Programming Language (5)
Basics of Programming Language Implementation

田浦

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Two basic forms of language implementation

- interpreter: interprets and executes programs (takes a program and an input; and computes the output)
- compiler: translates programs into a machine (assembly) code, that can directly execute by the processor
  - ahead-of-time (AOT): the entire program is compiled before execution
  - just-in-time (JIT): programs are incrementally compiled as they get executed (e.g., a function at a time)

regardless of details, the central issue is how to translate a source program $\rightarrow$ machine code

Why do you want to build a language, today?

- new hardware
  - GPUs (CUDA, OpenACC, OpenMP), AI chips, Quantum, ...
  - new instruction set (e.g., SIMD, matrix, ...) of the processor
- new general purpose languages
  - Scala, Julia, Go, Rust, etc.
- special purpose (domain specific) languages
  - statistics (R, MatLab, etc.)
  - data processing (SQL, NoSQL, SPARQL, etc.)
  - deep learning
  - constraint solving, proof assistance (Coq, Isabelle, etc.)
  - macro (Visual Basic (MS Office), Emacs Lisp (Emacs), Javascript (web browser), etc.)

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What a machine (assembly) code looks like

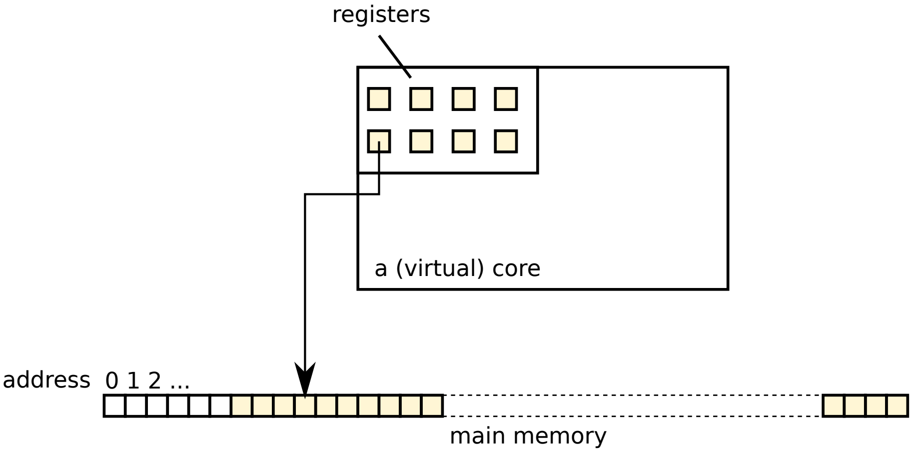
- it *is* just another programming language
- it has many features present in programming languages

expressions	arithmetic instructions
if statement	compare / conditional jump instructions
variables	*registers* and *memory*
tructs and arrays	memory and load/store instructions

compilation is nothing like a magic; it's more like translating English to French

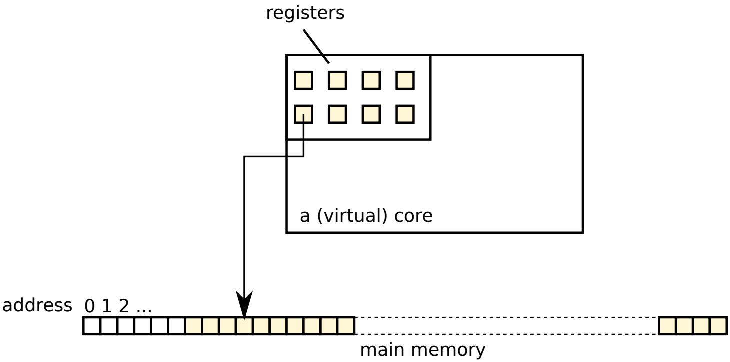
What a CPU (core) looks like

- a small number (typically < 100) of *registers*
  - each register can hold a small amount of (e.g., 64 bit) data
- majority of data are stored in *memory* (a few to $\sim$ 1000 GB)



Memory

- where majority of data your program processes are stored
- memory is essentially a large flat array indexed by integers, often called *addresses*
- an address is just an integer

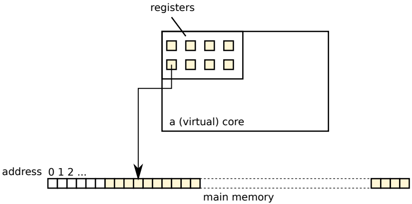


What a CPU (core) does

- a special register, called *program counter* or *instruction pointer* specifies the address to fetch the next instruction at
- a CPU core is essentially a machine that does the following

```
repeat:
  inst = memory[program counter]
  execute inst
```

- an instrcution
  - performs some computation of values on a few registers or a memory location, and
  - changes the program counter (typically to the next instruction on memory)



Exercise objectives

- `pl06_how_it_gets_compiled`
- learn how a compiler does the job,
- by inspecting assembly code generated from functions of the source language

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Registers

- general-purpose 64 bit integer registers: `r{a,b,c,d}x`, `rdi`, `rsi`, `r[8-15]`, `rbp`
- general-purpose floating point number registers: `xmm[0-15]`
- stack pointer register: `rsp`
- a compare flag register: `eflags`, not directly used by instructions
  - implicitly set by compare instructions
  - implicitly used by conditional jump instructions
- an instruction pointer register: `rip`, not directly used by instructions
  - set by every instruction
- https://wiki.cdot.senecapolytechnic.ca/wiki/X86_64_Register_and_Instruction_Quick_Start

Frequently used instructions

learn details and other instructions from the exercise

- `addq` (+), `leaq` (+), `subq` (−), `imulq` (×), `idivq` (/)
- `movq` : move values between registers or between register and memory (load/store)
- `cmpq` : compare two values and set the result into the `eflags` register
- `jl` (<), `jle` (≤), `jg` (>), `jge` (≥), `je` (=), `jne` (≠) : jump if a condition (indicated by `eflags`) is met
- `call`, `ret` : call or return from a function

How to read instructions and operands

- e.g., `addq` instructios takes two operands

```
addq x,y
```

and its effect is

```
y += x
```

- many two operand instructions behave similarly

```
opq x,y ≡ y = y op x
```

- especially confusing is `subq`

```
subq x,y ≡ y = y - x
```

- (operand order actually depends on assembler)

Syntax of operands

- `$`n : immediate value of n
- `%`R : register named R
- `(...)` : address operand (details in the next slide)

where

- n : a constant (`4`, `8`, etc.)
- R : regiser name (`rax`, `rbx`, `rdi`, etc.)

ex.

- `addq $1,%rax` : add 1 to `%rax` register
- `subq $1,%rax` : subtract 1 from `%rax` register

Address operands

- an address operand `(...)` specifies an address, and can be
  - `(%`R`)` : R
  - n`(%`R`)` : $R + n$
  - n`(%`R`,`s`,`R'`)` : $R + sR' + n$
- where
  - n, s : integer constants
  - R, R' : register names
- ex.
  - `mulq (%rdi),%rax` : reads address specified by `%rdi` and multiply `%rax` by it
  - `movq %rax,(%rdi)` : writes the value of `%rax` to the address specified by `%rdi`
  - `leaq 4(%rdi),%rax` : `%rax = %rdi + 4`; this instruction does not read/write memory

Things to watch in the exercise

- calling convention or ABI : function's incoming parameters and the return value are put in places (typically registers) predetermined by convention
- observe where incoming parameters are by compiling simple functions like

```
f(int x, int y) = x + y
```

- change parameter types and function body to know
  - how data are represented (integers, floating point numbers, arrays, structs, etc.)
  - how various expressions are implemented (arithmatic, array access, structure access, etc.)