

Introduction to The x86 Microprocessor

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Protected Mode

- Memory Segmentation and Privilege Levels
 - Definition of a segment
 - Segment selectors
 - Local Descriptor Tables
 - Segment Aliasing, Overlapping
 - Privilege protection
 - Defining Privilege Levels
 - Changing Privilege levels

Organization

- Basic Introduction
 - Structured Computer Organization
- Memory Management
 - Architectural Support to Operating Systems and users
- Process Management
 - Architectural Support to Operating Systems
 - Task Switching and Interrupt/Exception Handling
- Legacy Management
 - Instruction set compatibility across evolving processor Architectures
 - Evolution of Instruction Sets – MMX Instructions

Intel Processor operation modes

- Intel processor runs in five modes of operations
 - Real Mode
 - Protected Mode
 - Virtual 8086 mode
 - IA 32e – Extended Memory model for 64-bits
 - Compatibility mode – execute 32 bit code in 64-bit mode without recompilation. No access to 64-bit address space
 - 64-bit mode – 64-bit OS accessing 64-bit address space and 64-bit registers
 - System Management mode
- **Real mode** is equivalent to 8086 mode of operation with some extensions
- **Protected Mode** is what is commonly used
- **Virtual 8086 mode** is used to run 8086 compatible programs *concurrently* with other protected mode programs

Structured Computer Organization

Programming Language level

Assembly Language level

Operating Systems level

Microprogramming level

Digital Logic level

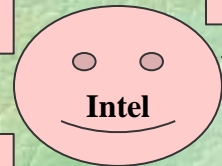
Computer
Architecture

Compilers ask for features from the Architecture to induce more sophistication in the Programming Languages

Compiled code/
Assembly code
Advanced Addressing modes
Sophisticated Instruction set

Support for Memory Management and Task Management
Multiuser OS - Protection, Virtual Memory, Context Switching

Understanding How I manage these demands makes my biography interesting



Memory Management

■ Multi User Operating Systems

- Ease of Programming
- Process Mobility in the Address Space
- Multiprocess Context switching
- Protection across Processes
 - Intra process protection: Separation of Code, Data and Stack
 - Inter process protection

■ Virtual Memory

- 4GB address space for every process



Ensured
by
Segmentation



Ensured
by
Paging

```

if (j>k)
    max = j
else
    max = k

```



```

Code_Segment:
    mov EAX, [0]
    mov EBX, [4]
    cmp EAX,EBX
    jle 0x7 //Label_1
    mov [8], EAX
    jmp 0x5 //Label_2

Label_1: mov [8], EBX
Label_2: ....

Data Segment:
0: // Allocated for j
4: // Allocated for k
8: // Allocated for max

```

Address of j: 2100
Address of k: 2104
Address of max: 2108

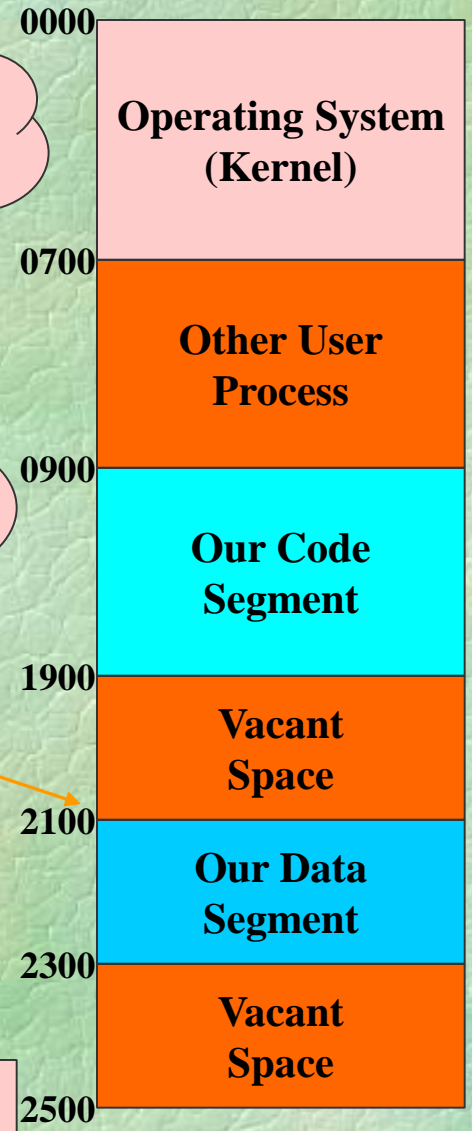
Code and Data segments are separate and both assumed to start from 0

Every Memory Data Access should add the value stored in Data Segment Register By default.

Segment Register (Data)

2100

Main Memory



Ease Of Programming

```
if (j>k)
    max = j
else
    max = k
```



```
Code_Segment:
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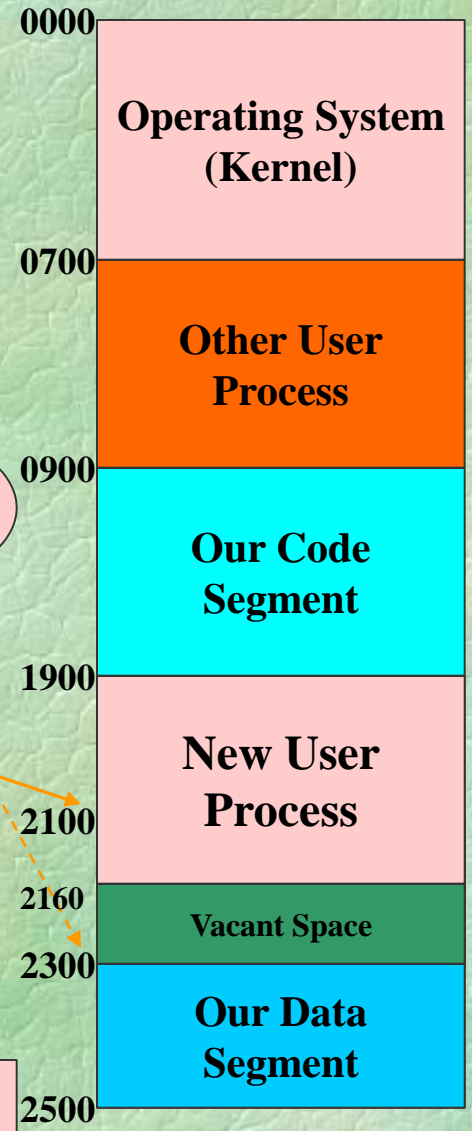
Address of j: 2300
Address of k: 2304
Address of max: 2308

A new process needs
a
segment of size 260
The space is
available
but not contiguous

Segment Register (Data)

2300

Main Memory



Process Mobility

General Purpose Registers

	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
	EAX																AH	(AX)	AL													
	EBX																BH	(BX)	BL													
	ECX																CH	(CX)	CL													
DS	EDX																DH	(DX)	DL													
ES	ESI																SI															
FS	EDI																DI															
GS	EBP																BP															
SS	ESP																SP															

64-bit and above Registers

- RAX, RBX, RCX, RDX, RSI, RSP, RDI, RBP – 64 bit General purpose registers sharing space with its corresponding 32-bit registers
- R8-R15, additional general purpose registers
 - R8D – R15D (32 bit counter part)
 - R8W – R15W (16 bit counter part)
- ST0-ST7, 80 bit floating point
- MMX0-MMX7, 64-bit multi media
- XMM0-XMM7, 128-bit registers – used for floating point and packed integer arithmetic

Segment Registers



Code Segment

Data Segment

Stack Segment

Extra Segment

Multiple Segments

- The segment register can change its values to point to different segments at different times.
- X86 architecture provides additional segment registers to access multiple data segments at the same time.
 - DS, ES, FS and GS
- X86 supports a separate Stack Segment Register (SS) and a Code segment Register (CS) in addition.
- By default a segment register is fixed for every instruction, for all the memory access performed by it. For eg. all data accessed by MOV instruction take DS as the default segment register.
- An **segment override prefix** is attached to an instruction to change the segment register it uses for memory data access.

`mov [10], eax`

- this will move the contents of eax register to memory location 0510

Opcode: `0x89 0x05 0x10`

`mov [ES:10], eax`

-this will move the contents of eax register to memory location 3510

Opcode

`0x26 0x89 0x05 0x10`

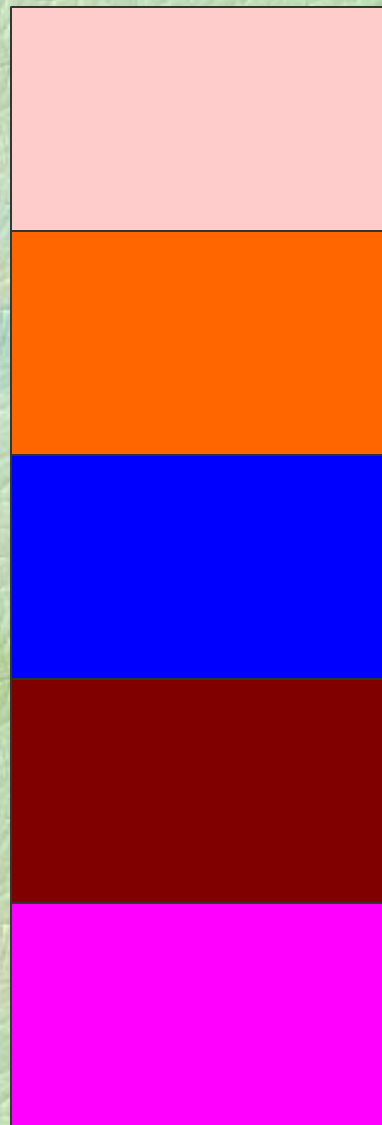
“0x26” is the segment override prefix.

DS

C
S

SS

E
S



0000

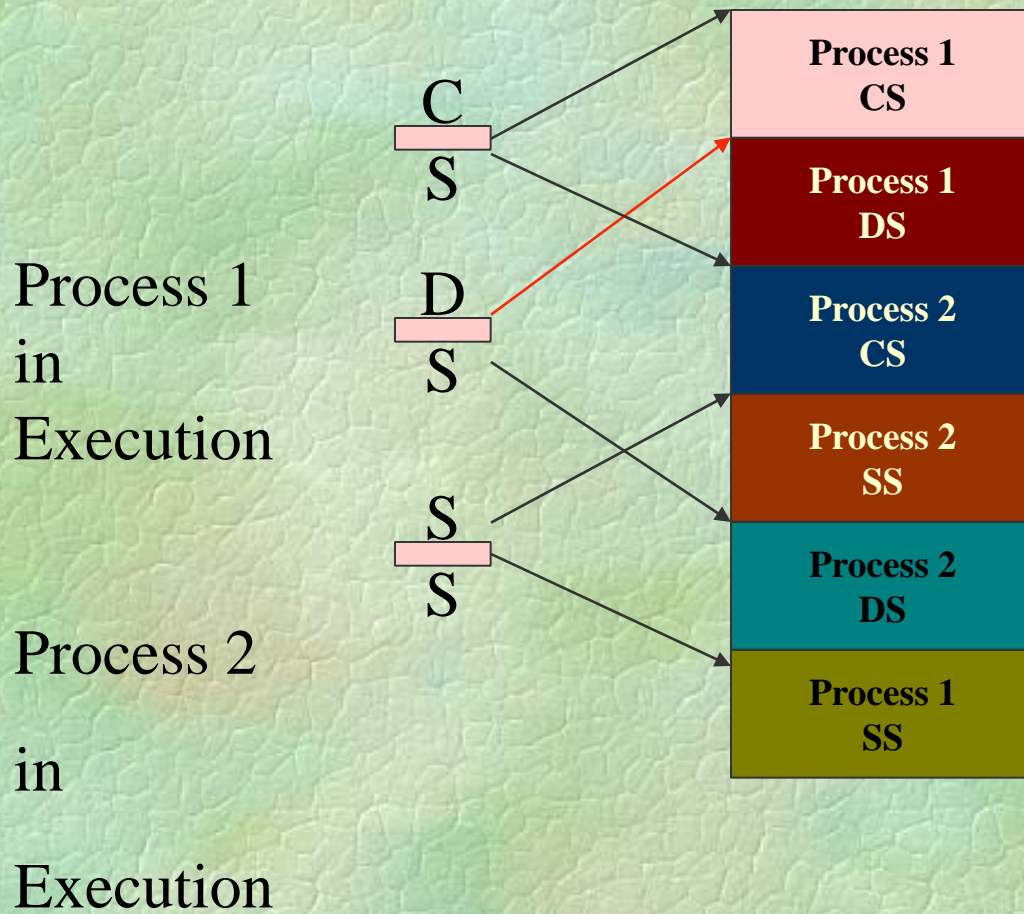
0500

1500

2500

3500

Multiple Segments



Multiprocess Context switching

Other Registers

- EFLAGS – 32 Bit Register

	VM	RF		NT	IO PL	IO PL	OF	DF	IF	TF	SF	ZF		AF		PF		CF
--	-----------	-----------	--	-----------	------------------	------------------	-----------	-----------	-----------	-----------	-----------	-----------	--	-----------	--	-----------	--	-----------

Bits 1,3,5,15,22-31 are RESERVED.

18: AC, 19:VIF, 20: VIP, 21:ID

Details of the flags

- CF – Carry Flag

- Set by arithmetic instructions that generate a carry or borrow. Also can be set, inverted and cleared with the STC, CLC or CMC instructions respectively.

- PF – Parity Flag

- Set by most instructions if the least significant eight bits of the destination operand contain an even number of 1 bits.

Details of the flags

- AF – Auxiliary Flag
 - If a carry or borrow from the most significant nibble of the least significant byte – Aids BCD arithmetic
- ZF – Zero Flag
 - Set by most instructions if the result of the arithmetic operation is zero

Details of the flags

- SF – Sign Flag
 - On signed operands, this tells whether the result is positive or negative
- TF – Trace Flag
 - On being set it allows single-step through programs. Executes exactly one instruction and generates an internal exception 1 (debug fault)

Details of the flags

- IF – Interrupt Flag
 - When set, the processor recognizes the external hardware interrupts on INTR pin. On clearing, anyway has not effect on NMI (external non maskable interrupt) pin or internally generated faults, exceptions, traps etc. This flag can be set and cleared using the STI and CLI instructions respectively
- DF – Direction Flag
 - Specifically for string instructions. $DF = 1$ increments ESI and EDI, while $DF = 0$ decrements the same. Set and cleared by STD and CLD instructions

Details of the flags

- OF – Overflow Flag
 - Most arithmetic instructions set this flag to indicate that the result was at least 1 bit too large to fit in the destination
- IOPL – Input Output Privilege Level flags
 - For protected mode operations – indicates the privilege level, 0 to 3, at which your code must be running in order to execute any I/O-related instructions

Details of the flags

- NT – Nested Task Flag
 - When set, it indicates that one system task has invoked another through a CALL instruction as opposed to a JMP. For multitasking this can be manipulated to our advantage
- RF – Resume Flag
 - It is related to Debug registers DR6 and DR7. By setting this, you can selectively mask some exceptions while you are debugging code

Details of the flags

- **VM – Virtual 8086 mode flag**
 - When it is set, the x86 processor is basically converted into a high-speed 8086 processor.
- **AC (bit 18) Alignment check flag** — Set this flag and the AM bit in the CR0 register to
 - enable alignment checking of memory references; clear the AC flag and/or the
 - AM bit to disable alignment checking.
- **VIF (bit 19) Virtual interrupt flag** — Virtual image of the IF flag. Used in conjunction
 - with the VIP flag. (To use this flag and the VIP flag the virtual mode extensions
 - are enabled by setting the VME flag in control register CR4.)

Details of the flags

- **VIP (bit 20) Virtual interrupt pending flag** — Set to indicate that an interrupt is pending;
 - clear when no interrupt is pending. (Software sets and clears this flag; the processor only reads it.) Used in conjunction with the VIF flag.
- **ID (bit 21) Identification flag** — The ability of a program to set or clear this flag indicates
 - support for the CPUID instruction.

Protected Mode Registers

- LDTR – Local Descriptor Table Register – 16 bits
- GDTR – Global Descriptor Table Register – 48 bits
- IDTR – Interrupt Descriptor Table Register – 48 bits
- TR – Task register – 16 bits

Other System Registers

- Control – CR0, CR2, CR3 (each 32-bits)
 - CR0 is very important
 - Bit 0 – PE bit – when set processor in protected mode else real mode
 - Bit 3 – TS bit – The processor sets this bit automatically every time it performs a task switch. This can be cleared using a CLTS instruction
 - Bit 31 – PG bit – when set paging MMU is enabled else it is disabled

Other System Registers

- Control – CR0, CR2, CR3 (each 32-bits)
 - CR2 – Read only register – deposits the last 32-bit linear address that caused a page-fault
 - CR3 – Stores the physical address of the PDB – Page Directory Base register. The paging tables are to be 4KB aligned and hence the 12 least significant bits are not stored and ignored

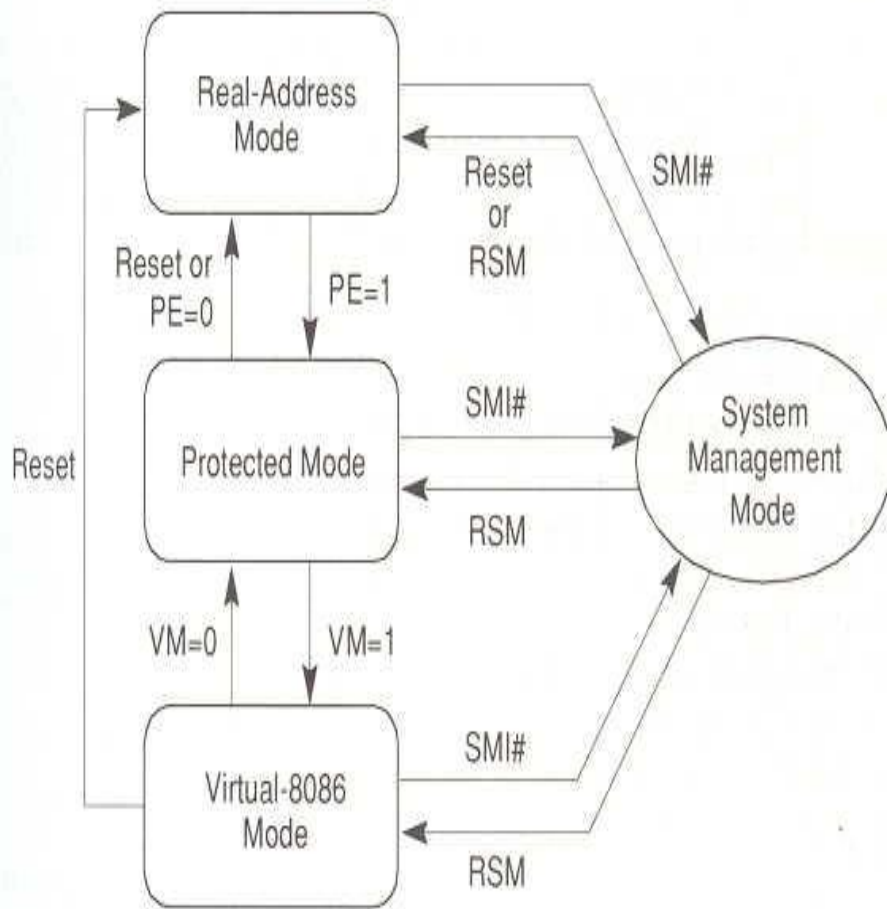
Other System Registers

- Debug Registers

- DR0, DR1, DR2, DR3, DR6, DR7
- DR0-DR3 can hold four linear address breakpoints so that if the processor generates these addresses a debug exception (Interrupt 1) is caused
- DR6 – Debug status register indicating the circumstances that may have caused the last debug fault
- DR7 – Debug control register. By filling in the various fields of this register, you can control the operation of the four linear address breakpoints

Other System Registers

- Test Registers – TR6 and TR7
 - Used to perform confidence checking on the paging MMU's Translation Lookaside Buffer (TLB).



Test Your Understanding

- There are ----- GPRs in the x86
- The x86 system in protected mode has -----
-- enabled by default
- Three salient features of using
Segmentation

Answers

- 1. Eight GPRs
- 2. Segmentation
- 3. Three Features
 - Code Mobility
 - Logically every segment can start with zero
 - Inter and Intra process protection ensuring data integrity.

- **Learnt so far**

- Intel Memory Management fundamentals
 - Motivation from a Computer Organization standpoint
 - Intel Register set – General Purpose Registers, Segment registers and system registers
 - x86 modes of operations

x86 Memory Management

- **To Learn**
 - Real and protected mode addressing in x86
 - Virtual Memory and paging
 - Addressing
 - Task switching and Interrupt handling
 - Legacy issues

Real Mode - Memory Addressing

- Segment $\ll 4$ + offset = 20 bit EA
- Segment size is a fixed 64K

DS = 0x1004

mov [0x1000], EAX

The **mov** will store the content of EAX in

$$0x10040 + 0x1000 = 0x11040$$

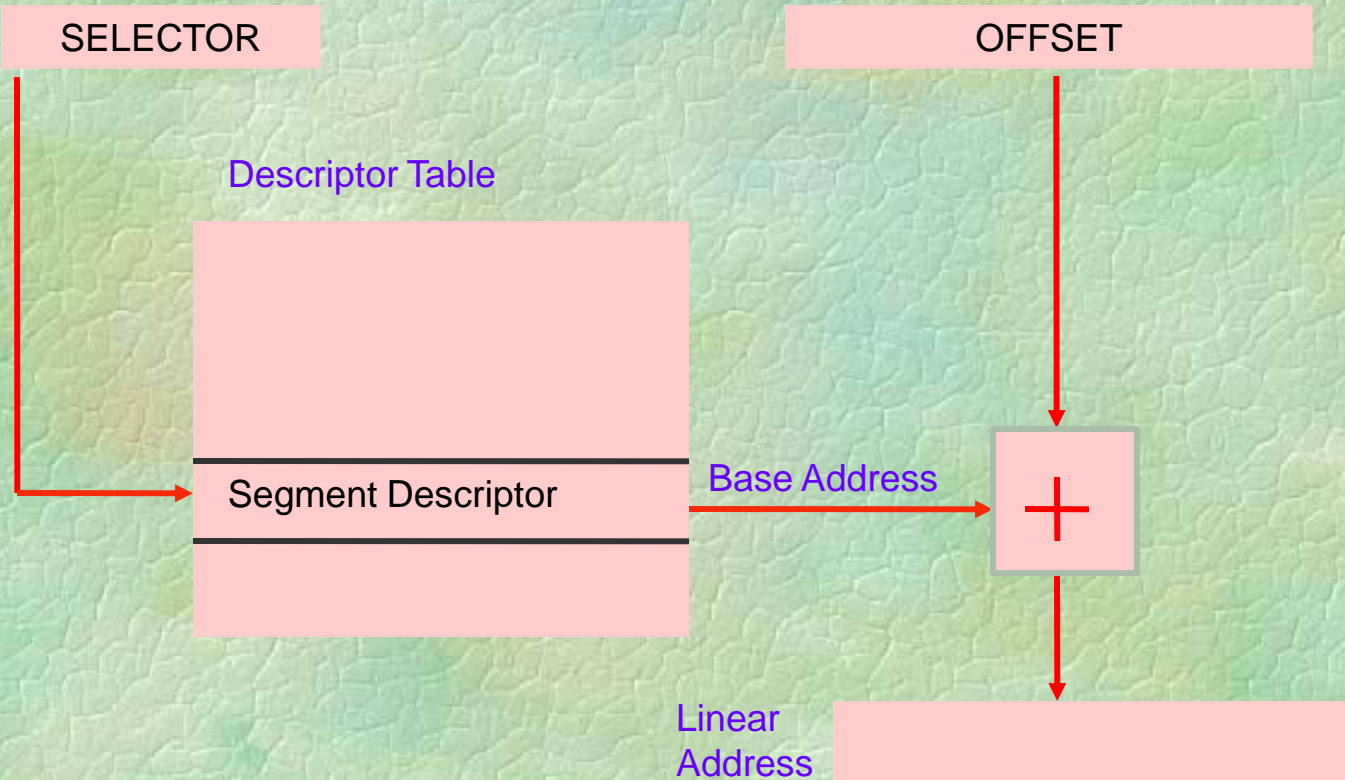
Why this stuff? - To get 1 MB addressing using 16-bit Segment Registers

Protected Mode Addressing

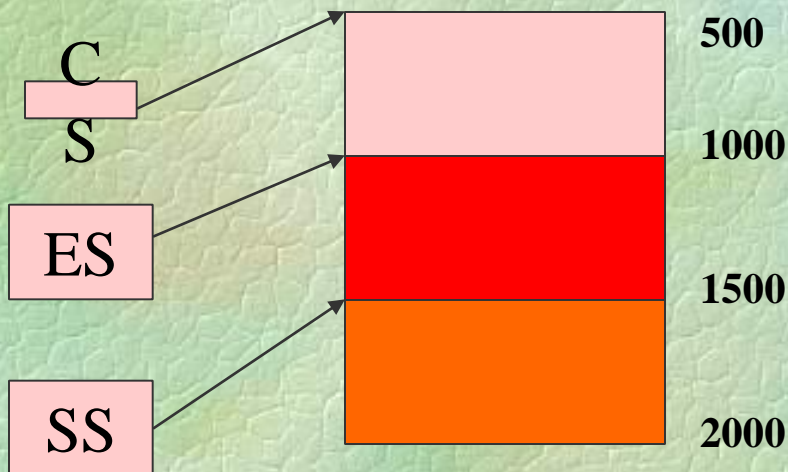
- `mov [DS:1000], EAX`
- Let value of DS be 0x10. This is used to select a *segment descriptor* in a *descriptor table*.
- The *segment descriptor* contains information about the *base address* of the segment, to which 1000 is added to get the effective address.
- The value stored in DS is called a *selector*.
- Henceforth we discuss protected mode.

Protected Mode Addressing

Logical
Address



- A process always executes from Code segment. It should not execute by accessing from adjoining Data or stack area or any other code area too.
- A stack should not overgrow into adjoining segments



Every segment is specified a start address and **limit**.

Architecture checks if limit is not exceeded.

POP EAX //Let SP be 2, Violation!!!

Intra and Inter process Protection

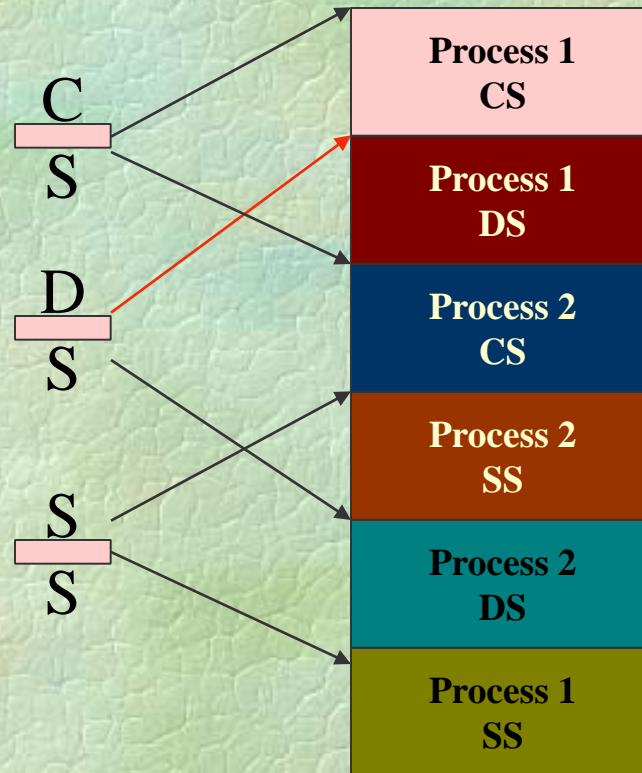
Process 1 should be prevented from loading CS, such that it can access the code of Process 2

Similarly for the DS,SS, ES, FS and GS

Privilege levels: [0-3] assigned to each segment.

0: Highest privilege

3: Lowest privilege



Interprocess Protection

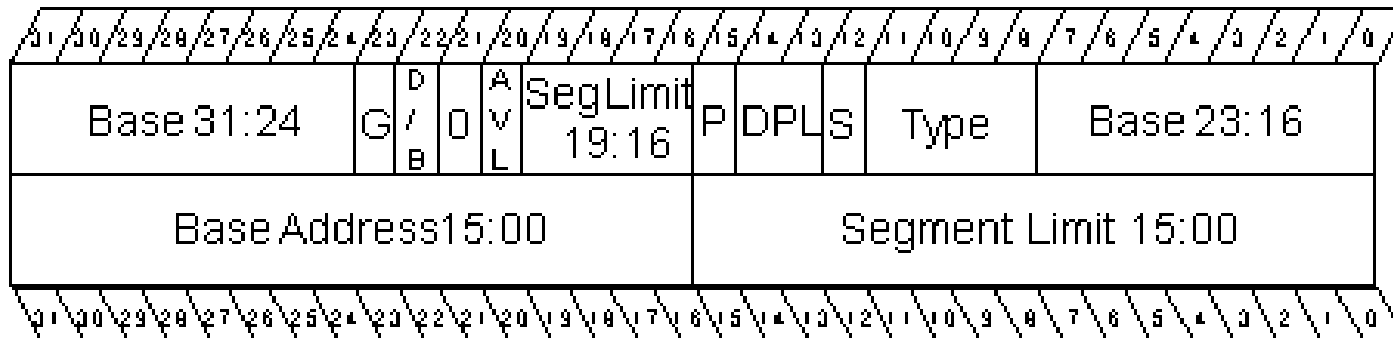
Privilege levels and Protection

- Every segment has an associated privilege level and hence any code segment will have an associated privilege level.
- The CPL (Current Privilege Level) of a process is the privilege level of the code segment, the code stored in which, it is executing.
- A process can access segments that have privilege levels numerically greater than or equal to (less privileged than) its CPL.

Protection Implementation

- Every segment is associated with a descriptor stored in a descriptor table.
- The privilege level of any segment is stored in its descriptor.
- The descriptor table is maintained in memory and the starting location of the table is pointed to by a Descriptor Table Register (DTR).
- The segment register stores an offset into this table.

Structure of a Descriptor



- AVL Available for use by system software
- BASE Segment Base Address
- D/B Default Operand Size (0 = 16-bit segment, 1 = 32-bit segment)
- DPL Descriptor Privilege Level
- G Granularity (0 = Byte, 1 = Page) of Limit
- LIMIT Segment Limit
- P Segment Present
- S Descriptor Type (0 = System, 1 = Application)
- TYPE Segment Type

Updating Segment registers

- Segment registers (DS, ES, SS, GS and FS) are updated by normal MOV instructions.
 - MOV AX, 0x10 ; MOV DS, AX
- The above command is successful if and only if the descriptor stored at the offset 0x10 in the descriptor table has a privilege level numerically greater than or equal to the CPL.
- A process with CPL = 3 cannot load the segment descriptor of CPL \leq 2, and hence cannot access the segments.

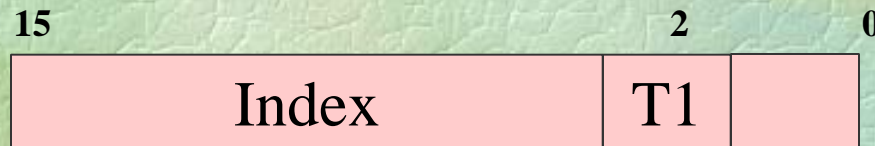
Updating segment registers

- The code segment register is updated by normal jump/call operations.
 - `jmp 0x20:0x1000`
 - This updates the CS by 0x20, provided the descriptor stored at offset 0x20 has a privilege level numerically greater than or equal to CPL
- Other modes of updating CS register
 - Numerically higher to lower Privilege Levels using CALL gates – useful for system calls.
 - Any privilege level to any other privilege level using task switch.

Descriptor Tables

- There are two descriptor tables
 - Global Descriptor Tables
 - Local Descriptor Tables
- The global descriptor table's base address is stored in GDTR
- The local descriptor table's base address is stored in LDTR
- The two *privileged instructions* LGDT and LLDT loads the GDTR and LDTR.

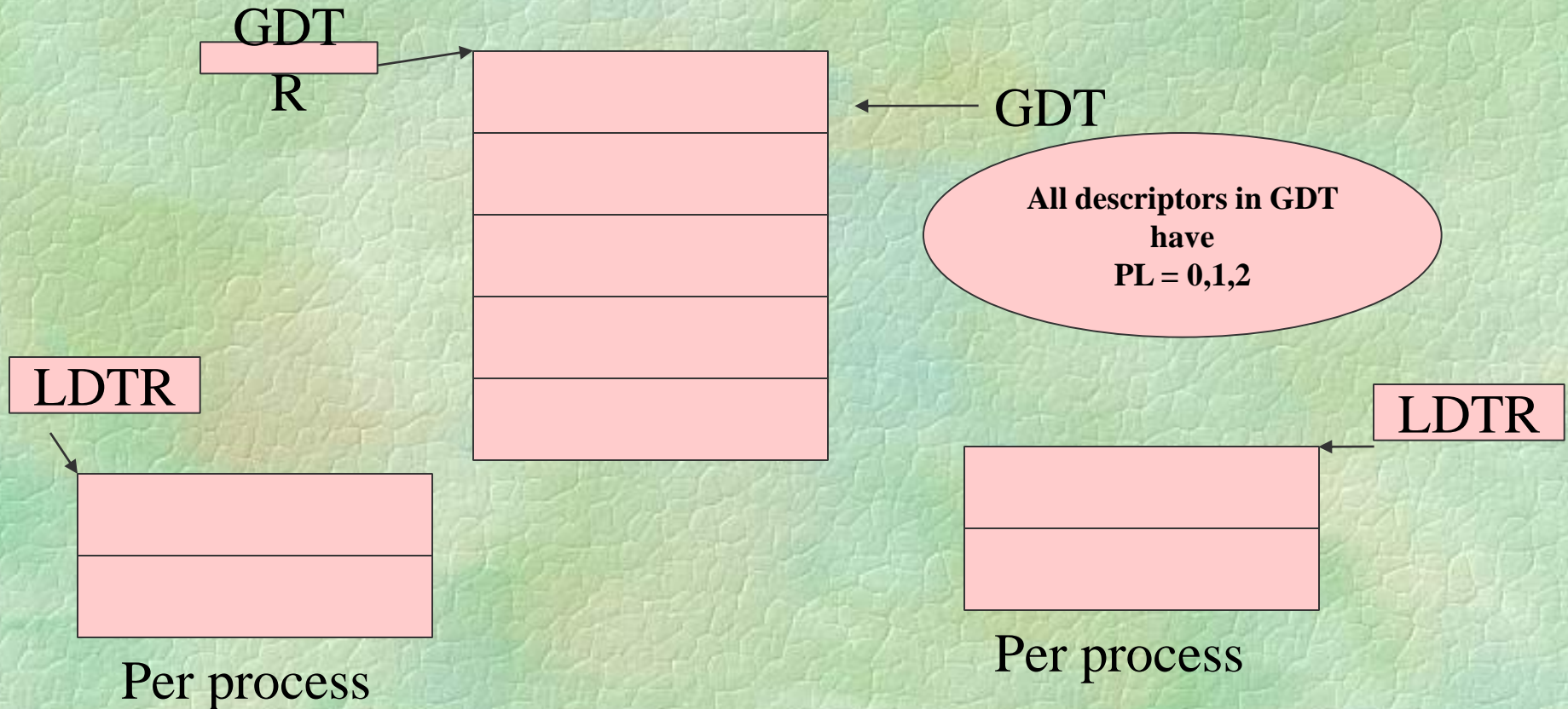
Structure of a Selector



T1 = 0 GDT
= 1 LDT

Since segment descriptors are each 8 bytes, the last three bits of the selector is zero, in which one of them is used for LDT/GDT access.

Two process each of PL = 3 should be allotted segments such that one should not access the segments of other.



If at all each process should access memory, it has to use the descriptors in its LDTR only and it cannot change the LDTR/LDT/GDTR/GDT contents as they would be maintained in a higher privileged memory area.

Did You Note!!

- There is an 100 % degradation in Memory access time – because every memory access is two accesses now, one for getting the base address and another for actually accessing the data.
- A solution indeed: Along with the segment registers, keep a shadow registers which stores additional necessary information.

Visible part

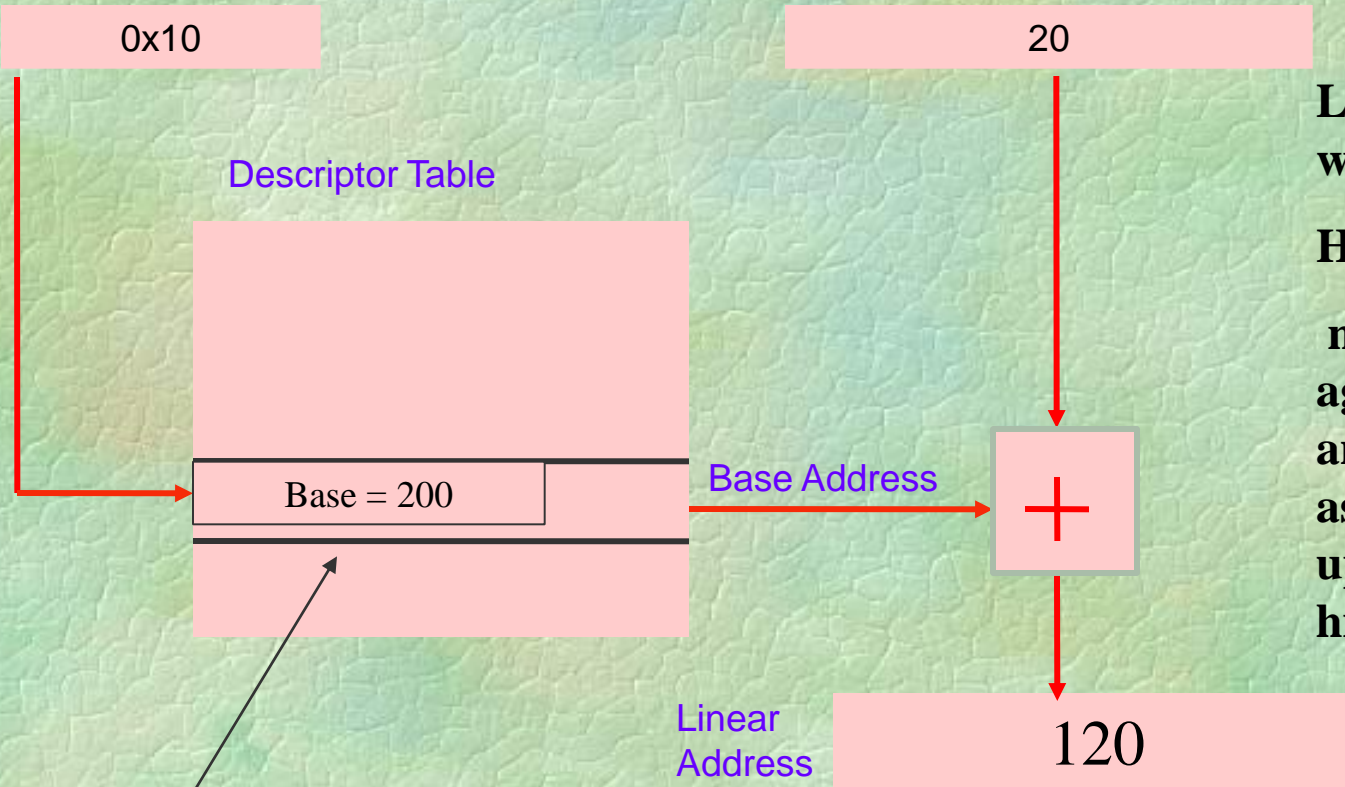
Hidden part

Visible part	Hidden part	
Segment selector	Base Address, Limit, DPL.	CS
		SS
		DS
		ES
		FS
		GS

Be Careful

add [DS:20],eax

Logical
Address



**Linear address
will still be 120**

Have to execute

**mov DS,0x10
again to get the
answer as 220,
as this would
update the
hidden part**

Changing Base

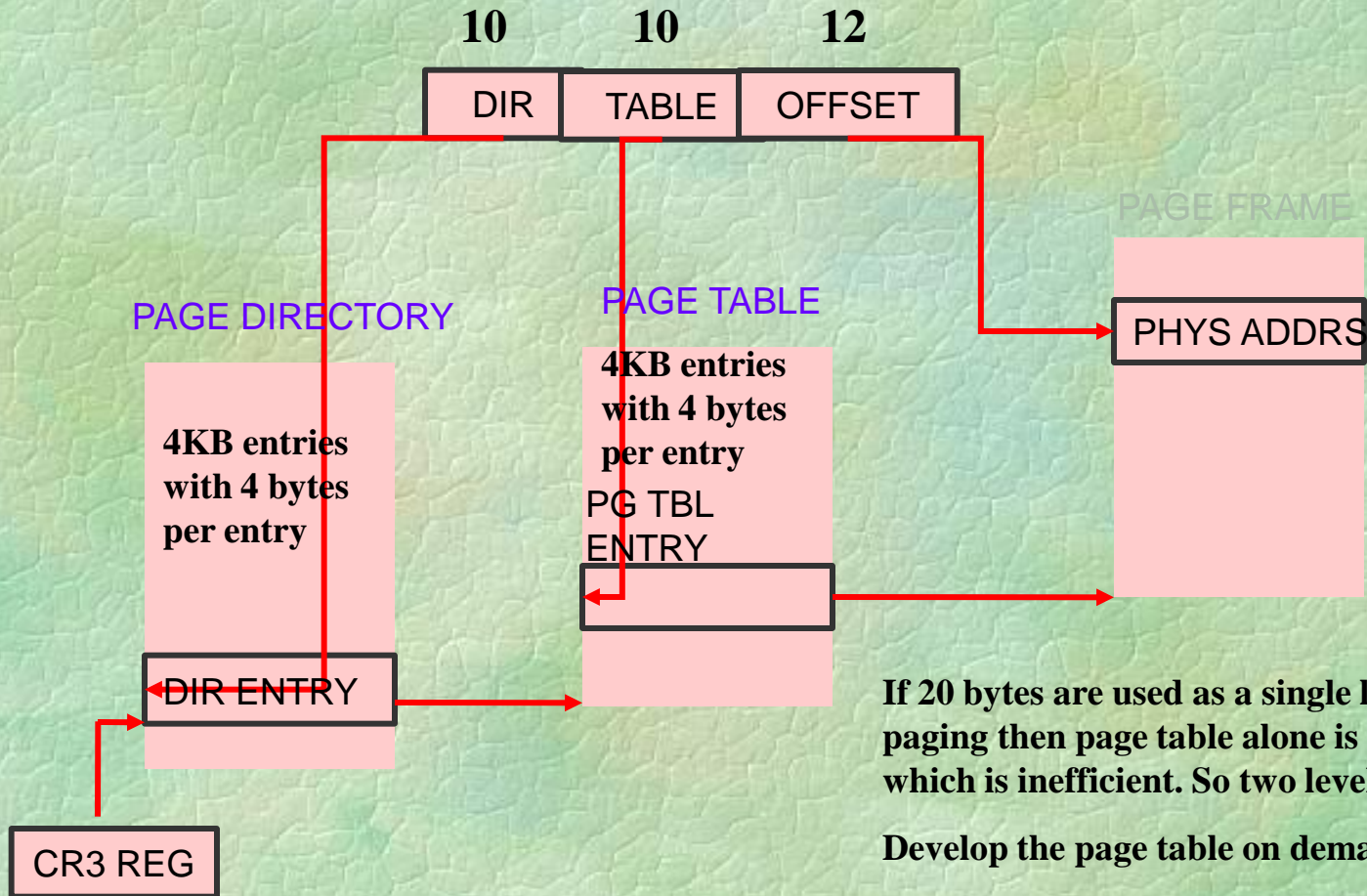
Virtual Memory and Paging

- It is always enough if the next instruction to be executed and the data needed to execute the same are available in the memory.
- The complete code and data segment need not be available.
- Use of paging to realize the stuff!
- By using segmentation the processor calculates an 32-bit effective address.

Paging fundamentals

- Each page is 4096 bytes
- Physical RAM has *page frames* like photo frames, which is also 4096 bytes.
- A page is copied into the page frame, if needed and removed to accommodate some other page.
- By this, a 4 GB code can run on a 128MB physical memory
- This is also called *demand paging*.

Protected Mode Addressing with paging



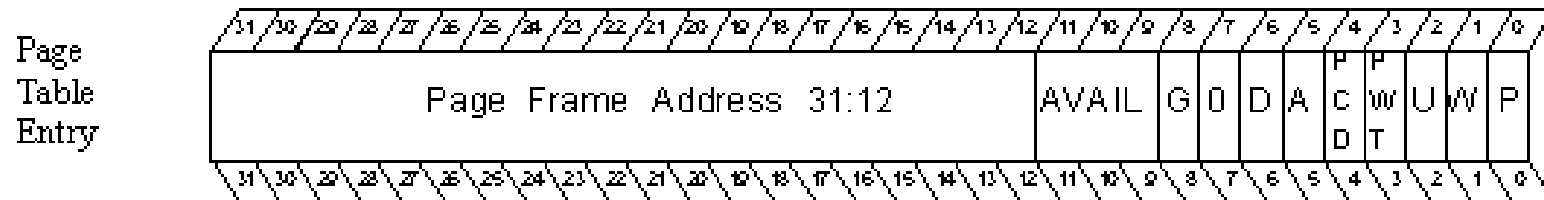
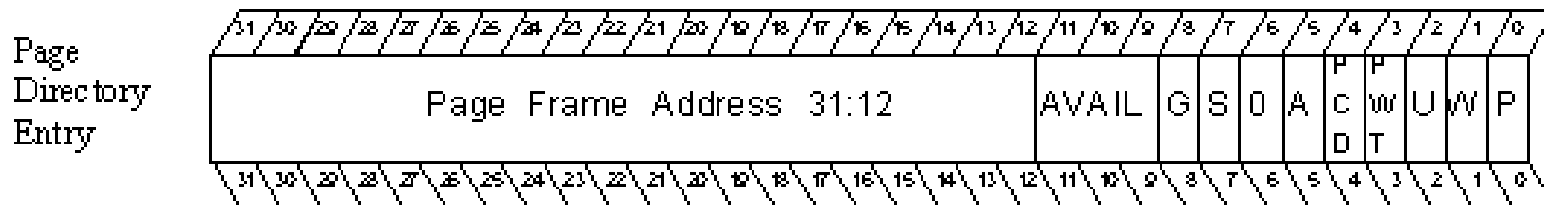
If 20 bytes are used as a single level paging then page table alone is 4 MB which is inefficient. So two level paging.

Develop the page table on demand

TLB's used to improve performance

Dirty bit accommodated in each page entry

Protected Mode Addressing - Paging entries



AVAIL	Available for use	W	Writeable
G	Global Page	P	Present
S	Size 0=4 K, 1=4 M	PCD	Page Cache Disable
A	Accessed	PWT	Page Write Through
D	Dirty (Modified)		
U	User/Supervisor		

Task Switching

- There are different types of descriptors in a Descriptor table.
- One of them is a task state segment descriptor.
- `jmp 0x10:<don't care>` and that 0x10 points to a TGD, then the current process context is saved and the new process pointed out by the task state segment descriptor is loaded.
- A perfect context switch.
- TSS descriptor only in a GDT.

Task State Segment

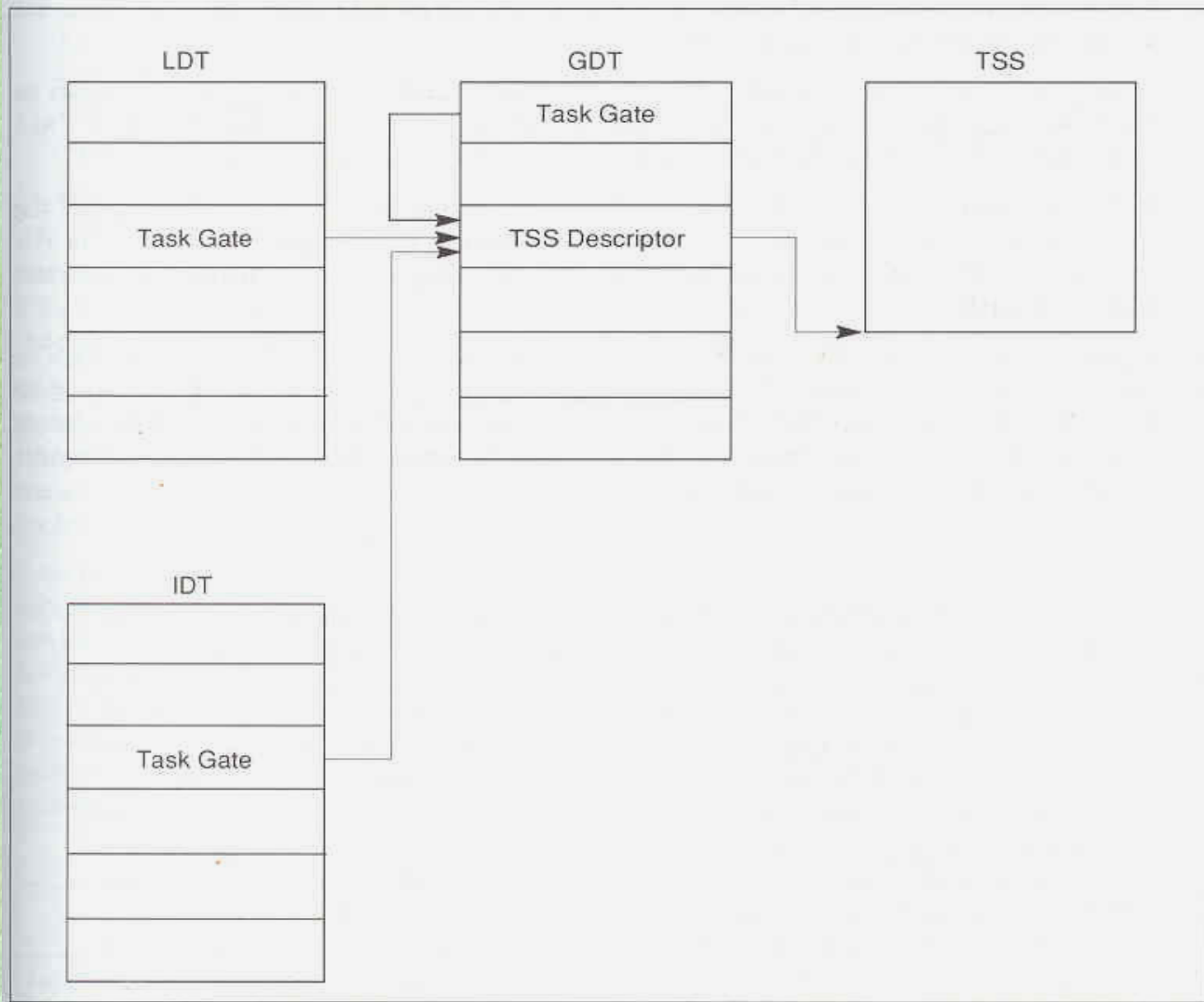
31	15	0	
I/O Map Base Address		T	100
		LDT Segment Selector	
		GS	96
		FS	88
		DS	84
		SS	80
		CS	76
		ES	72
EDI			68
ESI			64
EBP			60
ESP			56
EBX			52
EDX			48
ECX			44
EAX			40
EFLAGS			36
EIP			32
CR3 (PDBR)			28
		SS2	24
ESP2			20
		SS1	16
ESP1			12
		SS0	8
ESP0			4
		Previous Task Link	
			0

Reserved bits. Set to 0.

Task Switching

- Every process has an associated Task State Segment, whose starting point is stored in the Task register.
- A task switch happens due to a `jmp` or `call` instruction whose segment selector points to a Task state segment descriptor, which in turn points to the base of a new task state segment

Task Switching process



Interrupt Handling

- Processor generates interrupts that index into a Interrupt Descriptor Table, whose base is stored in IDTR and loaded using the *privileged instruction* LIDT.
- The descriptors in IDT can be
 - Interrupt gate: ISR handled as a normal call subroutine – uses the interrupted processor stack to save EIP,CS, (SS, ESP in case of stack switch – new stack got from TSS).
 - Task gate: ISR handled as a task switch
 - Needed for stack fault in CPL = 0 and double faults.

Interrupt Handling

- Processor handles a total of 255 interrupts
- 0-31 are used by machine or reserved
- 32-255 are user definable
- 0 – Divide error, goes to first descriptor in IDT
- 1 – Debug
- 8 – Double Fault
- 12 – Stack Segment fault
- 13 – General Protection Fault
- 14 – Page Fault

Instruction Set Architecture

INSTRUCTION PREFIX	ADDRESS- SIZE PREFIX	OPERAND- SIZE PREFIX	SEGMENT OVERRIDE
0 OR 1	0 OR 1	0 OR 1	0 OR 1

NUMBER OF BYTES			

OPCODE	MODR/M	SIB	DISPLACEMENT	IMMEDIATE
1 OR 2	0 OR 1	0 OR 1	0,1,2 OR 4	0,1,2 OR 4

NUMBER OF BYTES				

Legacy Issues

- 16-bit code in 32-bit architecture
- Address override prefix – 16-bit or 32-bit addresses in a 32-bit or 16-bit code segment
- Operand override prefix
 - Same opcode for say, `add EAX,EBX` and `add AX,BX`
 - Distinguished by the operand override prefix – 16-bit or 32-bit operands in a 32-bit or 16-bit code segment
- D flag in the code segment descriptor tells the size of the code segment, which is used above.

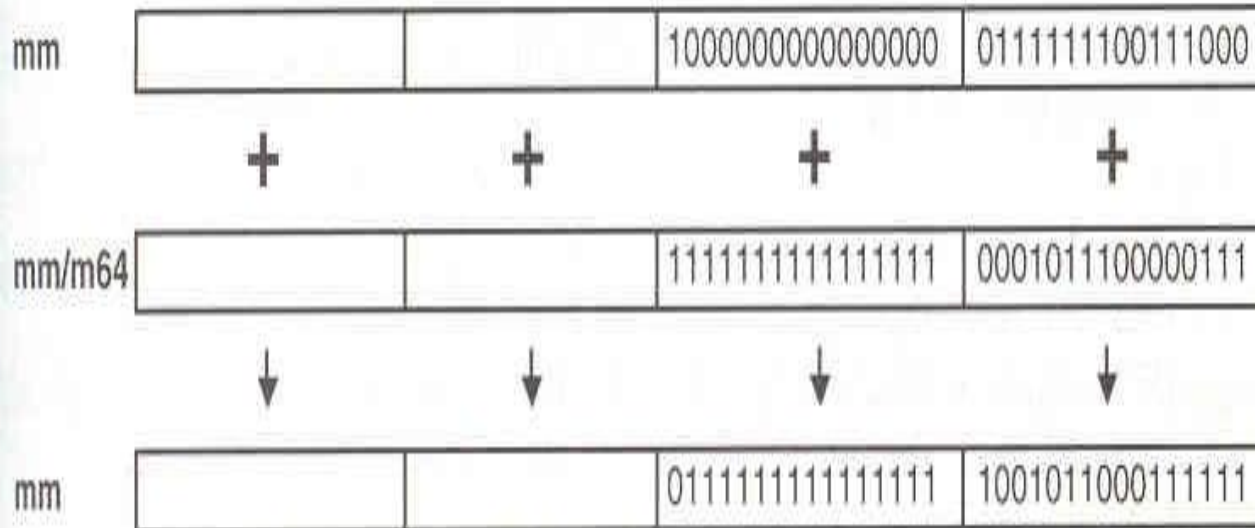
Legacy Issues

- mod r/m: says if it is a memory or register access
- sib: says if it is memory then what addressing is issued for effective address calculation.

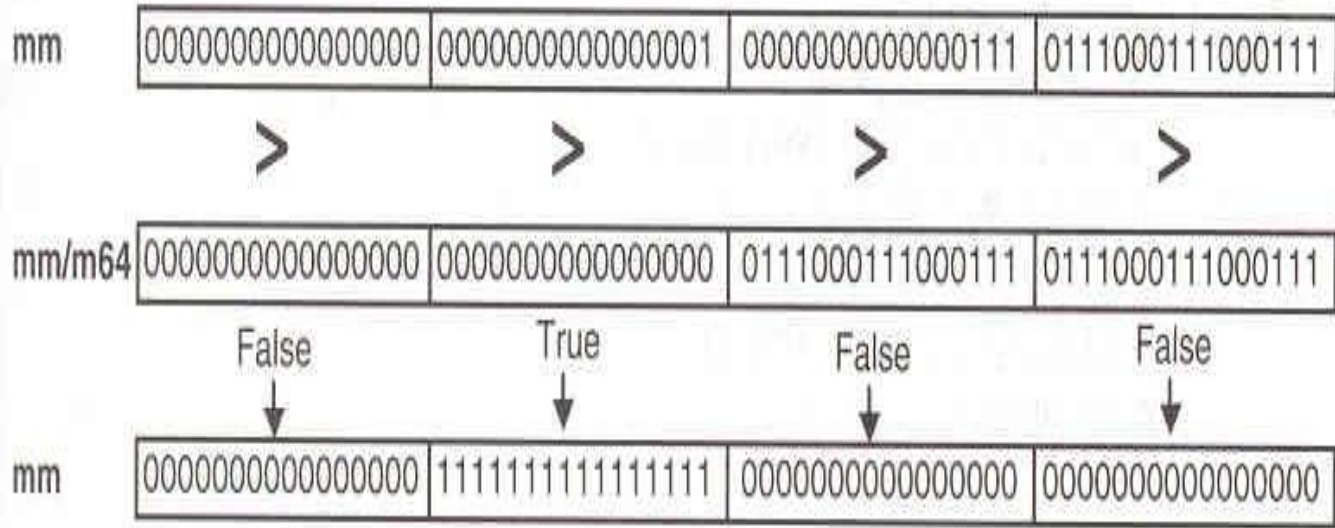
Evolving Instruction Sets

- The Multimedia Instruction set (MMX)
- First Major Extension to x86 since 1985
- 57 new instructions
 - Audio
 - Video
 - Speech Recognition and synthesis
 - Data communication
- Two byte Opcode with 0F prefix
- Use of Data parallelism at the instruction opcode level to speedup computation.

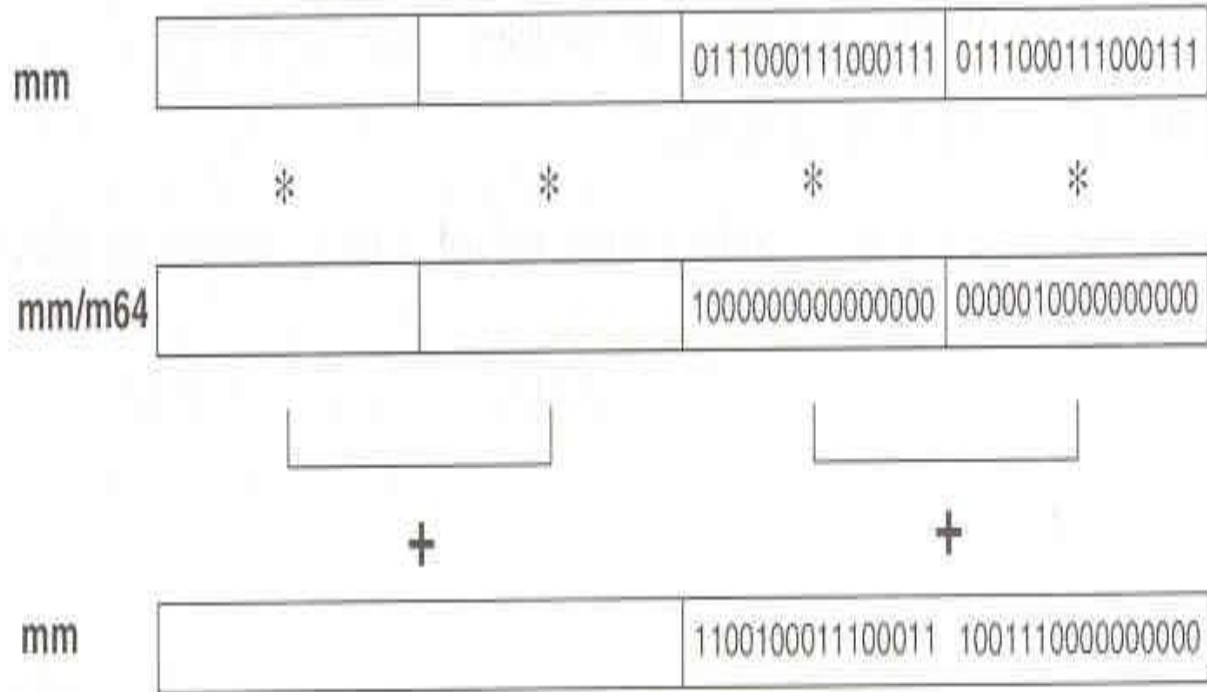
PADDW mm, mm/m64



PCMPGTW mm, mm/m64



PMADDWD mm, mm/m64



Question and Answers

x86 Memory Management

- To learn
 - Segmentation details
 - Privilege levels and switching

Memory Segmentation

- Segment Descriptors
 - 80886 to 80386+
 - In 8086, the program is not expected to generate a non-existent memory address. If it does, then the processor shall try to access the same and read bogus data, or crash
 - In 80386+ (and above) the segment attributes (base, limit, privilege etc) are programmable and no matter how privileged the code may be, it cannot access an area of memory unless that area is *described* to it.

Insight into 80386+ segments

- Segments are
 - Areas of memory
 - Defined by the programmer
 - Used for different purposes, such as code, data and stack
- Segments are not
 - All the same size
 - Necessarily paragraph aligned
 - Limited to 64KB

Segment Descriptors

- Describes a segment using 64-bits (0-63)
- Must be created for every segment
- Is created by the programmer
- Determines a segment's base address (32-bits) (Bits 16-39, 56-63)
- Determines a segment's size (20-bits) (Bits 0-15, 48-51)

Segment Descriptors (Cont'd)

- Defines whether a segment is a system segment (=0) or non-system (=1) (code, data or stack) segment (System bit) (Bit 44)
- Determines a segment's use/type (3-bits) (Bits 41-43) after the above classification
- Determines a segment's privilege level (2 bits) (Bits 45-46) – DPL (Descriptor Privilege Level) Bits

Segment Descriptor (Cont'd)

- Accessed (A)-bit: Bit 40, automatically set and not cleared by the processor when a memory reference is made to the segment described by this descriptor.
- Present (P)-bit: Bit 47, indicates whether the segment described by this descriptor is currently available in physical memory or not.
- Bits 40-47 of the descriptor is called the **Access Right Byte** of the descriptor.
- User (U)-bit and X bit: Bit 52 (U-bit) not used and Bit 53 (X-bit) reserved by Intel

Segment Descriptor (Cont'd)

- Default size (D)-bit: Bit 54, when this bit is cleared, operands contained within this segment are assumed to be 16 bits in size. When it is set, operands are assumed to be 32-bits.
- Granularity (G)-bit: Bit 55, when this bit is cleared the 20-bit limit field is assumed to be measured in units of 1byte. If it is set, the limit field is in units of 4096 bytes.

Types of non-system segment descriptors

- System bit $S = 1$
 - 000 – Data, Read only
 - 001 – Data, Read/Write
 - 010 – expand down, Read only
 - 011 – expand down, Read/Write
 - 100 – Code, Execute only
 - 101 – Code, Execute/Read
 - 110 – Conforming Code, Execute only
 - 111 - Conforming Code, Execute/Read

D-bit for different descriptors

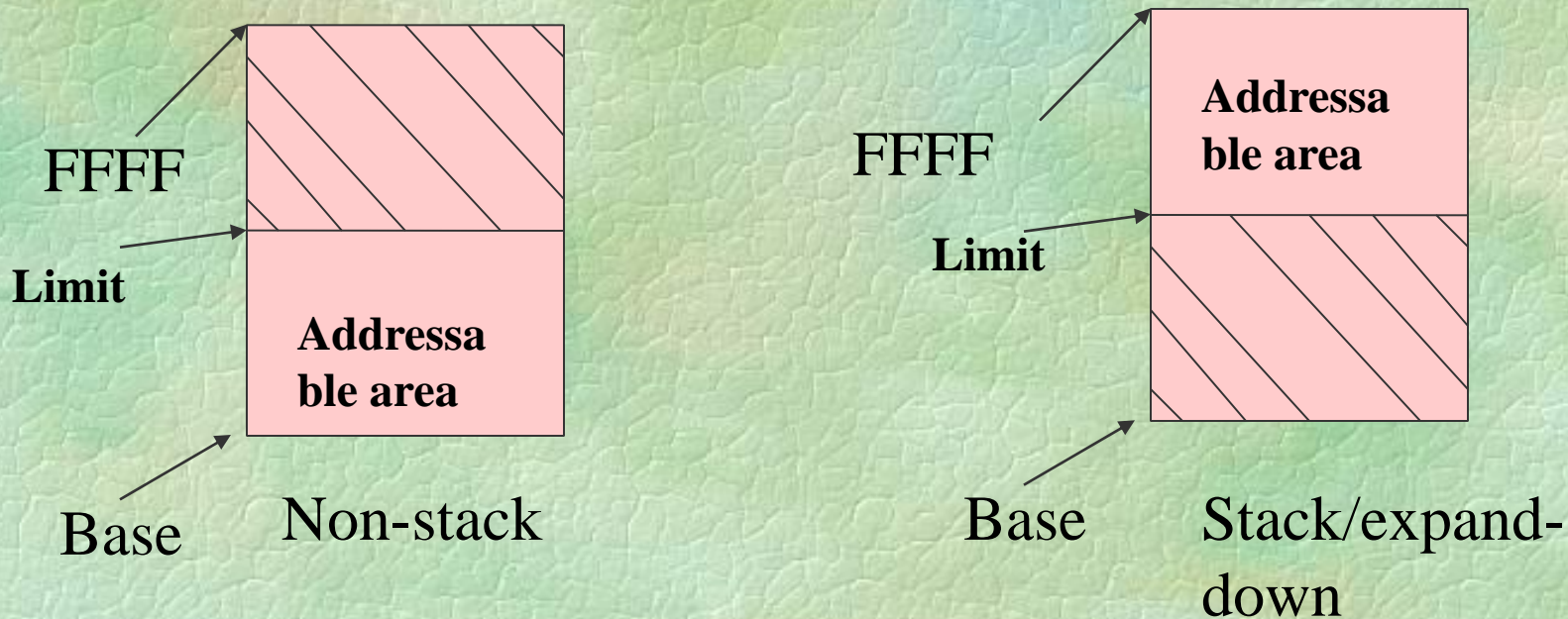
- Code segment
 - D = 0 then 16-bit 80286 code
 - D = 1 then 32-bit 80386+ code
- Stack Segment
 - D = 0 then stack operations are 16-bit wide, SP is used as a stack pointer, maximum stack size is FFFF (64 KB)
 - D = 1 then stack operations are 32-bit wide, ESP is used as a stack pointer, maximum stack size is FFFFFFFF (4 GB)

G-bit for descriptors

- $G = 0$ then a limit field in descriptor of value p indicates we can access $p-1$ bytes from base
- $G = 1$ then a limit field in descriptor of value p indicates we can access $(p * 4096) - 1$ bytes from base

Stack/expand down segments

- All offsets must be greater than limit.
- In stack descriptor, D and G bits are to be the same, else contradiction.



Descriptor Tables

- Descriptors are stored in three tables:
 - Global descriptor table (GDT)
 - Maintains a list of most segments
 - May contain special “system” descriptors
 - The first descriptor is a null descriptor
 - Interrupt descriptor table (IDT)
 - Maintains a list of interrupt service routines
 - Local descriptor table (LDT)
 - Is optional
 - Extends range of GDT
 - Is allocated to each task when multitasking is enabled
 - The first descriptor is a null descriptor

Locations of the tables

- In Memory
- Pointed out by GDTR, LDTR and IDTR for the GDT, LDT and IDT respectively.
- The GDTR and IDTR are 48-bits in length, the first 16-bits (least significant) storing the size (limit) of the table and the remaining storing a 32-bit address pointing to the base of the tables
- $\text{Limit} = (\text{no. of descriptors} * 8) - 1$
- LLDT stores a 16-bit *selector* pointing to an entry in the GDT.

Segment Selectors

- Out of several segments described in your GDT and LDT, which of the segment(s) that are currently being used are pointed to by the 16-bit CS,DS,ES,FS,GS and SS registers.
- Each store a selector
- Since descriptors are at 8-byte boundaries, the 16-bit selectors store the first most significant 13 bits to point to the corresponding descriptor.
- The bit 2 is the T1 bit, which when 0 (1) implies the selector is pointing to a descriptor in GDT (LDT).
- The bits (0-1) – are the Request Privilege Level (RPL) bits used for privilege assignments.

Loading Segment Selectors into segment registers

- Whenever segment registers are loaded, the following rules are checked by the processor and if violated an exception is raised thus giving high degree of memory protection
- **Rule 1:** Index field of the selector within limits of the GDT/LDT to be accessed – else raise a General Protection Fault exception.

Loading Segment Selectors into segment registers

- **Rule 2:** Loading a selector into DS,ES,FS or GS that points to a non-readable segment results in an exception
- **Rule 3:** For loading into SS, the segment pointed to should be readable and writable
- **Rule 4:** For loading into CS, the segment should be executable type
- **Rule 5:** Privilege level check rules to be described later

Loading segment selectors

- All segment registers except CS may be loaded using MOV, LDS, LES, LFS, LGS and LSS.
- The CS is loaded using a JMP or a CALL instruction – discussed later

Local Descriptor Table

- Is defined by a system descriptor (S=0) in GDT which is pointed to by the LDT.

The 64-bit descriptor in GDT

Base Address 31-24	0000	Limit 19-16	P	0000010	Base Address 23-0	Limit 15-0
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Privilege levels

- The need is to prevent
 - Users from interfering with one another
 - Users from examining secure data
 - Program bugs from damaging other programs
 - Program bugs from damaging data
 - Malicious attempts to compromise system integrity
 - Accidental damage to data

Privilege Protection

- Continuous checking by the processor on whether the application is privileged enough to
 - Type 1: Execute certain instructions
 - Type 2: Reference data other than its own
 - Type 3: Transfer control to code other than its own
- To manage this every segment has a privilege level called the DPL (Descriptor Privilege Level)
Bits 45,46

Descriptor Privilege Level

- Privilege levels apply to entire segments
- The privilege level is defined in the segment descriptor
- The privilege level of the code segment determines the Current Privilege Level (CPL)

Type 1: Privilege Checking

- Privileged Instructions

1. Segmentation and Protection Based (HLT, CLTS, LGDT, LIDT, LLDT, LTR, moving data to Control, Debug and Test registers)
2. Interrupt flag based (CLI, STI, IN, INS, OUT, OUTS)
3. Peripheral IO based

- First two types of privileged instructions can be executed only when $CPL = 0$, that is, these instructions can be in code segment with $DPL = 0$.

I/O instructions

- The I/O based privileged instructions are executed only if $CPL \leq IOPL$ in EFLAGS register.
- To add to the security the POPF/POPFD instructions which load values into the EFLAGS shall not touch the IOPL bit or IF bit if $CPL > 0$.

Type 2: Privilege Checking

- Reference data other than its own
- Load a selector into a DS, ES, FS and GS iff $\max(\text{RPL}, \text{CPL}) \leq \text{DPL}$
 - RPL may weaken your privilege level
 - Decreasing RPL will not strengthen your privilege level
 - Why?
 - Why to decrease RPL – will discuss later
- Load a descriptor into a stack iff $\text{DPL} = \text{CPL}$
- All these are in addition to the rules for loading segment selector, that were stated in Slides 87 and 88.

Type 3: Privilege Checking

- Transfer control to code other than its own. Essentially load a new selector into CS register
- jmp across code segments with same DPL
 - jmp <selector>:<offset of instruction from start of the new segment>
 - call <selector>:<offset of instruction from start of the new segment>

Type 3: Privilege Checking

- The above jmp, call and ret may be used
- To move between code segments provided the destination segment is
 - A code segment (executable permission)
 - Defined with the same privilege level
 - Marked present

Changing Privilege levels

- Control transfer from a code of some PL to another code with some other different PL.
- Using *conforming* code segments or a special segment descriptor called *call gates*.
- Conforming code segments confirms with the privilege level of the calling code. So if a control transfer happens from segment S to a confirming segment T, the privilege of T would be the privilege of S.

Conforming Code Segment

- The DPL of conforming code segment descriptor \leq CPL of invoking code.
- Therefore, CPL = 2 can invoke DPL = 1.
- CPL = 2 cannot invoke code with DPL = 3.
- Why?
 - If not, you JMP back or RET to the source code segment after executing the conforming code segment. This should permit return from a numerically low privilege code to a numerically high privilege code, without check.

CALL GATE descriptor

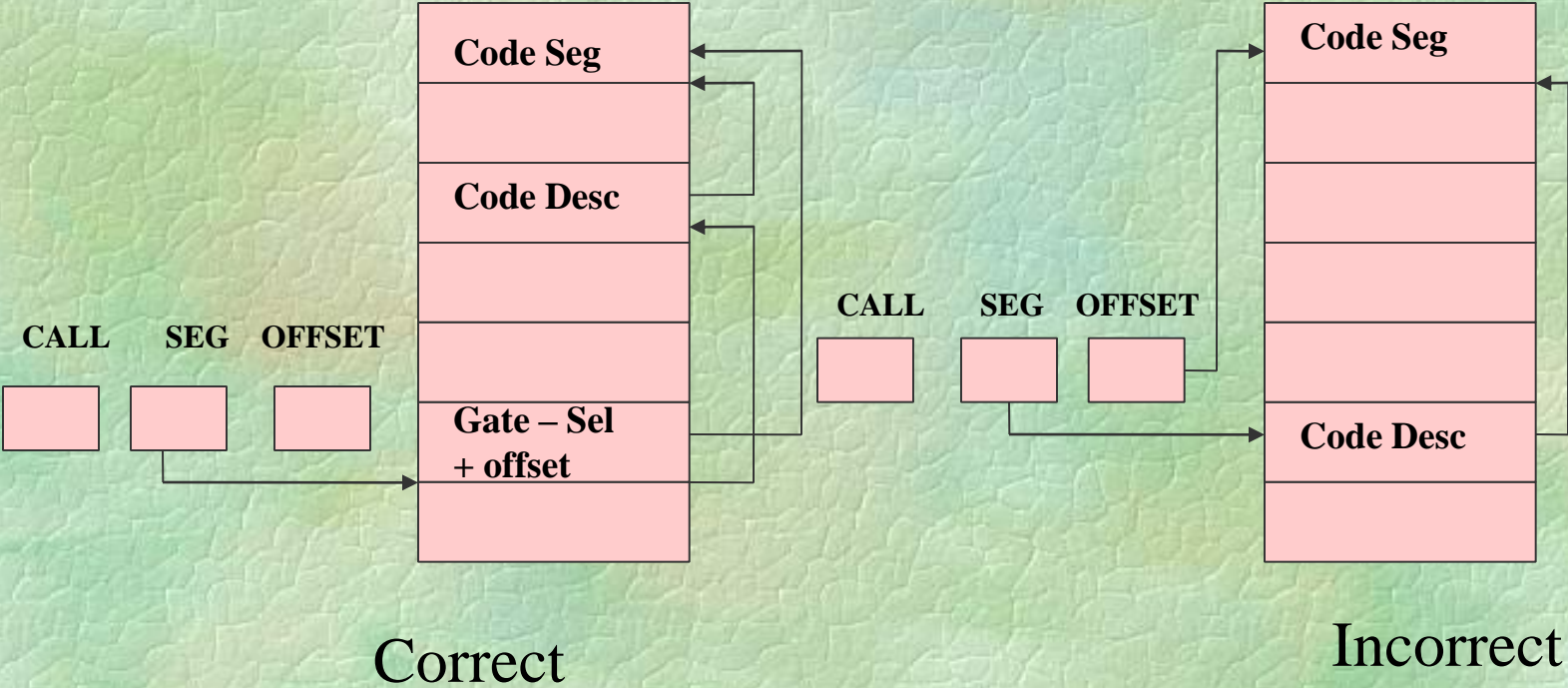
- Is defined by a system descriptor (S=0) in GDT which is used by the JMP or CALL.

The 64-bit descriptor in GDT

Destination offset 31-16	P, DPL	01100	000	WC	Destination Selector (16 bits)	Destination Offset 15-0
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- Not only the selector for the target code segment, but also the offset in the code segment from which you should start executing is specified. The source code segment can only use it like a black-box

Calling Higher privileged code



Call Gates

- Are defined like segment descriptors
- Occupy a slot in the descriptor tables
- Provide the only means to alter the current privilege level
- Define entry points to other privilege levels
- Must be invoked using a `CALL` Instruction

Call Gate accessibility

- Target DPL \leq Max (RPL, CPL) \leq Gate DPL
- For eg. CPL = 2 and the target PL = 0, you should use a Gate with PL = 2 or 3

Privilege levels and Stacks

- The stack PL = CPL always
- When changing the CPL, the processor automatically changes the stack!!!
- How – using the Task State Segment (TSS)
- The base of the TSS is stored in a Task register (TR) which is updated by the privileged instruction LTR
- The TSS associates a stack for each code for each of the privilege levels 0, 1 and 2

Task Switching process

