Compiled and interpreted languages

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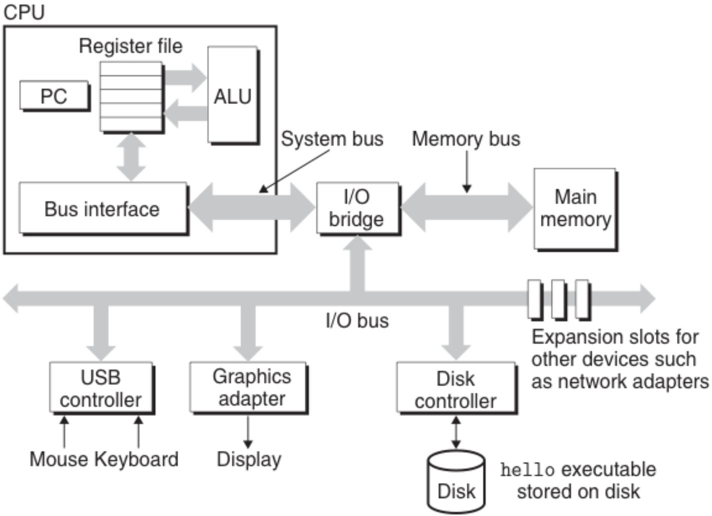
How computers execute code

Compiled and interpreted languages

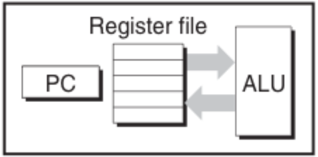
Tombstone diagrams

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.
  - x86-64 has 16 registers, each store 64 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.

x86-64 registers

- Imagine programming where these are all the variables you have available.
- No function parameters either.
- x86-64 assembly for adding numbers stored in registers `r8`, `r9`, `r10`:

```
addq %r8, %r9  ; r8 += r9
addq %r8, %r10 ; r8 += r10
```

64-bit register	Bytes 0-3	Bytes 0-1	Bytes 0
%rax	%eax	%ax	%al
%rcx	%ecx	%cx	%cl
%rdx	%edx	%dx	%dl
%rbx	%ebx	%bx	%bl
%rsi	%esi	%si	%sil
%rdi	%edi	%di	%dil
%rsp	%esp	%sp	%spl
%rbp	%ebp	%bp	%bpl
%r8	%r8d	%r8w	%r8b
%r9	%r9d	%r9w	%r9b
%r10	%r10d	%r10w	%r10b
%r11	%r11d	%r11w	%r11b
%r12	%r12d	%r12w	%r12b
%r13	%r13d	%r13w	%r13b
%r14	%r14d	%r14w	%r14b
%r15	%r15d	%r15w	%r15b

x86-64 instructions

There are thousands of x86-64 instructions.[1]

- All are encoded as bits and can be interpreted as numbers.
- Vary in size, but are always a whole number of bytes.

Instruction	Encoding in hex
`addq %r8, %r9`	`4D 01 C8`
`addq %r8, %r10`	`4D 01 D0`
`movq 0(%r9), %r8`	`4D 8B 41 F8`

- Different architectures have *different instructions*, *different registers*, and *different encodings*.
- Also two different syntaxes:
  - AT&T syntax (used for these slides, generated by default by GCC).
  - Intel syntax (probably more common among real assembly programmers).

[1] 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;
}
```

x86-64 assembly

```
cmpq $0, %r8   ; Compare 0 and r8
jns  .L2       ; Jump if r8 is greater
movq $0, %r8   ; Set r8 to 0
.L2:           ; Label
      ...
```

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

Loops as jumps

C code

```
while (x > 0) {
  x -= 1;
  y += 1;
}
```

x86-64 assembly

```
jmp  .L2          ; Jump to L2
.L3:
subq $1, %r8     ; x -= 1
addq $1, %r9     ; y += 1
.L2:
cmpq $0, %r8     ; Compare 0 and x
jg   .L3          ; Jump if x greater
```

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```

We can also write this in C.

```
    goto L2;
L3: x -= 1;
    y += 1;
L2: if (x > 0) goto L3;
```

Function calls at the assembly level

The CPU has no idea what a function is.

- **How a function call works at assemply 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.

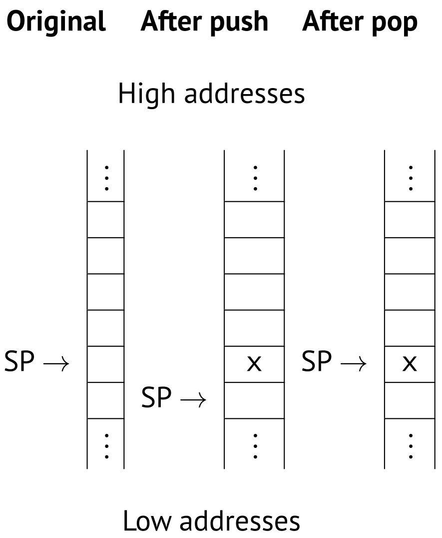
Actually

- 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];
```



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* to 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)

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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

Listing 1: `collatz.py`

```python
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`

```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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```

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`

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

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

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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`

```python
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	0.01*ms*	0.01*ms*	0.9×
10	0.01*ms*	0.01*ms*	1.4×
100	0.1*ms*	0.01*ms*	13.3×
1000	0.98*ms*	0.01*ms*	95.3×
10000	9.96*ms*	0.05*ms*	190.7×
100000	98.59*ms*	0.41*ms*	240.7×

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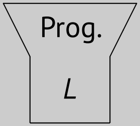
Tombstone diagrams

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

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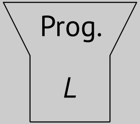
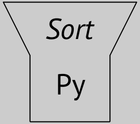
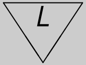


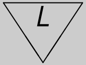
Example of program written in Python



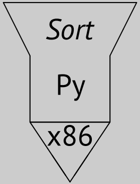
A machine that runs L programs



A machine that runs *L* programs



Example



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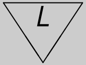

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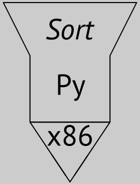
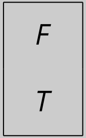


Incorrect! Languages (Python and x86) do not match!

An interpreter for *F*, written in *T*



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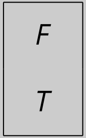

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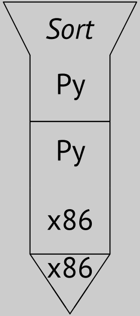
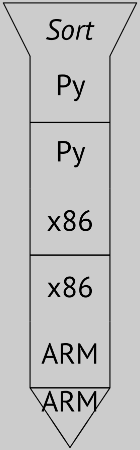
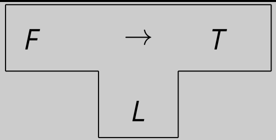


Stacking interpreters



A compiler from F to T, written in L



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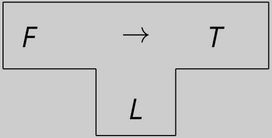

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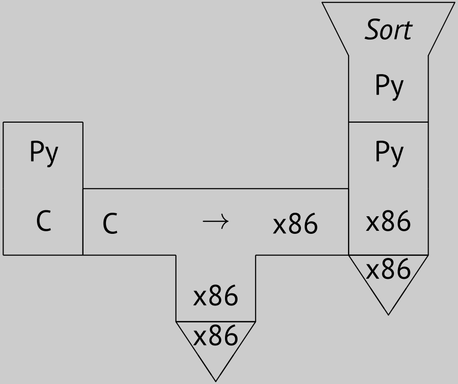

Compilers can be chained

Futhark $\rightarrow$ C $\rightarrow$ machine code

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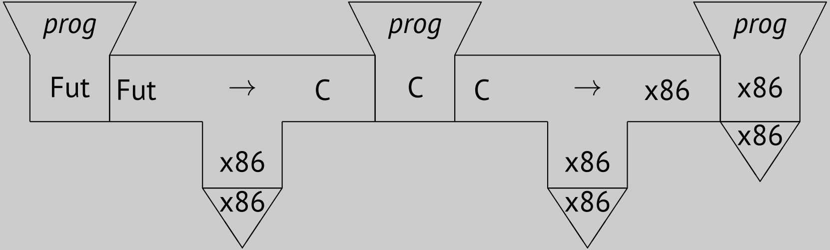
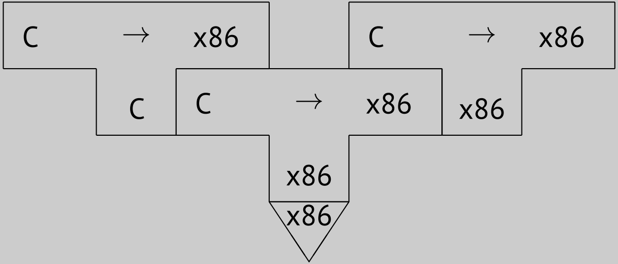


Compilers are also programs

- 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