COMP110: Principles of Computing

9: Compilers and interpreters

Learning outcomes

- **Explain** the difference between interpretation, just-in-time compilation and ahead-of-time compilation
- **Distinguish** the basic parts of a compilation pipeline and recall how they operate
- **Describe** how common high-level code structures translate to machine code

Worksheet E

- Compilers and machine code
- Due in class on **Monday 21st November** (next week)

Final worksheet submission

- Soon!!! (see MyFalmouth)
- Should be easy: "Download Zip" from GitHub, rename, upload to LearningSpace
- If any of your work is **not** on GitHub (e.g. images on imgur), be sure to **add it to the zip**!
  - Exception: SpaceChem **videos** can stay as YouTube links
- Even if you have submitted everything on time via GitHub, **late submission** to LearningSpace will have the standard penalty for late submission (40% cap)!

How programs are executed

Executing programs

- CPUs execute **machine code**

Executing programs

- CPUs execute **machine code**
- Programs must be **translated** into machine code for execution

Executing programs

- CPUs execute **machine code**
- Programs must be **translated** into machine code for execution
- There are three main ways of doing this:

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

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

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

Examples

Interpreted:

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

Compiled:

- C
- C++
- Swift

Examples

Interpreted:

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

Compiled:

- C
- C++
- Swift

JIT compiled:

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

Examples

Interpreted:

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

Compiled:

- C
- C++
- Swift

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

Interpreter vs compiler

- Run-time efficiency: compiler $>$ interpreter
  - The compiler translates the program **in advance**, on the developer's machine

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

Interpreter vs compiler

- Portability: compiler $<$ interpreter
  - A compiled program can only run on the operating system and CPU architecture it was compiled for

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

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

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

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

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

Interpreter vs compiler

- JIT compilers have similar pros/cons to interpreters

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)

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

Virtual machines

- Many modern interpreters and JIT compilers translate programs into **bytecode**

Virtual machines

- Many modern interpreters and JIT compilers translate programs into **bytecode**
- Bytecode is essentially machine code for a **virtual machine (VM)**

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

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

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

Assemblers

- **Assembly language** is designed to translate directly into machine code

Assemblers

- **Assembly language** is designed to translate directly into machine code
- An ahead-of-time compile for assembly language is called an **assembler**

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 C++ build process

Preprocessor

The C++ build process

Preprocessor

- Handles **header inclusion**, **macro expansion** and **conditional compilation**

The C++ build process

Preprocessor

- Handles **header inclusion**, **macro expansion** and **conditional compilation**
- Outputs modified C++ source code

The C++ build process

Preprocessor

- Handles **header inclusion**, **macro expansion** and **conditional compilation**
- Outputs modified C++ source code

Compiler

The C++ build process

Preprocessor

- Handles **header inclusion**, **macro expansion** and **conditional compilation**
- Outputs modified C++ source code

Compiler

- Translates each source file into an **object file** containing machine code

The C++ build process

Preprocessor

- Handles **header inclusion**, **macro expansion** and **conditional compilation**
- Outputs modified C++ source code

Compiler

- Translates each source file into an **object file** containing machine code
- May be configured to **optimise** code (e.g. calculate constant values, expand inline functions, re-order instructions to take advantage of CPU architecture, etc.)

The C++ build process

Preprocessor

- Handles **header inclusion**, **macro expansion** and **conditional compilation**
- Outputs modified C++ source code

Compiler

- Translates each source file into an **object file** containing machine code
- May be configured to **optimise** code (e.g. calculate constant values, expand inline functions, re-order instructions to take advantage of CPU architecture, etc.)

Linker

The C++ build process

Preprocessor

- Handles **header inclusion**, **macro expansion** and **conditional compilation**
- Outputs modified C++ source code

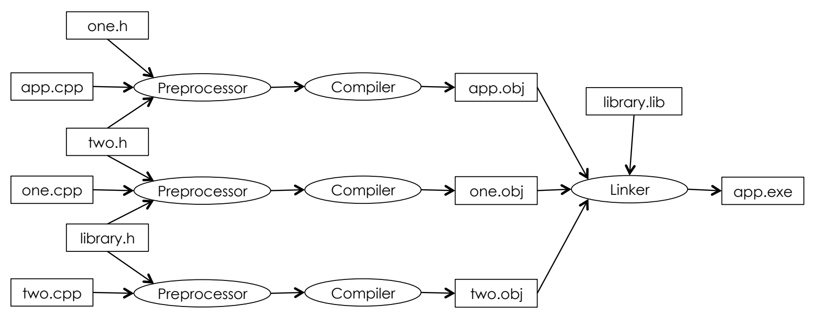
Compiler

- Translates each source file into an **object file** containing machine code
- May be configured to **optimise** code (e.g. calculate constant values, expand inline functions, re-order instructions to take advantage of CPU architecture, etc.)

Linker

- Combines the object files together with any external libraries to produce an **executable** (on Windows, a .exe file)

The C++ build process



The MIPS architecture

MIPS

MIPS

- An example of a **Reduced Instruction Set Computer (RISC)** 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

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

- 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

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

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)

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

Registers

- Memory locations inside the CPU

Registers

- Memory locations inside the CPU
- Faster to access than main memory

Registers

- Memory locations inside the CPU
- Faster to access than main memory
- Registers in MIPS architecture include:

Registers

- Memory locations inside the CPU
- Faster to access than main memory
- Registers in MIPS architecture include:
  - `$zero`: constant 0

Registers

- Memory locations inside the CPU
- Faster to access than main memory
- Registers in MIPS architecture include:
  - `$zero`: constant 0
  - `$t0`–`$t9`: temporary storage

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

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

Adding register values

```
ADD $d, $s, $t
```

Adding register values

```
ADD $d, $s, $t
```

- `$d`, `$s` and `$t` are register names

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`

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
```

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

Adding a constant

```
ADDI $d, $s, C
```

Adding a constant

```
ADDI $d, $s, C
```

- `$d` and `$s` are register names, `C` is an integer constant

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`

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

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

More fun with ADDI

- Socrative `FALCOMPED`

More fun with ADDI

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

```
ADDI $s0, $s1, 0
```

More fun with ADDI

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

```
ADDI $s0, $s1, 0
```

- What does this code do?

```
ADDI $s0, $zero, 12
```

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

Labels and jumping

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

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

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

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

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

Branching

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

```
BEQ $s, $t, Label
```

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`

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
```

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

Conditionals

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

Conditionals

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

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

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

Loops

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

Loops

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

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

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

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 $\geq$ 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
```

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

- Function calls can be implemented using the jump instruction:

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

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

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

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?

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

MIPS instructions

- Each line of MIPS assembly code can be translated into a **machine code instruction**

MIPS instructions

- Each line of MIPS assembly code can be translated into a **machine code instruction**
- 1 line of assembly = 1 instruction

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

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

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

Anatomy of an instruction

R-type instruction:

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

- **opcode** and **function** together specify the operation to execute

Anatomy of an instruction

R-type instruction:

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

- **opcode** and **function** together specify the operation to execute
  - E.g. `ADD` has opcode `000000` and function `100000`

Anatomy of an instruction

R-type instruction:

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

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

Anatomy of an instruction

R-type instruction:

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

Anatomy of an instruction

R-type instruction:

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

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`

Anatomy of an instruction

R-type instruction:

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

Anatomy of an instruction

I-type instruction:

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

Anatomy of an instruction

I-type instruction:

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

- **opcode** specifies the operation to execute

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`

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

Anatomy of an instruction

J-type instruction:

opcode 6 bits	address 26 bits

Anatomy of an instruction

J-type instruction:

opcode 6 bits	address 26 bits

- **opcode** specifies the operation to execute

Anatomy of an instruction

J-type instruction:

opcode	address
6 bits	26 bits

- **opcode** specifies the operation to execute
  - E.g. `J` has opcode `000010`

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