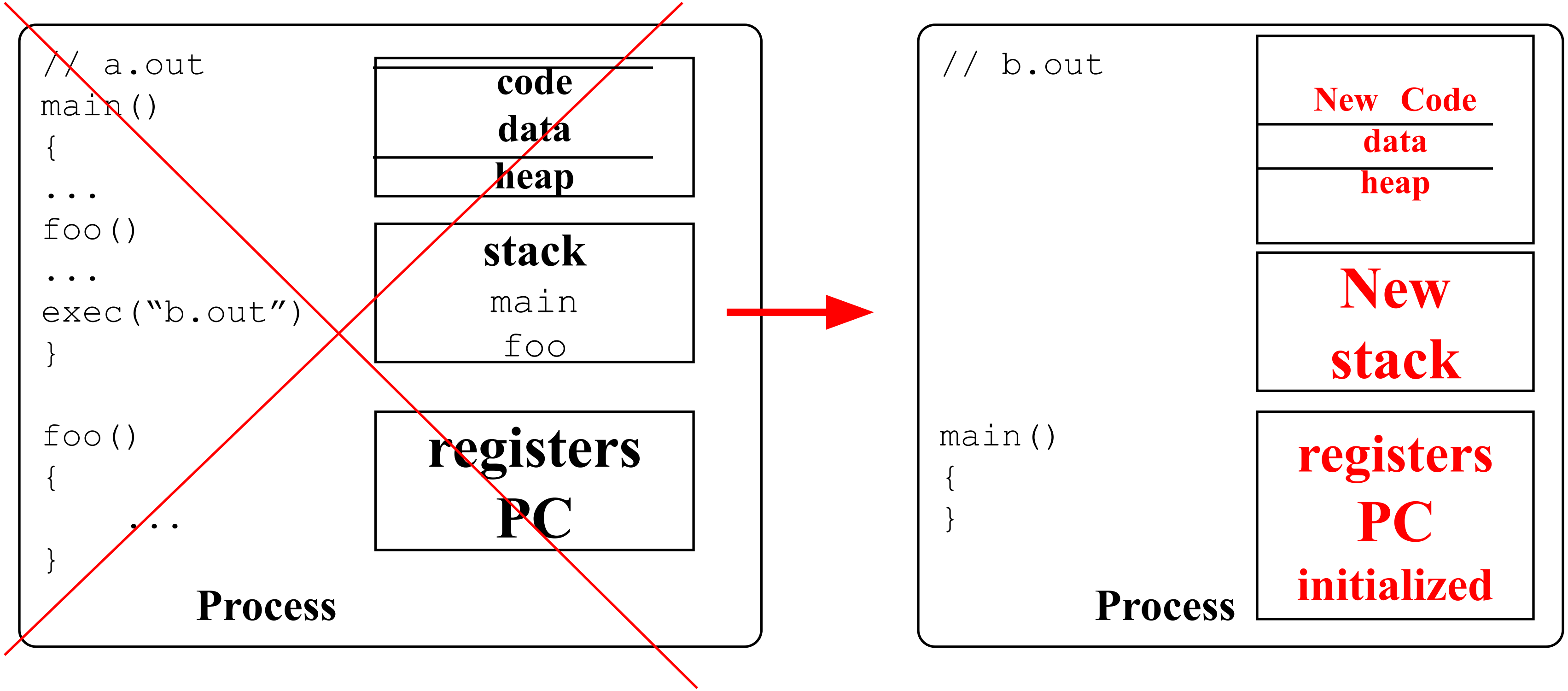

Recap: exec

Replaces current process with the content from new program.



```
// a.out
main()
{
...
foo()
...
exec(“b.out”)
}

foo()
{
      ...
}
```

code

data

heap

stack

main

foo

registers

PC

Process

```
// b.out




main()
{
}
```

New Code

data

heap

New stack

registers

PC

initialized

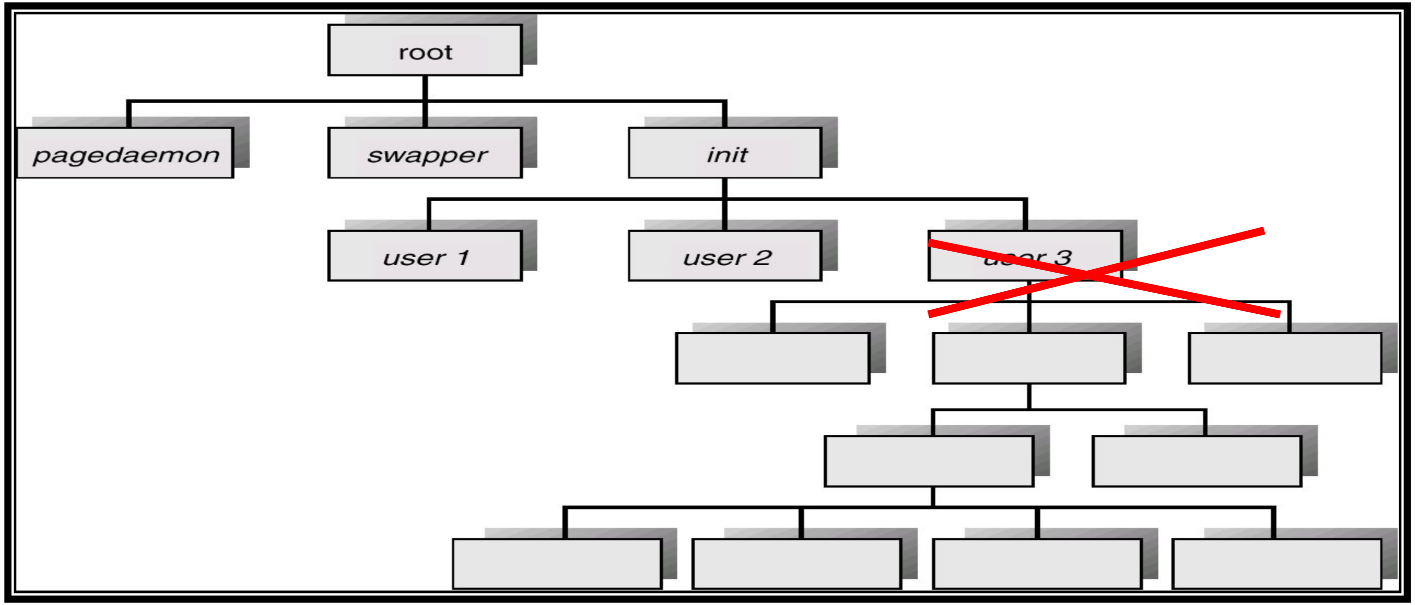
Process

Recap: wait

wait for a child process to finish

Recap: wait

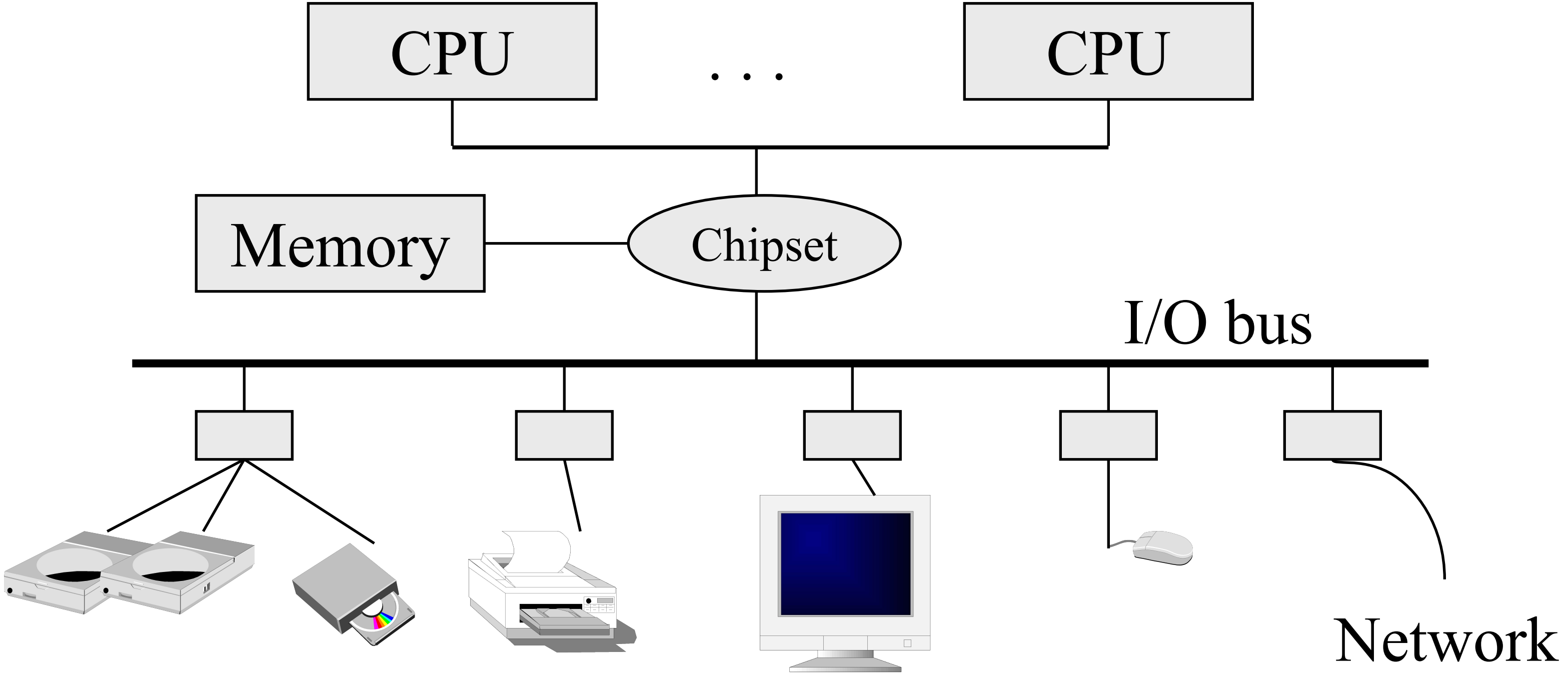
What happens when the parent process dies? what happens to child process?



Recap: How our shell works?

- Fork/exec

Handling Hardware / unexpected events



How to handle I/O from peripherals?

- Assume mail delivery
- Poll:
  - Checking for events at regular intervals
    - Checking mailbox daily
- Interrupt
  - Get explicitly notified
    - Secretary notifying you
- Which one is better?
  - Simple (inefficient) v/s Complex (efficient)

Interrupts

- Hardware Interrupts

- Software Interrupts

Hardware Interrupts

- A way of hardware interacting with CPU

- Example: a network device
  - NIC: “Hey, CPU, I have a packet received 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 Interrupts / exceptions

- A software mean to run code in ring 0 (e.g., int $0x30)
  - Telling CPU that ”Please run the interrupt handler at 0x30”

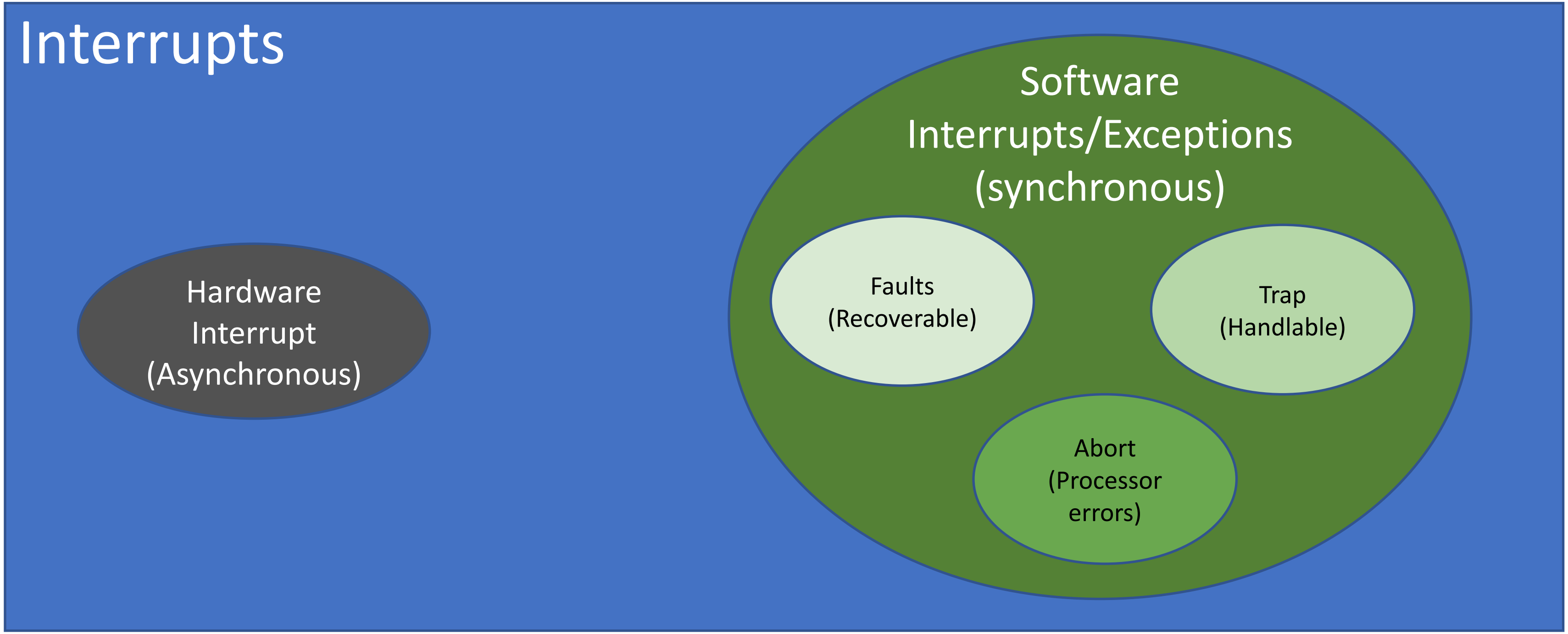
- Synchronous (caused by running an instruction, e.g., int $0x30)

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

Types of exceptions

- Classification based on how they are handled:
  - Fault
    - Exception occurred but can be fixed
    - IP points to the current instruction
  - Trap
    - Exception occurred but the program could continue execution
    - IP points to next instruction
  - Abort
    - Unhandlable exception
    - Hardware failures in processor

Interrupts classification


Interrupts
Hardware Interrupt (Asynchronous)
Software Interrupts/Exceptions (synchronous)
Faults (Recoverable)
Trap (Handlable)
Abort (Processor errors)

Handling Interrupts

- Interrupts are numbered

- We need to define “what to do” (i.e., code to run) when an interrupt with corresponding number occurs

Handling Interrupts

- Setting 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

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Load the base address into IDTR

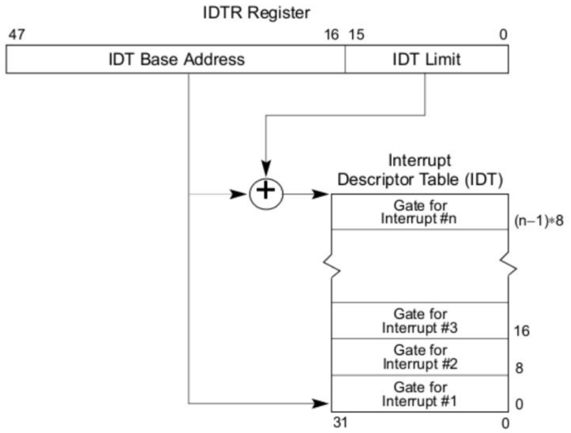

Figure 6-1. Relationship of the IDTR and IDT

Handling Interrupts

- Setting an Interrupt Descriptor Table (IDT)

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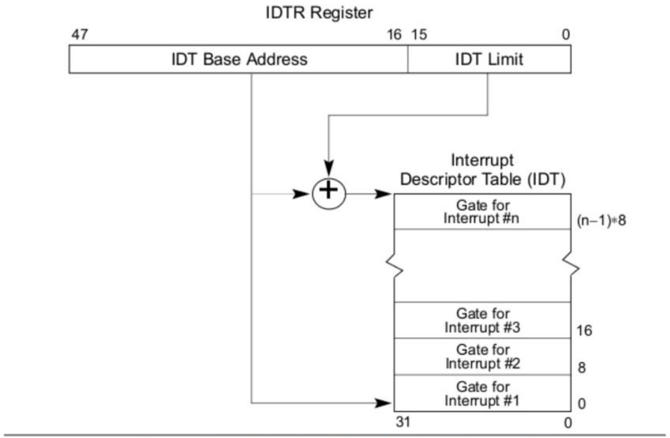

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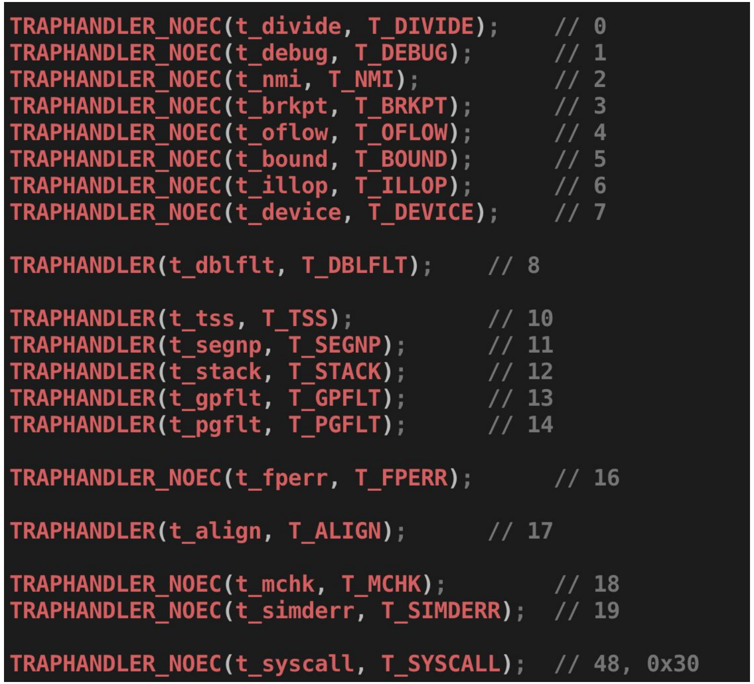

```
TRAPHANDLER_NOEC(t_divide, T_DIVIDE);     // 0
TRAPHANDLER_NOEC(t_debug, T_DEBUG);       // 1
TRAPHANDLER_NOEC(t_nmi, T_NMI);           // 2
TRAPHANDLER_NOEC(t_brkpt, T_BRKPT);       // 3
TRAPHANDLER_NOEC(t_oflow, T_OFLOW);       // 4
TRAPHANDLER_NOEC(t_bound, T_BOUND);       // 5
TRAPHANDLER_NOEC(t_illop, T_ILLOP);       // 6
TRAPHANDLER_NOEC(t_device, T_DEVICE);     // 7

TRAPHANDLER(t_dblflt, T_DBLFLT);     // 8

TRAPHANDLER(t_tss, T_TSS);           // 10
TRAPHANDLER(t_segnp, T_SEGNP);       // 11
TRAPHANDLER(t_stack, T_STACK);       // 12
TRAPHANDLER(t_gpflt, T_GPFLT);       // 13
TRAPHANDLER(t_pgflt, T_PGFLT);       // 14

TRAPHANDLER_NOEC(t_fperr, T_FPERR);       // 16

TRAPHANDLER(t_align, T_ALIGN);       // 17

TRAPHANDLER_NOEC(t_mchk, T_MCHK);         // 18
TRAPHANDLER_NOEC(t_simderr, T_SIMDERR);   // 19

TRAPHANDLER_NOEC(t_syscall, T_SYSCALL);   // 48, 0x30
```

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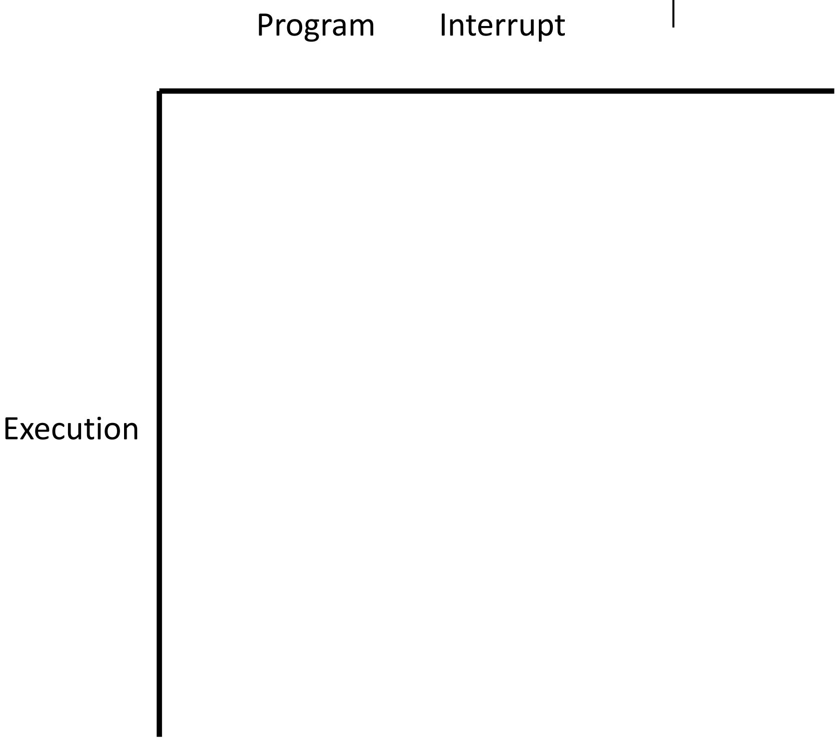

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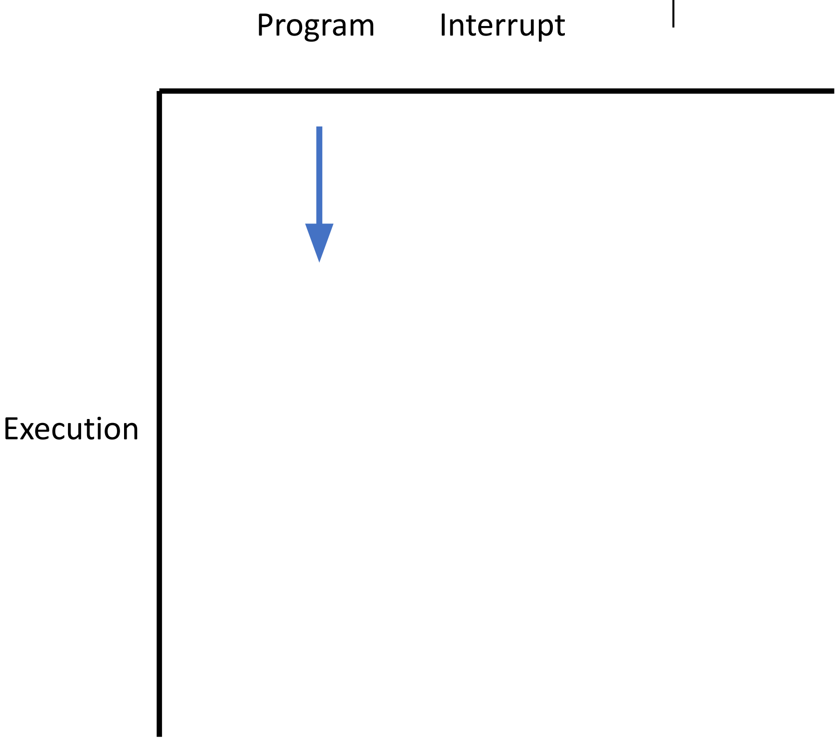

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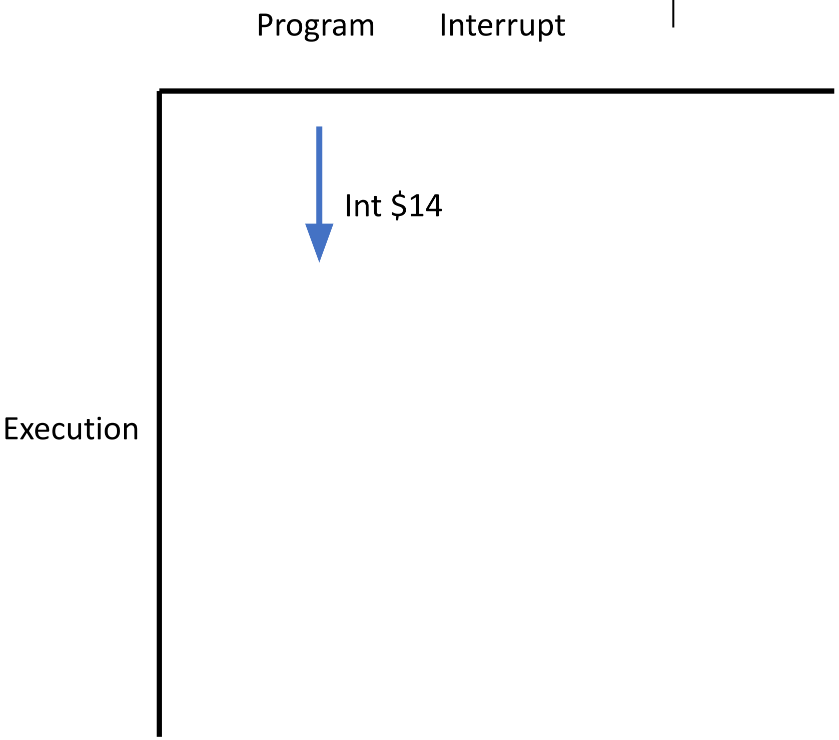

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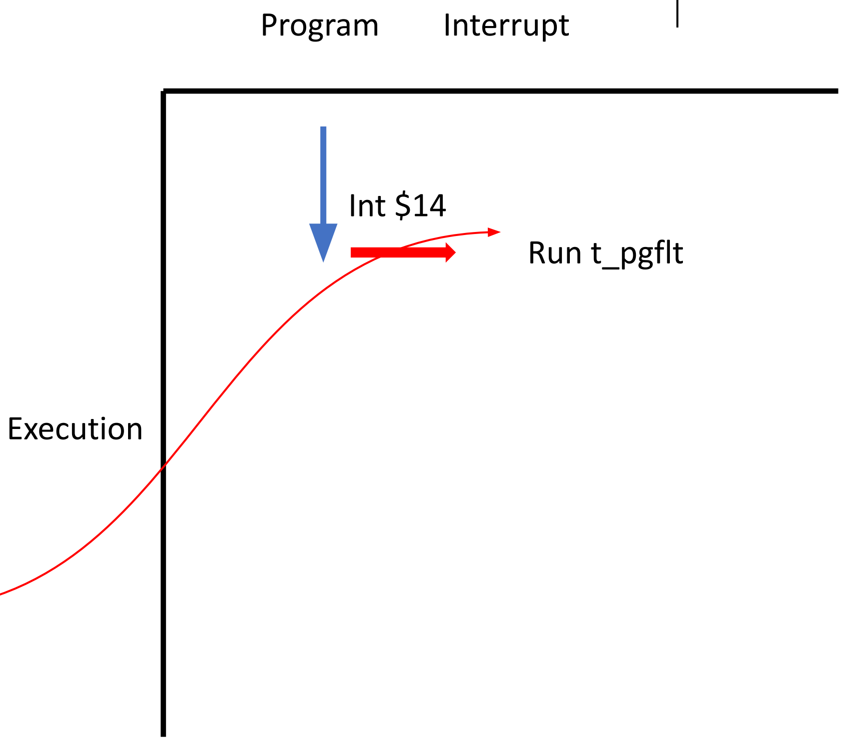

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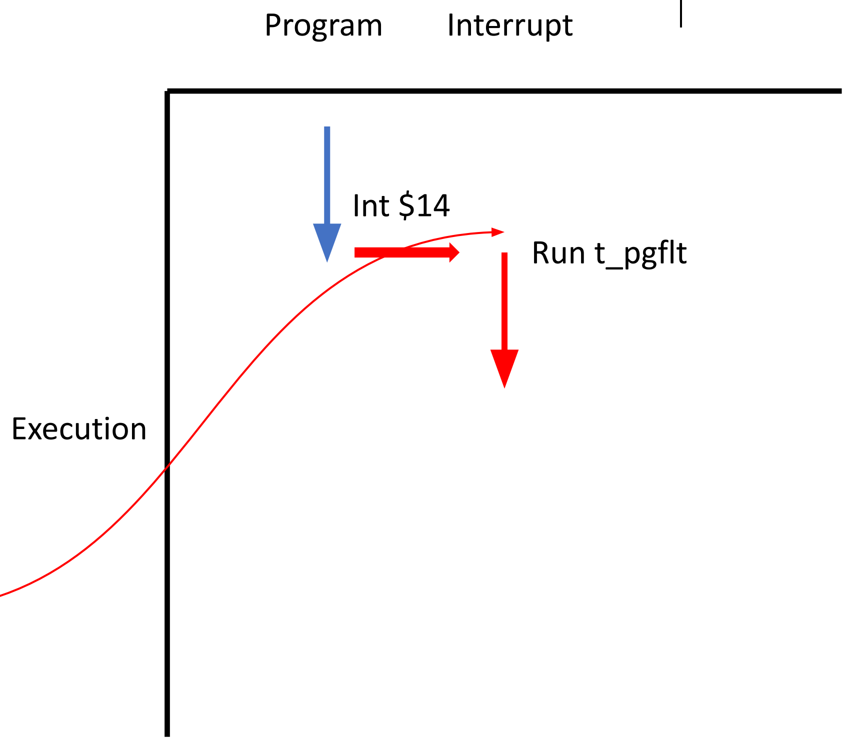
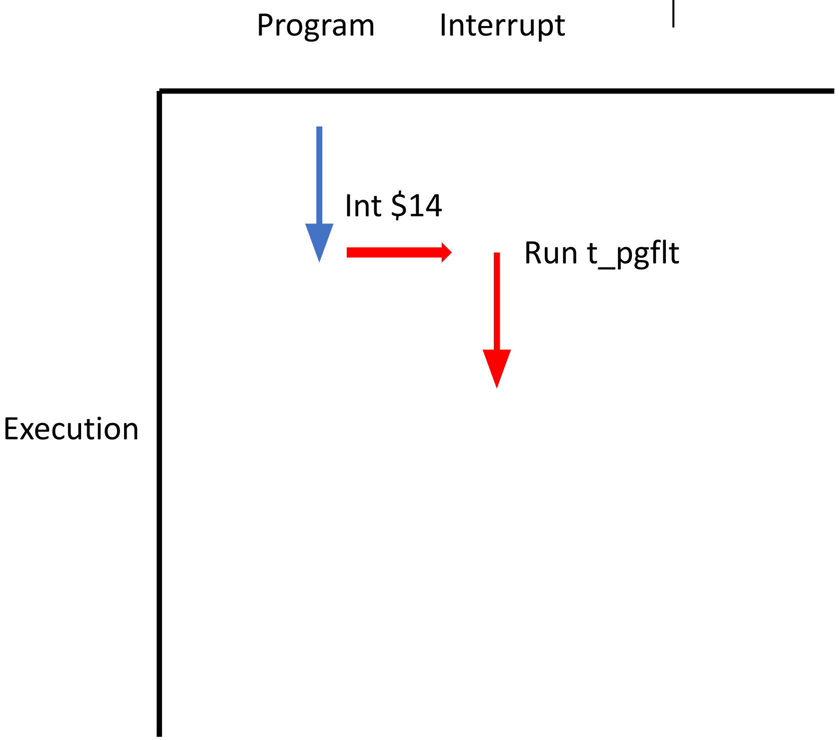


Simultaneous Interrupts

- What if another interrupt happens
  - During processing an interrupt?



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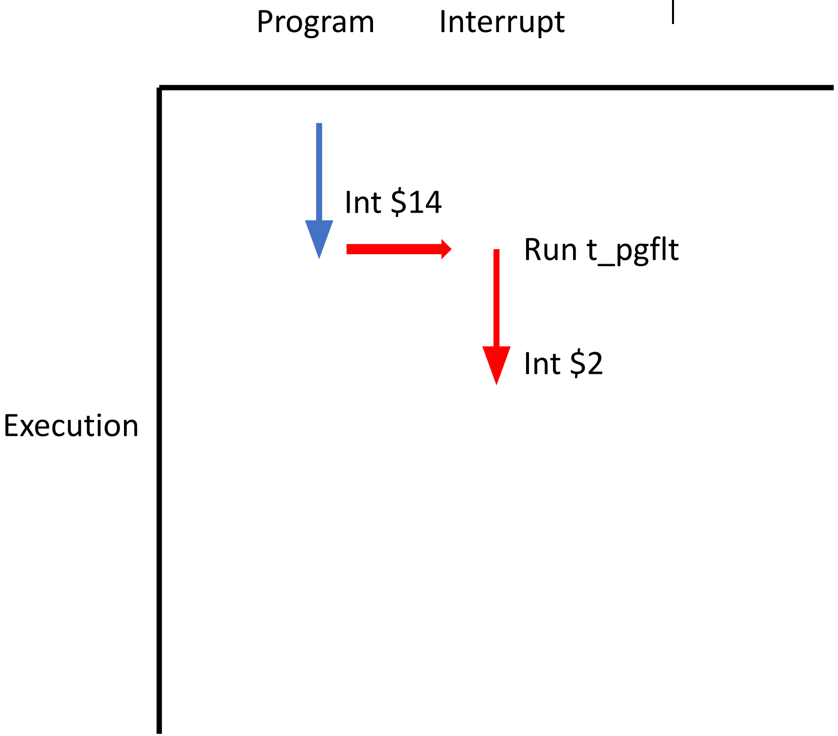

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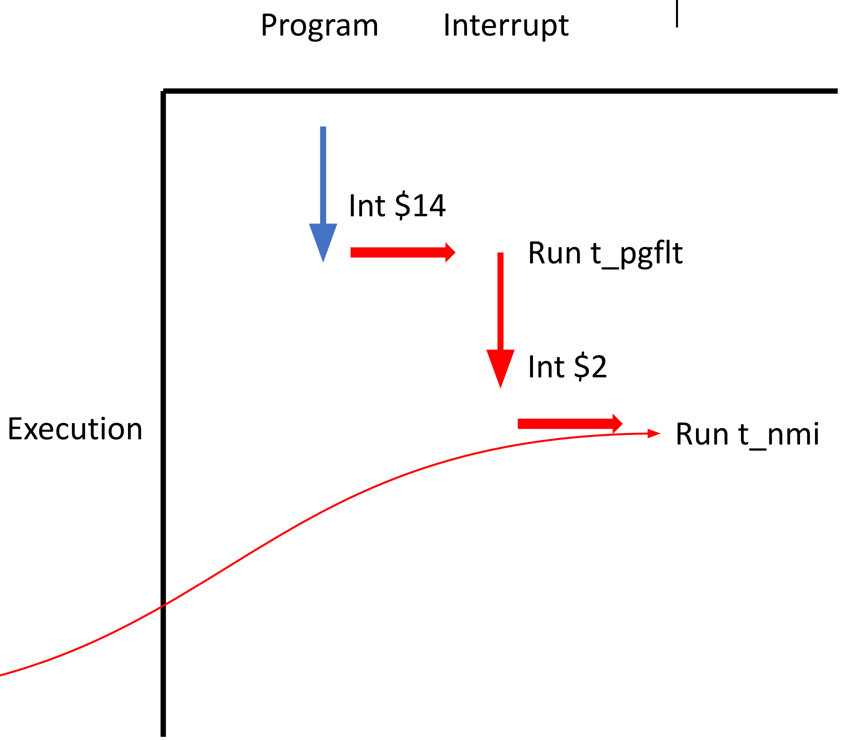

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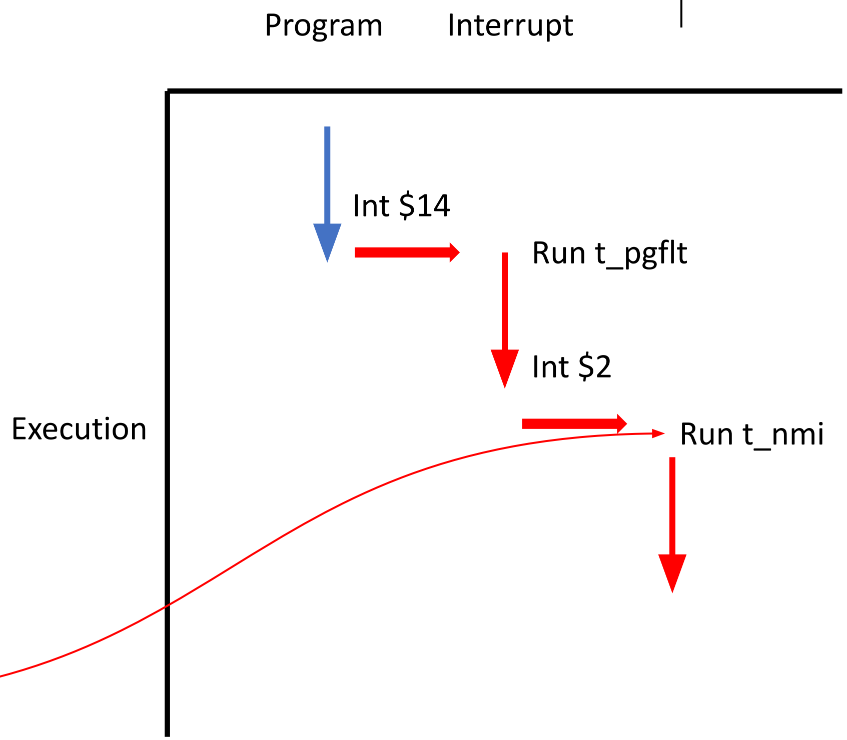

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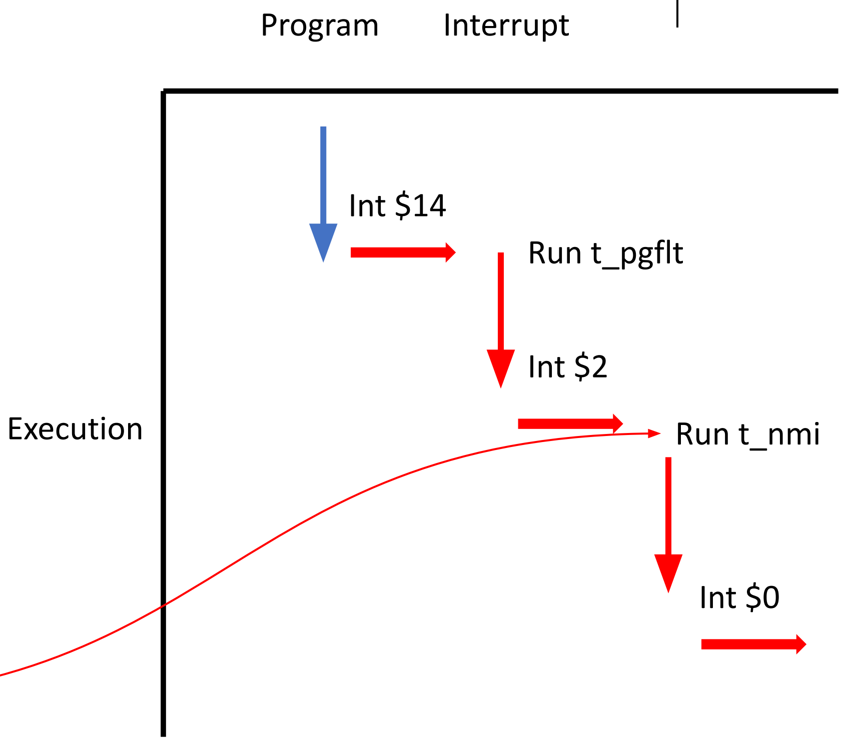

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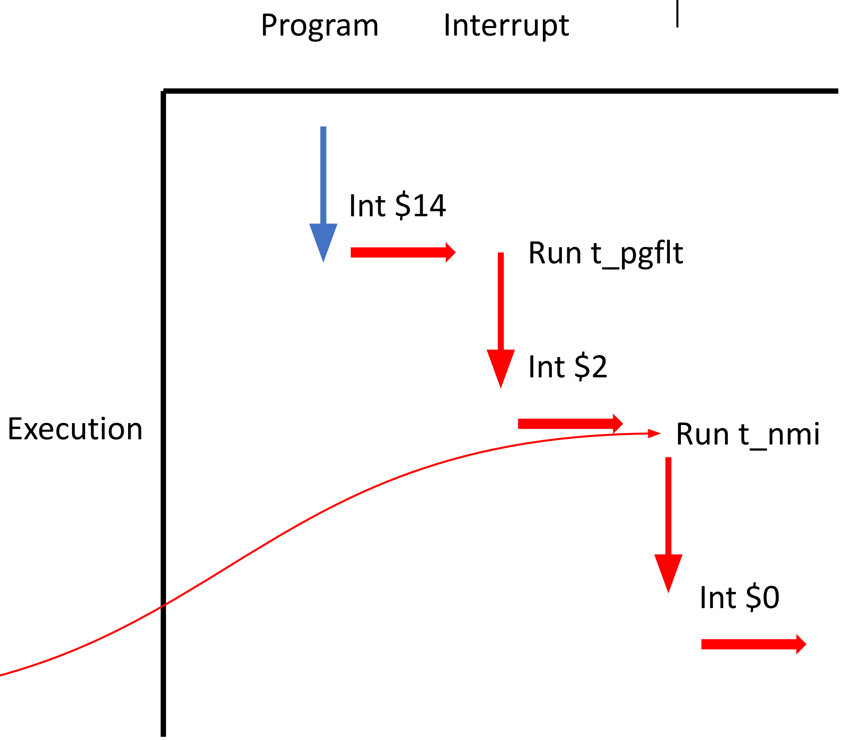
Simultaneous Interrupts

- What if another interrupt happens
  - During processing an interrupt?

- Handle interrupts indefinitely…
  - Cannot continue the program execution
  - Even cannot finish an interrupt handler…



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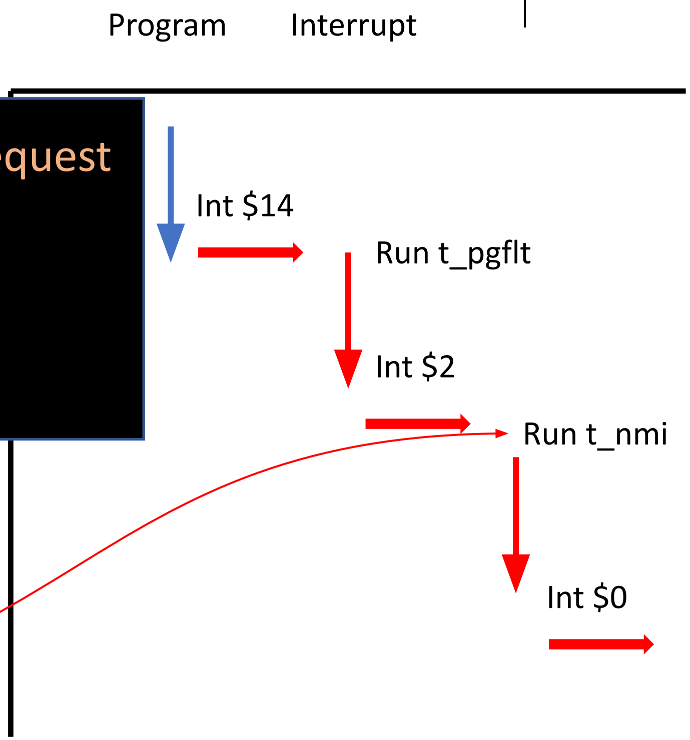
Simultaneous Interrupts

- What if another interrupt happens
  - During processing an interrupt?

Interrupt request coming during handling an interrupt request could make our interrupt handling never finish!

To avoid such an ‘infinite’ interrupt,
We disable interrupt while handling interrupt…



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Controlling Interrupts

- Enabled/disabled by OS

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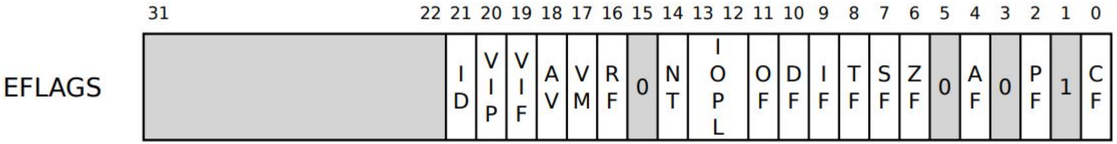

Status flags

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PF	Parity flag
AF	Auxiliary carry flag
ZF	Zero flag
SF	Sign flag
OF	Overflow flag

Control flags

DF	Direction flag

System flags

TF	Trap flag
IF	Interrupt enable flag
IOPL	I/O privilege level
NT	Nested task

RF	Resume flag
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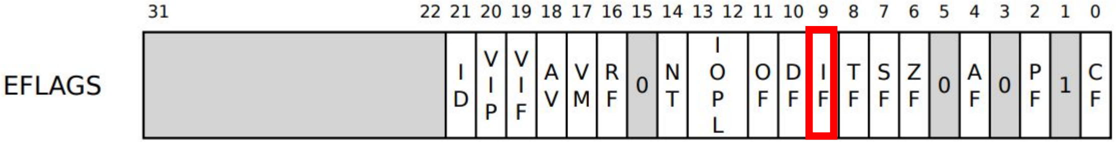

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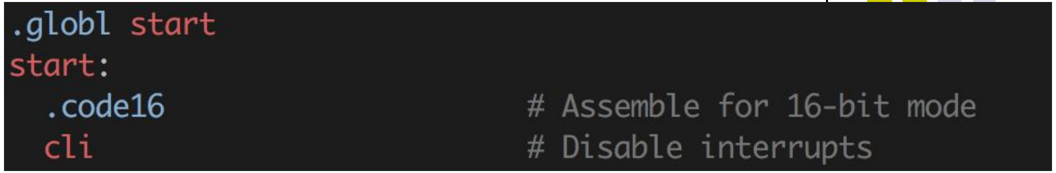

```
.globl start
start:
  .code16                         # Assemble for 16-bit mode
  cli                             # Disable interrupts
```

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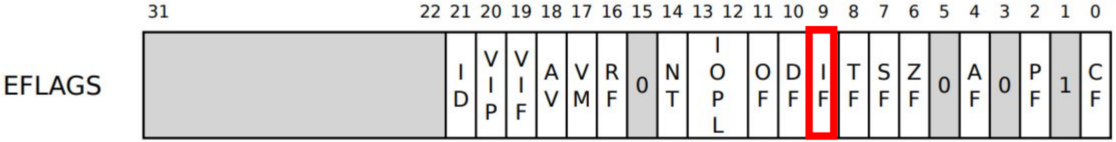

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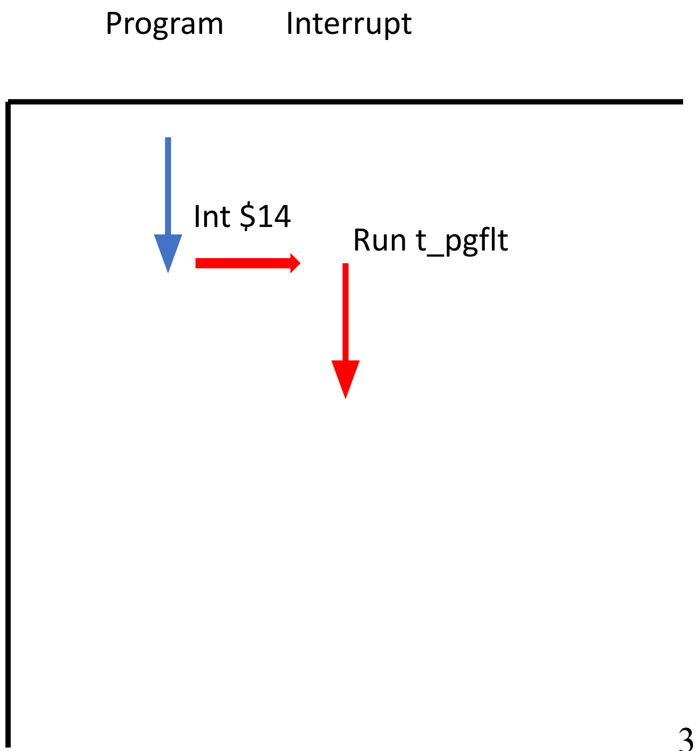
Executing interrupt handlers

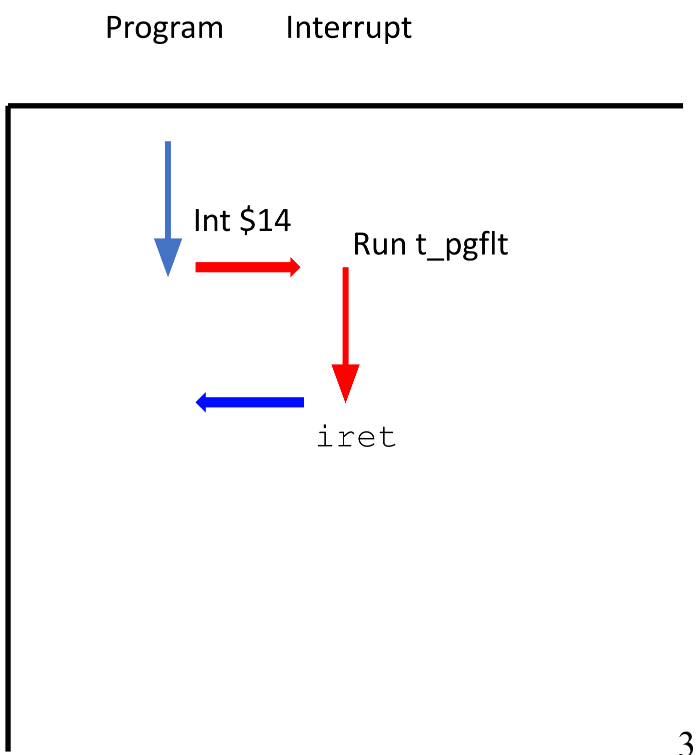
- We would like to handle the interrupt/exceptions at the kernel



Executing interrupt handlers

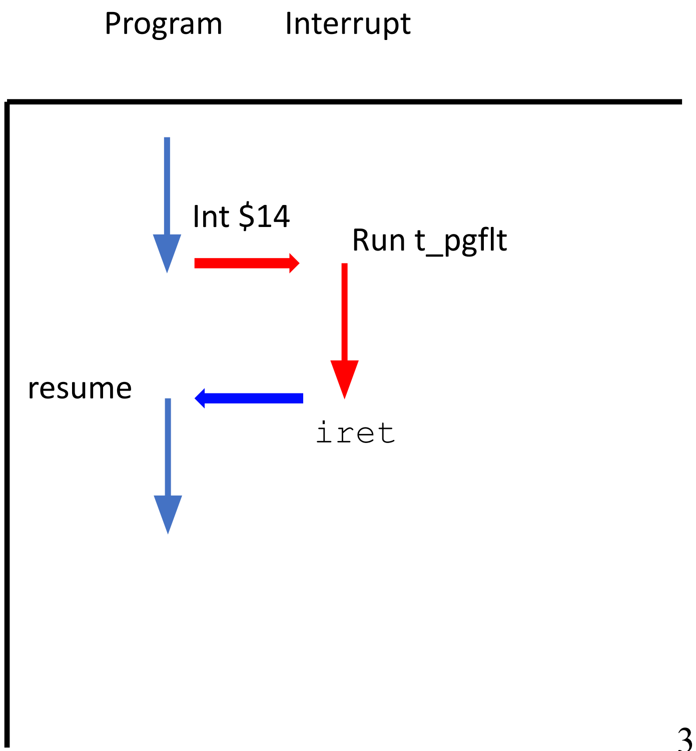
- We would like to handle the interrupt/exceptions at the kernel

- After handing that, we would like to go back to the previous execution

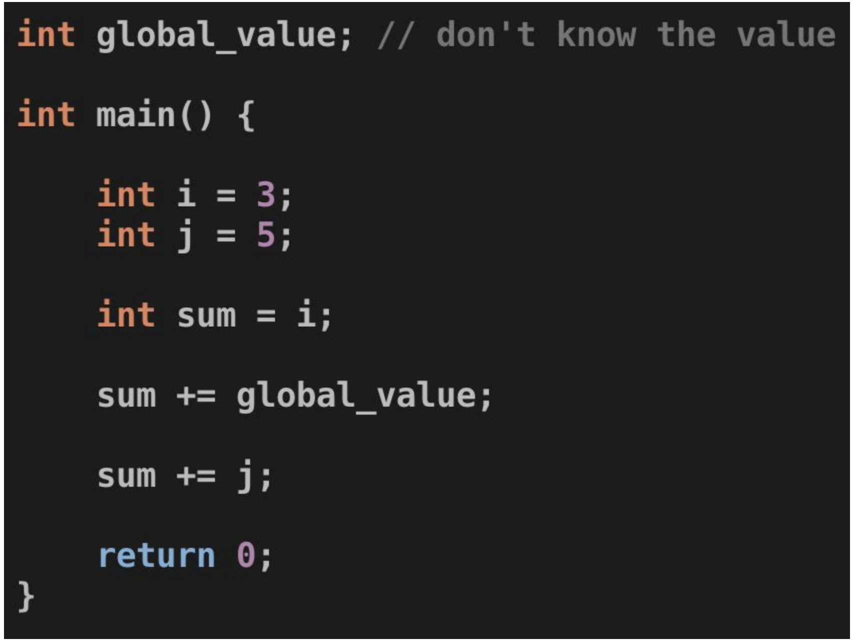


Executing interrupt handlers

- We would like to handle the interrupt/exceptions at the kernel
- After handing that, we would like to go back to the previous execution
- How?
  - Store an execution context



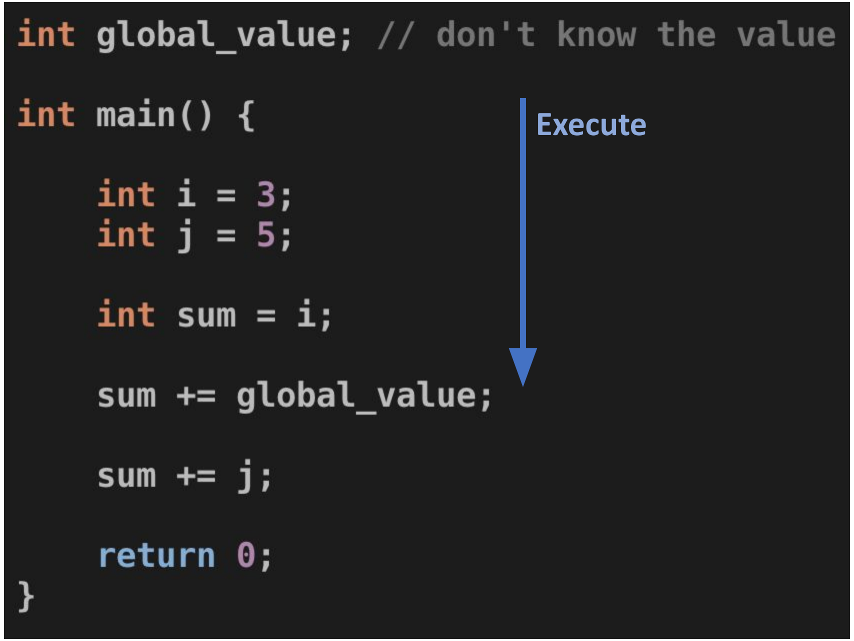
Execution Context



```
int global_value; // don't know the value

int main() {

    int i = 3;
    int j = 5;

    int sum = i;

    sum += global_value;

    sum += j;

    return 0;
}
```

Program Interrupt

Execution Context



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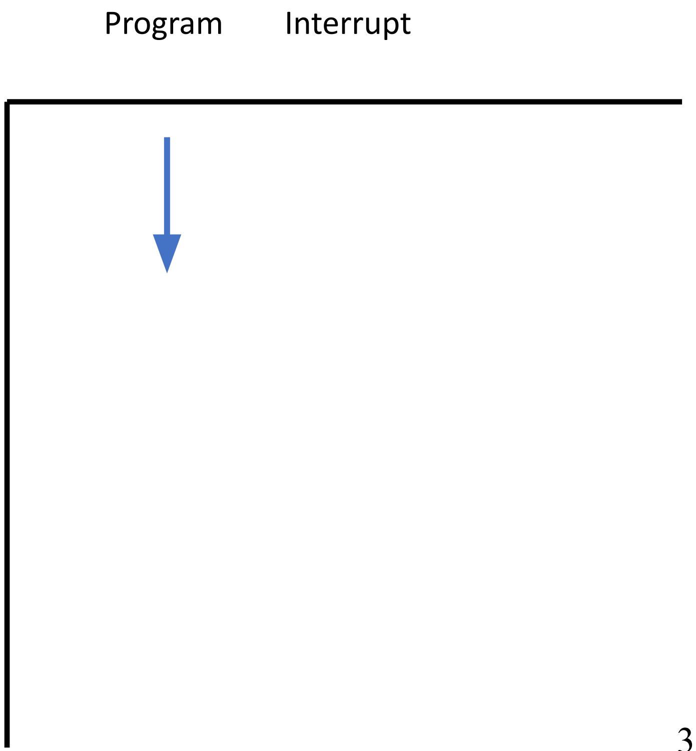
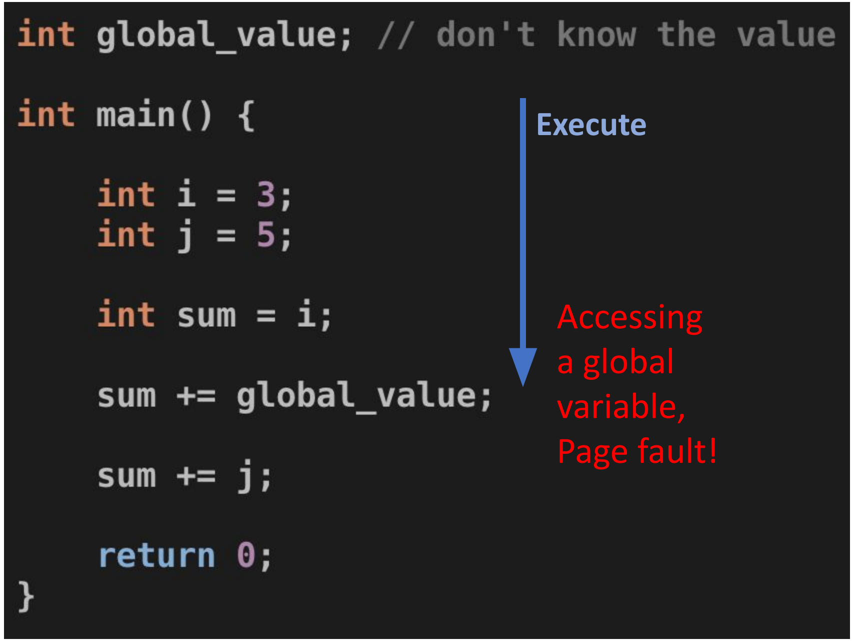


Program

Interrupt

Execution Context



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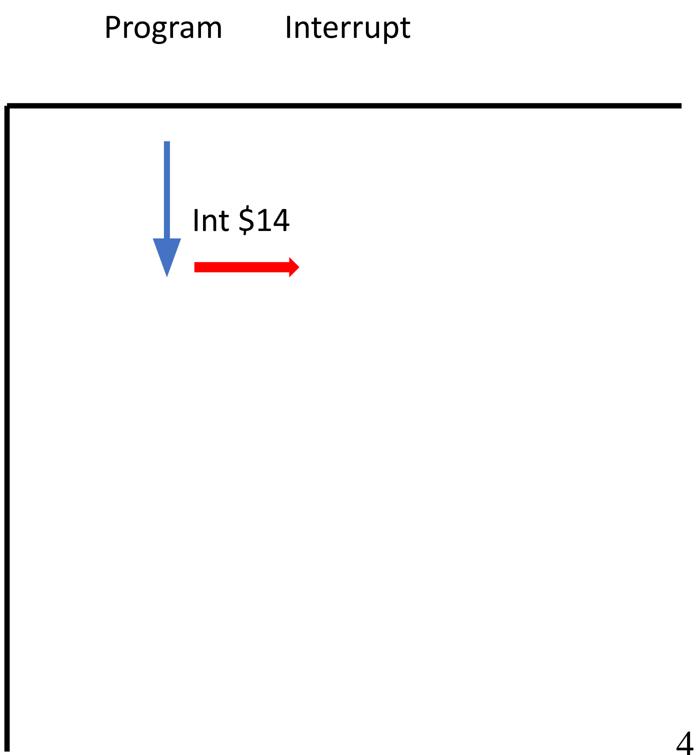
Execute

Accessing a global variable, Page fault!

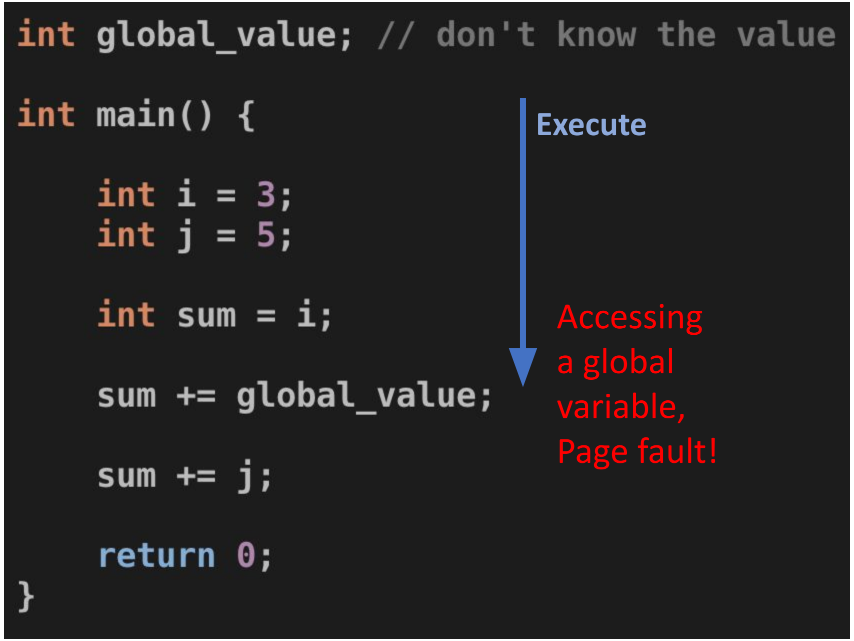


Program

Interrupt

Int $14

Execution Context



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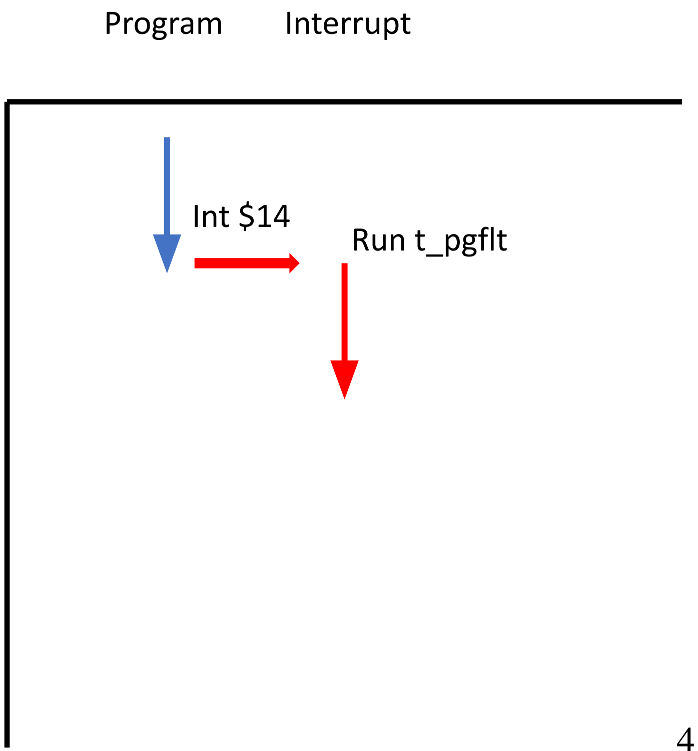

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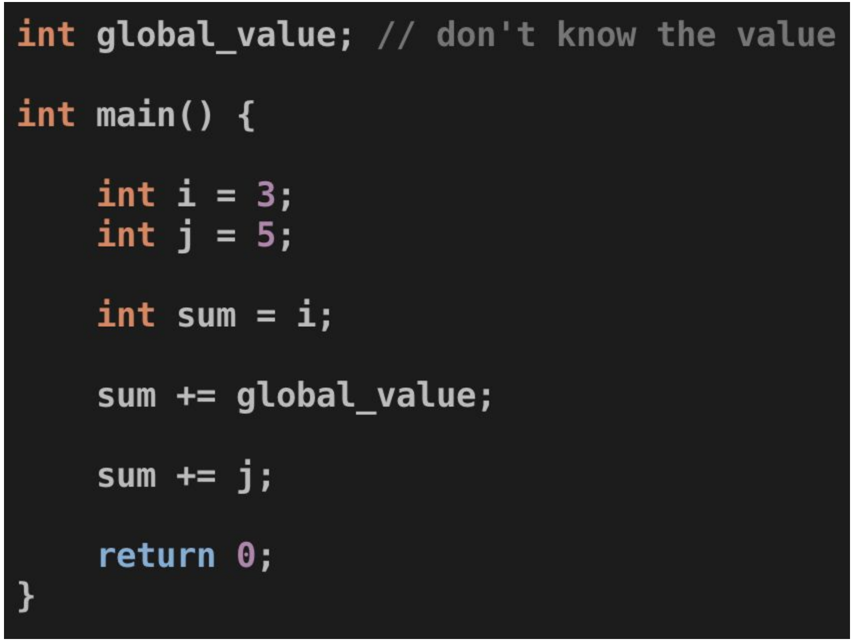

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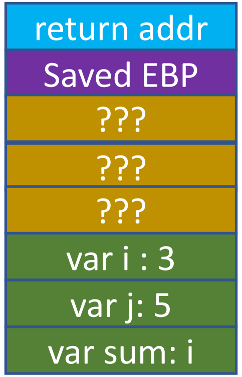
}
```



return addr

Saved EBP

???

???

???

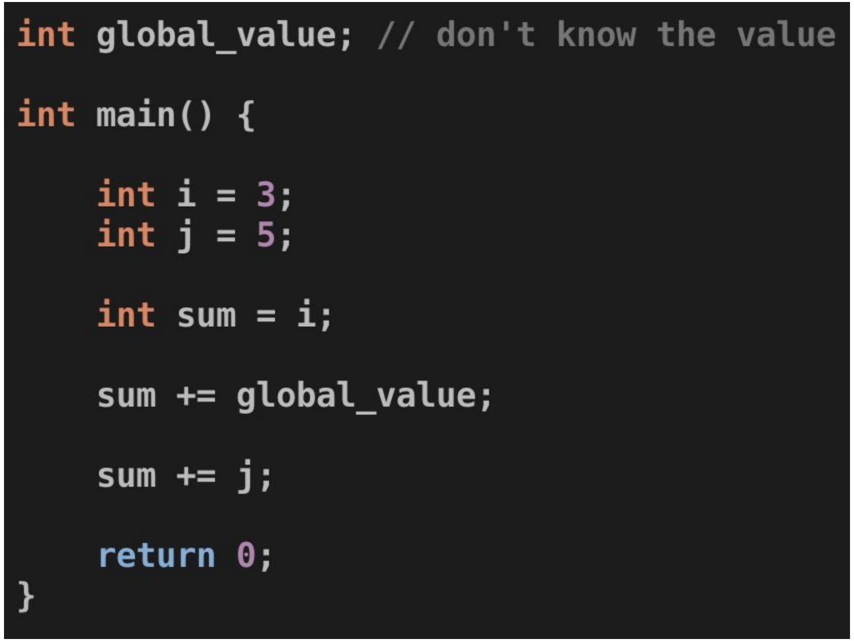
var i : 3

var j: 5

var sum: i

Program
Stack

Execution Context



```
int global_value; // don't know the value

int main() {

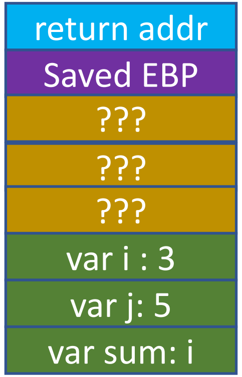
    int i = 3;
    int j = 5;

    int sum = i;

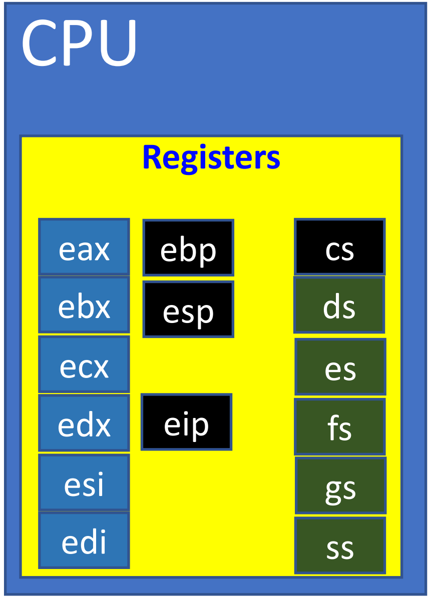
    sum += global_value;

    sum += j;

    return 0;
}
```



Program
Stack



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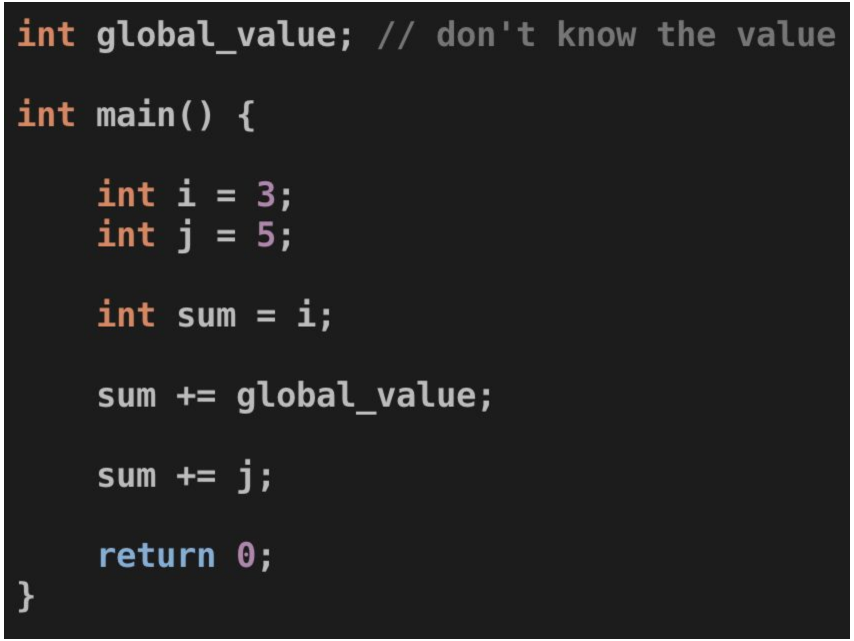

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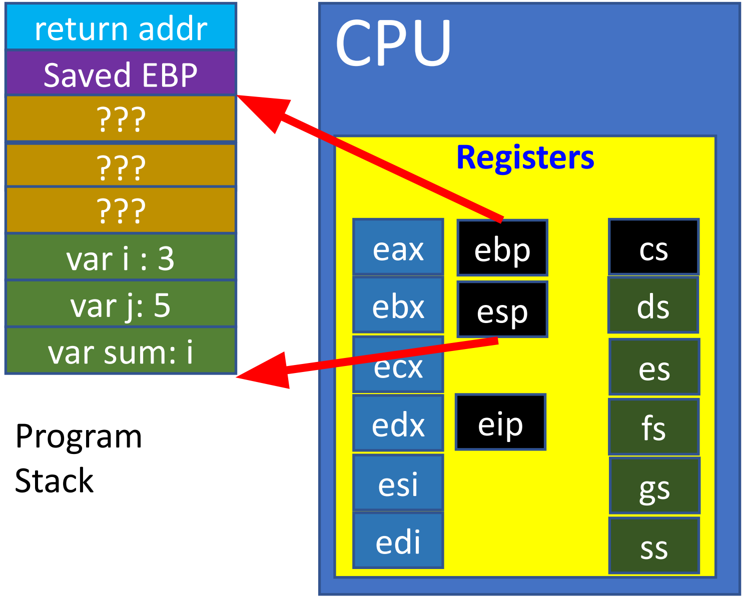

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Saved EBP

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var i : 3

var j: 5

var sum: i

Program
Stack

CPU

Registers

eax

ebx

ecx

edx

esi

edi

ebp

esp

eip

cs

ds

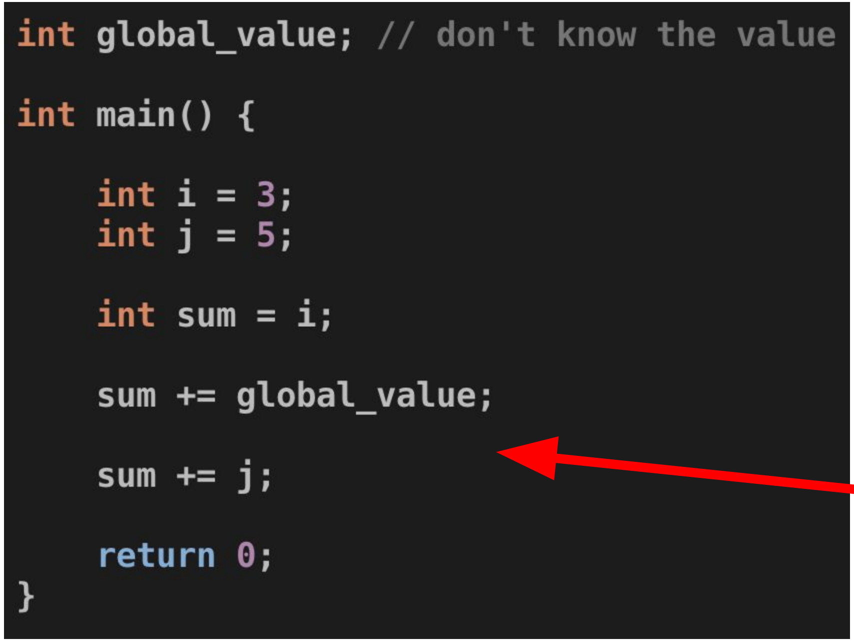
es

fs

gs

ss

Execution Context



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    return 0;
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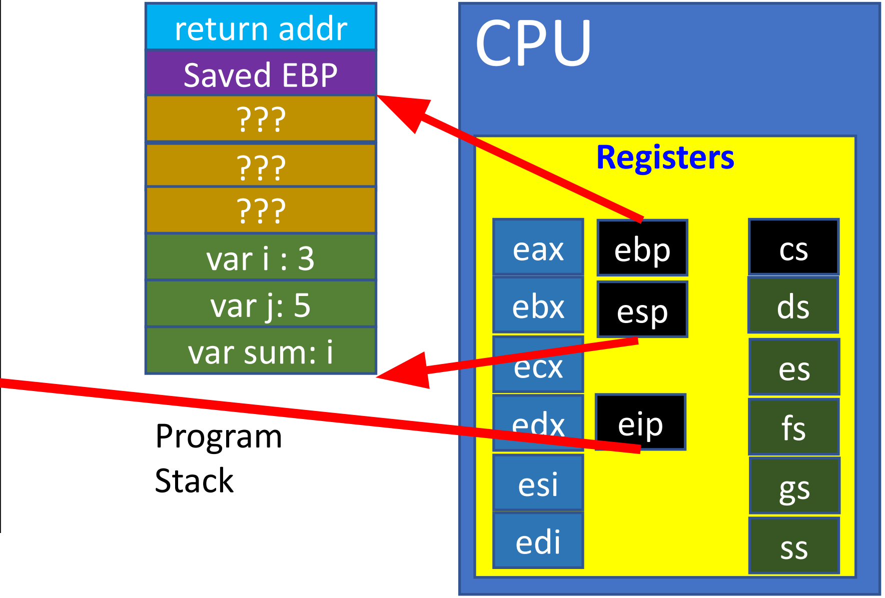

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CPU

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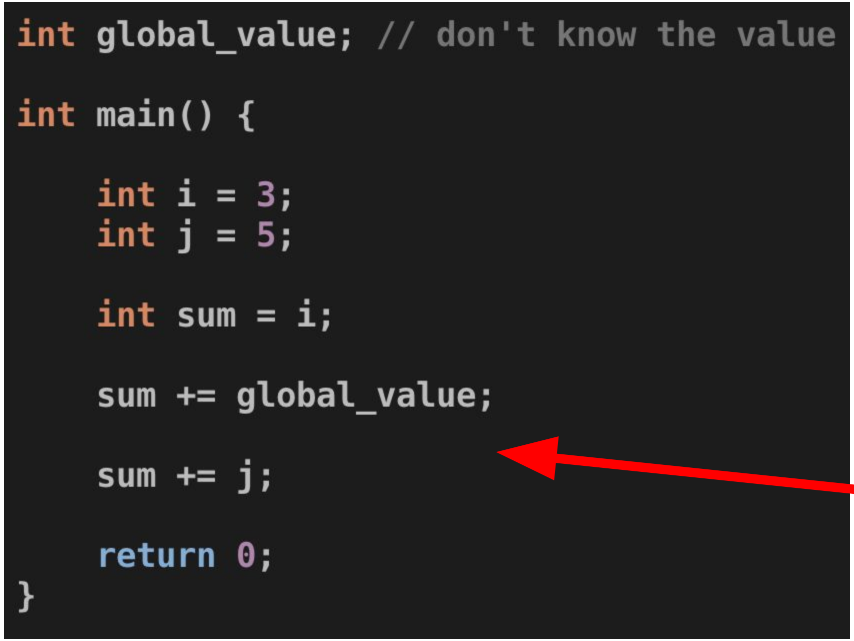

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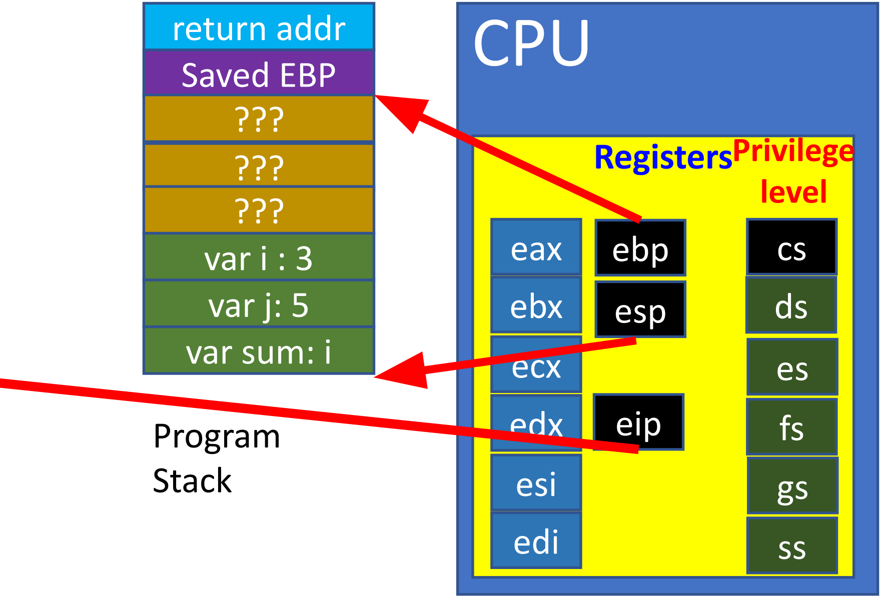


Storing an Execution Context

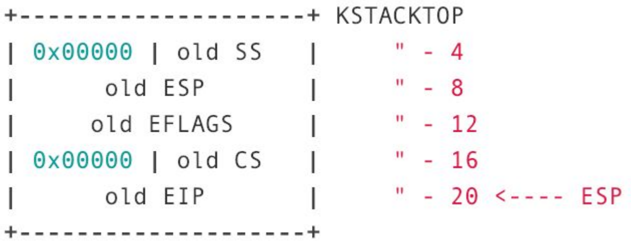
- CPU uses registers and memory (stack) for maintaining an execution context

- Let’s store them
  - Stack (%ebp, %esp)
  - Program counter (where our current execution is, %eip)
  - All general purpose registers (%eax, %edx, %ecx, %ebx, %esi, %edi)
  - EFLAGS
  - CS register (why? CPL!)

Storing an Execution Context

- CPU uses registers and memory (stack) for maintaining an execution context

CPU stores some of them for us.



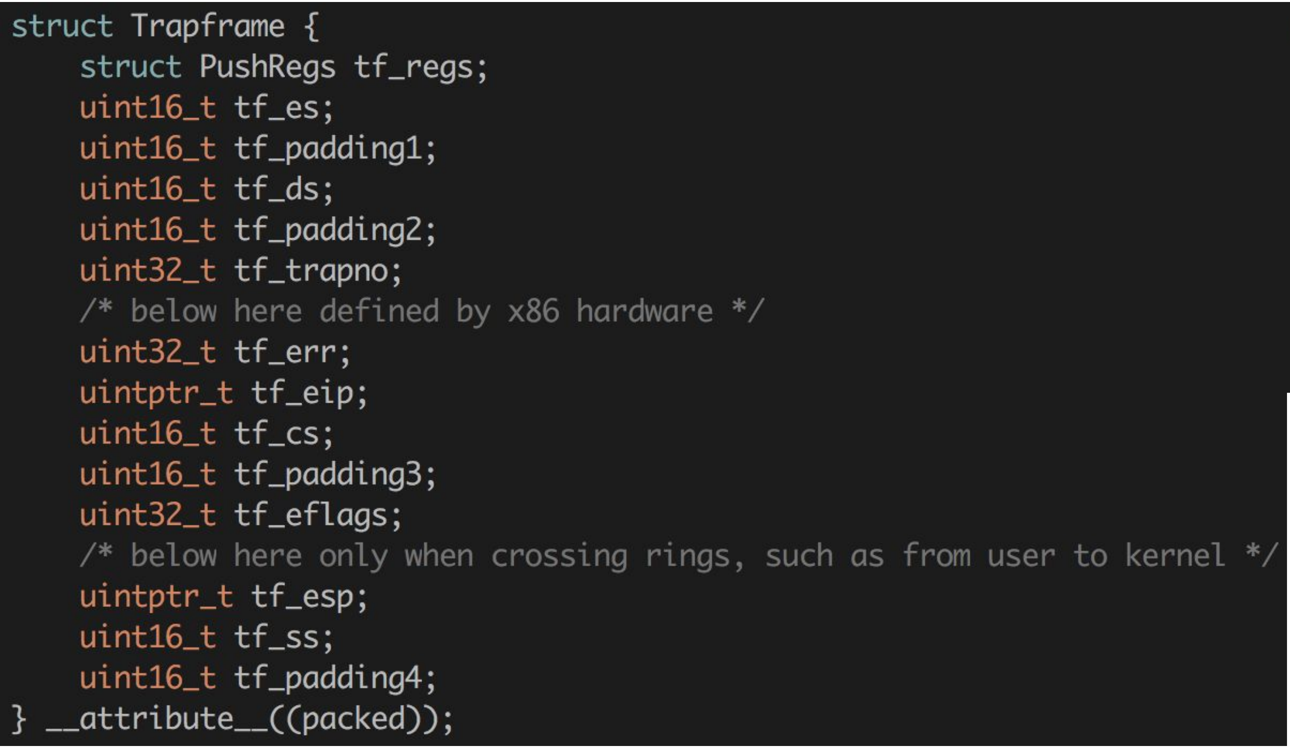
```
+--------------------+ KSTACKTOP
| 0x00000 | old SS   |     " - 4
|      old ESP       |     " - 8
|     old EFLAGS     |     " - 12
| 0x00000 | old CS   |     " - 16
|      old EIP       |     " - 20 <---- ESP
+--------------------+
```

But, CPU only stores esp, eip, EFLAGS, ss, cs

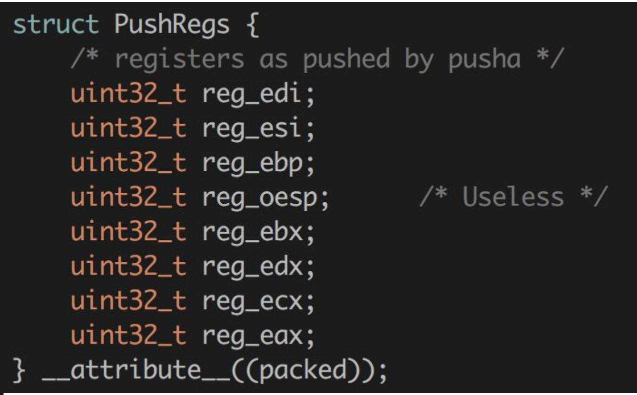
What about the others?

- Let’s store them
  - Stack (%ebp, %esp)
  - Program counter (where our current execution is, %eip)
  - All general purpose registers (%eax, %edx, %ecx, %ebx, %esi, %edi)
  - EFLAGS
  - CS register (why? CPL!)

TrapFrame structure in JOS



```
struct Trapframe {
    struct PushRegs tf_regs;
    uint16_t tf_es;
    uint16_t tf_padding1;
    uint16_t tf_ds;
    uint16_t tf_padding2;
    uint32_t tf_trapno;
    /* below here defined by x86 hardware */
    uint32_t tf_err;
    uintptr_t tf_eip;
    uint16_t tf_cs;
    uint16_t tf_padding3;
    uint32_t tf_eflags;
    /* below here only when crossing rings, such as from user to kernel */
    uintptr_t tf_esp;
    uint16_t tf_ss;
    uint16_t tf_padding4;
} __attribute__((packed));
```



```
struct PushRegs {
    /* registers as pushed by pusha */
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    uint32_t reg_edx;
    uint32_t reg_ecx;
    uint32_t reg_eax;
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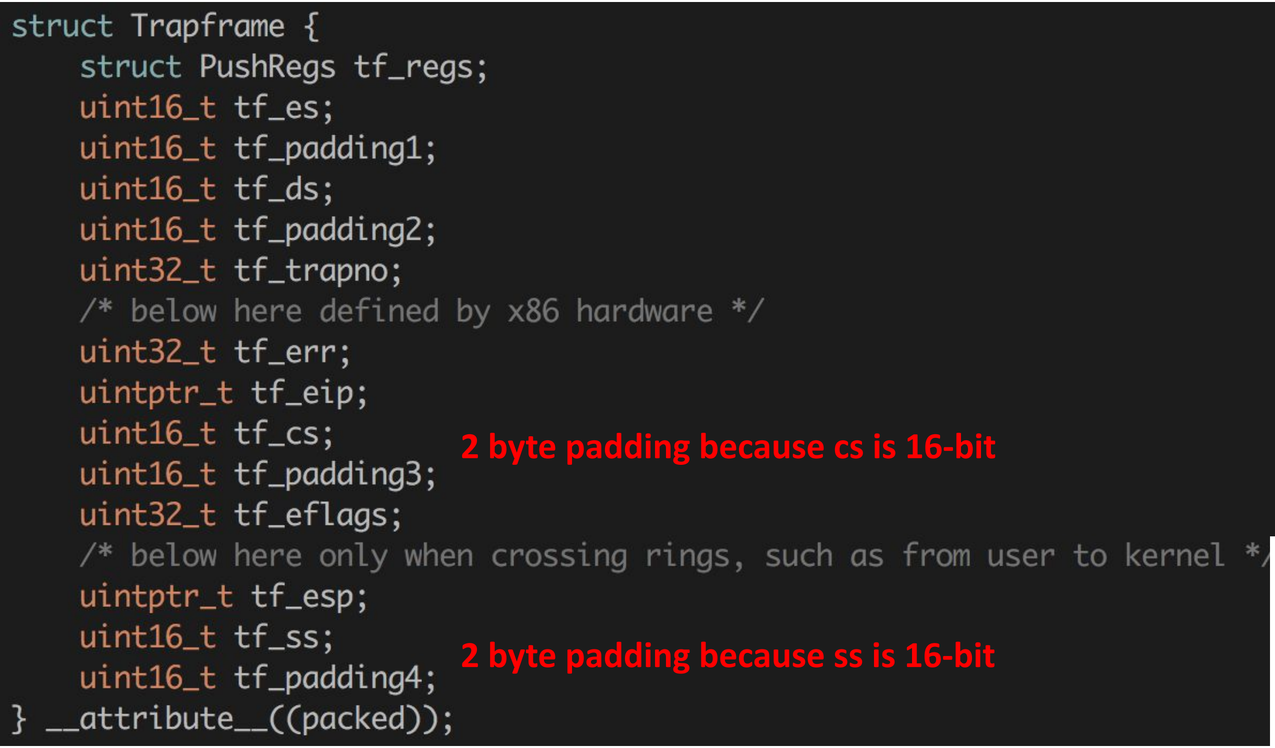
```

JOS stores additional information as Struct Trapframe

TrapFrame structure in JOS



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```
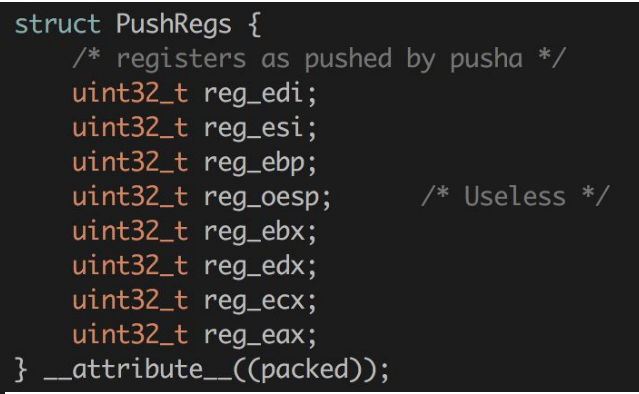

2 byte padding because cs is 16-bit

2 byte padding because ss is 16-bit



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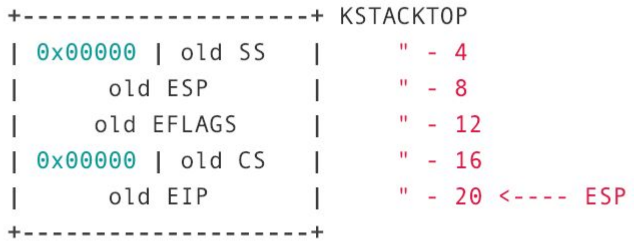

```
+--------------------+ KSTACKTOP
| 0x00000 | old SS   |     " - 4
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| 0x00000 | old CS   |     " - 16
|      old EIP       |     " - 20 <---- ESP
+--------------------+
```
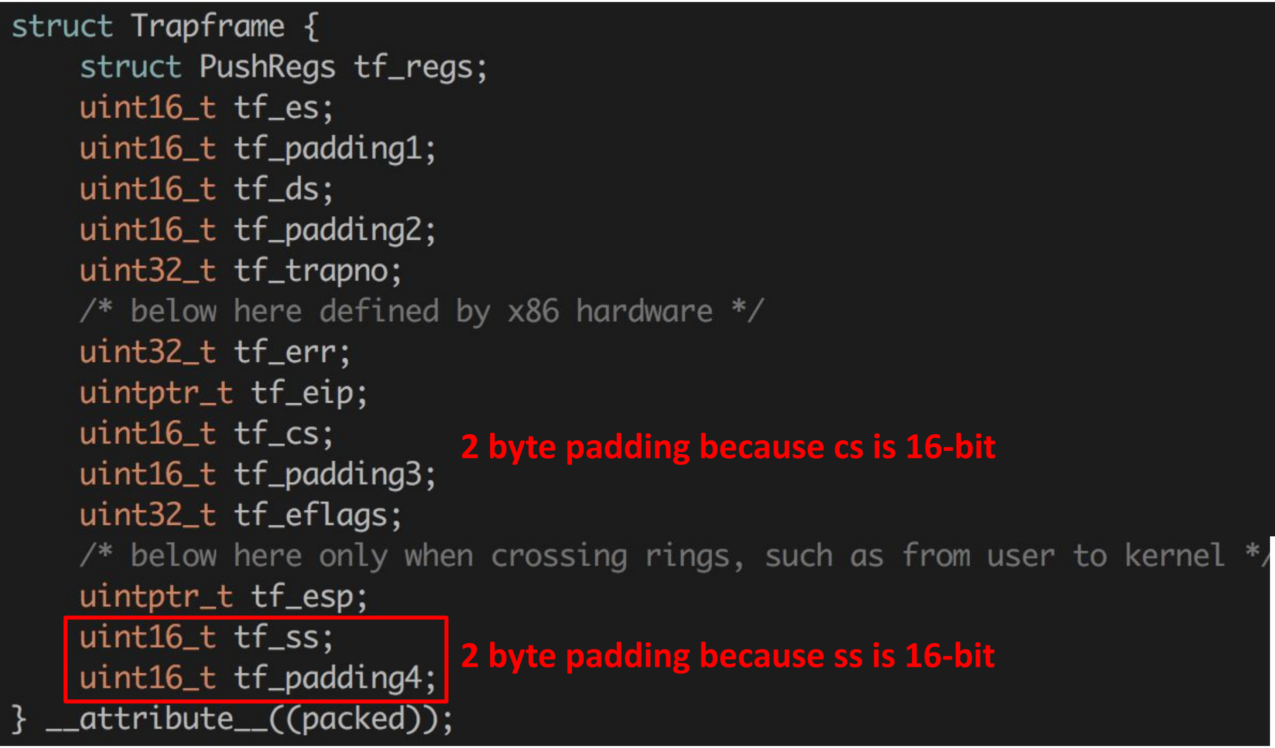

TrapFrame structure in JOS



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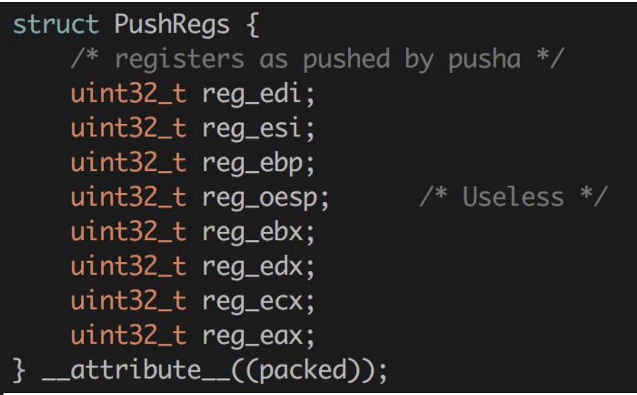

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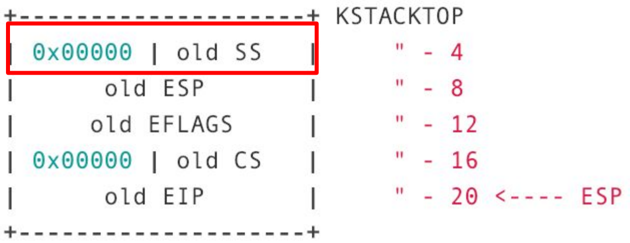

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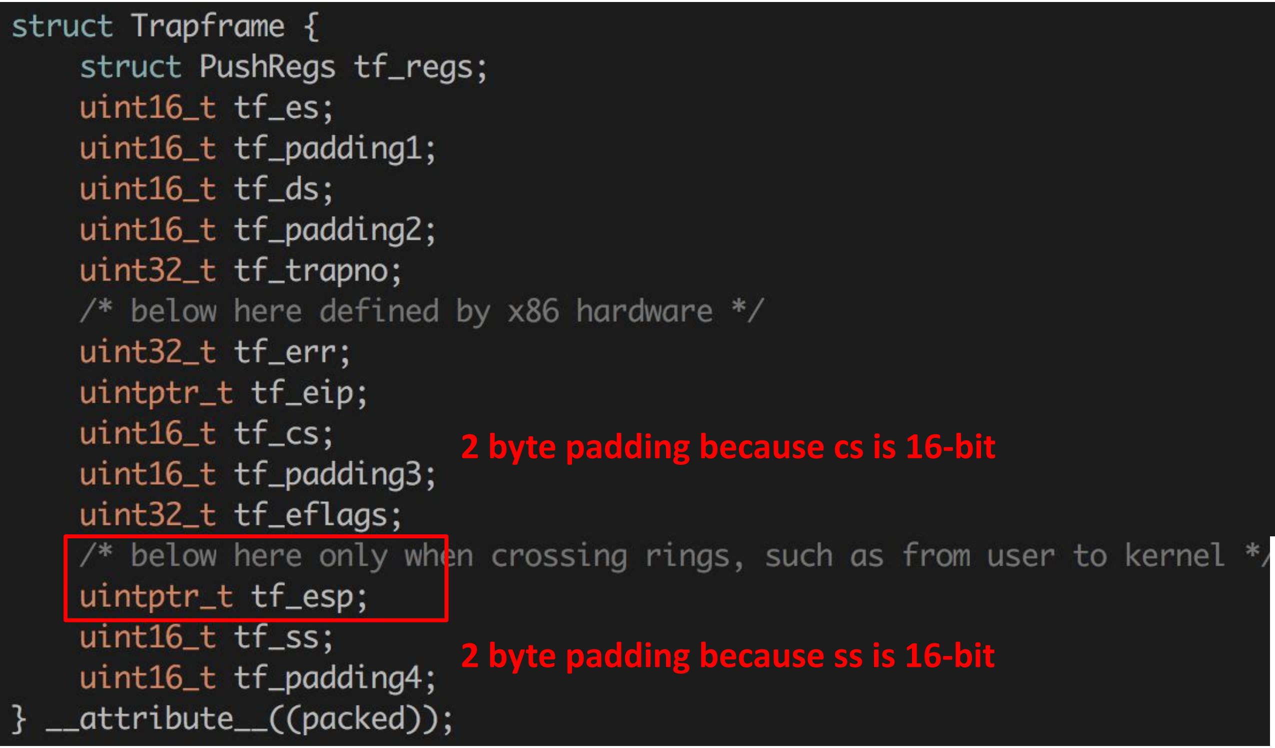
+--------------------+
```

TrapFrame structure in JOS



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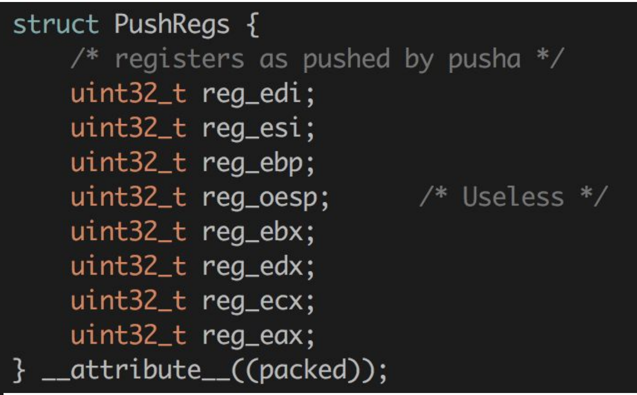

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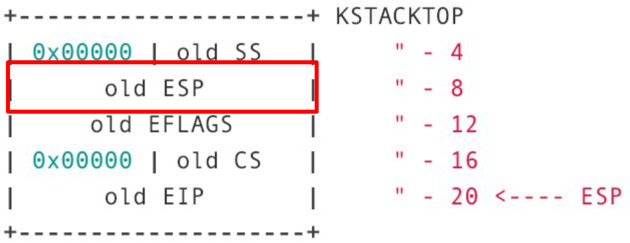

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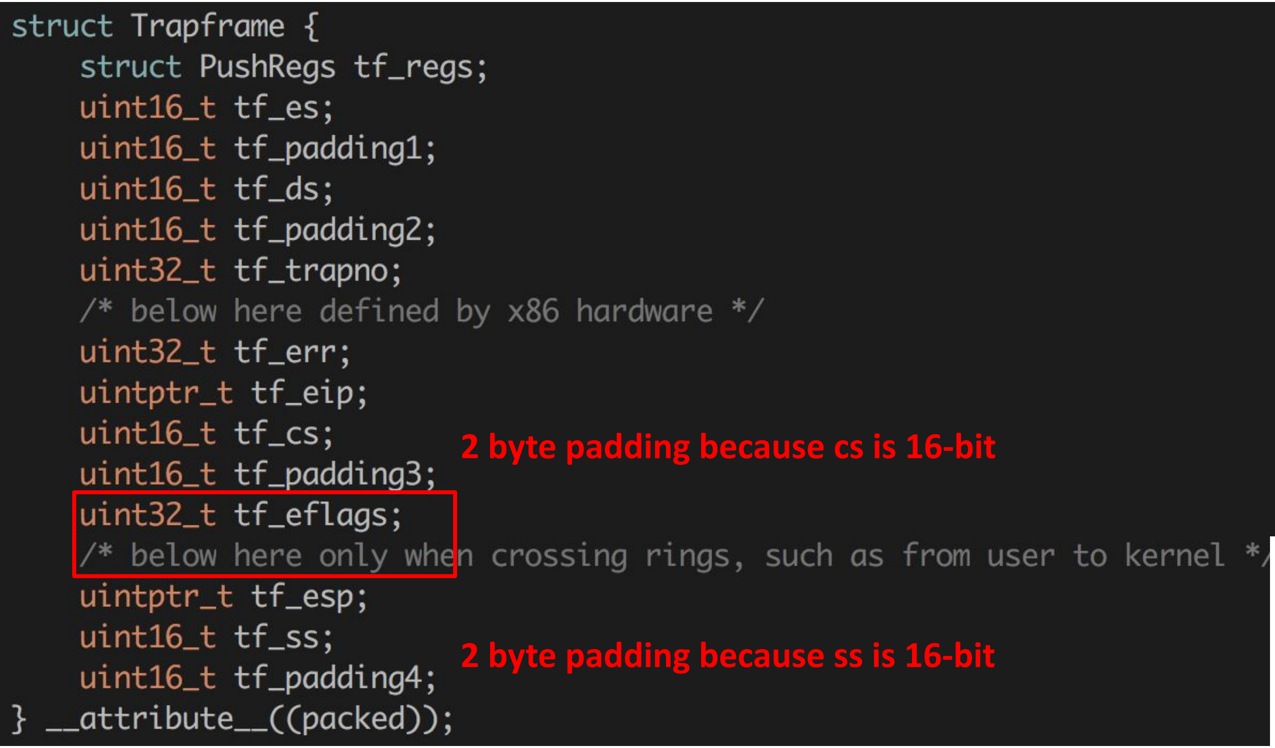
TrapFrame structure in JOS



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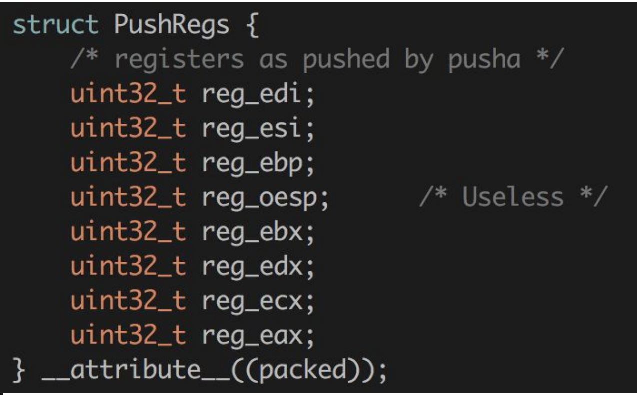

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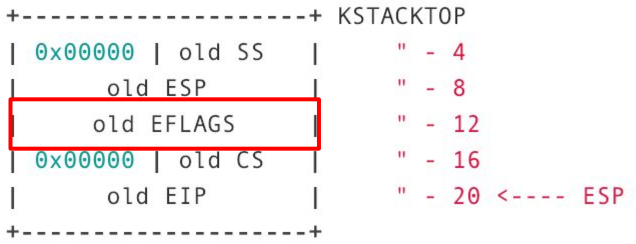

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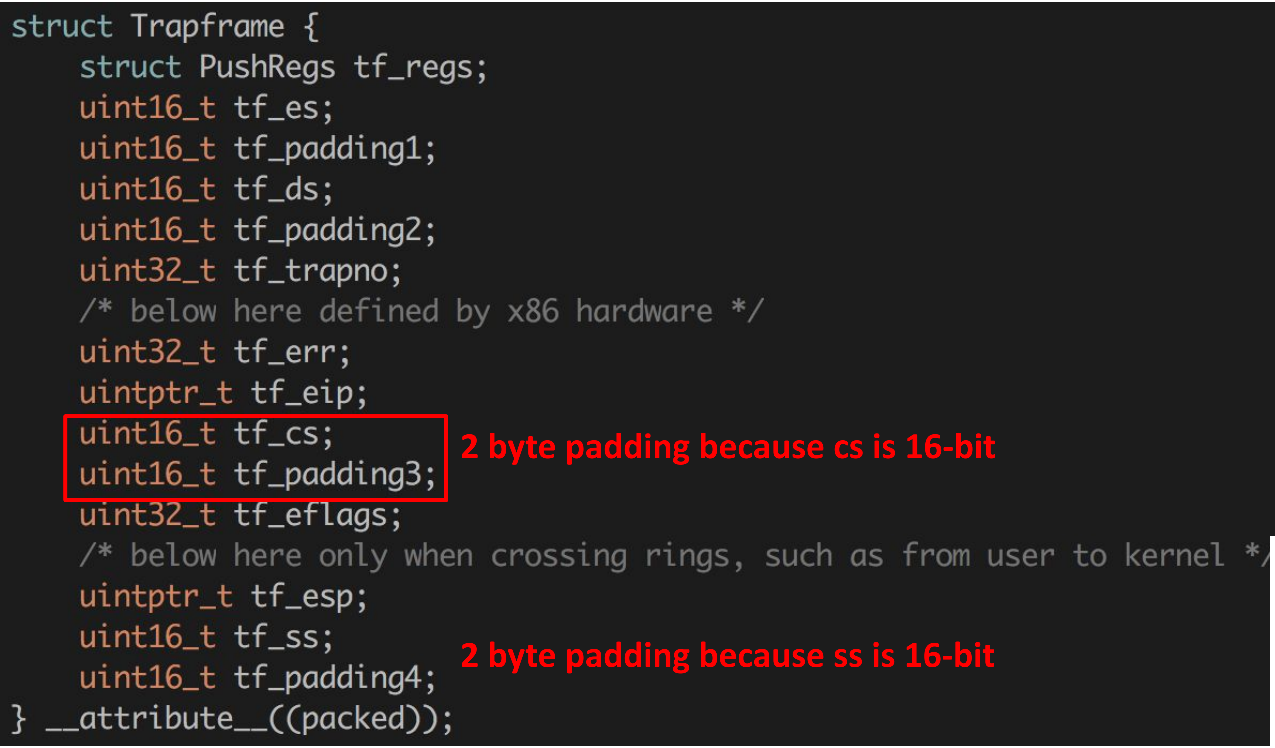

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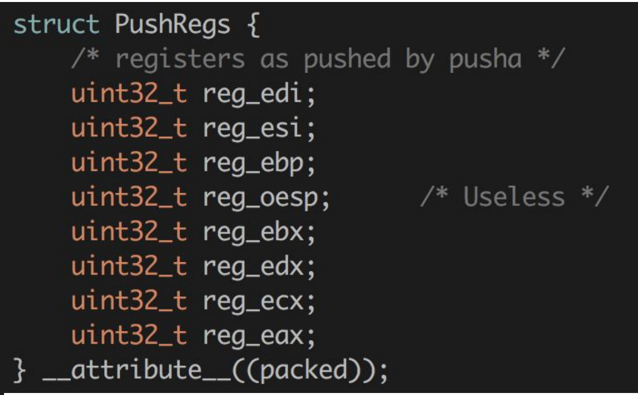

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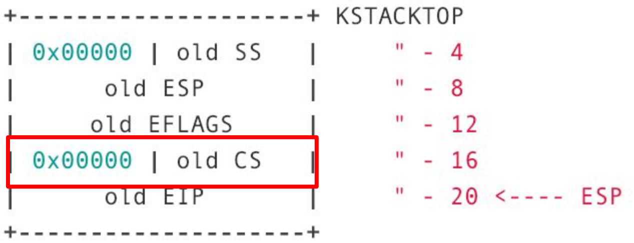

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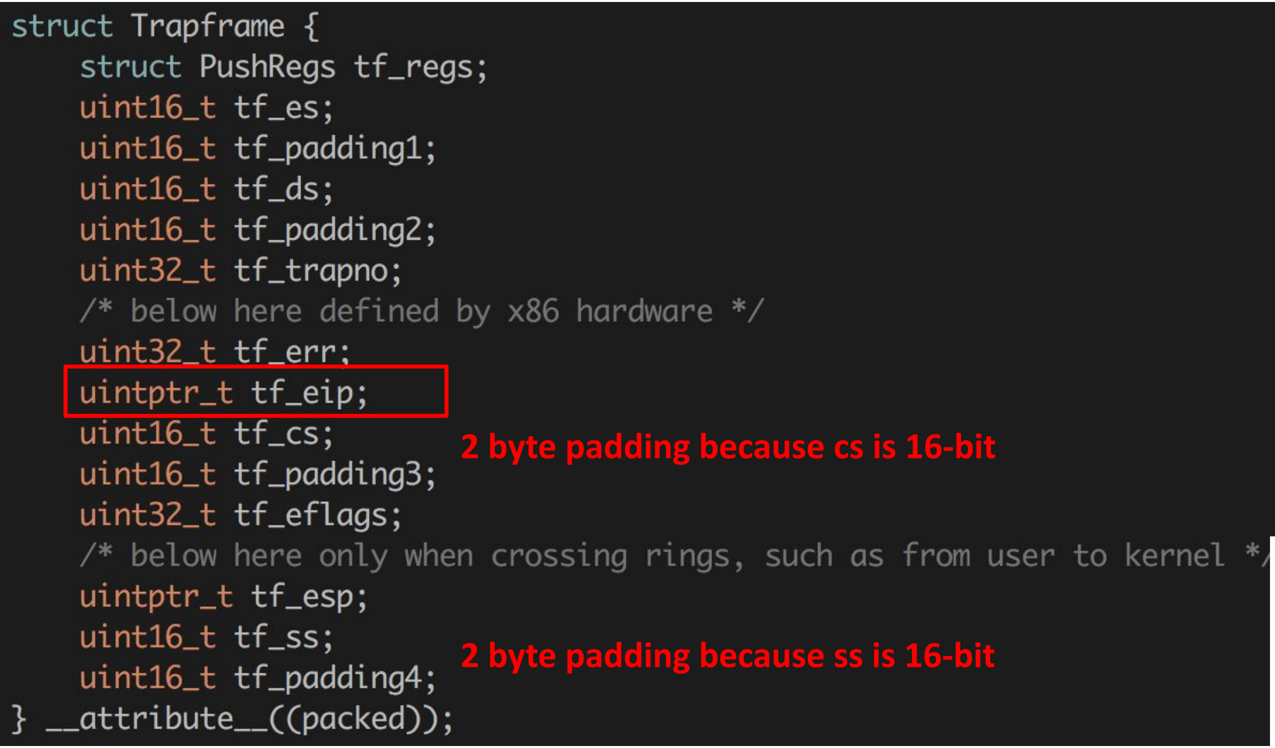
TrapFrame structure in JOS



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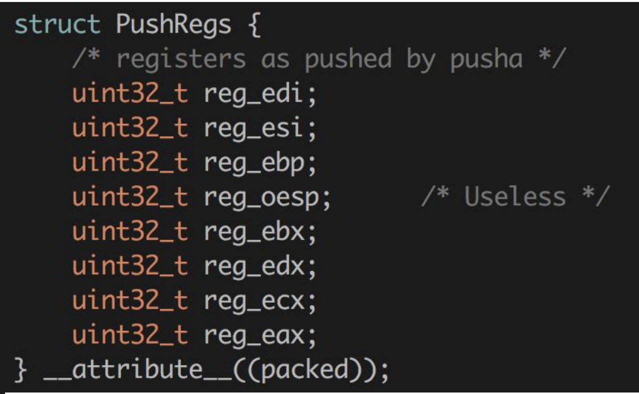

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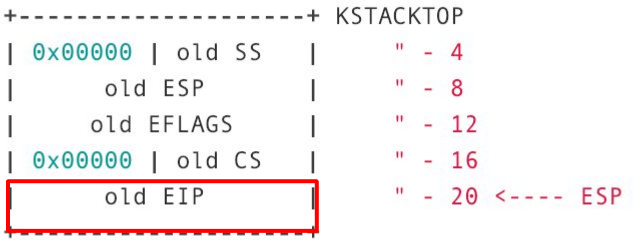
JOS stores additional information as Struct Trapframe



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+--------------------+
```
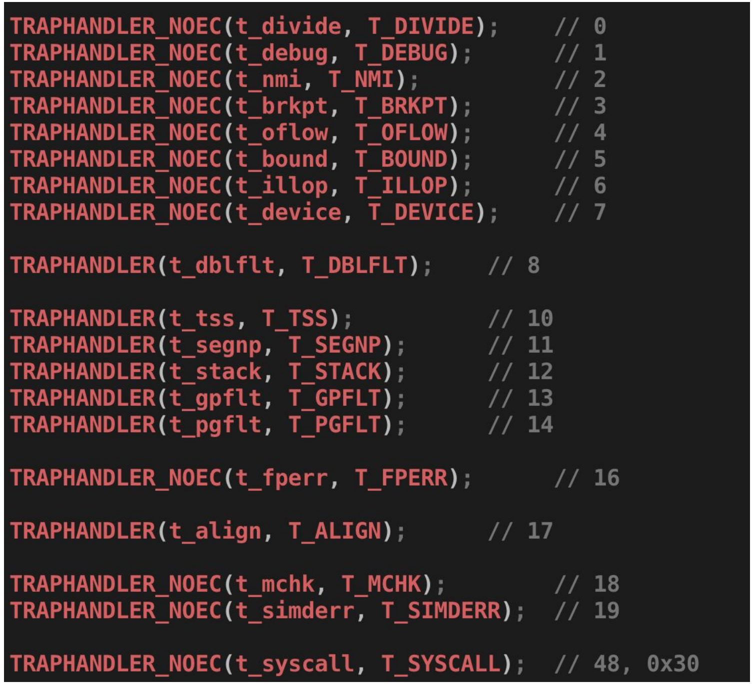

Setting up interrupt handlers

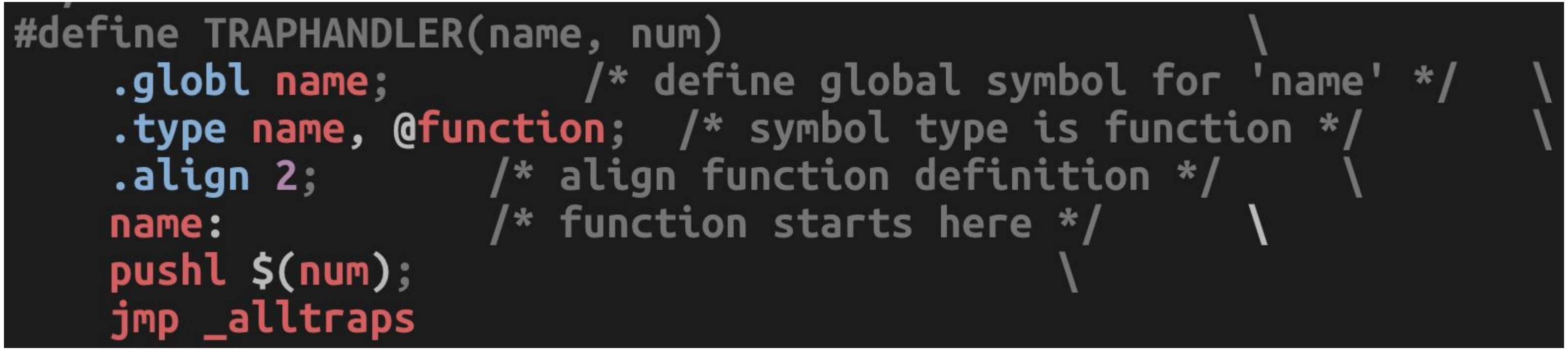
- You will define an interrupt gate per each interrupt/exception

- Using MACROs defined in trapentry.S
  - `TRAPHANDLER(name, num)`
  - `TRAPHANDLER_NOEC(name, num)`

- Gate generated by this macro should call
  - `trap()  in kern/trap.c`
  - `Implement _alltraps:`



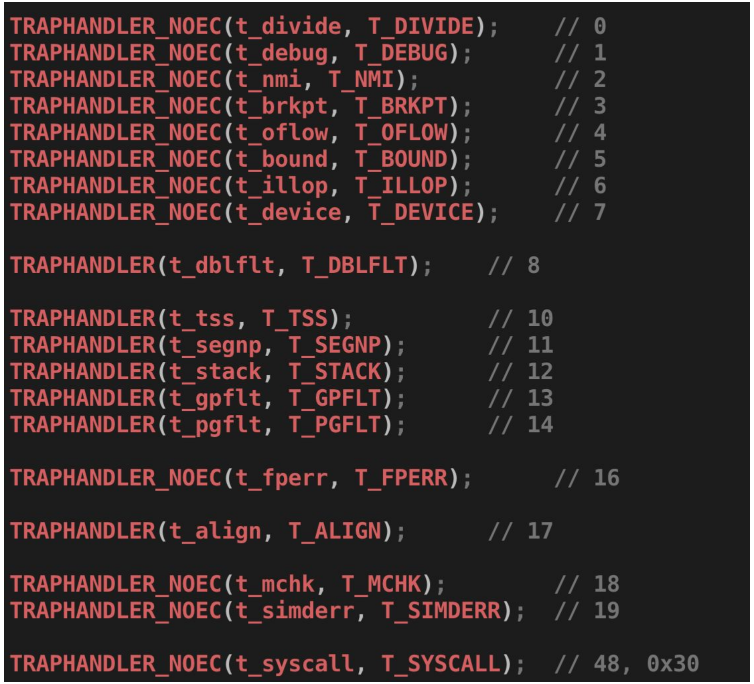
```
TRAPHANDLER_NOEC(t_divide, T_DIVIDE);    // 0
TRAPHANDLER_NOEC(t_debug, T_DEBUG);      // 1
TRAPHANDLER_NOEC(t_nmi, T_NMI);          // 2
TRAPHANDLER_NOEC(t_brkpt, T_BRKPT);      // 3
TRAPHANDLER_NOEC(t_oflow, T_OFLOW);      // 4
TRAPHANDLER_NOEC(t_bound, T_BOUND);      // 5
TRAPHANDLER_NOEC(t_illop, T_ILLOP);      // 6
TRAPHANDLER_NOEC(t_device, T_DEVICE);    // 7

TRAPHANDLER(t_dblflt, T_DBLFLT);    // 8

TRAPHANDLER(t_tss, T_TSS);          // 10
TRAPHANDLER(t_segnp, T_SEGNP);      // 11
TRAPHANDLER(t_stack, T_STACK);      // 12
TRAPHANDLER(t_gpflt, T_GPFLT);      // 13
TRAPHANDLER(t_pgflt, T_PGFLT);      // 14

TRAPHANDLER_NOEC(t_fperr, T_FPERR);      // 16

TRAPHANDLER(t_align, T_ALIGN);      // 17

TRAPHANDLER_NOEC(t_mchk, T_MCHK);        // 18
TRAPHANDLER_NOEC(t_simderr, T_SIMDERR);  // 19

TRAPHANDLER_NOEC(t_syscall, T_SYSCALL);  // 48, 0x30
```



```
#define TRAPHANDLER(name, num)                                  \
    .globl name;            /* define global symbol for 'name' */   \
    .type name, @function;  /* symbol type is function */      \
    .align 2;           /* align function definition */      \
    name:               /* function starts here */       \
    pushl $(num);                                   \
    jmp _alltraps
```

- Using MACROs defined in trapentry.S
  - `TRAPHANDLER(name, num)`
  - `TRAPHANDLER_NOEC(name, num)`

- Gate generated by this macro should call
  - `trap()  in kern/trap.c`
  - `Implement _alltraps:`



```
TRAPHANDLER_NOEC(t_divide, T_DIVIDE);    // 0
TRAPHANDLER_NOEC(t_debug, T_DEBUG);      // 1
TRAPHANDLER_NOEC(t_nmi, T_NMI);          // 2
TRAPHANDLER_NOEC(t_brkpt, T_BRKPT);      // 3
TRAPHANDLER_NOEC(t_oflow, T_OFLOW);      // 4
TRAPHANDLER_NOEC(t_bound, T_BOUND);      // 5
TRAPHANDLER_NOEC(t_illop, T_ILLOP);      // 6
TRAPHANDLER_NOEC(t_device, T_DEVICE);    // 7

TRAPHANDLER(t_dblflt, T_DBLFLT);     // 8

TRAPHANDLER(t_tss, T_TSS);           // 10
TRAPHANDLER(t_segnp, T_SEGNP);       // 11
TRAPHANDLER(t_stack, T_STACK);       // 12
TRAPHANDLER(t_gpflt, T_GPFLT);       // 13
TRAPHANDLER(t_pgflt, T_PGFLT);       // 14

TRAPHANDLER_NOEC(t_fperr, T_FPERR);      // 16

TRAPHANDLER(t_align, T_ALIGN);       // 17

TRAPHANDLER_NOEC(t_mchk, T_MCHK);        // 18
TRAPHANDLER_NOEC(t_simderr, T_SIMDERR);  // 19

TRAPHANDLER_NOEC(t_syscall, T_SYSCALL);  // 48, 0x30
```

Which interrupts has EC?

- Intel Manual
  - https://purs3lab.github.io/ee469/static_files/read/ia32/IA32-3A.pdf (page 186)

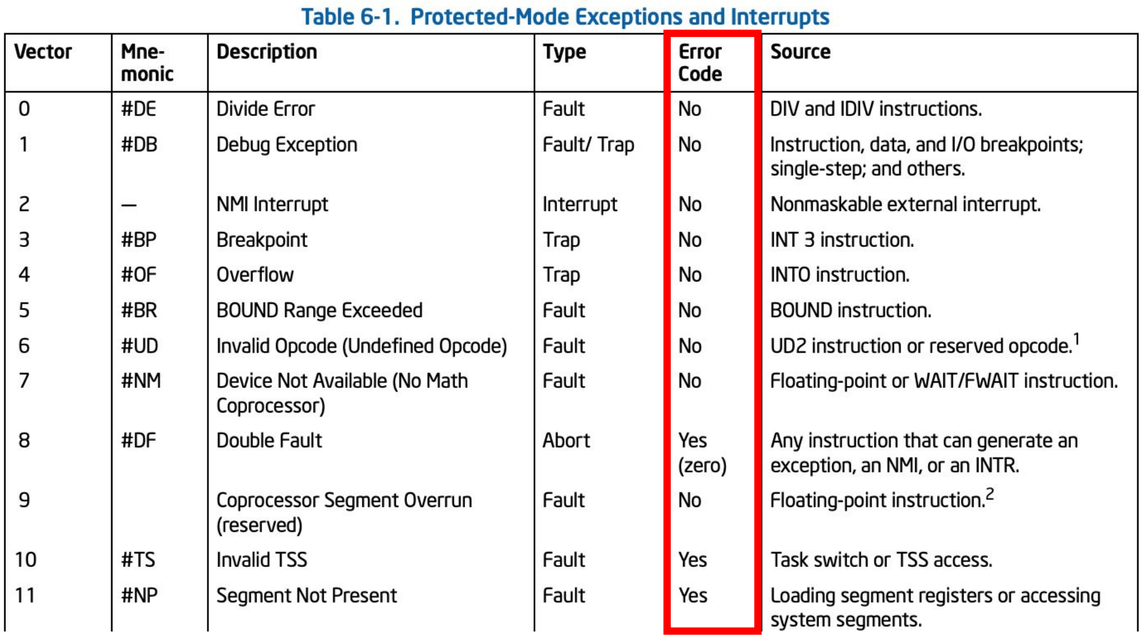
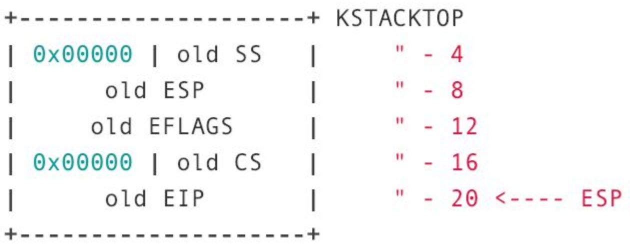


Table 6-1. Protected-Mode Exceptions and Interrupts

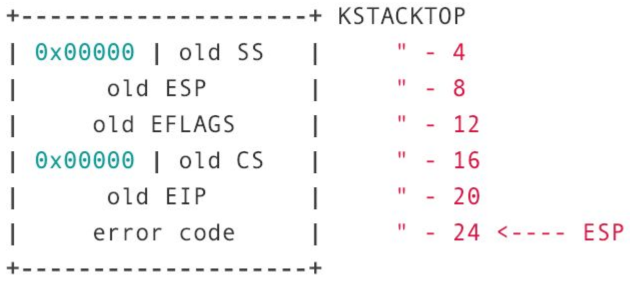
Vector	Mne-monic	Description	Type	Error Code	Source
0	#DE	Divide Error	Fault	No	DIV and IDIV instructions.
1	#DB	Debug Exception	Fault/ Trap	No	Instruction, data, and I/O breakpoints; single-step; and others.
2	—	NMI Interrupt	Interrupt	No	Nonmaskable external interrupt.
3	#BP	Breakpoint	Trap	No	INT 3 instruction.
4	#OF	Overflow	Trap	No	INTO instruction.
5	#BR	BOUND Range Exceeded	Fault	No	BOUND instruction.
6	#UD	Invalid Opcode (Undefined Opcode)	Fault	No	UD2 instruction or reserved opcode.[1]
7	#NM	Device Not Available (No Math Coprocessor)	Fault	No	Floating-point or WAIT/FWAIT instruction.
8	#DF	Double Fault	Abort	Yes (zero)	Any instruction that can generate an exception, an NMI, or an INTR.
9		Coprocessor Segment Overrun (reserved)	Fault	No	Floating-point instruction.[2]
10	#TS	Invalid TSS	Fault	Yes	Task switch or TSS access.
11	#NP	Segment Not Present	Fault	Yes	Loading segment registers or accessing system segments.

Processor handling of EC/NOEC interrupts



```
+--------------------+ KSTACKTOP
| 0x00000 | old SS   |     " - 4
|      old ESP       |     " - 8
|     old EFLAGS     |     " - 12
| 0x00000 | old CS   |     " - 16
|      old EIP       |     " - 20 <---- ESP
+--------------------+
```

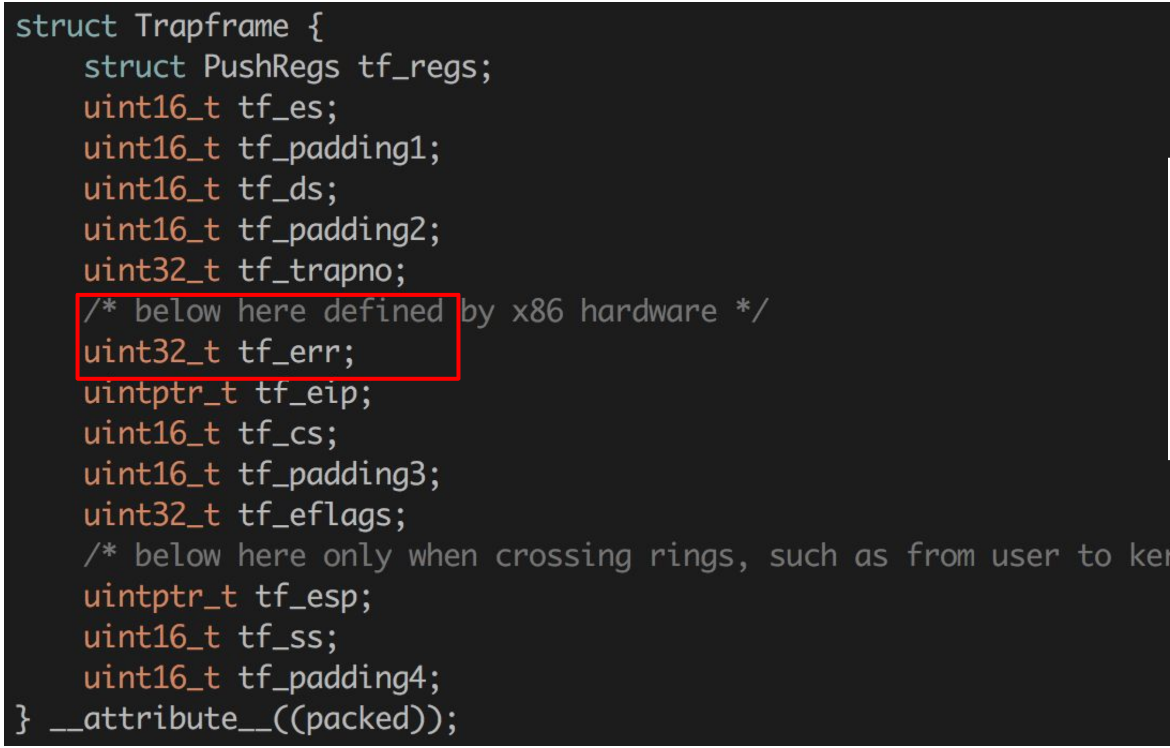
Interrupt context (on the stack)
When there is no error code



```
+--------------------+ KSTACKTOP
| 0x00000 | old SS   |     " - 4
|      old ESP       |     " - 8
|     old EFLAGS     |     " - 12
| 0x00000 | old CS   |     " - 16
|      old EIP       |     " - 20
|     error code     |     " - 24 <---- ESP
+--------------------+
```

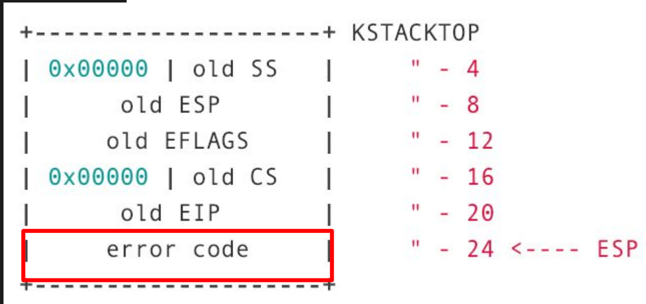
Interrupt context (on the stack)
When there is an error code

Handling TrapFrame for EC/NOEC



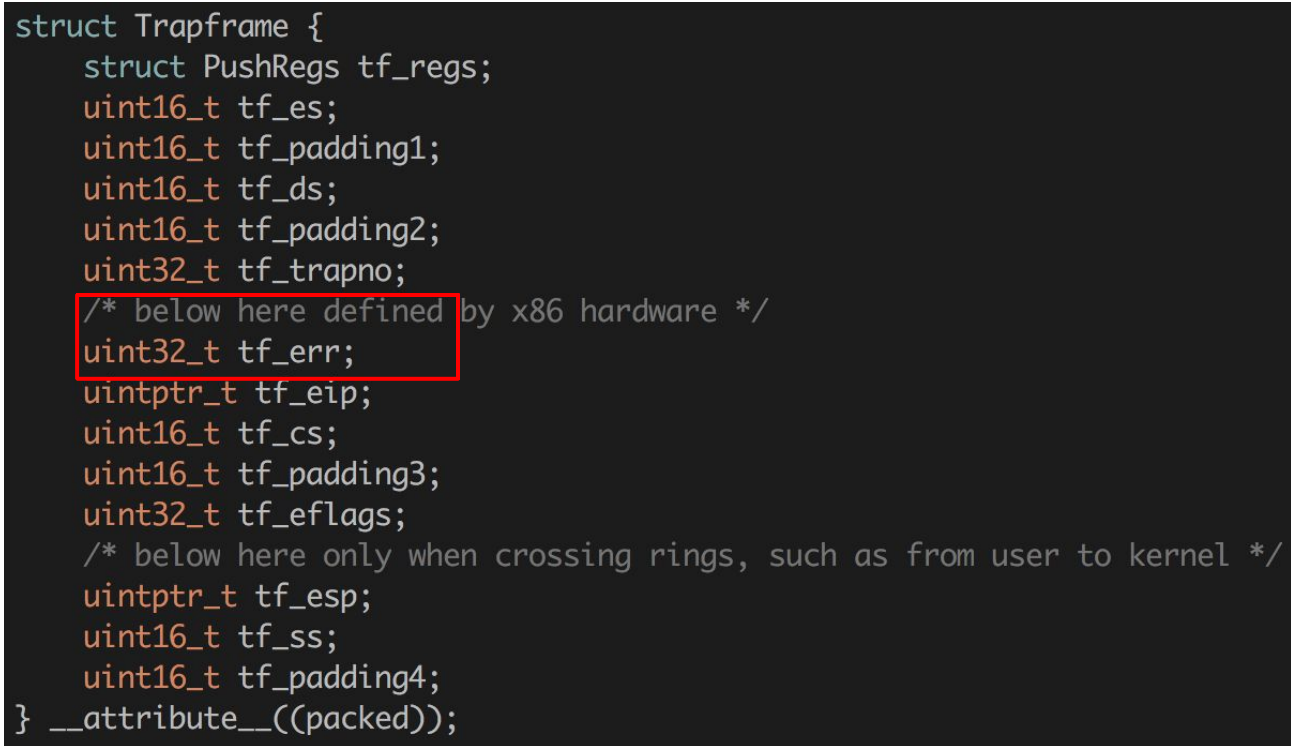
```
struct Trapframe {
    struct PushRegs tf_regs;
    uint16_t tf_es;
    uint16_t tf_padding1;
    uint16_t tf_ds;
    uint16_t tf_padding2;
    uint32_t tf_trapno;
    /* below here defined by x86 hardware */
    uint32_t tf_err;
    uintptr_t tf_eip;
    uint16_t tf_cs;
    uint16_t tf_padding3;
    uint32_t tf_eflags;
    /* below here only when crossing rings, such as from user to kernel */
    uintptr_t tf_esp;
    uint16_t tf_ss;
    uint16_t tf_padding4;
} __attribute__((packed));
```

Processor pushes the error code for EC interrupts



```
+--------------------+ KSTACKTOP
| 0x00000 | old SS   |     " - 4
|      old ESP       |     " - 8
|     old EFLAGS     |     " - 12
| 0x00000 | old CS   |     " - 16
|      old EIP       |     " - 20
|     error code     |     " - 24 <---- ESP
+--------------------+
```

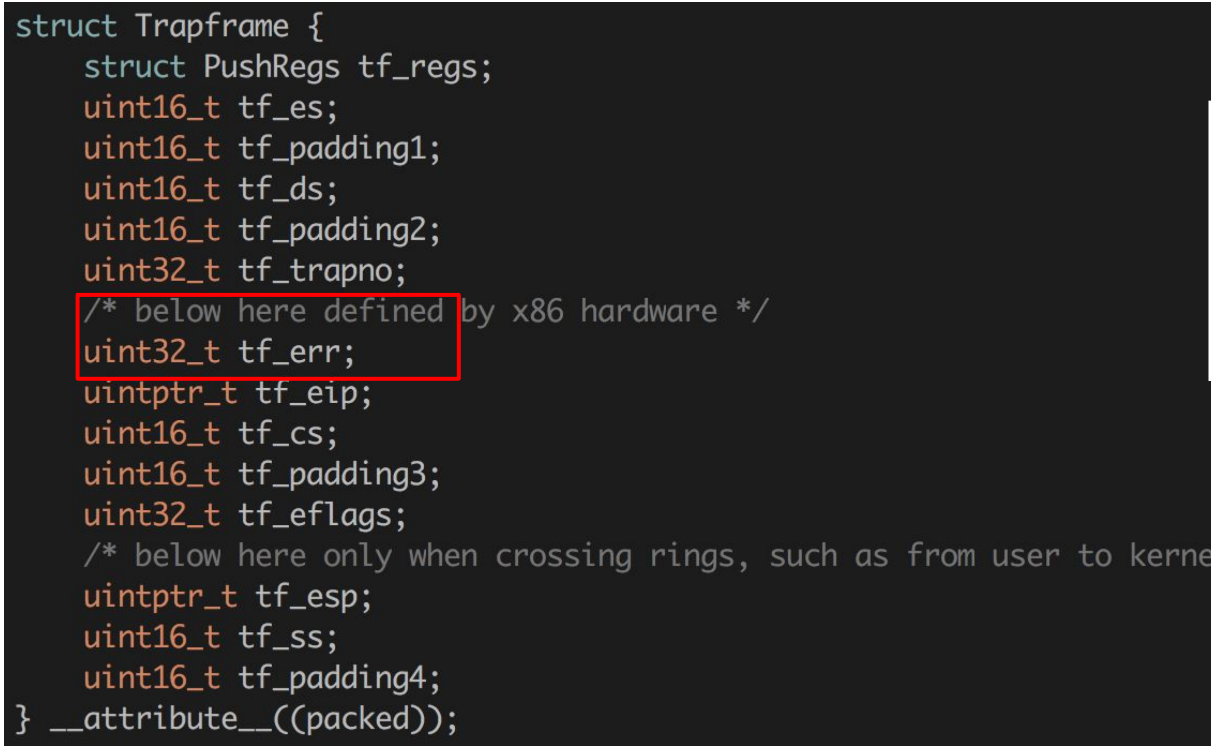
Handling TrapFrame for EC/NOEC



```
struct Trapframe {
    struct PushRegs tf_regs;
    uint16_t tf_es;
    uint16_t tf_padding1;
    uint16_t tf_ds;
    uint16_t tf_padding2;
    uint32_t tf_trapno;
    /* below here defined by x86 hardware */
    uint32_t tf_err;
    uintptr_t tf_eip;
    uint16_t tf_cs;
    uint16_t tf_padding3;
    uint32_t tf_eflags;
    /* below here only when crossing rings, such as from user to kernel */
    uintptr_t tf_esp;
    uint16_t tf_ss;
    uint16_t tf_padding4;
} __attribute__((packed));
```

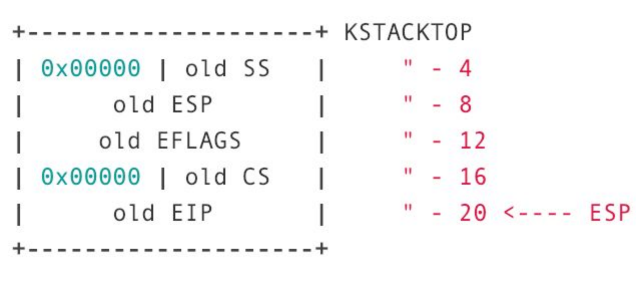
What about NOEC interrupts?

Handling TrapFrame for EC/NOEC



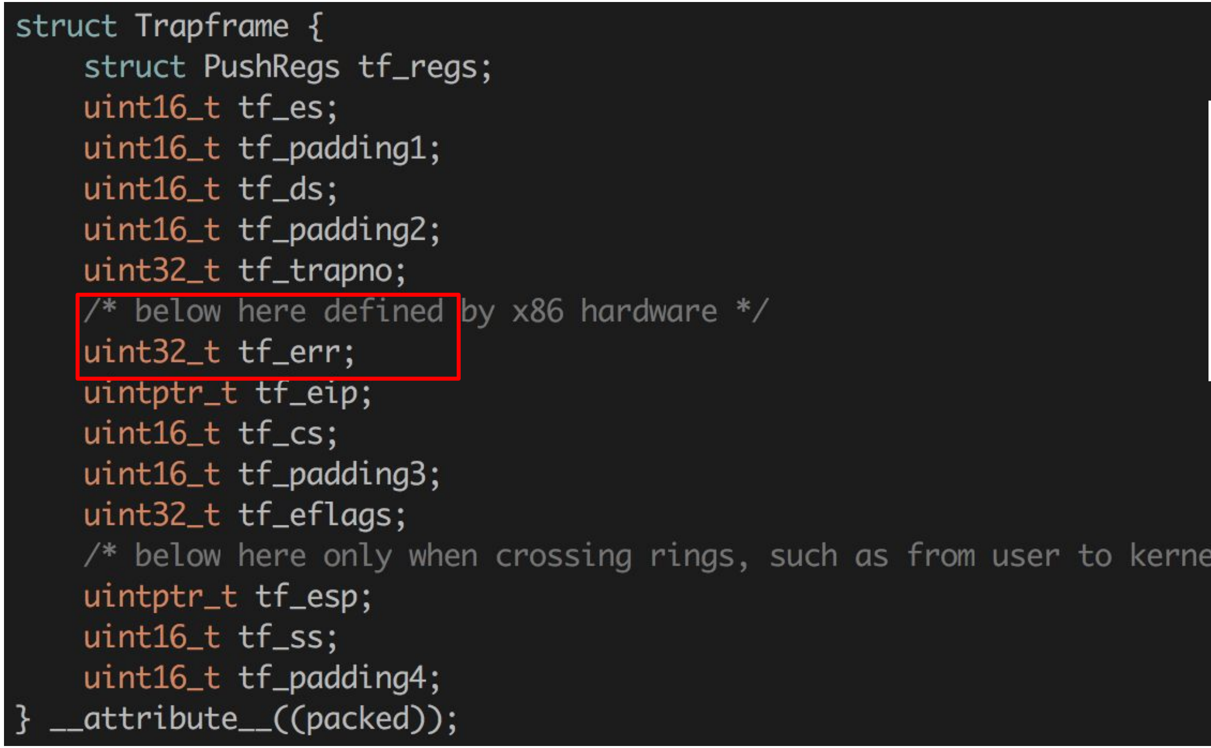
```
struct Trapframe {
    struct PushRegs tf_regs;
    uint16_t tf_es;
    uint16_t tf_padding1;
    uint16_t tf_ds;
    uint16_t tf_padding2;
    uint32_t tf_trapno;
    /* below here defined by x86 hardware */
    uint32_t tf_err;
    uintptr_t tf_eip;
    uint16_t tf_cs;
    uint16_t tf_padding3;
    uint32_t tf_eflags;
    /* below here only when crossing rings, such as from user to kernel */
    uintptr_t tf_esp;
    uint16_t tf_ss;
    uint16_t tf_padding4;
} __attribute__((packed));
```

What about NOEC interrupts?



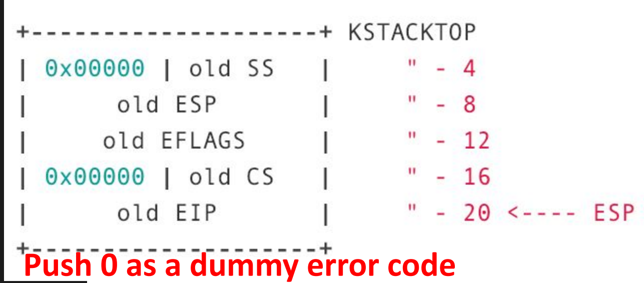
```
+--------------------+ KSTACKTOP
| 0x00000 | old SS   |     " - 4
|      old ESP       |     " - 8
|     old EFLAGS     |     " - 12
| 0x00000 | old CS   |     " - 16
|      old EIP       |     " - 20 <---- ESP
+--------------------+
```

Handling TrapFrame for EC/NOEC



```
struct Trapframe {
    struct PushRegs tf_regs;
    uint16_t tf_es;
    uint16_t tf_padding1;
    uint16_t tf_ds;
    uint16_t tf_padding2;
    uint32_t tf_trapno;
    /* below here defined by x86 hardware */
    uint32_t tf_err;
    uintptr_t tf_eip;
    uint16_t tf_cs;
    uint16_t tf_padding3;
    uint32_t tf_eflags;
    /* below here only when crossing rings, such as from user to kernel */
    uintptr_t tf_esp;
    uint16_t tf_ss;
    uint16_t tf_padding4;
} __attribute__((packed));
```

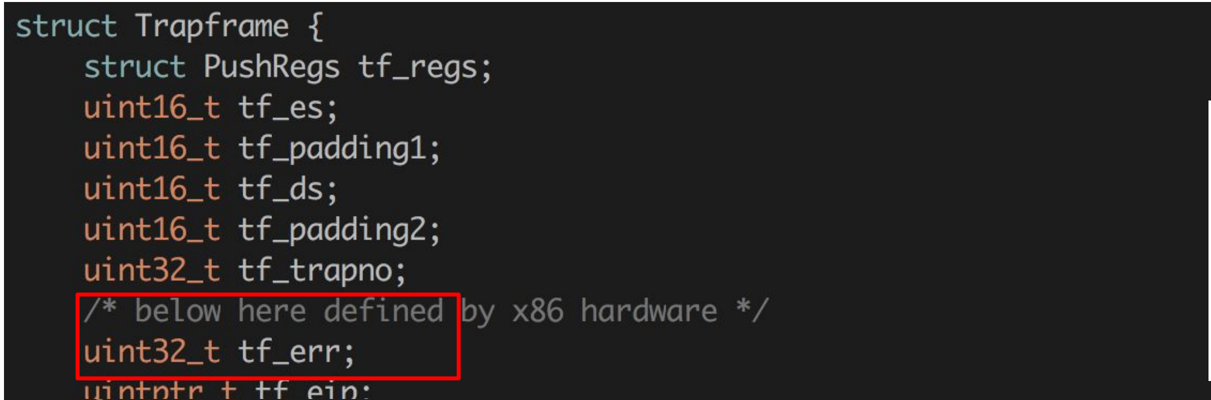
What about NOEC interrupts?



```
+--------------------+ KSTACKTOP
| 0x00000 | old SS   |     " - 4
|      old ESP       |     " - 8
|     old EFLAGS     |     " - 12
| 0x00000 | old CS   |     " - 16
|      old EIP       |     " - 20 <---- ESP
+--------------------+
```

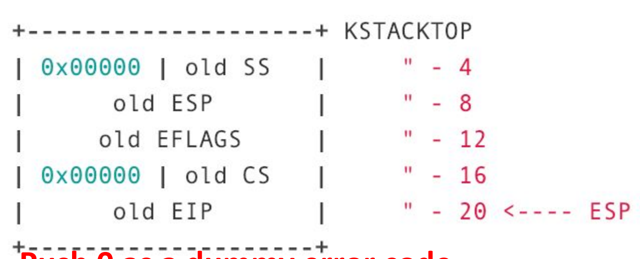
Push 0 as a dummy error code

Handling TrapFrame for EC/NOEC



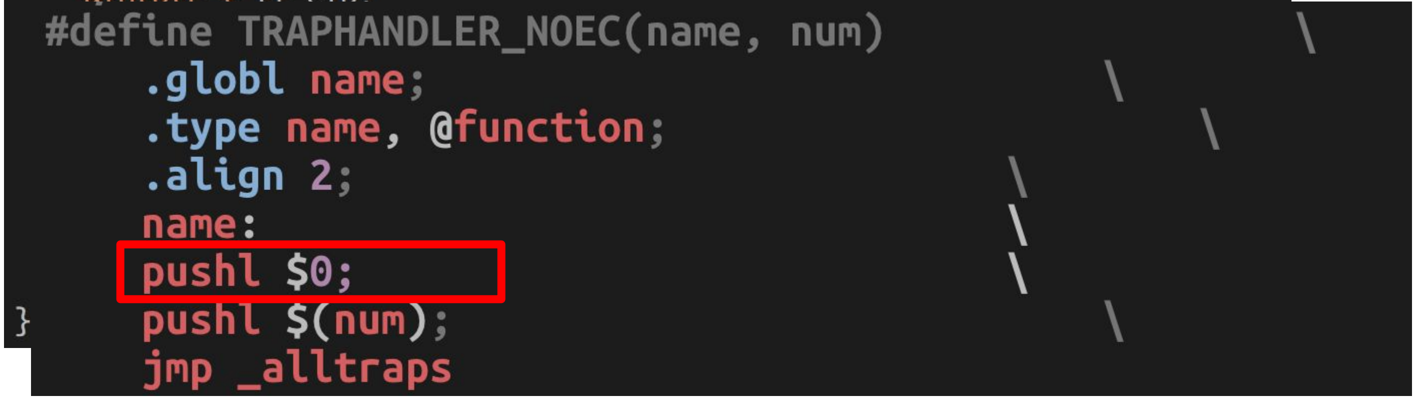
```
struct Trapframe {
    struct PushRegs tf_regs;
    uint16_t tf_es;
    uint16_t tf_padding1;
    uint16_t tf_ds;
    uint16_t tf_padding2;
    uint32_t tf_trapno;
    /* below here defined by x86 hardware */
    uint32_t tf_err;
    uintptr_t tf_eip;
}
```

What about NOEC interrupts?



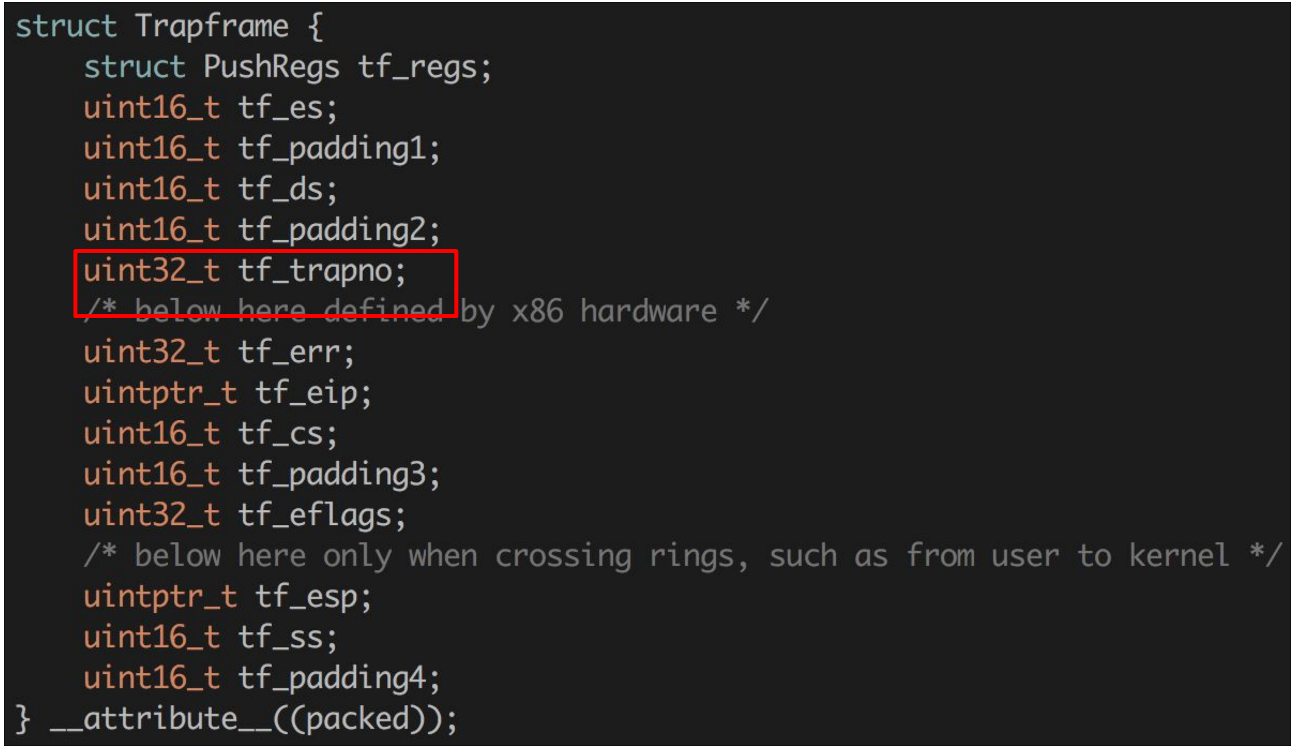
```
+--------------------+ KSTACKTOP
| 0x00000 | old SS   |     " - 4
|      old ESP       |     " - 8
|     old EFLAGS     |     " - 12
| 0x00000 | old CS   |     " - 16
|      old EIP       |     " - 20 <---- ESP
+--------------------+
```

Push 0 as a dummy error code



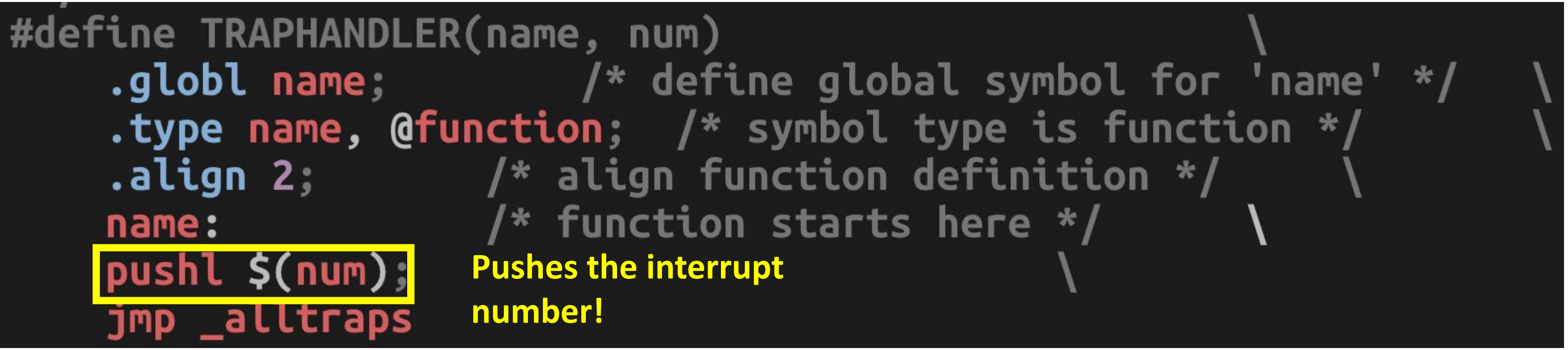
```
#define TRAPHANDLER_NOEC(name, num)                       \
    .globl name;                                \
    .type name, @function;                          \
    .align 2;                               \
    name:                                   \
    pushl $0;                               \
    pushl $(num);                               \
    jmp _alltraps
```

Handling Trap number



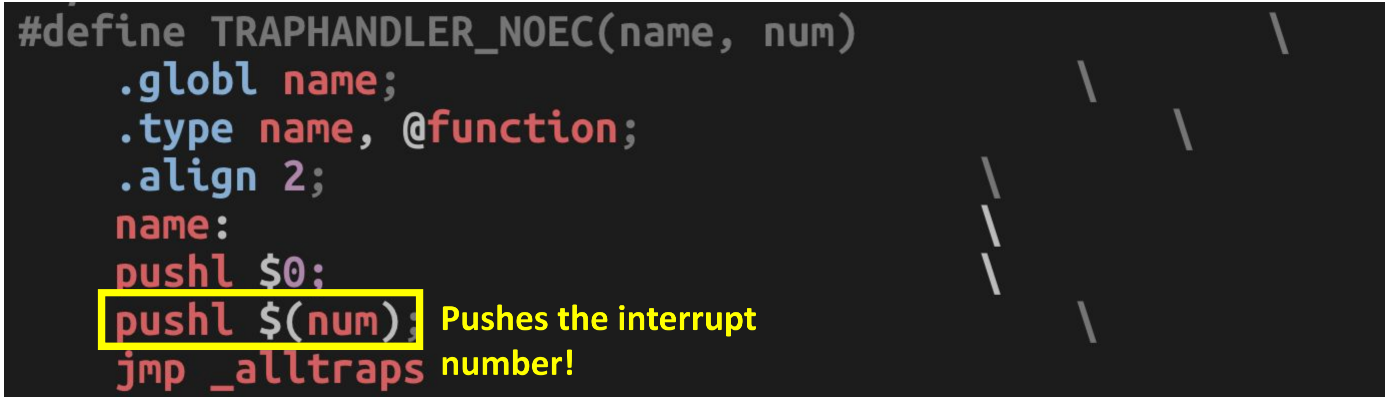
```
struct Trapframe {
    struct PushRegs tf_regs;
    uint16_t tf_es;
    uint16_t tf_padding1;
    uint16_t tf_ds;
    uint16_t tf_padding2;
    uint32_t tf_trapno;
    /* below here defined by x86 hardware */
    uint32_t tf_err;
    uintptr_t tf_eip;
    uint16_t tf_cs;
    uint16_t tf_padding3;
    uint32_t tf_eflags;
    /* below here only when crossing rings, such as from user to kernel */
    uintptr_t tf_esp;
    uint16_t tf_ss;
    uint16_t tf_padding4;
} __attribute__((packed));
```

Handling Trap number



```
#define TRAPHANDLER(name, num)                                    \
    .globl name;            /* define global symbol for 'name' */   \
    .type name, @function;  /* symbol type is function */           \
    .align 2;           /* align function definition */         \
    name:               /* function starts here */          \
    pushl $(num);                                       \
    jmp _alltraps
```

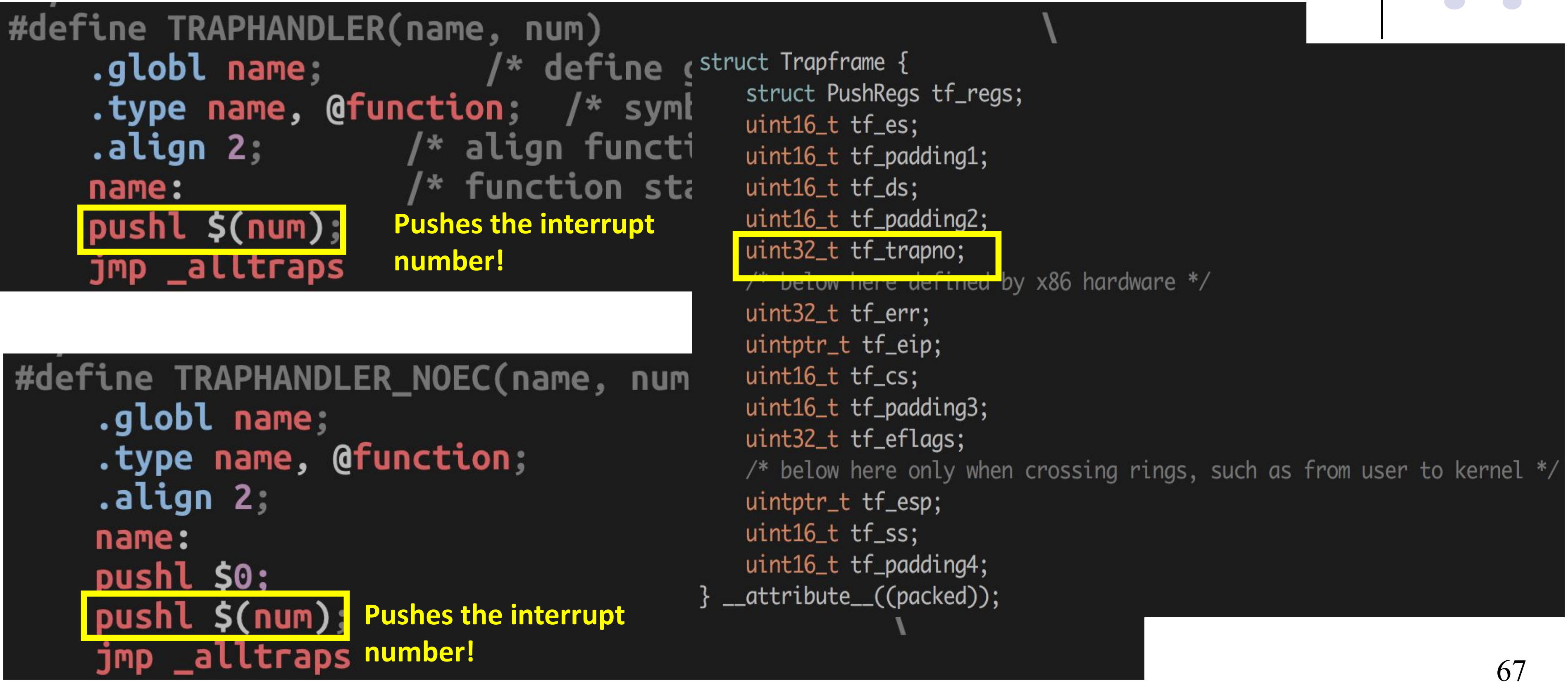
Pushes the interrupt number!



```
#define TRAPHANDLER_NOEC(name, num)                          \
    .globl name;                                         \
    .type name, @function;                                   \
    .align 2;                                        \
    name:                                            \
    pushl $0;                                        \
    pushl $(num);                                        \
    jmp _alltraps
```

Pushes the interrupt number!

Handling Trap number



```
#define TRAPHANDLER(name, num)                                        \
    .globl name;            /* define g
    .type name, @function;  /* symb
    .align 2;               /* align functi
    name:                   /* function sta
    pushl $(num);
    jmp _alltraps
```

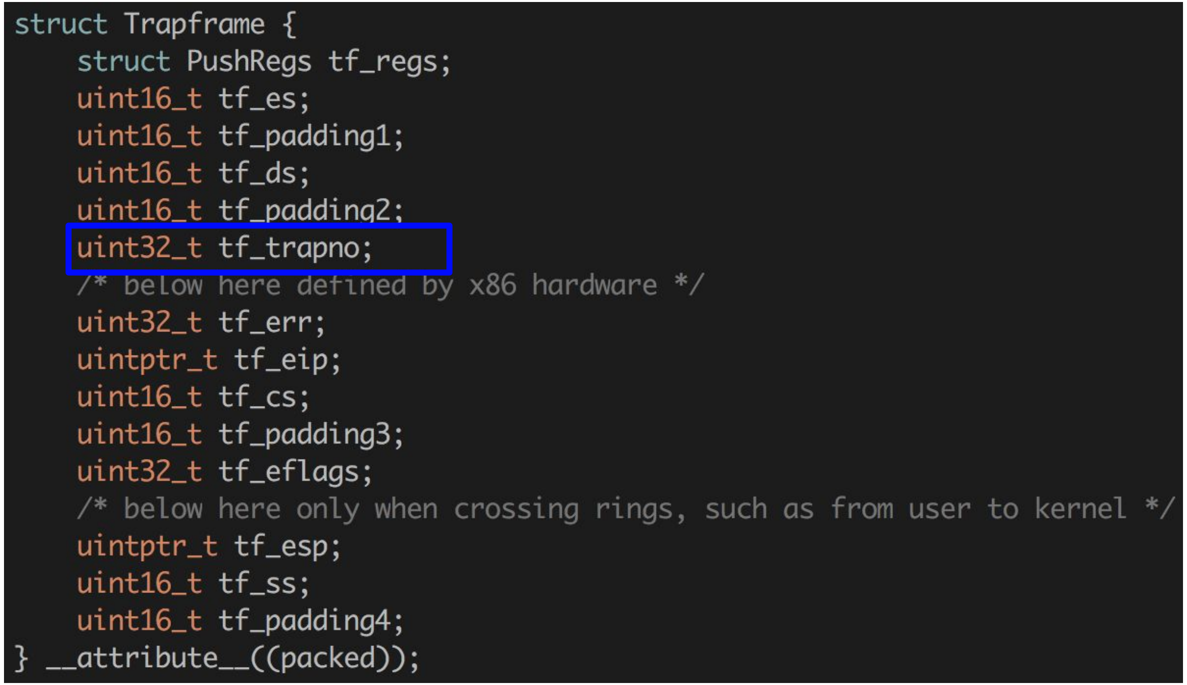
Pushes the interrupt number!

```
#define TRAPHANDLER_NOEC(name, num
    .globl name;
    .type name, @function;
    .align 2;
    name:
    pushl $0;
    pushl $(num);
    jmp _alltraps
```

Pushes the interrupt number!

```
struct Trapframe {
    struct PushRegs tf_regs;
    uint16_t tf_es;
    uint16_t tf_padding1;
    uint16_t tf_ds;
    uint16_t tf_padding2;
    uint32_t tf_trapno;
    /* below here defined by x86 hardware */
    uint32_t tf_err;
    uintptr_t tf_eip;
    uint16_t tf_cs;
    uint16_t tf_padding3;
    uint32_t tf_eflags;
    /* below here only when crossing rings, such as from user to kernel */
    uintptr_t tf_esp;
    uint16_t tf_ss;
    uint16_t tf_padding4;
} __attribute__((packed));
                    \
```

Setting up other parts of TrapFrame



```
struct Trapframe {
    struct PushRegs tf_regs;
    uint16_t tf_es;
    uint16_t tf_padding1;
    uint16_t tf_ds;
    uint16_t tf_padding2;
    uint32_t tf_trapno;
    /* below here defined by x86 hardware */
    uint32_t tf_err;
    uintptr_t tf_eip;
    uint16_t tf_cs;
    uint16_t tf_padding3;
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    /* below here only when crossing rings, such as from user to kernel */
    uintptr_t tf_esp;
    uint16_t tf_ss;
    uint16_t tf_padding4;
} __attribute__((packed));
```
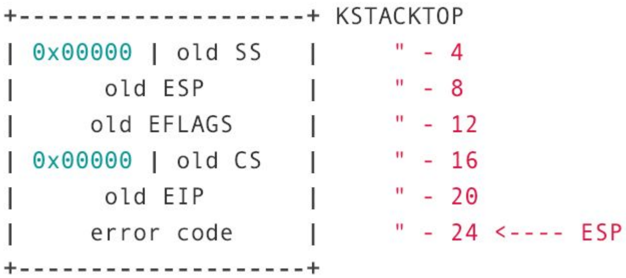
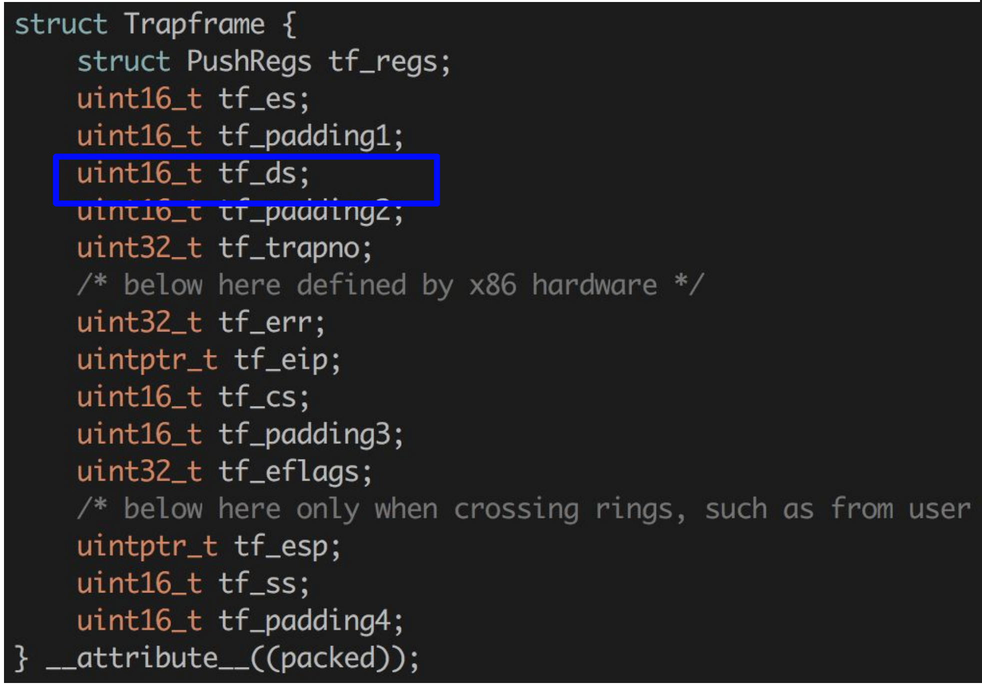



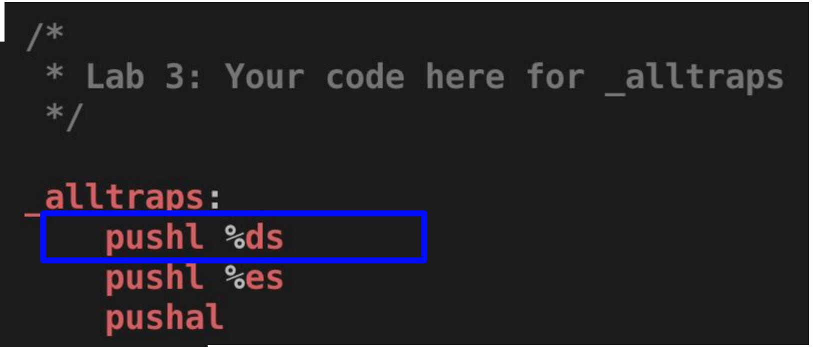
```
+--------------------+ KSTACKTOP
| 0x00000 | old SS   |     " - 4
|      old ESP       |     " - 8
|     old EFLAGS     |     " - 12
| 0x00000 | old CS   |     " - 16
|      old EIP       |     " - 20
|     error code     |     " - 24 <---- ESP
+--------------------+
```

Interrupt number!

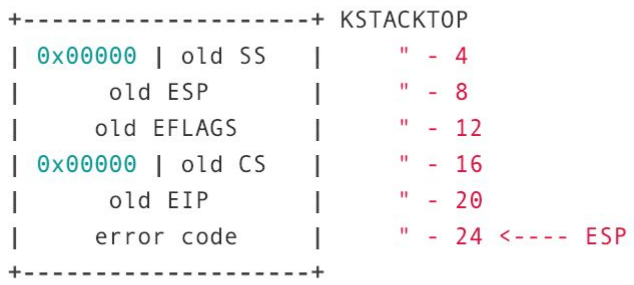
Setting up other parts of TrapFrame



```
struct Trapframe {
    struct PushRegs tf_regs;
    uint16_t tf_es;
    uint16_t tf_padding1;
    uint16_t tf_ds;
    uint16_t tf_padding2;
    uint32_t tf_trapno;
    /* below here defined by x86 hardware */
    uint32_t tf_err;
    uintptr_t tf_eip;
    uint16_t tf_cs;
    uint16_t tf_padding3;
    uint32_t tf_eflags;
    /* below here only when crossing rings, such as from user to kernel */
    uintptr_t tf_esp;
    uint16_t tf_ss;
    uint16_t tf_padding4;
} __attribute__((packed));
```



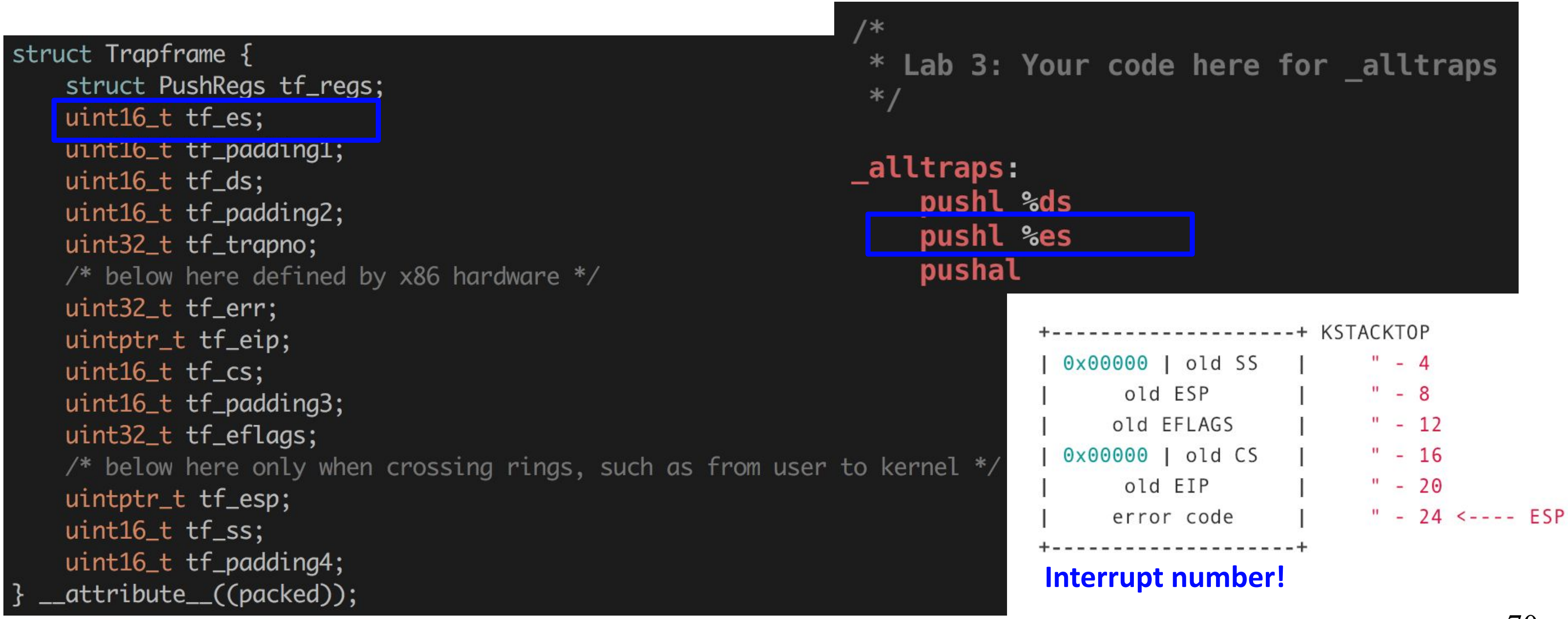
```
/*
 * Lab 3: Your code here for _alltraps
 */

_alltraps:
    pushl %ds
    pushl %es
    pushal
```



```
+--------------------+ KSTACKTOP
| 0x00000 | old SS   |     " - 4
|      old ESP       |     " - 8
|     old EFLAGS     |     " - 12
| 0x00000 | old CS   |     " - 16
|      old EIP       |     " - 20
|     error code     |     " - 24 <---- ESP
+--------------------+
```

Interrupt number!

Setting up other parts of TrapFrame



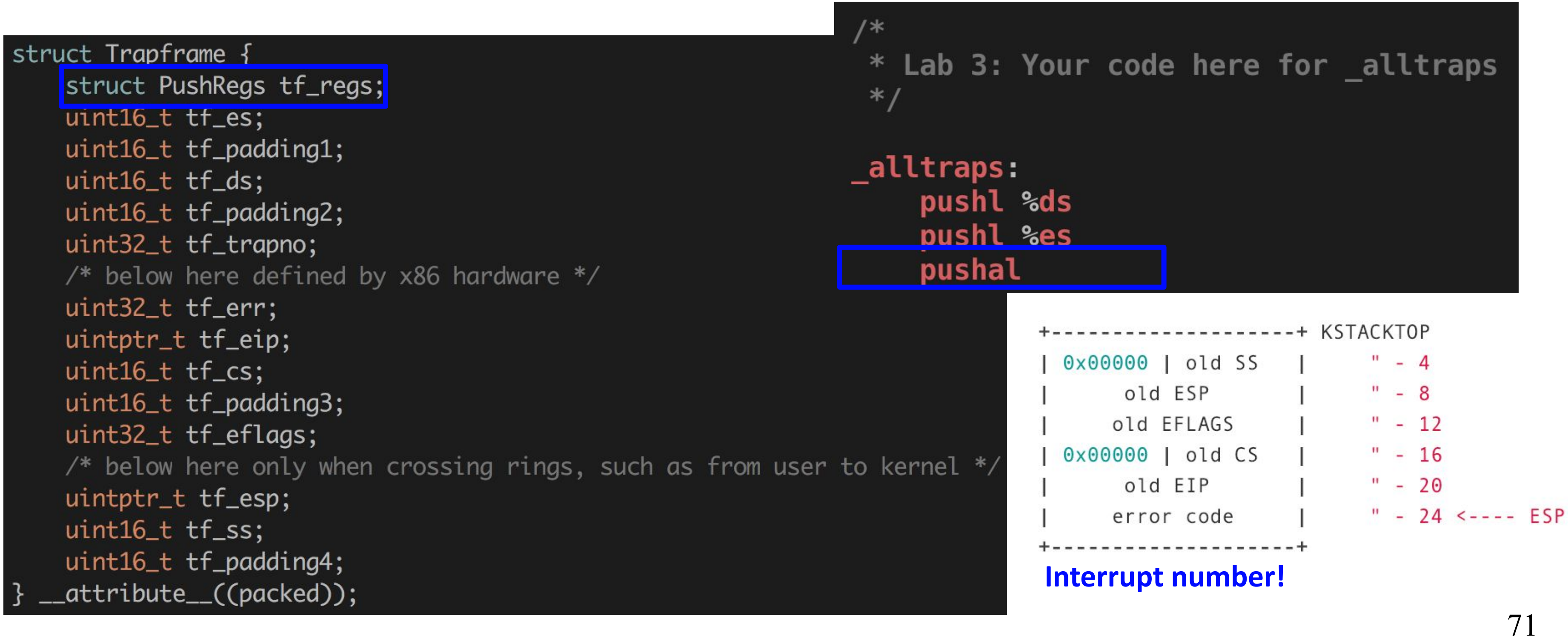
```
struct Trapframe {
	struct PushRegs tf_regs;
	uint16_t tf_es;
	uint16_t tf_padding1;
	uint16_t tf_ds;
	uint16_t tf_padding2;
	uint32_t tf_trapno;
	/* below here defined by x86 hardware */
	uint32_t tf_err;
	uintptr_t tf_eip;
	uint16_t tf_cs;
	uint16_t tf_padding3;
	uint32_t tf_eflags;
	/* below here only when crossing rings, such as from user to kernel */
	uintptr_t tf_esp;
	uint16_t tf_ss;
	uint16_t tf_padding4;
} __attribute__((packed));
```

```
/*
 * Lab 3: Your code here for _alltraps
 */

_alltraps:
	pushl %ds
	pushl %es
	pushal
```

```
+--------------------+ KSTACKTOP
| 0x00000 | old SS   |     " - 4
|      old ESP       |     " - 8
|     old EFLAGS     |     " - 12
| 0x00000 | old CS   |     " - 16
|      old EIP       |     " - 20
|     error code     |     " - 24 <---- ESP
+--------------------+
```

Interrupt number!

Setting up other parts of TrapFrame



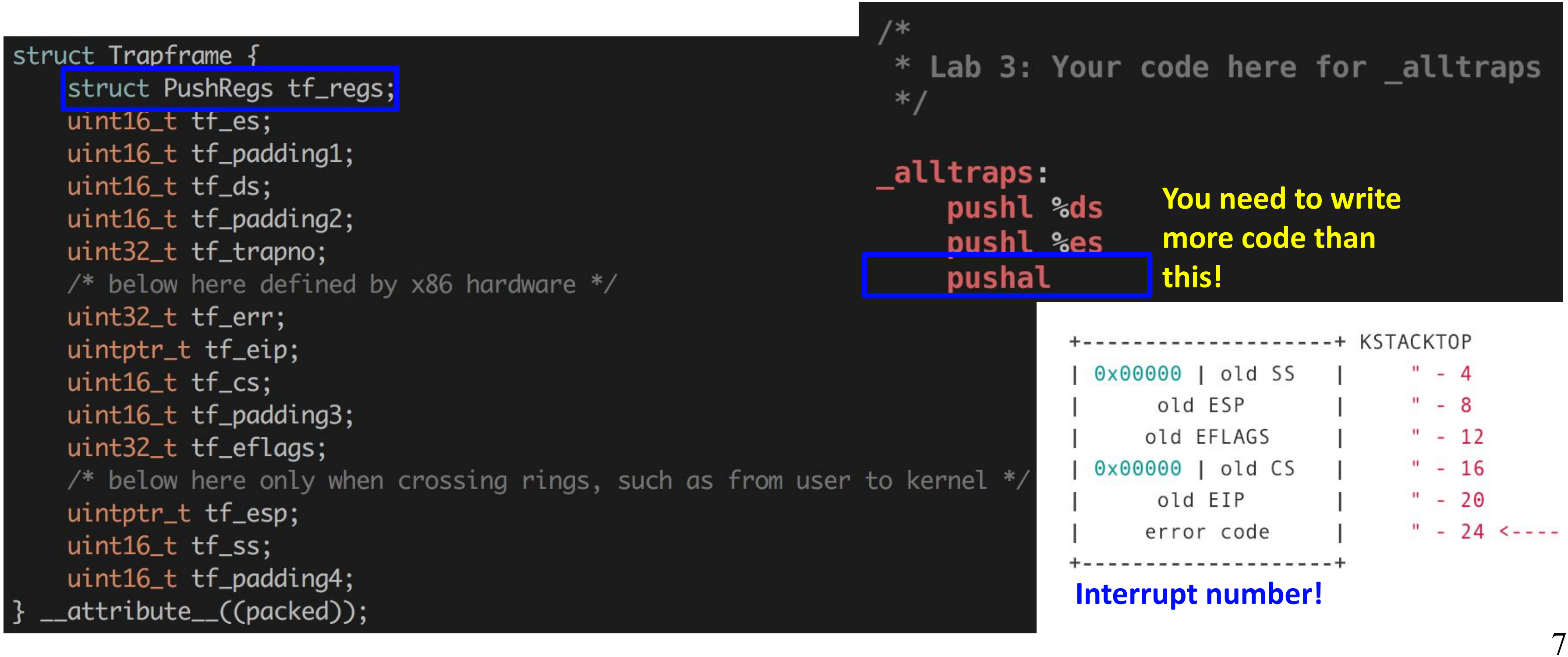
```
struct Trapframe {
    struct PushRegs tf_regs;
    uint16_t tf_es;
    uint16_t tf_padding1;
    uint16_t tf_ds;
    uint16_t tf_padding2;
    uint32_t tf_trapno;
    /* below here defined by x86 hardware */
    uint32_t tf_err;
    uintptr_t tf_eip;
    uint16_t tf_cs;
    uint16_t tf_padding3;
    uint32_t tf_eflags;
    /* below here only when crossing rings, such as from user to kernel */
    uintptr_t tf_esp;
    uint16_t tf_ss;
    uint16_t tf_padding4;
} __attribute__((packed));
```

```
/*
 * Lab 3: Your code here for _alltraps
 */

_alltraps:
        pushl %ds
        pushl %es
        pushal
```

```
+--------------------+ KSTACKTOP
| 0x00000 | old SS   |     " - 4
|      old ESP       |     " - 8
|     old EFLAGS     |     " - 12
| 0x00000 | old CS   |     " - 16
|      old EIP       |     " - 20
|     error code     |     " - 24 <---- ESP
+--------------------+
```

Interrupt number!

Setting up other parts of TrapFrame



```
struct Trapframe {
    struct PushRegs tf_regs;
    uint16_t tf_es;
    uint16_t tf_padding1;
    uint16_t tf_ds;
    uint16_t tf_padding2;
    uint32_t tf_trapno;
    /* below here defined by x86 hardware */
    uint32_t tf_err;
    uintptr_t tf_eip;
    uint16_t tf_cs;
    uint16_t tf_padding3;
    uint32_t tf_eflags;
    /* below here only when crossing rings, such as from user to kernel */
    uintptr_t tf_esp;
    uint16_t tf_ss;
    uint16_t tf_padding4;
} __attribute__((packed));
```

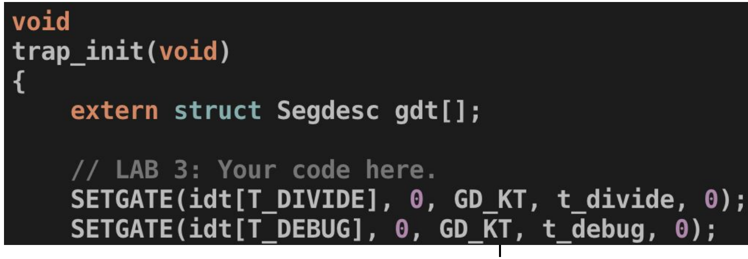
```
/*
 * Lab 3: Your code here for _alltraps
 */

_alltraps:
    pushl %ds
    pushl %es
    pushal
```

You need to write more code than this!

```
+--------------------+ KSTACKTOP
| 0x00000 | old SS   |     " - 4
|      old ESP       |     " - 8
|     old EFLAGS     |     " - 12
| 0x00000 | old CS   |     " - 16
|      old EIP       |     " - 20
|     error code     |     " - 24 <---- ESP
+--------------------+
```

Interrupt number!

JOS Interrupt Handling



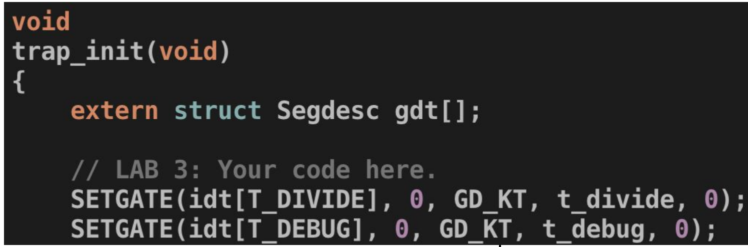
```
void
trap_init(void)
{
    extern struct Segdesc gdt[];

    // LAB 3: Your code here.
    SETGATE(idt[T_DIVIDE], 0, GD_KT, t_divide, 0);
    SETGATE(idt[T_DEBUG], 0, GD_KT, t_debug, 0);
```

- Setup the IDT at trap_init() in kern/trap.c

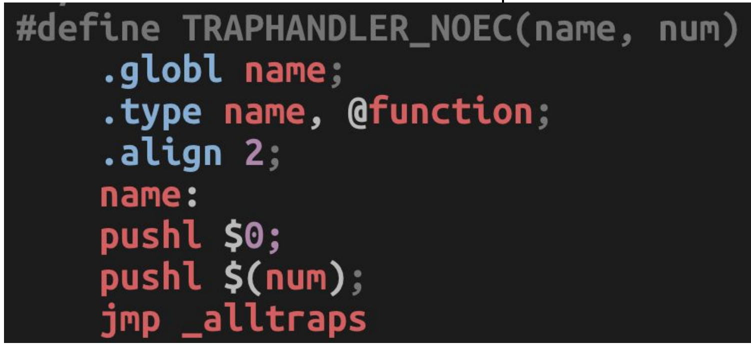
JOS Interrupt Handling

- Setup the IDT at trap_init() in kern/trap.c

- Interrupt arrives to CPU!
- Call interrupt hander in IDT
- Call _alltraps (in kern/trapentry.S)



```
void
trap_init(void)
{
	extern struct Segdesc gdt[];

	// LAB 3: Your code here.
	SETGATE(idt[T_DIVIDE], 0, GD_KT, t_divide, 0);
	SETGATE(idt[T_DEBUG], 0, GD_KT, t_debug, 0);
```

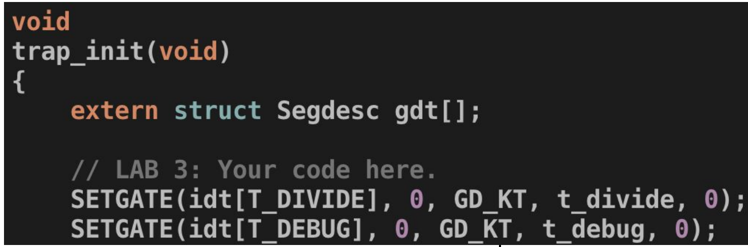


```
#define TRAPHANDLER_NOEC(name, num)
	.globl name;
	.type name, @function;
	.align 2;
	name:
	pushl $0;
	pushl $(num);
	jmp _alltraps
```

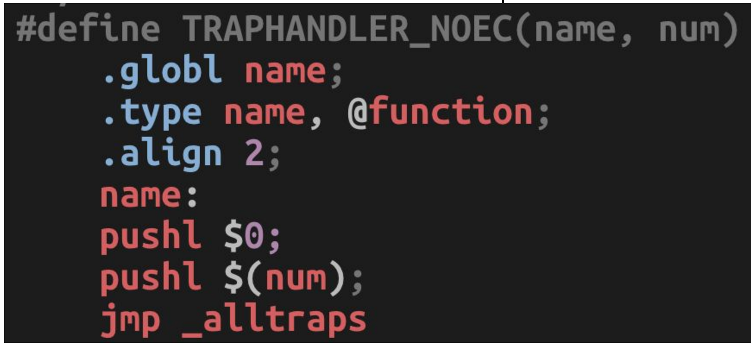
JOS Interrupt Handling

- Setup the IDT at trap_init() in kern/trap.c

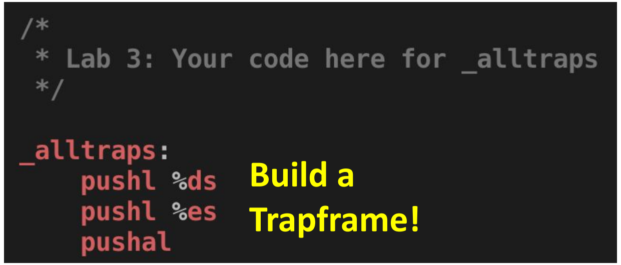
- Interrupt arrives to CPU!
- Call interrupt hander in IDT
- Call _alltraps (in kern/trapentry.S)
- Call trap() in kern/trap.c



```
void
trap_init(void)
{
    extern struct Segdesc gdt[];

    // LAB 3: Your code here.
    SETGATE(idt[T_DIVIDE], 0, GD_KT, t_divide, 0);
    SETGATE(idt[T_DEBUG], 0, GD_KT, t_debug, 0);
```



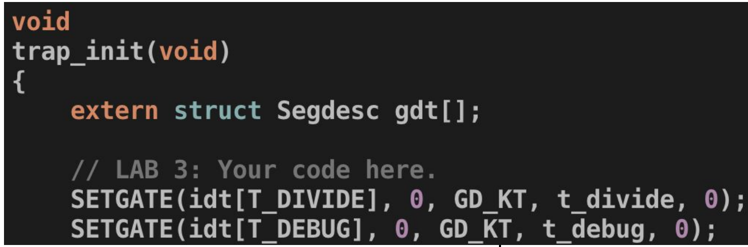
```
#define TRAPHANDLER_NOEC(name, num)
    .globl name;
    .type name, @function;
    .align 2;
    name:
    pushl $0;
    pushl $(num);
    jmp _alltraps
```



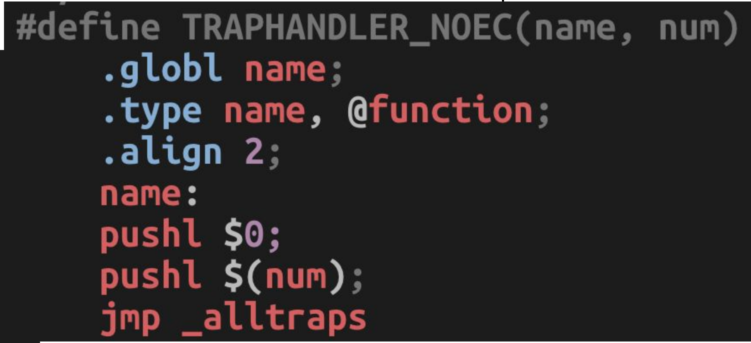
```
/*
 * Lab 3: Your code here for _alltraps
 */

_alltraps:
    pushl %ds
    pushl %es
    pushal
```

Build a Trapframe!

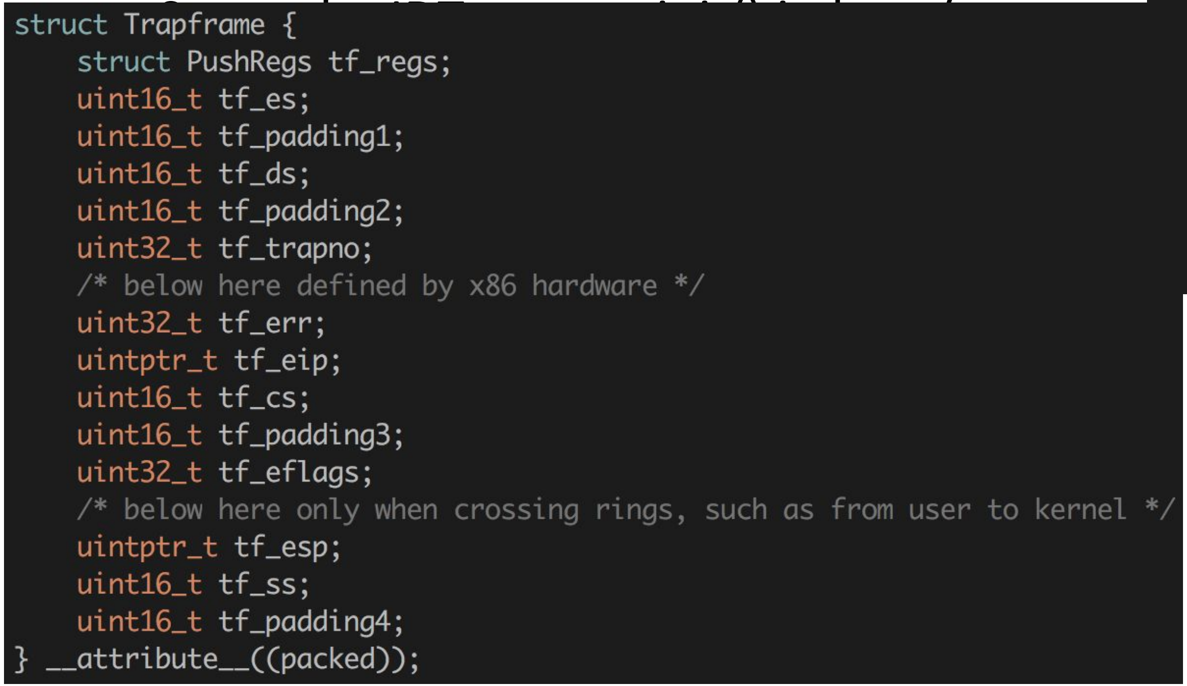
JOS Interrupt Handling



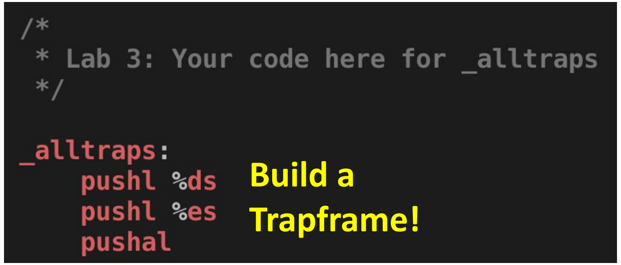
```
void
trap_init(void)
{
    extern struct Segdesc gdt[];

    // LAB 3: Your code here.
    SETGATE(idt[T_DIVIDE], 0, GD_KT, t_divide, 0);
    SETGATE(idt[T_DEBUG], 0, GD_KT, t_debug, 0);
```



```
#define TRAPHANDLER_NOEC(name, num)
    .globl name;
    .type name, @function;
    .align 2;
    name:
    pushl $0;
    pushl $(num);
    jmp _alltraps
```



```
struct Trapframe {
    struct PushRegs tf_regs;
    uint16_t tf_es;
    uint16_t tf_padding1;
    uint16_t tf_ds;
    uint16_t tf_padding2;
    uint32_t tf_trapno;
    /* below here defined by x86 hardware */
    uint32_t tf_err;
    uintptr_t tf_eip;
    uint16_t tf_cs;
    uint16_t tf_padding3;
    uint32_t tf_eflags;
    /* below here only when crossing rings, such as from user to kernel */
    uintptr_t tf_esp;
    uint16_t tf_ss;
    uint16_t tf_padding4;
} __attribute__((packed));
```



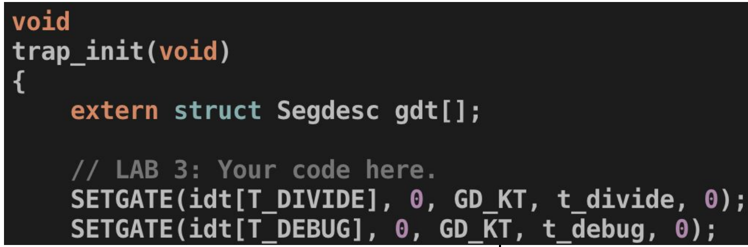
```
/*
 * Lab 3: Your code here for _alltraps
 */

_alltraps:
    pushl %ds
    pushl %es
    pushal
```

Build a Trapframe!

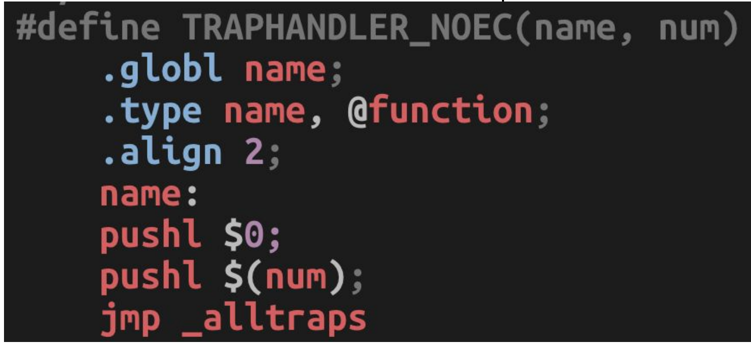
JOS Interrupt Handling

- Setup the IDT at trap_init() in kern/trap.c

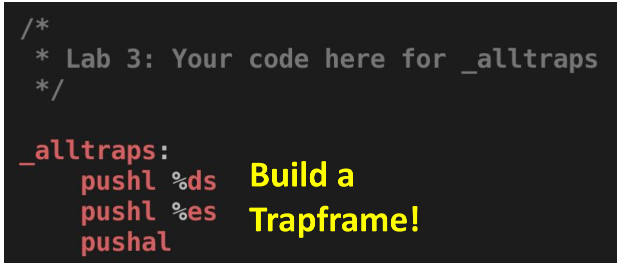
- Interrupt arrives to CPU!
- Call interrupt hander in IDT
- Call _alltraps (in kern/trapentry.S)
- Call trap() in kern/trap.c



```
void
trap_init(void)
{
	extern struct Segdesc gdt[];

	// LAB 3: Your code here.
	SETGATE(idt[T_DIVIDE], 0, GD_KT, t_divide, 0);
	SETGATE(idt[T_DEBUG], 0, GD_KT, t_debug, 0);
```

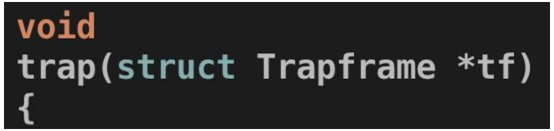


```
#define TRAPHANDLER_NOEC(name, num)
	.globl name;
	.type name, @function;
	.align 2;
	name:
	pushl $0;
	pushl $(num);
	jmp _alltraps
```



```
/*
 * Lab 3: Your code here for _alltraps
 */

_alltraps:
	pushl %ds
	pushl %es
	pushal
```

Build a Trapframe!

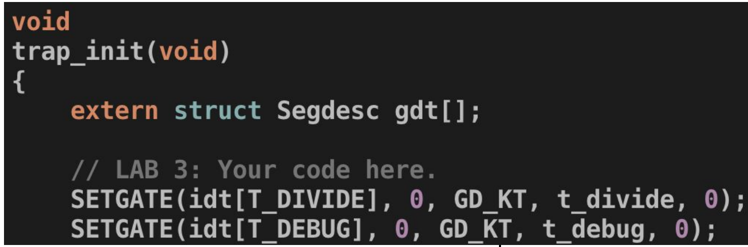


```
void
trap(struct Trapframe *tf)
{
```

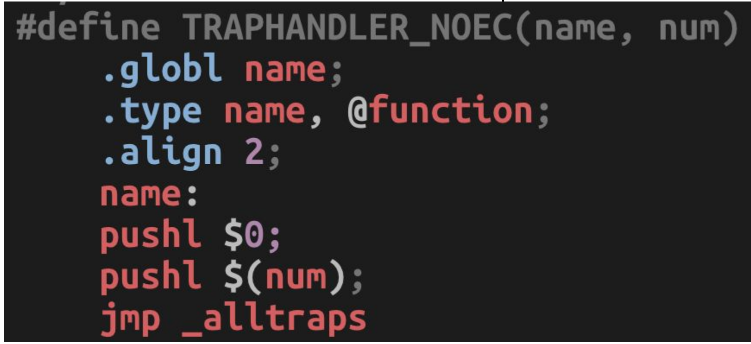
JOS Interrupt Handling

- Setup the IDT at trap_init() in kern/trap.c

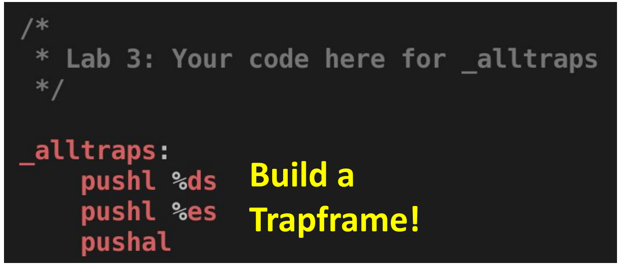
- Interrupt arrives to CPU!
- Call interrupt hander in IDT
- Call _alltraps (in kern/trapentry.S)
- Call trap() in kern/trap.c
- Call trap_dispatch() in kern/trap.c



```
void
trap_init(void)
{
	extern struct Segdesc gdt[];

	// LAB 3: Your code here.
	SETGATE(idt[T_DIVIDE], 0, GD_KT, t_divide, 0);
	SETGATE(idt[T_DEBUG], 0, GD_KT, t_debug, 0);
```

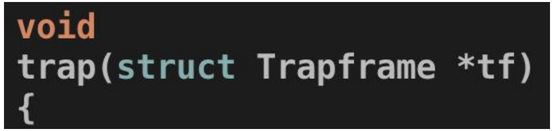


```
#define TRAPHANDLER_NOEC(name, num)
	.globl name;
	.type name, @function;
	.align 2;
	name:
	pushl $0;
	pushl $(num);
	jmp _alltraps
```

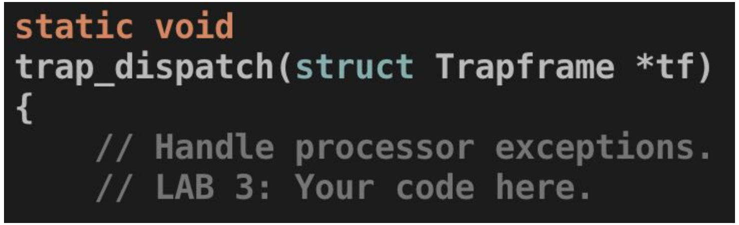


```
/*
 * Lab 3: Your code here for _alltraps
 */

_alltraps:
	pushl %ds
	pushl %es
	pushal
```

Build a Trapframe!



```
void
trap(struct Trapframe *tf)
{
```



```
static void
trap_dispatch(struct Trapframe *tf)
{
	// Handle processor exceptions.
	// LAB 3: Your code here.
```