Lab 5

Code generation with smart IRs

Objective

- Construct the CFG.
- Compute live ranges, construct the interference graph.
- Allocate registers and produce final code.

During the previous lab, you wrote a dummy code generator for the Mu language. In this lab the objective is to generate a more efficient TARGET18 code.

This lab lasts 2 sessions. **Your work is due on Tomuss before Nov 20th, 23h59.**

Installations We're going to use graphviz for visualization. If it is not already installed (e.g. on your personal machine), install it, for instance with:

```
apt-get install graphviz graphviz-dev
```

You may have to install the following PYTHON packages:

```
pip3 install --user networkx
pip3 install --user graphviz
pip3 install --user pygraphviz \
  --install-option="--include-path=/usr/include/graphviz" \
  --install-option="--library-path=/usr/lib/graphviz/"
```

If the last command errors out complaining about a missing `Python.h`, run:

```
apt-get install python3-dev
```

and then relaunch the command `pip3 install ....`

5.1 CFG construction

In class we have presented CFGs with maximal basic blocks. In this lab we will implement CFGs with minimal basic blocks that is CFG with one node per line of code/instruction (even comments).

EXERCISE #1 ► **CFG By hand**
What are the expected result of the CFG construction from the 3-address code of Lab5 for each of these programs ?

```
var n,u,v:int;
n=6;
u=12;
v=n+u;
log(v);
```

```
var x,y:int;
x=2;
if (x < 4)
   x=4;
else
   x=5;
log(x)
```

```
var x:int;
x=0;
while (x < 4){
   x=x+1;
}
```

EXERCISE #2 ► **CFG Construction**
We adapted `APICode18` to be able to deal with CFGs. Now `Instructions` have a list of predecessors (`self._in`) and successors (`self._out`) and a `TARGET18Prog` contains the initial control point (`self._start`) from which we can traverse the graph. This new feature allows us to easily construct the CFG of a program.

Constructing the graph consists in minor modifications of the code generation you made in previous lab. To avoid having to add edges manually in all cases of the visitor, the APICode18.py file manages this automatically: when adding an instruction, it creates an edge between the last instruction (`self._end`) and the instruction to be added. Read the code dealing with this, provided in `add_instruction`.

The only case not dealt with in the code is the case of jump statements. Jump statements should be chained to the target of the jump. Fix `addInstructionJUMP` and `addInstructionCondJUMP` to properly chain the instruction using `add_edge` (for unconditional jumps, you will need to disable the automatic chaining).

In order to print the CFG, `Main.py` already contains a call to the (`printDot`) function that generates a dot file from the CFG. This `dot` file and its corresponding `pdf` file will be generated next to the `mu` input file.

To print the dot file you have to modify a boolean variable in `Main.py` file. The file is printed as `<name>.dot.pdf` in the same directory as the source file.

Here you have to:

1. Test for lists of assignments (for instance `testdataflow/df01.mu`). You should see a chain of blocks.
2. Same for boolean expressions, and tests.
3. Same for while loops and if statements. You will see a linear chain of nodes until you have properly coded `addInstructionJUMP` and `addInstructionCondJUMP`.

5.2 Liveness analysis and Interference graph

For the liveness analysis, we recall the notations. A variable at the left-hand side of an assignement is *killed* by the block. A variable whose value is used in this block (before any assignment) is *generated.*

$$LV_{exit}(\ell) = \begin{cases} \emptyset & \text{if } \ell = \text{final} \\ \bigcup\{LV_{entry}(\ell') \mid (\ell,\ell') \in flow(G)\} \end{cases}$$

$$LV_{entry}(\ell) = \left(LV_{exit}(\ell) \setminus kill_{LV}(\ell)\right) \cup gen_{LV}(\ell)$$

The sets are initialised to $\emptyset$ and computed iteratively, until reaching a fixpoint.

From now on, you have to modify `APICode18.py`

EXERCISE #3 ► **Liveness Analysis, Initialisation**

Initialise the $\mathsf{Gen}(B)$ and $\mathsf{Kill}(B)$ for each kind of instruction (add, let, ...). This corresponds to the numerous TODOs `ADD GEN KILL INIT IF REQUIRED`.

We give you an example for the print instruction. Be careful to properly handle the following cases:

```
1 ADD temp1 temp1 12
```

and

```
LETI temp1 42
```

As an example, here is the expected initialisation for `testsdataflow/df04.mu`:

```
instr 0: comment
gen: {}
kill: {}

instr 1: leti temp_2 2
gen: {}
kill: {temp_2}

instr 2: let temp_1 temp_2
gen: {temp_2}
kill: {temp_1}

instr 3: comment
gen: {}
kill: {}

instr 6: leti temp_3 4
gen: {}
kill: {temp_3}

instr 8: leti temp_4 0
gen: {}
kill: {temp_4}

instr 9: cond_jump lbl_end_relational_2
                    temp_1 sge temp_3
gen: {temp_1,temp_3}
kill: {}
```

```
instr 10: leti temp_4 1
gen: {}
kill: {temp_4}

instr 7: lbl_end_relational_2
gen: {}
kill: {}

instr 11: cond_jump lbl_end_cond_1
                    temp_4 eq 0
gen: {temp_4}
kill: {}

instr 12: leti temp_5 4
gen: {}
kill: {temp_5}

instr 13: let temp_1 temp_5
gen: {temp_5}
kill: {temp_1}

instr 14: jump lbl_end_if_0
gen: {}
kill: {}

instr 5: lbl_end_cond_1
gen: {}
kill: {}

instr 15: leti temp_6 5
gen: {}
kill: {temp_6}

instr 16: let temp_1 temp_6
gen: {temp_6}
kill: {temp_1}

instr 17: sub3 r0 r0 0
gen: {}
kill: {r0}

instr 4: lbl_end_if_0
gen: {}
kill: {}
```

The exercise that follows is the most important of the Lab

EXERCISE #4 ► Liveness Analysis, fixpoint

Implement the fixpoint iteration as a method (`doDataflow`) in `APICode18.py` "while it is not finished, store the old values, do an iteration, decide if its finished". The `doDataflow` program method should make calls to `do_dataflow_onestep` instruction methods (which is given). To perform set comparison you can have a look there:

`https://docs.python.org/3/library/stdtypes.html?highlight=set#set`

Note that assignments on Python sets (`set1 = set2`) only do a reference assignments (modifications to `set2` will also impact `set1`). To copy a set, use `set1 = set2.copy()`.

Carefully check that your results are correct at least with the examples of the `testsdataflow/` directory. As an example, here is the expected output for `testsdataflow/df04.mu`: [1]

```
In: {0: {}, 1: {}, 2: {temp_2}, 3: {temp_1}, 4: {}, 5: {},
     6: {temp_1}, 7: {temp_4}, 8: {temp_3,temp_1},
     9: {temp_3,temp_1,temp_4}, 10: {}, 11: {temp_4},
     12: {}, 13: {temp_5}, 14: {}, 15: {}, 16: {temp_6}, 17: {}}
Out: {0: {}, 1: {temp_2}, 2: {temp_1}, 3: {temp_1}, 4: {}, 5: {},
      6: {temp_3,temp_1}, 7: {temp_4}, 8: {temp_3,temp_1,temp_4},
      9: {temp_4}, 10: {temp_4}, 11: {},
      12: {temp_5}, 13: {}, 14: {}, 15: {temp_6}, 16: {}, 17: {}}
```

EXERCISE #5 ► Interference graph

We recall that two temporaries x, y are in conflict if they are simultaneously alive after a given instruction, which means:

- There exists a block (an instruction) b and $x, y \in LV_{out}(b)$
- OR There exist a block b such that $x \in LV_{out}(b)$ and y is defined in the block
- OR the converse.

[1] Here $r7$ is the register we use to encode nop instructions, we can ignore it while during the dataflow analysis (but not during code generation!)

For the two last cases, consider the following list of instructions:

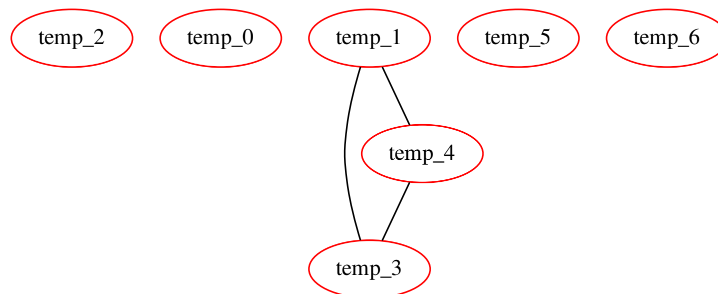
```
y=2
x=1
z=y+1
```

where x is not alive after the `x=1` statement, however x is in conflict with y since we generate the code for `x=1` while y is alive[2].

From the result of the previous exercise, construct the interference graph of your program (each time a pair of temporaries are in conflict, add an edge between them). We give you a non-oriented graph API (`LibGraph.py`) for that. Use the `print_dot` method and relevant tests to validate your code.

In this exercise, we care about correctness more than complexity. It is OK to write an $O(n^3)$ algorithm (for each t_1, for each t_2, for each control point c, check whether t_1 and t_2 have a conflict).

As an example, here is the conflict graph that should be obtained for `df04.mu`:



5.3 Register allocation and code production

Instead of the iterative algorithm of the course, we will implement the following algorithm for k register allocation [3]:

- Color the interference graph with $k-2$ colors.
- All the other variables will be allocated on the stack. To compute the offset from the stack pointer (sp), recolor the subgraph of remaining variables with an infinite number of colors.

Then the memory allocation:

- For non-spilled variable: replace the temporary with its associated color/register.
- For spilled variables: do the same as "all in mem" in Lab 4!

EXERCISE #6 ▶ Register Allocation

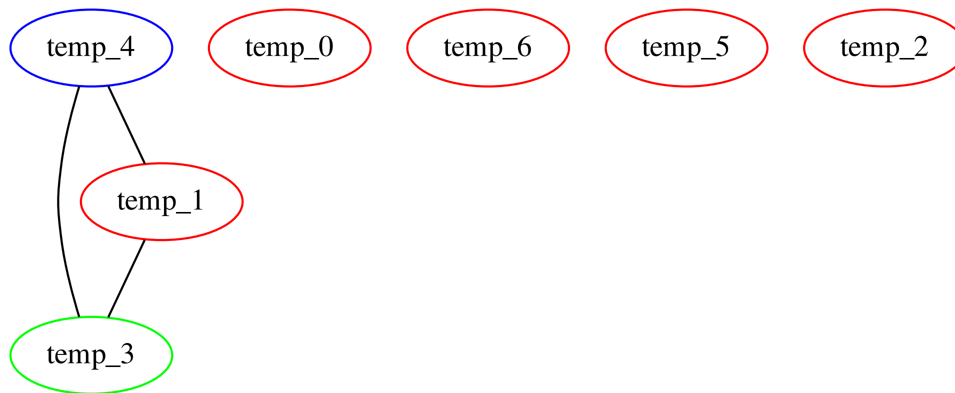
Use the algorithm (with k=8) and the coloration method of the `LibGraphes` class to allocate registers (or a place in memory). For that you have to complete the program method `smart_alloc`. Comments will help you design this (non trivial) function. The allocation itself is done by statement rewriting, like in Lab5. You **do** have to modify `Allocations.py`, it was a mistake, sorry..

Validate your allocation on tiny well chosen test files (especially tests that augment the register pressure) and all the benchmarks of the previous lab. We adapted the previous script for that.

On the `df04.mu` example, the graph coloring succeeds with:

[2] Another solution consists in eliminating dead code before generating the interference graph.

[3] $k = 8$ this year!



EXERCISE #7 ► **Massive tests**

Comment out all the print dot instructions, debug, ... and test on all test files you have. Make a clean archive with README, your test files, ... (same instructions as before) and put it on TOMUSS:

`http://tomuss-fr.univ-lyon1.fr`