CS 410/510

Languages & Low-Level Programming

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Fall 2018

Week 3: Segmentation, Protected Mode, Interrupts, and Exceptions

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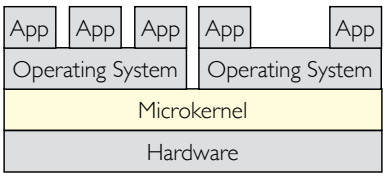
General theme for the next two weeks

- In a complex system …



- Question: how can we protect individual programs from interference with themselves, or with one another, either directly or by subverting lower layers?
- General approach: leverage programmable hardware features!

Diagrams and Code

- There are a lot of diagrams on these slides
  - Many of these are taken directly from the "Intel® 64 and IA-32 Architectures Software Developer's Manual", particularly Volume 3
  - There is a link to the full pdf file in the Reference section
- There is also a lot of code on these slides
- Remember that you can study these more carefully later if you need to!

Taking stock: Code samples ... so far

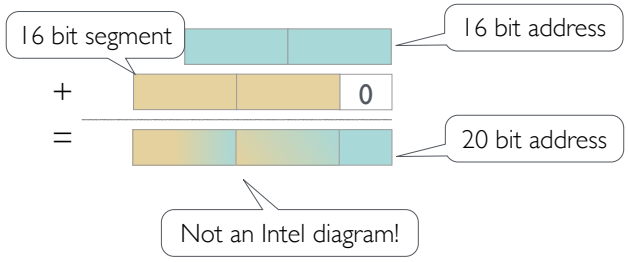
vram	video RAM simulation	vram.tar.gz
hello	boot and say hello on bare metal, via GRUB	hello.tar.gz
simpleio	a simple library for video RAM I/O	baremetal.tar.gz
bootinfo	display basic boot information from GRUB	
mimg	memory image bootloader & make tool	
example-mimg	display basic boot information from mimgload	
example-gdt	basic demo using protected mode segments (via a Global Descriptor Table)	prot.tar.gz
example-idt	context switching to user mode (via an Interrupt Descriptor Table)	

Segmentation

(or: where do "seg faults" come from?)

Breaking the 64KB barrier …

- The 8086 and 8088 CPUs in the original IBM PCs were 16 bit processors: in principle, they could only address 64KB
- Intel used **segmentation** to increase the amount of addressable memory from 64KB to 1MB:



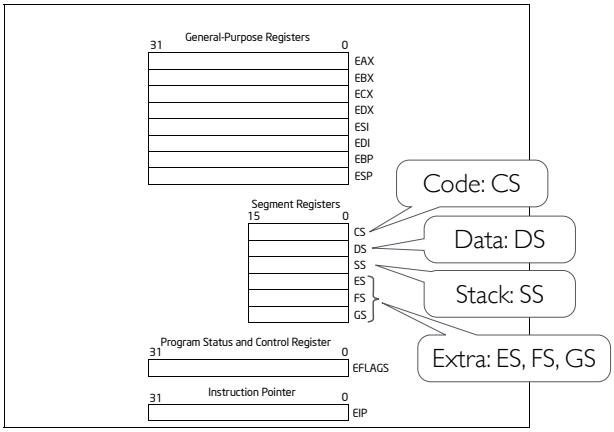


Figure 3-4. General System and Application Programming Registers

An Intel diagram!

How are segments chosen

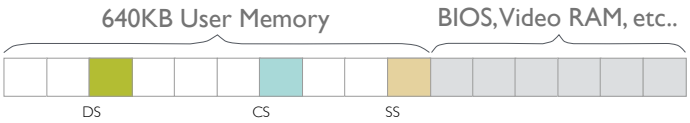
- The default choice of segment register is determined by the specific kind of address that is being used:

Table 3-5. Default Segment Selection Rules

Reference Type	Register Used	Segment Used	Default Selection Rule
Instructions	CS	Code Segment	All instruction fetches.
Stack	SS	Stack Segment	All stack pushes and pops. Any memory reference which uses the ESP or EBP register as a base register.
Local Data	DS	Data Segment	All data references, except when relative to stack or string destination.
Destination Strings	ES	Data Segment pointed to with the ES register	Destination of string instructions.

- If a different segment register is required, a single byte "segment prefix" can be attached to the start of the instruction

Back to breaking the 64KB barrier …



- Programs can be organized to use multiple segments:
- For example:
  - One segment for the stack
  - One segment for code
  - One segment for data
- We can relocate these segments to different physical addresses, just by adjusting the segment registers

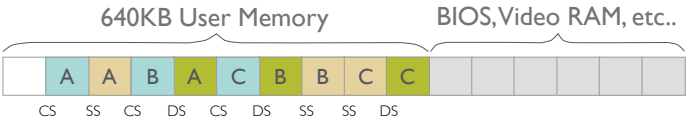
Back to breaking the 64KB barrier …

- Programs can be organized to use multiple segments:
- For example:
  - One segment for the stack
  - One segment for code
  - One segment for data
- We can relocate these segments to different physical addresses, just by adjusting the segment registers

Variations on the theme

- Programs can have multiple code and data segments
  - Programmers could use a standard "memory model"
  - Or use custom approaches to suit a specific application
- The machine provides special "far call" and "far jump" instructions that change CS and EIP simultaneously, allowing control transfers between distinct code segments
- There are six segment registers, so programs can have up to 6 active segments at a time (and more by loading new values in to the segment registers)
- Segments do not have to be exactly 64KB
- If segments do not overlap, then a stack overflow will not corrupt the contents of other segments - protection!

Accommodating multiple programs



- Now we can have multiple programs in memory at the same time, each with distinct code, data, and stack segments
- But what is to stop the code for one program from accessing and/or changing the data for another?
- Nothing!
- We would like to "protect" programs for interfering with one another, either by accident or design …

Protection!

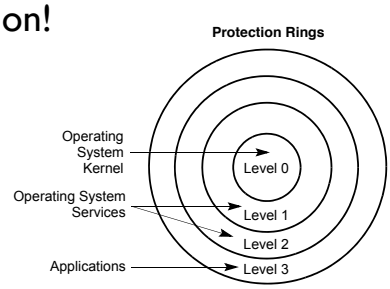


Figure 5-3. Protection Rings

- Ring 0 is sometimes called "supervisor" or "kernel mode"
- Ring 3 is often called "user mode"

Control registers

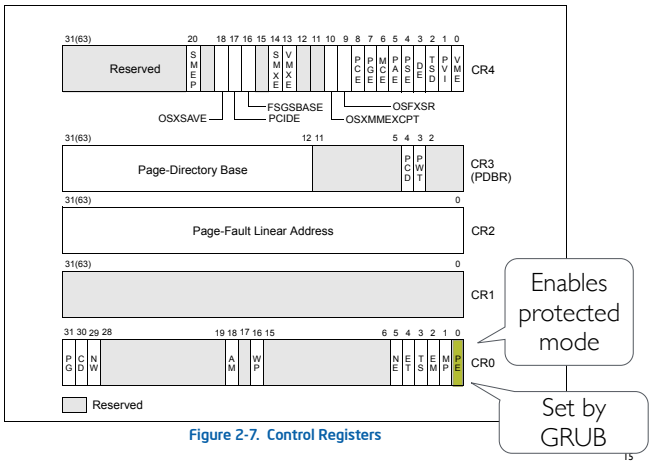
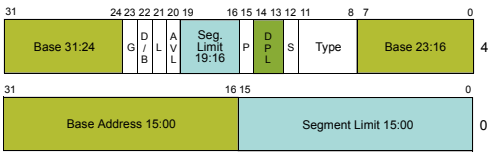


Figure 2-7. Control Registers

The current mode

- The current mode is saved in the two least significant bits of the CS register
- The value in CS can only be changed by a limited set of instructions (e.g., it cannot be the target of a `movw`), each of which performs a privilege check, if necessary, triggering a CPU exception if a violation occurs
- End result: user mode code cannot change its own privilege level to move out of Ring 3!

Segments in protected mode



L — 64-bit code segment (IA-32e mode only)
AVL — Available for use by system software
BASE — Segment base address
D/B — Default operation size (0 = 16-bit segment; 1 = 32-bit segment)
DPL — Descriptor privilege level
G — Granularity
LIMIT — Segment Limit
P — Segment present
S — Descriptor type (0 = system; 1 = code or data)
TYPE — Segment type

Figure 3-8. Segment Descriptor

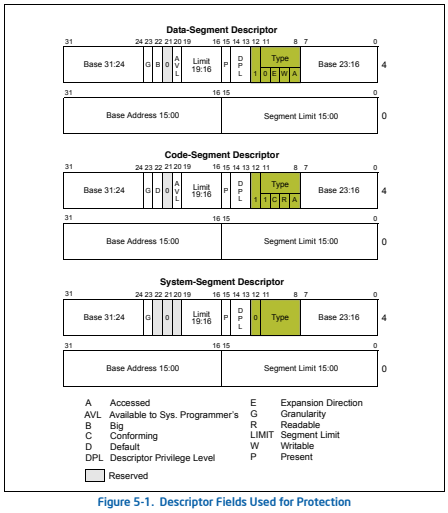


Figure 5-1. Descriptor Fields Used for Protection

Segment registers hold segment selectors

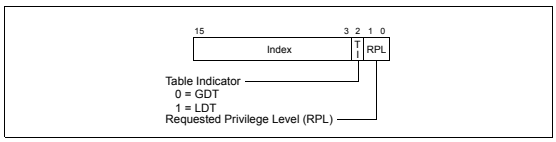


Figure 3-6. Segment Selector

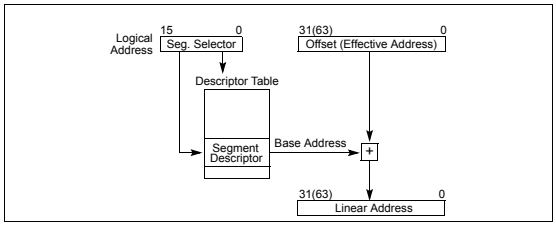


Figure 3-5. Logical Address to Linear Address Translation

The descriptor cache

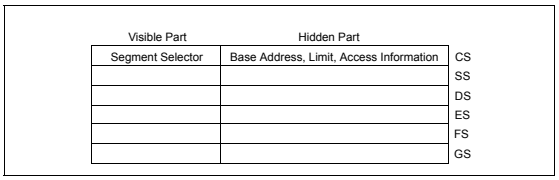


Figure 3-7. Segment Registers

Global and local descriptor tables

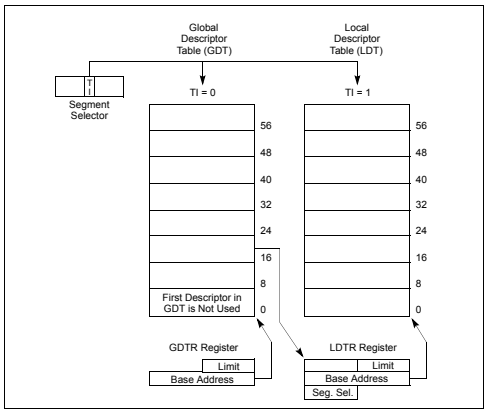


Figure 3-10. Global and Local Descriptor Tables

Achieving protection

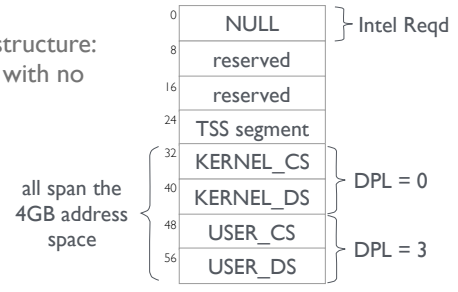
- The global and local descriptor tables are created by the kernel and cannot be changed by user mode programs
- The CPU raises an exception if a user mode program attempts to access:
  - a segment index outside the bounds of the GDT or LDT
  - a segment that is not marked for user mode access
  - an address beyond the limit of the associated segment
- The kernel can associate a different LDT with each process, providing each process with a distinct set of segments

Segments and capabilities

- The GDT and LDT for a given user mode program determine precisely which regions of memory that program can access
- As such, these entries are an example of a **capability** mechanism
- The user mode program refers to segments by their index in one of these tables, but it has no access to the table itself:
  - It cannot, in general, determine which regions of physical memory they are accessing
  - It cannot "fake" access to other regions of memory
- **The principle of least privilege**: limit access to the minimal set of resources that are required to perform a task

What if we don't want to use segments?

- Segmentation cannot be disabled in protected mode
- But we can come pretty close by using segments with:
  - base address 0
  - length = 4GB
- A common GDT structure: (e.g., in Linux, etc., with no LDT)

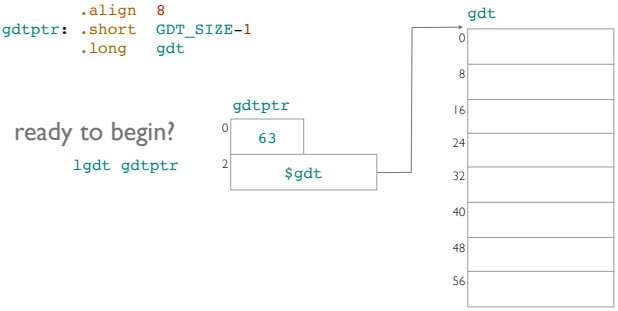


Storage for the GDT

```
        .set    GDT_ENTRIES, 8
        .set    GDT_SIZE, 8*GDT_ENTRIES # 8 bytes for each descriptor

        .data
        .align  128
gdt:    .space  GDT_SIZE, 0

        .align  8
gdtptr: .short  GDT_SIZE-1
        .long   gdt
```



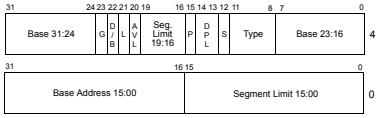
Calculating GDT descriptors

```
.macro  gdtset name, slot, base, limit, gran, dpl, type
.set    \name, (\slot<<3)|\dpl
.globl  \name
movl    $\base, %eax    # eax = bhi # bmd # blo
movl    $\limit, %ebx   # ebx = ~ # lhi # llo

mov     %eax, %edx      # edx = base
shl     $16, %eax       # eax = blo # 0
mov     %bx, %ax        # eax = blo # llo
movl    %eax, gdt+(8*\slot)

shr     $16, %edx       # edx = 0 # bhi # bmd
mov     %edx, %ecx      # ecx = 0 # bhi # bmd
andl    $0xff, %ecx     # ecx = 0 # 0   # bmd
xorl    %ecx, %edx      # edx = 0 # bhi # bmd
shl     $16,%edx        # edx = bhi # 0
orl     %ecx, %edx      # edx = bhi # 0 # bmd
andl    $0xf0000, %ebx  # ebx = 0 # lhi # 0
orl     %ebx, %edx      # edx = bhi # 0 # lhi # 0 # bmd
#
# The constant 0x4080 used below is a combination of:
#  0x4000      sets the D/B bit to indicate a 32-bit segment
#  0x0080      sets the P bit to indicate that descriptor is present
# (\gran<<15) puts the granularity bit into place
# (\dpl<<5)   puts the protection level into place
# \type       is the 5 bit type, including the S bit as its MSB
#
orl     $(((\gran<<15) | 0x4080 | (\dpl<<5) | \type)<<8), %edx
movl    %edx, gdt + (4 + 8*\slot)
.endm
```

macro assembler

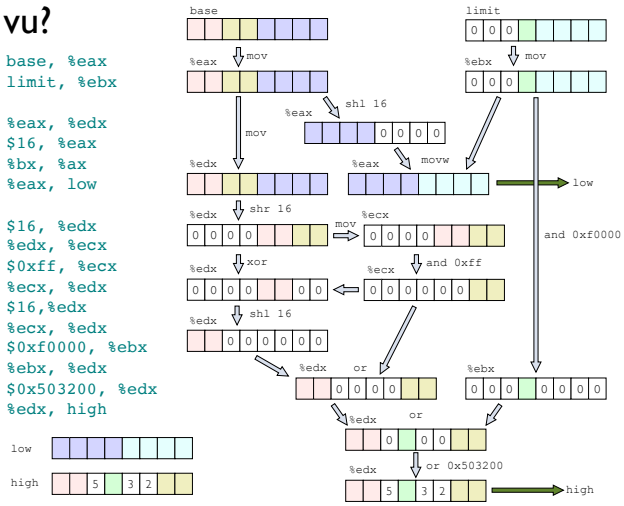


Deja vu?

```
movl    base, %eax
movl    limit, %ebx

mov     %eax, %edx
shl     $16, %eax
mov     %bx, %ax
movl    %eax, low

shr     $16, %edx
mov     %edx, %ecx
andl    $0xff, %ecx
xorl    %ecx, %edx
shl     $16,%edx
orl     %ecx, %edx
andl    $0xf0000, %ebx
orl     %ebx, %edx
orl     $0x503200, %edx
movl    %edx, high
```



Initializing the GDT entries

```
initGDT:# Kernel code segment:
        gdtset  name=KERN_CS, slot=4, dpl=0, type=GDT_CODE, \
                base=0, limit=0xffffff, gran=1

        # Kernel data segment:
        gdtset  name=KERN_DS, slot=5, dpl=0, type=GDT_DATA, \
                base=0, limit=0xffffff, gran=1

        # User code segment
        gdtset  name=USER_CS, slot=6, dpl=3, type=GDT_CODE, \
                base=0, limit=0xffffff, gran=1

        # User data segment
        gdtset  name=USER_DS, slot=7, dpl=3, type=GDT_DATA, \
                base=0, limit=0xffffff, gran=1

        # TSS
        gdtset  name=TSS, slot=3, dpl=0, type=GDT_TSS32, \
                base=tss, limit=tss_len-1, gran=0
```


Activating the GDT

```
        lgdt    gdtptr
        ljmp    $KERN_CS, $1f           # load code segment
1:
        mov     $KERN_DS, %ax           # load data segments
        mov     %ax, %ds
        mov     %ax, %es
        mov     %ax, %ss
        mov     %ax, %gs
        mov     %ax, %fs

        mov     $TSS, %ax               # load task register
        ltr     %ax

        ret
```


The Task State Segment

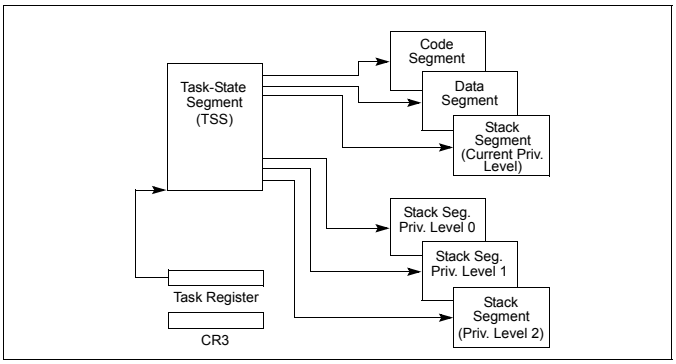


Figure 7-1. Structure of a Task

The Task State Segment

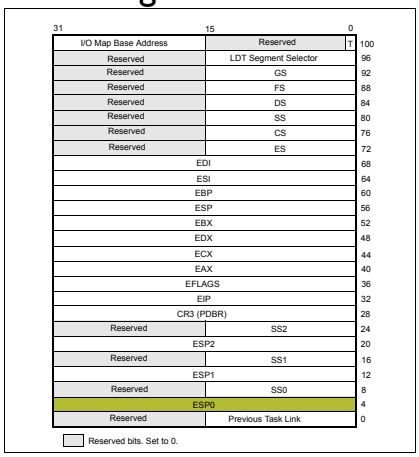


Figure 7-2. 32-Bit Task-State Segment (TSS)

Implementing the TSS

```
        .data
tss:    .short  0, RESERVED             # previous task link
esp0:   .long   0                       # esp0
        .short  KERN_DS, RESERVED       # ss0
        .long   0                       # esp1
        .short  0, RESERVED             # ss1
        .long   0                       # esp2
        .short  0, RESERVED             # ss2
        .long   0, 0, 0                 # cr3 (pdbr), eip, eflags
        .long   0, 0, 0, 0, 0           # eax, ecx, edx, ebx, esp
        .long   0, 0, 0                 # ebp, esi, edi
        .short  0, RESERVED             # es
        .short  0, RESERVED             # cs
        .short  0, RESERVED             # ss
        .short  0, RESERVED             # ds
        .short  0, RESERVED             # fs
        .short  0, RESERVED             # gs
        .short  0, RESERVED             # ldt segment selector
        .short  0                       # T bit
        .short  1000                    # I/O bit map base address
        .set    tss_len, .-tss
```


Interrupts and exceptions

Exceptions

- What happens if the program you run on a conventional desktop computer attempts:
  - division by zero?
  - to use an invalid segment selector?
  - to reference memory beyond the limits of a segment?
  - etc…
- What happens when there is no operating system to catch you?

Table 6-1. Protected-Mode Exceptions and Interrupts

Vector No.	Mnemonic	Description	Type	Error Code	Source
0	#DE	Divide Error	Fault	No	DIV and IDIV instructions.
1	#DB	RESERVED	Fault/ Trap	No	For Intel use only.
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 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 acc system segments.
12	#SS	Stack-Segment Fault	Fault	Yes	Stack operations and SS register l
13	#GP	General Protection	Fault	Yes	Any memory reference and other protection checks.
14	#PF	Page Fault	Fault	Yes	Any memory reference.
15	—	(Intel reserved. Do not use.)		No	
16	#MF	x87 FPU Floating-Point Error (Math Fault)	Fault	No	x87 FPU floating-point or WAIT/FWAIT instruction.
17	#AC	Alignment Check	Fault	Yes (Zero)	Any data reference in memory.[3]
18	#MC	Machine Check	Abort	No	Error codes (if any) and source are model dependent.[4]
19	#XM	SIMD Floating-Point Exception	Fault	No	SSE/SSE2/SSE3 floating-point instructions[5]
20	#VE	Virtualization Exception	Fault	No	EPT violations[6]
21-31	—	Intel reserved. Do not use.			
32-255	—	User Defined (Non-reserved) Interrupts	Interrupt		External interrupt or INT *n* instruction.

- **Faults** can generally be corrected, restarting the program *at* the faulting instruction
- **Traps** allow execution to be restarted *after* the trapping instruction
- **Aborts** do not allow a restart

Hardware and software interrupts

- **Hardware**: devices often generate interrupt signals to inform the kernel that a certain event has occurred:
  - a timer has fired
  - a key has been pressed
  - a buffer of data has been transferred
  - …
- **Software**: User programs often request services from an underlying operating system:
  - read data from a file
  - terminate this program
  - send a message
  - …
- These can all be handled in the same way …

The interrupt vector

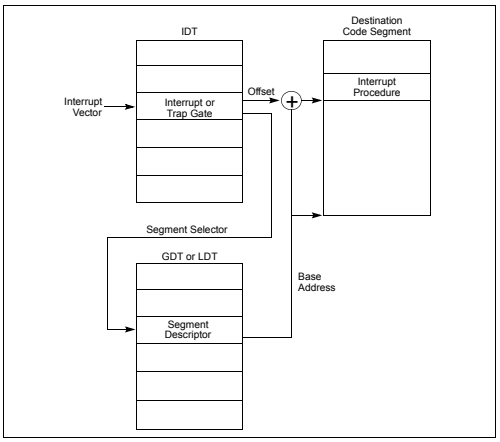


Figure 6-3. Interrupt Procedure Call

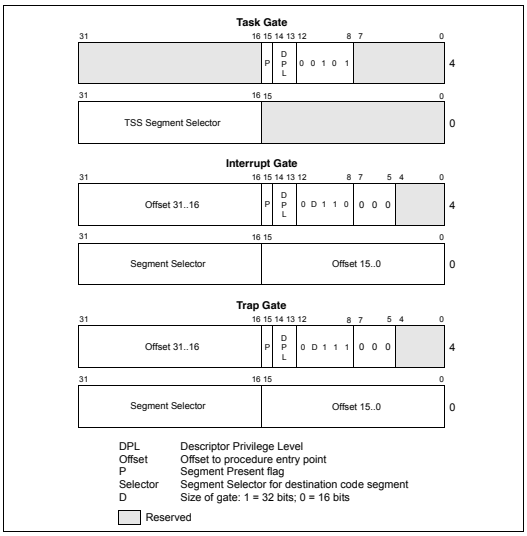


Figure 6-2. IDT Gate Descriptors

Storage for the IDT

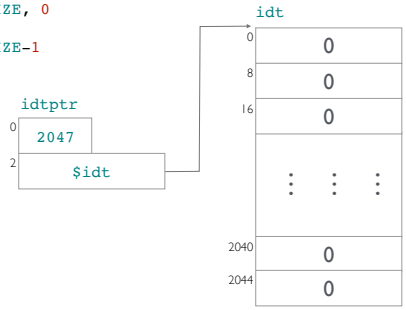
```
        .set    IDT_ENTRIES, 256        # Allow for all poss. interrupts
        .set    IDT_SIZE, 8*IDT_ENTRIES # Eight bytes for each idt desc.
        .set    IDT_INTR, 0x000         # Type for interrupt gate
        .set    IDT_TRAP, 0x100         # Type for trap gate

        .data
        .align  8
idt:    .space  IDT_SIZE, 0

idtptr: .short  IDT_SIZE-1
        .long   idt
```

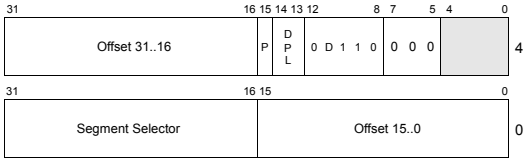
ready to begin?

lidt idtptr



Calculating IDT descriptors

```
.macro  idtcalc handler, slot, dpl=0, type=IDT_INTR, seg=KERN_CS
# type = 0x000 (IDT_INTR)  => interrupt gate
# type = 0x100 (IDT_TRAP)  => trap gate
#
# The following comments use # for concatenation of bitdata
#
mov     $\seg, %ax              # eax =   ? # seg
shl     $16, %eax               # eax = seg #   0
movl    $\handler, %edx         # edx = hhi # hlo
mov     %dx, %ax                # eax = seg # hlo
mov     $(0x8e00 | (\dpl<<13) | \type), %dx
movl    %eax, idt + (    8*\slot)
movl    %edx, idt + (4 + 8*\slot)
.endm
```



Initializing and activating the IDT

```
initIDT:# Fill in IDT entries

        # Add descriptors for protected mode exceptions:
        .irp    num, 0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,16,17,18,19
        idtcalc exc\num, slot=\num
        .endr

        # Add descriptors for hardware irqs:
        # ... except there aren't any here (yet)

        # Add descriptors for system calls:
        # These are the only idt entries that we will allow to be
        # called from user mode without generating a general
        # protection fault, so they are tagged with dpl=3.
        idtcalc handler=kputc, slot=0x80, dpl=3

        # Install the new IDT:
        lidt    idtptr
        ret
```

macro loop

Transferring control to a handler

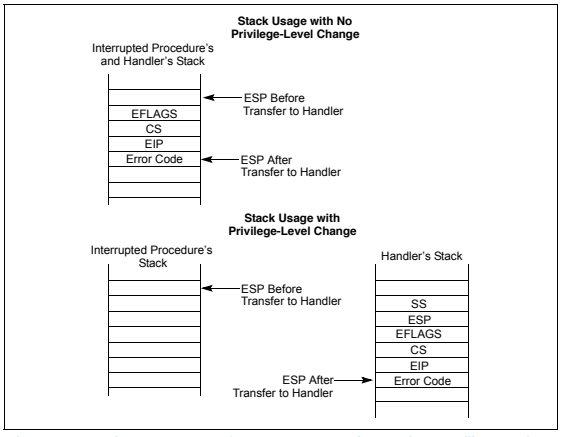
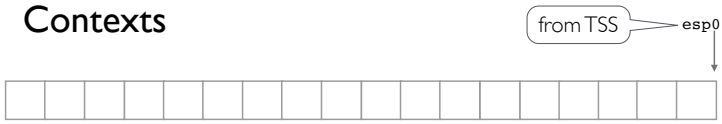
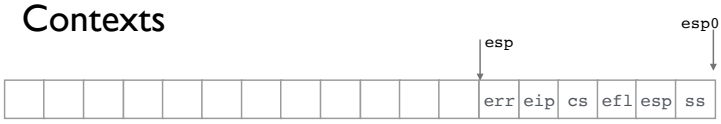


Figure 6-4. Stack Usage on Transfers to Interrupt and Exception-Handling Routines

Contexts



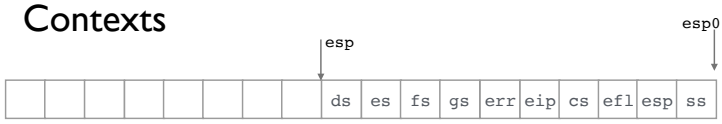
Contexts




```
struct Iret {
  unsigned error;
  unsigned eip;
  unsigned cs;
  unsigned eflags;
  unsigned esp;
  unsigned ss;
};
```

Automatic (CPU)

Contexts



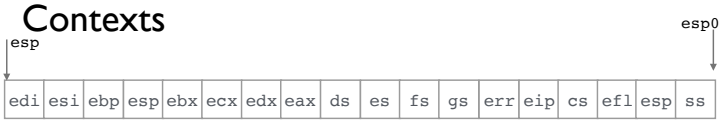

```
struct Segments {
  unsigned ds;
  unsigned es;
  unsigned fs;
  unsigned gs;
};
```

```
struct Iret {
  unsigned error;
  unsigned eip;
  unsigned cs;
  unsigned eflags;
  unsigned esp;
  unsigned ss;
};
```

```
push    %gs
push    %fs
push    %es
push    %ds
```

Automatic (CPU)

Contexts




```
struct Registers {
  unsigned edi;
  unsigned esi;
  unsigned ebp;
  unsigned esp;
  unsigned ebx;
  unsigned edx;
  unsigned ecx;
  unsigned eax;
};
```

```
struct Segments {
  unsigned ds;
  unsigned es;
  unsigned fs;
  unsigned gs;
};
```

```
struct Iret {
  unsigned error;
  unsigned eip;
  unsigned cs;
  unsigned eflags;
  unsigned esp;
  unsigned ss;
};
```

```
pusha
```

```
push    %gs
push    %fs
push    %es
push    %ds
```

Automatic (CPU)

Contexts


```
struct Registers {
  unsigned edi;
  unsigned esi;
  unsigned ebp;
  unsigned esp;
  unsigned ebx;
  unsigned edx;
  unsigned ecx;
  unsigned eax;
};
```

```
struct Segments {
  unsigned ds;
  unsigned es;
  unsigned fs;
  unsigned gs;
};
```

```
struct Iret {
  unsigned error;
  unsigned eip;
  unsigned cs;
  unsigned eflags;
  unsigned esp;
  unsigned ss;
};
```

Captures the "context" of the interrupted program

```
struct Context {
  struct Registers regs;
  struct Segments  segs;
  struct Iret      iret;
};
```


Table 6-1. Protected-Mode Exceptions and Interrupts

Vector No.	Mnemonic	Description	Type	Error Code	Source
0	#DE	Divide Error	Fault	No	DIV and IDIV instructions.
1	#DB	RESERVED	Fault/ Trap	No	For Intel use only.
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 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 acc system segments.
12	#SS	Stack-Segment Fault	Fault	Yes	Stack operations and SS register l
13	#GP	General Protection	Fault	Yes	Any memory reference and other protection checks.
14	#PF	Page Fault	Fault	Yes	Any memory reference.
15	—	(Intel reserved. Do not use.)		No	
16	#MF	x87 FPU Floating-Point Error (Math Fault)	Fault	No	x87 FPU floating-point or WAIT/FWAIT instruction.
17	#AC	Alignment Check	Fault	Yes (Zero)	Any data reference in memory.[3]
18	#MC	Machine Check	Abort	No	Error codes (if any) and source are model dependent.[4]
19	#XM	SIMD Floating-Point Exception	Fault	No	SSE/SSE2/SSE3 floating-point instructions[5]
20	#VE	Virtualization Exception	Fault	No	EPT violations[6]
21-31	—	Intel reserved. Do not use.			
32-255	—	User Defined (Non-reserved) Interrupts	Interrupt		External interrupt or INT *n* instruction.

- **Faults** can generally be corrected, restarting the program *at* the faulting instruction
- **Traps** allow execution to be restarted *after* the trapping instruction
- **Aborts** do not allow a restart

Exception handler

Some exceptions do not generate an error code …

```
        .macro  handler num, func, errorcode=0
exc\num:.if     \errorcode==0
        subl    $4, %esp        # Fake an error code if necessary
        .endif
        push    %gs             # Save segments
        push    %fs
        push    %es
        push    %ds
        pusha                   # Save registers

        push    %esp            # Push pointer to frame for handler
        movl    $\num, %eax
        call    \func
        addl    $4, %esp

        popa                    # Restore registers
        popl    %ds             # Restore segments
        popl    %es
        popl    %fs
        popl    %gs
        addl    $4, %esp        # remove error code
        iret
        .endm
```

call func(struct Context *esp) with num in eax

"return from interrupt"

Defining a family of (non) handlers

```
# Protected-mode exceptions and interrupts:
#
handler num=0,  func=nohandler                  # divide error
handler num=1,  func=nohandler                  # debug
handler num=2,  func=nohandler                  # NMI
handler num=3,  func=nohandler                  # breakpoint
handler num=4,  func=nohandler                  # overflow
handler num=5,  func=nohandler                  # bound
handler num=6,  func=nohandler                  # undefined opcode
handler num=7,  func=nohandler                  # nomath
handler num=8,  func=nohandler, errorcode=1     # doublefault
handler num=9,  func=nohandler                  # coproc seg overrun
handler num=10, func=nohandler, errorcode=1     # invalid tss
handler num=11, func=nohandler, errorcode=1     # segment not present
handler num=12, func=nohandler, errorcode=1     # stack-segment fault
handler num=13, func=nohandler, errorcode=1     # general protection
handler num=14, func=nohandler, errorcode=1     # page fault
handler num=16, func=nohandler                  # math fault
handler num=17, func=nohandler, errorcode=1     # alignment check
handler num=18, func=nohandler                  # machine check
handler num=19, func=nohandler                  # SIMD fp exception
```


Defining a family of (non) handlers

```
nohandler:                      # dummy interrupt handler
        movl    4(%esp), %ebx   # get frame pointer
        pushl   %ebx
        pushl   %eax
        pushl   $excepted
        call    printf
        addl    $12, %esp

1:      hlt
        jmp 1b

        ret
excepted:
        .asciz  "Exception 0x%x, frame=0x%x\n"
```

call printf(excepted, num, ctxt)

Initializing a context

```
struct Context user;

…

  initContext(&user, userEntry, 0);

…

void initContext(struct Context* ctxt, unsigned eip, unsigned esp) {
  extern char USER_DS[];
  extern char USER_CS[];
  printf("user data segment is 0x%x\n", (unsigned)USER_DS);
  printf("user code segment is 0x%x\n", (unsigned)USER_CS);
  ctxt->segs.ds     = (unsigned)USER_DS;
  ctxt->segs.es     = (unsigned)USER_DS;
  ctxt->segs.fs     = (unsigned)USER_DS;
  ctxt->segs.gs     = (unsigned)USER_DS;
  ctxt->iret.ss     = (unsigned)USER_DS;
  ctxt->iret.esp    = esp;
  ctxt->iret.cs     = (unsigned)USER_CS;
  ctxt->iret.eip    = eip;
  ctxt->iret.eflags = INIT_USER_FLAGS;
}
```


Initializing the flags

```
#define INIT_USER_FLAGS (3<<12 | 1<<9 | 1<<1)
```

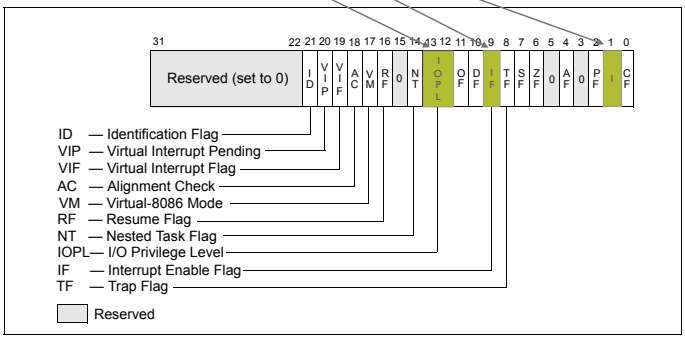


Figure 2-5. System Flags in the EFLAGS Register

Switching to a user program

From C:

```
   extern int switchToUser(struct Context* ctxt);
```

To Assembly:

```
        .set    CONTEXT_SIZE, 72
        .globl  switchToUser
switchToUser:
        movl    4(%esp), %eax   # Load address of the user context
        movl    %eax, %esp      # Reset stack to base of user context
        addl    $CONTEXT_SIZE, %eax
        movl    %eax, esp0      # Set stack address for kernel reentry
        popa                    # Restore registers
        pop     %ds             # Restore segments
        pop     %es
        pop     %fs
        pop     %gs
        addl    $4, %esp        # Skip error code
        iret                    # Return from interrupt
```

Entering a system call (kernel view)

Initialize IDT entry:

```
idtcalc handler=kputc, slot=0x80, dpl=3
```

Define a stub to handle the interrupt:

```
        .text
kputc:  subl    $4, %esp        # Fake an error code
        push    %gs             # Save segments
        push    %fs
        push    %es
        push    %ds
        pusha                   # Save registers
        leal    stack, %esp     # Switch to kernel stack
        jmp     kputc_imp
```

Provide a handler implementation:

```
void kputc_imp() {  /* A trivial system call */
   putchar(user.regs.eax);
   switchToUser(&user);
}
```

Why is this line so important?

Entering a system call (user view)

From C:

```
extern void kputc(unsigned);
```

To Assembly:

```
        .globl  kputc
kputc:  pushl   %eax
        mov     8(%esp), %eax
        int     $128
        popl    %eax
        ret
```


A recipe for adding a new system call

- Pick an unused interrupt number.
- Add code to initialize the corresponding IDT entry.
- Write and assembly code stub that saves the user program context and jumps to the handler code.
- Write the implementation of the handler. Be sure to use `switchToUser` (or equivalent) when the handler is done.
- Add user-level code to access the new system call. This often requires an assembly code fragment using the `int` instruction, and a declaration/prototype in the C code
- Color key for example-idt:
  kernel/init.s kernel/kernel.c user/userlib.s user/user.c

Reflections

- Bare Metal
  - Segmentation, protection, exceptions and interrupts
- Programming/Languages
  - Representation transparency, facilitates interlanguage interoperability
  - Memory areas
    - Vendor-defined layout: GDT, GDTTR, TSS, IDT, IDTR, IRet, Registers, …
    - Self-defined: Context, …
  - "Bitdata"
    - Segment and interrupt descriptors, eflags, cr0, …
  - Does the need for a "recipe" suggest a language weakness?

Let's see how all the pieces fit together …