COMP310: Legacy Game Systems

1: Assembly language

Learning outcomes

- **Explain** the historical significance of the 6502 CPU
- **Identify** the key components of the 6502 architecture
- **Read** and **write** simple programs in 6502 assembly language

Module introduction

Why Legacy Game Systems?

Why Legacy Game Systems?

- To better understand the **history** of videogame systems

Why Legacy Game Systems?

- To better understand the **history** of videogame systems
- To study low-level **machine architecture** without diving straight into complex modern architectures

Why Legacy Game Systems?

- To better understand the **history** of videogame systems
- To study low-level **machine architecture** without diving straight into complex modern architectures
- To make something under **constraints**:

Why Legacy Game Systems?

- To better understand the **history** of videogame systems
- To study low-level **machine architecture** without diving straight into complex modern architectures
- To make something under **constraints**:
  - Inspires **creativity**

Why Legacy Game Systems?

- To better understand the **history** of videogame systems
- To study low-level **machine architecture** without diving straight into complex modern architectures
- To make something under **constraints**:
  - Inspires **creativity**
  - Requires creative **problem solving**

Why Legacy Game Systems?

- To better understand the **history** of videogame systems
- To study low-level **machine architecture** without diving straight into complex modern architectures
- To make something under **constraints**:
  - Inspires **creativity**
  - Requires creative **problem solving**
  - Makes you a **better programmer**

Assignment 1: Constrained Development Task

Assignment 1: Constrained Development Task

- Design and implement a **de-make** of a well-known game

Assignment 1: Constrained Development Task

- Design and implement a **de-make** of a well-known game
- Your de-make must run on the **NES** and be written in **6502 assembly**

Assignment 1: Constrained Development Task

- Design and implement a **de-make** of a well-known game
- Your de-make must run on the **NES** and be written in **6502 assembly**
- **In week 3**: present a **proposal** and **Trello board**

Assignment 1: Constrained Development Task

- Design and implement a **de-make** of a well-known game
- Your de-make must run on the **NES** and be written in **6502 assembly**
- **In week 3**: present a **proposal** and **Trello board**
- **Tip**: scope carefully! Assembly programming is hard — keep it simple

Assignment 2: Research Journal

Assignment 2: Research Journal

- As a **group**, make the ultimate **NES programming wiki**

Assignment 2: Research Journal

- As a **group**, make the ultimate **NES programming wiki**
- **Tip**: use the wiki to record what you're already learning for your project. Don't leave it until the last minute!!!

FALMOUTH UNIVERSITY

The 6502 CPU architecture

MOS Technology 6502

MOS Technology 6502

- Designed by Chuck Peddle and team at **MOS Technology**

MOS Technology 6502

- Designed by Chuck Peddle and team at **MOS Technology**
- **8-bit** CPU, 16-bit addressing

MOS Technology 6502

- Designed by Chuck Peddle and team at **MOS Technology**
- **8-bit** CPU, 16-bit addressing
- Clocked between **1MHz** and **3MHz**

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**

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

Uses of the 6502

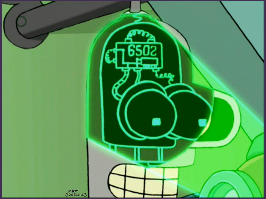
Uses of the 6502

Uses of the 6502

Uses of the 6502

Uses of the 6502

Uses of the 6502



Recap: hexadecimal notation

Recap: hexadecimal notation

- We usually write numbers in **decimal** i.e. **base 10**

Recap: hexadecimal notation

- We usually write numbers in **decimal** i.e. **base 10**
- Hexadecimal is **base 16**

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

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

How a CPU works

- Executes a series of **instructions** stored in **memory**

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**

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

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
- Instructions can read and write values in **registers** and in **memory**, and can perform **arithmetic and logical** operations on them

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
- 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

Registers on the 6502

- 6502 is an **8-bit** CPU, meaning each register stores **8 bits** of data

Registers on the 6502

- 6502 is an **8-bit** CPU, meaning each register stores **8 bits** of data
  - 1 byte

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

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**

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

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

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)

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

Assembly language

- Translates **directly** to machine code

Assembly language

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

Assembly language

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

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

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

Our first assembly program

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

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

Our first assembly program

```
LDA #$01
```

Our first assembly program

```
LDA #$01
```

- Store the value `01` (hexadecimal) into register A

Our first assembly program

```
LDA #$01
```

- Store the value `01` (hexadecimal) into register A
- `LDA` ("load accumulator") stores a value in register A

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)

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

Our first assembly program

```
STA $0200
```

Our first assembly program

```
STA $0200
```

- Write the value of register A into memory address `0200` (hex)

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

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)

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`
  - This may **not** be the case on other 6502-based systems!

Assembly to machine code

Assembly to machine code

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

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
```

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**

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 "high" byte comes before the "low" byte

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 "high" byte comes before the "low" byte
- Intel x86 is also little endian

Looping

Looping

- PC normally **advances** to the next instruction

Looping

- PC normally **advances** to the next instruction
- Some instructions **modify** the PC

Looping

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

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
```

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

Labels

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

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

- 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

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
```

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`

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

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

```
  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

Conditional branching

- Assembly language does not have **structured programming** constructs such as if/else, switch/case, for, while, etc.

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

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

Subroutines

Subroutines

- `JSR` (jump to subroutine) works like `JMP`, but stores the current PC

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`

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**

Addressing modes

Addressing modes

- Immediate: `LDA #$42`

Addressing modes

- Immediate: `LDA #$42`
  - Load the literal value 42 (hex) into register A

Addressing modes

- Immediate: `LDA #$42`
  - Load the literal value 42 (hex) into register A
- Absolute: `LDA $42`

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

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!

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
```

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

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`

Indexed addressing

```
LDA $0200,X
```

- Look up the value stored at memory address

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

  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
```

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?

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...

Next steps

Next steps

- **Work through** the tutorials on `http://skilldrick.github.io/easy6502/`

Next steps

- **Work through** the tutorials on `http://skilldrick.github.io/easy6502/`
- **Understand** and try to **modify** the Snake game code