Computer Architecture and Low Level Programming

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Outline

- x86 Assembly
  - Why use assembly?
  - Basic concepts
  - Different ways of using assembly

Main reasons for using assembly nowadays

- Understand how hardware works
  - This way, we can write more efficient software in terms of execution time, memory size, energy consumption and security
  - Reverse engineering to identify software flaws
- Making compilers, hardware drivers, processors
- Optimization
  - execution time
  - memory size
  - energy consumption

Main reasons for NOT writing assembly nowadays

- Development time
- Reliability and security
- Debugging
- Maintainability
- Portability

X86, X64 and IA-32

- What is **x86** and what **x64**?
  - **x86** is an Intel CPU architecture that originated with the 16-bit 8086 processor in 1978.
  - Today, the term "**x86**" is used generally to refer to any 32-bit processor compatible with the **x86** instruction set
  - **IA-32** (short for "Intel Architecture, 32-bit", sometimes also called i386 is the 32-bit version of the **x86** instruction set architecture
  - **x86-64** or x64 is the general name of a series of 64-bit processors and their associated instruction set architecture. These processors are compatible with **x86.**
- What 32bit mean?
  - 32bit Data/address bus, registers, …

Introduction to x86 Assembly Programming

- There are many different assemblers out there: MASM, NASM, GAS, AS86, TASM, A86, Terse, etc. All use radically different assembly languages.

- There are differences in the way you have to code for Linux, Windows, etc.

- GNU Assembler (GAS)

  - AT&T syntax for writing the assembly language
- Microsoft Macro Assembler (MASM)
- Netwide Assembler (NASM)

Pillars of assembly language

- Reserved words
- Identifiers
- Directives
- Sections (or segments)
- Instructions

Reserved Words

- Predefined purpose, e.g. mov is a reserved word and an instruction
- These cannot be used in any other way, e.g. for variable names
- **Case-insensitive:** Mov ≡ mov ≡ MOV

MASM

```
.386
.MODEL FLAT, stdcall
.STACK 4096
ExitProcess PROTO,
dwExitCode:DWORD

.data
sum DWORD 0

.code
_main PROC
mov eax, 25
mov ebx, 50
add eax, ebx
mov sum, eax

INVOKE ExitProcess, 0
_main ENDP
END
```

Identifiers

- **Programmer defined names given to items** such as variables, constants and procedures
- Length is limited to 247 characters
- Must begin with a letter (A-Z, a-z), underscore, question mark (?), at symbol (@) or dollar symbol ($)
- Please do not use: question mark (?), at symbol (@) or dollar symbol ($)
- Use camelCase for variables, e.g. sumOfProducts
- Use CamelCase for procedures, e.g. ExitProcess
- Use CONSTANT NAME for constants, e.g. GRAVITIONAL ACCELERATION

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```

Directives

- **Assembler specific commands: direct the assembler to do something**
- Example: ask the assembler to reserve 32-bit memory with literal value 42 in a variable called *answer* with DWORD directive. Code: *answer DWORD 42*
- **Other useful directives:**
  - ***.386*** Enables 80386 processor instructions
  - ***.model*** Sets the memory model. FLAT for 32-bit instructions, and stdcall for assembly instructions
  - ***.stack*** Sets the size of the stack memory segment for the program

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```

Program sections (or segments)

- Special sections pre-defined by the assembler
- Common segments:
  - ***.data*** uninitialised and initialised variables
  - ***.code*** executable code and instructions

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```

Instructions

- **Executable statements in a program**
- **Two basic parts:** *mnemonic and [operands]*
- *Mnemonic* is the instruction name as defined in the architecture's instruction sets
- Some do not require operands, some one or more
- Common code examples:
  - stc no operands sets the carry flag inc eax increment eax by one
  - mov eax, *5* moves literal value *5* to eax register

Intel's x86 instruction set manuals comprise over 2900 pages – it is large and complex

MASM

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_main ENDP
END
```

Label:	Mnemonic	Operand(s)	;Comment

Literals


```
00011111b   ; b is the radix character for binary
31          ; decimal values do not need radix characters
31d         ; but you can specify d for decimal
1Fh         ; h is the radix character for hexadecimal
37o         ; o is the radix character for octal
```


Radix	Base
b	Binary (base-2)
d	Decimal (base-10)
h	Hexadecimal (base-16)
q, o	Octal (base-8)


```
0FFFF0342h   ; the actual value is FFFF0342 in hexadecimal
```

```
"I don't understand contractions."             ; strings that have one
'"Good job," said the father to his son.'      ; type of quotes on the
                                               ; outside and a different
                                               ; type on the inside
```

String Literals

String Characters	D	a	i	s	y	,		d	a	i	s	y
ASCII Decimal Values	68	97	105	115	121	44	32	100	97	105	115	121


```
; motd contains a single-line string
motd  BYTE "Welcome to Earth...",0

; motd2 contains a multi-line string with a newline at the end
motd2 BYTE "Thank you for using our system.",0Dh,0Ah
      BYTE "All of your activity will be monitored"
      BYTE "by our system administrators",0Dh,0Ah,0
```


- Stored as Byte array, each character occupies one byte
- Must end with ‘0’
- Carriage return: ‘0Dh’
- Line-feed: ‘0Ah’

Data Types

- BYTE – 8bit unsigned integer
- SBYTE – 8bit signed integer
- WORD - 16bit unsigned integer
- SWORD - 16bit signed integer
- DWORD - 32bit unsigned integer
- SDWORD - 32bit signed integer
- QWORD – 64bit unsigned integer
- REAL4 – single precision floating point numbers (32bit)
- REAL8 - double precision floating point numbers (64bit)

Variables


```
charInput   BYTE 'A'
myArray     DWORD 41h, 75, 0C4h, 01010101b
```



```
.data
num DWORD  6             ; defines an initialized identifier
sum SDWORD ?             ; defines an uninitialized identifier
myArray   BYTE 10 DUP (1)  ; defines an array of initialized bytes
myUArray  BYTE 10 DUP (?)  ; defines an array of uninitialized bytes
```


myArray BYTE 10 DUP (1) ; duplicates 1 into the 10-bytes

Storage methods: Little Endian vs Big Endian

- x86 and x86 64 typically use *Little-Endian*, i.e., **all the bytes are stored in reverse order** (the bits inside a bit are stored normally)
- Store 12345678_{16} in memory

Big-Endian

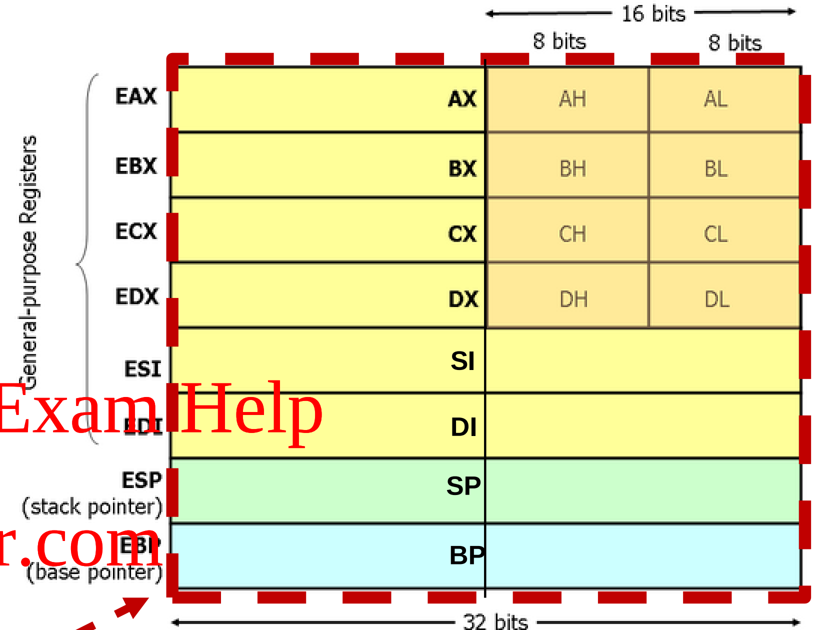
Memory Address	Data
0x00000000	12
0x00000008	34
0x00000010	56
0x00000018	78

Little-Endian

Memory Address	Data
0x00000000	78
0x00000008	56
0x00000010	34
0x00000018	12

Registers (1)

- The lower bytes of some of these registers may be accessed independently as 32, 16 or 8-bit registers
- Older processors use 8bit, 16bit or 32bit registers only – compatibility exists
- There are other registers too… (next slide)



	64-bit	32-bit	16-bit
General purpose registers	RAX	EAX	AX
	RBX	EBX	BX
	RCX	ECX	CX
	RDX	EDX	DX
	RSI	ESI	SI
	RDI	EDI	DI
	RBP	EBP	BP
	RSP	ESP	SP
	R8 – R15		

	64-bit	32-bit	16-bit
Segment registers	N/A	CS	CS
		DS	DS
		ES	ES
		SS	SS
		FS	
		GS	
Instruction pointer	RIP	EIP	IP
Flags register	RFLAGS	EFLAGS	FLAGS

Registers (2)

- **There are also eight 80bit floating point registers**
  - ST(0)-ST(7), arranged as a stack
- **Eight 64bit MMX vector registers**
  - Used with MMX instructions (physically they are the same as above)
- **Eight/Sixteen 128/256/512 bit vector registers**
  - 128bit use SSE instructions
  - 256bit use AVX instructions
  - 512bit use AVX2 instructions

Registers (3)

- ***rax/eax***: Default accumulator register.
  - Used for arithmetical operations
  - Function calls place return value.
  - Do not use it for data storage while performing such operations.
- ***rcx/ecx:*** Hold loop counter. Do not overwrite when looping!
- ***rbp/ebp***: Reference data on the stack; more on this later.
- ***rsp/esp***: Used for managing the stack – typically points to the top of the stack.
- ***rsi/esi*** and ***rdi/edi***: Index registers used in string operations.
- ***rip/eip:*** Instruction pointer - shows next instruction to be executed
- ***rflags/eflags***: Status and control registers; cannot be modified directly!

Notations

L A literal value (e.g. 42)

M A memory (variable) operand (e.g. numOfStudents)

R A register (e.g. eax)

- If you see a number followed by one of these notations, it represents the size of the notation. For instance, L8 means that it is a 8-bit literal value.
- If multiple notations appear segregated by a slash ('/'), it means that either of these two types may be used. For example, M/R means that either a memory type of a register may be used.

Data movement

- *mov eax, sum ; mov M/R, L/M/R (moving)*
- *xchg eax, sum ; xchg M/R, M/R (swapping)*

- For moving data:
  - Both operands must be the same size.
  - Both operands cannot be memory operands (must use a register as an intermediary).

Addition and subtraction

- *inc sum ; inc M/R (increment by one)*
- *dec sum ; dec M/R (decrement by one)*
- *add eax, sum ; add M/R, L/M/R (addition)*

- *sub eax, val ; sub M/R, L/M/R (subtraction)*

- *neg sum ; neg M/R (negate: 2's complement), this operation is equivalent to subtracting the operand from 0*

- In MASM, for addition and subtraction, the second component is added/subtracted from the first component, and the result is stored back into the first component.
- In AT&T the exact opposite

MUL (unsigned multiply)

2 x 3 =6

Multiplier	Multiplicand	Product
M8/R8	*al*	*ax*
M16/R16	*ax*	*dx:ax*
M32/R32	*eax*	*edx:eax*
M64/R64	*rax*	*rdx:rax*

- Multiplication may require more bytes to hold the results. Consider the following 2-bit multiplicand 310 (112) and 2-bit multiplier 310 (112). The product is 910 (10012), and it cannot be contained in 2-bits; it requires 4-bits. At most we require double the size of the multiplier or the multiplicand.
- Also, note that the parts of the product are saved in *high:low* format.

MUL - example

2 x 3 =6

Multiplier	Multiplicand	Product
M8/R8	al	ax
M16/R16	ax	dx:ax
M32/R32	eax	edx:eax
M64/R64	rax	rdx:rax


```
.data
var1  WORD 3000h
var2 WORD 100h

.code ; 16bit multiplication
mov ax,var1
mul var2 ; DX:AX = 00300000h, CF=1
```

CF=1 as DX contains non zero data

```
.data
var1 DWORD 3000h
var2 DWORD 100h

.code ; 32bit multiplication
mov eax,var1
mul var2 ; EDX:EAX = 0000000000300000h, CF=0
```

CF=0 as EDX is zero

IMUL – signed multiply

- ***imul*** is similar to ***mul***
- However:
  - It preserves the sign of the product by sign-extending it into the upper half of the destination register
  - It sets OF flag to '1' when the less significant register cannot store the result (including its sign)


```
.data
var1 BYTE 48 ; this is decimal
var2 BYTE 4  ; this is decimal

.code ; 8bit multiplication
mov al,var1
mul var2 ; AH:AL = 00C0h, OF=1
```

OF=1 as 8bits are not enough to hold the signed number $C0_{16}$ ($0\ 1100\ 0000_2$). A '0' is needed in AH to hold the sign

DIV (Unsigned Divide)

Divisor	Dividend	Quotient	Remainder
M8/R8	ax	al	ah
M16/R16	dx:ax	ax	dx
M32/R32	edx:eax	eax	edx
M64/R64	rdx:rax	rax	rdx


```
.code ; 16bit division
 mov dx,0h         ; clear dividend, high
 mov ax,8003h  ; dividend, low
 mov cx,100h     ; divisor
 div cx            ; AX = 0080h, DX = 3
```

```
.code ; 32bit division
 mov edx,0 ; clear dividend, high
 mov eax,8003h ; dividend, low
 mov ecx,100h ; divisor
 div ecx ; EAX = 0000 0080h, EDX = 3
```

Different Ways of writing Assembly

- There are 3 ways to write assembly
  - **Use Assembler**
    - It hard and time consuming
    - Best choice regarding performance
  - **Inline assembly (normally in C/C++)**
    - Very good choice regarding performance
    - However, different compilers use different syntax.
  - **Use Instrinsics from C/C++ as it is the most compatible language with assembly**
    - Much easier, no need to know assembly and deal with hardware details
    - Portable
    - Not all assembly instructions supported