

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

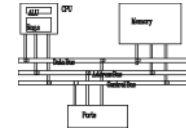


```
.data
count BYTE 100
wVal  WORD 2
.code

    mov bl,count
    mov ax,wVal
    mov count,al

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

Exercise . . .



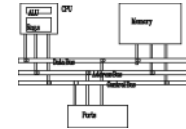
Explain why each of the following **MOV** statements are invalid:

```
.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.
```

Memory to memory



`.data`

`var1 WORD ?`

`var2 WORD ?`

`.code`

`mov ax, var1`

`mov var2, ax`

Copy smaller to larger



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

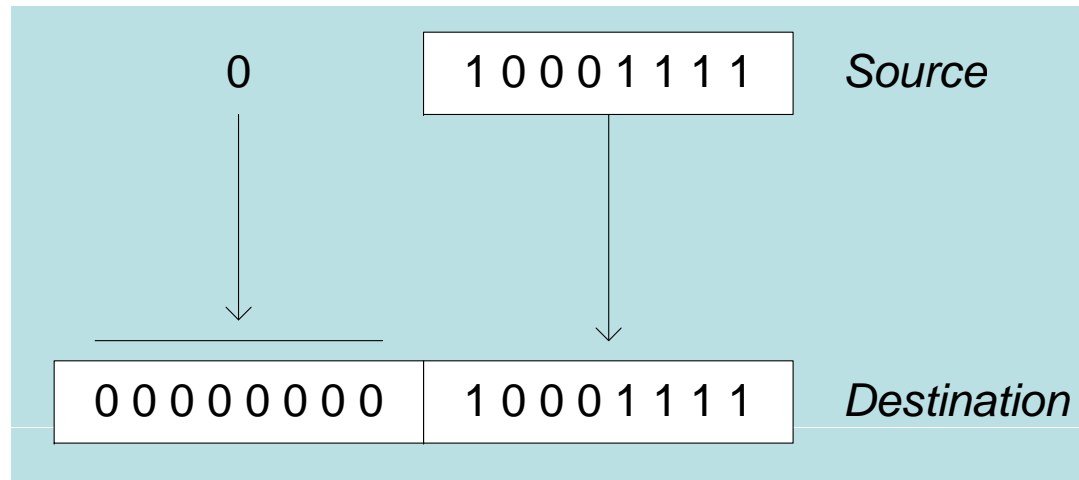
```
.data
signedVal SWORD -16 ; FFF0h
.code
mov ecx, 0 ; mov ecx, 0FFFFFFFFh
mov cx, signedVal
```

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

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.



```
movzx r32,r/m8  
movzx r32,r/m16  
movzx r16,r/m8
```

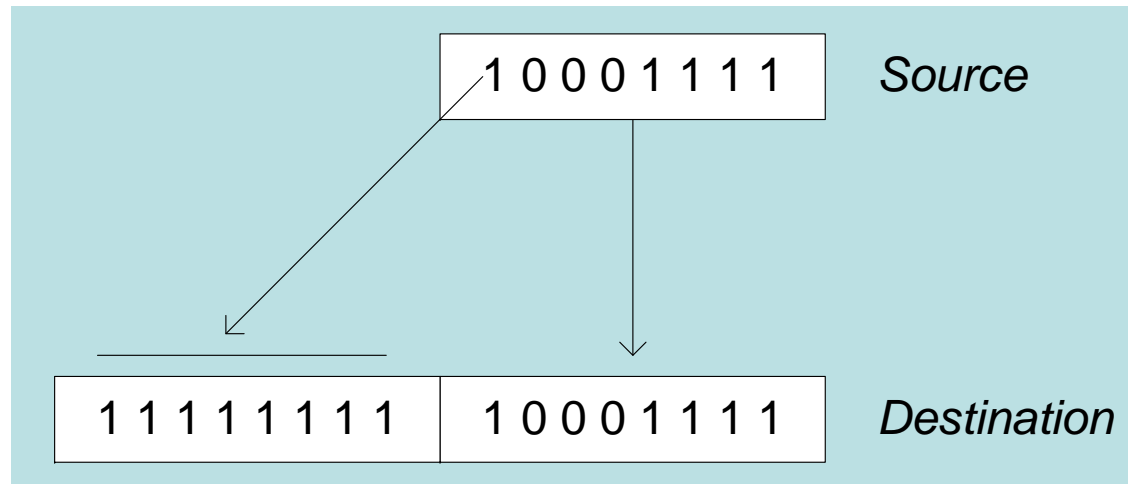
```
mov bl,10001111b  
movzx ax,bl ; zero-extension
```

The destination must be a register.

Sign extension



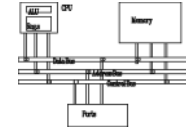
The **movsx** instruction fills the upper half of the destination with a copy of the source operand's sign bit.



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

The destination must be a register.

MOVZX MOVSX



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
```

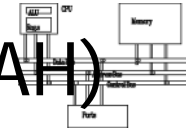
```
mov    bx,    0A69Bh
```

```
movsx  eax, bx          ; EAX=FFFFA69Bh
```

```
movsx  edx, bl          ; EDX=FFFFFF9Bh
```

```
movsx  cx,  bl          ; EAX=FF9Bh
```

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



.data

saveflags BYTE ?

.code

lahf

mov saveflags, ah

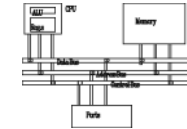
...

mov ah, saveflags

sahf

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

EFLAGS



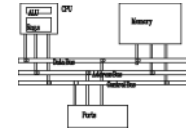
31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	0	0	0	0	ID	VIP	VIF	AC	VM	RF	0	NT	IOPL	OF	DF	IF	TF	SF	ZF	0	AF	0	PF	1	CF	

- X ID Flag (ID) —————
- X Virtual Interrupt Pending (VIP) —————
- X Virtual Interrupt Flag (VIF) —————
- X Alignment Check (AC) —————
- X Virtual-8086 Mode (VM) —————
- X Resume Flag (RF) —————
- X Nested Task (NT) —————
- X I/O Privilege Level (IOPL) —————
- S Overflow Flag (OF) —————
- C Direction Flag (DF) —————
- X Interrupt Enable Flag (IF) —————
- X Trap Flag (TF) —————
- S Sign Flag (SF) —————
- S Zero Flag (ZF) —————
- S Auxiliary Carry Flag (AF) —————
- S Parity Flag (PF) —————
- S Carry Flag (CF) —————

- 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.

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
```

Exchange two memory locations



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

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

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: $destination \leftarrow destination - 1$

INC and DEC Examples



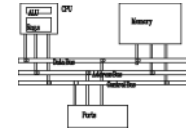
```
.data
myWord  WORD 1000h
myDword DWORD 10000000h

.code

    inc myWord          ; 1001h
    dec myWord          ; 1000h
    inc myDword         ; 10000001h

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

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
```

ADD and SUB Instructions



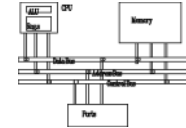
- **ADD** *destination, source*
 - Logic: $destination \leftarrow destination + source$
- **SUB** *destination, source*
 - Logic: $destination \leftarrow destination - source$
- Same operand rules as for the **MOV** instruction

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
```

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
```

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
```

Exercise ...



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

$$\mathbf{Rval = Xval - (-Yval + Zval)}$$

Assume that all values are signed doublewords.

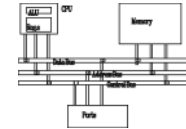
```
mov ebx,Yval
neg ebx
add ebx,Zval
mov eax,Xval
sub eax,ebx
mov Rval,eax
```


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.

Zero Flag (ZF)



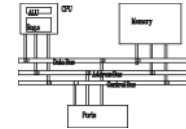
Whenever the destination operand equals Zero, the Zero flag is set.

```
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.

Sign Flag (SF)



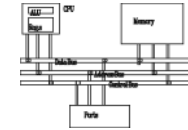
The Sign flag is set when the destination operand is negative. The flag is clear when the destination is positive.

```
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:

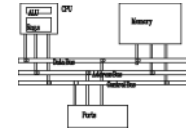
```
mov  al,0
sub  al,1           ; AL=11111111b, SF=1
add  al,2           ; AL=00000001b, SF=0
```

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

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
```

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.

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?

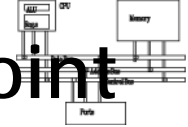
```
mov al,80h
```

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

```
mov al,-2
```

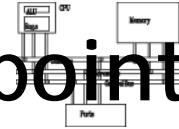
```
add al,+127          ; OF =
```

Signed/Unsigned Integers: Hardware Viewpoint



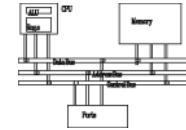
- All CPU instructions operate exactly the same on signed and unsigned integers
- The CPU cannot distinguish between signed and unsigned integers
- YOU, the programmer, are solely responsible for using the correct data type with each instruction

Overflow/Carry Flags: Hardware Viewpoint



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

Auxiliary Carry (AC) flag

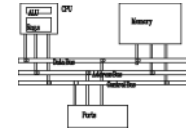


- AC indicates a carry or borrow of bit 3 in the destination operand.
- It is primarily used in binary coded decimal (BCD) arithmetic.

```
mov al, 0Fh
```

```
add al, 1          ; AC = 1
```

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
```

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

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:

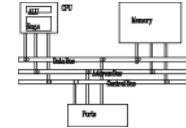
```
top:
    .
    .
    jmp top
```

LOOP Instruction



- The **LOOP** instruction creates a counting loop
- Syntax: **LOOP** *target*
- Logic:
 - $ECX \leftarrow ECX - 1$
 - if **ECX** **!= 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.

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:

$$00000009 \leftarrow 0000000E + FB$$

Exercise . . .



If the relative offset is encoded in a single byte,

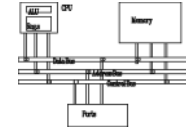
- (a) what is the largest possible backward jump?
- (b) what is the largest possible forward jump?

(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!

Exercise . . .



What will be the final value of AX?

10

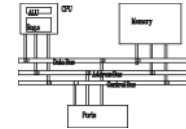
```
mov ax,6
mov ecx,4
L1:
  inc ax
  loop L1
```

How many times will the loop execute?

4,294,967,296

```
mov ecx,0
x2:
  inc ax
  loop x2
```

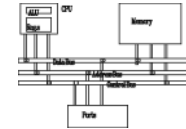
Nested Loop



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
```

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
```

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
```

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

NOT instruction



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

NOT *destination*

- Example:

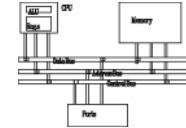
```
mov al, 11110000b
not al
```

```
NOT  0 0 1 1 1 0 1 1
      ───────────
      1 1 0 0 0 1 0 0 ——— inverted
```

NOT

X	$\neg X$
F	T
T	F

AND instruction



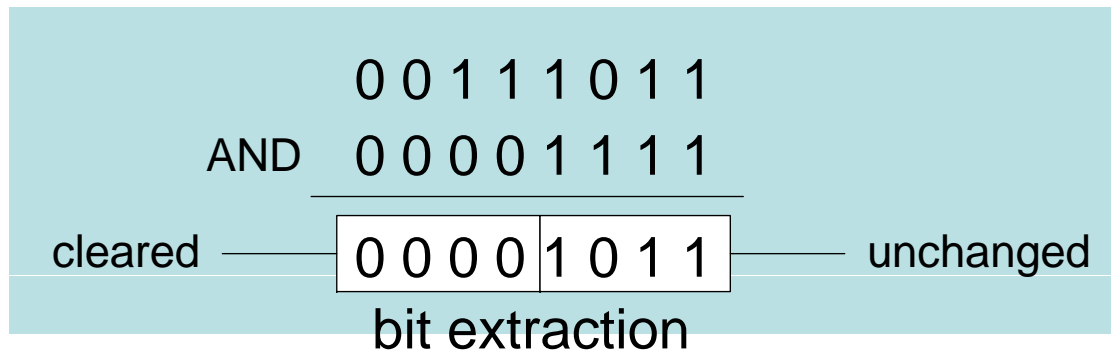
- Performs a bitwise Boolean AND operation between each pair of matching bits in two operands
- Syntax: (O=0,C=0,SZP)

AND *destination, source*

- Example:

```
mov al, 00111011b
```

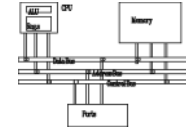
```
and al, 00001111b
```



AND

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

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*

- Example:

```
mov dl, 00111011b
```

```
or dl, 00001111b
```

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

OR

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

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

- Example:

```
mov dl, 00111011b
```

```
xor dl, 00001111b
```

```

          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

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

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.

<pre>mov al, 'a' ; AL = 01100001b and al, 11011111b ; AL = 01000001b</pre>
--

Applications (2 of 4)

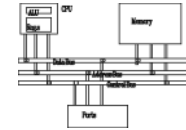


- Task: Convert a binary decimal byte into its equivalent ASCII decimal digit.
- Solution: Use the OR instruction to set bits 4 and 5.

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

The ASCII digit '6' = 00110110b

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
```

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.

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.

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

- Example: jump to a label if neither bit 0 nor bit 1 in AL is set.

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


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
```

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.

CMP instruction (3 of 3)



The comparisons shown here are performed with signed integers.

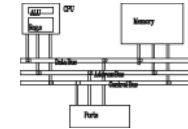
- Example: destination > source

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

- Example: destination < source

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

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

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
```

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:
```

Jcond instruction

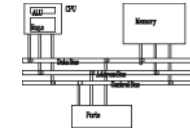


- A conditional jump instruction branches to a label when specific register or flag conditions are met

Jcond *destination*

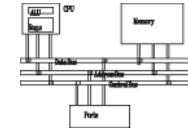
- Four groups: (some are the same)
 1. based on specific flag values
 2. based on equality between operands
 3. based on comparisons of unsigned operands
 4. based on comparisons of signed operands

Jumps based on specific flags



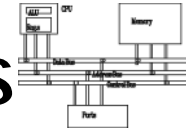
Mnemonic	Description	Flags
JZ	Jump if zero	ZF = 1
JNZ	Jump if not zero	ZF = 0
JC	Jump if carry	CF = 1
JNC	Jump if not carry	CF = 0
JO	Jump if overflow	OF = 1
JNO	Jump if not overflow	OF = 0
JS	Jump if signed	SF = 1
JNS	Jump if not signed	SF = 0
JP	Jump if parity (even)	PF = 1
JNP	Jump if not parity (odd)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

Jumps based on equality



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

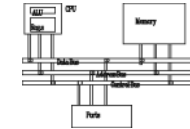
Jumps based on unsigned comparisons



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)

$> \geq < \leq$

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)

Examples



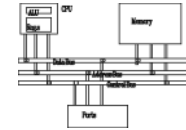
- Compare unsigned AX to BX, and copy the larger of the two into a variable named Large

```
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:
```

Examples

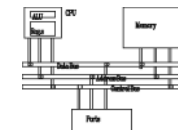


- Find the first even number in an array of unsigned integers

```
.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
...

```

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

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.

LOOPNZ and LOOPNE



- Syntax:

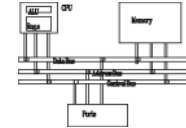
LOOPNZ *destination*

LOOPNE *destination*

- Logic:

- $ECX \leftarrow ECX - 1$;
- if $ECX \neq 0$ and $ZF=0$, jump to *destination*

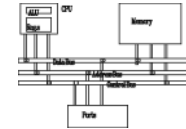
LOOPNZ example



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:
```

Exercise ...



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

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

quit:
```

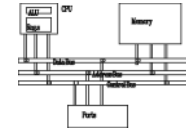
Solution



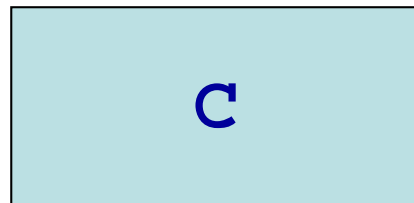
```
.data
array SWORD 50 DUP(?)
sentinel SWORD 0FFFFh
.code
    mov esi,OFFSET array
    mov ecx,LENGTHOF array
L1:cmp WORD PTR [esi],0 ; check for zero
    pushfd ; push flags on stack
    add esi,TYPE array
    popfd ; pop flags from stack
    loope L1 ; continue loop
    jz quit ; none found
    sub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

Conditional structures

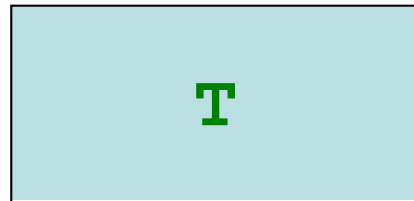
If statements



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

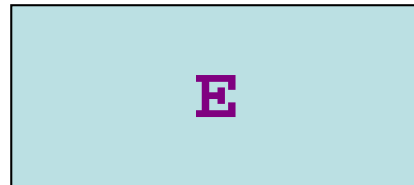


JNE else



JMP endif

else:



endif:

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:
```


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:
```

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:
```

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;
```

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:
```

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 a1,b1          ; first expression...
    jbe next           ; quit if false
    cmp b1,c1          ; second expression...
    jbe next           ; quit if false
    mov X,1            ; both are true
next:
```

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.)

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;
```

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,c1        ; no: is BL > CL?
    jbe next         ; no: skip next statement
L1:mov X,1           ; set X to 1
next:
```


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:
```

Exercise . . .

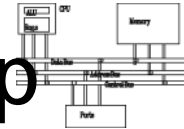


Implement the following loop, using unsigned 32-bit integers:

```
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:
```

Example: IF statement nested in a loop



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

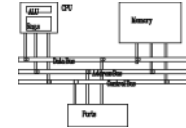
```
_while:  cmp    eax, ebx
         jae    _endwhile
         inc    eax
         cmp    ebx, ecx
         jne    _else
         mov    X, 2
         jmp    _while
_else:   mov    X, 3
         jmp    _while
_endwhile:
```

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

Table-driven selection

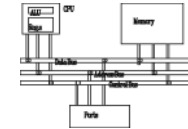


Step 1: create a table containing lookup values and procedure offsets:

```
.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
```

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

Shift and rotate

Shift and Rotate Instructions

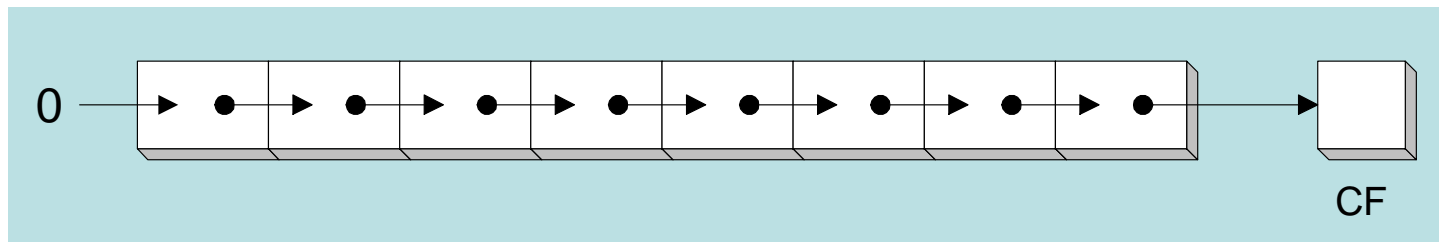


- Logical vs Arithmetic Shifts
- SHL Instruction
- SHR Instruction
- SAL and SAR Instructions
- ROL Instruction
- ROR Instruction
- RCL and RCR Instructions
- SHLD/SHRD Instructions

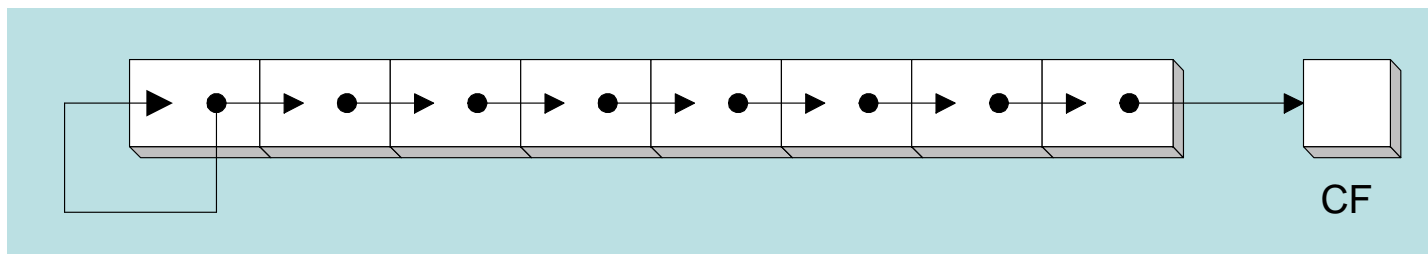
Logical vs arithmetic shifts



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



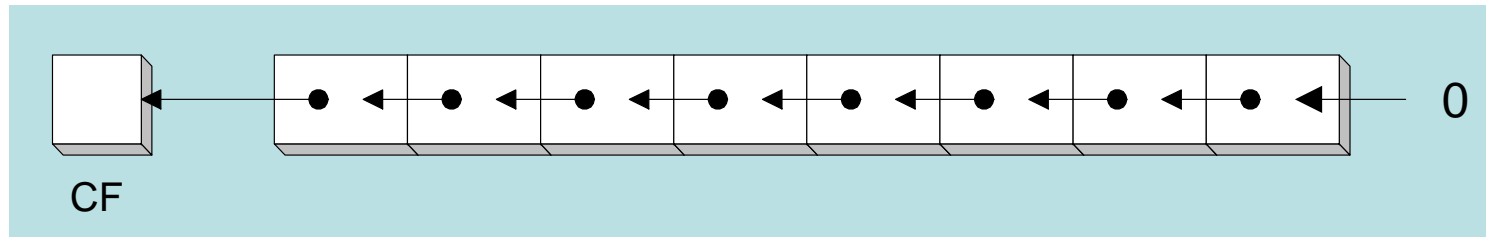
- An arithmetic shift fills the newly created bit position with a copy of the number's sign bit:



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`

Fast multiplication



Shifting left 1 bit multiplies a number by 2

```
mov dl,5  
shl dl,1
```

Before: 0 0 0 0 0 1 0 1 = 5

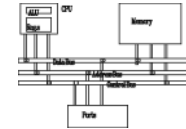
After: 0 0 0 0 1 0 1 0 = 10

Shifting left n bits multiplies the operand by 2^n

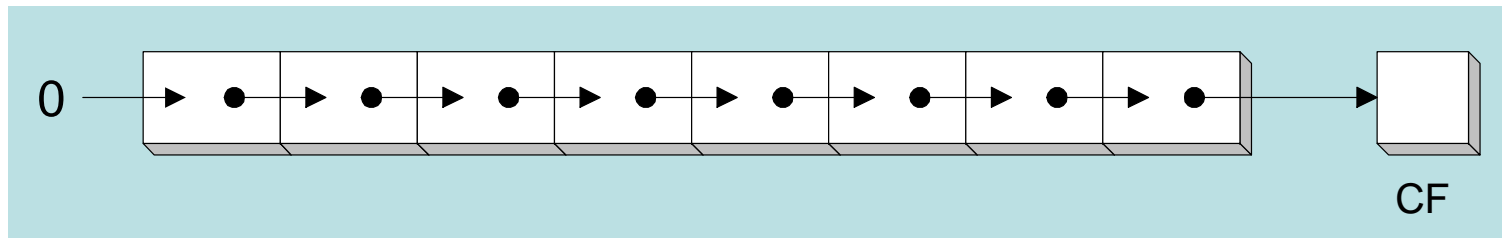
For example, $5 * 2^2 = 20$

```
mov dl,5  
shl dl,2           ; DL = 20
```

SHR instruction



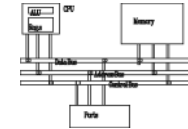
- The SHR (shift right) instruction performs a logical right shift on the destination operand. The highest bit position is filled with a zero.



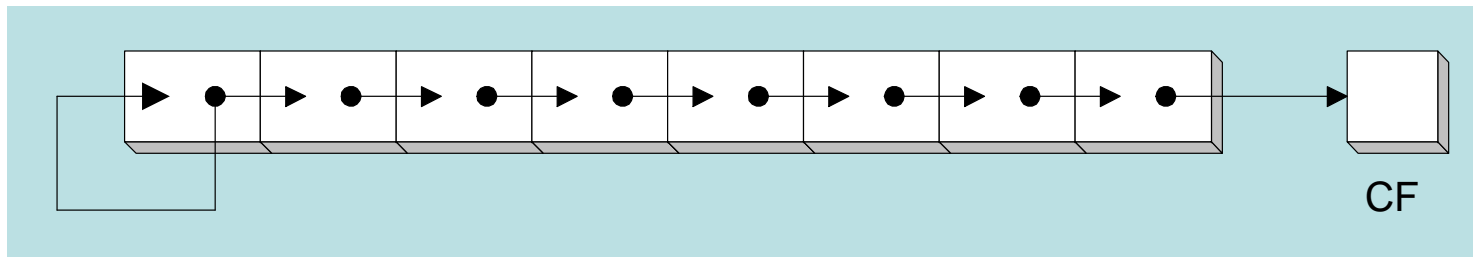
Shifting right n bits divides the operand by 2^n

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

SAL and SAR instructions

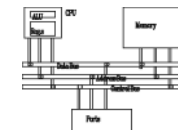


- SAL (shift arithmetic left) is identical to SHL.
- SAR (shift arithmetic right) performs a right arithmetic shift on the destination operand.



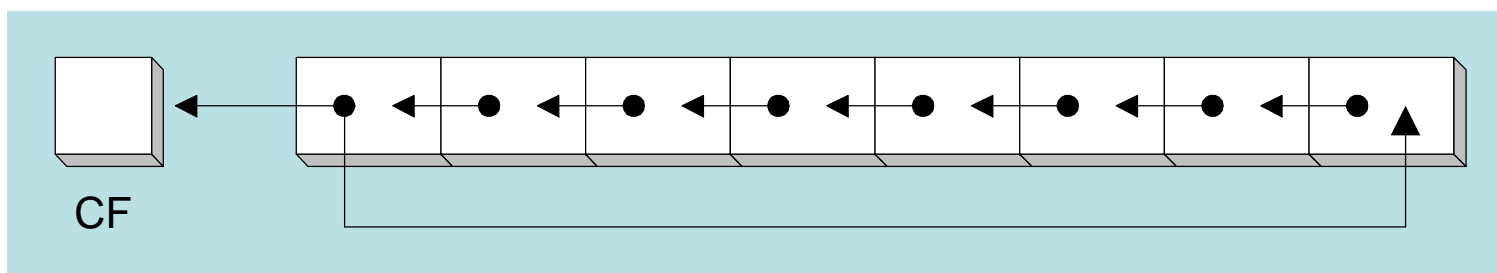
- An arithmetic shift preserves the number's sign.

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



ROL instruction

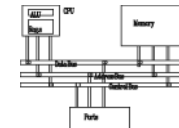
- ROL (rotate) shifts each bit to the left
- The highest bit is copied into both the Carry flag and into the lowest bit
- No bits are lost



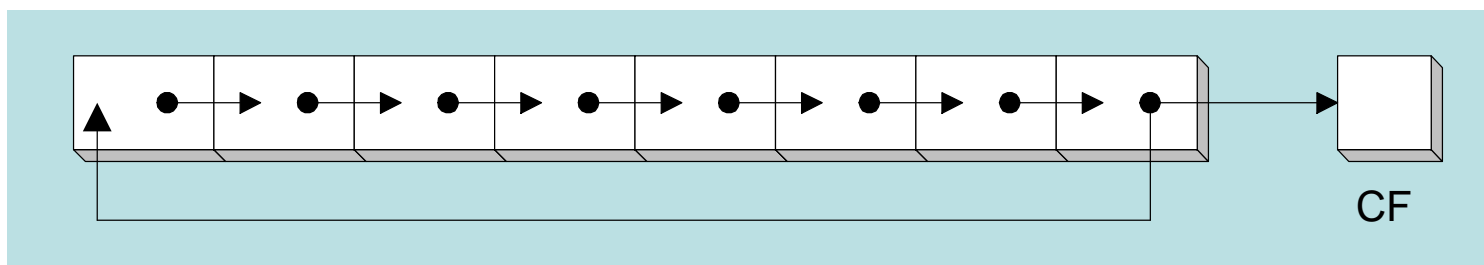
```
mov al,11110000b
rol al,1           ; AL = 11100001b

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

ROR instruction

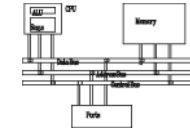


- ROR (rotate right) shifts each bit to the right
- The lowest bit is copied into both the Carry flag and into the highest bit
- No bits are lost



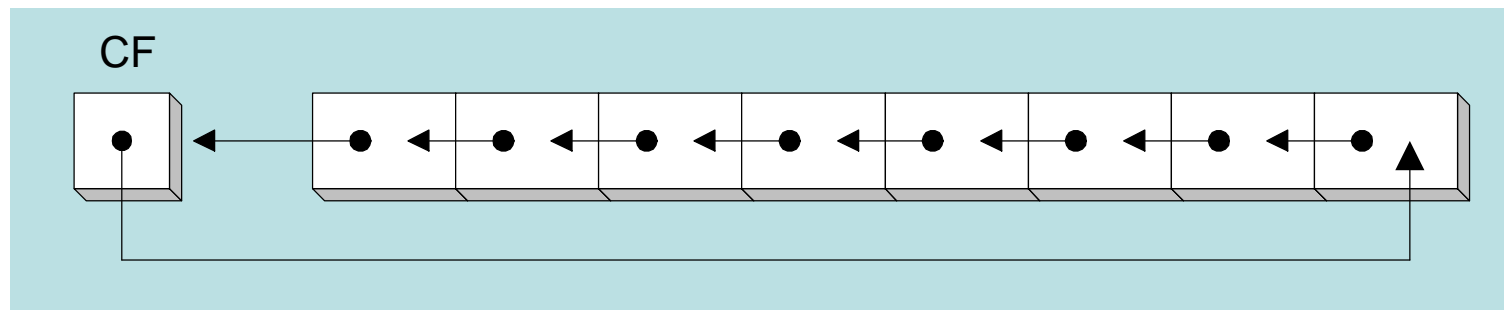
```
mov al,11110000b
ror al,1                ; AL = 01111000b

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



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

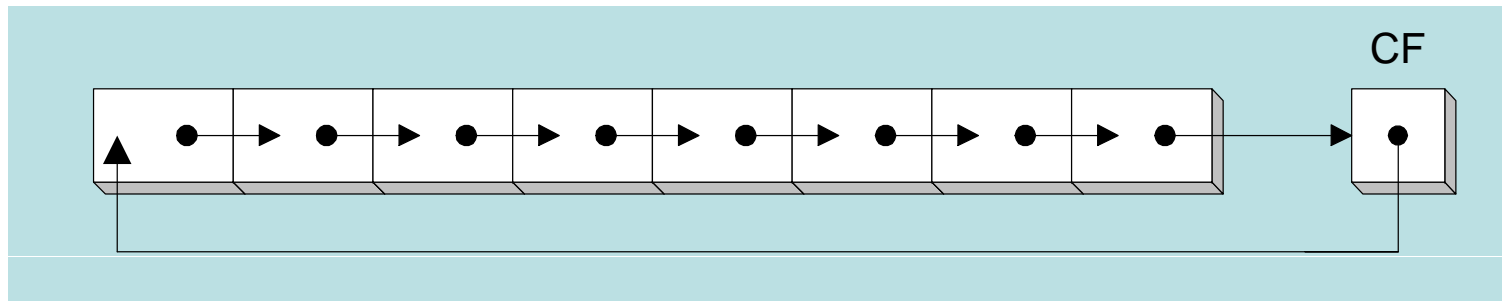


<code>clc</code>	<code>; CF = 0</code>
<code>mov bl,88h</code>	<code>; CF,BL = 0 10001000b</code>
<code>rcl bl,1</code>	<code>; CF,BL = 1 00010000b</code>
<code>rcl bl,1</code>	<code>; CF,BL = 0 00100001b</code>

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



<code>stc</code>	<code>; CF = 1</code>
<code>mov ah,10h</code>	<code>; CF,AH = 00010000 1</code>
<code>rcr ah,1</code>	<code>; CF,AH = 10001000 0</code>

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

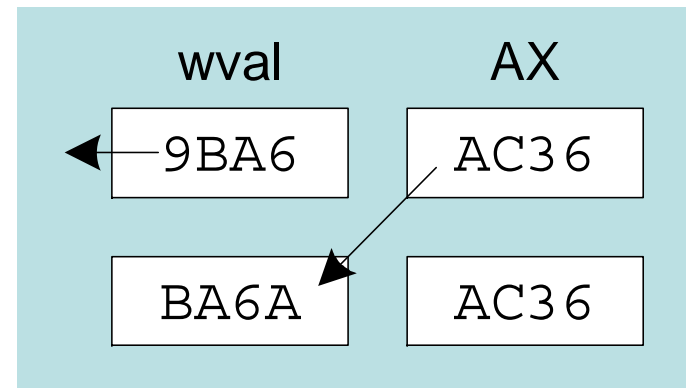
SHLD example



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
```

Before:



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

SHRD example

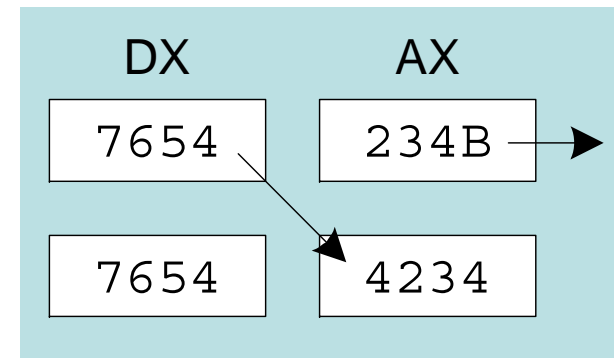


Shift AX 4 bits to the right and replace its highest 4 bits with the low 4 bits of DX:

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

Before:

After:

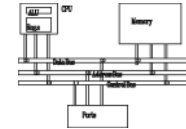


Shift and rotate applications



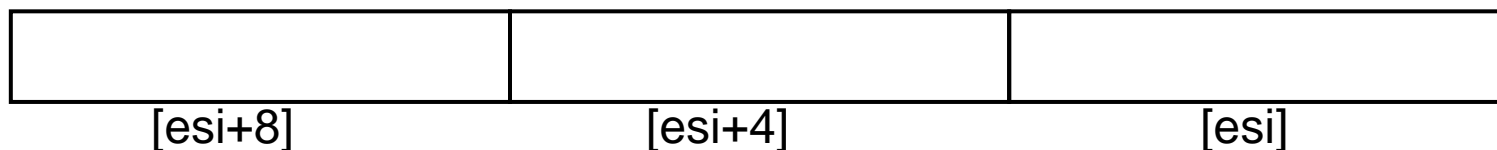
- Shifting Multiple Doublewords
- Binary Multiplication
- Displaying Binary Bits
- Isolating a Bit String

Shifting multiple doublewords

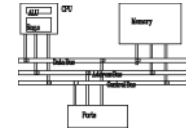


- Programs sometimes need to shift all bits within an array, as one might when moving a bitmapped graphic image from one screen location to another.
- The following shifts an array of 3 doublewords 1 bit to the right:

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



Binary multiplication

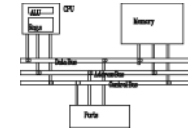


- We already know that SHL performs unsigned multiplication efficiently when the multiplier is a power of 2.
- Factor any binary number into powers of 2.
 - For example, to multiply $EAX * 36$, factor 36 into $32 + 4$ and use the distributive property of multiplication to carry out the operation:

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

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


Displaying binary bits



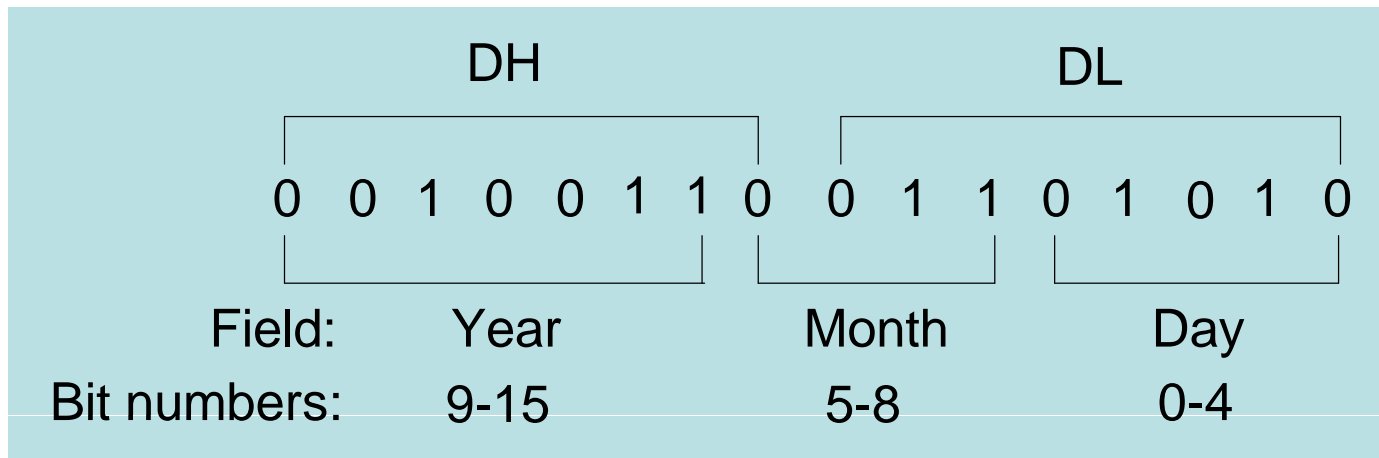
Algorithm: Shift MSB into the Carry flag; If CF = 1, append a "1" character to a string; otherwise, append a "0" character. Repeat in a loop, 32 times.

```
        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
```

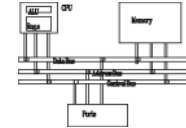
Isolating a bit string



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



Isolating a bit string



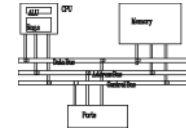
```
mov al,dl          ; make a copy of DL
and al,00011111b   ; clear bits 5-7
mov day,al          ; save in day variable
```

```
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
```

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*

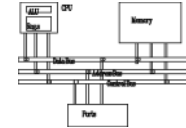
MUL *r/m16*

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

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
```

IMUL instruction



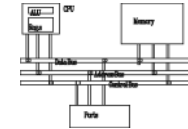
- IMUL (signed integer multiply) multiplies an 8-, 16-, or 32-bit signed operand by either AL, AX, or EAX (there are one/two/three operand format)
- Preserves the sign of the product by sign-extending it into the upper half of the destination register

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.

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

DIV examples



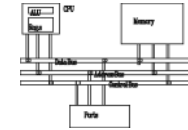
Divide 8003h by 100h, using 16-bit operands:

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

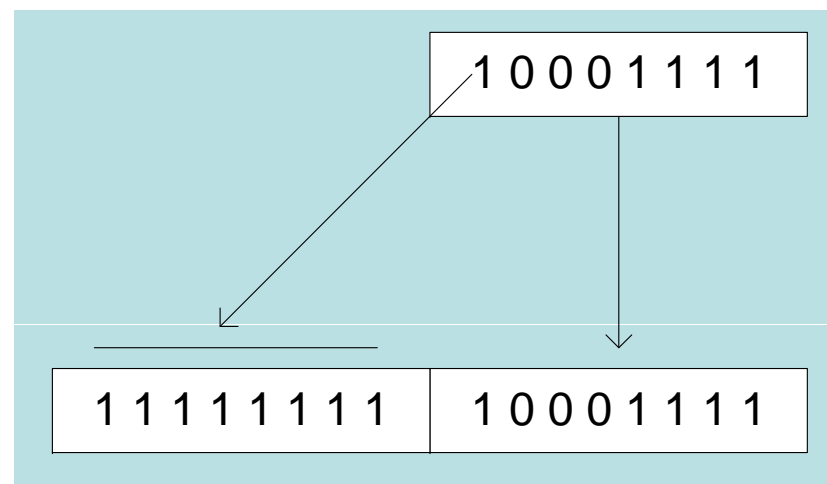
Same division, using 32-bit operands:

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

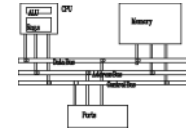
Signed integer division



- 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:



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,0FFFFFFF9Bh      ; -101 (32 bits)
cdq                      ; EDX:EAX = FFFFFFFF9Bh
                           ; -101 (64 bits)
```

IDIV instruction

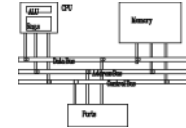


- IDIV (signed divide) performs signed integer division
- Uses same operands as DIV

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
```

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
```

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)

Arithmetic expressions

Implementing arithmetic expressions

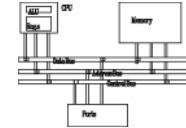


- Some good reasons to learn how to implement expressions:
 - Learn how compilers do it
 - Test your understanding of MUL, IMUL, DIV, and IDIV
 - Check for 32-bit overflow

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

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


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
```

Implementing arithmetic expressions



Example: `var4 = (var1 * -5) / (-var2 % 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.

Exercise . . .



Implement the following expression using signed 32-bit integers:

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

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

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
```

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
```

Extended addition and subtraction

ADC instruction



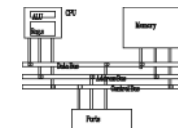
- ADC (add with carry) instruction adds both a source operand and the contents of the Carry flag to a destination operand.
- Example: Add two 32-bit integers (FFFFFFFFh + FFFFFFFFh), producing a 64-bit sum:

```
mov  edx,0
```

```
mov  eax,0FFFFFFFFh
```

```
add  eax,0FFFFFFFFh
```

```
adc  edx,0 ;EDX:EAX = 00000001FFFFFFFFEh
```



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
```


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`

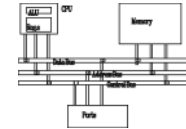
`mov ebx,OFFSET sum ; sum operand`

`mov ecx,2 ; number of doublewords`

`call Extended_Add`

`...`

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
```

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 reminder = 0xFFFFFFFF;
    for(size_t i = 0; i < length; i++){
        // must be zero extended
        reminder ^= (unsigned char)data[i];
        for(size_t bit = 0; bit < 8; bit++){
            if(reminder & 0x01)
                reminder = (reminder >> 1) ^ POLY;
            else
                reminder >>= 1;
        }
    }
    return reminder ^ 0xFFFFFFFF;
}
```