The BigDuck Programming Language

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Contents

Part I

Description and Technical Documentation

Chapter 1

Project

1.1 Introduction

1.1.1 Purpose

This document describes the software developement process, technical documentation, and user manual, for the final project of the Compiler Design course. Which consists on the design and implementation of a programming language and a virtual machine.

1.1.2 Scope

The programming language developed is specified to be a compiled imperative, with support of modules and structured types. Additionaly it is required to develop a virtual machine capable to execute the output code generated by the compiler.

1.2 Software Requirements

1.2.1 Analysis

Based on the specifications and recomendations given by the teachers, the following requirements were defined as necessary for the successful development of this project.

Functional requirements

1. The programming language must aim to solve a domain specific problem.
2. The compiler must support scoped and global variables.
3. The compiler must support numeric data types.
4. The compiler must support conditional statements.
5. The compiler must support loop statements.
6. The compiler must support modules.
7. The compiler must support recursion.
8. The compiler must support structured types.
9. The compiler must report compile-time errors.
10. The compiler must generate intermidiate code.
11. The virtual machine must execute generated code.
12. The virtual machine must manage program memory.
13. The virtual machine report run-time errors.

Non-Functional requirements

1. The language grammar must be non-ambiguous.
2. The compiler shall use a scanner and parser generation tool.
3. The compiler must be efficient in time and memory.
4. The virtual machine must be efficient in time and memory.

1.3 Software Developement Process

1.3.1 Developement Process Description

The project was developed throught weekly sprints, were each sprint consisted in developing a major feature needed for the programming language compilation or execution. It must be said that despite having an suggested schedule, the reality is that the project went a little bit different from this schedule. This is because some features were prioritize to be implemented first.

1.3.2 Weekly Log

Date	**Description**
Sep 20	Proposal Developement
Sep 27	Lexic and syntax analysis
Oct 4	Symbol table and sematic cube
Oct 11	Expressions compilation
Oct 18	Conditionals compilation
Oct 25	Loops compilation
Nov 1	Procedures compilation
Nov 8	Semantic analysis, memory layout, and virtual machine
Nov 15	Structured types compilation, and application specific code

1.3.3 Git Commitments

Note Not all commits are included in this table because some of them are not directly related with the project (like `README.md`, `.gitignore` updates or documentation advacements).

Date	Title	Observations
Sep 27	First Commit	The work done throught the previous HWs were really useful to getting to know ANTLR and make easier the developement.
Sep 29	Parser and Lexer working	It was necessary to make some changes on the grammar to make easier and more concise the implementation.
Oct 5	Advance in semantic analysis	The implementation of a symbol table can be somewhat easy if the concept of symbol is well defined.
Oct 8	Semantic for variables	Despite having a symbol table it is necessary to have additional flags to keep track the context of variables in order to have correct identification of variables.
Oct 9	Semantic for procedures and arguments	Some changes in the syntax were done, since it was not clear enough for the compiler and also for myself.
Oct 9	Variable and expression semantic done	Despite having a symbol table it is necessary to have additional flags to keep track the context of variables in order to have correct identification of variables.
Oct 14	TAC generation	Three address code can be simple to be generated by hand, however to implement it has to be done carefully.
Oct 16	Bugs corrected	There were associativity problems, this was due that all performed actions were done one level deeper on the syntax tree generation, thus as seen in class the associativity was done right to left.

Date	Title	Observations
Oct 25	Conditional and infinite loops implemented	It is important to keep track of loop jumps, otherwise there can be infinte loops on execution.
Oct 28	For style loop implemented	Looking at the generated code I can tell there are optimizations that can be done, however they are probably not done while generating the IR code, since sometimes context is needed to perform such optimizations.
Oct 28	Skip and break implemented	Despite having a jump stack and similar structures to handle the nesting of conditions and loops, some other structures like queues are necesarry to solve this control flow statements.
Nov 6	Procedures implemented	Procedure calls are fairly easy to understand however the details required for them to work in a virtual machine are still needed to be solved.
Nov 7	Semantics for expressions implemented	Despite having worked on the semantic cube, it was not used since it was not a priority. However now that I am seeking to working on the memory layout, having this validation will make it much more easy and reliable to implement.
Nov 8	Semantics for procedures implemented	The memory mapper is great stategy to create the context independant variables for each procedure.
Nov 9	Parameters semantics implemented	Way back to the implementation of the symbol table, I had already thought on having information regarding parameter types, thus the compiler had almost implemented this check.
Nov 9	Return type semantics implemented	Way back to the implementation of the symbol table, I had already thought on having information regarding return types, thus the compiler had almost implemented this check.

Date	Title	Observations
Nov 10	Variable-Address mapping implemented	Implementing the variable-address mapping right on expression compilation has the benefit to be more memory efficient, since only used variables are included on the memory count.
Nov 11	`.quack` file generation	Once the IR code was generated it was only necessary to append it to some instructions to initialize global memory.
Nov 14	Reading of `.quack` files and global memory initialization	The `.quack` files were change to only be a single line string of opcodes and addresses to simplify the reading. This files are meant for computer readability, not for humans.
Nov 14	Era, Goproc, Bool Operators implemented	I decided to implement this operators first because they are somewhat direct.
Nov 15	Basic language features implemented	The implementation of arithmetic operations on the virtual machine is long, boring, and repetitive, but easy. On the other side it is really interesting to see code execution.
Nov 15	Print implemented	Nothing to be said, just the implementation of the print instruction on the virtual machine.
Nov 15	Procedure calls implemented	This was a really interesting problem to solve since it involve on the implementation of a memory stack to handle procedure calls.
Nov 16	Procedure fully working in vm	I was originally stuck since there was no direct solution for this, however, after some thought I was able to implement a parameter buffer to then assign the correspondant values on the context of the function.

Date	Title	Observations
Nov 19	Arrays implemented	Arrays were perhaps one of the most *"challenging"* features to implement, not because of IR code generation, rather the implementation of indirection was not clear to do on the virtual machine. However after some thought I was able to come with a simple but efective solution to the problem.
Nov 19	Tensors implemented	n-dimensional arrays, or as I call them *tensors*, were actually super easy to implement after the experience gained with the implementation of arrays.
Nov 20	Special scalar procedures implemented	The implementation of this functions really helps with the user experience while using the language, since commonly used functions are no longer needed to be implemented on every program and also they are more eficient, since they are just a library call.
Nov 21	Special vectorial procedures implemented	Similar to scalar procedures, these were fairly easy to implement. It just required rebuilding the vectors inside the virtual machine and perform operations.
Nov 22	Procedure call nesting error message added	Throughtout testing I noticed that it was not possible currently to handle procedure call nesting. The solution is relatively easy (it requires stacks), however due to the remaining time, I decided to leave it out of the language for the delivery.

1.3.4 Test cases

No.	Description	Status
1	Support for global variables	Passed
2	Support for numeric data types	Passed
3	Support for conditional statements	Passed
4	Support for loop statements	Passed
5	Support for modules	Passed
6	Support for recursion	Passed
7	Support for structured types	Passed
8	Support for compile-time error	Passed
8	Support for intermidiate code generation	Passed
9	Support for execution of generated code	Passed
10	Support for memory management	Passed
11	Support for run-time errors	Passed

Chapter 2

Language

2.1 General Overview

2.1.1 Language Name

The programming language was given as a small joke, one of the homeworks on the semester was to develop a scanner and parser for a small language called LittleDuck. Therefore BigDuck could be considered as the next step for the previous mentioned language, even though there is no similarities but the name between these languages.

Additionaly to this, I really like birds and use them as a naming scheme for my devices, thus the decision seemed natural and adecuate.

2.1.2 Main Features Description

BigDuck is language aimed for the developement mathematical and scientific computations, numerical methods, and some basic statistics. Therefore this language includes integer and floating point arithmetic, trigonometric and trascendental functions, other commonly used math operations, and vector operations to support some statistical functions.

2.2 Language Errors

2.2.1 Compile-Time Errors

Error message	Description
Duplicate symbol	This occurs when the current symbol is already used on the declared scope.
Variable was not declared	This occurs when the current variable has not been previously declared.
Procedure was not declared	This occurs when current procedure has not been previously declared.
Void procedure used in expression	This occurs when there is no return value on the procedure call in an expression.
Procedure expected n arguments, given m	This occurs when the procedure call was given m arguments but it does not match with expectected n atributes specified on declaration.
Type error mismatch	This occurs when an operation can not be performed with the given operands.
Expected boolean expression	This occurs when an expression inside a condition (if's or loop's) does not evaluate to a boolean value.
Parameter expected to be a, given b	This occurs when the parameter of type b does not match with type a expected by the procedure.
Return type different from procedure sign	This occurs when the returned value does not match with the return type expected.
Tensor dimension must be constant	This occurs when a tensor is declared with variable dimension.
Tensor dimension must be greater than 0	This occurs when a tensor is declared with a not valid dimension.

Error message	Description
Index value must be of type int	This occurs when the index for a tensor does not resolve into an integer value.
Tensor access does not match with dimensions	This occurs when the number of indexes for a tensor does not match with the declared dimensions.
Scalar value cannot be indexed	This occurs when it is attempted to index a scalar variable.
Cannot use control flow statements outside of loops	This occurs when a control flow statement was used outside of a loop.
Procedure call nesting is not supported for user procedures	This occurs when it is attempted to call a function inside a user procedure parameter.
Cannot perform operation on scalar values	This occurs when it is attempted to use a vectorial function with an scalar value as a parameter.
Cannot perform operation on a boolean vector	This occurs when it is attempted to use a vectorial function for numeric types with an boolean vector as a parameter.
Cannot perform operation on higher dimensions	This occurs when it is attempted to use a vectorial function over a higher dimensional tensor.

2.2.2 Run-Time Errors

Error message	Description
Local address used in data segment	This occurs when it is attempted to initialize a local address before having a local context setup.
Invalid address used in data segment	This occurs when it is attempted to initialize an address that does not conform to with address specification.
Unexpected operator at data segment	This occurs when an operator is used on a segment it was not supposed to be.
Unexpected operator	This occurs when an the virtual machine cannot recognized a given operator.
Type error mismatch	This occurs when an operation can not be performed with the given operands.

Chapter 3

Compiler

3.1 Development Environment

The BigDuck compiler will be developed using the Go programming language. Antlr4 will be used as lexer and parser generator. And it will be developed on MacOS, any other system support is not considered. Nevertheless with access to a Go compiler and ANTLR, it should be possible to run the BigDuck compiler however this has not been tested.

3.2 Lexical Analisis

Reserved Keywords

proc	return	if	else	loop	break	skip	and
or	not	var	int	float	bool	true	false
print	read	sin	asin	cos	acos	tan	atan
atan2	exp	exp	ln	sqrt	pow	mod	abs
ceil	floor	mean	median	mode			

Tokens

```
    DIGITS → [0-9]+
    LETTER → [A-Za-z]
      SIGN → “ - ”
   CTE_INT → sign?  digits
 CTE_FLOAT → sign?  digits (\. digits)?
        ID → letter (letter | [0-9] | “ _ ”)*
   COMMENT → “ #| ” .*?  “ |# ” *
```

3.3 Syntactical Analisis

Note The following grammar is not a one-to-one description of the grammar used in the compiler, this is because there are addtional rules just to have some breakpoints on the grammar required for compilation.

```
program → vars_decl procs_decl

vars_decl → var_decl var_decl
          | ϵ
var_decl → VAR ID next_var var_type ‘‘ ; ’’ next_var_decl
next_var → ‘‘ , ’’ ID next_var
          | ϵ
next_var_decl → var_decl next_var_decl
          | ϵ

var_type → scalar | tensor

scalar → INT | FLOAT | BOOL

tensor → dimension scalar
dimension → ‘‘ [ ’’ num_expr ‘‘ ] next_dimension ’’
next_dimension → dimension next_dimension
          | ϵ

procs_decl → proc_decl procs_decl
          | ϵ

proc_decl → PROC ID proc_args ret_type local_decl block

proc_args → ‘‘ ( ’’ ‘‘ ) ’’
          | ‘‘ ( ’’ ID next_args scalar next_types ‘‘ ) ’’
next_args → ‘‘ , ’’ ID next_args
          | ϵ
next_types → ‘‘ ; ’’ ID next_args scalar next_types
          | ϵ
```

```
 ret_type → “ -> ” scalar
          | ε

bool_expr → and_expr next_bool
next_bool → OR bool_expr
          | ε

 and_expr → not_expr next_and
 next_and → AND bool_expr
          | ε

 not_expr → (NOT | ε ) bool_term
bool_term → “ ( ” bool_expr “ ) ”
          | rel_expr
          | TRUE
          | FALSE
          | variable
          | proc_call

 rel_expr → num_expr rel_op num_expr
   rel_op → “ = ”
          | “ /= ”
          | “ < ”
          | “ > ”
          | “ >= ”
          | “ <= ”

 num_expr → prod_expr next_sum
 next_sum → ( “ + ” | “ - ”) num_expr
          | ε

prod_expr → factor next_prod
next_prod → (“ * ” | “ / ”) prod_expr
          | ε
```

```
     factor → “ ( ” num_expr “ ) ”
            | CTE_INT
            | CTE_FLOAT
            | variable
            | proc_call
            | functions

   variable | ID (dimension | ϵ )

  proc_call → ID “ ( ” (param | ϵ ) “ ) ”
      param → param_term next_param
 param_term → bool_expr
            | num_expr
 next_param → “ , ” param
      block → “ { ” stmts “ } ”

      stmts → stmt stmts
            | ϵ
       stmt → assigment “ ; ”
            | condition
            | loop_stmt
            | ctrl_flow “ ; ”
            | ret_stmt “ ; ”
            | proc_call “ ; ”
            | built_in “ ; ”

 assignment → variable “ <- ” (num_expr | bool_expr)

  condition → IF bool_expr block (alter | ϵ )

      alter → IF bool_expr block (alter | ϵ )

       loop → LOOP (for_style | while_style | infinite) block
  for_style →  (assignment | ϵ ) “ ; ” bool_expr “ ; ” assignment
while_style → bool_expr
   infinite → ϵ
```

$$
\begin{aligned}
\texttt{built\_in} &\rightarrow \texttt{print} \\
&\mid \texttt{read} \\[1em]
\texttt{functions} &\rightarrow \texttt{u\_func} \\
&\mid \texttt{bin\_func} \\
&\mid \texttt{vec\_func} \\[1em]
\texttt{print} &\rightarrow \texttt{PRINT `` ( '' print\_param ``) ''} \\
\texttt{print\_param} &\rightarrow \texttt{print\_term print\_next\_param} \\
\texttt{print\_term} &\rightarrow \texttt{bool\_expr} \\
&\mid \texttt{num\_expr} \\
&\mid \texttt{CTE\_STRING} \\
\texttt{print\_next\_param} &\rightarrow \texttt{`` , '' print\_param} \\
&\mid \epsilon \\[1em]
\texttt{u\_func} &\rightarrow \texttt{u\_funcs `` ( '' num\_expr ``) ''} \\
\texttt{u\_funcs} &\rightarrow \texttt{SIN | ASIN | COS | ACOS | TAN | ATAN} \\
&\mid \texttt{EXP | LN | SQRT | ABS | CEIL | FLOOR} \\[1em]
\texttt{bin\_func} &\rightarrow \texttt{bin\_funcs `` ( '' num\_expr `` , '' num\_expr ``) ''} \\
\texttt{bin\_funcs} &\rightarrow \texttt{ATAN2 | POW | LOG | MOD} \\[1em]
\texttt{vec\_func} &\rightarrow \texttt{vec\_funcs `` ( '' variable ``) ''} \\
\texttt{vec\_funcs} &\rightarrow \texttt{MEAN | MEDIAN | MODE}
\end{aligned}
$$

3.4 IR Code and Semantic Analisis

3.4.1 Operation Code

For this project the operation code can be considered as an instruction set, since each of this operation indicates an action to be perform by the virtual machine in order to achieve some computation. The operator code names were chosen to be like mnemonics to facilitate some developement tasks.

Operator	**Description**
NOP	Null operator, mainly used as null value for compilation checks.
ASG	Assignation.
OR	Logical or.
AND	Logical and.
NOT	Logical not.
EQ	Value equality comparison.
NEQ	Value inequality comparison.
LES	Less than comparison.
GRE	Greater than comparison.
LEQ	Less than or equal comparison.
GEQ	Greater than or equal comparison.
SUB	Arithmetic substraction.
ADD	Arithmetic addition.
DIV	Arithmetic division.
MUL	Arithmetic multiplication.
GOPROC	Indicates change to a procedure.
ERA	Indicates the framesizes for new memory to be allocated.
PARAM	Indicates value of the parameter to be passed to a procedure.
RETURN	Indicates the value to be returned by a procedure.
ENDPROC	Clears the procedure context and restores program execution
ASSERT	Run-time check for tensor index correctness.

Operator	Description
PRINT	Prints value to STDOUT.
PRINTLN	Prints value and newline char to STDOUT.
READ	Reads value form STDIN, and assigns it to a value.
SIN	Trigonometric sin function.
ASIN	Trigonometric arcsin function.
COS	Trigonometric cos function.
ACOS	Trigonometric arccos function.
TAN	Trigonometric tan function.
ATAN	Trigonometric atan function.
ATAN2	Trigonometric atan2 function.
EXP	Exponential function.
LN	Natural logarithm function.
SQRT	Square root function.
POW	Raise number x to the y power.
LOG	Logarithm base b of x.
MOD	Modulus base b of n.
ABS	Absolute value function.
CEIL	Ceiling function.
FLOOR	Floor function.
MEAN	Mean of a vector.
MEDIAN	Meadian of a vector.
MODE	Mode of a vector.
SET	Initializes global address with givenn values.
PROGRAM	Indicates program starting point on executable.

3.4.2 Virtual Addresses

The following enumerations were already used throughout compilation.

Scope enumeration

```
0 local
1 global
```

Type enumeration

```
2 0010 int
3 0011 float
4 0100 bool
5 0101 string
```

Therefore it seemed natural to used it as flags on a bit mask in order to assign the virtual addresses. An additional flag was need to add to have support indirection and consequently pointers.

Memory map

```
1 addressing mode bit
1 scope bit
3 type bits
7 address nibbles
```

Examples

```
0 0010 ... 0000 0000 → local int at address 0
0 1011 ... 0000 1010 → global float at address 10
0 0100 ... 0001 0110 → local bool at address 22
0 1101 ... 0000 1011 → string at address 11
1 1010 ... 0000 0101 → local pointer at address 5
```

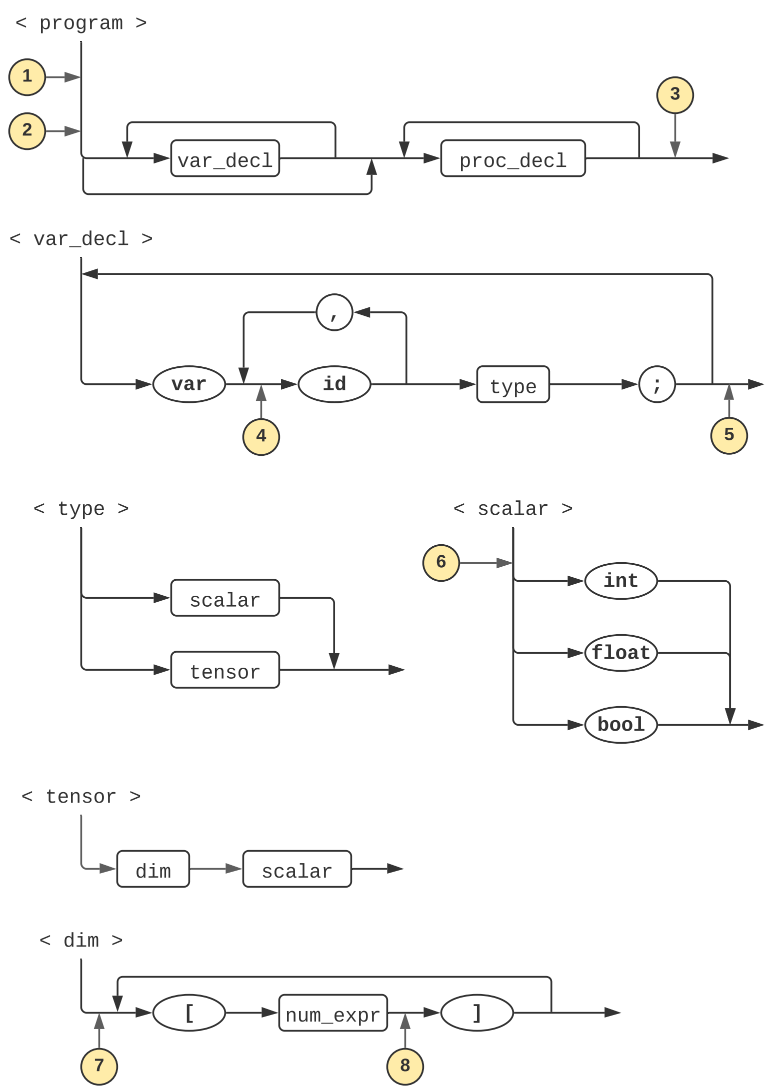
Note 1 All strings are global since they cannot be assigned to variables.

Note 2 All pointers are `int` since they hold an integer values.

This virtual address map can hold up to $2^{28} - 1 = 268,435,455$ addresses per each data type, which means that it can hold around 750 MB of data on a single program. I acknowledge that this is not the most memory efficient mapping however might be the simplest and most efective to implement.

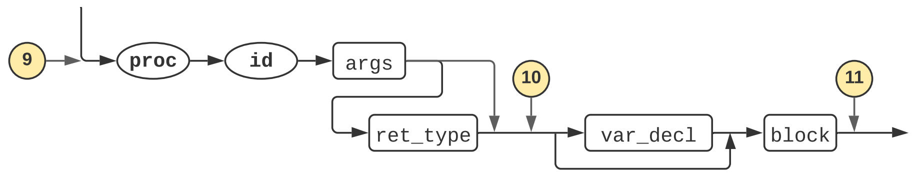
This page was left empty on purpose For easier read of the syntax diagrams with its actions, it is adviced to view the pdf by 2 pages. In such way that on left page are the diagrams and the right page are the actions description.

3.4.3 Syntax Diagrams with actions

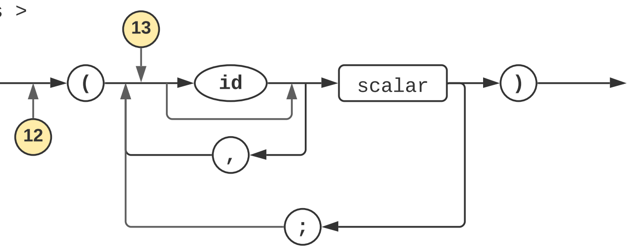


No.	Description
1	Compiler initialization
2	Generate era and goproc for starting procedure
3	If valid program the create obj file
4	If valid program the create obj file
5	Turn on in_decl flag
6	Turn off in_decl flag
7	Turn off in_decl flag
8	Use dimqueue and symqueue to create symbols and add each to symbol table, if symbol has been read then raise error

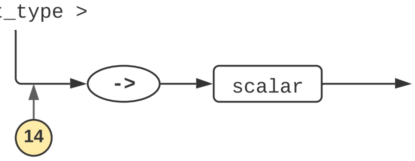
< proc_decl >



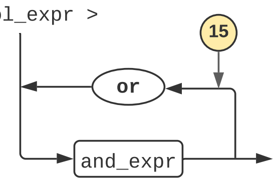
< args >



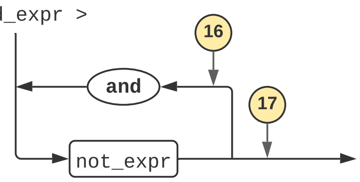
< ret_type >



< bool_expr >

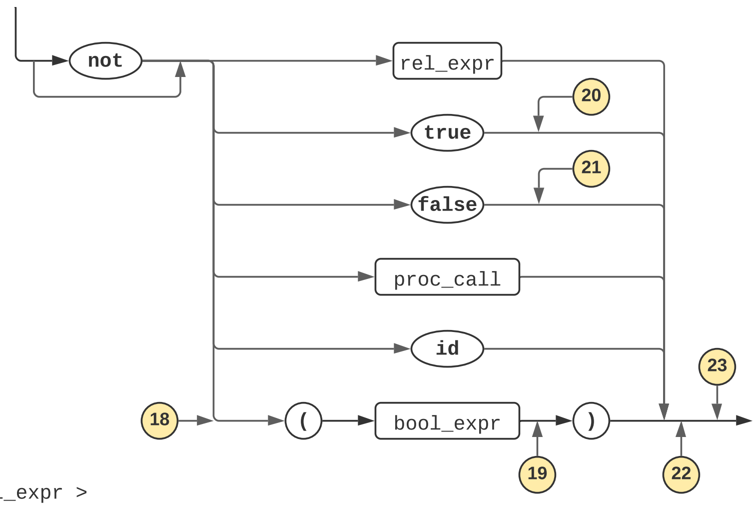


< and_expr >

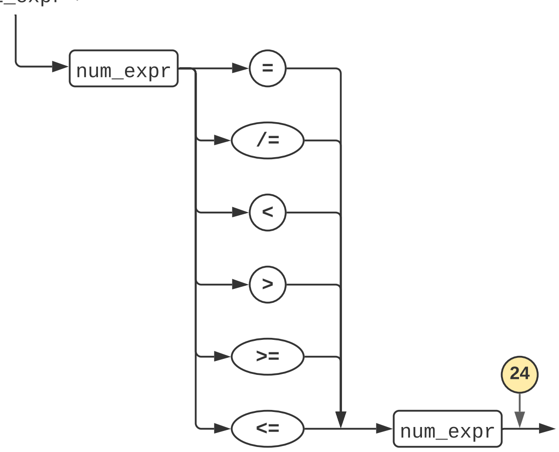


No.	Description
9	Add id to symbol table, if symbol has been read then raise error
10	Update procedure's parameter information, argc and ret_type
11	Generate endproc, update procedure's type counters, resolve recursive calls, and clear scope
12	Turn on in_decl and in_args flags
13	Push id to symqueue
14	Register return type
15	Push or to opstack
16	Push and to opstack
17	If or at top of opstack then GenerateOpTac

< not_expr >



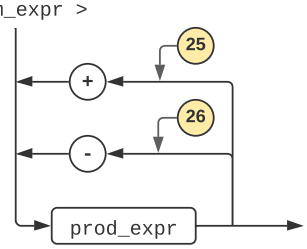
< rel_expr >



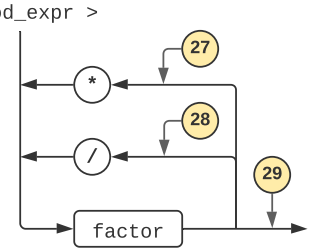
No.	Description
18	Push LPAREN to opstack
19	Push RPAREN to opstack
20	Push #t to argstack and push bool_t to typestack
21	Push #f to argstack and push bool_t to typestack
22	If and at top of opstack then GenerateOpTac
23	If not at top of opstack then GenerateOpTac
24	GenerateOpTac

Note Keep in mind actions 18 and 19, since they are reused.

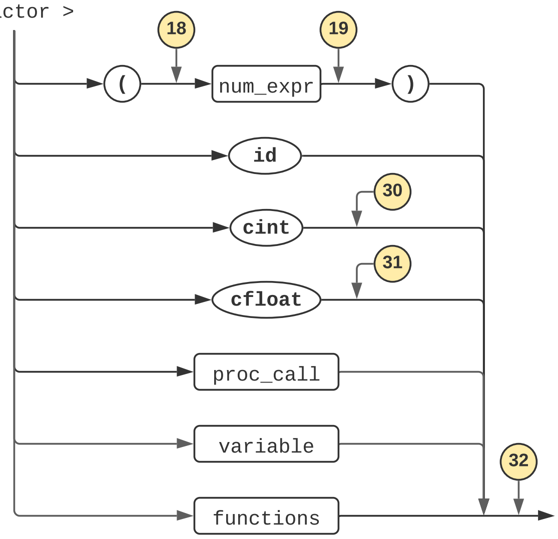
< num_expr >



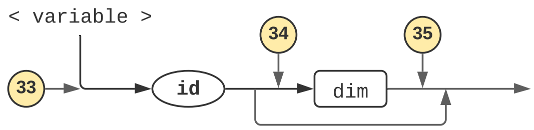
< prod_expr >



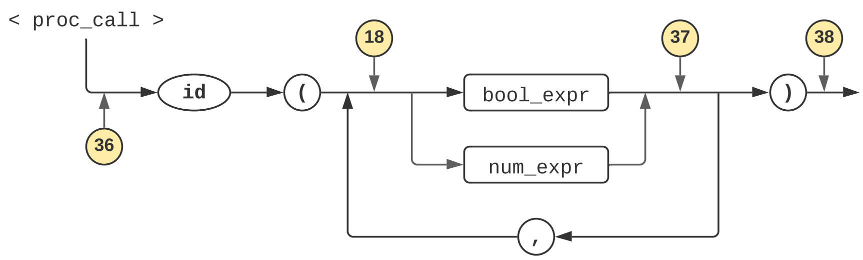
< factor >

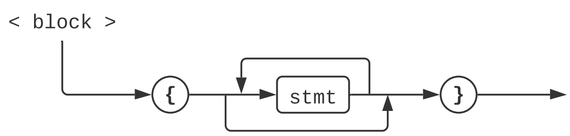


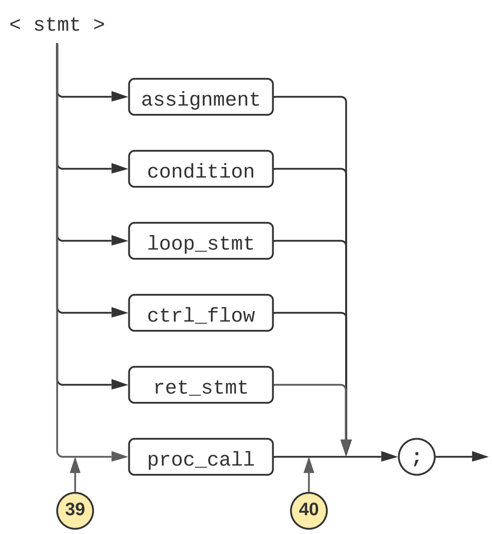
< variable >



No.	Description
25	Push + to opstack
26	Push — to opstack
27	Push * to opstack
28	Push / to opstack
29	If + or — at top of opstack then GenerateOpTac
30	Push int literal to argstack push int_t to typestack
31	Push float literal to argstack push float_t to typestack
32	If * or / at top of opstack then GenerateOpTac
33	Push id to argstack and its type to typestack
34	If id dimension is 0 then raise error else push LPAREN
35	Push RPAREN to opstack, if curr_dim is different from expected dimension then raise error

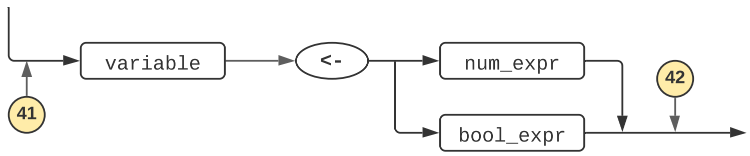

< proc_call >
id
(
18
bool_expr
num_expr
37
)
38
36
,


< block >
{
stmt
}

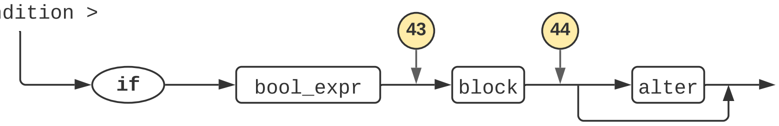

< stmt >
assignment
condition
loop_stmt
ctrl_flow
ret_stmt
proc_call
;
39
40

No.	Description
36	Init paramc, if curr_pcall is empty then assign id to curr_pcall else raise error, if exists in symtable the generate era else raise error
37	Push RPAREN to opstack, GenerateParamTac
38	if has return value then GenereteReturnTac else if in_stmt Generate goproc, if paramc different from procedures argc then raise error
39	Turn on in_stmt flag
40	Turn off in_stmt flag

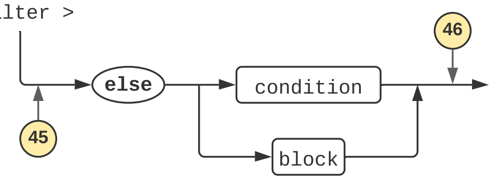
< assignment >



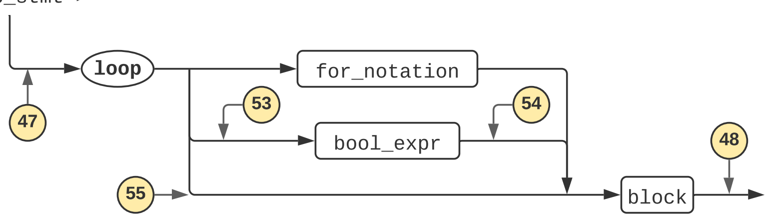
< condition >



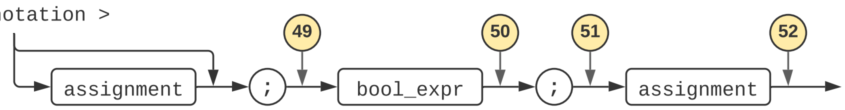
< alter >



< loop_stmt >

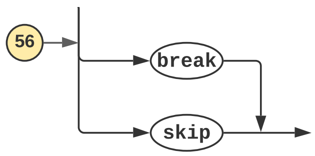


< for_notation >

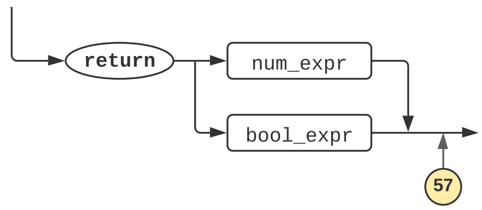


No.	Description
41	Push ← to opstack
42	GenerateOpTac
43	Push pc to jmpstack and GenerateJmpTac (JMF)
44	Pop jmpstack and use value fo FillJmpTac
45	Push pc to jmpstack and FillJmpTac
46	Pop jmpstack and use value fo FillJmpTac
47	Increment loop_nest
48	Fill unresolved jumps according loop style, fill skips and breaks, decrement loop_nest
49	Push pc to jmpstack and set loopstyle to ForStyle
50	Push pc to jmpstack, GenerateJmpTac (JMT), push pc to jmpstack and GenerateJmpTac (JMP)
51	Push pc to jmpstack
52	GenerateJmpTac (JMP), handle jumps for condition when true, false, and return from control variable assignment
53	Push pc to jmpstack and set loopstyle to WhileStyle
54	Push pc to jmpstack and GenerateJmpTac (JMF)
55	Push pc to jmpstack and set loopstyle to InfLoop

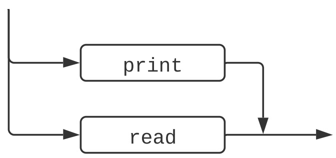
< ctrl_flow >



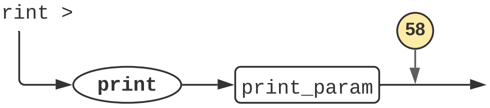
< ret_stmt >



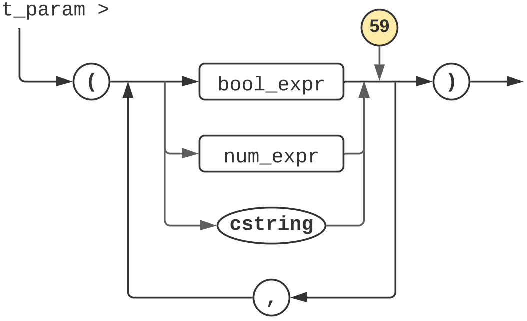
< built-in >



< print >



< print_param >



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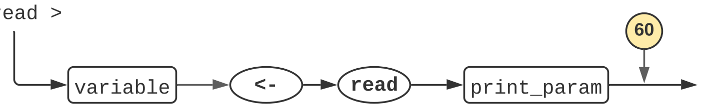
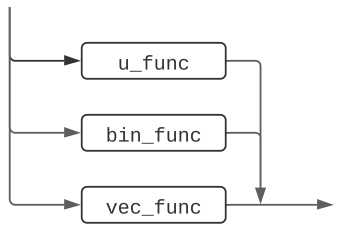
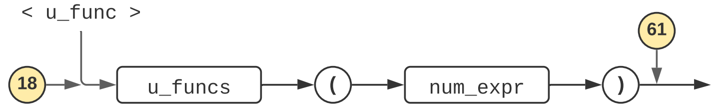


No.	Description
56	Push break or skip to its appropiate queue, GenerateJmpTac (JMP)
57	GenerateRetTac
58	Change last PRINT to PRINTLN
59	GeneratePrintTac
60	Pop argstack and typestack and use values to generate read TAC

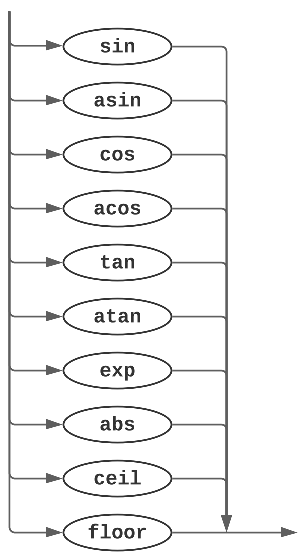
< functions >



< u_func >

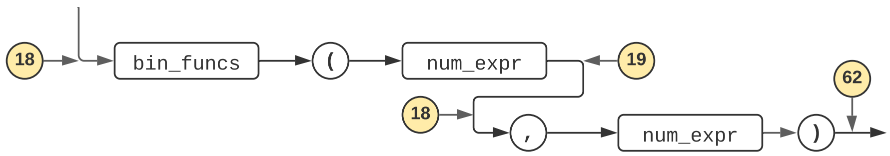


< u_funcs >

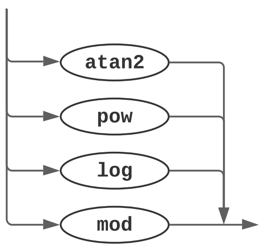


No.	Description
61	Push unary function to opstack, GenerateOpTac and push RPAREN to opstack

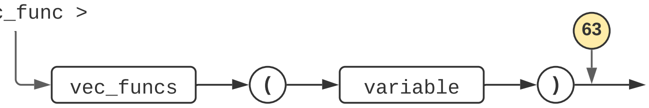
< bin_func >



< bin_funcs >



< vec_func >



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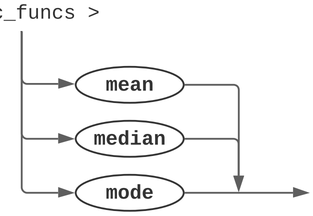


No.	Description
62	Push binary function to opstack, GenerateOpTac and push RPAREN to opstack
63	If variable exists and has appropiate dimensions then push vec function to opstack, GenerateOp-Stack

3.4.4 Semantic Consideration Table

Operator	**Type 1**	**Type2**	**Result type**
ASG	Int_t	Int_t	Int_t
ASG	Int_t	Float_t	Int_t
ASG	Int_t	Bool_t	Error_t
ASG	Float_t	Int_t	Float_t
ASG	Float_t	Float_t	Float_t
ASG	Float_t	Bool_t	Error_t
ASG	Bool_t	Int_t	Error_t
ASG	Bool_t	Float_t	Error_t
ASG	Bool_t	Bool_t	Bool_t
ADD	Int_t	Int_t	Int_t
ADD	Int_t	Float_t	Float_t
ADD	Int_t	Bool_t	Error_t
ADD	Float_t	Int_t	Float_t
ADD	Float_t	Float_t	Float_t
ADD	Float_t	Bool_t	Error_t
ADD	Bool_t	Int_t	Error_t
ADD	Bool_t	Float_t	Error_t
ADD	Bool_t	Bool_t	Error_t
SUB	Int_t	Int_t	Int_t
SUB	Int_t	Float_t	Float_t
SUB	Int_t	Bool_t	Error_t
SUB	Float_t	Int_t	Float_t
SUB	Float_t	Float_t	Float_t
SUB	Float_t	Bool_t	Error_t
SUB	Bool_t	Int_t	Error_t
SUB	Bool_t	Float_t	Error_t
SUB	Bool_t	Bool_t	Error_t

Operator	**Type 1**	**Type2**	**Result type**
MUL	Int_t	Int_t	Int_t
MUL	Int_t	Float_t	Float_t
MUL	Int_t	Bool_t	Error_t
MUL	Float_t	Int_t	Float_t
MUL	Float_t	Float_t	Float_t
MUL	Float_t	Bool_t	Error_t
MUL	Bool_t	Int_t	Error_t
MUL	Bool_t	Float_t	Error_t
MUL	Bool_t	Bool_t	Error_t
DIV	Int_t	Int_t	Int_t
DIV	Int_t	Float_t	Float_t
DIV	Int_t	Bool_t	Error_t
DIV	Float_t	Int_t	Float_t
DIV	Float_t	Float_t	Float_t
DIV	Float_t	Bool_t	Error_t
DIV	Bool_t	Int_t	Error_t
DIV	Bool_t	Float_t	Error_t
DIV	Bool_t	Bool_t	Error_t
AND	Int_t	Int_t	Error_t
AND	Int_t	Float_t	Error_t
AND	Int_t	Bool_t	Error_t
AND	Float_t	Int_t	Error_t
AND	Float_t	Float_t	Error_t
AND	Float_t	Bool_t	Error_t
AND	Bool_t	Int_t	Error_t
AND	Bool_t	Float_t	Error_t
AND	Bool_t	Bool_t	Bool_t

Operator	**Type 1**	**Type2**	**Result type**
OR	Int_t	Int_t	Error_t
OR	Int_t	Float_t	Error_t
OR	Int_t	Bool_t	Error_t
OR	Float_t	Int_t	Error_t
OR	Float_t	Float_t	Error_t
OR	Float_t	Bool_t	Error_t
OR	Bool_t	Int_t	Error_t
OR	Bool_t	Float_t	Error_t
OR	Bool_t	Bool_t	Bool_t
NOT	Int_t	Int_t	Error_t
NOT	Int_t	Float_t	Error_t
NOT	Int_t	Bool_t	Error_t
NOT	Float_t	Int_t	Error_t
NOT	Float_t	Float_t	Error_t
NOT	Float_t	Bool_t	Error_t
NOT	Bool_t	Int_t	Error_t
NOT	Bool_t	Float_t	Error_t
NOT	Bool_t	Bool_t	Bool_t
EQ	Int_t	Int_t	Bool_t
EQ	Int_t	Float_t	Bool_t
EQ	Int_t	Bool_t	Error_t
EQ	Float_t	Int_t	Bool_t
EQ	Float_t	Float_t	Bool_t
EQ	Float_t	Bool_t	Error_t
EQ	Bool_t	Int_t	Error_t
EQ	Bool_t	Float_t	Error_t
EQ	Bool_t	Bool_t	Bool_t

Operator	**Type 1**	**Type2**	**Result type**
NEQ	Int_t	Int_t	Bool_t
NEQ	Int_t	Float_t	Bool_t
NEQ	Int_t	Bool_t	Error_t
NEQ	Float_t	Int_t	Bool_t
NEQ	Float_t	Float_t	Bool_t
NEQ	Float_t	Bool_t	Error_t
NEQ	Bool_t	Int_t	Error_t
NEQ	Bool_t	Float_t	Error_t
NEQ	Bool_t	Bool_t	Bool_t
LES	Int_t	Int_t	Bool_t
LES	Int_t	Float_t	Bool_t
LES	Int_t	Bool_t	Error_t
LES	Float_t	Int_t	Bool_t
LES	Float_t	Float_t	Bool_t
LES	Float_t	Bool_t	Error_t
LES	Bool_t	Int_t	Error_t
LES	Bool_t	Float_t	Error_t
LES	Bool_t	Bool_t	Error_t
GRE	Int_t	Int_t	Bool_t
GRE	Int_t	Float_t	Bool_t
GRE	Int_t	Bool_t	Error_t
GRE	Float_t	Int_t	Bool_t
GRE	Float_t	Float_t	Bool_t
GRE	Float_t	Bool_t	Error_t
GRE	Bool_t	Int_t	Error_t
GRE	Bool_t	Float_t	Error_t
GRE	Bool_t	Bool_t	Error_t

Operator	**Type 1**	**Type2**	**Result type**
LEQ	Int_t	Int_t	Bool_t
LEQ	Int_t	Float_t	Bool_t
LEQ	Int_t	Bool_t	Error_t
LEQ	Float_t	Int_t	Bool_t
LEQ	Float_t	Float_t	Bool_t
LEQ	Float_t	Bool_t	Error_t
LEQ	Bool_t	Int_t	Error_t
LEQ	Bool_t	Float_t	Error_t
LEQ	Bool_t	Bool_t	Error_t
GEQ	Int_t	Int_t	Bool_t
GEQ	Int_t	Float_t	Bool_t
GEQ	Int_t	Bool_t	Error_t
GEQ	Float_t	Int_t	Bool_t
GEQ	Float_t	Float_t	Bool_t
GEQ	Float_t	Bool_t	Error_t
GEQ	Bool_t	Int_t	Error_t
GEQ	Bool_t	Float_t	Error_t
GEQ	Bool_t	Bool_t	Error_t
SIN	Int_t	Int_t	Float_t
SIN	Int_t	Float_t	Error_t
SIN	Int_t	Bool_t	Error_t
SIN	Float_t	Int_t	Error_t
SIN	Float_t	Float_t	Float_t
SIN	Float_t	Bool_t	Error_t
SIN	Bool_t	Int_t	Error_t
SIN	Bool_t	Float_t	Error_t
SIN	Bool_t	Bool_t	Error_t

Operator	**Type 1**	**Type2**	**Result type**
ASIN	Int_t	Int_t	Float_t
ASIN	Int_t	Float_t	Error_t
ASIN	Int_t	Bool_t	Error_t
ASIN	Float_t	Int_t	Error_t
ASIN	Float_t	Float_t	Float_t
ASIN	Float_t	Bool_t	Error_t
ASIN	Bool_t	Int_t	Error_t
ASIN	Bool_t	Float_t	Error_t
ASIN	Bool_t	Bool_t	Error_t
COS	Int_t	Int_t	Float_t
COS	Int_t	Float_t	Error_t
COS	Int_t	Bool_t	Error_t
COS	Float_t	Int_t	Error_t
COS	Float_t	Float_t	Float_t
COS	Float_t	Bool_t	Error_t
COS	Bool_t	Int_t	Error_t
COS	Bool_t	Float_t	Error_t
COS	Bool_t	Bool_t	Error_t
ACOS	Int_t	Int_t	Float_t
ACOS	Int_t	Float_t	Error_t
ACOS	Int_t	Bool_t	Error_t
ACOS	Float_t	Int_t	Error_t
ACOS	Float_t	Float_t	Float_t
ACOS	Float_t	Bool_t	Error_t
ACOS	Bool_t	Int_t	Error_t
ACOS	Bool_t	Float_t	Error_t
ACOS	Bool_t	Bool_t	Error_t

Operator	**Type 1**	**Type2**	**Result type**
TAN	Int_t	Int_t	Float_t
TAN	Int_t	Float_t	Error_t
TAN	Int_t	Bool_t	Error_t
TAN	Float_t	Int_t	Error_t
TAN	Float_t	Float_t	Float_t
TAN	Float_t	Bool_t	Error_t
TAN	Bool_t	Int_t	Error_t
TAN	Bool_t	Float_t	Error_t
TAN	Bool_t	Bool_t	Error_t
ATAN	Int_t	Int_t	Float_t
ATAN	Int_t	Float_t	Error_t
ATAN	Int_t	Bool_t	Error_t
ATAN	Float_t	Int_t	Error_t
ATAN	Float_t	Float_t	Float_t
ATAN	Float_t	Bool_t	Error_t
ATAN	Bool_t	Int_t	Error_t
ATAN	Bool_t	Float_t	Error_t
ATAN	Bool_t	Bool_t	Error_t
ATAN2	Int_t	Int_t	Float_t
ATAN2	Int_t	Float_t	Error_t
ATAN2	Int_t	Bool_t	Error_t
ATAN2	Float_t	Int_t	Error_t
ATAN2	Float_t	Float_t	Float_t
ATAN2	Float_t	Bool_t	Error_t
ATAN2	Bool_t	Int_t	Error_t
ATAN2	Bool_t	Float_t	Error_t
ATAN2	Bool_t	Bool_t	Error_t

Operator	Type 1	Type2	Result type
EXP	Int_t	Int_t	Float_t
EXP	Int_t	Float_t	Float_t
EXP	Int_t	Bool_t	Error_t
EXP	Float_t	Int_t	Float_t
EXP	Float_t	Float_t	Float_t
EXP	Float_t	Bool_t	Error_t
EXP	Bool_t	Int_t	Error_t
EXP	Bool_t	Float_t	Error_t
EXP	Bool_t	Bool_t	Error_t
LN	Int_t	Int_t	Float_t
LN	Int_t	Float_t	Error_t
LN	Int_t	Bool_t	Error_t
LN	Float_t	Int_t	Error_t
LN	Float_t	Float_t	Float_t
LN	Float_t	Bool_t	Error_t
LN	Bool_t	Int_t	Error_t
LN	Bool_t	Float_t	Error_t
LN	Bool_t	Bool_t	Error_t
SQRT	Int_t	Int_t	Float_t
SQRT	Int_t	Float_t	Float_t
SQRT	Int_t	Bool_t	Error_t
SQRT	Float_t	Int_t	Float_t
SQRT	Float_t	Float_t	Float_t
SQRT	Float_t	Bool_t	Error_t
SQRT	Bool_t	Int_t	Error_t
SQRT	Bool_t	Float_t	Error_t
SQRT	Bool_t	Bool_t	Error_t

Operator	**Type 1**	**Type2**	**Result type**
POW	Int_t	Int_t	Float_t
POW	Int_t	Float_t	Float_t
POW	Int_t	Bool_t	Error_t
POW	Float_t	Int_t	Float_t
POW	Float_t	Float_t	Float_t
POW	Float_t	Bool_t	Error_t
POW	Bool_t	Int_t	Error_t
POW	Bool_t	Float_t	Error_t
POW	Bool_t	Bool_t	Error_t
LOG	Int_t	Int_t	Float_t
LOG	Int_t	Float_t	Float_t
LOG	Int_t	Bool_t	Error_t
LOG	Float_t	Int_t	Float_t
LOG	Float_t	Float_t	Float_t
LOG	Float_t	Bool_t	Error_t
LOG	Bool_t	Int_t	Error_t
LOG	Bool_t	Float_t	Error_t
LOG	Bool_t	Bool_t	Error_t
MOD	Int_t	Int_t	Float_t
MOD	Int_t	Float_t	Float_t
MOD	Int_t	Bool_t	Error_t
MOD	Float_t	Int_t	Float_t
MOD	Float_t	Float_t	Float_t
MOD	Float_t	Bool_t	Error_t
MOD	Bool_t	Int_t	Error_t
MOD	Bool_t	Float_t	Error_t
MOD	Bool_t	Bool_t	Error_t

Operator	**Type 1**	**Type2**	**Result type**
ABS	Int_t	Int_t	Float_t
ABS	Int_t	Float_t	Error_t
ABS	Int_t	Bool_t	Error_t
ABS	Float_t	Int_t	Error_t
ABS	Float_t	Float_t	Float_t
ABS	Float_t	Bool_t	Error_t
ABS	Bool_t	Int_t	Error_t
ABS	Bool_t	Float_t	Error_t
ABS	Bool_t	Bool_t	Error_t
CEIL	Int_t	Int_t	Float_t
CEIL	Int_t	Float_t	Float_t
CEIL	Int_t	Bool_t	Error_t
CEIL	Float_t	Int_t	Float_t
CEIL	Float_t	Float_t	Float_t
CEIL	Float_t	Bool_t	Error_t
CEIL	Bool_t	Int_t	Error_t
CEIL	Bool_t	Float_t	Error_t
CEIL	Bool_t	Bool_t	Error_t
FLOOR	Int_t	Int_t	Float_t
FLOOR	Int_t	Float_t	Error_t
FLOOR	Int_t	Bool_t	Error_t
FLOOR	Float_t	Int_t	Error_t
FLOOR	Float_t	Float_t	Float_t
FLOOR	Float_t	Bool_t	Error_t
FLOOR	Bool_t	Int_t	Error_t
FLOOR	Bool_t	Float_t	Error_t
FLOOR	Bool_t	Bool_t	Error_t

Operator	**Type 1**	**Type2**	**Result type**
MEAN	Int_t	Int_t	Float_t
MEAN	Int_t	Float_t	Float_t
MEAN	Int_t	Bool_t	Error_t
MEAN	Float_t	Int_t	Float_t
MEAN	Float_t	Float_t	Float_t
MEAN	Float_t	Bool_t	Error_t
MEAN	Bool_t	Int_t	Error_t
MEAN	Bool_t	Float_t	Error_t
MEAN	Bool_t	Bool_t	Error_t
MEDIAN	Int_t	Int_t	Float_t
MEDIAN	Int_t	Float_t	Float_t
MEDIAN	Int_t	Bool_t	Error_t
MEDIAN	Float_t	Int_t	Float_t
MEDIAN	Float_t	Float_t	Float_t
MEDIAN	Float_t	Bool_t	Error_t
MEDIAN	Bool_t	Int_t	Error_t
MEDIAN	Bool_t	Float_t	Error_t
MEDIAN	Bool_t	Bool_t	Error_t
MODE	Int_t	Int_t	Float_t
MODE	Int_t	Float_t	Float_t
MODE	Int_t	Bool_t	Error_t
MODE	Float_t	Int_t	Float_t
MODE	Float_t	Float_t	Float_t
MODE	Float_t	Bool_t	Error_t
MODE	Bool_t	Int_t	Error_t
MODE	Bool_t	Float_t	Error_t
MODE	Bool_t	Bool_t	Error_t

3.5 Memory Management

3.5.1 Data structures

Tree listener

Element	**Description**
filename	Keeps the name of the source code to produce the executable.
valid	Flag to indicate whether an error has been found or not.
debug	Flag to indicate whether debug mode is toggled.
symtable	Table to keep track of the variable symbols and procedures used in source code.
symqueue	Queue to keep track of which symbols are under the same declaration list.
typequeue	Queue to keep track of which symbols are under the same declaration line.
paramqueue	Queue to keep track of which symbols are on the procedures parameters.
dimmqueue	Queue to keep track of which the dimensions used by a tensor.
in_decl	Flag to know if it is reading a variable declaration.
in_args	Flag to know if it is reading the arguments of a procedure.
in_stmt	Flag to know if it is reading a statement.
scope	Flag to know the current scope.
argc	Counter for arguments used in a procedure call.
loop_nest	Counter to keep track of loop nesting.
ret_type	Variable to keep track of current procedure's return type.
curr_proc	Variable to keep track of the name of current procedure.

Element	Description
ir_code	Array of TACs (three-address code) generated by the compiler.
data_seg	Array of TACs used for data segment generated by the compiler.
op_stack	Stack of operators for expression compilation.
arg_stack	Stack of arguments for operators for expression compilation.
type_stack	Stack of type variables for expression compilation.
pc	Program counter to keep track of generated TACs.
tmpc	Temporal counter to keep track of generated temporal variables.
tmpc	Temporal counter to keep track of generated temporal variables.
paramc	Parameter counter to keep track of number of parameters given to a procedure.
loopstyle	Variable to keep track of which kind of loop syntax is used.
startpoint	Variable to keep track of where to start the program.
startproc	Variable to keep track of the name of initial procedure.
curr_line	Variable to keep track of current line.
curr_column	Variable to keep track of current column.
curr_pcall	Variable to keep track of the name of current procedure call.
curr_tensor	Variable to keep track of the name of current tensor in use.
curr_dim	Variable to keep track of the name of current dimension index used in tensor indexing.
memmap	Memory mapper, to assign a memory address to a used variable.

Symbol

Element	Description
Stype	Enumeration to indicate the type of a variable.
Dim	Array to keep track of the dimensions of a variable.
Baddress	Base address, to keep track of base address for tensiorial types.
Argc	Argument count, to keep track of the arguments required for procedure.
TypeArgs	Array to keep track of the number of arguments of a procedure.
RetType	Variable to keep track of the return type of an argument.
Startpoint	Variable to keep track of the starting point of a procedure.
Paddress	Parameter address, array to keep track of the reserved addresses for the parameter.
Type count	Counters for the amount of variables of each type required.

Symbol Table

Element	Description
table	An array of size 2 of hash tables that take strings as keys and Symbols as values.

Memory mapper

Element	Description
memcache	Hash table of strings as keys and int as value, to store every symbol with a memory address.
Typecount	An array of size 2 of hash table that takes strings as keys and ints as values, to store a counter of used memory per scope and type.

3.5.2 Code generation overview

The general flow of the compiler is determined by the tree generated by the ANTRL parser. ANTLR parser indicates an interface, and the BigDuckListener, or tree listener for short, is an implementation of this interface. This interface has methods defined for entering and exiting each rule defined on `BigDuck.g4`. The implementation of this interface is on `tree_listener.go` here are all the data structures, mentioned on the previous section, used for compilation.

The code generation is scattered across `tree_listener.go` and `tac_gen.go`. The latter contains some specific and more complex methods that allows code generation of common elements like; operations, jumps, parameters, etc.

All data structures are defined inside the `structs` directory and the file `structs/enums.go` contains all the used enumerations for data types, operation code, scope, etc.

For symbol recognition, the symbols are constructed and sent to the symbol table. The symbol table has two tables, one for global variables, and a second for local variables. For symbol lookups the local scope is searched first and then the global scope is searched.

For address assignment, it is mostly done within the `GenerateOpTac`, this has the consecuence that only used variables have assigned memory. Before generating the TAC, a request is done to the memory mapper, which manages all addresses for variables. The only exceptions are parameters and tensors, which they are allocated whether there is TAC that uses these addresses or not.

Chapter 4

Virtual Machine

4.1 Development Environment

The BigDuck compiler will be developed using the Go programming language. Antlr4 will be used as lexer and parser generator. And it will be developed on MacOS, any other system support is not considered. Nevertheless with access to a Go compiler and ANTLR, it should be possible to run the BigDuck compiler however this has not been tested.

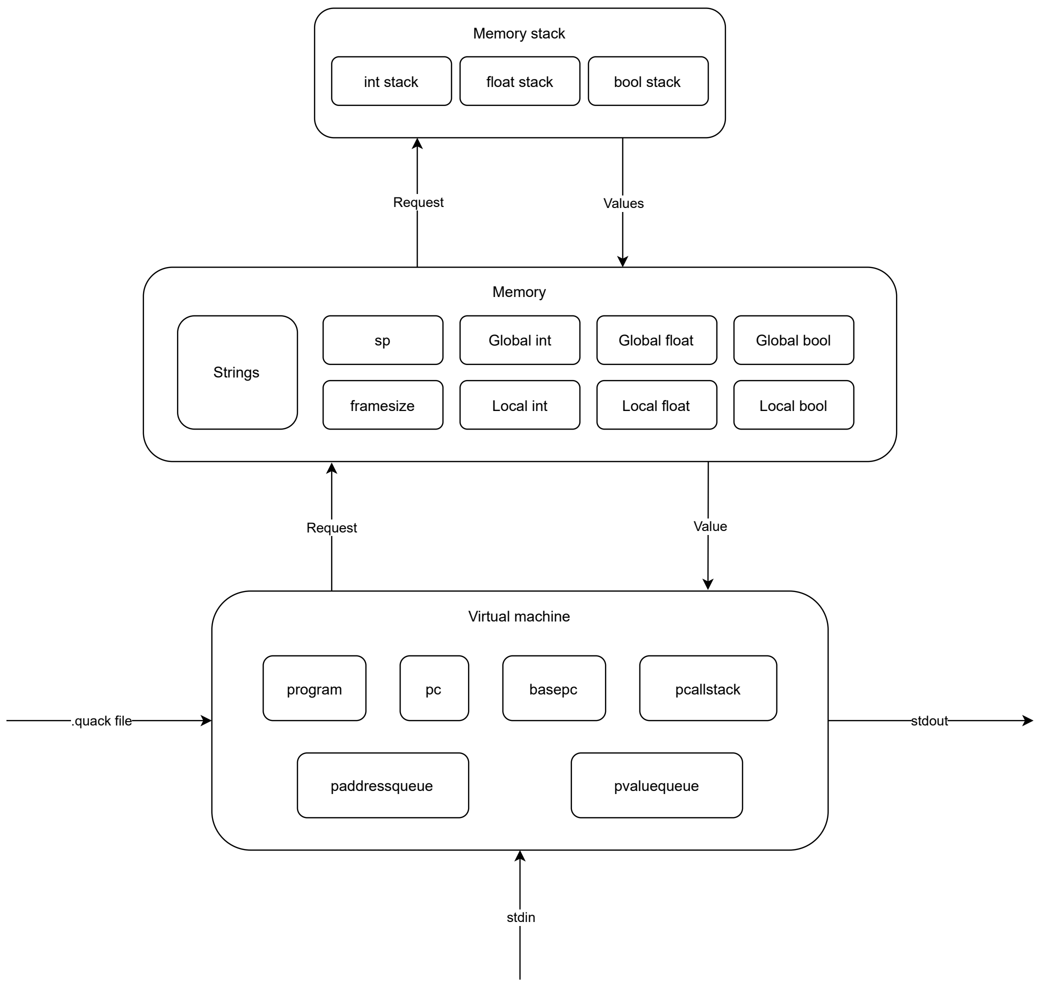
4.2 Memory Management

4.2.1 Architecture

The BigDuck virtual machine is influenced by the architecture used by the MOS 6502 8-bit microprocesor (mainly because this was the one we study in depth on the Computer Organization course). The features taken directly from this processor are the usage of stack pointers to handle function calls and recursion, and the usage of a program counter to keep track program execution.

There are three components, the *virtual* machine which is the one that manages program execution, the *memory* which stores all values and has stack pointers to handle contexts, and the *memory stack* which stores the frame sizes used by each context.

Figure 4.1: Architecture Diagram



4.2.2 Data Structures

Virtual machine

Element	Description
program	Array of three-address code structures which contains program instructions.
pc	Program counter, keeps track of the current instruction to execute.
basepc	Base program counter, points to the beginning of the program segment on the executable.
pcallstack	Procedure call stack, stores the next pc value before jumping to a procedure's code.
paddressqueue	Parameter address queue, stores the addresses of the parameters given to a procedure.
pvaluequeue	Parameter address queue, stores the value of the parameters given to a procedure.

Memory

Element	Description
strings	Stores string values.
sp	Stack pointer, points to the beginning of the frame on each memory pool.
framesize	Stores the size of the current frame.
Local and global pools	For each type, there are 2 pools to maintain the values used in each scope.

Memory Stack

Element	Description
Type stack	Stores the framesizes used by each procedure call.

4.2.3 Virtual Address Translation

Since the memory map is really simple, the virtual address translation is really simple. The following functions take the information embedded in the virtual address to determine; scope, type, address, and addressing mode.

```
func GetScope(address int) int {
    return address & (0x1 << 31) >> 31
}

func GetType(address int) int {
    return address & (0x7 << 28) >> 28
}

func GetAddress(address int) int {
    return address & 0x0ffffff
}

func IsPointer(address int) bool {
    return address & (0x1 << 32) != 0
}
```

4.2.4 Code execution overview

The general flow of the virtual machine starts by parsing the executable, the executable consiste of a series of strings separated by spaces, each string may represent an operation, address, or value.

After parsing the executable the instructions are passed to the virtual machine. First the global memory is initialized, and the code execution is performed. The program counter is a number that tells which instruction is to execute next. After reading the instruction, according to the operator the action is performed over the operators if any.

The memory is handle by the memory struct, this struct maintains the information to handle global and local memory. According to the virtual address the virtual machine determines which memory pool to access, and even for pointers the logic is done by the virtual machine. The memory struct has no decision and only holds values.

Chapter 5

Execution Evidence

5.1 Test Cases

5.1.1 Factorial

```
#| Iterative factorial implementation |#
proc fact_iter(n int) -> int
    var acc int;
{
    loop acc <- 1; n > 0; n <- n - 1 {
        acc <- n * acc;
    }

    return acc;
}

#| Recursive factorial implementation |#
proc fact_rec(n int) -> int {
    if n <= 0 {
        return 1;
    } else {
        return n * fact_rec(n - 1);
    }
}
```

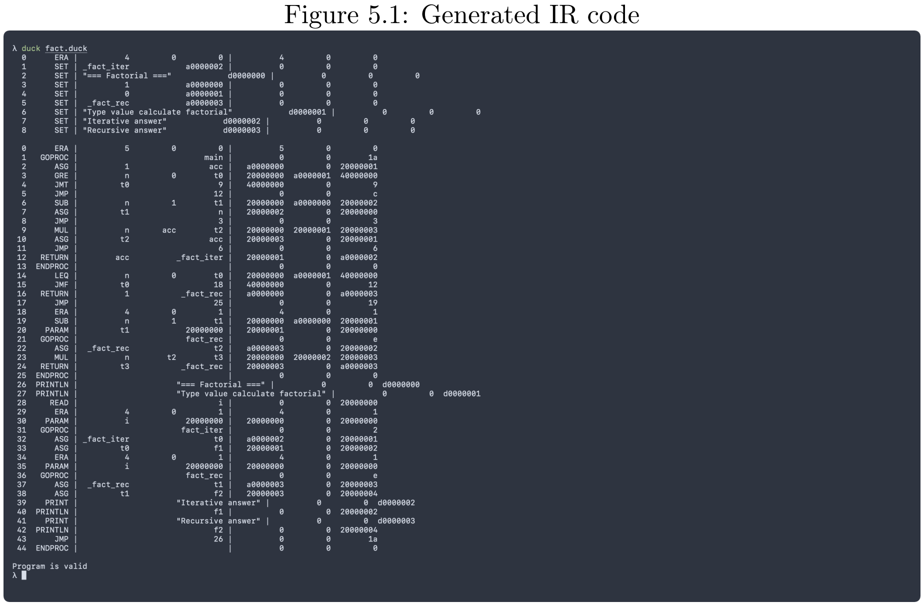
```
#| Main procedure |#
proc main()
    var f1, f2, i int;
{
    loop {
        print("=== Factorial ===");

        i <- read("Type value calculate factorial");

        f1 <- fact_iter(i);
        f2 <- fact_rec(i);

        print("Iterative answer", f1);
        print("Recursive answer", f2);
    }
}
```

Figure 5.1: Generated IR code



```
λ duck fact.duck
  0      ERA |          4         0         0 |          4         0         0
  1      SET | _fact_iter          a0000002 |          0         0         0
  2      SET | "=== Factorial ==="          d0000000 |          0         0         0
  3      SET |          1          a0000000 |          0         0         0
  4      SET |          0          a0000001 |          0         0         0
  5      SET |  _fact_rec          a0000003 |          0         0         0
  6      SET | "Type value calculate factorial"          d0000001 |          0         0         0
  7      SET | "Iterative answer"          d0000002 |          0         0         0
  8      SET | "Recursive answer"          d0000003 |          0         0         0

  0      ERA |          5         0         0 |          5         0         0
  1   GOPROC |                           main |          0         0        1a
  2      ASG |          1                 acc |   a0000000         0  20000001
  3      GRE |          n         0        t0 |   20000000  a0000001  40000000
  4      JMT |         t0                   9 |   40000000         0         9
  5      JMP |                             12 |          0         0         c
  6      SUB |          n         1        t1 |   20000000  a0000000  20000002
  7      ASG |         t1                   n |   20000002         0  20000000
  8      JMP |                              3 |          0         0         3
  9      MUL |          n       acc        t2 |   20000000  20000001  20000003
 10      ASG |         t2                 acc |   20000003         0  20000001
 11      JMP |                              6 |          0         0         6
 12   RETURN |        acc          _fact_iter |   20000001         0  a0000002
 13  ENDPROC |                                |          0         0         0
 14      LEQ |          n         0        t0 |   20000000  a0000001  40000000
 15      JMF |         t0                  18 |   40000000         0        12
 16   RETURN |          1           _fact_rec |   a0000000         0  a0000003
 17      JMP |                             25 |          0         0        19
 18      ERA |          4         0         1 |          4         0         1
 19      SUB |          n         1        t1 |   20000000  a0000000  20000001
 20    PARAM |         t1            20000000 |   20000001         0  20000000
 21   GOPROC |                       fact_rec |          0         0         e
 22      ASG |  _fact_rec                  t2 |   a0000003         0  20000002
 23      MUL |          n        t2        t3 |   20000000  20000002  20000003
 24   RETURN |         t3           _fact_rec |   20000003         0  a0000003
 25  ENDPROC |                                |          0         0         0
 26  PRINTLN |                   "=== Factorial ===" |          0         0  d0000000
 27  PRINTLN |                   "Type value calculate factorial" |          0         0  d0000001
 28     READ |                              i |          0         0  20000000
 29      ERA |          4         0         1 |          4         0         1
 30    PARAM |          i            20000000 |   20000000         0  20000000
 31   GOPROC |                      fact_iter |          0         0         2
 32      ASG | _fact_iter                  t0 |   a0000002         0  20000001
 33      ASG |         t0                  f1 |   20000001         0  20000002
 34      ERA |          4         0         1 |          4         0         1
 35    PARAM |          i            20000000 |   20000000         0  20000000
 36   GOPROC |                       fact_rec |          0         0         e
 37      ASG |  _fact_rec                  t1 |   a0000003         0  20000003
 38      ASG |         t1                  f2 |   20000003         0  20000004
 39    PRINT |                   "Iterative answer" |          0         0  d0000002
 40  PRINTLN |                             f1 |          0         0  20000002
 41    PRINT |                   "Recursive answer" |          0         0  d0000003
 42  PRINTLN |                             f2 |          0         0  20000004
 43      JMP |                             26 |          0         0        1a
 44  ENDPROC |                                |          0         0         0

Program is valid
λ
```

Figure 5.2: Program output

```
λ duck run fact.quack
=== Factorial ===
Type value calculate factorial
0
Iterative answer 1
Recursive answer 1
=== Factorial ===
Type value calculate factorial
1
Iterative answer 1
Recursive answer 1
=== Factorial ===
Type value calculate factorial
2
Iterative answer 2
Recursive answer 2
=== Factorial ===
Type value calculate factorial
3
Iterative answer 6
Recursive answer 6
=== Factorial ===
Type value calculate factorial
4
Iterative answer 24
Recursive answer 24
=== Factorial ===
Type value calculate factorial
5
Iterative answer 120
Recursive answer 120
=== Factorial ===
Type value calculate factorial
6
Iterative answer 720
Recursive answer 720
=== Factorial ===
Type value calculate factorial
7
Iterative answer 5040
Recursive answer 5040
=== Factorial ===
Type value calculate factorial
8
Iterative answer 40320
Recursive answer 40320
=== Factorial ===
Type value calculate factorial
9
Iterative answer 362880
Recursive answer 362880
=== Factorial ===
Type value calculate factorial
10
Iterative answer 3628800
Recursive answer 3628800
=== Factorial ===
Type value calculate factorial
^C
λ
```

5.1.2 Fibonacci

```
#| Iterative fibbonaci implementation |#
proc fib_iter(n int) -> int
    var f0, f1, tmp int;
{
    f0 <- 0;
    f1 <- 1;

    loop ; n > 0; n <- n - 1 {
        tmp <- f1;
        f1 <- f0 + f1;
        f0 <- tmp;
    }

    return f0;
}
```

```
#| Recursive fibbonaci implementation |#
proc fib_rec(n int) -> int {
    if n <= 0 {
        return 0;
    } else if n = 1 {
        return 1;
    } else {
        return fib_rec(n - 1) + fib_rec(n - 2);
    }
}

#| Main procedure |#
proc main()
    var f1, f2, i int;
{
    loop {
        print("=== Fibonacci ===");

        i <- read("Type value of the nth fibonacci to calculate");

        f1 <- fib_iter(i);
        f2 <- fib_rec(i);

        print("Iterative answer", f1);
        print("Recursive answer", f2);
    }
}
```

Figure 5.3: Generated IR code

```
 0      ERA |        5        0        0 |         5        0        0
 1   GOPROC |                       main |         0        0       26
 2      ASG |        0                f0 |  a0000000        0 20000001
 3      ASG |        1                f1 |  a0000001        0 20000002
 4      GRE |        n        0       t0 |  20000000 a0000000 40000000
 5      JMT |       t0                10 |  40000000        0        a
 6      JMP |                         15 |         0        0        f
 7      SUB |        n        1       t1 |  20000000 a0000001 20000003
 8      ASG |       t1                 n |  20000003        0 20000000
 9      JMP |                          4 |         0        0        4
10      ASG |       f1               tmp |  20000002        0 20000004
11      ADD |       f0       f1       t2 |  20000001 20000002 20000005
12      ASG |       t2                f1 |  20000005        0 20000002
13      ASG |      tmp                f0 |  20000004        0 20000001
14      JMP |                          7 |         0        0        7
15   RETURN |       f0         _fib_iter |  20000001        0 a0000002
16  ENDPROC |                            |         0        0        0
17      LEQ |        n        0       t0 |  20000000 a0000000 40000000
18      JMF |       t0                21 |  40000000        0       15
19   RETURN |        0          _fib_rec |  a0000000        0 a0000003
20      JMP |                         37 |         0        0       25
21       EQ |        n        1       t1 |  20000000 a0000001 40000001
22      JMF |       t1                25 |  40000001        0       19
23   RETURN |        1          _fib_rec |  a0000001        0 a0000003
24      JMP |                         37 |         0        0       25
25      ERA |        6        0        2 |         6        0        2
26      SUB |        n        1       t2 |  20000000 a0000001 20000001
27    PARAM |       t2          20000000 |  20000001        0 20000000
28   GOPROC |                    fib_rec |         0        0       11
29      ASG | _fib_rec                t3 |  a0000003        0 20000002
30      ERA |        6        0        2 |         6        0        2
31      SUB |        n        2       t4 |  20000000 a0000004 20000003
32    PARAM |       t4          20000000 |  20000003        0 20000000
33   GOPROC |                    fib_rec |         0        0       11
34      ASG | _fib_rec                t5 |  a0000003        0 20000004
35      ADD |       t3       t5       t6 |  20000002 20000004 20000005
36   RETURN |       t6          _fib_rec |  20000005        0 a0000003
37  ENDPROC |                            |         0        0        0
38  PRINTLN |                 "=== Fibonacci ===" |         0        0 d0000000
39  PRINTLN |                 "Type value of the nth fibonacci to calculate" |         0        0 d0000001
40     READ |                          i |         0        0 20000000
41      ERA |        6        0        1 |         6        0        1
42    PARAM |        i          20000000 |  20000000        0 20000000
43   GOPROC |                   fib_iter |         0        0        2
44      ASG |_fib_iter                t0 |  a0000002        0 20000001
45      ASG |       t0                f1 |  20000001        0 20000002
46      ERA |        6        0        2 |         6        0        2
47    PARAM |        i          20000000 |  20000000        0 20000000
48   GOPROC |                    fib_rec |         0        0       11
49      ASG | _fib_rec                t1 |  a0000003        0 20000003
50      ASG |       t1                f2 |  20000003        0 20000004
51    PRINT |                 "Iterative answer" |         0        0 d0000002
52  PRINTLN |                         f1 |         0        0 20000002
53    PRINT |                 "Recursive answer" |         0        0 d0000003
54  PRINTLN |                         f2 |         0        0 20000004
55      JMP |                         38 |         0        0       26
56  ENDPROC |                            |         0        0        0

Program is valid
λ
```

Figure 5.4: Program output

```
λ duck run fib.quack
=== Fibonacci ===
Type value of the nth fibonacci to calculate
0
Iterative answer 0
Recursive answer 0
=== Fibonacci ===
Type value of the nth fibonacci to calculate
1
Iterative answer 1
Recursive answer 1
=== Fibonacci ===
Type value of the nth fibonacci to calculate
2
Iterative answer 1
Recursive answer 1
=== Fibonacci ===
Type value of the nth fibonacci to calculate
3
Iterative answer 2
Recursive answer 2
=== Fibonacci ===
Type value of the nth fibonacci to calculate
4
Iterative answer 3
Recursive answer 3
=== Fibonacci ===
Type value of the nth fibonacci to calculate
5
Iterative answer 5
Recursive answer 5
=== Fibonacci ===
Type value of the nth fibonacci to calculate
6
Iterative answer 8
Recursive answer 8
=== Fibonacci ===
Type value of the nth fibonacci to calculate
7
Iterative answer 13
Recursive answer 13
=== Fibonacci ===
Type value of the nth fibonacci to calculate
8
Iterative answer 21
Recursive answer 21
=== Fibonacci ===
Type value of the nth fibonacci to calculate
9
Iterative answer 34
Recursive answer 34
=== Fibonacci ===
Type value of the nth fibonacci to calculate
10
Iterative answer 55
Recursive answer 55
=== Fibonacci ===
Type value of the nth fibonacci to calculate
^C
λ
```

5.1.3 Find

```
#| Main procedure |#
proc main()
    var array [5]int;
    var x, i, size int;
    var exists bool;
{
    size <- 5;

    print("=== Array ===");

    loop i <- 0; i < size; i <- i + 1 {
        array[i] <- read("Type value at position", i);
    }

    print("=== Value to find ===");

    x <- read("Type value to find");

    loop i <- 0; i < size; i <- i + 1 {
        if x = array[i] {
            exists <- true;
            break;
        }
    }

    print("=== Result ===");

    if exists {
        print("Value", x, "was found in array at position", i);
    } else {
        print("Value", x, "was not found in array");
    }
}
```

Figure 5.5: Generated IR code

```
 3      SET | "was not found in array"          d0000007 |        0        0        0
 4      SET | "=== Array ==="          d0000000 |        0        0        0
 5      SET | "Type value to find"          d0000003 |        0        0        0
 6      SET |         5          a0000000 |        0        0        0
 7      SET | "was found in array at position"          d0000006 |        0        0        0
 8      SET |  536870912          a0000003 |        0        0        0
 9      SET | "Type value at position"          d0000001 |        0        0        0
10      SET |        #t          c0000000 |        0        0        0
11      SET |         1          a0000002 |        0        0        0
12      SET |         0          a0000001 |        0        0        0
13      SET |   "Value"          d0000005 |        0        0        0

 0      ERA |        12        0        4 |        c        0        4
 1   GOPROC |                          main |        0        0        2
 2      ASG |         5                 size |  a0000000        0  20000005
 3  PRINTLN |                    "=== Array ===" |        0        0  d0000000
 4      ASG |         0                    i |  a0000001        0  20000006
 5      LES |         i     size          t0 |  20000006  20000005  40000000
 6      JMT |        t0                   11 |  40000000        0        b
 7      JMP |                              17 |        0        0       11
 8      ADD |         i        1          t1 |  20000006  a0000002  20000007
 9      ASG |        t1                    i |  20000007        0  20000006
10      JMP |                               5 |        0        0        5
11   ASSERT |         i        0           5 |  20000006        0  a0000000
12      ADD |         i 536870912         t2 |  20000006  a0000003 120000008
13    PRINT |                    "Type value at position" |        0        0  d0000001
14  PRINTLN |                               i |        0        0  20000006
15     READ |                              t2 |        0        0 120000008
16      JMP |                               8 |        0        0        8
17  PRINTLN |                    "=== Value to find ===" |        0        0  d0000002
18  PRINTLN |                    "Type value to find" |        0        0  d0000003
19     READ |                               x |        0        0  20000009
20      ASG |         0                    i |  a0000001        0  20000006
21      LES |         i     size          t3 |  20000006  20000005  40000001
22      JMT |        t3                   27 |  40000001        0       1b
23      JMP |                              34 |        0        0       22
24      ADD |         i        1          t4 |  20000006  a0000002  2000000a
25      ASG |        t4                    i |  2000000a        0  20000006
26      JMP |                              21 |        0        0       15
27   ASSERT |         i        0           5 |  20000006        0  a0000000
28      ADD |         i 536870912         t5 |  20000006  a0000003 12000000b
29       EQ |         x       t5          t6 |  20000009 12000000b  40000002
30      JMF |        t6                   33 |  40000002        0       21
31      ASG |        #t               exists |  c0000000        0  40000003
32      JMP |                              34 |        0        0       22
33      JMP |                              24 |        0        0       18
34  PRINTLN |                    "=== Result ===" |        0        0  d0000004
35      JMF |    exists                   41 |  40000003        0       29
36    PRINT |                         "Value" |        0        0  d0000005
37    PRINT |                               x |        0        0  20000009
38    PRINT |                    "was found in array at position" |        0        0  d0000006
39  PRINTLN |                               i |        0        0  20000006
40      JMP |                              44 |        0        0       2c
41    PRINT |                         "Value" |        0        0  d0000005
42    PRINT |                               x |        0        0  20000009
43  PRINTLN |                    "was not found in array" |        0        0  d0000007
44  ENDPROC |                                 |        0        0        0

Program is valid
λ
```

Figure 5.6: Program output

```
λ duck run find.quack
=== Array ===
Type value at position 0
451
Type value at position 1
432
Type value at position 2
52
Type value at position 3
92
Type value at position 4
3
=== Value to find ===
Type value to find
0
=== Result ===
Value 0 was not found in array
λ duck run find.quack
=== Array ===
Type value at position 0
234
Type value at position 1
82
Type value at position 2
42
Type value at position 3
22
Type value at position 4
53
=== Value to find ===
Type value to find
22
=== Result ===
Value 22 was found in array at position 3
λ
```

5.1.4 Sort

```
#| Main procedure |#
proc main()
    var array [5]int;
    var i, j, tmp, size int;
    var is_sorted bool;
{
    size <- 5;

    print("=== Fill array ===");

    loop i <- 0; i < size; i <- i + 1 {
        array[i] <- read("Type value at position", i);
    }

#| Bubble sort |#
    loop i <- 0; i < size - 1; i <- i + 1 {
        is_sorted <- true;

        loop j <- i + 1; j < size; j <- j + 1 {
            if array[i] > array[j] {
                tmp <- array[i];
                array[i] <- array[j];
                array[j] <- tmp;
                is_sorted <- false;
            }
        }

        if is_sorted {
            break;
        }
    }

    print("=== Sorted array ===");
    print(array);
}
```

Figure 5.7: Generated IR code

```
 6      JMT |         t0                  11 |   40000000         0         b
 7      JMP |                             17 |          0         0        11
 8      ADD |          i         1        t1 |   20000006  a0000002  20000007
 9      ASG |         t1                   i |   20000007         0  20000006
10      JMP |                              5 |          0         0         5
11   ASSERT |          i         0         5 |   20000006         0  a0000000
12      ADD |          i 536870912        t2 |   20000006  a0000003 120000008
13    PRINT |                    "Type value at position" |         0         0  d0000001
14  PRINTLN |                              i |          0         0  20000006
15     READ |                             t2 |          0         0 120000008
16      JMP |                              8 |          0         0         8
17      ASG |          0                   i |   a0000001         0  20000006
18      SUB |       size         1        t3 |   20000005  a0000002  20000009
19      LES |          i        t3        t4 |   20000006  20000009  40000001
20      JMT |         t4                  25 |   40000001         0        19
21      JMP |                             56 |          0         0        38
22      ADD |          i         1        t5 |   20000006  a0000002  2000000a
23      ASG |         t5                   i |   2000000a         0  20000006
24      JMP |                             18 |          0         0        12
25      ASG |         #t           is_sorted |   c0000000         0  40000002
26      ADD |          i         1        t6 |   20000006  a0000002  2000000b
27      ASG |         t6                   j |   2000000b         0  2000000c
28      LES |          j      size        t7 |   2000000c  20000005  40000003
29      JMT |         t7                  34 |   40000003         0        22
30      JMP |                             53 |          0         0        35
31      ADD |          j         1        t8 |   2000000c  a0000002  2000000d
32      ASG |         t8                   j |   2000000d         0  2000000c
33      JMP |                             28 |          0         0        1c
34   ASSERT |          i         0         5 |   20000006         0  a0000000
35      ADD |          i 536870912        t9 |   20000006  a0000003 12000000e
36   ASSERT |          j         0         5 |   2000000c         0  a0000000
37      ADD |          j 536870912       t10 |   2000000c  a0000003 12000000f
38      GRE |         t9       t10       t11 |  12000000e 12000000f  40000004
39      JMF |        t11                  52 |   40000004         0        34
40   ASSERT |          i         0         5 |   20000006         0  a0000000
41      ADD |          i 536870912       t12 |   20000006  a0000003 120000010
42      ASG |        t12                 tmp |  120000010         0  20000011
43   ASSERT |          i         0         5 |   20000006         0  a0000000
44      ADD |          i 536870912       t13 |   20000006  a0000003 120000012
45   ASSERT |          j         0         5 |   2000000c         0  a0000000
46      ADD |          j 536870912       t14 |   2000000c  a0000003 120000013
47      ASG |        t14                 t13 |  120000013         0 120000012
48   ASSERT |          j         0         5 |   2000000c         0  a0000000
49      ADD |          j 536870912       t15 |   2000000c  a0000003 120000014
50      ASG |        tmp                 t15 |   20000011         0 120000014
51      ASG |         #f           is_sorted |   c0000001         0  40000002
52      JMP |                             31 |          0         0        1f
53      JMF |  is_sorted                  55 |   40000002         0        37
54      JMP |                             56 |          0         0        38
55      JMP |                             22 |          0         0        16
56  PRINTLN |                    "=== Sorted array ===" |          0         0  d0000002
57    PRINT |                          array |          0         0  20000000
58    PRINT |                          array |          0         0  20000001
59    PRINT |                          array |          0         0  20000002
60    PRINT |                          array |          0         0  20000003
61  PRINTLN |                          array |          0         0  20000004
62  ENDPROC |                                |          0         0         0

Program is valid
λ
```

Figure 5.8: Program output

```
λ duck run sort.quack
=== Fill array ===
Type value at position 0
24
Type value at position 1
53
Type value at position 2
56
Type value at position 3
2
Type value at position 4
9
=== Sorted array ===
2 9 24 53 56
λ duck run sort.quack
=== Fill array ===
Type value at position 0
29
Type value at position 1
40
Type value at position 2
2
Type value at position 3
7
Type value at position 4
44
=== Sorted array ===
2 7 29 40 44
λ duck run sort.quack
=== Fill array ===
Type value at position 0
10
Type value at position 1
-2
Type value at position 2
14
Type value at position 3
8
Type value at position 4
8
=== Sorted array ===
-2 8 8 10 14
λ
```

5.1.5 Matrix multiplication

```
#| Main procedure |#

proc main()
    var a [2][2]int;
    var b [2][2]int;
    var c [2][2]int;
    var i, j, k, I, J, K int;
{
    I <- 2;
    J <- 2;
    K <- 2;

    print("=== Fill matrices ===");

    loop i <- 0; i < I; i <- i + 1 {
        loop k <- 0; k < K; k <- k + 1 {
            a[i][k] <- read("Type value at a[", i, "][", k, "]");
        }
    }

    loop k <- 0; k < K; k <- k + 1 {
        loop j <- 0; j < J; j <- j + 1 {
            b[k][j] <- read("Type value at b[", k, "][", j, "]");
        }
    }

    loop i <- 0; i < I; i <- i + 1 {
        loop j <- 0; j < J; j <- j + 1 {
            loop k <- 0; k < K; k <- k + 1 {
                c[i][j] <- c[i][j] + a[i][k] * b[k][j];
            }
        }
    }

    print("=== Result ===");
    print(c);
}
```

Figure 5.9: Generated IR code

```
 56  PRINTLN |                       "]" |        0        0  d0000003
 57     READ |                       t13 |        0        0 12000001b
 58      JMP |                        44 |        0        0        2c
 59      JMP |                        37 |        0        0        25
 60      ASG |         0               i | a0000001        0  2000000f
 61      LES |         i         I   t14 | 2000000f 2000000c  40000004
 62      JMT |       t14              67 | 40000004        0        43
 63      JMP |                       107 |        0        0        6b
 64      ADD |         i         1   t15 | 2000000f a0000002  2000001c
 65      ASG |       t15               i | 2000001c        0  2000000f
 66      JMP |                        61 |        0        0        3d
 67      ASG |         0               j | a0000001        0  20000017
 68      LES |         j         J   t16 | 20000017 2000000d  40000005
 69      JMT |       t16              74 | 40000005        0        4a
 70      JMP |                       106 |        0        0        6a
 71      ADD |         j         1   t17 | 20000017 a0000002  2000001d
 72      ASG |       t17               j | 2000001d        0  20000017
 73      JMP |                        68 |        0        0        44
 74      ASG |         0               k | a0000001        0  20000011
 75      LES |         k         K   t18 | 20000011 2000000e  40000006
 76      JMT |       t18              81 | 40000006        0        51
 77      JMP |                       105 |        0        0        69
 78      ADD |         k         1   t19 | 20000011 a0000002  2000001e
 79      ASG |       t19               k | 2000001e        0  20000011
 80      JMP |                        75 |        0        0        4b
 81   ASSERT |         i         0     2 | 2000000f        0  a0000000
 82      MUL |         i         2   t20 | 2000000f a0000000  2000001f
 83   ASSERT |         j         0     2 | 20000017        0  a0000000
 84      ADD |       t20         j   t21 | 2000001f 20000017  20000020
 85      ADD |       t21 536870920   t22 | 20000020 a0000005 120000021
 86   ASSERT |         i         0     2 | 2000000f        0  a0000000
 87      MUL |         i         2   t23 | 2000000f a0000000  20000022
 88   ASSERT |         j         0     2 | 20000017        0  a0000000
 89      ADD |       t23         j   t24 | 20000022 20000017  20000023
 90      ADD |       t24 536870920   t25 | 20000023 a0000005 120000024
 91   ASSERT |         i         0     2 | 2000000f        0  a0000000
 92      MUL |         i         2   t26 | 2000000f a0000000  20000025
 93   ASSERT |         k         0     2 | 20000011        0  a0000000
 94      ADD |       t26         k   t27 | 20000025 20000011  20000026
 95      ADD |       t27 536870912   t28 | 20000026 a0000003 120000027
 96   ASSERT |         k         0     2 | 20000011        0  a0000000
 97      MUL |         k         2   t29 | 20000011 a0000000  20000028
 98   ASSERT |         j         0     2 | 20000017        0  a0000000
 99      ADD |       t29         j   t30 | 20000028 20000017  20000029
100      ADD |       t30 536870916   t31 | 20000029 a0000004 12000002a
101      MUL |       t28       t31   t32 | 120000027 12000002a  2000002b
102      ADD |       t25       t32   t33 | 120000024 2000002b  2000002c
103      ASG |       t33             t22 | 2000002c        0 120000021
104      JMP |                        78 |        0        0        4e
105      JMP |                        71 |        0        0        47
106      JMP |                        64 |        0        0        40
107  PRINTLN |                "=== Result ===" |        0        0  d0000005
108    PRINT |                         c |        0        0  20000008
109  PRINTLN |                         c |        0        0  20000009
110    PRINT |                         c |        0        0  2000000a
111  PRINTLN |                         c |        0        0  2000000b
112  ENDPROC |                           |        0        0         0

Program is valid
λ
```

Figure 5.10: Program output

```
λ duck run mat_mul.quack
=== Fill matrices ===
Type value at a[ 0 ][ 0 ]
1
Type value at a[ 0 ][ 1 ]
0
Type value at a[ 1 ][ 0 ]
0
Type value at a[ 1 ][ 1 ]
1
Type value at b[ 0 ][ 0 ]
5
Type value at b[ 0 ][ 1 ]
3
Type value at b[ 1 ][ 0 ]
7
Type value at b[ 1 ][ 1 ]
2
=== Result ===
5 3
7 2
λ duck run mat_mul.quack
=== Fill matrices ===
Type value at a[ 0 ][ 0 ]
2
Type value at a[ 0 ][ 1 ]
6
Type value at a[ 1 ][ 0 ]
3
Type value at a[ 1 ][ 1 ]
5
Type value at b[ 0 ][ 0 ]
-1
Type value at b[ 0 ][ 1 ]
0
Type value at b[ 1 ][ 0 ]
4
Type value at b[ 1 ][ 1 ]
6
=== Result ===
22 36
17 30
λ
```

5.1.6 Built-in procedures

```
proc main()
    var data [5]float;
    var pi, ans1, ans2, ans3 float;
{
    pi <- 3.14159;

    print("=== Trigonometric functions ===");

    ans1 <- sin(pi / 2);
    ans2 <- asin(ans1);
    print("sin(pi / 2) =", ans1, "asin(sin(pi / 2) =", ans2);

    ans1 <- cos(0);
    ans2 <- acos(ans1);
    print("cos(0) =", ans1, "acos(cos(0) =", ans2);

    ans1 <- tan(pi / 4);
    ans2 <- atan(ans1);
    ans3 <- atan2(1, 1);
    print("tan(pi /4) =", ans1);
    print("atan(tan(pi /4)) =", ans2, "atan2(1, 1) =", ans3);

    print("");
    print("=== Trascendental functions ===");

    ans1 <- exp(1);
    print(ans1);

    ans1 <- ln(ans1);
    print("ln(exp(1) =", ans1);

    ans1 <- log(125, 5);
    print("log(125, 5) =", ans1);

    print("");
    print("=== Other functions ===");

    ans1 <- pow(3, 5);
    print("pow(3, 5) =", ans1);

    ans1 <- sqrt(2);
    print("sqrt(2) =", ans1);

    ans1 <- mod(41, 3);
```

```
    print("mod(41, 3) =", ans1);

    ans1 <- abs(-12);
    print("abs(-12) =", ans1);

    ans1 <- ceil(1.5);
    print("ceil(1.5) =", ans1);

    ans1 <- floor(1.5);
    print("floor(1.5) =", ans1);

    print("");
    print("=== Vectorial functions ===");

    data[0] <- pi;
    data[1] <- exp(1);
    data[2] <- sqrt(2);
    data[3] <- (1 + sqrt(5)) / 2;
    data[4] <- 2;

    print("vector = [", data, "]");

    ans1 <- mean(data);
    ans2 <- median(data);
    ans3 <- mode(data);

    print("mean =", ans1);
    print("median =", ans2);
    print("mode =", ans3);
}
```

Figure 5.11: Generated IR code

```
 58      ASG |        t14                ans1 |   20000000         0  30000008
 59    PRINT |                   "mod(41, 3) =" |         0         0  d000000f
 60  PRINTLN |                           ans1 |         0         0  30000008
 61      ABS |        -12                 t15 |   a0000008         0  30000017
 62      ASG |        t15                ans1 |   30000017         0  30000008
 63    PRINT |                   "abs(-12) =" |         0         0  d0000010
 64  PRINTLN |                           ans1 |         0         0  30000008
 65     CEIL |        1.5                 t16 |   b0000001         0  30000018
 66      ASG |        t16                ans1 |   30000018         0  30000008
 67    PRINT |                   "ceil(1.5) =" |         0         0  d0000011
 68  PRINTLN |                           ans1 |         0         0  30000008
 69    FLOOR |        1.5                 t17 |   b0000001         0  30000019
 70      ASG |        t17                ans1 |   30000019         0  30000008
 71    PRINT |                   "floor(1.5) =" |         0         0  d0000012
 72  PRINTLN |                           ans1 |         0         0  30000008
 73  PRINTLN |                             "" |         0         0  d0000008
 74  PRINTLN |                   "=== Vectorial functions ===" |         0         0  d0000013
 75   ASSERT |          0         0          5 |   a0000001         0  a0000005
 76      ADD |          0 805306368        t18 |   a0000001  a0000009 120000001
 77      ASG |         pi                 t18 |   30000005         0 120000001
 78   ASSERT |          1         0          5 |   a0000003         0  a0000005
 79      ADD |          1 805306368        t19 |   a0000003  a0000009 120000002
 80      EXP |          1                 t20 |   a0000003         0  3000001a
 81      ASG |        t20                 t19 |   3000001a         0 120000002
 82   ASSERT |          2         0          5 |   a0000000         0  a0000005
 83      ADD |          2 805306368        t21 |   a0000000  a0000009 120000003
 84     SQRT |          2                 t22 |   a0000000         0  3000001b
 85      ASG |        t22                 t21 |   3000001b         0 120000003
 86   ASSERT |          3         0          5 |   a0000006         0  a0000005
 87      ADD |          3 805306368        t23 |   a0000006  a0000009 120000004
 88     SQRT |          5                 t24 |   a0000005         0  3000001c
 89      ADD |          1       t24        t25 |   a0000003  3000001c  3000001d
 90      DIV |        t25         2        t26 |   3000001d  a0000000  3000001e
 91      ASG |        t26                 t23 |   3000001e         0 120000004
 92   ASSERT |          4         0          5 |   a0000002         0  a0000005
 93      ADD |          4 805306368        t27 |   a0000002  a0000009 120000005
 94      ASG |          2                 t27 |   a0000000         0 120000005
 95    PRINT |                   "vector = [" |         0         0  d0000014
 96    PRINT |                           data |         0         0  30000000
 97    PRINT |                           data |         0         0  30000001
 98    PRINT |                           data |         0         0  30000002
 99    PRINT |                           data |         0         0  30000003
100    PRINT |                           data |         0         0  30000004
101  PRINTLN |                            "]" |         0         0  d0000015
102     MEAN |       data         5        t28 |   30000000  a0000005  3000001f
103      ASG |        t28                ans1 |   3000001f         0  30000008
104   MEDIAN |       data         5        t29 |   30000000  a0000005  30000020
105      ASG |        t29                ans2 |   30000020         0  3000000a
106     MODE |       data         5        t30 |   30000000  a0000005  30000021
107      ASG |        t30                ans3 |   30000021         0  30000011
108    PRINT |                       "mean =" |         0         0  d0000016
109  PRINTLN |                           ans1 |         0         0  30000008
110    PRINT |                     "median =" |         0         0  d0000017
111  PRINTLN |                           ans2 |         0         0  3000000a
112    PRINT |                       "mode =" |         0         0  d0000018
113  PRINTLN |                           ans3 |         0         0  30000011
114  ENDPROC |                                |         0         0         0

Program is valid
λ
```

Figure 5.12: Program output

```
λ duck run built_in.quack
=== Trigonometric functions ===
sin(pi / 2) = 0.9999999999991198 asin(sin(pi / 2) = 1.570795000005679
cos(0) = 1 acos(cos(0) = 0
tan(pi /4) = 0.9999986732059835
atan(tan(pi /4)) = 0.7853974999999999 atan2(1, 1) = 0.7853981633974483

=== Trascendental functions ===
2.718281828459045
ln(exp(1) = 1
log(125, 5) = 3.0000000000000004

=== Other functions ===
pow(3, 5) = 243
sqrt(2) = 1.4142135623730951
mod(41, 3) = 2
abs(-12) = 12
ceil(1.5) = 2
floor(1.5) = 1

=== Vectorial functions ===
vector = [ 3.14159 2.718281828459045 1.4142135623730951 1.618033988749895 2 ]
mean = 2.178423875916407
median = 2
mode = 3.14159
λ
```

Chapter 6

Code Documentation

6.1 General Code Overview

The codebase, ommiting `doc`, `examples` and `vim`, has the following structure.

```
(main directory)
  - BigDuck.g4
  - Makefile
  - README.md
  - compiler.go
  - main.go
  - parser*
  - run.go
  - structs
      - enums.go
      - linked_list.go
      - memory.go
      - memory_mapper.go
      - memory_stack.go
      - queue.go
      - semantic_cube.go
      - stack.go
      - stack_pointer.go
      - symbol_table.go
      - tac.go
      - virtual_machine.go
  - tac_gen.go
  - tree_listener.go
```

Note The parser directory is generated by ANTLR, thus it will not be talk about, however all the details for lexical an syntax analizer are there.

6.2 Modules Description

The order of files is given by their usage on an execution.

File name	Description
main.go	Is the starting point of the program, according to the given arguments it will determine to run the compiler or the virtual machine using the filename given.
compiler.go	Makes an instance of the tree listener and runs the ANTLR lexer and parser.
tree_listener.go	Makes an implementation of the grammar listener interface provided by ANTLR, it contains a method for entering and exiting a grammar rule. All compilation actions are embedded in this methods.
tac_gen	For any non-trivial or repetitive action for generation of TAC, there is an implementation of methods, for tree_listener, in this file.
run.go	Parsers the `.quack` file and builds a TAC array to be given to the virutal machine, and the runs it.
structs	Contains all the data strutures used for compilation and execution. I will not go throught each file since they are self explanatory.

6.3 Code excerpts

On the following section, there some excerpts of code with some descriptions.

6.3.1 GenerateOpTac

```
func (l *BigDuckListener) GenerateOpTAC(pointer int) {
```

The signature of this method is read as a method for a pointer to a BigDuckListener, this means that there is mutability on the struct. The pointer int argument indicates if there is an allocation for a new pointer and which argument of the operation is the pointer.

```
    var args [3]string
    var types [3]int
    var i, argc int

    op := l.PopOp()

    is_unary, _ := structs.IsUnaryOp[op]

    if is_unary {
        argc = 0
    } else {
        argc = 1
    }
```

Retrieving basic information for TAC generation; operator, argument count, if it is a unary operator.

```
    for i = argc; i >= 0; i-- {
        item, _ := l.argstack.Pop()
        args[i], _ = item.(string)
        item, _ = l.typestack.Pop()
        types[i], _ = item.(int)
    }
```

Getting arguments and types from argstack and typestack.

```
if structs.Cube[op][types[0]][types[argc]] == structs.Error_t {
    l.valid = false;
    fmt.Printf("line %d:%d type error mismatch\n", l.curr_line, l.curr_col)
} else if op != structs.ASG {
    types[2] = structs.Cube[op][types[0]][types[argc]]
    l.typestack.Push(types[2])
}
```

Check with semantic cube, and if operator not assignment (meaning there is a temporal variable generated) the push the type of the result into typestack.

```
if op == structs.ASG {
    args[2] = args[0]
    args[0] = args[1]
    args[1] = ""
    types[2] = types[0]
    types[0] = types[1]
    types[1] = 0
} else {
    args[2] = "t" + strconv.Itoa(l.tmpc)
    l.argstack.Push(args[2])
    l.tmpc++
}
```

Because the target address on assigment is on the retrieved variables, then it necessary to make some adjusments to the order of the arguments. Otherwise create a new temporal and push it into argstack.

```
    var address [3]int

    for i = 0; i < 3; i++ {
        scope, _, exists := l.symtable.Lookup(args[i])

        if exists || (len(args[i]) > 0 && args[i][0] == 't') {
            if i + 1 == pointer {
                l.memmap.RegisterPointer(scope, args[i])
            }

            address[i] = l.memmap.GetAddress(scope, args[i], types[i])

        } else if len(args[i]) > 0 {
            address[i] = l.memmap.GetAddress(structs.Global, args[i], types[i])
        }
    }
```

For each argument, test if it is variable or temporal then, if it matches with pointer allocate the pointer and lastly get its address, else register as global variable and get address.

```
    l.ir_code = append(
        l.ir_code,
        structs.Tac{
            Op: op,
            Args: args,
            Address: address})
    l.pc++
}
```

Lastly create a new TAC, append it to the array of TACs, and increment progam counter.

6.3.2 Memory methods

```
func (m *memory) InitGlobal(ic, fc, bc int) {
    m.Strings = make(map[int]string, ic)
    m.MemI[Global] = make([]int, ic)
    m.MemF[Global] = make([]float64, fc)
    m.MemB[Global] = make([]bool, bc)
    m.framesize = make(map[int]int)
    m.Sp = make(map[int]int)
}
```

Create slices (Go's name for dynamic arrays) for each global memory pool per type, and initialize framesizes and stack pointers.

```
func (m *memory) InitLocal(ic, fc, bc int) {
    m.MemI[Local] = append(m.MemI[Local], make([]int, ic)...)
    m.MemF[Local] = append(m.MemF[Local], make([]float64, fc)...)
    m.MemB[Local] = append(m.MemB[Local], make([]bool, bc)...)

    m.memstack.Push(ic, fc, bc)
}
```

Increment memory pools' capacity and push allocated memory into memory stack to keep track of memory used in procedure calls.

```
func (m *memory) PushContext() {
    m.Sp[Int_t]     += m.framesize[Int_t]
    m.Sp[Float_t]   += m.framesize[Float_t]
    m.Sp[Bool_t]    += m.framesize[Bool_t]

    ic, fc, bc := m.memstack.Top()
    m.framesize[Int_t]      = ic
    m.framesize[Float_t]    = fc
    m.framesize[Bool_t]     = bc
}
```

Increment stack pointers by current frame size, and update framesizes.

```
func (m *memory) PopContext() {
    ic, fc, bc := m.memstack.Pop()

    m.MemI[Local] = append(
        []int(nil), m.MemI[Local][:len(m.MemI[Local]) - ic]...)
    m.MemF[Local] = append(
        []float64(nil), m.MemF[Local][:len(m.MemF[Local]) - fc]...)
    m.MemB[Local] = append(
        []bool(nil), m.MemB[Local][:len(m.MemB[Local]) - bc]...)

    ic, fc, bc = m.memstack.Top()

    m.framesize[Int_t]      = ic
    m.framesize[Float_t]    = fc
    m.framesize[Bool_t]     = bc

    m.Sp[Int_t]     -= m.framesize[Int_t]
    m.Sp[Float_t]   -= m.framesize[Float_t]
    m.Sp[Bool_t]    -= m.framesize[Bool_t]
}
```

Shrink memory pools, and restore framesizes and stack pointers.

Part II

User Manual

Chapter 7

A Quick Tour

7.1 Enviroment Setup

Welcome to the BigDuck programming language reference. Through this chapter it is going to be presented all the syntax and features present on this programming language.

Once downloaded the codebase, on any UNIX-like environment (like macOS or Linux) you can use Make to build the compiler. Just be sure you have installed ANTLR 4.9 on its usual directory `/usr/local/lib/`. However if you are on macOS Monterey, it is almost certain that you can run the `duck` executable like any other executable from the terminal.

After getting the compiler, create a new text file with the `.duck` file extension, and type the following text.

```
proc main() {
    print("Hello, World!");
}
```

Every BigDuck program starts by the last procedure declared (procedures will be explained in more detail further in the chapter). The print command displays on screen the text inside the quotation marks.

Run this program with the following commands.

```
duck hello.duck
duck run hello.quack
```

The first command compiles the source code and creates a new file, called executable, with the same name of the source code file just with the extension changed to `.quack`. The second command will read the file and execute it.

7.2 Variables

To work with values it is necessary to store them in variables. Variables can be thought of containers for values in memory, therefore, you can used them to make any desired computation.

Look at the following example for variable declaration.

```
proc main()
    var a, b, c int;
    var x, y float;
    var condition bool;
{
    print(a, b, c);     #| prints: 0 0 0 |#
    print(x, y);        #| prints: 0 0   |#
    print(condition);   #| prints: false |#
}
```

As you can see you have to start with the keyword `var` followed by a list of names separated by commas, and closed by type keyword. This tells to the language that every name on the list will be of the same type.

On the BigDuck language there are 3 primitive types; `int`, `float`, and `bool`. Which are enough for any kind of numeric and logic operation.

The text that is enclosed by `#|` and `|#` is ignored by the compiler, this are called comments and are used to clarify a section of code. In this case they show the output of performing such instructions.

On the BigDuck language all variables are initialize to their respective zero value, for ints and floats is `0`, and for bools is `false`. The next section we will discuss on how to change this values and work with variables.

7.3 Statements

On any computational language exists the notion of *sequencing*, this could be for instructions, operations, functions, etc. This sequencing mechanism allows us to indicate the order and steps to be taken by an algorithm.

7.3.1 Assignments

After the declaration of a variable, the assignment operator `<-` allows to indicate a value to be hold by the variable. It will remain this value untill another asignment is performed.

7.3.2 Arithmetic Expressions

In order to perform operations on values or variables, there are several operators that can be used for different purposes. For example take a look at the following program.

```
proc main()
    var a, b float;
{
    a <- 1;
    b <- 1;
    print(a + b);   #| prints: 2 |#
    a <- 1 + b;     #| now a holds the value: 2 |#
    b <- 5 * b;     #| now b holds the value: 5 |#
    print(a / b);   #| prints: 2 / 5 = 0.4 |#
}
```

7.3.3 Operator Precedence and Associativity

As in mathematics, the order of operations is important for certain operations, thus it is advice to have into consideration the following table. The earlier the operator appear on the table, the higher is its precedence. All Operator are left to right associative to provide a natural left to right reading.

Operator	**Usage**
`()`	`(expression)`
`*`, /	`a * b`, `a / b`
`+`, `-`	`a + b`, `a - b`
=, /=, <, >, <=, <=,	`a <relation> b`
`not`	`not a`
`and`	`a and b`
`or`	`a or b`
`<-`	`a <- b`

As you can see multiplication and division, addition and substraction, or relational operators have the same precedence. The order of evaluation is resolved by giving priority to one that was read first.

Therefore the expression `a + b - c` is equal to `(a + b) - c`, and it is **not equal** to `a + (b - c)`.

7.4 Conditional Statements

On any computational language exists the notion of *decisions*. The decision mechanism is use to perform certain instructions under certain conditions.

The BigDuck language allows for decisions to be taken during program execution. For an example take a look at the following program.

```
proc main()
    var a, b int;
{
    a <- read("Type a value for a");
    b <- read("Type a value for b");

    if a = b {
        print("a equals b");
    } else {
        print("a does not equals b");
    }
}
```

The first two instructions are a especial syntax to indicate that the user can give a value and assign it to a variable. Despite these looking like the value obtained by read is assigned to the variable, the whole line is the read and assigment, therefore no operation can be inmediately applied to a read value. This desicion was taken to enforce legibility.

Whether the given values for a and b are equal or not, the program will print a diffent message. The first print is performed when the if clause condition holds true, otherwise the else clause will be perfomed.

Else clauses can be omitted like here.

```
proc main()
    var a, b int;
{
    a <- read("Type a value for a");
    b <- read("Type a value for b");

    if a = b {
        print("a equals b");
    }
}
```

And you can stack if else clauses for multiple cases.

```
proc main()
    var a, b int;
{
    a <- read("Type a value for a");
    b <- read("Type a value for b");

    if a < b {
        print("a is less than b");

    } else if a > b {
        print("a is greater than b");

    } else {
        print("a equals b");
    }
}
```

7.5 Loop Statements

On any computational language exists the notion of *loops*. The looping mechanism allow us to concisely tell the computer to perform some operations n amount of times. Otherwise we would have to sequence n amount of times the same instruction and this would not be managable on the long run (also some computations explicitly require a looping mechanism).

7.5.1 Infinite Loop

The easiest way to loop instructions is shown by the next example.

```
proc main() {
    loop {
        print("Hello, World!");
    }
}
```

If you run this program you will see that it never ends and it is going to fill the console with `‘‘Hello, World!’’`, to stop the program type `ctrl` + `c`. The infinite loop is useful for interactive programs, where it is up to the user when to end the program.

There are other mechanisms to stop an infinite loops, they will be covered in depth on Subsection 7.5.5.

7.5.2 While Loop

Most of the times it is desired to end a loop when a condition is met, thus the BigDuck language provide syntax for handling this kind of loops. A while loop is a type of loop that continues until the loop condition is false.

```
proc main()
    var i int;
{
    i <- 1;

    loop i < 10 {
        print("i value is", i);
        i <- i + 1;
    }
}
```

The previous program prints all numbers starting from 1 up to 9, 10 will not be printed because the condition `i < 10` is no longer true.

7.5.3 For Loop

Many times when looping, there is going to be a control variable, for example on the previous program it was `i`. Since this is really common there is and special syntax for this kind of loop. The following program is equivalent to the previous one, however is using the for loop syntax.

```
proc main()
    var i int;
{
    loop i <- 1; i < 10; i <- i + 1 {
        print("i value is", i);
    }
}
```

As you can it is much more compact and explicit on how the loop will behave. The first statements is an assigment to initialize the control variable (is only performed once), the second statement is the loop condition, and the third statement is an assigment statement to modify the control variable.

At this point you may think that the while syntax is redundant against the for syntax. However this is not true, the recommendation is to use the while syntax when you are not sure how many iterations is going to take the loop. On the other side, for style syntax is best when you know beforehand how is the loop going to behave.

7.5.4 Do While Loop

The next type of loop does not have a dedicated syntax, however it is also a common type of loop present on many programming languages. Therefore here is provided an idiom to achieve the same goal.

```
proc main()
    var i int;
    var ok bool;
{
    loop ok <- false; not ok; ok <- i = 2 {
        i <- read("Type 2 to exit the loop");
    }
}
```

Do while loops are at least run one time, by assuming that it is not ok to exit the loop the program will enter inside the loop. And at every iteration it is tested whether the condition to exit is met.

7.5.5 Control Flow Statements

Throughtout loops sometimes it is required to exit earlier or go to the next iteration. This could be achieve by using logic, however it can be messy and obfuscate the meaning of the code. Take a look at the following program.

```
proc main() {
    loop #| Exit condition |# {
        if #| Condition skip iterations|# {
            skip;
        }

        if #| Condition to break from loop |# {
            break;
        }
    }
}
```

When a skip statement is reached, the following code on the loop will be ignored and the next iteration is going to be reached. However the break statement exits the loop. These are usefull to avoid unnecessary operations or to make the code more readable.

7.6 Procedures

At this point everything has been done inside the main procedure, this means that all code written in main belongs to the same context. With context it is meant that all variables and flow of the program is self contained in the procedure. This may be good enough for small programs, however as the complexity increases you start seeing code repetition or related code to perform an action.

Many programming languages, including BigDuck, are able to provide different contexts through; functions, procedures, methods, etc. On this language it is done through procedure, whose syntax is the following.

```
proc name(args) -> type
    vars
{
}
```

Where `name` is the procedure name, `args` is a list of arguments to be passed to a procedure, `type` indicates the return type of the procedure, and `vars` indicate local variables to be use.

The following are examples of procedures.

```
proc square(x float) -> float {
    return x * x;
}

proc distance(x1, y1, x2, y2 float) -> float {
    return sqrt(square(x2 - x1) - square(y2 - y1));
}

proc close_enough(x1, y1, x2, y2 float) -> bool {
    return distance(x1, y1, x2, y2) > 0.01;
}

proc get_circle_area(r float) -> float {
    return 3.14159 * square(r);
}
```

Using procedures is not only helpful to write less code, but it also helps to make the code more abstract (hiding unnecessary information), and it allows to handle problems with more ease.

The last thing to cover about procedures is recursion. Recursion can be seen as a higher level form of loops, this is because it covers all the use cases of loops and can be a cleaner solution. However sometimes may be harder to think in a recursive solution or viceverse, thus it remains at the taste of the user to decide when to use recursion or loops.

A classic use case for recursion is for the implementation of the factorial function. In mathematics the factorial function is defined the following way.

$$f : \mathbb{N} \to \mathbb{N} \Rightarrow f(x) = \begin{cases} 1 & \text{if } n \leq 0 \\ n \cdot f(n-1) & \end{cases}$$

The iterative approach (the one using loops) is not as easy to understand and make take sometime to realize that it computes the same function.

```
proc factorial(n int) -> int
    var prod int;
{
    prod <- 1;

    loop n > 0 {
        prod <- prod * n;
    }

    return prod;
}
```

However the recursive definition resembles better the mathematical definition.

```
proc factorial(n int) -> int {
    if n <= 0 {
        return 1;
    } else {
        return n * factorial(n - 1);
    }
}
```

7.7 Tensorial Types

As your programs get more complex, you will notice that certain variables are related to other variables. Many programming languages offer many tools for handling complex relationships for data modelling.

However the BigDuck language provides the simplest kind of structured data called tensors, commonly refered as arrays or multidimensional arrays. The name was picked from mathematics since it generalizes the notion of an ordered tuple that can be indexed (known as vectors).

Look at the following program, which defines a 1-D tensor.

```
proc main()
    var a [5]int;
{
    a[1] <- 12;
    print(a[1])     #| prints: 12 |#
}
```

This syntax indicates the language that the variable `a` can be accessed by values from 0 and less than 5, therefore indexing by 5 produces an error. If no index was given, it will be given the first value of the tensor.

For higher dimensional tensors just keep adding more dimensions like here.

```
proc main()
    var a [2][5]int;
{
    a[0][1] <- 12;
    print(a[0][1])     #| prints: 12 |#
}
```

7.8 Built-in Procedures

Before ending this quick tour of the language, it will be presented the signatures for built-in functions. You may ask, aren't these also procedures? And you would be correct, the thing is that functions are a special subset of procedures, the property of functions is that the mapping between input and output is constant. In other words, functions will always give the same output for the same input, however with procedures this cannot be said.

Leaving terminolgy a side, the following are functions that are always available on the language, thus it is not possible to use these names for other procedures. These functions were chosen since they are the most commly used for any kind of mathematical or scietific computing.

Trigonometric functions

```
proc sin(x float) -> float
proc asin(x float) -> float
proc cos(x float) -> float
proc acos(x float) -> float
proc tan(x float) -> float
proc atan(x float) -> float
proc atan2(x, y float) -> float
```

Trascendental functions

```
proc exp(x float) -> float
proc ln(x float) -> float
proc log(x, b float) -> float
```

Other functions

```
proc pow(x, y float) -> float
proc sqrt(x float) -> float
proc mod(n, b float) -> float
proc abs(x float) -> float
proc ceil(x float) -> float
proc floor(x float) -> float
```

Vectorial functions

```
proc mean(x []float) -> float
proc median(x []float) -> float
proc mode(x []float) -> float
```