COMP110: Principles of Computing

12: Machine Code

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Worksheets

Worksheet 8

Due **today**!

Worksheet 9

Due **Monday 6th January 2020**!

Final hand-in

- You are required to make a **final submission** of all your worksheets by the **summative deadline**
- See MyFalmouth for the deadline
- Upload a zip containing all your worksheet submissions to LearningSpace
  - Worksheets 2 and 8: save the "review" of your quiz attempt as a PDF
  - All other worksheets: put the files from your GitHub submission into a folder
- **If** you have changed your work since opening a pull request, please include a README file detailing which worksheets you have changed!
- Viva sessions in January

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How programs are executed

Executing programs

- CPUs execute **machine code**
- Programs must be **translated** into machine code for execution
- There are three main ways of doing this:
  - An **interpreter** is an application which reads the program source code and executes it directly
  - An **ahead-of-time (AOT) compiler**, often just called a **compiler**, is an application which converts the program source code into executable machine code
  - 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

Compiled:

- C
- C++
- Swift
- Rust

JIT compiled:

- Java
- C#
- JavaScript (in modern web browsers)
- Jython

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
  - 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

Interpreter vs compiler

- 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
  - 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

Interpreter vs compiler

- 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

Interpreter vs compiler

- JIT compilers have similar pros/cons to interpreters
  - Runtime efficiency: JIT $>$ interpreter (e.g. code inside a loop only needs to be translated once, then can be executed many times)
  - Ease of development: JIT $<$ interpreter

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

- **Assembly language** is designed to translate directly into machine code
- An ahead-of-time compile for assembly language is called an **assembler**
- Generally much simpler than an AOT compiler for a higher-level language

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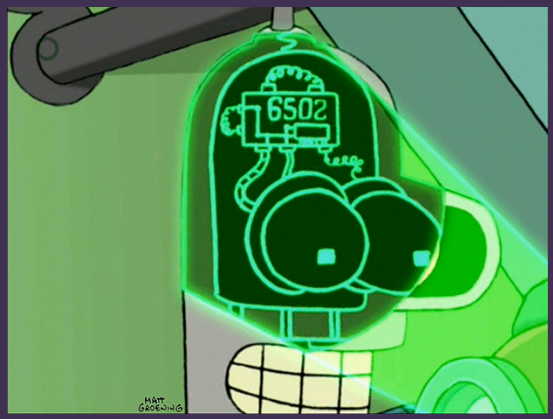
The 6502 CPU architecture

MOS Technology 6502

- Designed by Chuck Peddle and team at **MOS Technology**
- **8-bit** CPU, 16-bit addressing
- Clocked between **1MHz** and **3MHz**
- First produced in **1975**
- Still in production **today**

Uses of the 6502



Recap: hexadecimal notation

- We usually write numbers in **decimal** i.e. **base 10**
- Hexadecimal is **base 16**
- Uses extra digits:
  - `A`=10, `B`=11, ..., `F`=15

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

How a CPU works

- Executes a series of **instructions** stored in **memory**
- An instruction is stored as an **opcode** followed by 0 or more **arguments**
- CPU has several **registers**, each storing a single value
  - Memory locations inside the CPU
  - Faster to access than main memory
- Instructions can read and write values in **registers** and in **memory**, and can perform **arithmetic and logical** operations on them
- The **program counter (PC)** register stores the address of the next instruction to execute

Registers on the 6502

- 6502 is an **8-bit** CPU, meaning each register stores **8 bits** of data
  - 1 byte
  - A number between 0 and 255
- A = **accumulator**
- X, Y = **index** registers
- SP = **stack pointer** register
- PC = **program counter** register (16 bits)
- **Status** register, composed of seven 1-bit **flags**

Assembly language

- Translates **directly** to machine code
- I.e. 1 line of assembly = 1 CPU instruction
- 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

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

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

Our first assembly program

```
LDA #$01
```

- Store the value `01` (hexadecimal) into register A
- `LDA` ("load accumulator") stores a value in register A
- `#` denotes a literal number (as opposed to a memory address)
- `$` denotes hexadecimal notation

Our first assembly program

```
STA $0200
```

- 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

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

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

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

- PC normally **advances** to the next instruction
- Some instructions **modify** the PC
- E.g. `JMP` (jump) sets the PC to the specified address

```
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

- Don't use explicit jump locations in your code, it's not maintainable!
- 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
    JMP start
```

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

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
```

$X = 8$

do

$X = X - 1$

memory[0200] $= X$

while $X \neq 3$

memory[0201] $= X$

Conditional branching

- Assembly language does not have **structured programming** constructs such as if/else, switch/case, for, while, etc.
- However all of these can be implemented using branch instructions
- ... which is exactly how compilers implement them

Conditionals

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

```
  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

- `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

- 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
```

- Look up the value stored at memory address

  `0200` + (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
```

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

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