COMP110: Principles of Computing

12: Machine Code

Worksheets

Worksheet 8

Due **today**!

Worksheet 9

Due **Monday 6th January 2020**!

Final hand-in

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- Viva sessions in January

FALMOUTH UNIVERSITY

How programs are executed

Executing programs

- CPUs execute **machine code**

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  - A **just-in-time (JIT) compiler** is halfway between the two — it compiles the program on-the-fly at runtime

Examples

Interpreted:

- Python
- Lua
- JavaScript (in old web browsers)
- Bespoke scripting languages

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NB: technically any language could appear in any column here, but this is where they typically are

Interpreter vs compiler

- Run-time efficiency: compiler $>$ interpreter

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Interpreter vs compiler

- Run-time efficiency: compiler > interpreter
  - The compiler translates the program **in advance**, on the developer's machine
  - The interpreter translates the program **at runtime**, on the user's machine — this takes extra time

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- Portability: compiler $<$ interpreter
  - A compiled program can only run on the operating system and CPU architecture it was compiled for
  - An interpreted program can run on any machine, as long as a suitable interpreter is available

Interpreter vs compiler

- Ease of development: compiler $<$ interpreter

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Interpreter vs compiler

- Ease of development: compiler $<$ interpreter
    - Writing an AOT or JIT compiler (especially a good one) is hard, and required in-depth knowledge of the target machine
    - Writing an interpreter is easy in comparison

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- Dynamic language features: compiler $<$ interpreter
  - The interpreter is already on the end user's machine, so programs can use it e.g. to dynamically generate and execute new code
  - The AOT compiler is not generally on the end user's machine, so this is more difficult

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Virtual machines

- Many modern interpreters and JIT compilers translate programs into **bytecode**
- Bytecode is essentially machine code for a **virtual machine (VM)**
- Translation from source code to bytecode can be done ahead of time
- At runtime, translate the bytecode (by interpretation or JIT compilation) into machine code for the physical machine
- E.g. a Java JAR file, a .NET executable, a Python .pyc or .pyo file all contain bytecode for their respective VMs

Assemblers

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- An ahead-of-time compile for assembly language is called an **assembler**
- Generally much simpler than an AOT compiler for a higher-level language

The 6502 CPU architecture

MOS Technology 6502

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Uses of the 6502

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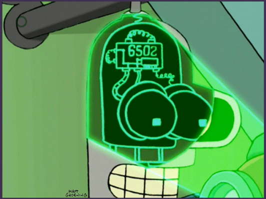

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Hex	Dec	Hex	Dec	Hex	Dec
00	0	10	16	F0	240
01	1	11	17	F1	241
⋮	⋮	⋮	⋮	⋮	⋮
09	9	19	25	F9	249
0A	10	1A	26	FA	250
0B	11	1B	27	FB	251
0C	12	1C	28	FC	252
0D	13	1D	29	FD	253
0E	14	1E	30	FE	254
0F	15	1F	31	FF	255

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- The **program counter (PC)** register stores the address of the next instruction to execute

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- PC = **program counter** register (16 bits)
- **Status** register, composed of seven 1-bit **flags**

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- An **assembler** translates assembly to machine code
  - I.e. an assembler is a "compiler" for assembly language
- Each CPU architecture has its own instruction set therefore its own assembly language

Our first assembly program

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```
LDA #$01
STA $0200
LDA #$05
STA $0201
LDA #$08
STA $0202
```

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Try it out! `http://skilldrick.github.io/easy6502/`

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- `$` denotes hexadecimal notation

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- Note that address is a **16-bit** number (2 bytes, 4 hex digits)

Our first assembly program

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STA $0200
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- Write the value of register A into memory address `0200` (hex)
- `STA` ("store accumulator") copies the value of register A into main memory
- Note that address is a **16-bit** number (2 bytes, 4 hex digits)
- In this emulator the display is "memory mapped", with 1 byte per pixel, starting from address `0200`
  - Real systems are usually more complicated than this!

Assembly to machine code

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A9 01
8D 00 02
A9 05
8D 01 02
A9 08
8D 02 02
```

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Note that the 6502 is **little endian**

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LDA  #$05
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Note that the 6502 is **little endian**

- In 16-bit values, the "low" byte comes before the "high" byte
- Intel x86 is also little endian

Looping

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INC $0200 ; add 1 to the value at address 0200
JMP $0600 ; jump back to beginning of program
```

- In this emulator the program always starts at address `0600`
  - This may **not** be the case on other 6502-based systems!

Labels

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start:
    INC $0200
    JMP start
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start:
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- `start` is essentially a constant with value `$0600`

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- Can add a **label** to a line of code, by giving a name followed by a colon
- Labels can then be used in instructions

```
start:
    INC  $0200
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```

- `start` is essentially a constant with value `$0600`
- The assembled code is exactly the same as for the previous slide

Conditional branching

Conditional branching

```
   LDX #$08       ; set X=8
decrement:
   DEX            ; subtract 1 from X
   STX $0200      ; store X in top left pixel
   CPX #$03       ; compare X to 3
   BNE decrement  ; if not equal, jump
   STX $0201      ; store X in next pixel
   BRK            ; halt execution
```

Conditional branching

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  LDX #$08        ; set X=8
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  DEX             ; subtract 1 from X
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  CPX #$03        ; compare X to 3
  BNE decrement   ; if not equal, jump
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  BRK             ; halt execution
```

$X = 8$
do
  $X = X - 1$
  $\text{memory}[0200] = X$
while $X \neq 3$
$\text{memory}[0201] = X$

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- However all of these can be implemented using branch instructions
- ... which is exactly how compilers implement them

Conditionals

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- Branching allows us to implement **if statements**

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```
    CPX #$01        ; compare X to 1
    BMI else        ; if X < 1, jump
    DEY             ; Y = Y - 1
    JMP end         ; skip over else block
else:
    INY             ; Y = Y + 1
end:
```

Conditionals

- Branching allows us to implement **if statements**

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  CPX #$01        ; compare X to 1
  BMI else        ; if X < 1, jump
  DEY             ; Y = Y - 1
  JMP end         ; skip over else block
else:
  INY             ; Y = Y + 1
end:
```

if $X \geq 1$ **then**

$Y = Y - 1$

else

$Y = Y + 1$

end if

Subroutines

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- `JSR` (jump to subroutine) works like `JMP`, but stores the current PC
- `RTS` (return from subroutine) jumps back to the instruction after the `JSR`
- These are used to implement **function calls**
- Return addresses are stored on a **stack**

Addressing modes

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- Immediate: `LDA #$42`

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- That `#` makes a big difference!

Addressing modes

- Immediate: `LDA #$42`
  - Load the literal value 42 (hex) into register A
- Absolute: `LDA $42`
  - Load the value stored at memory address 42 (hex) into register A
- That `#` makes a big difference!
- Note that these actually assemble to **different** CPU instructions

Indexed addressing

```
LDA $0200,X
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- Look up the value stored at memory address

$$\texttt{0200} + (\text{value of X register})$$

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Indexed addressing

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LDA $0200,X
```

- Look up the value stored at memory address

  $$\texttt{0200} + (\text{value of X register})$$

  and store it in A
- Can also do `LDA $0200,Y`
- ... but **only** `X` and `Y` registers can be used for indexed addressing

Indexed addressing

```
  LDX #0        ; X=0
loop:
  TXA           ; A=X
  STA $0200,X   ; store A to 0200+X
  INX           ; X++
  JMP loop      ; loop forever
```

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loop:
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- Why does it stop $\frac{1}{4}$ of the way down?

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```

- Why does it stop $\frac{1}{4}$ of the way down?
- Hint: it stops after filling 256 pixels...

FALMOUTH UNIVERSITY

Workshop