Chapter 4 – Control Flow

With the instructions we have seen so far, we can only write programs as purely linear sequences of instructions. However most algorithms need to break this sequential pattern in order to make choices during execution. For example the programmer might want to do one thing *or* another, depending on some condition. To express such choices, general-purpose programming languages offer various syntax constructs known as **control structures**, like if-then-else statements, “for” loops, or “while” loops.

Our goal for today is to understand how control structures are implemented at the assembly level.

1 Branch instructions

Idea To implement control structures, the SCAT processor provides **branch** (aka **jump**) instructions. Instead of incrementing the PC to advance to the next instruction, a *branch* instruction overwrites the PC with a well-chosen value. As a result, the CPU will appear to *jump* to that location and continue executing from there.

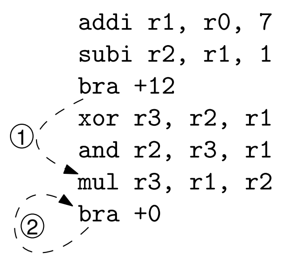
Syntax The simplest of these jumps is called “branch always”. Its syntax is the mnemonic `bra` followed by an **offset** e.g. “`bra +8`” or “`bra -12`”. Its effect is to *add* the offset to the PC, instead of adding 4 like ordinary instructions. For instance, “`bra +8`” will *skip* the following instruction, and jump to the one after that. Similarly, “`bra -12`” will rewind execution by three instructions.

Note 1: “`bra +0`” is effectively an infinite loop that will jump to itself forever. When this happens, our simulator stops executing.

Note 2: in practice, the CPU itself does not know about `bra`, it is an example of a **pseudo-instruction**. What happens is the assembler translates every `bra` into an `addi` with PC as destination register.

Note 3: speaking of pseudo-instructions, “`bra +0`” can also be spelled as “`halt`”.

Exercise 1 Read the code below and “execute” the program on paper: predict the resulting value, as well as all successive values of the PC register (reminder: each instruction occupies one 4-byte word). To make the exercise easier, we augmented the code with a **control flow diagram**: arrows indicate jumps, and circled numbers indicate the chronological order in which these arrows are “taken” by the CPU.



```
addi r1, r0, 7
subi r2, r1, 1
bra +12
xor r3, r2, r1
and r2, r3, r1
mul r3, r1, r2
bra +0
```

Exercise 2 Now verify your previous result: Type this code in a text file, then assemble it and run the executable in the simulator. Reminder: use the `step` command to execute just one instruction.

2 Conditional Jumps

Conditional jump instructions are useful to implement choices: the jump is either taken or ignored, depending on some condition on the values of registers. For instance "`beq ri, rj, offset`" jumps if and only if the values of Ri and Rj are equal. The other possible conditions are listed below.

asm	Name	comp code	Description
`beq`	Branch if equal	0000	`if (rd == rs1) PC += sxt(imm)`
`bne`	Branch if not equal	0001	`if (rd != rs1) PC += sxt(imm)`
`blt`	Branch if lower than	0010	`if (rd <  rs1) PC += sxt(imm)`
`bge`	Branch if greater or equal	0011	`if (rd >= rs1) PC += sxt(imm)`

In machine code, conditional jumps are encoded as follows:

- bits 31–28 are always 0b0011 to indicate a type 3 instruction.
- bits 27–24 indicate the desired comparison.
- bits 23–20 and 19–16 indicate which registers to compare.
- the remaining 16 bits encode the offset i.e. the desired jump distance, should the jump be taken.

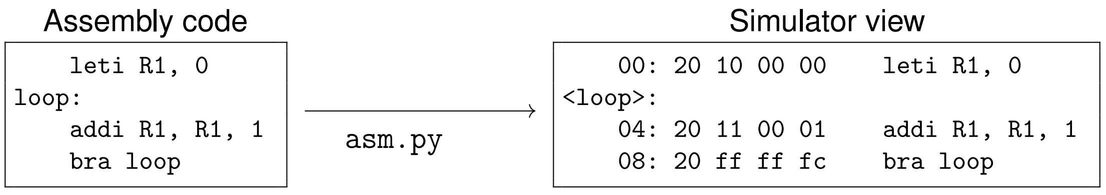
31 28	27 24	23 20	19 16	15 0
0 0 1 1	comp	rd	rs1	imm

Exercise 3 Choose two arbitrary numbers *A* and *B* between 0 and 1000. Write a program that uses the `leti` pseudo-instruction to assign these numbers to R3 and R4. Then, using conditional and/or mandatory jump(s), your program should set register R5 to the maximum of *A* and *B*. Use `bra +0` to halt execution afterwards.

On paper, draw a control flow diagram for this program.

3 Symbolic labels

As you may have noticed, calculating jump offsets by hand is not practical. Fortunately, virtually all assemblers (ours included) offer an alternative, more comfortable syntax to work with jumps. Any program location can be given a **label** (i.e. a name) and jump instructions can use labels as their destination. When translating assembly into machine code, the assembler keeps track of the actual memory address of every label, and computes jump offsets accordingly.
This syntax is illustrated below: a label is just a name followed by a colon character (":"). In assembly, labels usually go at the very beginning of the line, and all machine instructions are indented by e.g. four spaces. This is not mandatory, but following this convention will make your code more readable.
Now look at machine code on the right. Observe how both `leti` and `bra` pseudo-instructions get translated into `addi` (opcode 0x20). To help with debugging, the leftmost column of the simulator shows both labels and numeric addresses. The middle column is the raw memory contents (four bytes per line). The rightmost column shows the original source code.



```
    leti R1, 0
loop:
    addi R1, R1, 1
    bra loop
```

```
   00: 20 10 00 00    leti R1, 0
<loop>:
   04: 20 11 00 01    addi R1, R1, 1
   08: 20 ff ff fc    bra loop
```

Exercise 4 In the diagram above, draw an arrow to represent the jump. In this case, what is the numeric value of the offset ?

Exercise 5 Given a positive integer N, let us define $N!$ (pronounced "factorial N") as the multiplicative product of all positive integers up to N. In other words, $N! = N \times (N-1) \times ... \times 2 \times 1$. For example, $5! = 5 \times 4 \times 3 \times 2 \times 1 = 120$.
Write a program that uses a loop to compute the factorial of an integer initially stored in `R1`.
On paper, draw a control flow diagram for this program.

You may find these simulator commands useful:

- `step` to execute one instruction
- `continue` to execute the program until it stops by itself
- `breakpoint address_or_label` to place a new **break point** at some location
- `help cmd_name` to get help on some command

4 Putting it all together: Euclid's GCD Algorithm

In this part you're going to write a program involving both an if-then-else construct and a while loop. Our excuse is to compute the *greatest common divisor* of two integers i.e. to find out the largest integer that divides both numbers. But instead of performing repeated divisions, we will follow Euclid's algorithm. To quote Wikipedia[1]:

> *"The method introduced by Euclid for computing greatest common divisors is based on the fact that, given two positive integers a and b such that a > b, the common divisors of a and b are the same as the common divisors of a − b and b.*
> *So, Euclid's method for computing the greatest common divisor of two positive integers consists of replacing the larger number by the difference of the numbers, and repeating this until the two numbers are equal: that is their greatest common divisor. "*

Example Let's unroll the algorithm on a=12 and b=8.

- As stated above, $gcd(12, 8)$ is the same as $gcd(12 - 8, 8)$ i.e. $gcd(4, 8)$.
- We then repeat this step: $gcd(4, 8)$ is the same as $gcd(4, 8 - 4)$ i.e. $gcd(4, 4)$.
- In conclusion, we find that $gcd(12, 8) = gcd(4, 4) = 4$

Exercise 6 (pen & paper) With the same technique, compute $gcd(48, 18)$ and $gcd(1071, 462)$.

Exercise 7 (assembly) Write a program to compute $gcd(a, b)$ for any values of a and b. Your code will start by initializing two registers, as illustrated below:

```
leti R1, 48 ; argument a
leti R2, 18 ; argument b
...
```

Don't hesitate to reuse some of the code you wrote for the previous exercises (maximum, factorial).

[1] `https://en.wikipedia.org/wiki/Greatest_common_divisor`. Go look it up !