CS444/544 Operating Systems II

Lecture 9

Handling Interrupt/Exceptions

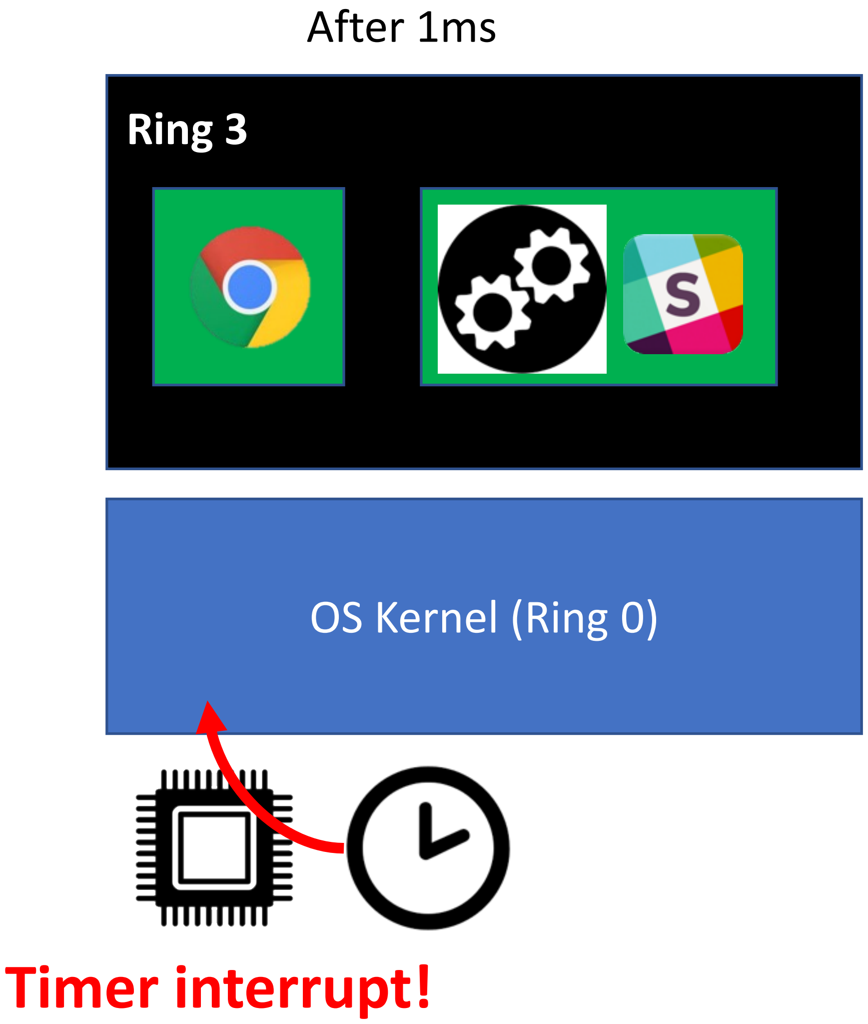
5/1/2024

Acknowledgement: Slides drawn heavily from Yeongjin Jiang

Oregon State University

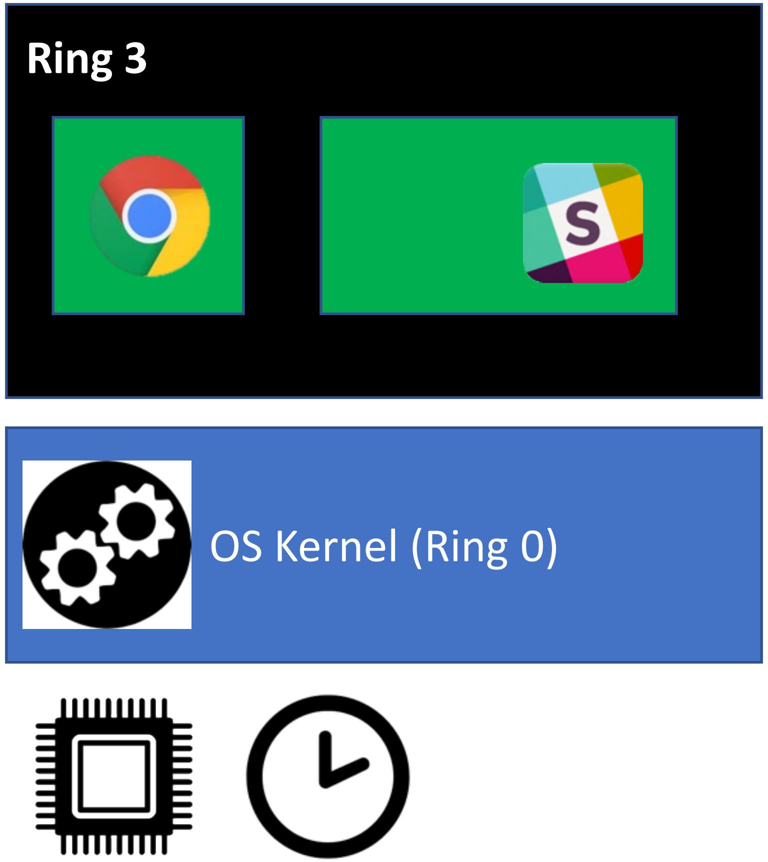
Recap: Timer Interrupt and Multitasking

- Preemptive Multitasking (Lab 4)
- CPU generates an interrupt to force execution at kernel after some time quantum
  - E.g., 1000Hz, on each 1ms..



Recap: Timer Interrupt and Multitasking

- Preemptive Multitasking (Lab 4)
- CPU generates an interrupt to force execution at kernel after some time quantum
  - E.g., 1000Hz, on each 1ms..
- Guaranteed execution in kernel
  - Let kernel mediate resource contention



Recap: Timer Interrupt and Multitasking

- Preemptive Multitasking (Lab 4)
- CPU generates an interrupt to force execution at kernel after some time quantum
  - E.g., 1000Hz, on each 1ms..
- Guaranteed execution in kernel
  - Let kernel mediate resource contention

Recap: Interrupt

- Asynchronous (can happen at any time of execution)
- Mostly caused by external hardware
- Read
  - https://en.wikipedia.org/wiki/Intel_8259
  - https://en.wikipedia.org/wiki/Advanced_Programmable_Interrupt_Controller
- Software interrupt
  - int $0x30 ← system call in JOS

Recap: Exceptions

- Synchronous (an execution of an instruction can generate this)

- Faults
  - Faulting instruction has not finished yet (e.g., page fault)
  - Can resume the execution after handling the fault
- Non-fault exceptions
  - The instruction (generated exception) has been executed (e.g., breakpoint)
  - Cannot resume the instruction (if so, it will trap indefinitely…)
- Some exceptions are fatal
  - Triple fault (halts the machine)

Handling Interrupt/Exceptions

- Set 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

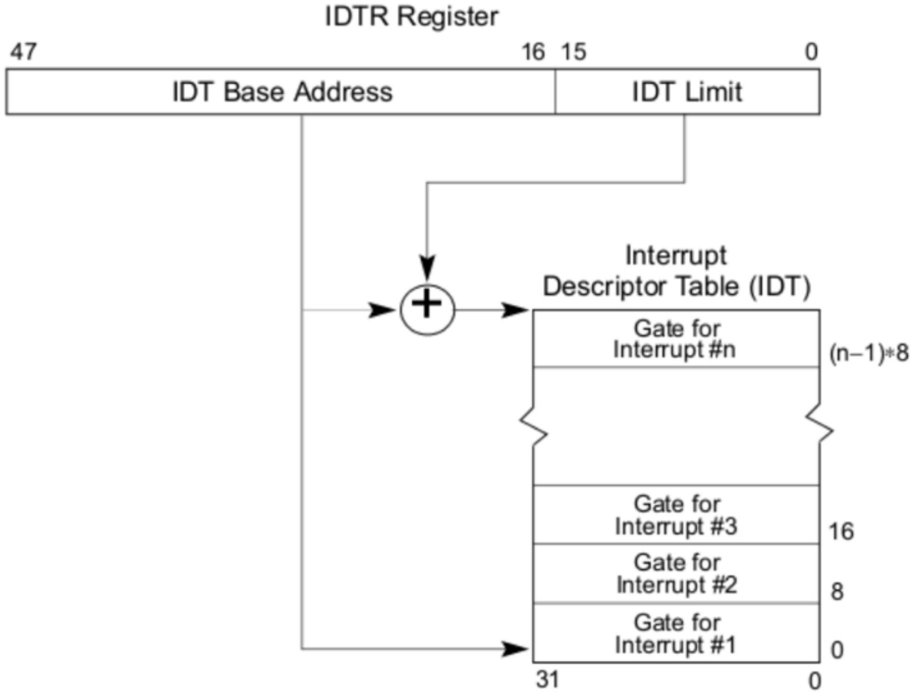


Figure 6-1. Relationship of the IDTR and IDT

Handling Interrupt/Exceptions

- Set an Interrupt Descriptor Table (IDT)

Interrupt Number	Code address
0 (Divide error)	t_divide
1 (Debug)	t_debug
2 (NMI, Non-maskable Interrupt)	t_nmi
3 (Breakpoint)	t_brkpt
4 (Overflow)	t_oflow
…	
8 (Double Fault)	t_dblflt
…	
14 (Page Fault)	t_pgflt
…	…
0x30 (syscall in JOS)	t_syscall

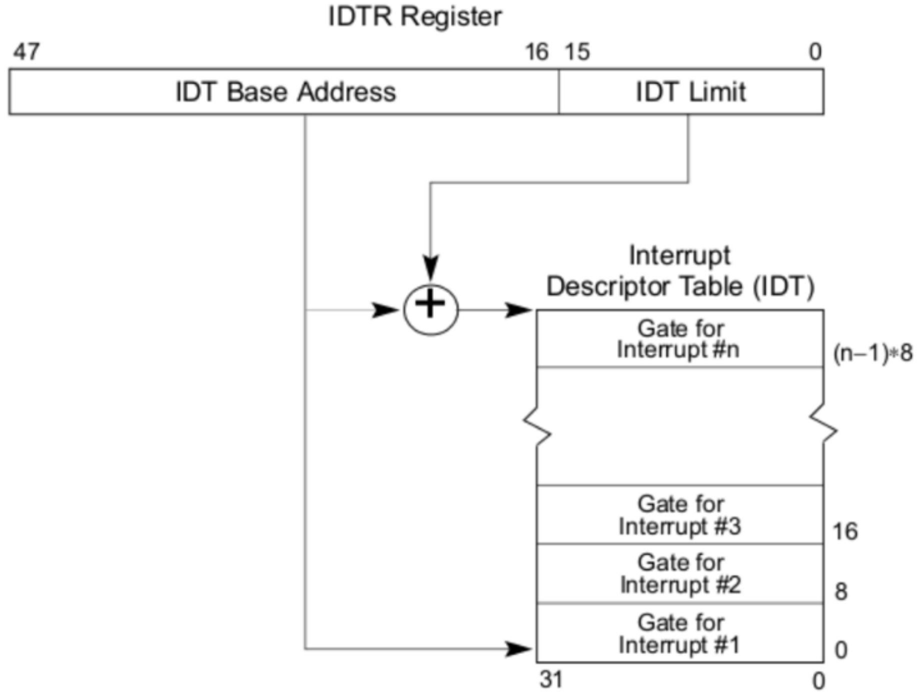


Figure 6-1. Relationship of the IDTR and IDT

Handling Interrupt/Exceptions

- Set an Interrupt Descriptor Table (IDT)

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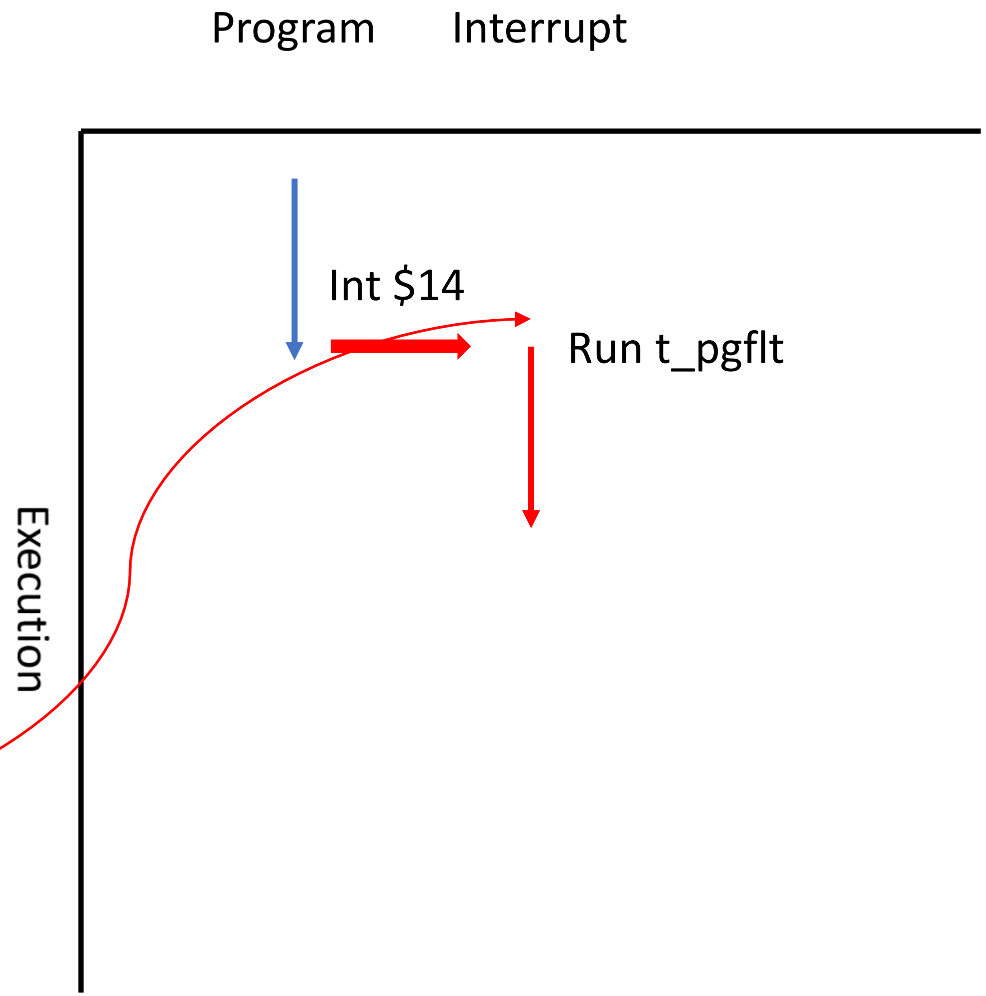
0 (Divide error)	t_divide
1 (Debug)	t_debug
2 (NMI, Non-maskable Interrupt)	t_nmi
3 (Breakpoint)	t_brkpt
4 (Overflow)	t_oflow
…	
8 (Double Fault)	t_dblflt
…	
14 (Page Fault)	t_pgflt
…	…
0x30 (syscall in JOS)	t_syscall

```
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
```

Interrupt/Exception Handler

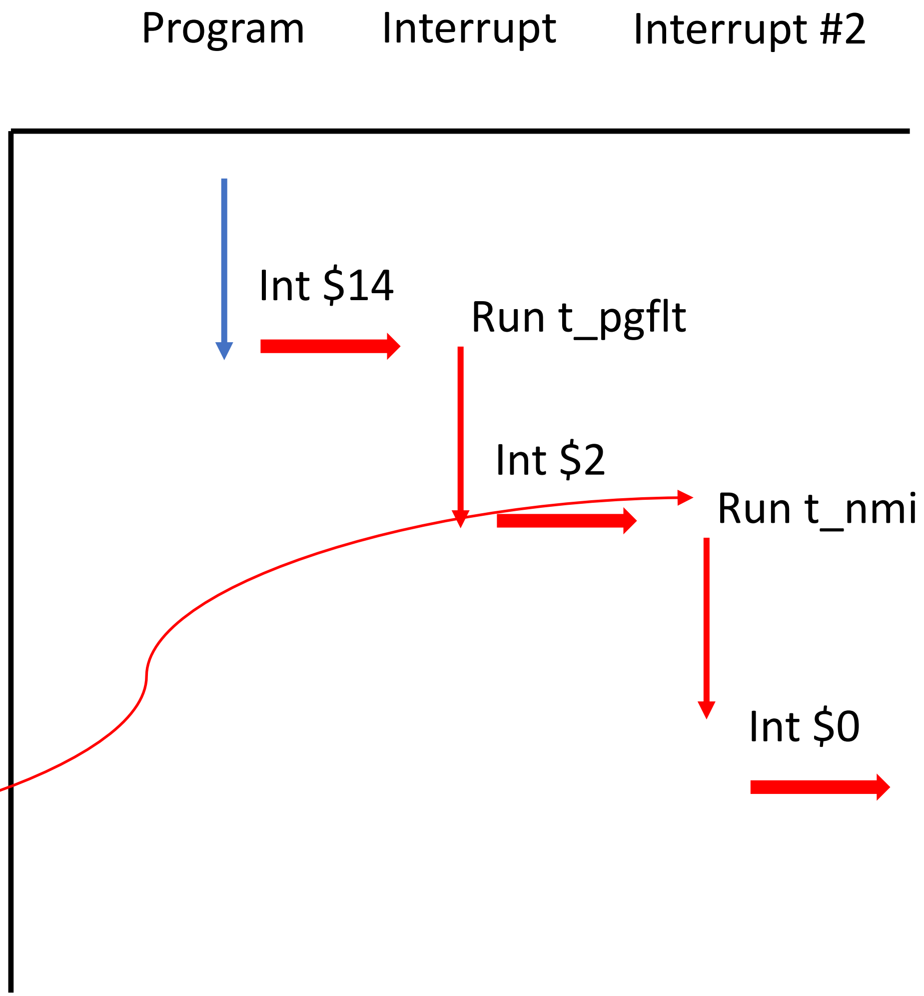
- Processing Interrupt/Exception

Interrupt Number	Code address
0 (Divide error)	t_divide
1 (Debug)	t_debug
2 (NMI, Non-maskable Interrupt)	t_nmi
3 (Breakpoint)	t_brkpt
4 (Overflow)	t_oflow
…	
8 (Double Fault)	t_dblflt
…	
14 (Page Fault)	t_pgflt
…	…
0x30 (syscall in JOS)	t_syscall



Interrupt/Exception Handler

- What if another interrupt happens
  - During processing an interrupt?
- Handle interrupts indefinitely…
  - Cannot continue the program execution
  - Even cannot finish an interrupt handler…



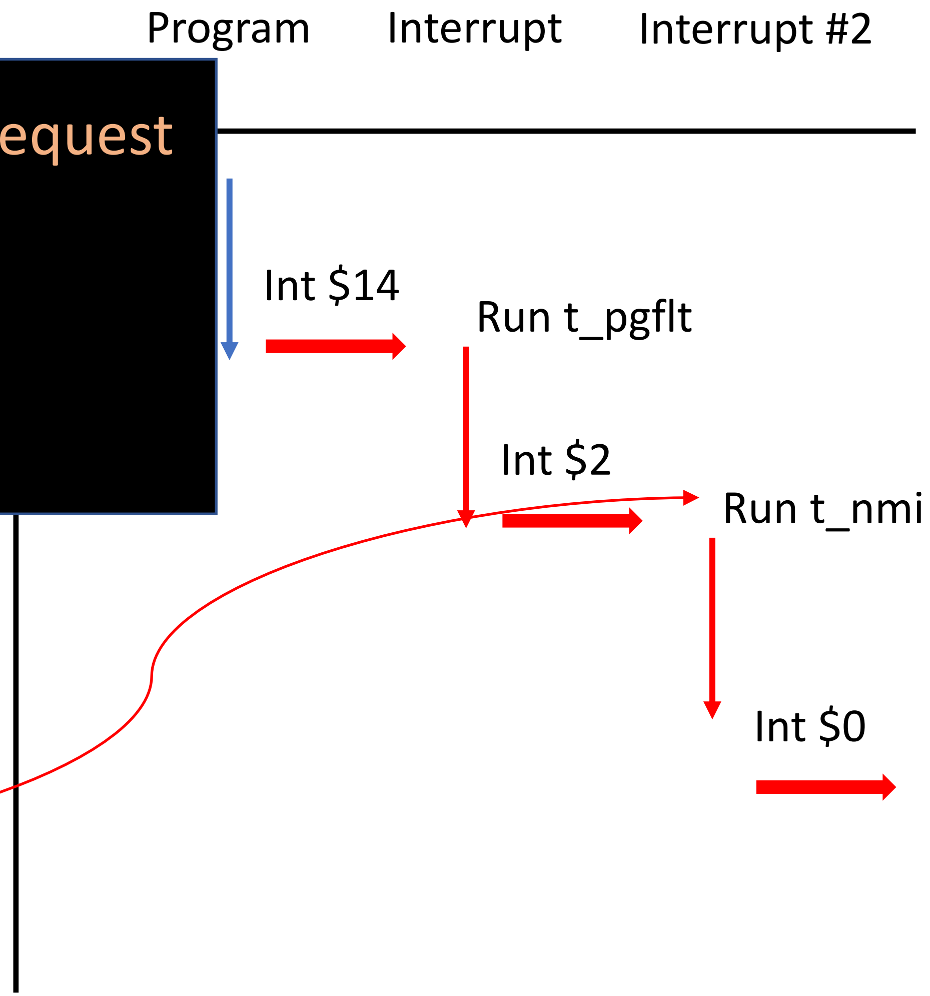
Interrupt Number	Code address
0 (Divide error)	t_divide
1 (Debug)	t_debug
2 (NMI, Non-maskable Interrupt)	t_nmi
…	

Interrupt/Exception Handler

- What if another interrupt happens

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

To avoid such an 'infinite' interrupt,
We **disable interrupt** while handling interrupt…

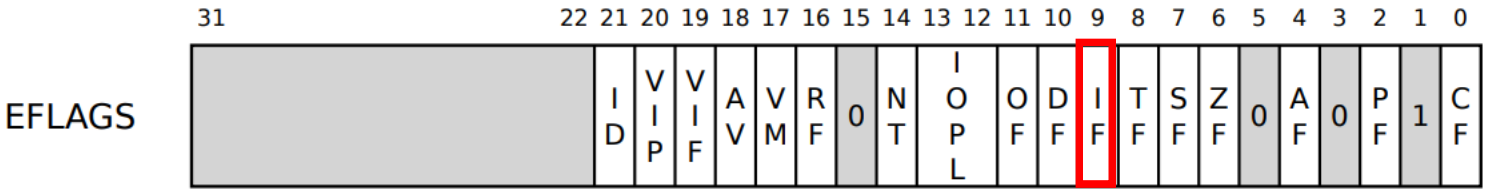


Interrupt Number	Code address
0 (Divide error)	t_divide
1 (Debug)	t_debug
2 (NMI, Non-maskable Interrupt)	t_nmi
…	

Controlling Hardware Interrupt

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

- Enabled/disabled by CPU
- IF flag in EFLAGS indicates this
  - `sti (set interrupt flag, turn on)`
  - `cli (clear interrupt flag, turn off)`



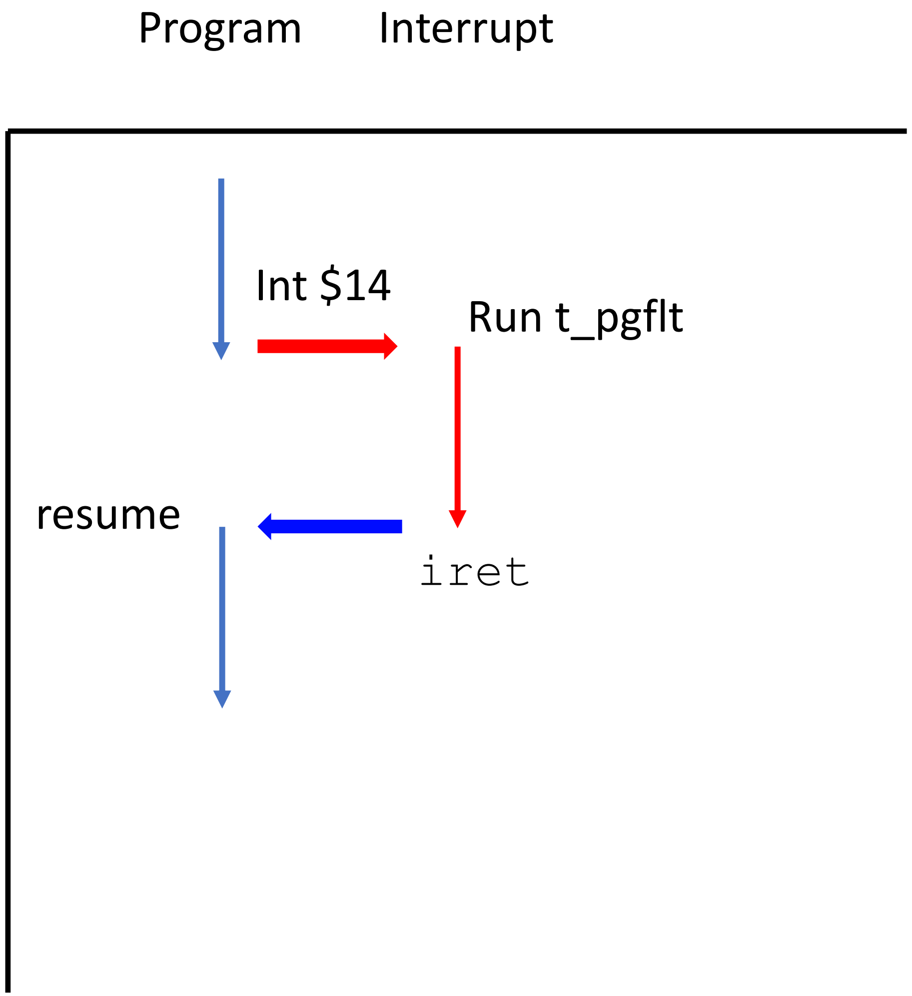
Status flags
- CF Carry flag
- PF Parity flag
- AF Auxiliary carry flag
- ZF Zero flag
- SF Sign flag
- OF Overflow flag

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
- VM Virtual-8086 mode
- AC Alignment check
- VIF Virtual intr. flag
- VIP Virtual intr. pending
- ID ID flag

Interrupt/Exceptions Stop Current Execution

- 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

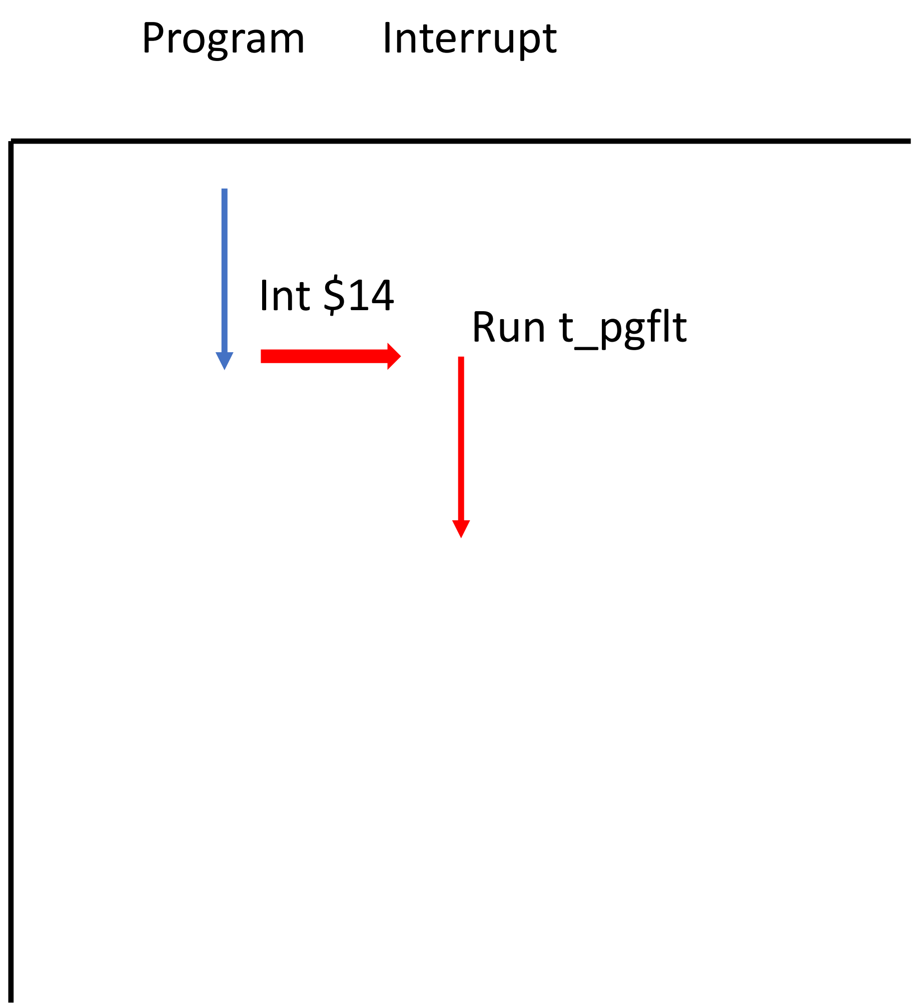


Storing an Execution Context

```
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;
}
```

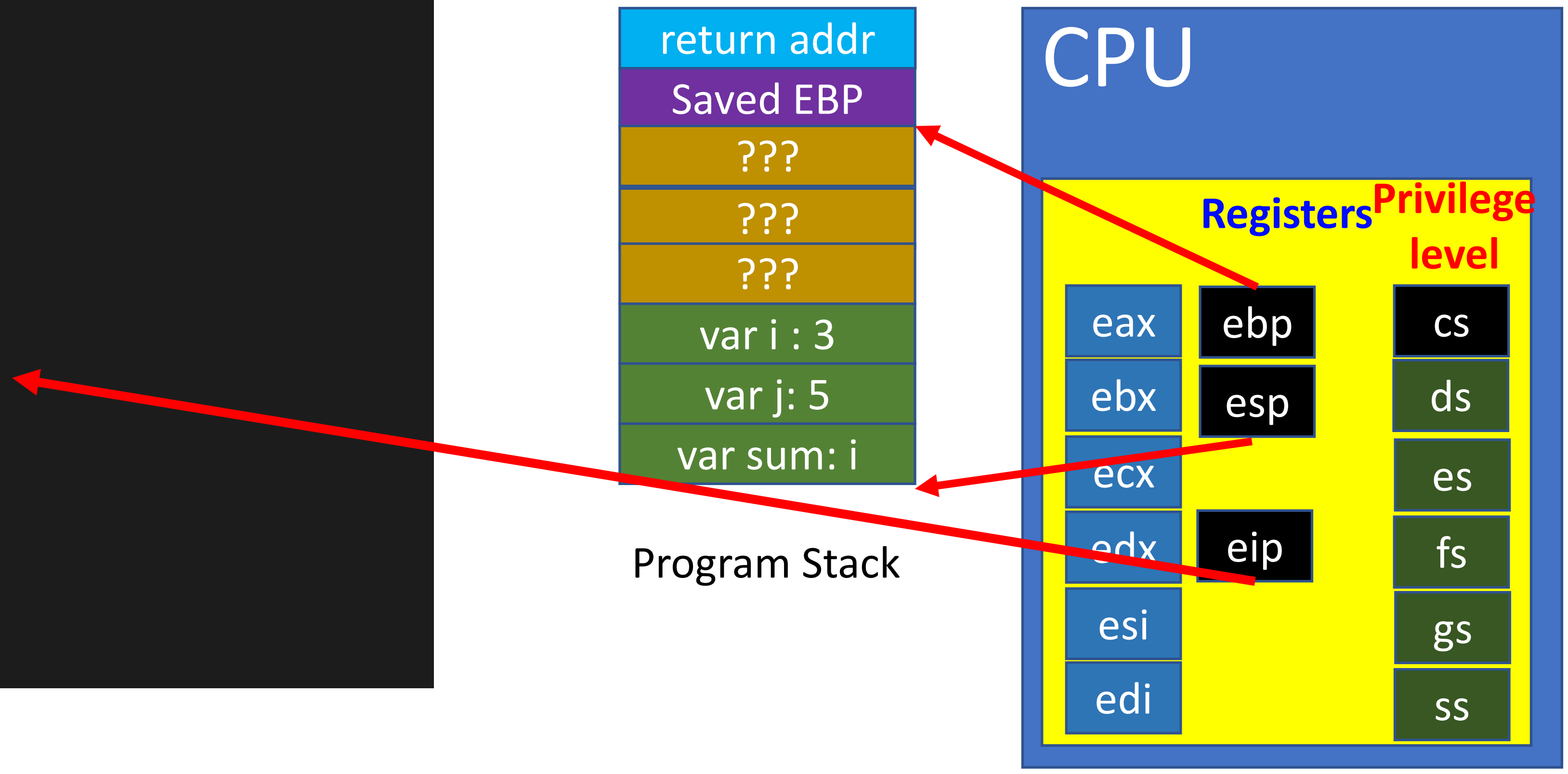
Execute

Accessing
a global variable,
Page fault!



How to Store an Execution Context?

```c
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;
}
```



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!)

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

CPU only stores
esp, eip, EFLAGS, ss, cs
What about the others?

TrapFrame in JOS Stores the Context

```c
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));
```

2 byte padding because cs is 16-bit

2 byte padding because ss is 16-bit

```c
struct PushRegs {
    /* registers as pushed by pusha */
    uint32_t reg_edi;
    uint32_t reg_esi;
    uint32_t reg_ebp;
    uint32_t reg_oesp;      /* Useless */
    uint32_t reg_ebx;
    uint32_t reg_edx;
    uint32_t reg_ecx;
    uint32_t reg_eax;
} __attribute__((packed));
```

JOS stores additional information as Struct Trapframe

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

How does JOS Handle Interrupt?

- You will setup 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

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

How Can You Know an Interrupt/Exception has EC/NOEC?

- Intel Manual
  - [IA-32 Developer's Manual]
  - (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.

EC? NOEC? Error Code!

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

JOS Implementation

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

Pushes the interrupt number!

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

Push 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!

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

Push the interrupt number!

How Can We Store a 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
+--------------------+
```

Push the interrupt number!

JOS Interrupt Handling

```
struct Trapframe {
    struct PushRegs tf_regs;
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    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));
```

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

```
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);
```

```
fine 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)
{
```

In trap_dispatch()

- All Interrupt/Exceptions comes to this function
  - Check trap number from tf->trapno
- Handle the following interrupts
  - T_PGFLT (page fault, 14)
  - T_BRKPT (breakpoint, 3)
  - T_SYSCALL (system call, 48)

```
// Handle processor exceptions.
// LAB 3: Your code here.

switch (tf->tf_trapno) {
    case T_PGFLT:
    {
        // handle page fault here
    }
    case T_BRKPT:
    {
        // handle breakpoint here
    }
    case T_SYSCALL:
    {
        // handle system call here
    }
    default:
    {
    }
}
```

System Call

- An API of an OS for system services
- User-level Application calls functions in kernel
  - Open
  - Read
  - Write
  - Exec
  - Send
  - Recv
  - Socket
  - Etc…

What Kind of System Call Do We Implement in Lab 3?

- See kern/syscall.c
- `void sys_cputs(const char *s, size_t len)`
  - Print a string in s to the console
- `int sys_cgetc(void)`
  - Get a character from the keyboard
- `envid_t sys_getenvid(void)`
  - Get the current environment ID (process ID)
- `int sys_env_destroy(envid_t)`
  - Kill the current environment (process)

Required for Implementing scanf, printf, etc…

How Can We Pass Arguments to System Calls?

- In JOS
  - eax = system call number
  - edx = 1^{st} argument
  - ecx = 2^{nd} argument
  - ebx = 3^{rd} argument
  - edi = 4^{th} argument
  - esi = 5^{th} argument
- E.g., calling sys_cputs(“asdf”, 4);
  - eax = 0
  - edx = address of “asdf”
  - ecx = 4
  - ebx, edi, esi = not used
- And then
  - Run `int $0x30`

```
/* system call numbers */
enum {
	SYS_cputs = 0,
	SYS_cgetc,
	SYS_getenvid,
	SYS_env_destroy,
	NSYSCALLS
};
```

Will add more as
our lab implementation progresses

How Can We Pass Arguments to System Calls?

- E.g., calling sys_cputs(“asdf”, 4);
  - eax = 0
  - edx = address of “asdf”
  - ecx = 4
  - ebx, edi, esi = not used
- And then
  - Run `int $0x30`
- At interrupt handler
  - Read syscall number from the eax of tf
    - syscall number is 0 -> calling SYS_cputs
  - Read 1st argument from the edx of tf
    - Address of “adsf”
  - Read 2nd argument from ecx of tf
    - 4
  - call sys_cputs(“asdf”, 4) // in kernel

```
/* system call numbers */
enum {
    SYS_cputs = 0,
    SYS_cgetc,
    SYS_getenvid,
    SYS_env_destroy,
    NSYSCALLS
};
```

How Can We Pass Arguments to System Calls?

- In Linux x86 (32-bit)
  - eax = system call number
  - ebx = 1st argument
  - ecx = 2nd argument
  - edx = 3rd argument
  - esi = 4th argument
  - edi = 5th argument
- See table
  - https://syscalls.kernelgrok.com/ : lists 337 system calls…

0	sys_restart_syscall	0x00
1	sys_exit	0x01
2	sys_fork	0x02
3	sys_read	0x03
4	sys_write	0x04
5	sys_open	0x05
6	sys_close	0x06
7	sys_waitpid	0x07
8	sys_creat	0x08
9	sys_link	0x09
10	sys_unlink	0x0a
11	sys_execve	0x0b

How Can We Invoke a System Call?

- Set all arguments in the registers
  - Order: edx ecx ebx edi esi
- int $0x30 (in JOS)
  - Software interrupt 48
- int $0x80 (in 32bit Linux)
  - Software interrupt 128

System Call Handling Routine (User)

- User calls a function
  - cprintf -> calls sys_cputs()
- sys_cputs() at user code will call syscall() (lib/syscall.c)
  - This syscall() is at lib/syscall.c
  - Set args in the register and then
- int $0x30
- Now kernel execution starts…

System Call Handling Routine (Kernel)

- CPU gets software interrupt
- TRAPHANDLER_NOEC(T_SYSCALL…)
- _alltraps()
- trap()
- trap_dispatch()
  - Get registers that store arguments from struct Trapframe *tf
  - Call syscall() using those registers
    - This syscall() is at kern/syscall.c

System Call Handling Routine (Return to User)

- Finishing handling of syscall (return of syscall())
- trap() calls env_run()
  - Get back to the user environment!
- env_pop_tf()
  - Runs `iret`
- Back to Ring 3!

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

```
void
env_pop_tf(struct Trapframe *tf)
{
    asm volatile(
        "\tmovl %0,%%esp\n"
        "\tpopal\n"
        "\tpopl %%es\n"
        "\tpopl %%ds\n"
        "\taddl $0x8,%%esp\n" /* skip tf_trapno and tf_errcode */
        "\tiret\n"
        : : "g" (tf) : "memory");
    panic("iret failed");  /* mostly to placate the compiler */
}
```

Restore the CPU state from the trap frame

Software Interrupt Handling (e.g., syscall)

- Execution…
- int $0xAA

Ring 3

- Call trap gate
- Handle trap!
- Pop context
- iret

Ring 0

- Execution resumes…

Ring 3