

Compiled and interpreted languages

Troels Henriksen

How computers execute code

Compiled and interpreted languages

Tombstone diagrams

Learning Objectives

Today is very practical! ...hopefully you will be convinced of this before we are done.

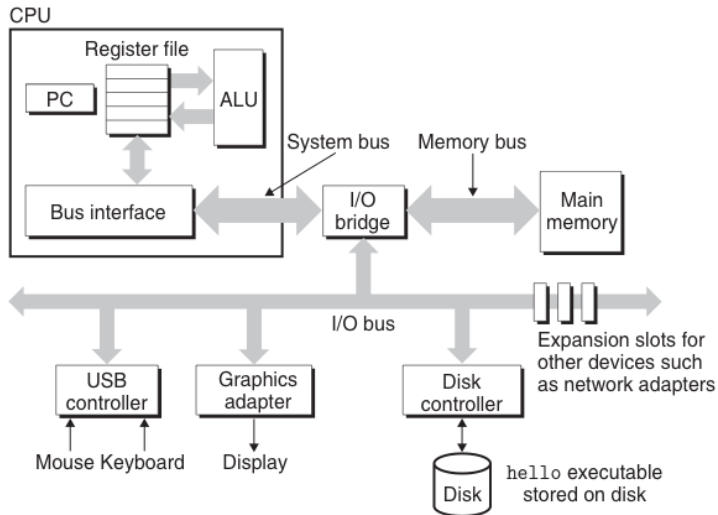
Main Things You Should Understand At The End

- Why are some languages considered faster than others?
- How do we compare runtime performance?
- What are compiled and interpreted languages?
- How can they be combined, and why would we want to do that?
- Is there a model we can use for reasoning about compilers, interpreters, and machines?

We will simplify a lot today!

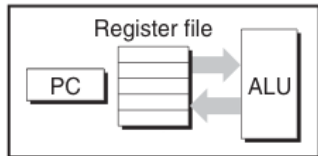
- Pretty much all of my observations could have a *yes, but in edge cases...* followup.

The role of the processor



- Central processing unit (CPU).
- Reads data from memory, operates on it, writes it back.
- Also sends commands to other parts of the computer (e.g. IO).

How the CPU works—conceptually and physically



- Data is stored in a small set of fixed-size *registers*.
 - ▶ Imagine a fixed collection of named variables.
 - ▶ RISC-V has 32 registers, each store 32 bits.
- Register contents sent to *Arithmetic-Logical Unit* to perform small operations.
 - ▶ “Interpret these two register contents as integers and add the second to the first.”
 - ▶ Others instructions copy data between registers and memory.
 - ▶ *Instructions modify the machine state.*

do forever:

```
instr = memory[PC]           # Fetch instruction
executeInstruction(instr)    # Execute instruction
PC += 1                      # Go to next instruction
```

- *Program counter* (PC) stores address of currently executing instruction.
- Implement control flow by manipulating PC.

RISC-V registers

```
int x0, x1, x2, x3, x4, x5, x6, x7;  
int x8, x9, x10, x11, x12, x13, x14, x15;  
int x16, x17, x18, x19, x20, x21, x22, x23;  
int x24, x25, x26, x27, x28, x29, x30, x31;
```

- Imagine programming where these are all the variables you have available.
- No function parameters either.
- RISC-V assembly for adding numbers stored in registers x10, x11, x12:

```
add x10, x10, x11  # x10 = x10 + x11  
add x10, x10, x12  # x10 = x10 + x12
```

[https://www.cs.cornell.edu/courses/cs3410/2019sp/riscv/
interpreter/](https://www.cs.cornell.edu/courses/cs3410/2019sp/riscv/interpreter/)

Machine instructions

CPUs can have thousands of instructions.¹

- (RISC-V is a bit simpler.)
- All are encoded as bits and can be interpreted as numbers.
- For RISC-V, always four bytes per instruction.

Instruction	Encoding in hex
add x1, x2, x3	00 31 00 b3
add x4, x5, x6	00 62 72 33
lw x7, 10(x4)	00 a2 23 83

- Different architectures have *different instructions, different registers, and different encodings*.
- Most are *conceptually* similar, but differ in specifics.

¹[https:](https://stefanheule.com/blog/how-many-x86-64-instructions-are-there-anyway/)

Structured control flow as jumps

- Some instructions modify the program counter.
- These are used to implement control flow.

C code

```
if (x < 0) {  
    x = 0;  
}
```

RISC-V assembly

```
bne x0, x8, L2  # Jump if x0 != x8  
addi x8, x0, x0 # x8 = x0 + x0  
.L2:  
...
```

- Instructions like `bne` set PC, which changes which instruction is read next.
- Labels like `L2` are just for humans.
 - ▶ The actual encoding of `bne` contains a byte offset to be added to PC.

Loops as jumps

C code

```
while (a > 0) {  
    a -= 1;  
    b += 1;  
}
```

RISC-V assembly

```
j .L2          ; Jump to L2  
.L3:  
subi x8, x8, 1 ; x -= 1  
addi x9, x9, 1 ; y += 1  
.L2:  
blt x0, x8, L3 ; Jump if x0 < x8
```

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```

We can also write this in C.

```
    goto L2;  
L3: a -= 1;  
    b += 1;  
L2: if (a > 0) goto L3;
```

Function calls at the assembly level

The CPU has no idea what a function is.

- **How a function call works at assembly level.**

1. Jump somewhere by modifying PC.
2. Run instructions from there.
3. One of those will jump back to just after the instruction that did step 1.

- **Questions that must be answered:**

1. How does a function know where to “jump back”?
 - ▶ I.e. the address of the calling instruction.
2. How do we avoid clobbering the registers in use by the caller?
 - ▶ Registers are a bit like programming exclusively with global variables—all functions use the same ones.

The stack to the rescue

Conceptually

- A stack is a data structure on which we can *push* and *pop* values at the top.
- **Before calling a function:**
 - ▶ Push values of all registers to the stack.
 - ▶ Push address of calling instruction.
 - ▶ Now function will know where to jump back to!
- **After returning from function:**
 - ▶ Restore registers by popping them from stack.
- Important that function never pops more than it pushed.

Actually

- The stack is just normal memory, with the *stack pointer* (SP) being a register dedicated to storing address of stack top.

- **Pushing x to the stack:**

`mem[SP] = x;`

`SP--;`

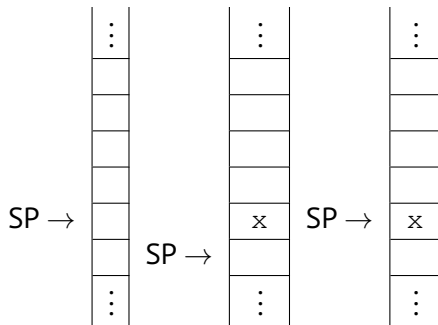
- **Popping x from stack:**

`SP++;`

`x = mem[SP];`

Original After push After pop

High addresses



Low addresses

Takeaways

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- CPUs execute instructions in sequence.
 - ▶ Instructions are stored in memory.
- An instruction modifies the machine state.
 - ▶ May also cause execution to jump elsewhere.
- Must move data from memory into registers to operate on them.
 - ▶ Registers are a very scarce resource.
- **Writing assembly code by hand is extremely tedious and completely impractical for all but the smallest programs.**
 - ▶ *Compilers* convert high-level languages to machine code.

How computers execute code

Compiled and interpreted languages

Tombstone diagrams

Roughly two kinds of languages

Compiled languages are transformed to machine code before execution (e.g. C)

Interpreted languages are run directly by a software *interpreter* (e.g. Python).

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Pedantic disclaimer

Compilation/interpretation is strictly a property of *implementations*, not *languages*.

- You could have a C interpreter or Python compiler.
- But most (not all!) languages are built with a specific implementation technique in mind.
- A few languages (Lisp, JavaScript) have lots of *very* different implementations...

We teach you the big picture—the details are always more complicated in practice!

Tradeoffs

- Compiled languages
 - + Almost always faster.
 - Require compilation after every change.
 - Usually cannot run program fragments in isolation.
 - Tend to have more restrictions (e.g. static typing).
 - Much more difficult to implement.

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Let us look at the scale of the overhead.

The Collatz conjecture

$$f(n) = \left\{ \begin{array}{ll} \frac{n}{2} & \text{if } n \text{ is even} \\ 3n + 1 & \text{if } n \text{ is odd} \end{array} \right\}$$

- **Conjecture:** if we apply this function to some number greater than 1, we will eventually reach 1.
- To disprove this conjecture, we only need *a single counter-example* that goes into a cycle instead.
- People write programs to investigate the behaviour of this sequence.
 - ▶ Especially if you are not good at number theory.

Listing 1: collatz.py

```
import sys

def collatz(n):
    i = 0
    while n != 1:
        if n % 2 == 0:
            n = n // 2
        else:
            n = 3 * n + 1
        i = i + 1
    return i

k = int(sys.argv[1])
for n in range(1, k):
    print(n, collatz(n))
```

Listing 2: collatz.c

```
#include <stdio.h>
#include <stdlib.h>

int collatz(int n) {
    int i = 0;
    while (n != 1) {
        if (n % 2 == 0) {
            n = n / 2;
        } else {
            n = 3 * n + 1;
        }
        i++;
    }
    return i;
}

int main(int argc, char** argv) {
    int k = atoi(argv[1]);
    for (int n = 1; n < k; n++) {
        printf("%d %d\n", n, collatz(n));
    }
}
```

Benchmarking collatz.py

```
$ time python3 ./collatz.py 100000 >/dev/null
```

```
real    0m1.368s
```

```
user    0m1.361s
```

```
sys     0m0.007s
```

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$$\text{Speedup: } \frac{1.368}{0.032} = 42.75$$

Combining interpretation and compilation

- Interpreted languages can be fast when
 - ▶ Most of the run-time is spent waiting data from files or network
 - ▶ They mostly call functions written in faster compiled languages
- **Best of both worlds:** flexibility of interpretation and speed of C

Different ways to compile

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To executable program `collatz`

```
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- Can be run directly

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To object file `collatz.o`

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- Can be *linked* with other object files
- Can be processed further

Different ways to compile

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```

- Can be run directly

To object file `collatz.o`

```
$ gcc collatz.c -c -o collatz.o
```

- Can be *linked* with other object files
- Can be processed further

To shared object file `libcollatz.so`

```
$ gcc collatz.c -fPIC -shared -o libcollatz.so
```

- Can be linked *at run-time* by a running program
- How compiled programs support dynamic “plug-ins”

All output files contain fully compiled machine code.

Calling C from Python

Compiling C program to shared library

```
$ gcc collatz.c -fPIC -shared -o libcollatz.so
```

Listing 3: collatz-ffi.py

```
import ctypes
import sys

c_lib = ctypes.CDLL('./libcollatz.so')

k = int(sys.argv[1])
for n in range(1, k):
    print(n, c_lib.collatz(n))
```

```
$ time python3 ./collatz-ffi.py 100000 >/dev/null
```

```
real    0m0.165s
```

```
user    0m0.163s
```

```
sys      0m0.003s
```

Speedup: $\frac{1.368}{0.165} = 8.2$

```
$ time python3 ./collatz-ffi.py 100000 >/dev/null
```

```
real    0m0.165s
user    0m0.163s
sys     0m0.003s
```

Speedup: $\frac{1.368}{0.165} = 8.2$

- Slower than pure C by about $5\times$.
- Faster if we made fewer “foreign” calls, but each took more time.
- Ideal case is single foreign function call that operates on many values.
- **This is exactly how NumPy works!**

NumPy performance

```
def f_python(v):  
    for i in range(len(v)):  
        v[i] = v[i]*2 + 3
```

```
def f_numpy(v):  
    return v * 2 + 3
```

Size of v	f_python	f_numpy	Difference
1	0.01ms	0.01ms	0.9×
10	0.01ms	0.01ms	1.4×
100	0.1ms	0.01ms	13.3×
1000	0.98ms	0.01ms	95.3×
10000	9.96ms	0.05ms	190.7×
100000	98.59ms	0.41ms	240.7×

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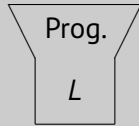
Tombstone diagrams

Now a high-level view

- We've looked at some technical details of compilers and interpreters
- Do we also have a high-level model?

Tombstone diagrams

A program written in L

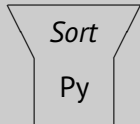


Tombstone diagrams

A program written in L



Example of program written in Python



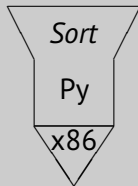
A machine that runs L programs



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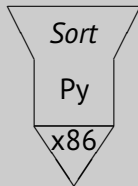
Example



A machine that runs L programs



Example



Incorrect! Languages (Python and x86) do not match!

An interpreter for F , written in T

F

T

An interpreter for F , written in T

F

T

Example

Sort

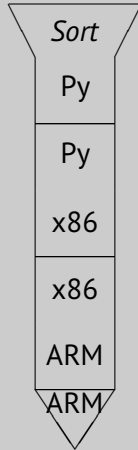
Py

Py

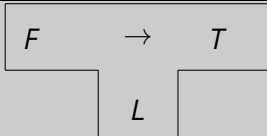
x86

x86

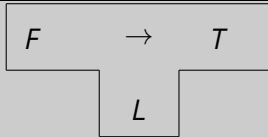
Stacking interpreters



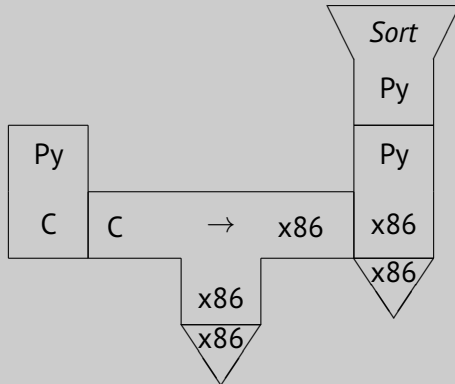
A compiler from F to T , written in L



A compiler from F to T , written in L



Example



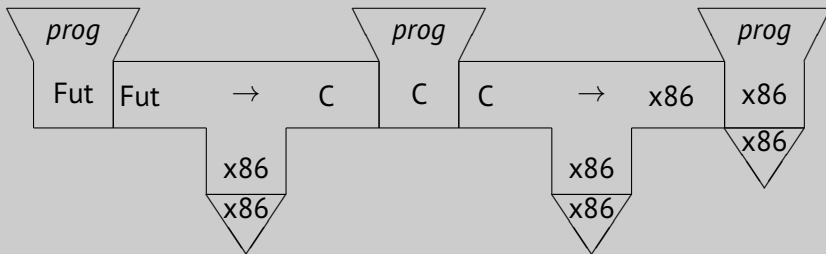
Compilers can be chained

Futhark \rightarrow C \rightarrow machine code

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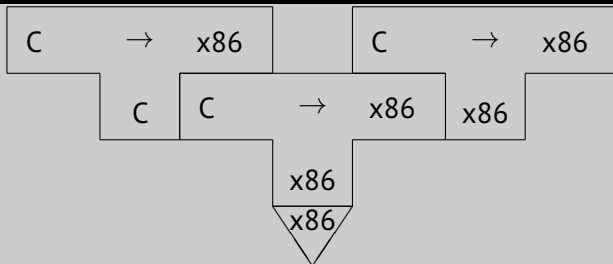
Example



Compilers are also programs

- A C compiler is usually written in a high-level language, not in machine code
- Use old version of the compiler to compile the new version of the compiler

Example



- All the way back to the first computers, where some primordial primitive compiler or assembler was written in machine code

Advantages and limitations of tombstone diagrams

- + Abstracts away technical details of object files, compilation modes etc
- Cannot express more complex situations such as dynamic linking
- In practice mostly used for visualising **bootstrapping**—the process of writing compilers in the language they compile, or bringing up new hardware

Conclusions

- Compiled languages tend to be fast, but less flexible
- Interpreted languages tend to be slower, but more flexible
- **Best of both worlds:** write computational primitives in fast languages, call them from slow languages
 - ▶ NumPy works like this
- Tombstone diagrams make the relationship between compiler, interpreter, and machine clear
 - ▶ Although in day-to-day work, we only use simple compositions