CSC 370 – Computer Architecture and Organization

Lecture 9 – IA-32 Architecture

The Intel Microprocessor Family

- The Intel family owes its origins to the ***8080***, an 8-bit processor which could only access 64 kilobytes of memory.
- The ***8086*** (1978) had 16-bit registers, a 16-bit data bus, 20-bit memory using segmented memory. The IBM PC used the ***8088***, which was identical except it used an 8-bit data bus.
- ***8087*** - a math co-processor that worked together with the 8086/8088. Without it, floating point arithmetic require complex software routines.
- ***80286*** - ran in real mode (like the 8086/8088) or in protected mode could access up tp 16MB using 24-bit addressing with a clock speed between 12 and 25 MHz. Its math co-processor was the 80287.

The Intel Microprocessor Family (continued)

- 80386 or ***i386*** (1985) - used 32-bit registers and a 32-bit data bus. It could operate in real, protected or virtual mode. In virtual mode, multiple real-mode programs could be run.
- ***i486*** - The instruction set was implemented with up to 5 instructions fetched and decoded at once. SX version had its FPU disabled.
- The Pentium processor had an original clock speed of 90 MHz and cold decode and executed two instructions at the same time, using ***dual pipelining***.

IA-32 Processor Modes of Operations

- There are three basic modes of operation on IA-32 processors:
  - ***Protected Mode*** – The native processor state, where all instructions and features are available. Each process is given its own memory segment and the processor catches any process attempting to go outside its own segment
  - ***Real-address Mode*** – The processor acts as if it were an Intel 8086 processor with its more limited environment
  - ***System Management Mode*** – provides a mechanism for implementation power management and system security

IA-32 Processor Address Space

- In protected mode IA-32 processors can access up to 4 Gigabytes of storage, with memory addresses from 0 to 2^{32}-1.
- In real mode, a maximum of 1 megabyte of memory can be accessed with memory addresses from 0 to 2^{20}-1.
- The IA-32 processors provide a Virtual 8086 where multiple MS-DOS programs can run safely within an Windows environment.

P6 Processor Family

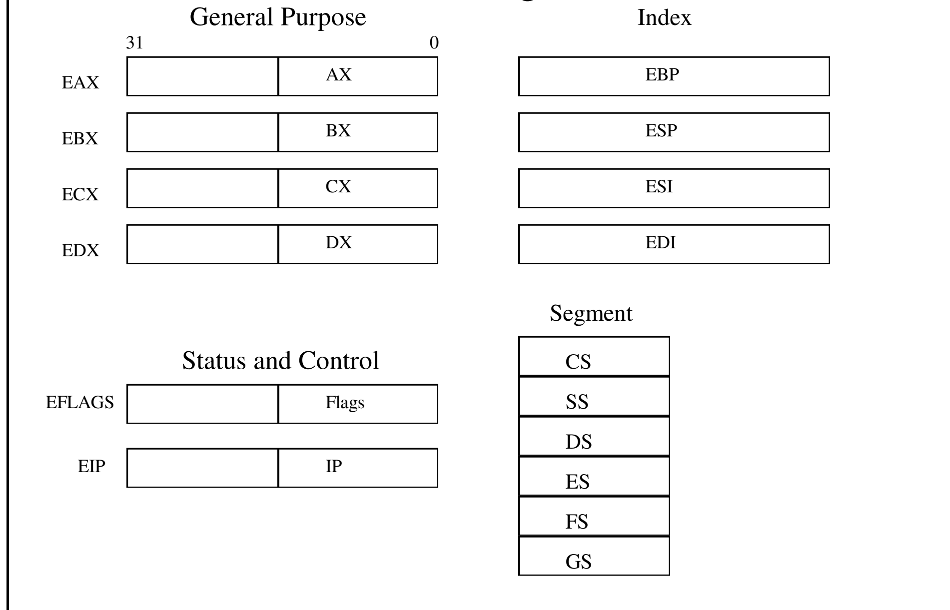
- The P6 family of processors was introduced in 1995.
- It includes the Pentium Pro, Pentium II, Pentium III and Pentium 4.
- The Pentium II introduces MMX technology for multimedia applications.
- The Pentium III introduced SIMD with 128-bit registers to move larger amounts of data.
- The Pentium 4 uses NetBurst micro-architecture to allow the processors to operate at higher speeds.

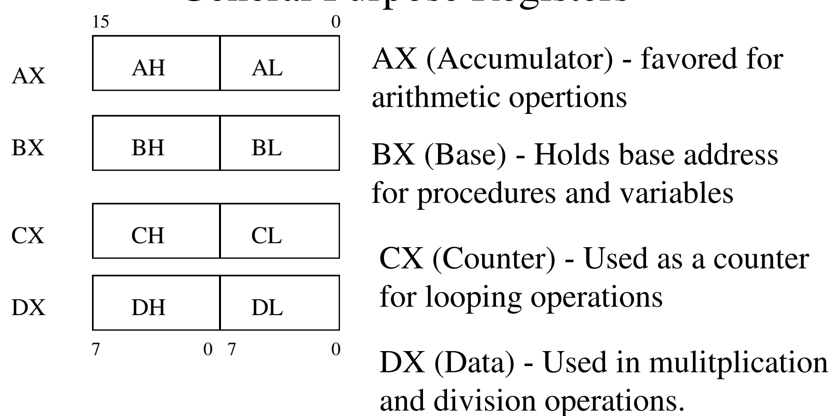
CISC Architecture

- The Intel processors have been based on the CISC (***C***omplex ***I***nstruction ***S***et ***C***omputer) approach to processor design.
- CISC processors have large , powerful instruction sets that can include many high-level operations. But the size of the instruction set makes the control unit relatively slow.

RISC Architecture

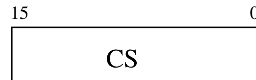
- RISC computers use smaller, streamlined instruction sets that allow their control units to be quicker.
- Intel processors are backwards-compatible and are basically CISC but use RISC features such as pipelining and superscalar.


32-bit Register
General Purpose
Index
31
0
EAX
AX
EBX
BX
ECX
CX
EDX
DX
EBP
ESP
ESI
EDI
Segment
Status and Control
EFLAGS
Flags
EIP
IP
CS
SS
DS
ES
FS
GS

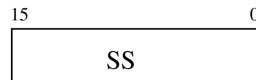

16-bit Processor Architecture
General Purpose Registers
15
0
AX
AH
AL
BX
BH
BL
CX
CH
CL
DX
DH
DL
7
0
7
0
AX (Accumulator) - favored for arithmetic opertions
BX (Base) - Holds base address for procedures and variables
CX (Counter) - Used as a counter for looping operations
DX (Data) - Used in mulitplication and division operations.

Segment Registers

Segment registers are used to hold base addresses for program code, data and the stack.



CS (Code Segment) - holds the base address for all executable instructions in the program



SS (Stack Segment) - holds the base address for the stack

DS (Data Segment) - holds the base address for variables

ES (Extra Segment) - an additional base address value for variable.

Index Registers

Index Registers contain the offsets for data and instructions.

Offset - distance (in bytes) from the base address of the segment.

BP (Base Pointer) - contains an assumed offset from the SS register; used to locate variables passed between procedures.

SP (Stack Pointer) - contains the offset for the top of the stack.

SI (Source Index) - Points to the source string in string move instructions.

DI (Destination Index) - Points to the source destination in string move instructions.

Status and Control Registers

IP

IP (Instruction Pointer) - contains the offset of the next instruction to be executed within the current code segment.

x	x	x	x	O	D	I	T	S	Z	x	A	x	P	x	C

Flags register contain individual bits which indicate CPU status or arithmetic results. They are usually set by specific instructions.

O = Overflow
D = Direction
I = Interrupt
T = Trap
x = undefined

S = Sign
Z = Zero
A = Auxiliary Carry
P = Parity
C = Carry

Flags

There are two types of flags: control flags (which determine how instructions are carried out) and status flags (which report on the results of operations.

Control flags include:

- ***Direction*** Flag (DF) - affects the direction of block data transfers (like long character string). 1 = up; 0 - down.
- ***Interrupt*** Flag (IF) - determines whether interrupts can occur (whether hardware devices like the keyboard, disk drives, and system clock can get the CPU's attention to get their needs attended to.
- ***Trap*** Flag (TF) - determines whether the CPU is halted after every instruction. Used for debugging purposes.

Status Flags

- Status Flags include:
  - ***Carry*** Flag (CF) - set when the result of **unsigned** arithmetic is too large to fit in the destination. 1 = carry; 0 = no carry.
  - ***Overflow*** Flag (OF) - set when the result of **signed** arithmetic is too large to fit in the destination. 1 = overflow; 0 = no overflow.
  - ***Sign*** Flag (SF) - set when an arithmetic or logical operation generates a negative result. 1 = negative; 0 = positive.
  - ***Zero*** Flag (ZF) - set when an arithmetic or logical operation generates a result of zero. Used primarily in jump and loop operations. 1 =zero; 0 = not zero.
  - ***Auxiliary Carry*** Flag - set when an operation causes a carry from bit 3 to 4 or borrow (frombit 4 to 3). 1 = carry, 0 = no carry.
  - ***Parity*** - used to verify memory integrity. Even # of 1s = Even parity; Odd # of 1s = Odd Parity

Floating-Point Unit

80-bit Data Registers

ST(0)
ST(1)
ST(2)
ST(3)
ST(4)
ST(5)
ST(6)
ST(7)

Opcode Register

48-bit Pointer Registers

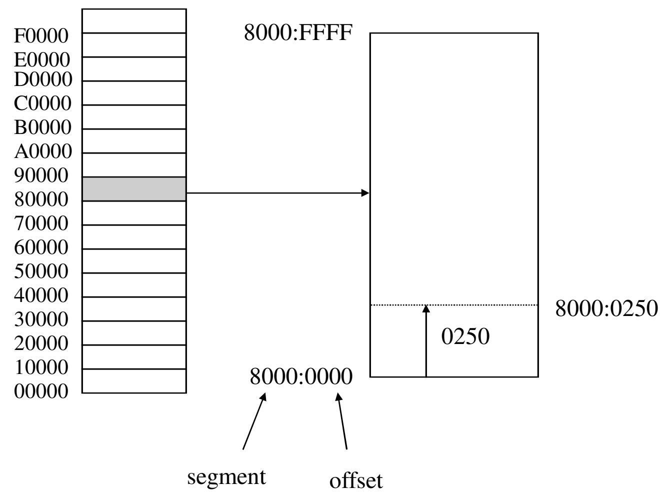
FPU Instruction Pointer

FPU Data Pointer

16-bit Control Registers

Tag Register
Control Register
Status Register

Segmented Memory Map, Real-Address Mode



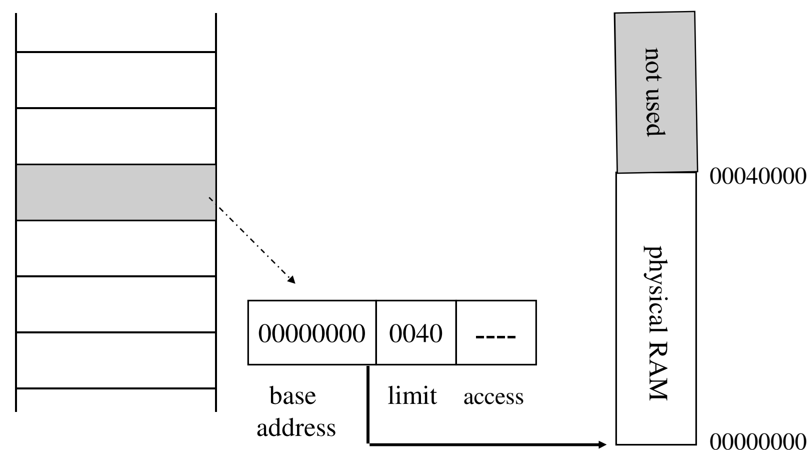
Relocatable addressing

- This is an example of relocatable addressing, which allows programs on mulitasking systems to be moved from one area of memory to another without rearranging every address referenced.
- Addresses can be rearranged simply by changing the value of the appropriate segment register.

Protected Mode Memory Management

- When the processor runs in protected mode, a program can access up to 4 gigabytes of memory.
- Although the programmer's view of memory is a flat image of 4 GB, the operating system works in the background to create and maintain this image.
- The segment registers point to segment descriptor tables, which define locations of the program segments:
  - CS refers to the code segment's descriptor table
  - DS refers to the data segment's descriptor table
  - SS refers to the stack segment's descriptor table

Flat Segmentation Memory Model



Paging

- IA-32 architecture also allows memory segments to be divided into 4K units called ***pages***.
- Many of these pages of memory are saved on disk in a swap file and are loaded into memory (and rewritten in the swap file) when the CPU needs a page that is not present in physical memory. This situation is called a ***page fault***.
- The use of paging and swap files allows the memory used to be several times larger than physical memory; it is known as ***virtual memory***.

Examples of Integer Constants

• 26	Decimal
• 1Ah	Hexadecimal
• 1101b	Binary
• 36q	Octal
• 2Bh	Hexadecimal
• 42Q	Octal
• 36D	Decimal
• 47d	Decimal

Examples of Integer Expressions

Expression	Value
`16 / 5`	3
`- (3 + 4) * (6 - 1)`	-35
`-3 + 4 * 6 - 1`	20
`4 + 5 * 2`	1
`-5 + 2`	
`12 - 1 MOD 5`	
`(4 + 2) * 6`	

Real Number Constants

- There are two types of real number constants:
  - ***Decimal reals***, which contain a sign followed by a number with decimal fraction and an exponent:

    `[sign] integer.[integer][exponent]`

    Examples:

    `2.    +3.0 -44.2E+05 26.E5`
  - ***Encoded reals***, which are represented exactly as they are stored:

    `3F80000r`

Characters Constants

- A character constant is a single character enclosed in single or double quotation marks.
- The assembler converts it to the equivalent value in the binary code ***ASCII***:

```
'A'
"d"
```

String Constants

- A string constant is a string of characters enclosed in single or double quotation marks:

```
'ABC'
"x"
"Goodnight, Gracie"
'4096'
"This isn't a test"
'Say "Goodnight, " Gracie'
```

Reserved Words

- Reserved words have a special meaning to the assembler and cannot be used for anything other than their specified purpose.
- They include:
  - Instruction mnemonics
  - Directives
  - Operators in constant expressions
  - Predefined symbols such as **`@data`** which return constant values at assembly time.

Examples of Identifiers

var1	**open_file**
_main	**_12345**
@@myfile	**$first**
Count	**MAX**
xVal	

Directives

- Directives are commands for the ***assembler***, telling it how to assemble the program.
- Directives have a syntax similar to assembly language but do not correspond to Intel processor instructions.
- Directives are also case-insensitive:
- Examples

```
.data
.code
name    PROC
```

Instructions

- An instruction in Assembly language consists of a name (or label), an instruction mnemonic, operands and a comment
- The general form is:

  [*name*] [*mnemonic*] [*operands*] [; *comment*]
- Statements are free-form; i.e, they can be written in any column with any number of spaces between in each operand as long as they are on one line and do not pass column 128.

Labels

- Labels are identifiers that serve as place markers within the program for either code or data.
- These are replaces in the machine-language version of the program with numeric addresses.
- We use them because they are more readable:

```
mov    ax, [9020]
```

vs.

```
mov ax, MyVariable
```

Code Labels

- Code labels mark a particular point within the program's code.
- Code labels appear at the beginning and are immediately followed by a colon:

```
target:
   mov     ax, bx
   … …
   jmp target
```

Data Labels

- Labels that appear in the operand field of an instruction:

```
mov    first, ax
```

- Data labels must first be declared in the data section of the program:

```
first BYTE 10
```

Instruction Mnemonics

- Instruction mnemonics are abbreviations that identify the operation carried out by the instruction:

`mov`	- move a value to another location
`add`	- add two values
`sub`	- subtract a value from another
`jmp`	- jump to a new location in the program
`mul`	- multiply two values
`call`	- call a procedure

Operands

- Operands in an assembly language instruction can be:
  - constants `96`
  - constant expressions `2 + 4`
  - registers `eax`
  - memory locations `count`

Operands and Instructions

- All instructions have a predetermined number of operands.
- Some instructions use no operands:

```
stc     ; set the Carry Flag
```

- Some instructions use one operand:

```
inc     ax    ; add 1 to AX
```

- Some instructions use two operands:

```
mov     count, bx ; add BX to count
```

Example: Adding Three Numbers

```
TITLE Add And Subtract  (AddSub.asm)
; This program adds and subtracts 32-bit
; integers.
INCLUDE     Irvine32.inc
.code
main  PROC
  mov eax, 10000h       ;Copies 10000h into EAX
  add eax, 40000h       ;Adds 40000h to EAX
  sub eax, 20000h ; Subtracts 20000h from EAX
  call DumpRegs   ; Call the procedure DumpRegs
  exit            ; Call Windows procedure Exit
                  ; to halt the program
main  ENDP        ; marks the end of main
  end main        ; last line to be assembled
```

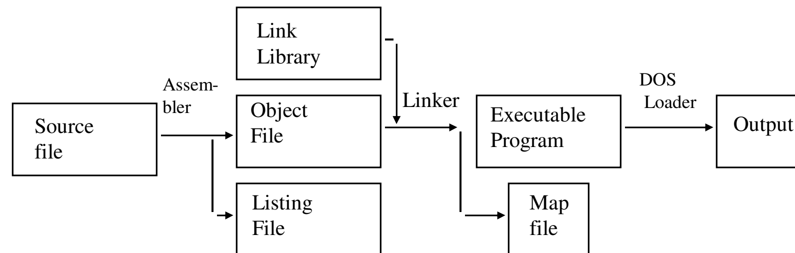
marks the program's title Treated like a comment

Copies the file's contents into the program

Program output

```
EAX=00030000  EBX=00530000  ECX=0063FF68  EDX=BFFC94C0
ESI=817715DC  EDI=00000000  EBP=0063FF78  ESP=0063FE3C
EIP=00401024  EFL=00000206  CF=0  SF=0  ZF=0  OF=0
```

Assembling, Linking and Running Programs



Intrinsic Data Types

Type	Usage
BYTE	8-bit unsigned integer
SBYTE	8-bit signed integer
WORD	16-bit unsigned integer; also Near Pointer in Real Mode
SWORD	16-bit signed integer
DWORD	32-bit unsigned integer; also Near pointer in Protected Mode
SDWORD	32-bit signed integer

Defining 32-bit Data

- The **DWORD** and **SDWORD** directives allocate storage of one or more 32-bit integers:

```
val1    DWORD      12345678h ; unsigned
val2    SDWORD     -21474836648; signed
val3    DWORD      20 DUP(?)
                        ; unsigned array
```

Arrays of Doublewords

- You can create an array of word values by listing them or using the **DUP** operator:

```
myList    DWORD 1, 2, 3, 4, 5
```

Offset	0000	0004	0008	000C	0010
Value:	1	2	3	4	5

Defining 64-bit and 80-bit Data

- The **QWORD** directive allocate storage of one or more 64-bit (8-byte) values:

```
quad1     QWORD       1234567812345678h
```

- The **TBYTE** directive allocate storage of one or more 80-bit integers, used mainly for binary-coded decimal numbers:

```
val1      TBYTE       1000000000123456789h
```

Defining Real Number Data

- There are three different ways to define real values:
  - REAL4 defines a 4-byte single-precision real value.
  - REAL8 defines a 8-byte double-precision real value.
  - REAL10 defines a 10-byte extended double-precision real value.
- Each requires one or more real constant initializers.

Examples of Real Data Definitions

```
rVal1       REAL4    -2.1
rVal2       REAL8    3.2E-260
rVal3       REAL10   4.6E+4096
ShortArray REAL4    20 DUP(?)

rVal1       DD   -1.2
rVal2       dq   3.2E-260
rVal3       dt   4.6E+4096
```

Ranges For Real Numbers

Data Type	Significant Digits	Approximate Range
Short Real	6	1.18×10^{-38} to 3.40×10^{38}
Long Real	15	2.23×10^{-308} to 1.79×10^{308}
Extended Real	19	3.37×10^{-4932} to 1.18×10^{4932}

Little Endian Order

- Consider the number 12345678h:

Little-endian

Address	Value
0000:	78
0001:	56
0002:	34
0003:	12

Big-endian

Address	Value
0000:	12
0001:	34
0002:	56
0003:	78

Adding Variables to AddSub

```
TITLE Add And Subtract   (AddSub2.asm)
; This program adds and subtracts 32-bit
  integers.
; and stores the sum in a variable
INCLUDE   Irvine32.inc
.data
val1      DWORD10000h
val2      DWORD40000h
val3      DWORD20000h
finalVal  DWORD?
```

```
.code
main PROC
  mov     eax, val1 ; Start with 10000h
  add     eax, val2 ; Add 40000h
  sub     eax, val3 ; Subtract 2000h
  mov     finalVal, eax  ; Save it
  call    DumpRegs  ; Display the
                    ; registers
  exit
main ENDP
  end     main
```

mov Instruction

- The ***mov*** instruction copies data from one location to another.
- The following formats are legal for moving data to or from general purpose registers:
  - **mov** *reg, reg*
  - **mov** *mem, reg*
  - **mov** *reg, mem*
- The following formats are legal for immediate operands
  - **mov** *mem, immed*
  - **mov** *reg, immed*
- The following format are legal for segment registers:
  - **mov** *segreg, r/m16* ; not CS
  - **mov** *r/m16, segreg*

Moving Data From Memory to Memory

- Memory to memory moves cannot be done in a single instruction; it requires two instructions:

```
.data
var1 WORD ?
var2 WORD ?
… …
.code
     mov  ax, var1
     mov  var1, ax
```

mov Instruction Examples

Examples of **mov** instructions

```
.data
   Count     BYTE   10
   Total     WORD   4126h
   Bigval    DWORD  12345678h

.code
   mov al, bl       ; 8-bit register to register
   mov bl, count    ; 8-bit memory to register
   mov count, 26    ; 8-bit immediate to memory
   mov bl, 1        ; 8-bit immediate to register
   mov dx, cx       ; 16-bit register to register
   mov bx, 8FE2h    ; 16-bit immediate to register
   mov eax, ebx     ; 32-bit register to register
   mov edx, bigVal  ; 32-bit memory to register
```

Arithmetic Instructions

Assembly language include many instructions to perform basic arithmetic. They include:

- inc
- dec
- add
- sub

`inc` and `dec` Instructions

- The ***inc*** and ***dec*** instructions have the format:

```
inc     reg/mem     ; add 1 to destination's
                    ; contents
dec     reg/mem     ; subtract 1 to
                    ; destination's contents
```

- The operand can be either a register or memory operand.
- All status flags (except Carry) are affected.

inc and **dec** - Examples

- Simple examples

```
inc     al     ; increment 8-bit register
dec     bx     ; decrement 16-bit register
inc     eax    ; increment 32-bit register
inc     val1   ; increment memory operand
```

- Another example

```
.data
myWord      WORD  1000h
.code
      inc   myWord      ; 1001h
      mov   bx, myWord
      dec   bx          ; 1000h
```

add Instruction

- ***add*** adds a *source* operand to the *destination* operand of the **same size**.
- Format:

  add *destination*, *source*
- *Source* is unchanged; *destination* stores the sum. All the status flags are affected.
- The sizes must match and only one can be a memory location.

`add` Instruction - Examples

- Simple examples

```
add      cl, al      ; add 8-bit register to register
add      eax, edx    ; add 32-bit register-to-register
add      bx, 1000h   ; add immediate value to 16-bit reg
add      var1, ax    ; add 16-bit register to memory
add      var1, 10    ; add immediate value to memory
```

- Numeric example

```
.data
var1  DWORD 10000h
var2  DWORD 20000h
.code
      mov   eax, var1
      add   eax, var2   ; 30000h
```

`sub` Instruction

- ***sub*** subtracts a *source* operand from the *destination* operand of the **<u>same size</u>**.
- Format:

  `sub` *destination*, *source*
- *Source* is unchanged; *destination* stores the difference. All the status flags are affected.
- The sizes must match and only one can be a memory location.

Flags Affected by **add** and **sub**

- If **add** or **sub** generates a result of zero, ZF is set
- If **add** or **sub** generates a negative result, SF is set.
- Examples:

```
mov      ax, 10
sub      ax, 10       ; AX = 0, ZF = 1
mov      bx, 1
sub      bx, 2        ; BX = FFFF, SF = 1
```

- **inc** and **dec** affect ZF but not CF.

```
mov      bl, 4Fh
add      bl, 0B1h     ; BF = 00, ZF = 1, CF = 1
mov      ax, 0FFFFh
inc      ax           ; ZF = 1 (CF unchanged)
```

Flags Affected by **add** and **sub** (continued)

- The Overflow flag is useful when performing signed arithmetic:

```
mov      al, +126
add      al, 2        ; AL = 80h, OF = 1
126        01111110
 +2      + 00000010
-128     0 10000000

mov      al, -128
sub      al, 2        ; AL = 7Eh, OF = 1
-128       10000000
-  -2     -11111110
-126     1 10000000
```

Implementing Arithmetic Expressions

- Imagine we are implementing the statement

```
  Rval = -Xval + (Yval - Zval)
.data
Rval        SDWORD      ?
Xval        SDWORD      26
Yval        SDWORD      30
Zval        SDWORD      40
.code
; first term: -Xval
      mov   eax, Xval
      neg   eax         ; EAX = -26
```

Implementing Arithmetic Expressions (continued)

```
; second term: (Yval - Zval)
      mov   ebx, Yval
      sub   ebx, Zval   ; EBX = -10

; add the terms and store
      add   eax, ebx
      mov   Rval, eax   ; Rval = -36
```

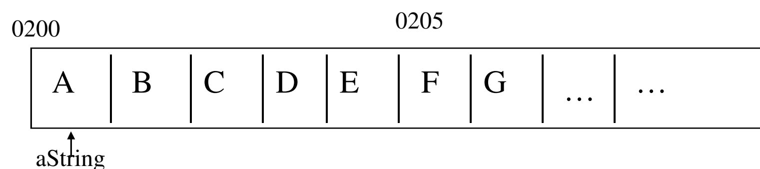
Indirect Operands

- An indirect operand is a register containing the offset for data in a memory location.
  - The register points to a label by placing its offset in that register
  - This is very convenient when working with arrays; it is just a matter of incrementing the address so that it points to the next array element.
  - The ESI, EDI, EBX, EBP, SI, DI, BX and BP registers can be used for indirect operands as well as the 32-bit general purpose registers (with a restriction on the ESP).

Indirect Operands: A Real Mode Example

- We create a string in memory at offset 0200 and set the BX to the string's offset; we can process any element in the string by adding to the offset:
-

```
.data
……
aString  BYTE  "ABCDEFG"
.code
mov      bx, offset aString      ; BX = 0200
add      bx, 5                   ; BX = 0205
mov      dl, [bx]                ; DL = 'F'
```



Indirect Operands: A Protected Mode Example

```
.data
val1  BYTE  10h
.code
      mov   esi   OFFSET val1
      mov   al, [esi]         ; AL = 10h
      mov   [esi], bl    ; The variable to
                         ; which ESI points is
                         ; changed
      mov   esi, 0
      mov   ax, [esi]    ; General Protection
                         ; Error
      inc   [esi] ; Error - needs size
      inc   byte ptr [esi]    ; Works!
```

Arrays

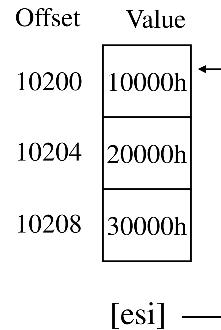
- Indirect arrays are useful when manipulating arrays:

```
.data
arrayB      BYTE        10h, 20h, 30h
.code
      mov   esi, OFFSET arrayB
      mov   al, [esi]         ; AL = 10h
      inc   esi
      mov   al, [esi]         ; AL = 20h
      inc   esi
      mov   al, [esi]         ; AL = 30h
```

Arrays of Doublewords

- If we use an array of 32-bit integers, we add 4 to ESI to address each subsequent array element:

```
.data
arrayD  DWORD   10000h, 20000h, 30000h
.code
      mov   esi, OFFSET arrayD
      mov   eax, [esi]  ; first #
      add   esi, 4
      mov   eax, [esi]  ; second #
      add   esi, 4
      mov   eax, [esi]  ; third #
```



Indexed Operands

- An indexed operand adds a constant to a register to generate an effective address.
- Any of the 32-bit general purpose register may be used as an index registers.
- There are two forms that are legal:

```
constant[reg]
[constant+reg]
```

- In both cases, we are combining the constant offset of a variable label with the contents of a register.

Indexed Operands – An Example

```
.data
arrayB      BYTE  10h, 20h, 30h
arrayW      WORD  1000h, 2000h, 3000h
.code
      mov   esi, 0
      mov   al, [arrayB+esi]  ; AL = 10h

      mov   esi, OFFSET arrayW
      mov   ax, [esi]         ; AX = 1000h
      mov   ax, [esi+2]       ; AX = 2000h
      mov   ax, [esi+4]       ; AX = 3000h
```

Transfer of Control

- A transfer of control is way of altering the order in which instructions are executed.
- The two basic ways are:
  - ***Unconditional transfer*** – the program branches to a statement elsewhere in the program
  - ***Conditional transfer*** – the program branches to a statement elsewhere in the program ***IF*** some condition is true.

JMP Instruction

- The JMP statement causes an unconditional transfer to the target address within the same code segment.
- The syntax is:

  `JMP` *targetLabel*

  where the targetLabel is the offset of an instruction elsewhere in the program.
- Example:

```
top:
   … …
     jmp top; infinite loop
```

`LOOP` Instruction

- The LOOP instruction is used to end a block of statements that will be performed a predetermined number of times, with the number of times stored in the ECX (or CX) register.
- The syntax is:

  `LOOP` *destination*

  where destination is the label of the statement to which it jumps if the (E)CX register is nonzero.
- Because the (E)CX register controls the loop, it is extremely unwise to change it during the loop.

Nested Loops

- In writing nested loops, it is important to save the outer loop's counter:

```
.data
count DWORD ?
.code
      mov   ecx, 100    ; set outer loop's count
L1:   mov   count, ecx  ; save outer loop count
      mov   ecx, 20     ; set inner loop count
L2:   … …
      loop  L2          ; repeat inner loop
      mov   ecx, count  ; restore outer loop count
      loop  L1
```

Summing An Integer Array

```
TITLE Summing An Array  (SumArray.asm)

INCLUDE      Irvine32.inc
.data
intarray     WORD  100h, 200h, 300h, 400h

.code
main  PROC
  mov edi, OFFSET intarray
                      ; address of intarray
  mov ecx, LENGTHOF intarray; ; loop counter
  mov ax, 0
```

```
L1:
  add ax, [edi]         ; add an integer
  add edi, TYPE intarray; point to next integer
  loop     L1           ; repeat ECX = 0
  call DumpRegs
  exit
main  endp
  end main
```

Procedures

- As programs get larger and larger, it becomes necessary to divide them into a series of ***procedures***.
- A procedure is a block of logically-related instruction that can be called by the main program or another procedure.
- Each procedure should have a single purpose and be able to do its job independent of the rest of the program.

Runtime Stack

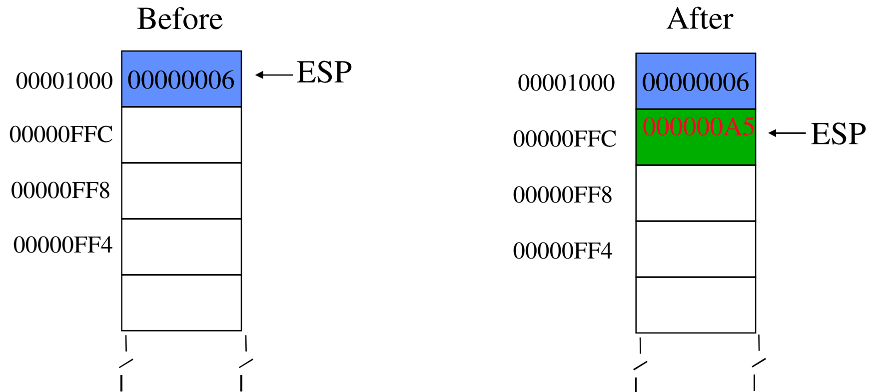
- The runtime stack is a memory array that is managed directly by the CPU using the SS and ESP registers.
- In Protected mode, the SS register holds a segment descriptor and is not modified byu user programs; the ESP register holds a 32-bit offset into some memory location on the stack.

The Intel Processor's Stack

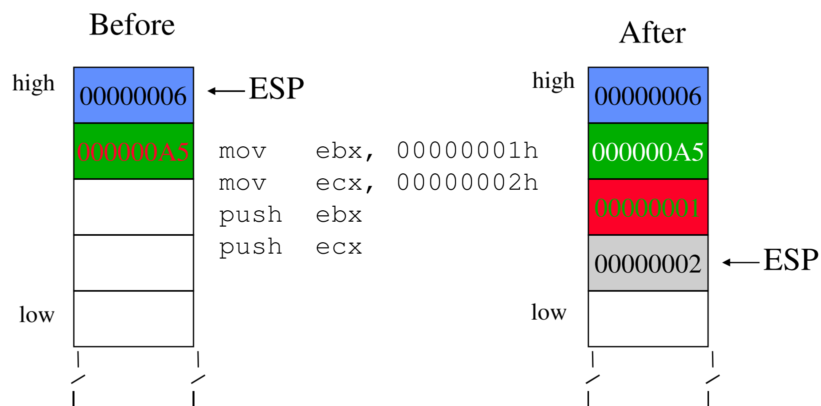
- The stack in an Intel processor is a special memory area.
  - The stack is a temporary holding area for addresses and data.
  - Most of the data held here allows a program to return (successfully) to the calling program and procedures or to pass parameters.
  - The stack resides in the stack segment.

Stack Operations - Push

```
mov    eax, 00000A5h
push   eax
```

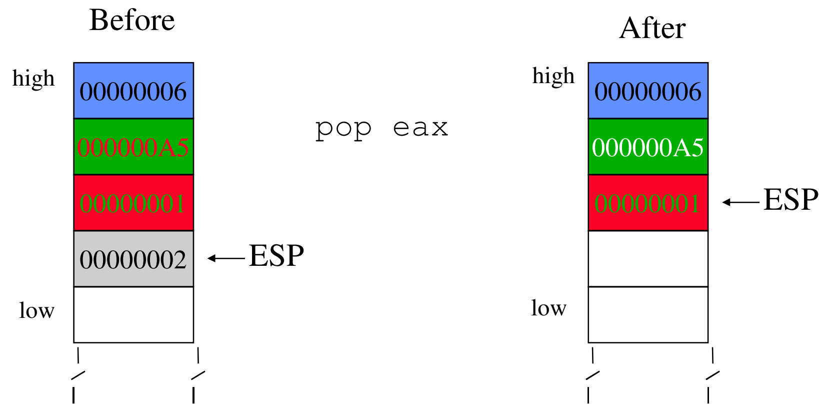


Stack Operations - Push (continued)




```
mov    ebx, 00000001h
mov    ecx, 00000002h
push   ebx
push   ecx
```

Stack Operations - Pop



Uses of the Stack

- There are several important uses of stacks in programs:
  - A stack makes an excellent temporary save area for registers, allowing a program to use them as a scratch area and then to restore them.
  - When a subroutine is called, the CPU saves a return address on the stack, allowing the program to return to the location after the procedure call.
  - When calling a procedure, you can push ***arguments*** on the stack , allowing the procedure to retrieve them.
  - High-level languages create an area on the stack inside subroutines where procedure store local variables and them discard them when it leaves the procedure.

Stack Operations - PUSH

- PUSH Instruction
  - Decrements ESP and copies a 16-bit or 32-bit register or memory operand onto the stack at the location indicated by SP.
  - With 80286+ processors, you can push an immediate operand onto the stack.
  - Examples:

```
push ax      ; push a 16-bit register operand
push ecx     ; push a 32-bit register operand
push memval  ; push a 16-bit memory operand
push 1000h   ; push an immediate operand
```

Stack Operations - POP

- POP Instruction
  - copies the contents of the stack pointed to by ESP into a register or variable and increments ESP.
  - CS and IP cannot be used as operands.
  - Examples:

```
pop cx      ; pop stack into 16-bit register
pop memval; pop stack into 16-bit memory
              operand
pop eds     ; pop stack into 32-bit register
```

Procedures

- In general, there are two types of subprograms: functions and procedures (or subroutines).
  - ***Functions*** return a value (or ***result***).
  - ***Procedures*** (or ***subroutines***) do not.
  - The terms procedures and subroutines are used interchangeably although some languages use one term and others use the other.
  - Calling a procedure implies that there is a return. Also implies is that the state of the program, (register values, etc.) are left unaffected when the program returns to the calling procedure or program.

PROC and ENDP Directives

- PROC and ENDP mark the beginning and end of a procedure respectively.

```
.code
main proc
  … …
  call   MySub
  … …
  main endp
                  ; Nb: procedures cannot overlap
  MySub  proc     ; one must have endp before
  …                     ; the next can have proc
  ret
  MySub endp
```

The **`exit`** Instruction

- While all other procedures end with the **`ret`** instruction, **`exit`** is used by the main procedure.
- **`exit`** is actually an not an instruction but an alias for

  `INVOKE ExitProcess, 0`

  the Windows system function for terminating programs
- In Irvine16.inc, it is defined as

```
mov     ah, 4ch
int     21h
```

Passing Parameters

- Passing arguments in registers
  - The most common method for passing parameter between the calling program (or procedure) and the procedures that it calls is through the registers
  - It is efficient because the called procedure has immediate and direct use of the parameters and registers are faster than memory.
  - Example: WriteInt

```
.data
aNumber      DWORD        234
.code
             mov          eax, aNumber
             call         WriteInt
```

Preserving Registers

- Ordinarily procedures have the responsibility to preserve register contents.
  - This ensures that the main procedure has no surprises.
  - What would happen here if WriteInt modified ECX?

```
.data
DECIMAL_RADIX = 10
LIST_COUNT=20
aList        dw     LIST_COUNT dup(?)
.code
    mov      ecx, LIST_COUNT
    mov      ebx, DECIMAL_RADIX
    mov      esi, offset aList
L1: mov      eax, [si]
    call     WriteInt
    add      esi, size aList
    loop     L1
```

Using Registers to Return a Value

- Some functions will use a register as a method of returning a value to the calling procedure:

```
SumOf     proc
          push eax
          mov  eax, ebx
          add  eax, ecx
          pop  eax ; Error – EAX reset to orig.
                   ;         value
          ret
SumOf     endp
```

Procedure **ArraySum**

```
ArraySum PROC
;--------------------------------------------
;  Calculates the sum of an array of 32-bit integers.
;  Receives:  ESI - the array offset
;             ECX = # of elements in array
;  Returns    EAX - the sum of the array
;--------------------------------------------
   push       esi          ; save ESI, ECX
   push       ecx
   mov        eax, 0       ; Sum = 0
L1:add        eax, [esi]   ; Sum = Sum + x[i]
   add        esi, 4       ; Point to next integer
   loop       L1           ; Repeat for array size

   pop        ecx
   pop        esi
   ret
ArraySum ENDP
```

Calling **ArraySum**

```
TITLE Driver for Array Sum    (ArrayDr.asm)
INCLUDE     Irvine32.inc
.data
array       DWORD 10000h, 20000h, 30000h, 40000h
theSum      DWORD ?
.code
main  PROC
  mov       esi, OFFSET array ; ESI points to array
  mov       ecx, LENGTHOF array ;ECX = array count
  call      ArraySum          ; calculate the sum
  mov       theSum, eax       ; returned in EAX
  call      WriteHex          ; Is it correct?
  exit
main  ENDP
ArraySum PROC… …
  END main
```

Procedure goes here

`CMP` Instruction

- The CMP instruction sets the flags ***<u>as if</u>*** it had performed subtraction on the operand.
- Neither operand is changed.
- The CMP instruction takes the forms:

```
CMP reg, reg        CMP mem, reg
CMP reg, mem        CMP mem, immed
CMP reg, immed
```

`CMP` Results

CMP Results	ZF	CF
destination < source	0	1
destination > source	0	0
destination = source	1	0

CMP Results

CMP Results	**Flags**
destination < source	SF ≠ OF
destination > source	SF = OF
destination = source	ZF = 1

CMP Instruction : Examples

- Subtracting 5-10 requires a borrow:

```
mov     ax, 5
cmp     ax, 10     ; CF = 1
```

- Subtracting 1000 from 1000 results in zero.

```
mov     ax, 1000
mov     cx, 1000
cmp     cx, ax     ; ZF = 1
```

- Subtracting 0 from 105 produces a positive difference:

```
mov     si, 105
cmp     si, 0;     ZF = 0 and CF = 0
```

Setting & Clearing Individual Flags

- Setting and Clearing the Zero Flag

```
and    al, 0    ; Set Zero Flag
or     al, 1    ; Clear Zero Flag
```

- Setting and Clearing the Sign Flag

```
or     al, 80h  ; Set Sign Flag
and    al, 7fh  ; Clear Sign Flag
```

Setting & Clearing Individual Flags

- Setting and Clearing the Carry Flag

```
stc           ; Set Carry Flag
clc           ; Clear Carry Flag
```

- Setting and Clearing the Overflow Flag

```
mov    al, 7fH  ; AL = +127
inc    al       ; AL = 80H; OF = 1
or     eax, 0   ; Clear Overflow
                ; Flag
```

Conditional Structures – An Example

- Compare AL to Zero. Jump to L1if the zero flag was set by the comparison:

```
    cmp  al, 0
    jz       L1
    … …
L1:
```

Conditional Structures – Another Example

- Perform a bitwise AND on the DL register . Jump to L2 if the Zero flag is clear:

```
    and      dl, 10110000b
    jnz      L2
    … …
L2:
```

J*cond* Instruction

- A conditional jump instruction branches to a destination label when a flag condition is true.
- If the flag is false, the instruction immediately following the conditional jump is performed instead.
- The syntax is:

  J*cond* *destination*

Limitations of Conditional Jumps

- Microsoft Macro assembler limits jumps to a label within the current procedure and within –128 to +127 of the current address.
- To jump to another procedure, you must use a global label:

```
    jc   MyLabel   ; Jump if Carry
                   ; (flag is set)
  … …
MyLabel::
```

Examples of Conditional Jumps

- In all three cases, the jump is made:

```
mov   ax, 5
cmp   ax, 5
je    L1    ; jump if equal

mov   ax, 5
cmp   ax, 6
jl    L1    ; jump if less

mov   ax, 5
cmp   ax, 4 ; jump if greater
```

Jumps based on General Comparisons

Mnemonic	Description	Flags/Registers
JZ	Jump if zero	ZF = 1
JE	Jump if equal	ZF = 1
JNZ	Jump if not zero	ZF = 0
JNE	Jump if not equal	ZF = 0

Jumps based on General Comparisons

Mnenomic	Description	Flags/Registers
JC	Jump if carry	CF = 1
JNC	Jump if not carry	CF = 0
JCXZ	Jump if CX = 0	CX = 0
JECXZ	Jump if ECX = 0	ECX = 0

Jumps based on General Comparisons

Mnenomic	Description	Flags/Registers
JP	Jump if Parity even	PF = 1
JNP	Jump if Parity odd	PF = 0

Jumps based on Unsigned Comparisons

Mnenomic	Description	Flag(s)
JA	Jump if above (op1 > op2)	CF = 0 & ZF = 0
JNBE	Jump if not below or equal	CF = 0 & ZF = 0
JAE	Jump if above or equal	CF = 0
JNB	Jump if not below	CF = 0

Jumps based on Unsigned Comparisons

Mnenomic	Description	Flag(s)
JB	Jump if below (op1 < op2)	CF = 1
JNAE	Jump if not above	CF = 1
JBE	Jump if below or equal	CF = 1 or ZF = 1
JNA	Jump if not above	CF = 1 or ZF = 1

Jumps based on Signed Comparisons

Mnenomic	Description	Flag(s)
JG	Jump if greater	SF = 0 & ZF =0
JNLE	Jump if not less than or equal	SF = 0 & ZF =0
JGE	Jump if greater than or equal	SF = OF
JNL	Jump if not less than	SF = OF

Jumps based on Signed Comparisons

Mnenomic	Description	Flag(s)
JL	Jump if less	SF <> OF
JNGE	Jump if not greater than or equal	SF <> OF
JLE	Jump if less than or equal	ZF = 1 or SF = <> OF
JNG	Jump if not greater than	ZF = 1 or SF = <> OF

Jumps based on Signed Comparisons

Mnenomic	Description	Flag(s)
JS	Jump if signed (op1 is negative)	SF = 1
JNS	Jump if not signed	SF = 0
JO	Jump if overflow	OF = 1
JNO	Jump if not overflow	OF = 0

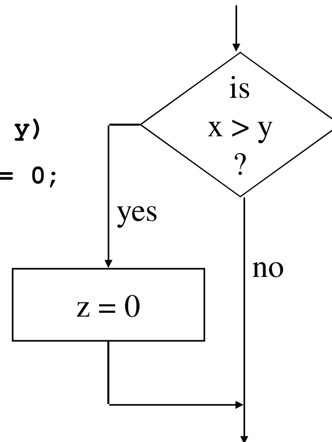
Example – Smallest of Three Integers

```
.data
V1    WORD   ?
V2    WORD   ?
V3    WORD   ?
.code
      mov   ax, V1   ; assume that V1 is smallest
      cmp   ax, V2   ; IF AX <= V2 then
      jbe   L1       ; jump to L1
      mov   ax, V2   ; else move V2 to AX
L1:   cmp   ax, V3   ; if AX <= V3 then
      jbe   L2       ;   jump to L3
      mov   ax, V3   ; else move to V3 to AX
L2:                  ; smallest is in AX
```

Writing IF-THEN

In C++:

```
if  (x > y)
      z = 0;
```



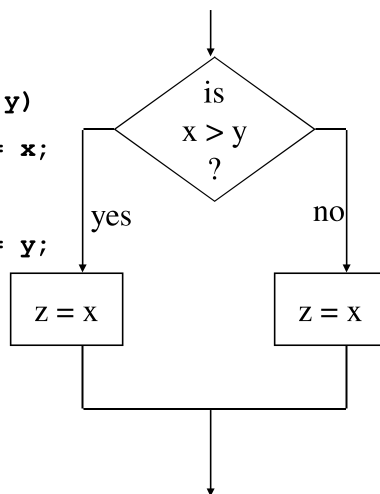
In Assembler

```
      mov ax, x
      cmp ax, y
      jng L1
      mov ax, 0
      mov z, ax
 L1:
```

Writing IF-THEN-ELSE

In C++:

```
if  (x > y)
      z = x;
else
      z = y;
```



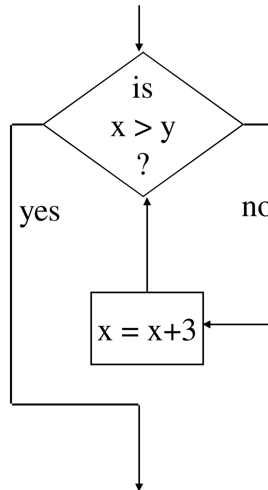
In Assembler

```
      mov ax, x
      cmp ax, y
      jng L1
      mov ax, x
      jmp L2
L1:
      mov ax, y
L2:
      mov z, ax
```

Writing WHILE loops

In C++:

```
while (x <= y)
    x = x + 3;
```



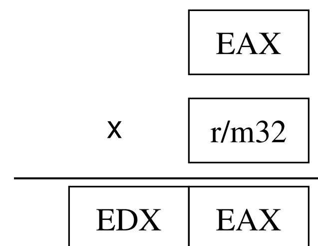
In Assembler

```
L1:
        mov ax, x
        cmp ax, y
        jg L2
        mov ax, x
        add x, 3
        jmp L1
L2:
```

IMUL Instruction

- The **IMUL** instruction multiplies an 8-, 16, or 32-bit ***signed*** operand by either the AL, AX or EAX register (depending on the operand's size).
- The instruction formats are:

```
IMUL    r/m8
IMUL    r/m16
IMUL    r/m32
```



IMUL Instruction (continued)

- The **IMUL** instruction sets the Carry and Overflow flags if the upper half of the product is not a sign extension of the low-order product.equal to zero.
- E.g., if AX is multiplied by a 16-bit multiplier, the product is stored in DX:AX. IF the AX contains a negative value and the DX is not all 1s, the Carry and Overflow flags are set.

IMUL Instruction - Examples

- 8-bit signed multiplication (48 * 4)

```
mov       al, 48
mov       bl, 4
imul      bl    ; AX = 00C0h, OF = 1
```

- 16-bit signed multiplication (-4 * 4)

```
    mov   al, -4
    mov   bl, 4
    imul  bl    ; AX = FFF0h, OF = 0
```

- 32-bit signed multiplication (12345h*1000h)

```
    mov   eax, +4823424
    mov   ebx, -423
    imul  ebx   ; EDX:EAX =
                ; FFFFFFFF86636D80h, OF = 0
```

CBW, CWD and CDQ Instructions

- **CBW** intends the sign bit of AL into the AH register.
- **CWD** intends the sign bit of AX into the DX register.
- **CDQ** intends the sign bit of EAX into the EDX register.

```
.data
byteVal     SBYTE       -65   ; 9Bh
wordVal     SWORD       -65   ; FF9Bh
dwordVal    SDWORD      -65   ;FFFFFF9Bh
.code
  mov       al, byteVal ; AL = 9Bh
  cbw                   ; AX = FF9Bh
  mov       ax, wordVal ; AX = FF9Bh
  cwd                   ; DX:AX = FFFFFF9Bh
  mov       eax, dwordVal; EAX = FFFFFF9Bh
  cdq             ; EDX:EAX = FFFFFFFFFFFFFF9Bh
```

IDIV Instruction

- The **IDIV** instruction divides an 8-, 16, or 32-bit ***signed*** divisor into either the AL, AX or EAX register (depending on the operand's size).
- Signed division requires that the sign bit be extend into the AH, DX or EDX (depending on the operand's size) using **CBW**, **CWD** or **CDQ**.

IDIV Instruction – 8-bit Example

```
.data
byteVal     SBYTE -48
.code
            mov   al, byteVal ; dividend
            cbw               ; extend Al into AH
            mov   bl, 5       ; divisor
            idiv  bl          ; AL = -9, AH = -3
```

IDIV Instruction – 16-bit Example

```
.data
wordVal     SWORD -5000
.code
            mov   ax, wordVal ; dividend, low
            cwd               ; extend AX into DX
            mov   bx, 256     ; divisor
            idiv  bx          ; quotient AX = -19
                              ; rem. DX = -136
```

IDIV Instruction – 32-bit Example

```
.data
wordVal     SWORD -50000
.code
      mov   eax, dwordVal     ; dividend, low
      cdq               ; extend EAX into EDX
      mov   ebx, 256    ; divisor
      idiv  bx          ; quotient EAX = -195
                        ; remainder EDX = -80
```