

National University of Singapore

CS4212 Project Assignment 3

AY 2015/2016 Semester 1

Due Date: 22th November 2015 (Sunday, 23:59 Hrs)

In this final assignment, you are required to construct the back-end of the compiler for a subset of MOOL language, called MOOI (as in “MOOL mInus”). You have already translated valid MOOL programs into three-address code in *IR3* representation in your Assignment 2. In this assignment, you will be required to produce two artefacts (per team).

1. **You need to produce a MOOI compiler.** Specifically, while the front end of the MOOI compiler is given to you, you need to complete the compiler implementation by adding its backend. In particular, you are required to translate *IR3*-programs (corresponding to MOOI programs) into ARM assembly codes.
2. **You need to write a report.** This report describes how you intend to design those specific features available in MOOL but not in MOOI.

BONUS! If you can **implement** correctly most of the features of MOOL which are not available in MOOI, you can receive bonus point (up to 10 points).

Assessment The assessment of this Assignment is done by **team presentation**. Detail is as follows:

- **Code:** Your team will meet up with the TA to walk through your code, and to respond to questions raised by the TA during the session.
- **Design:** Your team will also do a presentation to explain the intended design for handling the features of MOOL language which are not available in MOOI language.
- **Bonus:** You may wish to demonstrate the implementation of these features, for the sake of securing your bonus points.
- The session for the above assessment activities will last for around 1 hour. All team members must be present. The time window in which you can make an appointment is **between 26th November till 30th November 2015, weekends and public holidays included**.
- **Marks:** The quality of the compiler you developed will constitute 60% of the total mark for Assignment 3, whereas the design constitutes 40% marks. The bonus is 10 marks outside the total marks of 100 for Assignment 3.

1 Forming Team

You are allowed to **work in groups of maximum four students**. Please go to the discussion forum to declare your group; also use the forum to request for team forming. Please do so by 25th October, 2015 (Sunday).

The earlier you declare your team, you earlier you begin your assignment. If you did not declare to be part of a team, we consider you a single-person team. If you need help finding a team, please post your request in the appropriate Forum topic.

All members in a team should contribute to the team's effort in all aspects of compiler construction, including documentation.

If you are very happy with a particular contribution of another member in the team, you can openly praise him/her by posting his/her name and contribution in the discussion forum, under the topic heading Project Assignment 3 (Honorable Mention). No tangible reward will be provided to the named person, nor the person who posts. But, who knows what intangible rewards there might be!

If you are unhappy with the contribution of another member in the team, you can send either the lecturer or the TA (or both) a private email describing your concern, and we shall investigate. Any team member found to be a free rider can get as low as zero mark for the assignment.

2 MOOI

MOOI is a sublanguage of MOOL language. Following is a list of features which MOOI **does not** have but MOOL has:

1. **Class hierarchy:** MOOI does not accept class hierarchy. Thus, effectively, MOOI is an *object-based* language rather than an *object-oriented* language.
2. **Access mode:** Attribute and method declarations in a MOOI class does not have access keyword such as *private*. Therefore, all attributes and methods declared in MOOI can be accessed called from somewhere outside the class.
3. **Method overriding/overloading:** MOOI does not allow method overriding, nor does it allow method overloading. As such, all method calls can be access statically (ie., during compilation.)

Even though MOOI is a sub-language, it is worth noticing that the front-end of compiler (that you will receive from this Assignment) will nevertheless operate on entire MOOL language. So, it's possible for you to provide as input both MOOI and MOOL programs to the compiler. This enables you to consider the possibility of writing the back-end compilation of MOOL program, thus scoring bonuses.

3 Resources and Expected Implementations

You are given the following resources:

1. Instructions on how to set up your machine to run ARM assembly programs. This is available in Appendix A.
2. A folder containing the following items:
 - (a) A compiler (comprising a set of OCaml code) that takes in MOOI programs and generates *IR3* code, and it is your job to enhance this to develop ARM code. You can add more Ocaml codes to complete the compiler.
 - (b) A Makefile that enables you to create the compiler. You may wish to modify this file.
 - (c) A subfolder named `testcases` that contains some MOOI programs accepted by the MOOI compiler and their corresponding ARM code produced. Please note that the ARM code are meant for your reference. As different teams will develop different optimizations, choose different register allocation strategy, the ARM code produced by different teams will be different.

In constructing the back-end compiler, you are required to implement the following:

1. Generation of offsets for each variable access;
2. Smart algorithms used for register allocation and assignment. Your grade will depend on the efficiency of register allocation and assignment.
3. An option for users to turn on and turn off a set of optimizations you have implemented. (Note, just one option to turn on/off all optimizations, not individual optimizations.) Again, your grade will depend on the efficiency and effectiveness of these implemented optimizations.

As the ARM code that you are about to handle represents a subset of the actual arm assembly instruction set, we include two simplifications in MOOI programs to be compiled (which you might wish to ignore, but without bonus rewarded):

1. As we don't consider ARM instructions that handles floating-point numbers, we do not allow the use of any operations related to floating-point operation. Thus, the accepted MOOL programs should not involve any division operation.
2. We skip the complication involved in reading data from console and convert it to the desired type. Therefore, the accepted MOOL program will not have `readln` statement. Consequently, your MOOL program cannot read any input; the program will assume all data is available for its computation.

4 Delivery

4.1 Where to begin?

1. **Elect a leader** for the team, whether you like it or not. This is especially important when you have even number of members in your team. Once elected, give respect him/her.
2. **Create an individual journal** to record the decisions made, the thoughts, your reflections. If possible, elect a secretary to record decisions made. Regardless, someone (and hopefully everyone) must keep records of the happenings.
3. You should start by **understanding the ARM architecture** and make sure that all members in your team understand how to run the system. If possible, try to obtain a fairly well understanding of the system by 29th October.
4. You should also plan out the tasks to be completed, and list down the tasks as detail as possible, and order them based on the actual timeline given. Find out the **critical path** in your execution, and put in place finer checks on tasks that fall on the critical path. In other words, do your project management!
5. Of course, delegate the tasks to individual members to work on, with deadline set.

4.2 Consultation

You will continue to use mainly the discussion forum to post your questions and help others in answering their questions. The TA will be active on the forum.

4.3 Defense

Important

You are required to book an appointment with the TA to (1) demonstrate the working of your program and (2) present your design idea for those non-MOOIrelated features. The session will happen between 26st November and 30th November 2015. Each of the appointment will be *one hour* long. During the session, you will show how your program will run against a set of test suites. You will have the chance to explain your design and implementation, and to debug your programs, as determined by the TA. For demonstrating the working of your code, if you require more than allotted time to complete the testing, you can request for a second (which is also the last) 30-minute session with the TA, sometimes later (up till 3rd Dec).

4.4 Submission of your product

In addition to testing your program in person, you are also required to:

- Create a good set of sample MOOL programs to test your product. Put in a subfolder those sample programs that you have created, and show their corresponding result.
- Create a **readme** text file to describe how one can make use of your test suites to validate the correctness of your programs.
- Create a **Design** text file detailing the idea you have about implementing those non-MOOI-related features.

Please submit a zipped item, named after you, containing the following documents to IVLE CS4212 website under the “Project Assignment 3 Submission” folder.

1. Your product.
2. Three sample programs that you have tried on your product
3. A document, named **CS4212 2015 Project Assignment 3 Details**, describing your product, the content of your submission, and any important information which you would like to share with us.

A Information about ARM Assembly Code

A.1 Setting up the ARM System

The arm assembly code generated by your compiler will be tested and executed on an Android system. Executing the code requires first generating object code, from the arm assembly code generated by your compiler, and second an environment in which to execute the code. In order to perform these two steps you will need to install Android NDK and Android SDK.

Android NDK

The NDK is a toolset that allows you to generate executable code for Android. In order to set up NDK you will first need to download a distribution for your system from:

<http://developer.android.com/tools/sdk/ndk/index.html>.

After downloading you will need to compile the toolset for your system. For Windows users this requires first installing Cygwin. Compiling is done by the following commands in a Cygwin or Unix shell:

```
$ export NDK="pathToDownload/android-ndk-r9-windows-x86_64/
android-ndk-r9"    With homebrew and OSX: export NDK="/usr/local/Cellar/android-ndk/r10d/"
$ $NDK/build/tools/make-standalone-toolchain.sh --platform=android-3
--install-dir=/tmp/my-android-toolchain --system=windows-x86_64
```

which will output: \$NDK/build/tools/make-standalone-toolchain.sh --platform=android-3 --
toolchain=arm-linux-androideabi4.9 --system=darwin-x86_64

```
Auto-config: --toolchain=arm-linux-androideabi-4.6
Copying prebuilt binaries...
Copying sysroot headers and libraries...
Copying libstdc++ headers and libraries...
Copying files to: /tmp/my-android-toolchain
Cleaning up...
Done.
```

Android SDK

The Android SDK provides the API libraries and developer tools necessary to execute the code for Android. The code for Android can be executed either on an emulator or a device running Android which has the developer tools enabled and is connected to the computer on which the SDK is installed and running.

In order to set up SDK you will first need to download a distribution for your system from: <http://developer.android.com/sdk/index.html>. The following steps are for Windows. Linux and Mac require the same sequence of commands.

Setting up an emulator and starting the emulator is then done using the commands:

```
$ pathToDownload/adt-bundle-windows-x86_64-20130729/sdk/tools/  
android avd  
$ pathToDownload/adt-bundle-windows-x86_64-20130729/sdk/tools/  
emulator -avd  
givenNameOfEmulator
```

A.2 Generating Executable Code for Android

Compiling and executing code for Android is done by the following sequence of steps run in a Cygwin or Unix shell:

1. Set up the compiler:

```
$ export PATH=/tmp/my-android-toolchain/bin:$PATH  
$ export CC=arm-linux-androideabi-g++
```

2. Compile using normal C/C++ commands or else a makefile. C, C++ assembler

```
$ $CC -o out input.s
```

3. Start an Android emulator:

```
$ pathToDownload/adt-bundle-windows-x86_64-20130729/sdk/tools/  
emulator -avd givenNameOfEmulator
```

4. After the emulator has booted, use adb to copy the object code to the emulator:

```
$ export PATH=pathToDownload/adt-bundle-windows-x86_64-20130729/  
sdk/platform-tools:$PATH  
$ adb push out /data/local/tmp
```

5. Then use adb to get a shell on Android:

```
$ adb shell  
root@android:/ # cd /data/local/tmp  
root@android:/data/local/tmp # ./out  
Hello World!  
root@android:/data/local/tmp # ls -la  
-rwx----- root root 140888 2013-10-07 06:17 out  
root@android:/data/local/tmp # exit  
$
```

```

1.  .data
2.  L1:
3.  .asciz "Hello World"
4.
5.  .text
6.  .global main
7.  .type main, %function
8.  main:
9.      stmfd sp!,{fp,lr,v1,v2,v3,v4,v5}
10.     add fp,sp,#24
11.     sub sp,fp,#32
12.     ldr a1,=L1
13.     bl printf(PLT)
14.
15. .L1exit:
16.     mov a4,#0
17.     mov a1,r3
18.     sub sp,fp,#24
19.     ldmfd sp!,{fp,pc,v1,v2,v3,v4,v5}

```

Figure 1: Hello World in ARM Assembler

A.3 Organization of ARM Assembly Code

An ARM assembly program is composed of a sequence of instructions. A simple “Hello World” program is shown in Figure A.3. The first part of the code (Lines 1-3) is optional and represents the data section of the program. The beginning of this section is denoted by the `.data` directive at Line 1. Line 5 denotes the start of the code section. Line 6 is mandatory and denotes the variable to be exported by the code. Line 7 sets the type of the exported variable as a function. Lines 8-19 represent the code section which is composed of the instructions for the main function.

A.3.1 Execution Environment

In order to understand the instructions in the code section you must first understand ARM registers and memory management. The memory model for an arm program is composed of registers, the stack, and the heap. The registers are used to hold values which are operated on by general data processing instructions such as arithmetic operations, boolean operations, compare operations and so on. As ARM is a RISC load and store architecture, before using a value stored in memory, this value must first be loaded into a register. After updating the value the memory can be updated to the new value by a store operation.

The stack is used to store local variables and temporary computations for functions as well as to create temporary register workspace for subroutines. Any registers that are needed can be pushed onto the stack at the start of the subroutine and popped off again at the end so as to restore them

Register	Name	Role
0	a1	Argument 1 / integer result / scratch register
1	a2	Argument 2 / scratch register
2	a3	Argument 3 / scratch register
3	a4	Argument 4 / scratch register
4	v1	Register variable 1
5	v2	Register variable 2
6	v3	Register variable 3
7	v4	Register variable 4
8	v5	Register variable 5
9	sb/v6	Static base / register variable 6
10	sl/v7	Stack limit / register variable 7
11	fp	Frame pointer
12	ip	Scratch reg. / new sb in inter-link-unit calls
13	sp	Lower end of current stack frame
14	lr	Link address / scratch register
15	pc	Program counter

Table 1: ARM registers

before return to the caller. The heap is used for dynamic data such as objects. Allocating objects on the stack can cause problems if objects are passed as arguments between functions. The memory is byte addressable with word (four bytes) addresses starting at multiples of four. In terms of registers, ARM has 15 general purpose registers in total, all of which are 32-bits long. These registers and their purpose are listed in Table 1.

A.3.2 Selected ARM Instruction Set

The set of instructions to be used in your assembly code is defined in the file `arm_structs.ml` in the workbin. This definition file is optional for your assignment. You can choose you define your own datatypes for ARM instructions.

The selected subset of arm instruction includes memory access instructions such LDR (Load) and STR (Store), general data processing instructions such as ADD, AND, CMP(compare), and control transfer or (branch instructions). The details of all these instructions can be found in section 4 in the

Arm_Assembler_Guide.pdf in the workbin. In order to understand how the datatypes defined in `arm_structs.ml` map to the instruction formats in Arm_Assembler_Guide.pdf let's look at the definitions.

1. General data processing instructions for performing arithmetic or boolean operations have the following format:

```
op{cond}{S} Rd, Rn, Operand2
```

where:

op is one of ADD, SUB, RSB, ADC, SBC, or RSC.

cond is an optional condition code.
 S is an optional suffix. If S is specified, the condition code flags are updated on the result of the operation.
 Rd is the ARM register for the result.
 Rn is the ARM register holding the first operand.
 Operand2 is a flexible second operand

This ARM format corresponds to the OCaml defined type:

```
data_instr_type =
  cond * bool * reg * reg * operand2_type
```

which can be instantiated as: `ADD ("",false,rd,r1,(RegOp r2))`

2. Memory access instructions LDR and STR have the following format:

```

op{cond}{B}{T} Rd, [Rn]
op{cond}{B} Rd, [Rn, FlexOffset]{!}
op{cond}{B} Rd, label
op{cond}{B}{T} Rd, [Rn], FlexOffset
where:
  op is either LDR (Load Register) or STR (Store Register)
```

This ARM format corresponds to the OCaml defined types:

```

type mem_instr_type =
  cond * word_type * reg * address_type

type address_type =
| LabelAddr of string
| Reg of reg
| RegPreIndexed of reg * int * bool
| RegPostIndexed of reg * int

type word_type = string
```

3. Instructions to compare values have the following format:

```

CMP{cond} Rn, Operand2
CMN{cond} Rn, Operand2
TST{cond} Rn, Operand2
TEQ{cond} Rn, Operand2
```

This ARM format corresponds to the OCaml defined type:

```
type cmp_instr_type = cond * reg * operand2_type
```

which can be instantiated to compare values in two registers for equality as: `CMP ("eq",r1, (RegOp r2))`).

4. Instructions to move a value from one register to another have with/without negating it have the following format:

```
MOV{cond}{S} Rd, Operand2
MVN{cond}{S} Rd, Operand2
```

This ARM format corresponds to the OCaml defined type:

```
type mov_instr_type = cond * bool * reg * operand2_type
```

which can be instantiated to perform a move when the greater than flag is set as: `MOV ("gt",r1, (RegOp r2))`).

5. Instructions to perform a jump with/without saving the return address in a link register have the following format:

```
B{cond} label
BL{cond} label
```

This ARM format corresponds to the OCaml defined constructors:

```
type arm_instr =
  ...
  | B of cond * label
  | BL of cond * label
  ...
```

which can be instantiated to perform a method call (an operation which requires saving the return address) to a method `methodName` as: `BL ("", "methodName")`).

There are a few more instructions not presented here such as instructions to load and store a list of registers (`stmfd`, `ldmfd`), an instruction for multiplication. These are presented at large in the assembly guide and defined in `arm_structs.ml` in the workbin.

A.3.3 Calling sequence

ARM defines a set of rules for function entry and exit so that:

- Object code generated by different compilers can be linked
- Procedures can be called between high-level languages and assembly languages.

These rules define:

- The mechanism for argument passing
- The usage of registers
- The usage of the stack
- The format of the stack-based data structure

The mechanism for argument passing involves passing the first four arguments in register a1-a4 and placing the rest, if the called function defines more than 5 parameters, on top of the stack. The return value is then placed in a1.

In terms of registers usage we can broadly classify all registers in two categories:

- Caller-saved that may change during a function call and thus the values stored in them prior to the method call must be saved by the caller before executing the method call.
- Callee-saved that must return unchanged after executing the body of a function.

The first category, caller-saved, contains registers r0-r3, or a1-a4. These registers, as the names in Table 1 suggest, are used to pass the first four arguments to a method call. Register a1 is also used to return the result. Lines 12 and 13 in the hello world example show a method call to a printf function and the passing of argument 1 in register a1. As registers a1 to a4 do not contain any values prior to the method call they are not saved by the caller before executing the call.

The second category, callee-saved, contains registers r4-r15. Registers r4-r8, also called v1-v5, are register variables that can be used as scratch registers to perform computations. Registers r9-r15 are registers for special purposes which can also be used as temporary variables if saved properly.

As callee-saved registers must be returned unchanged by a function they are saved in the prologue of a function and restored in the epilogue of the function. Line 9 in Figure A.3 saves registers v1-v5 and fp and lr using the instruction stmfd. The d suffix of stmfd denotes that saving is based on a descending stack which involves that the stack grows to small addresses (descending). The f in stmfd denotes that the stack pointer points to the last full location (full). The instruction at line 9 also post-updates the stack pointer (sp). Line 10 sets the frame pointer to point to the beginning of the stack frame for the function. Lines 18-19 restore the callee saved registers to their initial values. Line 18 sets the stack pointer to the top address (smallest address) pointing to a register saved in the epilogue. The ldmfd instruction at line 19, the reverse of stmfd, then loads from a full descending stack values into registers v1-v5 and fp and pc. By moving the value in lr (link register) in the pc register the control will be returned to the caller code.

In terms of stack management, traditionally, a stack grows down in memory, with the last “pushed” value at the lowest address. The ARM also supports ascending stacks, where the stack structure grows up through memory. The value of the stack pointer can either: point to the last occupied address (Full stack) and so needs pre-decrementing (ie before the push); or it can point to the next occupied address (Empty stack) and so needs post-decrementing (ie after the push). The stack type to be used is given by the postfix to the instruction: STMFD / LDMFD for Full Descending stack, STMED / LDMED for Empty Descending stack, etc. In our “Hello World” example we used a full descending stack.

A.3.4 Calling external functions

The MOOL language memory model depends on dynamic memory as well as static memory. Objects will reside in dynamic memory, or the heap, while other primitive variables and partial computations will reside on the stack. In order to allocate heap space you can make use of the existing function `_Znwj`. Calling this function is done as follows:

```
1.    mov a1,#4
2.    bl _Znwj(PLT)
3.    mov v5,a1
```

As can be seen the function takes one parameter which is the size in bytes of the memory space to be allocated (Line 1). The return is the address of the memory space allocated, which is returned after the call in argument register `a1` (Line 3).

Printing to the standard output can also be done using an external function. This function is `printf`. As can be seen from the hello world program in order to print a string literal the address of the string is loaded into register `a1` (Line 12) and then a branch instruction to the external function is performed (Line 13).

```
12.    ldr a1,=L1
13.    bl printf(PLT)
```

Calling `printf` to output an integer value requires two parameters. The first parameter specifies the format of the output. For this scenario the format specifies that an integer value is to be output (Lines 1-2, Line 2). The second parameter contains the value of the integer to be output which is 4 in this example (Line 4).

```
1. L4:
2.    .asciz "%i"
3.    ldr a1,=L4
4.    mov a2,#4
5.    bl printf(PLT)
```

B Samples of MOOL Compilation Results

```
class Main {
    void main(){
        Int a;
        Int b;
        Int i;
        Int d;
```

```

Int t1;
Int t2;
Compute help;

a = 1;
b = 2;
i = 3;
d = 4;

help = new Compute();

t1 = help.addSquares(a,b) + help.square(i);
t2 = help.square(d); // Should be equal to 16

if(t2>t1){
println("Square of d larger than sum of squares");
// Should be the output
}
else{
println("Square of d smaller than sum of squares");
}
}
}

class Compute {

    Bool computedSquares;
    Int chachedValue;

    Int square(Int a){
        return a*a;
    }

    Int add(Int a, Int b){
        return a+b;
    }

    Int addSquares(Int a, Int b){
        if(computedSquares){
            return chachedValue;
        }
        else{
            computedSquares = true;
            return add(square(a),square(b));
        }
    }
}

```

```
}  
}
```

```
.data  
  
L1:  
.asciz "Square of d larger than sum of squares"  
  
L2:  
.asciz "Square of d smaller than sum of squares"  
.text  
.global main  
  
Compute_1:  
stmfd sp!,{fp,lr,v1,v2,v3,v4,v5}  
add fp,sp,#24  
sub sp,fp,#28  
add v3,a2,a3  
mov a1,v3  
b .L4exit  
  
.L4exit:  
sub sp,fp,#24  
ldmfd sp!,{fp,pc,v1,v2,v3,v4,v5}  
  
Compute_2:  
stmfd sp!,{fp,lr,v1,v2,v3,v4,v5}  
add fp,sp,#24  
sub sp,fp,#48  
ldr a3,[a1,#4]  
cmp a3,#0  
beq .3  
ldr a1,[a1,#0]  
mov a1,a1  
b .L3exit  
b .4  
  
.3:  
mov v5,#1  
mov v5,v5  
str v5,[a1,#4]  
mov a1,a1  
mov a2,a2
```

```

bl Compute_0(PLT)
mov a3,a1
str a3,[fp,#-44]
mov a1,a1
ldr a2,[fp,#-36]
bl Compute_0(PLT)
mov v5,a1
mov a1,a1
ldr a2,[fp,#-44]
mov a3,v5
bl Compute_1(PLT)
mov a2,a1
mov a1,a2
b .L3exit

.4:

.L3exit:
sub sp,fp,#24
ldmfd sp!,{fp,pc,v1,v2,v3,v4,v5}

Compute_0:
stmfd sp!,{fp,lr,v1,v2,v3,v4,v5}
add fp,sp,#24
sub sp,fp,#28
mul a4,a2,a2
mov a1,a4
b .L2exit

.L2exit:
sub sp,fp,#24
ldmfd sp!,{fp,pc,v1,v2,v3,v4,v5}

main:
stmfd sp!,{fp,lr,v1,v2,v3,v4,v5}
add fp,sp,#24
sub sp,fp,#68
mov v5,#1
mov a4,v5
mov v5,#2
mov a3,v5
mov v5,#3
mov a2,v5
mov v5,#4
mov v1,v5
str a4,[fp,#-28]

```

```

str a3,[fp,#-32]
str a2,[fp,#-36]
mov a1,#8
bl _Znwj(PLT)
mov a4,a1
str a4,[fp,#-52]
ldr a1,[fp,#-52]
ldr a2,[fp,#-28]
ldr a3,[fp,#-32]
bl Compute_2(PLT)
mov v5,a1
ldr a1,[fp,#-52]
ldr a2,[fp,#-36]
bl Compute_0(PLT)
mov a4,a1
add a1,v5,a4
str a1,[fp,#-44]
ldr a1,[fp,#-52]
mov a2,v1
bl Compute_0(PLT)
mov a3,a1
ldr a4,[fp,#-44]
cmp a3,a4
movgt a1,#1
movle a1,#0
cmp a1,#0
beq .1
ldr a1,=L1
bl printf(PLT)
b .2

.1:
ldr a1,=L2
bl printf(PLT)

.2:

.L1exit:
mov a4,#0
mov a1,a4
sub sp,fp,#24
ldmfd sp!,{fp,pc,v1,v2,v3,v4,v5}

```