

Intel x86 Instruction Set Architecture

Computer Organization and Assembly Languages

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with slides by Kip Irvine

Data Transfers Instructions

MOV instruction



- Move from source to destination. Syntax:
`MOV destination, source`
- Source and destination have the same size
- No more than one memory operand permitted
- CS, EIP, and IP cannot be the destination
- No immediate to segment moves

MOV instruction



```
.data
count BYTE 100
wVal  WORD 2
.code
  mov bl,count
  mov ax,wVal
  mov count,a1

  mov al,wVal      ; error
  mov ax,count     ; error
  mov eax,count    ; error
```

Exercise . . .



Explain why each of the following **MOV** statements are invalid:

```
.data
bVal  BYTE  100
bVal2 BYTE  ?
wVal  WORD  2
dVal  DWORD 5
.code
  mov ds,45      ; a.
  mov esi,wVal   ; b.
  mov eip,dVal   ; c.
  mov 25,bVal    ; d.
  mov bVal2,bVal ; e.
```

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Memory to memory



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

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Copy smaller to larger



```
.data
count WORD 1
.code
mov ecx, 0
mov cx, count

.data
signedVal SWORD -16 ; FFF0h
.code
mov ecx, 0      ; mov ecx, 0FFFFFFFh
mov cx, signedVal
```

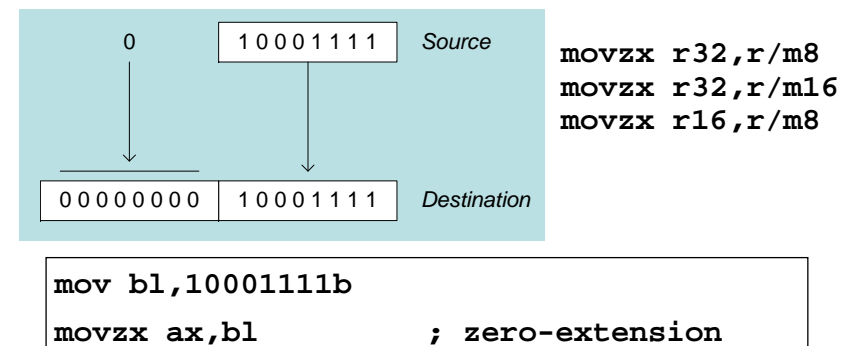
MOVZX and **MOVSX** instructions take care of extension for both sign and unsigned integers.

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Zero extension



When you copy a smaller value into a larger destination, the **MOVZX** instruction fills (extends) the upper half of the destination with zeros.



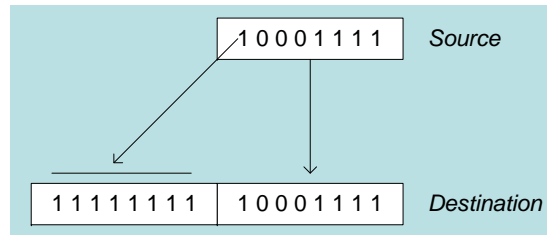
The destination must be a register.

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Sign extension



The `movsx` instruction fills the upper half of the destination with a copy of the source operand's sign bit.



```
mov bl,10001111b
movsx ax,bl      ; sign extension
```

The destination must be a register.

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MOVZX MOVSSX



From a smaller location to a larger one

```
mov  bx, 0A69Bh
movzx eax, bx      ; EAX=0000A69Bh
movzx edx, bl      ; EDX=0000009Bh
movzx cx,  bl      ; EAX=009Bh
```

```
mov  bx, 0A69Bh
movsx eax, bx      ; EAX=FFFFFFA69Bh
movsx edx, bl      ; EDX=FFFFFF9Bh
movsx cx,  bl      ; EAX=FF9Bh
```

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LAHF/SAHF (load/store status flag from/to AH)



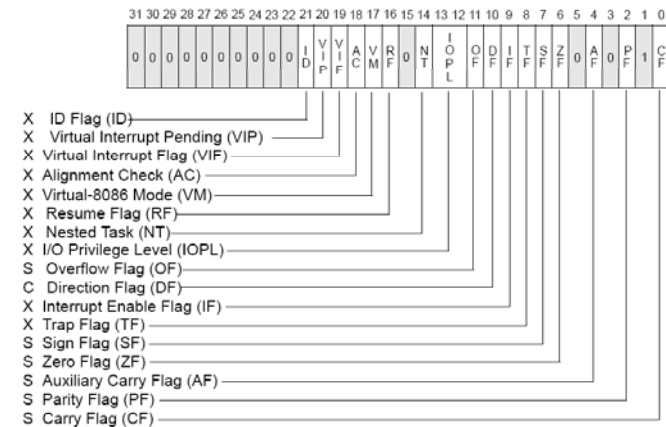
```
.data
saveflags BYTE ?

.code
lahf
mov  saveflags, ah
...
mov  ah, saveflags
sahf
```

S,Z,A,P,C flags are copied.

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EFLAGS



S Indicates a Status Flag
C Indicates a Control Flag
X Indicates a System Flag

Reserved bit positions. DO NOT USE.
Always set to values previously read.

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XCHG Instruction



XCHG exchanges the values of two operands. At least one operand must be a register. No immediate operands are permitted.

```
.data
var1 WORD 1000h
var2 WORD 2000h
.code
xchg ax,bx      ; exchange 16-bit regs
xchg ah,al      ; exchange 8-bit regs
xchg var1,bx    ; exchange mem, reg
xchg eax,ebx    ; exchange 32-bit regs

xchg var1,var2  ; error 2 memory operands
```

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Exchange two memory locations



```
.data
var1 WORD 1000h
var2 WORD 2000h
.code
mov ax, val1
xchg ax, val2
mov val1, ax
```

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Arithmetic Instructions

Addition and Subtraction



- **INC** and **DEC** Instructions
- **ADD** and **SUB** Instructions
- **NEG** Instruction
- Implementing Arithmetic Expressions
- Flags Affected by Arithmetic
 - Zero
 - Sign
 - Carry
 - Overflow

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INC and DEC Instructions



- Add 1, subtract 1 from destination operand
 - operand may be register or memory
- **INC** *destination*
 - Logic: $destination \leftarrow destination + 1$
- **DEC** *destination*
 - Logic: $destination \leftarrow destination - 1$

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INC and DEC Examples



```
.data
myWord  WORD 1000h
myDword DWORD 10000000h
.code
    inc myWord      ; 1001h
    dec myWord      ; 1000h
    inc myDword     ; 10000001h

    mov ax,00FFh
    inc ax          ; AX = 0100h
    mov ax,00FFh
    inc al         ; AX = 0000h
```

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Exercise...



Show the value of the destination operand after each of the following instructions executes:

```
.data
myByte BYTE 0FFh, 0
.code
    mov al,myByte    ; AL = FFh
    mov ah,[myByte+1] ; AH = 00h
    dec ah          ; AH = FFh
    inc al         ; AL = 00h
    dec ax         ; AX = FEFF
```

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ADD and SUB Instructions



- **ADD** *destination, source*
 - Logic: $destination \leftarrow destination + source$
- **SUB** *destination, source*
 - Logic: $destination \leftarrow destination - source$
- Same operand rules as for the **MOV** instruction

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ADD and SUB Examples



```
.data
var1 DWORD 10000h
var2 DWORD 20000h
.code
; ---EAX---
mov eax,var1      ; 00010000h
add eax,var2      ; 00030000h
add ax,0FFFFh     ; 0003FFFFh
add eax,1         ; 00040000h
sub ax,1          ; 0004FFFFh
```

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NEG (negate) Instruction



Reverses the sign of an operand. Operand can be a register or memory operand.

```
.data
valB BYTE -1
valW WORD +32767
.code
mov al,valB       ; AL = -1
neg al            ; AL = +1
neg valW          ; valW = -32767
```

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Implementing Arithmetic Expressions



HLL compilers translate mathematical expressions into assembly language. You can do it also. For example:

$$Rval = -Xval + (Yval - Zval)$$

```
Rval DWORD ?
Xval  DWORD 26
Yval  DWORD 30
Zval  DWORD 40
.code
mov eax,Xval
neg eax      ; EAX = -26
mov ebx,Yval
sub ebx,Zval ; EBX = -10
add eax,ebx
mov Rval,eax ; -36
```

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Exercise...



Translate the following expression into assembly language. Do not permit Xval, Yval, or Zval to be modified:

$$Rval = Xval - (-Yval + Zval)$$

Assume that all values are signed doublewords.

```
mov ebx,Yval
neg ebx
add ebx,Zval
mov eax,Xval
sub eax,ebx
mov Rval,eax
```

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Flags Affected by Arithmetic



- The ALU has a number of status flags that reflect the outcome of arithmetic (and bitwise) operations
 - based on the contents of the destination operand
- Essential flags:
 - Zero flag – destination equals zero
 - Sign flag – destination is negative
 - Carry flag – unsigned value out of range
 - Overflow flag – signed value out of range
- The **MOV** instruction never affects the flags.

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Zero Flag (ZF)



Whenever the destination operand equals Zero, the Zero flag is set.

```
mov cx,1
sub cx,1      ; CX = 0, ZF = 1
mov ax,0FFFFh
inc ax        ; AX = 0, ZF = 1
inc ax        ; AX = 1, ZF = 0
```

A flag is set when it equals 1.

A flag is clear when it equals 0.

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Sign Flag (SF)



The Sign flag is set when the destination operand is negative. The flag is clear when the destination is positive.

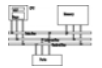
```
mov cx,0
sub cx,1      ; CX = -1, SF = 1
add cx,2      ; CX = 1, SF = 0
```

The sign flag is a copy of the destination's highest bit:

```
mov al,0
sub al,1      ; AL=11111111b, SF=1
add al,2      ; AL=00000001b, SF=0
```

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Carry Flag (CF)



- Addition and CF: copy carry out of MSB to CF
- Subtraction and CF: copy inverted carry out of MSB to CF
- **INC/DEC** do not affect CF
- Applying **NEG** to a nonzero operand sets CF

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Exercise . . .



For each of the following marked entries, show the values of the destination operand and the Sign, Zero, and Carry flags:

```
mov ax,00FFh
add ax,1      ; AX= 0100h SF= 0 ZF= 0 CF= 0
sub ax,1      ; AX= 00FFh SF= 0 ZF= 0 CF= 0
add al,1      ; AL= 00h   SF= 0 ZF= 1 CF= 1
mov bh,6Ch
add bh,95h    ; BH= 01h   SF= 0 ZF= 0 CF= 1

mov al,2
sub al,3      ; AL= FFh   SF= 1 ZF= 0 CF= 1
```

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Overflow Flag (OF)



The Overflow flag is set when the signed result of an operation is invalid or out of range.

```
; Example 1
mov al,+127
add al,1      ; OF = 1,   AL = ??

; Example 2
mov al,7Fh    ; OF = 1,   AL = 80h
add al,1
```

The two examples are identical at the binary level because 7Fh equals +127. To determine the value of the destination operand, it is often easier to calculate in hexadecimal.

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A Rule of Thumb



- When adding two integers, remember that the Overflow flag is only set when . . .
 - Two positive operands are added and their sum is negative
 - Two negative operands are added and their sum is positive

What will be the values of OF flag?

```
mov al,80h
add al,92h    ; OF =

mov al,-2
add al,+127   ; OF =
```

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Signed/Unsigned Integers: Hardware Viewpoint



- All CPU instructions operate exactly the same on signed and unsigned integers
- The CPU cannot distinguish between signed and unsigned integers
- YOU, the programmer, are solely responsible for using the correct data type with each instruction

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Overflow/Carry Flags: Hardware Viewpoint

- How the **ADD** instruction modifies OF and CF:
 - CF = (carry out of the MSB)
 - OF = (carry out of the MSB) XOR (carry into the MSB)
- How the **SUB** instruction modifies OF and CF:
 - NEG the source and ADD it to the destination
 - CF = INVERT (carry out of the MSB)
 - OF = (carry out of the MSB) XOR (carry into the MSB)

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Auxiliary Carry (AC) flag

- AC indicates a carry or borrow of bit 3 in the destination operand.
- It is primarily used in binary coded decimal (BCD) arithmetic.

```
mov al, 0Fh
add al, 1      ; AC = 1
```

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Parity (PF) flag

- PF is set when LSB of the destination has an even number of 1 bits.

```
mov al, 10001100b
add al, 00000010b; AL=10001110, PF=1
sub al, 10000000b; AL=00001110, PF=0
```

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Jump and Loop

JMP and LOOP Instructions



- Transfer of control or branch instructions
 - unconditional
 - conditional
- **JMP** Instruction
- **LOOP** Instruction
- **LOOP** Example
- Summing an Integer Array
- Copying a String

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JMP Instruction



- **JMP** is an unconditional jump to a label that is usually within the same procedure.
- Syntax: **JMP** *target*
- Logic: $EIP \leftarrow target$
- Example:

```
top:
.
.
jmp top
```

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LOOP Instruction



- The **LOOP** instruction creates a counting loop
- Syntax: **LOOP** *target*
- Logic:
 - $ECX \leftarrow ECX - 1$
 - if **ECX** $\neq 0$, jump to *target*
- Implementation:
 - The assembler calculates the distance, in bytes, between the current location and the offset of the target label. It is called the relative offset.
 - The relative offset is added to EIP.

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LOOP Example



The following loop calculates the sum of the integers 5 + 4 + 3 + 2 + 1:

offset	machine code	source code
00000000	66 B8 0000	mov ax,0
00000004	B9 00000005	mov ecx,5
00000009	66 03 C1	L1:add ax,cx
0000000C	E2 FB	loop L1
0000000E		

When **LOOP** is assembled, the current location = 0000000E. Looking at the **LOOP** machine code, we see that -5 (FBh) is added to the current location, causing a jump to location 00000009:

$$00000009 \leftarrow 0000000E + FB$$

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Exercise . . .



If the relative offset is encoded in a single byte,

- (a) what is the largest possible backward jump?
- (b) what is the largest possible forward jump?

(a) -128

(b) +127

Average sizes of machine instructions are about 3 bytes, so a loop might contain, on average, a maximum of 42 instructions!

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Exercise . . .



What will be the final value of AX?

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```
mov ax,6
mov ecx,4
L1:
inc ax
loop L1
```

How many times will the loop execute?

4,294,967,296

```
mov ecx,0
X2:
inc ax
loop X2
```

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Nested Loop



If you need to code a loop within a loop, you must save the outer loop counter's ECX value. In the following example, the outer loop executes 100 times, and the inner loop 20 times.

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

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Summing an Integer Array



The following code calculates the sum of an array of 16-bit integers.

```
.data
intarray WORD 100h,200h,300h,400h
.code
mov edi,OFFSET intarray ; address
mov ecx,LENGTHOF intarray ; loop counter
mov ax,0 ; zero the sum
L1:
add ax,[edi] ; add an integer
add edi,TYPE intarray ; point to next
loop L1 ; repeat until ECX = 0
```

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Copying a String



The following code copies a string from source to target.

```
.data
source BYTE "This is the source string",0
target BYTE sizeof source DUP(0),0

.code
mov esi,0 ; index register
mov ecx,sizeof source ; loop counter
L1:
mov al,source[esi] ; get char from source
mov target[esi],al ; store in the target
inc esi ; move to next char
loop L1 ; repeat for entire string
```

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Conditional Processing

Status flags - review



- The Zero flag is set when the result of an operation equals zero.
- The Carry flag is set when an instruction generates a result that is too large (or too small) for the destination operand.
- The Sign flag is set if the destination operand is negative, and it is clear if the destination operand is positive.
- The Overflow flag is set when an instruction generates an invalid signed result.
- Less important:
 - The Parity flag is set when an instruction generates an even number of 1 bits in the low byte of the destination operand.
 - The Auxiliary Carry flag is set when an operation produces a carry out from bit 3 to bit 4

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NOT instruction



- Performs a bitwise Boolean NOT operation on a single destination operand
- Syntax: (no flag affected)

NOT destination

- Example:

```
mov al, 11110000b
not al
```

```
NOT 00111011
    11000100 — inverted
```

NOT

X	$\neg X$
F	T
T	F

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AND instruction



- Performs a bitwise Boolean AND operation between each pair of matching bits in two operands
- Syntax: (O=0,C=0,SZP)

AND destination, source

AND

- Example:
`mov al, 00111011b`
`and al, 00001111b`

x	y	$x \wedge y$
0	0	0
0	1	0
1	0	0
1	1	1

```

      0 0 1 1 1 0 1 1
AND   0 0 0 0 1 1 1 1
-----
cleared — 0 0 0 0 1 0 1 1 — unchanged
           bit extraction
    
```

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OR instruction



- Performs a bitwise Boolean OR operation between each pair of matching bits in two operands
- Syntax: (O=0,C=0,SZP)

OR destination, source

OR

- Example:
`mov dl, 00111011b`
`or dl, 00001111b`

x	y	$x \vee y$
0	0	0
0	1	1
1	0	1
1	1	1

```

      0 0 1 1 1 0 1 1
OR   0 0 0 0 1 1 1 1
-----
unchanged — 0 0 1 1 1 1 1 1 — set
    
```

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XOR instruction



- Performs a bitwise Boolean exclusive-OR operation between each pair of matching bits in two operands
- Syntax: (O=0,C=0,SZP)

XOR destination, source

XOR

- Example:
`mov dl, 00111011b`
`xor dl, 00001111b`

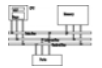
x	y	$x \oplus y$
0	0	0
0	1	1
1	0	1
1	1	0

```

      0 0 1 1 1 0 1 1
XOR   0 0 0 0 1 1 1 1
-----
unchanged — 0 0 1 1 0 1 0 0 — inverted
    
```

XOR is a useful way to invert the bits in an operand and data encryption

Applications (1 of 4)



- Task: Convert the character in AL to upper case.
- Solution: Use the AND instruction to clear bit 5.

```

mov al, 'a'           ; AL = 01100001b
and al, 11011111b    ; AL = 01000001b
    
```

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Applications (2 of 4)



- Task: Convert a binary decimal byte into its equivalent ASCII decimal digit.
- Solution: Use the OR instruction to set bits 4 and 5.

```
mov al,6           ; AL = 00000110b
or  al,00110000b  ; AL = 00110110b
```

The ASCII digit '6' = 00110110b

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Applications (3 of 4)



- Task: Jump to a label if an integer is even.
- Solution: AND the lowest bit with a 1. If the result is Zero, the number was even.

```
mov ax,wordVal
and ax,1           ; low bit set?
jz  EvenValue     ; jump if Zero flag set
```

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Applications (4 of 4)



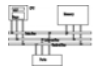
- Task: Jump to a label if the value in AL is not zero.
- Solution: OR the byte with itself, then use the JNZ (jump if not zero) instruction.

```
or  al,al
jnz IsNotZero    ; jump if not zero
```

ORing any number with itself does not change its value.

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TEST instruction



- Performs a nondestructive **AND** operation between each pair of matching bits in two operands
- No operands are modified, but the flags are affected.
- Example: jump to a label if either bit 0 or bit 1 in AL is set.
- Example: jump to a label if neither bit 0 nor bit 1 in AL is set.

```
test al,00000011b
jnz  ValueFound
```

```
test al,00000011b
jz   ValueNotFound
```

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CMP instruction (1 of 3)



- Compares the destination operand to the source operand
 - Nondestructive subtraction of source from destination (destination operand is not changed)
- Syntax: (OSZCAP)
CMP destination, source
- Example: destination == source

```
mov al,5  
cmp al,5 ; Zero flag set
```

- Example: destination < source

```
mov al,4  
cmp al,5 ; Carry flag set
```

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CMP instruction (2 of 3)



- Example: destination > source

```
mov al,6  
cmp al,5 ; ZF = 0, CF = 0
```

(both the Zero and Carry flags are clear)

The comparisons shown so far were unsigned.

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CMP instruction (3 of 3)



The comparisons shown here are performed with signed integers.

- Example: destination > source

```
mov al,5  
cmp al,-2 ; Sign flag == Overflow flag
```

- Example: destination < source

```
mov al,-1  
cmp al,5 ; Sign flag != Overflow flag
```

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Conditions



unsigned	ZF	CF
destination < source	0	1
destination > source	0	0
destination = source	1	0

signed	flags
destination < source	SF != OF
destination > source	SF == OF
destination = source	ZF = 1

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Setting and clearing individual flags



```
and al, 0          ; set Zero
or  al, 1          ; clear Zero
or  al, 80h        ; set Sign
and al, 7Fh        ; clear Sign
stc                 ; set Carry
clc                 ; clear Carry

mov al, 7Fh
inc al              ; set Overflow

or  eax, 0          ; clear Overflow
```

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Conditional jumps

Conditional structures



- There are no high-level logic structures such as if-then-else, in the IA-32 instruction set. But, you can use combinations of comparisons and jumps to implement any logic structure.
- First, an operation such as **CMP**, **AND** or **SUB** is executed to modified the CPU flags. Second, a conditional jump instruction tests the flags and changes the execution flow accordingly.

```
        CMP AL, 0
        JZ  L1
        :
L1:
```

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Jcond instruction



- A conditional jump instruction branches to a label when specific register or flag conditions are met
Jcond destination
- Four groups: (some are the same)
 1. based on specific flag values
 2. based on equality between operands
 3. based on comparisons of unsigned operands
 4. based on comparisons of signed operands

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Jumps based on specific flags



Mnemonic	Description	Flags
JZ	Jump if zero	ZF = 1
JNZ	Jump if not zero	ZF = 0
JC	Jump if carry	CF = 1
JNC	Jump if not carry	CF = 0
JO	Jump if overflow	OF = 1
JNO	Jump if not overflow	OF = 0
JS	Jump if signed	SF = 1
JNS	Jump if not signed	SF = 0
JP	Jump if parity (even)	PF = 1
JNP	Jump if not parity (odd)	PF = 0

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Jumps based on equality



Mnemonic	Description
JE	Jump if equal ($leftOp = rightOp$)
JNE	Jump if not equal ($leftOp \neq rightOp$)
JCXZ	Jump if CX = 0
JECXZ	Jump if ECX = 0

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Jumps based on unsigned comparisons



Mnemonic	Description
JA	Jump if above (if $leftOp > rightOp$)
JNBE	Jump if not below or equal (same as JA)
JAE	Jump if above or equal (if $leftOp \geq rightOp$)
JNB	Jump if not below (same as JAE)
JB	Jump if below (if $leftOp < rightOp$)
JNAE	Jump if not above or equal (same as JB)
JBE	Jump if below or equal (if $leftOp \leq rightOp$)
JNA	Jump if not above (same as JBE)

> ≥ < ≤

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Jumps based on signed comparisons



Mnemonic	Description
JG	Jump if greater (if $leftOp > rightOp$)
JNLE	Jump if not less than or equal (same as JG)
JGE	Jump if greater than or equal (if $leftOp \geq rightOp$)
JNL	Jump if not less (same as JGE)
JL	Jump if less (if $leftOp < rightOp$)
JNGE	Jump if not greater than or equal (same as JL)
JLE	Jump if less than or equal (if $leftOp \leq rightOp$)
JNG	Jump if not greater (same as JLE)

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Examples



- Compare unsigned AX to BX, and copy the larger of the two into a variable named Large

```
mov Large,bx
cmp ax,bx
jna Next
mov Large,ax
Next:
```

- Compare signed AX to BX, and copy the smaller of the two into a variable named Small

```
mov Small,ax
cmp bx,ax
jnl Next
mov Small,bx
Next:
```

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Examples



- Find the first even number in an array of unsigned integers

```
.data
intArray DWORD 7,9,3,4,6,1
.code
...
mov ebx, OFFSET intArray
mov ecx, LENGTHOF intArray
L1: test DWORD PTR [ebx], 1
    jz found
    add ebx, 4
    loop L1
...
```

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BT (Bit Test) instruction



- Copies bit *n* from an operand into the Carry flag
- Syntax: **BT** *bitBase*, *n*
 - *bitBase* may be *r/m16* or *r/m32*
 - *n* may be *r16*, *r32*, or *imm8*
- Example: jump to label L1 if bit 9 is set in the AX register:

```
bt AX,9          ; CF = bit 9
jc L1           ; jump if Carry
```

- **BTC** *bitBase*, *n*: bit test and complement
- **BTR** *bitBase*, *n*: bit test and reset (clear)
- **BTS** *bitBase*, *n*: bit test and set

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Conditional loops

LOOPZ and LOOPE



- Syntax:
 LOOPE *destination*
 LOOPZ *destination*
- Logic:
 - $ECX \leftarrow ECX - 1$
 - if $ECX \neq 0$ and $ZF=1$, jump to *destination*
- The destination label must be between -128 and +127 bytes from the location of the following instruction
- Useful when scanning an array for the first element that meets some condition.

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LOOPNZ and LOOPNE



- Syntax:
 LOOPNZ *destination*
 LOOPNE *destination*
- Logic:
 - $ECX \leftarrow ECX - 1$;
 - if $ECX \neq 0$ and $ZF=0$, jump to *destination*

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LOOPNZ example



The following code finds the first positive value in an array:

```
.data
array SWORD -3,-6,-1,-10,10,30,40,4
sentinel SWORD 0
.code
    mov esi,OFFSET array
    mov ecx,LENGTHOF array
next:
    test WORD PTR [esi],8000h    ; test sign bit
    pushfd                      ; push flags on stack
    add esi,TYPE array
    popfd                       ; pop flags from stack
    loopnz next                ; continue loop
    jnz quit                   ; none found
    sub esi,TYPE array         ; ESI points to value
quit:
```

75

Exercise ...



Locate the first nonzero value in the array. If none is found, let ESI point to the sentinel value:

```
.data
array SWORD 50 DUP(?)
sentinel SWORD 0FFFFh
.code
    mov esi,OFFSET array
    mov ecx,LENGTHOF array
L1: cmp WORD PTR [esi],0    ; check for zero

quit:
```

76

Solution



```
.data
array SWORD 50 DUP(?)
sentinel SWORD 0FFFFh
.code
    mov esi,OFFSET array
    mov ecx,LENGTHOF array
L1:cmp WORD PTR [esi],0 ; check for zero
    pushfd ; push flags on stack
    add esi,TYPE array
    popfd ; pop flags from stack
    loope L1 ; continue loop
    jz quit ; none found
    sub esi,TYPE array ; ESI points to value
quit:
```

77

Conditional structures

If statements



if **C** then **T** else **E**

C

JNE else

T

JMP endif

else:

E

endif:

79

Block-structured IF statements



Assembly language programmers can easily translate logical statements written in C++/Java into assembly language. For example:

```
if( op1 == op2 )
    X = 1;
else
    X = 2;
```

```
mov eax,op1
cmp eax,op2
jne L1
mov X,1
jmp L2
L1: mov X,2
L2:
```

80

Example



Implement the following pseudocode in assembly language. All values are unsigned:

```
if( ebx <= ecx )
{
    eax = 5;
    edx = 6;
}
```

```
    cmp ebx,ecx
    ja  next
    mov eax,5
    mov edx,6
next:
```

81

Example



Implement the following pseudocode in assembly language. All values are 32-bit signed integers:

```
if( var1 <= var2 )
    var3 = 10;
else
{
    var3 = 6;
    var4 = 7;
}
```

```
    mov eax,var1
    cmp eax,var2
    jle L1
    mov var3,6
    mov var4,7
    jmp L2
L1: mov var3,10
L2:
```

82

Compound expression with AND



- When implementing the logical AND operator, consider that HLLs use short-circuit evaluation
- In the following example, if the first expression is false, the second expression is skipped:

```
if ( a1 > b1 ) AND ( b1 > c1 )
    X = 1;
```

83

Compound expression with AND



```
if ( a1 > b1 ) AND ( b1 > c1 )
    X = 1;
```

This is one possible implementation . . .

```
    cmp a1,b1          ; first expression...
    ja  L1
    jmp next
L1:
    cmp b1,c1          ; second expression...
    ja  L2
    jmp next
L2:                    ; both are true
    mov X,1            ; set X to 1
next:
```

84

Compound expression with AND



```
if (a1 > b1) AND (b1 > c1)
    x = 1;
```

But the following implementation uses 29% less code by reversing the first relational operator. We allow the program to "fall through" to the second expression:

```
cmp al,b1      ; first expression...
jbe next       ; quit if false
cmp bl,cl      ; second expression...
jbe next       ; quit if false
mov X,1        ; both are true
next:
```

85

Exercise . . .



Implement the following pseudocode in assembly language. All values are unsigned:

```
if( ebx <= ecx
  && ecx > edx )
{
    eax = 5;
    edx = 6;
}
```

```
cmp ebx,ecx
ja next
cmp ecx,edx
jbe next
mov eax,5
mov edx,6
next:
```

(There are multiple correct solutions to this problem.)

86

Compound Expression with OR



- In the following example, if the first expression is true, the second expression is skipped:

```
if (a1 > b1) OR (b1 > c1)
    x = 1;
```

87

Compound Expression with OR



```
if (a1 > b1) OR (b1 > c1)
    x = 1;
```

We can use "fall-through" logic to keep the code as short as possible:

```
cmp al,b1      ; is AL > BL?
ja L1          ; yes
cmp bl,cl      ; no: is BL > CL?
jbe next       ; no: skip next statement
L1:mov X,1      ; set X to 1
next:
```

88

WHILE Loops



A WHILE loop is really an IF statement followed by the body of the loop, followed by an unconditional jump to the top of the loop. Consider the following example:

```
while( eax < ebx)
    eax = eax + 1;
```

```
_while:
    cmp eax,ebx    ; check loop condition
    jae _endwhile ; false? exit loop
    inc eax       ; body of loop
    jmp _while    ; repeat the loop
_endwhile:
```

89

Exercise . . .



Implement the following loop, using unsigned 32-bit integers:

```
while( ebx <= val1)
{
    ebx = ebx + 5;
    val1 = val1 - 1
}
```

```
_while:
    cmp ebx,val1 ; check loop condition
    ja _endwhile ; false? exit loop
    add ebx,5    ; body of loop
    dec val1
    jmp while    ; repeat the loop
_endwhile:
```

90

Example: IF statement nested in a loop



```
while(eax < ebx)
{
    eax++;
    if (ebx==ecx)
        X=2;
    else
        X=3;
}
```

```
_while:  cmp  eax, ebx
        jae  _endwhile
        inc  eax
        cmp  ebx, ecx
        jne  _else
        mov  X, 2
        jmp  _while
_else:   mov  X, 3
        jmp  _while
_endwhile:
```

91

Table-driven selection



- Table-driven selection uses a table lookup to replace a multiway selection structure (switch-case statements in C)
- Create a table containing lookup values and the offsets of labels or procedures
- Use a loop to search the table
- Suited to a large number of comparisons

92

Table-driven selection



Step 1: create a table containing lookup values and procedure offsets:

```
.data
CaseTable BYTE 'A'          ; lookup value
          DWORD Process_A   ; address of procedure
          EntrySize = ($ - CaseTable)
          BYTE 'B'
          DWORD Process_B
          BYTE 'C'
          DWORD Process_C
          BYTE 'D'
          DWORD Process_D

NumberOfEntries = ($ - CaseTable) / EntrySize
```

93

Table-driven selection



Step 2: Use a loop to search the table. When a match is found, we call the procedure offset stored in the current table entry:

```
mov ebx,OFFSET CaseTable ; point EBX to the table
mov ecx,NumberOfEntries ; loop counter

L1:cmp al,[ebx]           ; match found?
    jne L2               ; no: continue
    call NEAR PTR [ebx + 1] ; yes: call the procedure
    jmp L3               ; and exit the loop
L2:add ebx,EntrySize     ; point to next entry
    loop L1              ; repeat until ECX = 0

L3:
```

required for procedure pointers

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Shift and rotate

Shift and Rotate Instructions



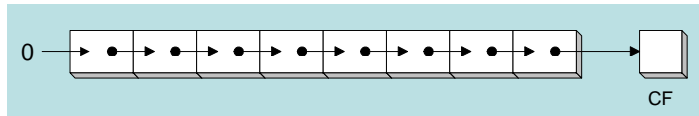
- Logical vs Arithmetic Shifts
- SHL Instruction
- SHR Instruction
- SAL and SAR Instructions
- ROL Instruction
- ROR Instruction
- RCL and RCR Instructions
- SHLD/SHRD Instructions

96

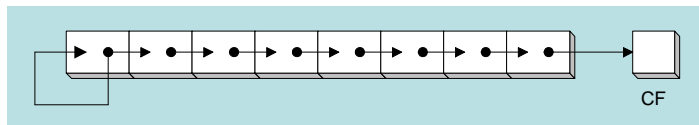
Logical vs arithmetic shifts



- A logical shift fills the newly created bit position with zero:



- An arithmetic shift fills the newly created bit position with a copy of the number's sign bit:

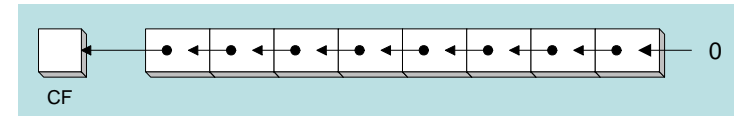


97

SHL instruction



- The SHL (shift left) instruction performs a logical left shift on the destination operand, filling the lowest bit with 0.



- Operand types: `SHL destination, count`

`SHL reg, imm8`

`SHL mem, imm8`

`SHL reg, CL`

`SHL mem, CL`

98

Fast multiplication



Shifting left 1 bit multiplies a number by 2

<pre>mov dl,5 shl dl,1</pre>	Before: <code>00000101</code> = 5
	After: <code>00001010</code> = 10

Shifting left n bits multiplies the operand by 2^n

For example, $5 * 2^2 = 20$

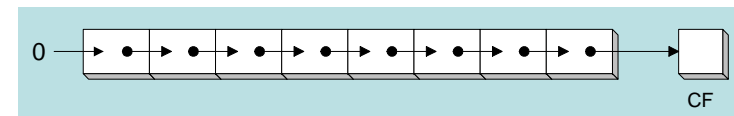
<pre>mov dl,5 shl dl,2</pre>	<code>; DL = 20</code>
------------------------------	------------------------

99

SHR instruction



- The SHR (shift right) instruction performs a logical right shift on the destination operand. The highest bit position is filled with a zero.



Shifting right n bits divides the operand by 2^n

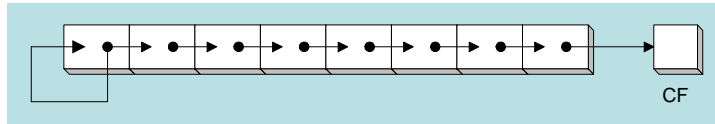
<pre>mov dl,80 shr dl,1</pre>	<code>; DL = 40</code>
<pre>shr dl,2</pre>	<code>; DL = 10</code>

100

SAL and SAR instructions



- SAL (shift arithmetic left) is identical to SHL.
- SAR (shift arithmetic right) performs a right arithmetic shift on the destination operand.



An arithmetic shift preserves the number's sign.

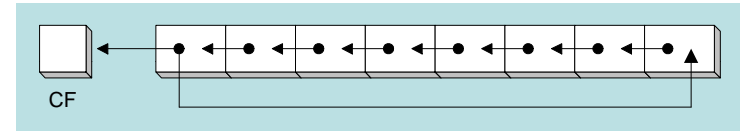
```
mov dl,-80
sar dl,1      ; DL = -40
sar dl,2      ; DL = -10
```

101

ROL instruction



- ROL (rotate) shifts each bit to the left
- The highest bit is copied into both the Carry flag and into the lowest bit
- No bits are lost



```
mov al,11110000b
rol al,1      ; AL = 11100001b

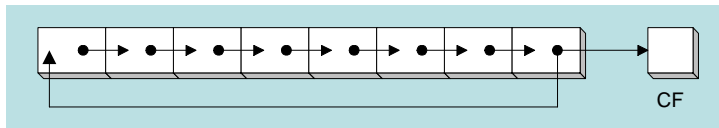
mov dl,3Fh
rol dl,4      ; DL = F3h
```

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ROR instruction



- ROR (rotate right) shifts each bit to the right
- The lowest bit is copied into both the Carry flag and into the highest bit
- No bits are lost



```
mov al,11110000b
ror al,1      ; AL = 01111000b

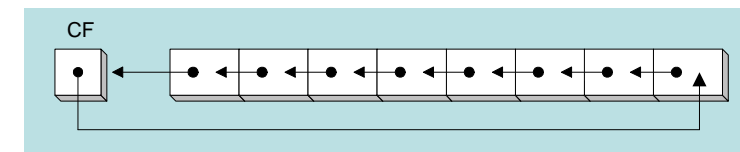
mov dl,3Fh
ror dl,4      ; DL = F3h
```

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RCL instruction



- RCL (rotate carry left) shifts each bit to the left
- Copies the Carry flag to the least significant bit
- Copies the most significant bit to the Carry flag



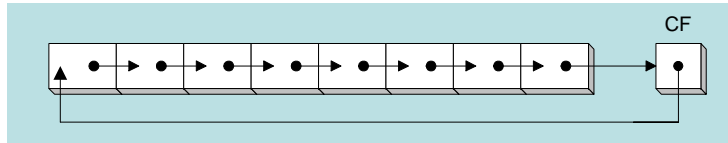
```
clc          ; CF = 0
mov bl,88h   ; CF,BL = 0 10001000b
rcl bl,1     ; CF,BL = 1 00010000b
rcl bl,1     ; CF,BL = 0 00100001b
```

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RCR instruction



- RCR (rotate carry right) shifts each bit to the right
- Copies the Carry flag to the most significant bit
- Copies the least significant bit to the Carry flag



```
stc          ; CF = 1
mov ah,10h   ; CF,AH = 00010000 1
rcr ah,1     ; CF,AH = 10001000 0
```

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SHLD instruction



- Syntax: (shift left double)
SHLD destination, source, count
- Shifts a destination operand a given number of bits to the left
- The bit positions opened up by the shift are filled by the most significant bits of the source operand
- The source operand is not affected

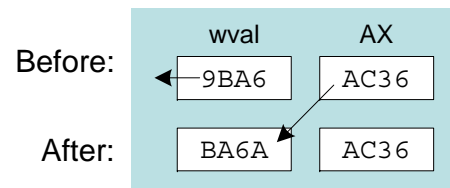
106

SHLD example



Shift **wval** 4 bits to the left and replace its lowest 4 bits with the high 4 bits of **AX**:

```
.data
wval WORD 9BA6h
.code
mov ax,0AC36h
shld wval,ax,4
```



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SHRD instruction



- Syntax:
SHRD destination, source, count
- Shifts a destination operand a given number of bits to the right
- The bit positions opened up by the shift are filled by the least significant bits of the source operand
- The source operand is not affected

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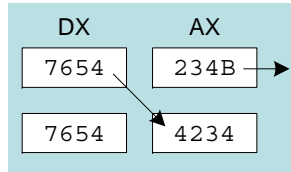
SHRD example



Shift AX 4 bits to the right and replace its highest 4 bits with the low 4 bits of DX:

```
mov ax,234Bh
mov dx,7654h
shrd ax,dx,4
```

Before:



After:

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Shift and rotate applications



- Shifting Multiple Doublewords
- Binary Multiplication
- Displaying Binary Bits
- Isolating a Bit String

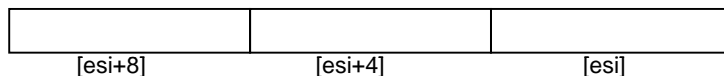
110

Shifting multiple doublewords



- Programs sometimes need to shift all bits within an array, as one might when moving a bitmapped graphic image from one screen location to another.
- The following shifts an array of 3 doublewords 1 bit to the right:

```
shr array[esi + 8],1 ; high dword
rcr array[esi + 4],1 ; middle dword,
rcr array[esi],1 ; low dword,
```



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Binary multiplication



- We already know that SHL performs unsigned multiplication efficiently when the multiplier is a power of 2.
- Factor any binary number into powers of 2.
 - For example, to multiply $EAX * 36$, factor 36 into $32 + 4$ and use the distributive property of multiplication to carry out the operation:

```
EAX * 36
= EAX * (32 + 4)
= (EAX * 32) + (EAX * 4)
```

```
mov eax,123
mov ebx,eax
shl eax,5
shl ebx,2
add eax,ebx
```

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Displaying binary bits



Algorithm: Shift MSB into the Carry flag; If CF = 1, append a "1" character to a string; otherwise, append a "0" character. Repeat in a loop, 32 times.

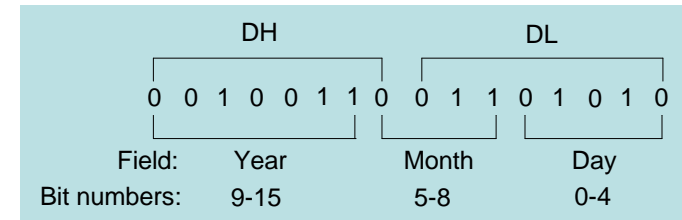
```
mov ecx,32
mov esi,offset buffer
L1: shl eax,1
mov BYTE PTR [esi],'0'
jnc L2
mov BYTE PTR [esi],'1'
L2: inc esi
loop L1
```

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Isolating a bit string



- The MS-DOS file date field packs the year (relative to 1980), month, and day into 16 bits:



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Isolating a bit string



```
mov al,dl ; make a copy of DL
and al,00011111b ; clear bits 5-7
mov day,al ; save in day variable
```

```
mov ax,dx ; make a copy of DX
shr ax,5 ; shift right 5 bits
and al,00001111b ; clear bits 4-7
mov month,al ; save in month variable
```

```
mov al,dh ; make a copy of DX
shr al,1 ; shift right 1 bit
mov ah,0 ; clear AH to 0
add ax,1980 ; year is relative to 1980
mov year,ax ; save in year
```

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Multiplication and division

MUL instruction



- The MUL (unsigned multiply) instruction multiplies an 8-, 16-, or 32-bit operand by either AL, AX, or EAX.
- The instruction formats are:

MUL r/m8

MUL r/m16

MUL r/m32

Implied operands:

Multiplicand	Multiplier	Product
AL	<i>r/m8</i>	AX
AX	<i>r/m16</i>	DX:AX
EAX	<i>r/m32</i>	EDX:EAX

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MUL examples



100h * 2000h, using 16-bit operands:

```
.data
val1 WORD 2000h
val2 WORD 100h
.code
mov ax,val1
mul val2 ; DX:AX=00200000h, CF=1
```

The Carry flag indicates whether or not the upper half of the product contains significant digits.

12345h * 1000h, using 32-bit operands:

```
mov eax,12345h
mov ebx,1000h
mul ebx ; EDX:EAX=0000000012345000h, CF=0
```

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IMUL instruction



- IMUL (signed integer multiply) multiplies an 8-, 16-, or 32-bit signed operand by either AL, AX, or EAX (there are one/two/three operand format)
- Preserves the sign of the product by sign-extending it into the upper half of the destination register

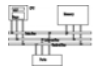
Example: multiply 48 * 4, using 8-bit operands:

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

OF=1 because AH is not a sign extension of AL.

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DIV instruction



- The DIV (unsigned divide) instruction performs 8-bit, 16-bit, and 32-bit division on unsigned integers
- A single operand is supplied (register or memory operand), which is assumed to be the divisor
- Instruction formats:

DIV r/m8

DIV r/m16

DIV r/m32

Default Operands:

Dividend	Divisor	Quotient	Remainder
AX	<i>r/m8</i>	AL	AH
DX:AX	<i>r/m16</i>	AX	DX
EDX:EAX	<i>r/m32</i>	EAX	EDX

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DIV examples



Divide 8003h by 100h, using 16-bit operands:

```
mov dx,0           ; clear dividend, high
mov ax,8003h       ; dividend, low
mov cx,100h        ; divisor
div cx             ; AX = 0080h, DX = 3
```

Same division, using 32-bit operands:

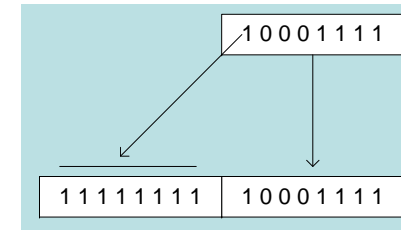
```
mov edx,0          ; clear dividend, high
mov eax,8003h      ; dividend, low
mov ecx,100h       ; divisor
div ecx           ; EAX=00000080h,EDX=3
```

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Signed integer division



- Signed integers must be sign-extended before division takes place
 - fill high byte/word/doubleword with a copy of the low byte/word/doubleword's sign bit
- For example, the high byte contains a copy of the sign bit from the low byte:



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CBW, CWD, CDQ instructions



- The CBW, CWD, and CDQ instructions provide important sign-extension operations:
 - CBW (convert byte to word) extends AL into AH
 - CWD (convert word to doubleword) extends AX into DX
 - CDQ (convert doubleword to quadword) extends EAX into EDX
- For example:

```
mov eax,0FFFFFF9Bh ; -101 (32 bits)
cdq                ; EDX:EAX = FFFFFFFF9Bh
                  ; -101 (64 bits)
```

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IDIV instruction



- IDIV (signed divide) performs signed integer division
 - Uses same operands as DIV
- Example: 8-bit division of -48 by 5

```
mov al,-48
cbw      ; extend AL into AH
mov bl,5
idiv bl  ; AL = -9, AH = -3
```

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IDIV examples



Example: 16-bit division of -48 by 5

```
mov ax,-48
cwd      ; extend AX into DX
mov bx,5
idiv bx  ; AX = -9, DX = -3
```

Example: 32-bit division of -48 by 5

```
mov eax,-48
cdq      ; extend EAX into EDX
mov ebx,5
idiv ebx ; EAX = -9, EDX = -3
```

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Arithmetic expressions

Divide overflow



- *Divide overflow* happens when the quotient is too large to fit into the destination.

```
mov ax, 1000h
mov bl, 10h
div bl
```

It causes a CPU interrupt and halts the program. (divided by zero cause similar results)

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Implementing arithmetic expressions



- Some good reasons to learn how to implement expressions:
 - Learn how compilers do it
 - Test your understanding of MUL, IMUL, DIV, and IDIV
 - Check for 32-bit overflow

Example: `var4 = (var1 + var2) * var3`

```
mov eax,var1
add eax,var2
mul var3
jo TooBig ; check for overflow
mov var4,eax ; save product
```

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Implementing arithmetic expressions

Example: $\text{eax} = (-\text{var1} * \text{var2}) + \text{var3}$

```
mov eax,var1
neg eax
mul var2
jo TooBig ; check for overflow
add eax,var3
```

Example: $\text{var4} = (\text{var1} * 5) / (\text{var2} - 3)$

```
mov eax,var1 ; left side
mov ebx,5
mul ebx ; EDX:EAX = product
mov ebx,var2 ; right side
sub ebx,3
div ebx ; final division
mov var4,eax
```

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Implementing arithmetic expressions

Example: $\text{var4} = (\text{var1} * -5) / (-\text{var2} \% \text{var3});$

```
mov eax,var2 ; begin right side
neg eax
cdq ; sign-extend dividend
idiv var3 ; EDX = remainder
mov ebx,edx ; EBX = right side
mov eax,-5 ; begin left side
imul var1 ; EDX:EAX = left side
idiv ebx ; final division
mov var4,eax ; quotient
```

Sometimes it's easiest to calculate the right-hand term of an expression first.

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Exercise . . .

Implement the following expression using signed 32-bit integers:

$\text{eax} = (\text{ebx} * 20) / \text{ecx}$

```
mov eax,20
mul ebx
div ecx
```

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Exercise . . .

Implement the following expression using signed 32-bit integers. Save and restore ECX and EDX:

$\text{eax} = (\text{ecx} * \text{edx}) / \text{eax}$

```
push ecx
push edx
push eax ; EAX needed later
mov eax,ecx
mul edx ; left side: EDX:EAX
pop ecx ; saved value of EAX
div ecx ; EAX = quotient
pop edx ; restore EDX, ECX
pop ecx
```

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Exercise . . .



Implement the following expression using signed 32-bit integers. Do not modify any variables other than var3:

$$\text{var3} = (\text{var1} * -\text{var2}) / (\text{var3} - \text{ebx})$$

```
mov eax,var1
mov edx,var2
neg edx
mul edx      ; left side: edx:eax
mov ecx,var3
sub ecx,ebx
div ecx      ; eax = quotient
mov var3,eax
```

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Extended addition and subtraction

ADC instruction



- ADC (add with carry) instruction adds both a source operand and the contents of the Carry flag to a destination operand.
- Example: Add two 32-bit integers (FFFFFFFFh + FFFFFFFFh), producing a 64-bit sum:

```
mov edx,0
mov eax,0FFFFFFFFh
add eax,0FFFFFFFFh
adc edx,0 ;EDX:EAX = 00000001FFFFFFFFEh
```

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Extended addition example



- Add two integers of any size
- Pass pointers to the addends (ESI, EDI) and sum (EBX), ECX indicates the number of doublewords

```
L1:
mov eax,[esi] ; get the first integer
adc eax,[edi] ; add the second integer
pushfd       ; save the Carry flag
mov [ebx],eax ; store partial sum
add esi,4    ; advance all 3 pointers
add edi,4
add ebx,4
popfd       ; restore the Carry flag
loop L1     ; repeat the loop
adc word ptr [ebx],0 ; add leftover carry
```

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Extended addition example



```
.data
op1 QWORD 0A2B2A40674981234h
op2 QWORD 08010870000234502h
sum DWORD 3 dup(?)
      ; = 0000000122C32B0674BB5736
.code
...
mov esi,OFFSET op1 ; first operand
mov edi,OFFSET op2 ; second operand
mov ebx,OFFSET sum ; sum operand
mov ecx,2           ; number of doublewords
call Extended_Add
...
```

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SBB instruction



- The SBB (subtract with borrow) instruction subtracts both a source operand and the value of the Carry flag from a destination operand.
- The following example code performs 64-bit subtraction. It sets EDX:EAX to 0000000100000000h and subtracts 1 from this value. The lower 32 bits are subtracted first, setting the Carry flag. Then the upper 32 bits are subtracted, including the Carry flag:

```
mov edx,1           ; upper half
mov eax,0           ; lower half
sub eax,1           ; subtract 1
sbb edx,0           ; subtract upper half
```

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Assignment #4 CRC32 checksum



```
unsigned int crc32(const char* data,
                  size_t length)
{
    // standard polynomial in CRC32
    const unsigned int POLY = 0xEDB88320;
    // standard initial value in CRC32
    unsigned int remainder = 0xFFFFFFFF;
    for(size_t i = 0; i < length; i++){
        // must be zero extended
        remainder ^= (unsigned char)data[i];
        for(size_t bit = 0; bit < 8; bit++){
            if(remainder & 0x01)
                remainder = (remainder >> 1) ^ POLY;
            else
                remainder >>= 1;
        }
    }
    return remainder ^ 0xFFFFFFFF;
}
```

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