COMP110: Principles of Computing

10: Machine Architecture

Learning outcomes

- **Explain** the difference between interpretation, just-in-time compilation and ahead-of-time compilation
- **Describe** how common high-level code structures translate to machine code
- **Explain** how floating-point numbers are represented in the computer

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

The MIPS architecture

MIPS

- An example of a **Reduced Instruction Set Computer (RISC)** architecture
  - Small number of simple instructions — computational power comes from executing many instructions per second
  - Compare with **Complex Instruction Set Computer (CISC)** architecture (e.g. Intel x86) — large number of complex instructions — fewer instructions per second, but shorter programs
- MIPS was popular in 1980s – 2000s
  - Embedded systems
  - Consoles (Nintendo 64, PlayStation 1 and 2)
- Easier to understand than most CPU instruction sets in common use today

Online MIPS simulator

`http://rivoire.cs.sonoma.edu/cs351/wemips/`

Registers

- Memory locations inside the CPU
- Faster to access than main memory
- Registers in MIPS architecture include:
  - **`$zero`**: constant 0
  - **`$t0–$t9`**: temporary storage
  - **`$s0–$s7`**: saved temporary storage
- Each register holds a single 32-bit value

Adding register values

```
add $d, $s, $t
```

- `$d`, `$s` and `$t` are register names
- This adds the value of `$s` to the value of `$t`, and stores the result in `$d`

```
sub $d, $s, $t
```

- Subtracts the value of `$t` from the value of `$s`, and stores the result in `$d`

Adding a constant

```
addi $d, $s, C
```

- **`$d`** and **`$s`** are register names, `c` is an integer constant
- This adds the value of **`$s`** to `c`, and stores the result in **`$d`**
- **`addi`** = “add immediate” — as in `c` is specified immediately in the code, not looked up from a register
- There is no **`subi`** instruction — to subtract `c`, add `-c`

More fun with addi

- Socrative `FALCOMPED`
- What does this code do?

```
addi $s0, $s1, 0
```

- What does this code do?

```
addi $s0, $zero, 12
```

- MIPS does not have dedicated instructions for setting a register value to a constant or to the value of another register — it has to be done with **`addi`**

Control flow in MIPS

Labels and jumping

- In assembly code, can set a **label** on any line:

```
MyLabel: add $s0, $s1, 1
```

- Some instructions use labels to refer to a location in the code
- E.g. the `j` instruction simply jumps (backwards or forwards) to the specified line:

```
j MyLabel
```

Branching

- **Branching** is **conditional jumping**

```
beq $s, $t, Label
```

- This jumps to `Label` **if and only if** the value of `$s` equals the value of `$t`

```
bne $s, $t, Label
```

- This jumps to `Label` **if and only if** the value of `$s` does not equal the value of `$t`

Conditionals

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

```
if s0 != 0:
    s1 += 1
else:
    s2 += 1
```

```
beq $s0, $zero, Else
addi $s1, $s1, 1
j End
Else: addi $s2, $s2, 1
End:
```

Loops

- Branching allows us to implement **while loops**

```
i = 0
total = 0
limit = 10

while i != limit:
    total += i
    i += 1
# end while
```

```
addi $s0, $zero, 0
addi $s1, $zero, 0
addi $s2, $zero, 10

Loop: beq $s0, $s2, LoopEnd
add $s1, $s1, $s0
addi $s0, $s0, 1
j Loop
LoopEnd:
```

Exercise

Write a piece of Python code equivalent to the following:

```
addi $s0, $zero, 10
addi $s1, $zero, 0

Loop: beq $s0, $zero, LoopEnd
add $s1, $s1, $s0
addi $s0, $s0, -1
j Loop
LoopEnd:
```

Not quite a while loop

- Socrative `FALCOMPED`
- What is the difference between these two programs?
- (NB: assume **`$s0`** ≥ 0)

```
addi $s1, $zero, 0

Loop: beq $s0, $zero, ↩
    LoopEnd
add $s1, $s1, $s0
addi $s0, $s0, -1
j Loop
LoopEnd:
```

```
addi $s1, $zero, 0

Loop: add $s1, $s1, $s0
addi $s0, $s0, -1
bne $s0, $zero, Loop
```

The code on the right implements a **do-while** loop (which Python doesn't have, but other languages do)

Function calls

- Function calls can be implemented using the jump instruction:
  - To call the function: save the address of the instruction after the current one, then jump to the function
  - To return from the function: jump to the previously saved address
- MIPS has `jal` and `jr` instructions and `$ra` register for this purpose
- Socrative `FALCOMPED`: why save the return address? Why not just hard-code it into the program?
- Nested function calls require a **stack** of return addresses

MIPS machine code

MIPS instructions

- Each line of MIPS assembly code can be translated into a **machine code instruction**
- 1 line of assembly = 1 instruction
- Each instruction is a **32 bit** value
- First 6 bits specify the **opcode**; how the remaining 26 bits are interpreted depends on which opcode it is

Anatomy of an instruction

R-type instruction:

opcode	\$s	\$t	\$d	shift	function
6 bits	5 bits	5 bits	5 bits	5 bits	6 bits

- **opcode** and **function** together specify the operation to execute
  - E.g. **`add`** has opcode `000000` and function `100000`
  - E.g. **`sub`** has opcode `000000` and function `100010`
- Some instructions specify a **shift** amount
  - For **`add`** **`sub`** etc these 5 bits are ignored
- Registers are identified by a 5-bit number
  - E.g. **`$zero`** → `00000`, **`$s0`** → `01000`, **`$s1`** → `01001`
  - There are 32 registers

Example

```
add $s0, $s0, $s1
```

↓

```
opcode   s     t     d    shift function
000000 01000 01001 01001 00000 100000
```

Anatomy of an instruction

I-type instruction:

opcode	\$s	\$t	C
6 bits	5 bits	5 bits	16 bits

- **opcode** specifies the operation to execute
  - E.g. **`addi`** has opcode `001000`
- `c` is specified as a 16-bit number

Example

```
addi $s0, $s1, 123
```

↓

```
opcode   s     t             C
001000 01001 01000 0000000001111011
```

Anatomy of an instruction

J-type instruction:

opcode 6 bits	address 26 bits

- **opcode** specifies the operation to execute
  - E.g. `J` has opcode `000010`
- **address** is specified as a 26-bit number

Representing numbers

Powers of 10

$$10^6 = 1\underbrace{000000}_{\text{6 zeroes}}$$

$$10^1 = 10$$

$$10^0 = 1$$

$$10^{-1} = 0.1$$

$$10^{-6} = 0.\underbrace{00000}_{\text{5 zeroes}}1$$

Scientific notation

- A way of writing **very large** and **very small** numbers
- $a \times 10^b$, where
  - a ($1 \leq |a| < 10$) is the **mantissa**
  - (a is a positive or negative number with a single non-zero digit before the decimal point)
  - b (an integer) is the **exponent**
- E.g. 1 light year = 9.461×10^{15} metres
- E.g. Planck's constant = 6.626×10^{-34} joules
- Socrative `FALCOMPED`

Scientific notation in code

Instead of writing $\boxed{\times 10}$, write `e` (no spaces)

```
lightYear = 9.461e15
plancksConstant = 6.626e-34
```

Floating point numbers

- Similar to scientific notation, but **base 2** (binary)
- $\pm\text{mantissa} \times 2^{\text{exponent}}$
- Sign is stored as a single bit: $0 = +$, $1 = -$
- Mantissa is a binary number with a 1 before the point; only the digits after the point are stored
- Exponent is a signed integer, stored with a **bias**

IEEE 754 floating point formats

Type	Sign	Exponent	Mantissa	Total
Single precision	1 bit	8 bits	23 bits	32 bits
Double precision	1 bit	11 bits	52 bits	64 bits

Exponent is stored with a **bias**:

- Single precision: store exponent $+ 127$
- Double precision: store exponent $+ 1023$

- Python uses double precision
- Other languages have `float` (single) and `double` types

Example

`0 10000001 10100000000000000000000`

- Exponent: $129 - 127 = 2$
- Mantissa: binary 1.101
- $1 + \frac{1}{2} + \frac{1}{8} = 1.625$
- $1.625 \times 2^2 = 6.5$
- Alternatively: $1.101 \times 2^2 = 110.1$
- $= 4 + 2 + \frac{1}{2} = 6.5$

Socrative `FALCOMPED`

What is the value of this number expressed in IEEE 754 single precision format?

```
0 01111100 10011000000000000000000
```

You have **5 minutes**, and you **may** use a calculator! (Unless your calculator does IEEE 754 conversion...)

Precision of floating point numbers

- Precision **varies** by **magnitude**
- Numbers near 0 can be stored more accurately than numbers further from 0
- Analogy: in scientific notation with 3 decimal places
  - Around 3.142×10^0: can represent a difference of 0.001
  - Around 3.142×10^3: can represent a difference of 1
  - Around 3.142×10^6: can represent a difference of 1000

Range of floating point numbers

Type	Smallest value	Largest value
Single precision	$\pm 1.175 \times 10^{-38}$	$\pm 3.403 \times 10^{38}$
Double precision	$\pm 2.225 \times 10^{-308}$	$\pm 1.798 \times 10^{308}$

Rounding errors

- Many numbers cannot be represented exactly in IEEE float
  - Similar to how decimal notation cannot exactly represent $\frac{1}{3} = 0.3333333\ldots$ or $\frac{1}{7} = 0.142857\ldots$
- Decimal: can represent $\frac{a}{b}$ exactly iff $b = 2^m 5^n$
- Binary: can represent $\frac{a}{b}$ exactly iff $b = 2^n$
- In particular, IEEE float can't represent $\frac{1}{10} = 0.1$ exactly!
- This can lead to **rounding errors** with some calculations
  - E.g. according to Python, $0.1 + 0.2 - 0.3 = 5.551 \times 10^{-17}$

Testing for equality

- Due to rounding errors, using `==` or `!=` with floating point numbers is almost always a bad idea
- E.g. in Python, `0.1 + 0.2 == 0.3` evaluates to `False`
- Better to check for **approximate equality**: calculate the difference between the numbers, and check that it's smaller than some threshold

```
THRESHOLD = 1e-5
def is_approx_equal(a, b):
    return abs(b - a) < THRESHOLD
```

Decimal types

- Python (and other languages) provide a `decimal` type
- Uses base 10 rather than base 2, so avoids some of the gotchas with IEEE float
- ... however not natively supported by the CPU, hence much slower