How Programming Languages Work (Basics)

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Contents

Introduction 2
CPU and machine code : an overview 9
A glance at ARM64 machine (assembly) code 18
ARM64 instructios 26

Introduction

Why you want to make a language, today?

- new hardware
  - GPUs, AI chips, Quantum, …
  - new instructions (e.g., SIMD, matrix, …)
- new general purpose languages
  - Scala, Julia, Go, Rust, etc.

Why you want to make a language, today?

- 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.)

Taxonomy : interaction mode

- **interactive / read-eval-print-loop (REPL)**
  - type code directly or load source code in a file interactively
  - Julia
- **batch compile**
  - convert source into an executable file
  - and run it (typically the “main” function)
  - Go, Rust
- some language implementations provide both
  - OCaml

Taxonomy : execution strategy

- **interpreter** executes source code directly with its input
  - interpreter (*source-code*, *input*) $\rightarrow$ *output*
- **compiler** first converts source code into ***a machine (assembly) code*** that is directly executed by the CPU
  - compiler (*source-code*) $\rightarrow$ *machine-code*;
  - *machine-code* (*input*) $\rightarrow$ *output*
- **translator** or **transpiler** are like compiler, but convert into another language, not machine (assembly) code

A (minor) note: machine code vs. assembly code

- in many contexts, they are used almost interchangeably
- machine (assembly) *languages* are almost interchangeable, too
- if asked a difference,
  - ***machine*** code is *the* real encoding of instructions interpretable by a CPU
  - ***assembly*** code refers to a *textual (human-readable) representation* of machine code

Taxonomy : compiler/translator

- **ahead-of-time (AOT)** compiler converts all the program parts into assembly before execution
- **just-in-time (JIT)** compiler converts program parts incrementally as they get executed (e.g., a function at a time)

CPU and machine code : an overview

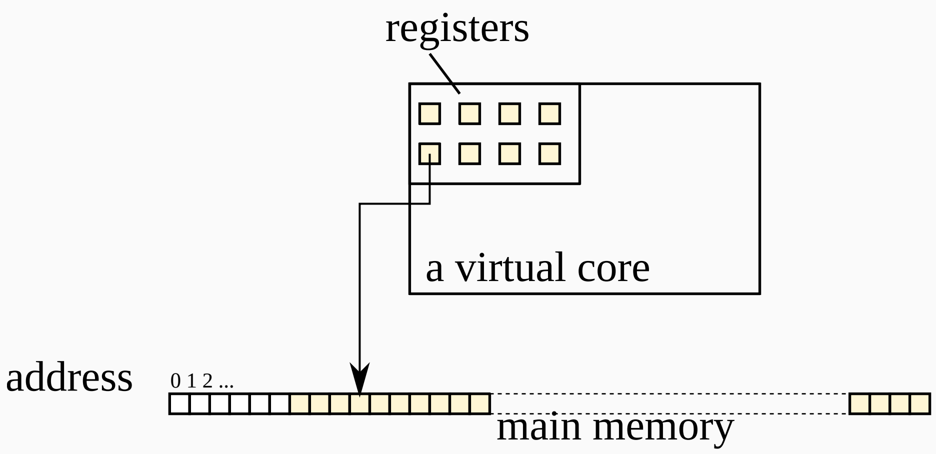
High-level (programming) languages vs. assembly languages

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

high-level language	**assembly language**
variables	*registers* and *memory*
structs and arrays	memory and load/store instructions
expressions	arithmetic instructions
if / loop	compare, conditional branch instructions
functions	branch and link instructions

What a CPU looks like

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

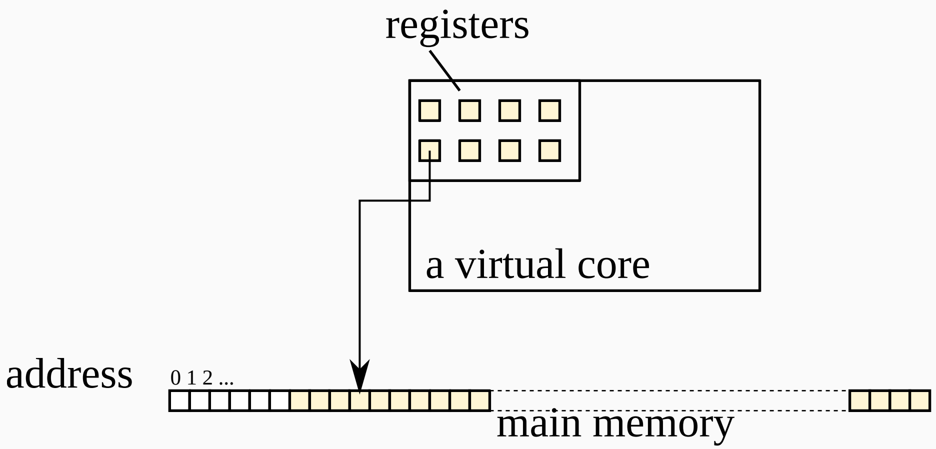


Terminology note : CPU $\ni$ core $\ni$ virtual core

- a ***CPU*** has multiple (typically, 2 to $>$100) ***cores***
- a core has multiple (typically, 1 to a few) ***virtual cores*** or ***hardware threads***
- each virtual core has its own registers and is capable of fetching and executing instructions
- a single instruction sequence is executed by a single OS-level ***thread***, which is on a single virtual core at any given time
- this course is only concerned about single-thread execution

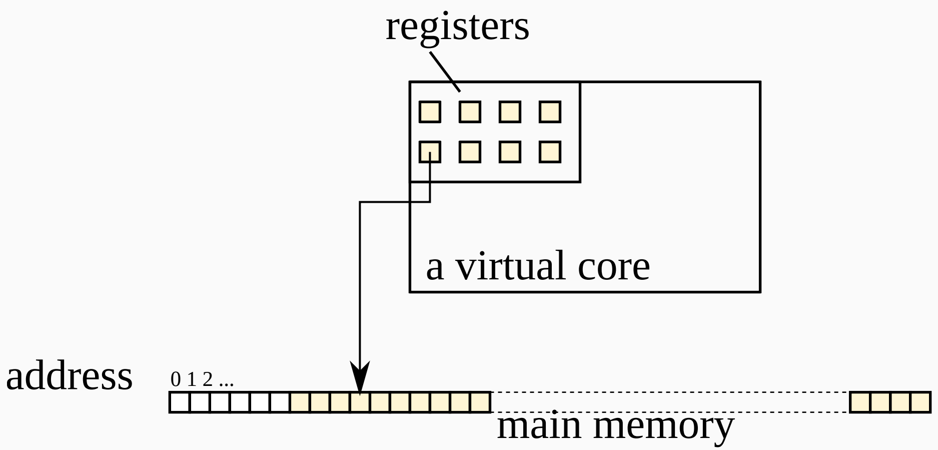
Main memory

- ≈ a large array indexed by integers, called ***addresses***
- in machine code level, ***an address is just an integer***



Main memory

- each address typically stores 8 bits (a ***byte***) of data
- a larger word is stored in consecutive addresses. e.g.,
  - 32 bit (4 byte) word occupies 4 consecutive addresses
  - 64 bit (8 byte) word occupies 8 consecutive addresses



What a virtual core does

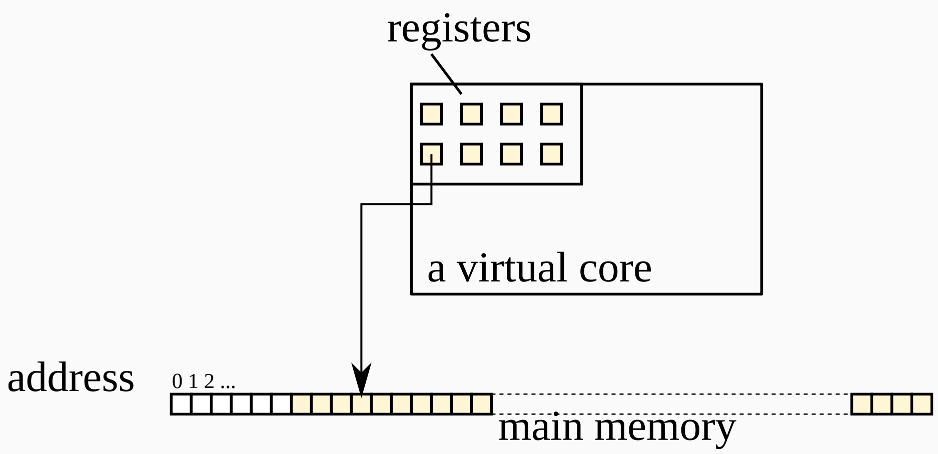
- a virtual core is a machine that does the following:

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

- ***program counter*** (or ***instruction pointer***) is the register that specifies the address to fetch the next instruction from

What an istruction does

1. perform some computation on specified register(s) or a memory address
2. change the program counter,
    - typically to the address of the instruction immediately following it
    - except branch / jump instructions



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

A glance at ARM64 machine (assembly) code

A glance at ARM64 machine (assembly) code

Rust (add123.rs)

```
#[no_mangle]
pub fn add123(x:i64, y:i64) -> i64 {
    y + 123
}
```

```
$ rustc -O --emit asm --crate-type lib
add123.rs -o add123.s
```

assembly (add123.s)

```
        .text
        .file   "pl06.1ebfa1..."
        .section .text.add123,...
        .globl  add123
        .p2align        2
        .type   add123,@function
add123:
        .cfi_startproc
        add     x0, x1, #123
        ret
.Lfunc_end0:
        .size   add123, .Lfunc_...
        .cfi_endproc
```

Insignificant lines

- indented lines starting with a dot (e.g., `.file`, `.section`, `.text`, etc.) are ***directives*** (not instructions) and largely not important
- unindented lines ending in a colon (e.g., `add123:`) are ***labels*** used to human-readably specify jump targets

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        .text
        .file   "pl06.1ebfa1..."
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        .globl  add123
        .p2align        2
        .type   add123,@function
add123:
        .cfi_startproc
        add     x0, x1, #123
        ret
.Lfunc_end0:
        .size
add123, .Lfunc_end0-add123
        .cfi_endproc
```

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```
add123:
        add     x0, x1, #123
        ret
.Lfunc_end0:
```

How to read assembly

- focus on lines that are *instructions*
- look for a label *similar to* the function name — where its instructions start
  - the label may not be exactly the same as the function name (*name mangling*)

```
add123:

        add     x0, x1, #123
        ret
.Lfunc_end0:
```

How to read instructions

- ex.

```
add     x0, x1, #123
```

performs `x0 = x1 + 123`

- `add` is an ***instruction name*** or *mnemonic*
- takes a few ***operands*** (`x0`, `x1`, and `#123`)
  - `x0`, `x1` : register
  - `#123` : constant (***immediate value*** or ***literal***)

ARM64 registers

- integer registers $\times$ 32
  - 64 bit : `x0, x1, ..., x31`
  - 32 bit : `w0, w1, ..., w31`
    - the lower 32 bits of `x0, x1, ..., x31`
- floating point registers $\times$ 32
  - 64 bit (double precision) : `d0, d1, ..., d31`
  - 32 bit (single precision): `s0, s1, ..., s31`
    - the lower 32 bits of `d0, d1, ..., d31`

Implicit registers

- ***condition code register* (CC)** — holds the result of the last compare instruction
- ***program counter register* (PC)** — holds the address of the next instruction

SIMD registers

- pack a few floating point numbers / integers in a register
- a SIMD instruction can perform an operation on all values on SIMD register(s)
- important for performance, but omitted in this course for brevity

ARM64 instructios

ARM64 instruction categories

- arithmetic / move
- load / store
- compare and conditional branches
- unconditional branch
- branch-and-link and return

Sources

- when you encouter unfamiliar instructions, see Arm A-profile A64 Instruction Set Architecture
- Cheat sheet
- Google / AI

Arithmetic / move

assembly	pseudo C
`sub x0, x1, x2`	`x0 = x1 - x2`
`add x0, x1, x2`	`x0 = x1 + x2`
`mov x0, x1`	`x0 = x1`
`...`	`...`

- typically takes three operands
- the result is written to the first operand

Load / store

	assembly	pseudo C
basic load	`ldr x0,[x1]`	`x0 = *(long*)x1`
basic store	`str x0,[x1]`	`*(long*)x1 = x0`
offset	`ldr x0,[x1,#8]`	`x0 = *(long*)(x1+8)`
scaled offset	`ldr x0,[x1,x2,lsl #3]`	`x0 = *(long*)(x1 + (x2<<3))`
pre-increment	`ldr x0,[x1,#8]!`	`x1 += 8; x0 = *(long*)x1`
post-increment	`ldr x0,[x1],#8`	`x0 = *(long*)x1; x1 += 8`
negative offset	`ldur x0,[x1,#-8]`	`x0 = *(long*)(x1 - 8)`
load pair	`ldp x0,x1,[x2]`	`x0 = *(long*)x2;` `x1 = *(long*)(x2 + 8)`

- there are similar variations for store

Compare and conditional branches

`cmp x0,x1`	CC = `x0 - x1`
`b.eq` *label*	if CC $= 0$, goto *label*
`b.lt` *label*	if CC < 0 (signed), goto *label*
`b.le` *label*	if CC ≤ 0 (signed), goto *label*
`b.lo` *label*	if CC < 0 (unsigned), goto *label*
…	…

- notes:
  - CC = *condition code register*
  - CC does not hold the value of `x0 - x1` itself
  - but holds whether it is > 0, $= 0$, < 0, etc. as a bit sequence

Other jump variants

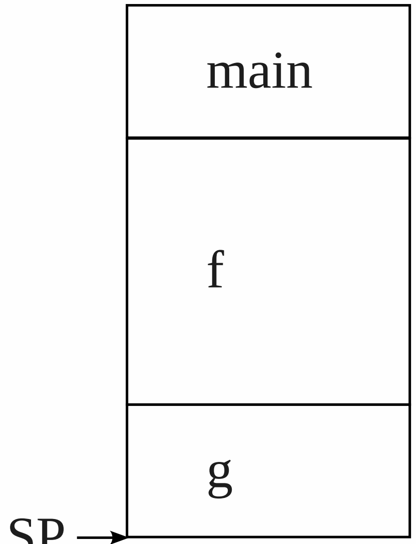
`b` *label*	goto *label*	
`bl` *label*	goto *label*; `x30 =` the next address of the `bl`	(∗)
`ret`	goto the address in `x30`	(†)

- (∗) used for calling a function; set `x30` to the address to return after the function
- (†) used for returning from a function; jump to the "return address", presumably set by the `bl` instruction that called it

How function calls work — overview

- memory may be required to execute a function, to remember local variables
  - ***activation frame*** or ***stack frame*** of a function call
- since life time of a function call is nested inside that of the caller, they are typically LIFO data structure (i.e., stack)

```
int main() {
  ... f(...) ...
  ... i(...) ...
}
void f(...) {
  ... g(...) ...
  ... h(...) ...
}
```



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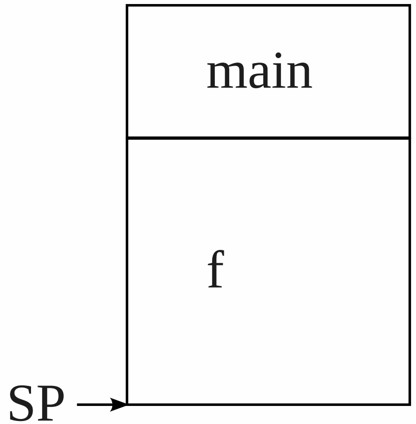

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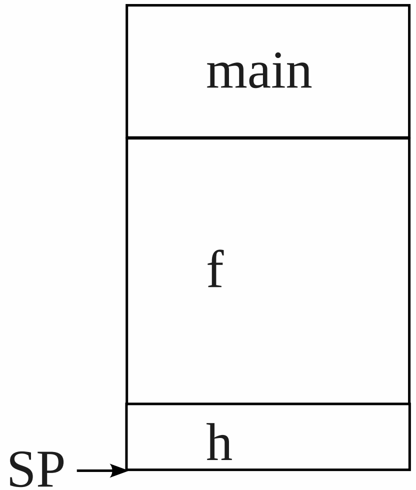

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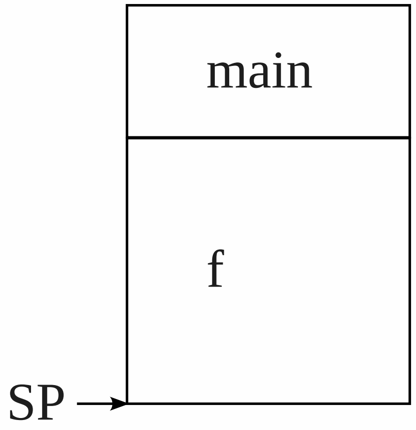

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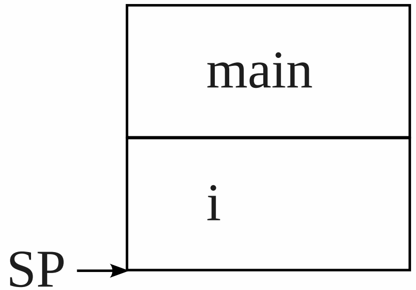

Note about the stack data structure

- a register, typically called ***stack pointer*** or ***SP***, points to the end of the used part of the stack
- the entire stack is typically a single contiguous region, but it doesn't have to
- if it is, allocating an activation frame from the stack just entails bumping a stack pointer

```
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  ... i(...) ...
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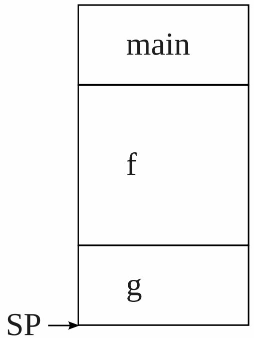


Looking into a function call

- rules must exist for function calls to work
  1. where are arguments
  2. where to jump after finished ***(return address)***
  3. where to use if the function wants to use memory
  4. which registers must be preserved across a call
  5. where to pass the return value
- they are variously called
  - *calling convention*, *register usage convention*, or
  - ***Application Binary Interface (ABI)***

Applicatoin Binary Interface (ABI) of ARM64

Omitting details you should learn through experiments (and which may be language-dependent),

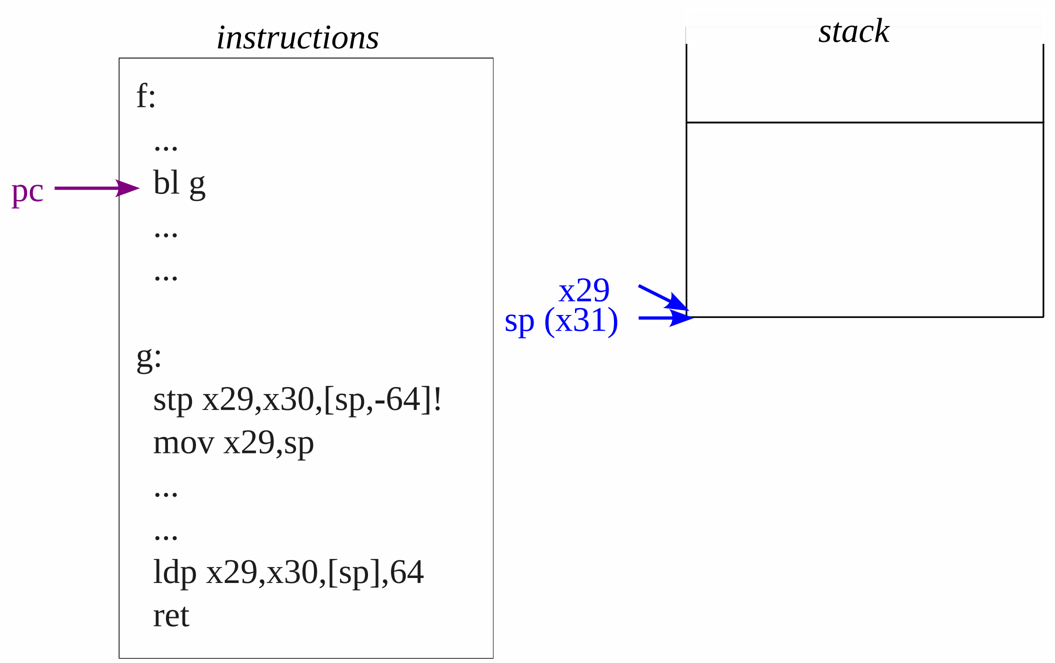
- upon entry:
  - arguments: `x0, x1, ...` (integers), `d0, d1, ...` (floats)
  - return address: `x30`
  - `sp` points to the end of the stack, below which the callee can use for its purpose

Applicatoin Binary Interface (ABI) of ARM64

- upon return:
  - return value: `x0` (integer), `d0` (float)
  - `x19` - `x28` must hold the same values as those upon entry ***(callee-save registers)***
  - the following registers must also be preserved
    - `x29` (*frame pointer*),
    - `x30` (*link register* or *return address register*),
    - `sp` (*stack pointer*)
- `x0` - `x15` can be destroyed by the callee ***(caller-save registers)***

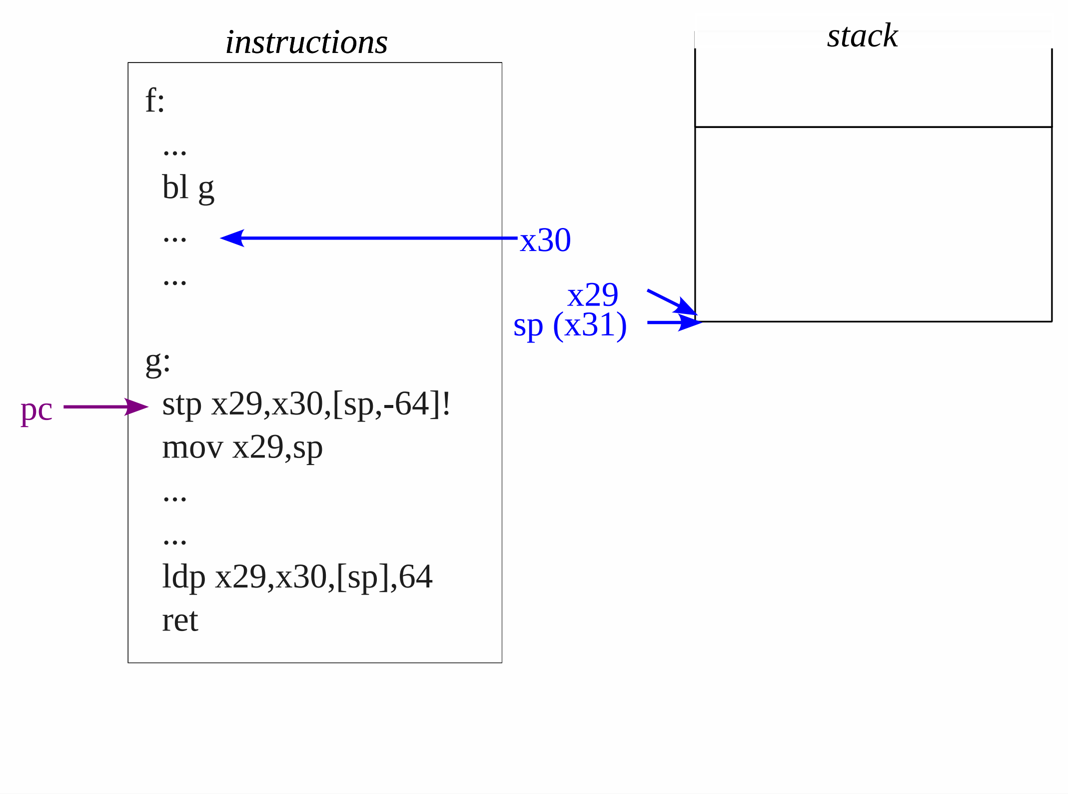
A function call in action

- say `f` is calling `g`
- `f` puts arguments at right places and executes `bl g` instruction



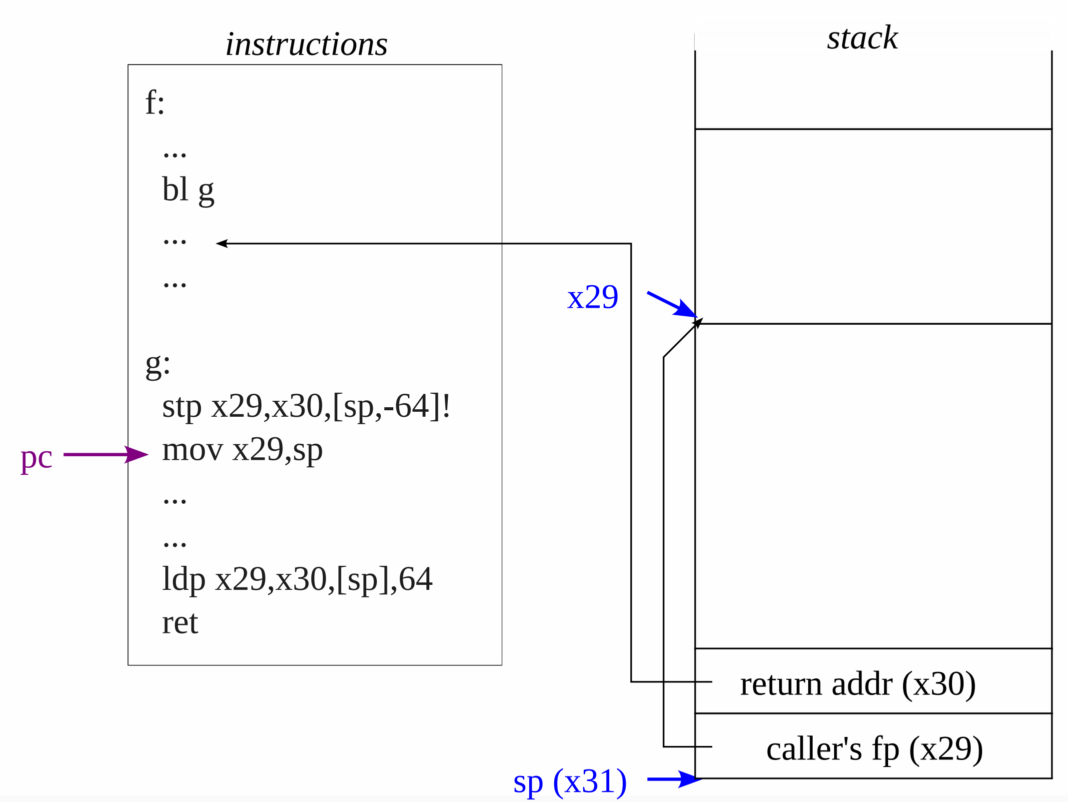
A function call in action

- `x30` now holds the ***return address*** (address of the instruction immediately following `bl g`)
- if `g` calls another function, it first extends the stack and saves `x30` and `x29` (typically by `stp x29,x30,[sp,#-??]`)



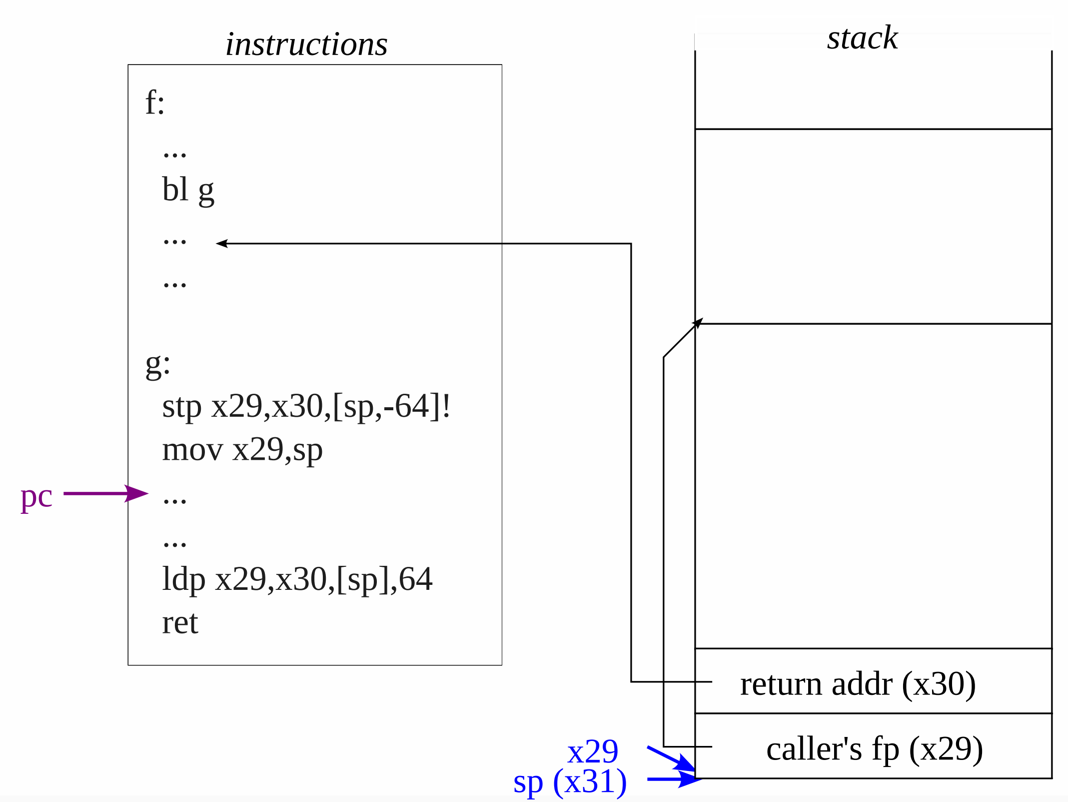
A function call in action

- it then sets up ***frame pointer*** (`x29`), typically to the same as `sp` (more on this later)



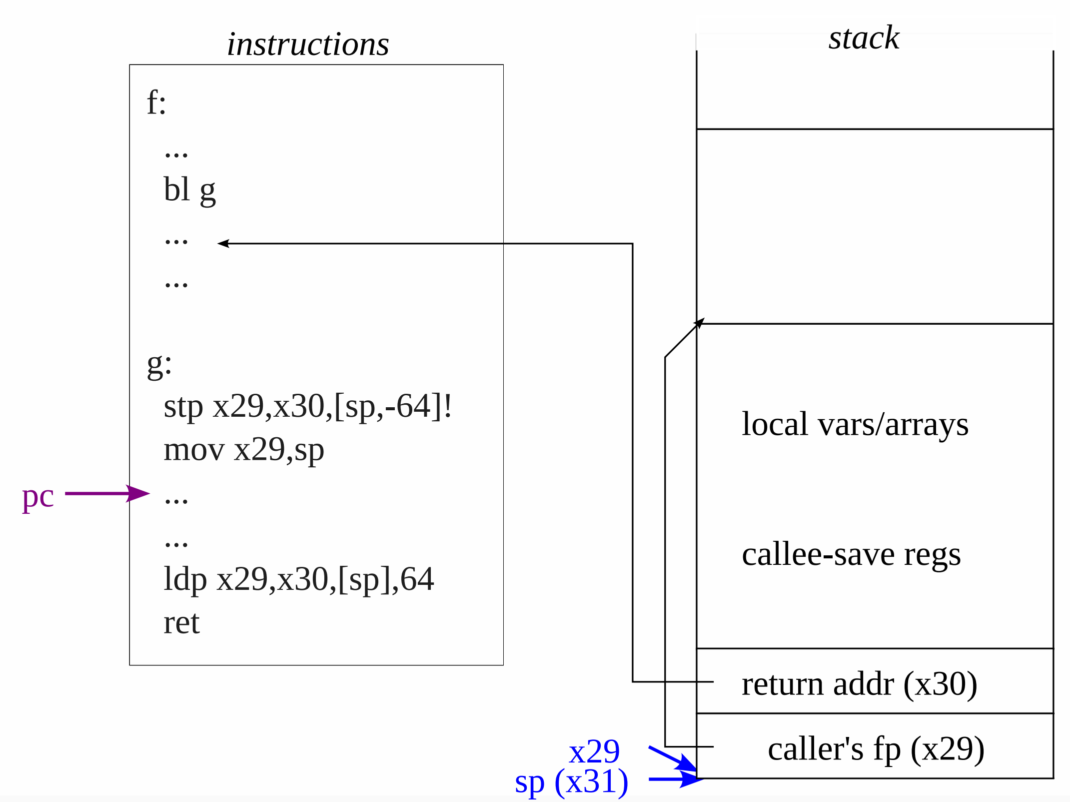
A function call in action

- if it uses some callee-save registers, it saves them on stack



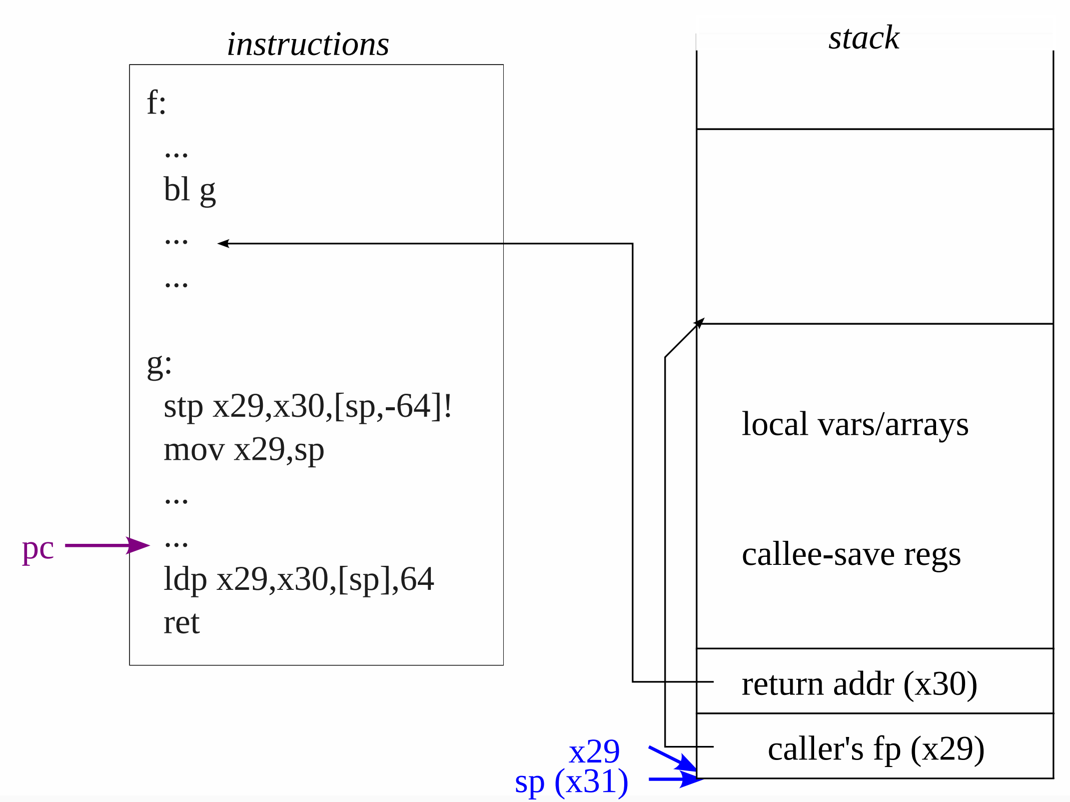
A function call in action

- `g` is now really ready to execute …



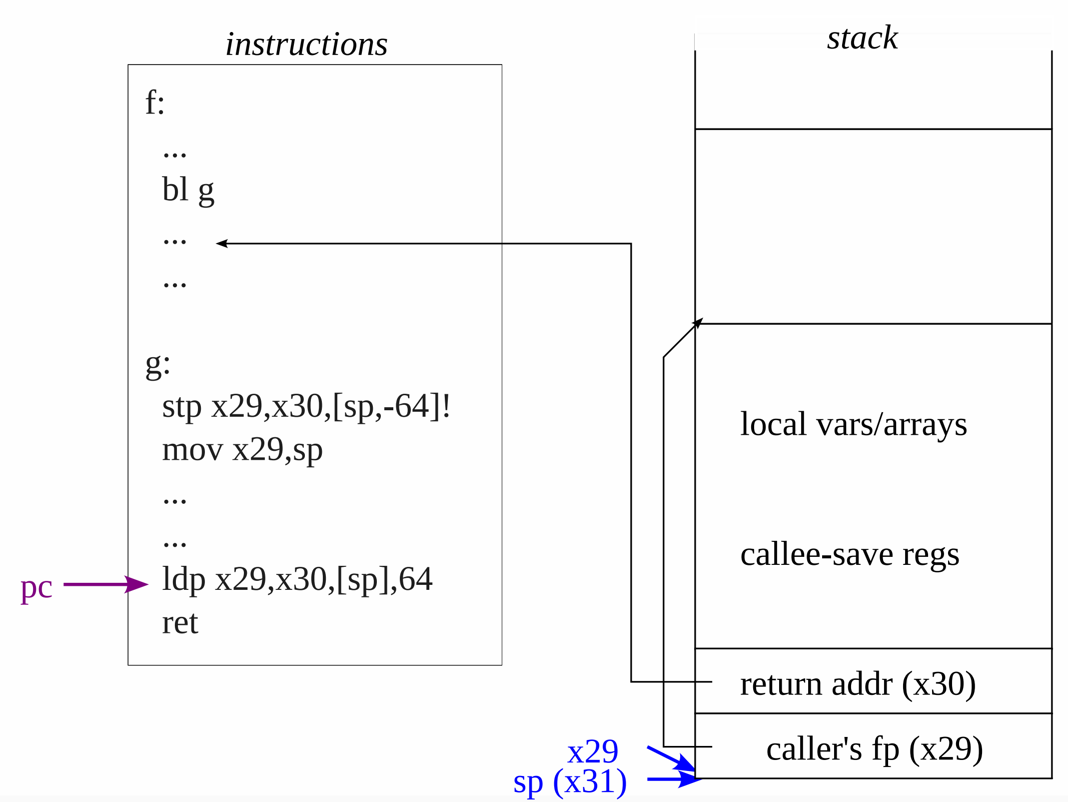
A function call in action

- … before it returns,
- it restores callee-save registers, if any



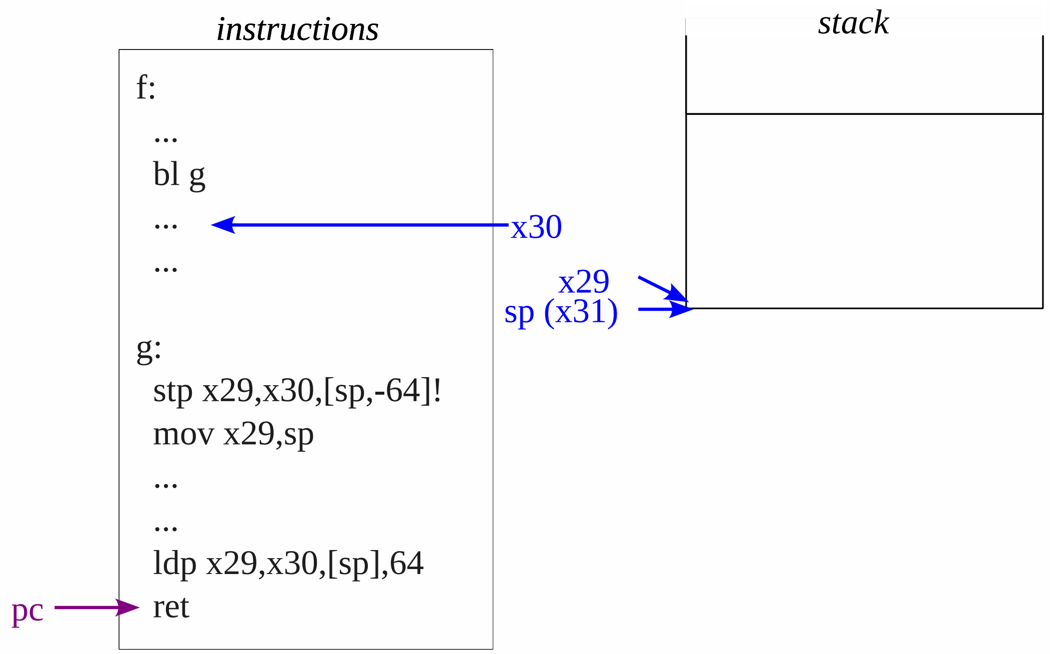
A function call in action

- it then restores `x29` and `x30` and shrinks the stack (typically by `ldp x29,x30,[sp],??`)



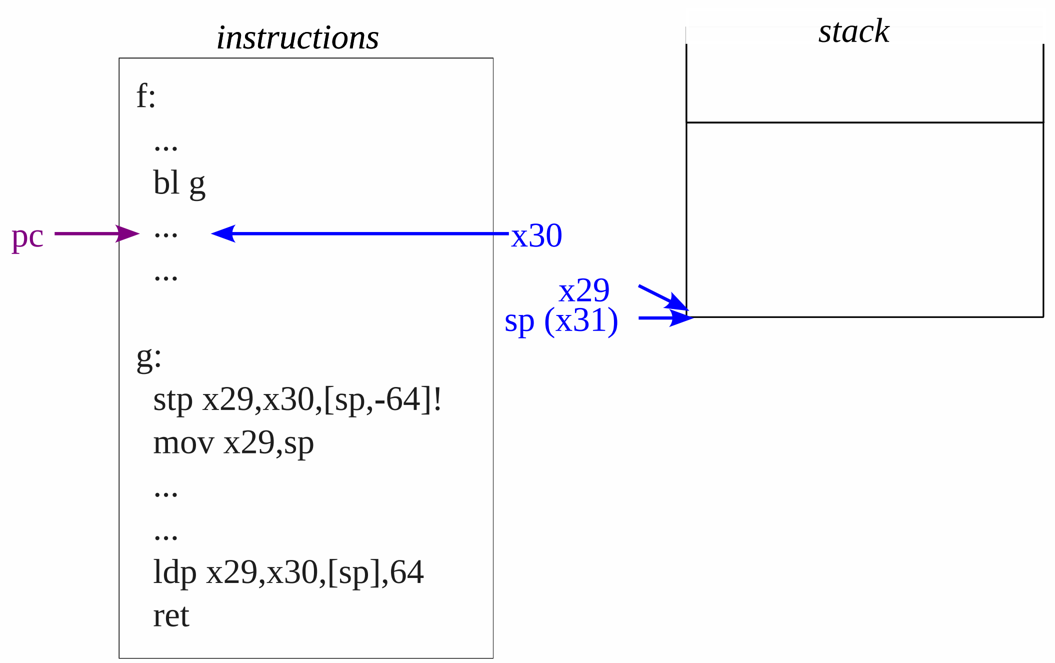
A function call in action

- it finally executes `ret`, which jumps to the address in `x30`, which should hold the return address just restored



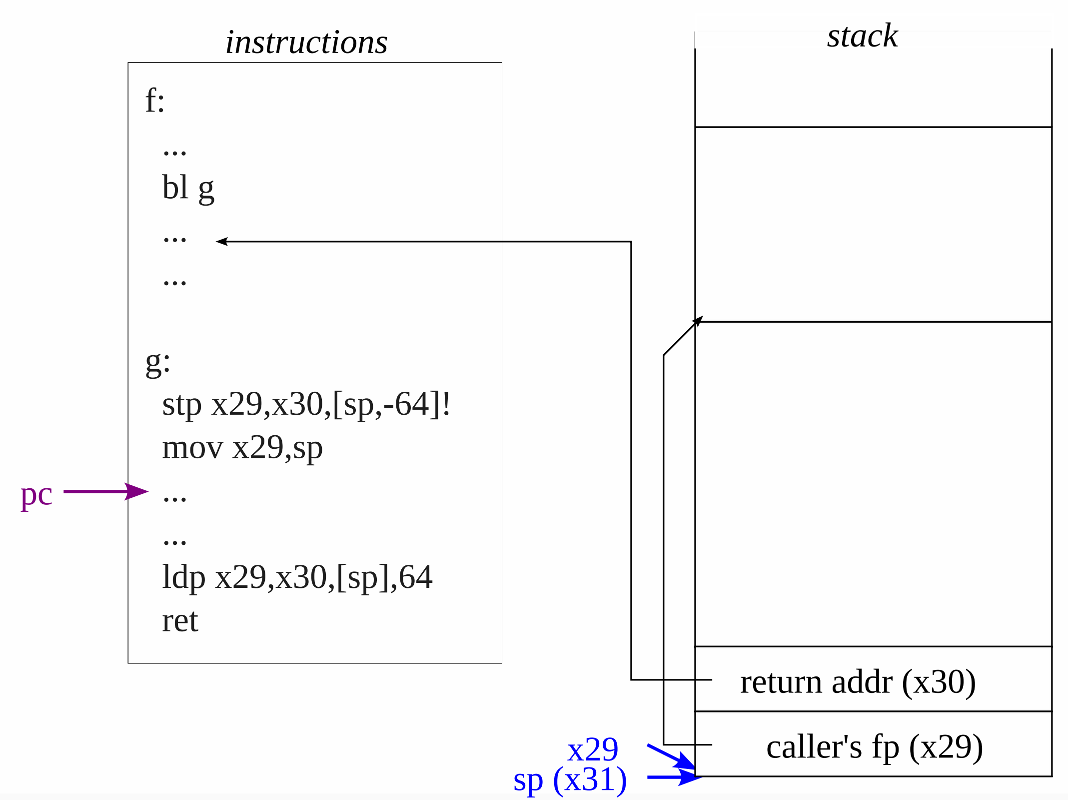
A function call in action

- execution of `f` continues, from the instruction immediately following the `bl`



Note: stack pointer (SP) and frame pointer (FP)

- they are usually the same
- more generally,
  - SP may change while executing a function (e.g., when dynamically allocating memory from stack with `alloca`)
  - FP is fixed and always points to where the caller's FP is stored



Things to learn in the exercise

1. **calling convention / ABI:** how a function call works
2. **control flow:** how conditionals and loops are implemented
3. **data representation:** how various data types (ints, floats, structs, pointers, arrays) are represented