CS 242P – Winter Quarter 2023 – Prof. Dr. Michael Franz

MCS Course on Compilers
Main Project

In the main project assignment for this course, you will be asked to construct an optimizing compiler for the small and simple programming language `smpl`. The syntax of `smpl` is given at the end of this handout; the semantics of the various syntactical constructs are hopefully more or less obvious.

While it won't win any prizes for elegance, `smpl` was designed to be parsed by an LL parser with a single symbol lookahead. For example, for this reason assignments start with the keyword `let` and function calls start with the keyword `call` – you may consider this is a little bit ugly, but it removes the grammatical ambiguity that exists in many programming languages in which both assignments and function calls start with the same grammatical construct. For example, in C++ you may need to parse an unbounded number of symbols before you can decide whether you are seeing an assignment or a function call:

a[p->x + 17] -> f = 7   *// assign 7 to a member pointed to by array element a[p->x+17]*
a[p->x + 17] -> f (7)   *// call a routine stored in a function pointer a[p->x+17]->f*

Only when you reach the equal sign in the first example or the opening parenthesis in the second can you decide whether this is an assignment or a function call, and there is no upper limit to the number of symbols / characters that you may need to parse before you can make that decision. The `smpl` language doesn't have this problem, nor does it have the "dangling else" issue that affects many programming languages.

`smpl` has integers and arrays, and two kinds of functions: functions are either explicitly declared as `void` and don't return anything, or they return an integer. There are three predefined functions *InputNum*, *OutputNum*, and *OutputNewLine*. All arguments to functions are scalar (arrays cannot be passed as parameters). Note that, as is common in many programming languages, the names of these built-in functions are not keywords of the language grammar but regular identifiers that just happen to be defined already when parsing starts.

We will not be using any lexer or parser generator tools in this course but will build everything from scratch. It is much easier to understand what is going on, and you will have more control over the project. And because the language grammar is in the class LL(1), you should be able to build a recursive descent parser in no more than 2-3 hours. In fact, you should be able to build directly on the tokenizer and parser that you already constructed during the second warm-up assignment. The objective of this course is not to teach you about parsing, but about program optimization, which is a far more interesting problem that far fewer people understand.

The one tool that we *will* be using in this class is a graph visualization tool. It is almost impossible to debug the kind of complex dynamic data structures that are used in optimizing compilers without such tools. I would suggest that you use the simplest graph description language around, which is called "Dot" and which you can learn in about 5 minutes. The easiest way to translate a Dot graph description into a graph image is pasting the Dot program into the *http://www.webgraphviz.com* website, but there are many open-source graph viewers available as well that you can install on your machine.

This is a complex project and there is a danger that you will be overwhelmed by it. I strongly recommend that you start off by implementing a subset of the language first, leaving out user-defined functions and arrays altogether – and then add these only after you have thoroughly debugged the rest of your compiler. The built-in input and output functions of the language can be mapped directly onto the corresponding operations available in the intermediate representation.

Project Step 1

Build a simple recursive-descent parser for a subset of the `smpl` language that leaves out user-defined functions and arrays. Your front-end should generate an SSA-based intermediate representation (IR) appropriate for subsequent optimizations. Your intermediate representation will be a dynamic data structure in memory that models both individual instructions and super-imposed basic blocks. Perform copy propagation and common subexpression elimination.

The operations encoded in instruction nodes consist of an operator and up to two operands. The following operators are available (the meaning of *Phi* and *adda* will be explained in the lecture):

const #literal	define a constant
add x y	addition
sub x y	subtraction
mul x y	multiplication
div x y	division
cmp x y	comparison
adda x y	add two addresses *x* und *y (used only with arrays)*
load y	load from memory address y
store y x	store *y* to memory address *x*
phi x1 x2	***compute Phi(x1, x2)***

end	end of program
bra y	branch to *y*
bne x y	branch to *y* on *x* not equal
beq x y	branch to *y* on *x* equal
ble x y	branch to *y* on *x* less or equal
blt x y	branch to *y* on *x* less
bge x y	branch to *y* on *x* greater or equal
bgt x y	branch to *y* on *x* greater

In order to model the built-in input and output routines, we add three more operations:

read	read
write x	write
writeNL	writeNewLine

The language `smpl` discourages but does not prohibit the use of uninitialized variables. When you detect such a case, your compiler should emit a warning, but should continue compiling while assigning an initial value of zero.

In order to simplify your compiler, you may assume that all input programs are syntactically correct, that constant arithmetic doesn't generate overflow or divide-by-zero conditions, that variables are declared before they are used, and that no variable is declared more than once in the same lexical scope.

Project Step 2

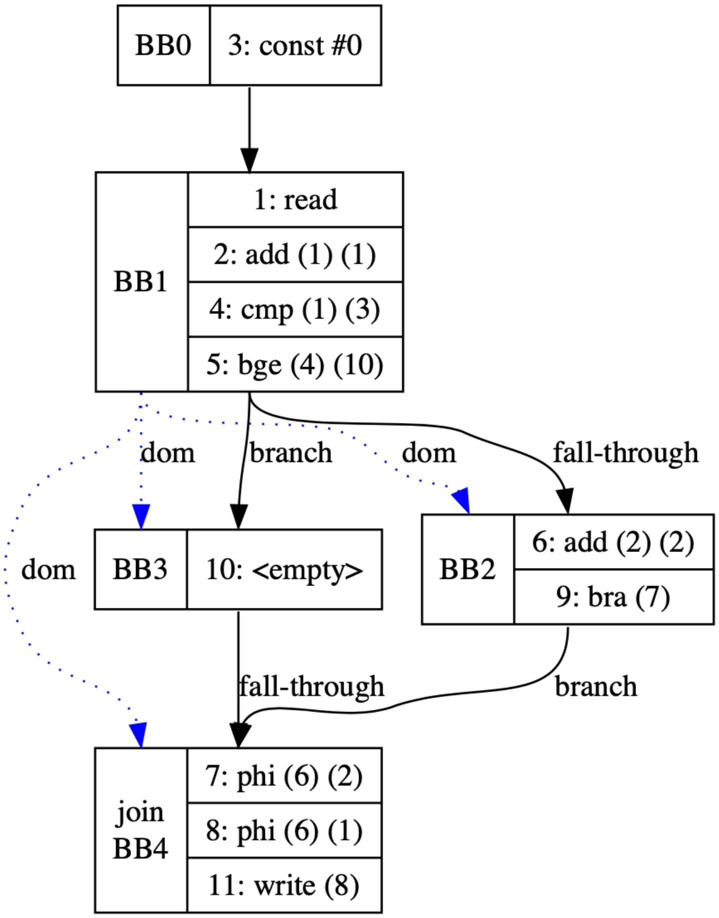
Build an IR visualization tool for your compiler that can walk the IR generated by your front-end and that generates a graph program appropriate for a graph visualizer. For example, the source program

```
main
var a, b, c, d, e; {
  let a <- call InputNum();
  let b <- a;
  let c <- b;
  let d <- b + c;
  let e <- a + b;
  if   a < 0   then   let d <- d + e; let a <- d   else   let d <- e   fi;
  call OutputNum(a)
}.
```

might be translated into the following graph program in the *Dot* graph language:

```
digraph G {
    bb0 [shape=record, label="<b>BB0 | {3: const #0}"];
    bb1 [shape=record, label="<b>BB1 |
                              {1: read|2: add (1) (1)|4: cmp (1) (3)|5: bge (4) (10)}"];
    bb2 [shape=record, label="<b>BB2| {6: add (2) (2)|9: bra (7)}"];
    bb3 [shape=record, label="<b>BB3| {10: \<empty\>}"];
    bb4 [shape=record, label="<b>join\nBB4|
                             {7: phi (6) (2)|8: phi (6) (1)|11: write (8)}"];
bb0:s -> bb1:n ;
bb1:s -> bb2:n  [label="fall-through"];
bb1:s -> bb3:n [label="branch"];
bb2:s -> bb4:n  [label="branch"];
bb3:s -> bb4:n  [label="fall-through"];
bb1:b -> bb2:b [color=blue, style=dotted, label="dom"]
bb1:b -> bb3:b [color=blue, style=dotted, label="dom"]
bb1:b -> bb4:b [color=blue, style=dotted, label="dom"]
}
```

Using a graph drawing engine such as GraphViz, this is then automatically translated into the following:



Note that the automatic graph layout engine in this case put the ***else*** block on the left and the ***then*** block on the right.

Project Step 3 (required for everyone)

After you are confident that your conversion to SSA works correctly, extend your compiler by adding array operations. This step also requires that you implement common subexpression elimination on redundant array loads that can be eliminated safely, since loads going to memory are among the most expensive operations on almost any platform.

Project Step 4 (required only for groups of two or more)

When you are confident that arrays have been implemented correctly, add user-defined functions to your language. In the compiler's IR, each function is modeled as a separate control flow graph. You will need to introduce an additional type of node in your IR that represents calls, linking the call location to the function being called and any actual parameters passed in the call to the formal parameters specified in the called function.

To make things much easier, you may interpret the `smpl` language definition in such a way that global variables are accessible only from inside the main() function.

Optional Project Step 5 (required only for groups of two or more)

Implement a global register allocator for your compiler. For this purpose, track the live ranges of all the individual values generated by the program being compiled, and build an interference graph. Color the resulting graph, assuming that the target machine has 5 general-purpose data registers. If more registers are required, map the values that cannot be accommodated onto virtual registers in memory. Eliminate all Phi-Instructions, inserting move-instructions wherever necessary. Display the final result using graph visualization, and perform experiments to test your implementation.

Optional Project Step 6 (required only for groups of three or four)

Write a code generator that emits optimized (CSE, copy propagation, register allocation) *native* programs in the *native load format of a real platform*. You may use the DLX processor simulator (groups of three) or choose your target platform from x86/Windows, x86/Linux (required for groups of four).

EBNF for the `smpl` Programming Language

letter = “a” | “b” | … | “z”.
digit = “0” | “1” | … | “9”.
relOp = “==“ | “!=“ | “<“ | “<=“ | “>“ | “>=“.

ident = letter {letter | digit}.
number = digit {digit}.

designator = ident{ "[" expression "]" }.
factor = designator | number | “**(**“ expression “**)**” | funcCall[1] .
term = factor { (“*” | “/”) factor}.
expression = term {(“+” | “-”) term}.
relation = expression relOp expression .

assignment = “**let**” designator “**<-**” expression.
funcCall = “**call**” ident [[2] “**(**“ [expression { “**,**” expression }] “**)**”].
ifStatement = “**if**” relation “**then**” statSequence [“**else**” statSequence] “**fi**”.
whileStatement = “**while**” relation “**do**” StatSequence “**od**”.
returnStatement = “**return**” [expression] .

statement = assignment | funcCall[3] | ifStatement | whileStatement | returnStatement.
statSequence = statement { “**;**” statement } [“**;**”][4] .

typeDecl = “**var**” | “**array**” “[“ number “]” { “[“ number “]” }.
varDecl = typeDecl indent { “**,**” ident } “**;**” .
funcDecl = [“**void**”] “**function**” ident formalParam “**;**” funcBody “**;**” .
formalParam = “**(**“ [ident { “**,**” ident }] “**)**” .
funcBody = { varDecl } “**{**” [statSequence] “**}**”.
computation = “**main**” { varDecl } { funcDecl } “**{**” statSequence “**}**” “**.**” .

Predefined Functions

InputNum()	read a number from the standard input
OutputNum(x)	write a number to the standard output
OutputNewLine()	write a carriage return to the standard output

[1] only non-void functions can be used in expressions, for example `y <- call f(x) + 1;`
[2] functions without parameters can be called with or without parantheses
[3] only void functions can be used in statements, e.g. `call do(); call this(x); call do;`
[4] the semicolon is a statement separator; non-strictly necessary terminating semicolons are optional