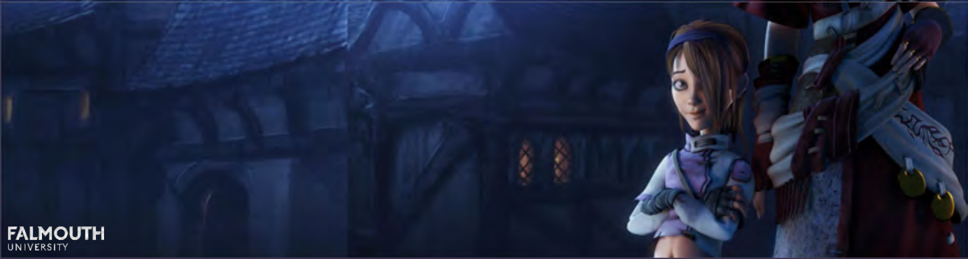
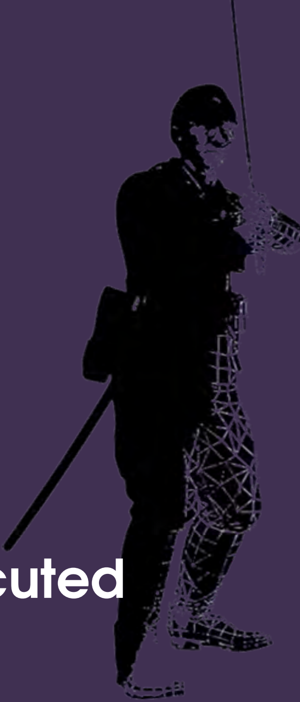


COMP110: Principles of Computing

12: Machine Code

Worksheets

- Worksheet 8 due **this Wednesday**
- Worksheet 9 due **in January**
- Summative submission of worksheets 1-9 due **in January** (check MyFalmouth for exact date!)
- Worksheet sign-off sessions **this week** and **4-6 January**



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
- Ruby
- Perl
- ~~JavaScript~~
- GML
- Bespoke scripting languages

Compiled:

- C
- C++
- Swift
- Rust
- Go
- Blueprints (via C++)

JIT compiled:

- Java
- C#
- JavaScript

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

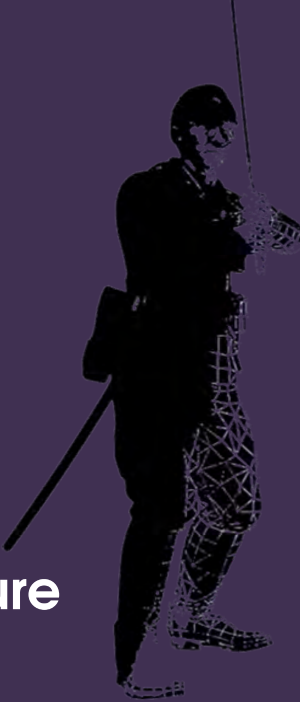
- JIT compilers have similar pros/cons to interpreters
  - Runtime efficiency: JIT $>$ interpreter (e.g. code inside a loop only needs to be translated once, then can be executed many times)
  - Ease of development: JIT $<$ interpreter

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

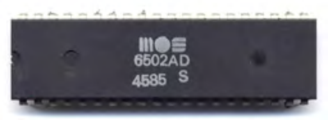
Assemblers

- **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



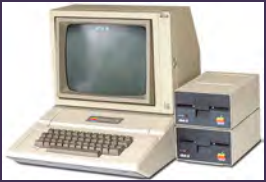
The 6502 CPU architecture

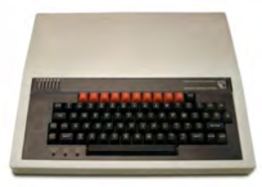
MOS Technology 6502

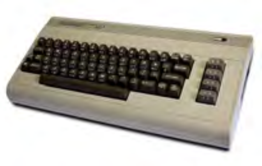


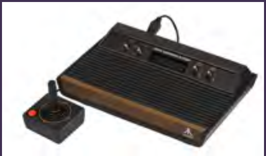
- Designed by Chuck Peddle and team at **MOS Technology**
- **8-bit** CPU, 16-bit addressing
- Clocked between **1MHz** and **3MHz**
- First produced in **1975**
- Still in production **today**

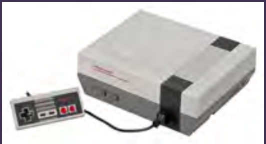
Uses of the 6502

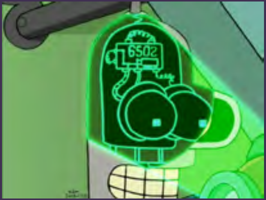












Recap: hexadecimal notation

- 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**
  - Includes information on the previous operation e.g. whether a calculation resulted in zero, negative, overflow...

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

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

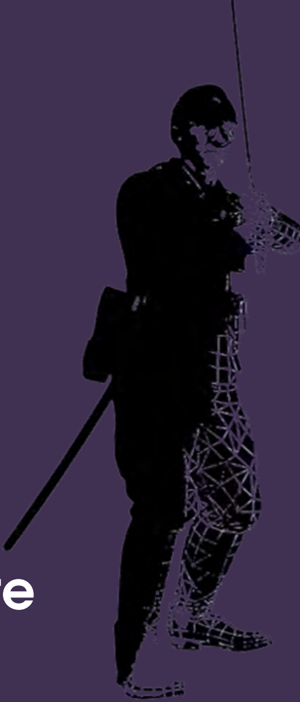
  $$\texttt{0200} + (\text{value of X register})$$

  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
```

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

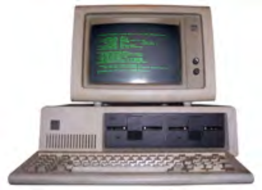


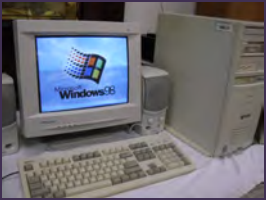
The x86 CPU Architecture

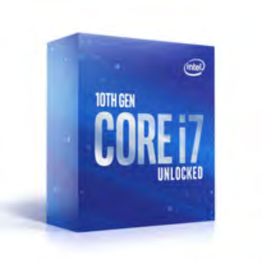
Intel x86

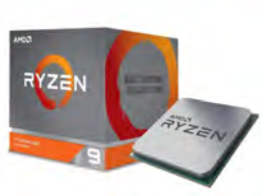
- Introduced in 1978 with the Intel 8086 (16-bit)
- Extended to 32-bit in 1985 with the Intel 80306
- Extended to 64-bit (x86-64 or x64) in 2003 with the AMD Opteron

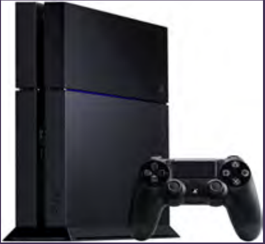
Uses of Intel x86

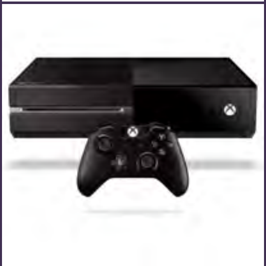










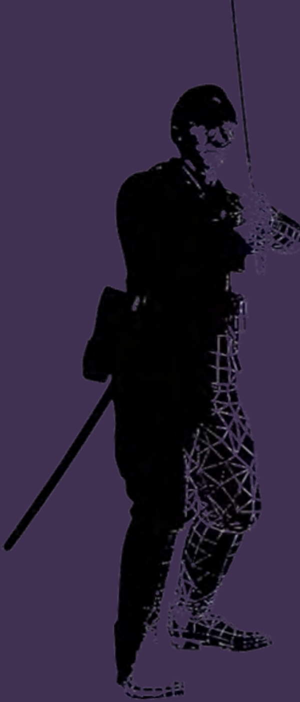


Backwards compatibility

- New CPUs have built upon the x86 instruction set over the years
- x86-64 includes 64, 32 and 16-bit instructions
- Technically, a PC from 2020 could run the same OS and software as the IBM 5150

Features of modern x86-64

- x87 floating point unit
  - Hardware support for IEEE754 floating point
- SIMD instructions
  - SIMD = Single Instruction, Multiple Data
  - E.g. one instruction to multiply 4 pairs of numbers in parallel
- Security features
  - AES encryption and decryption
  - Secure random number generation
- Multiple cores and hyperthreading
  - CPU can do more than one thing at once



RISC vs CISC

CISC

- x86 is what's known as a **CISC architecture**
- CISC = Complex Instruction Set Computer
- x86-64 has **thousands** of instructions

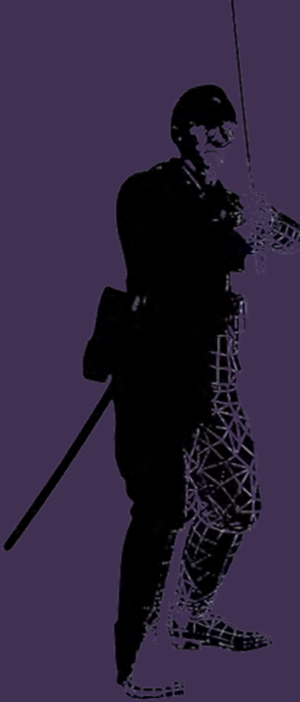
RISC

- RISC = Reduced Instruction Set Computer
- E.g. ARM (Advanced RISC Machine) architecture
- Widely used in mobile (Apple and Android)
- **Tens** or **hundreds** of instructions

RISC vs CISC

- CISC generally leads to **shorter programs** — CISC does more per instruction
- RISC generally leads to **simpler hardware** — instructions are simpler
- This also leads to better efficiency in terms of **power** and **heat**
- Assembly programmers and compiler developers need to worry about the difference — it is abstracted away from the rest of us
- Nowadays the main reason to use CISC is **backwards compatibility**
- Apple are moving to RISC for Mac computers — will PCs ever follow suit?

Workshop



Workshop

- Work through the Easy 6502 article/tutorial linked on LearningSpace
- Start work on Worksheet 9 (TIS-100)