Report on

Mini Compiler for the C language written in C

Submitted in partial fulfillment of the requirements for ***Sem VI***

Compiler Design Laboratory

Bachelor of Technology
in
Computer Science & Engineering

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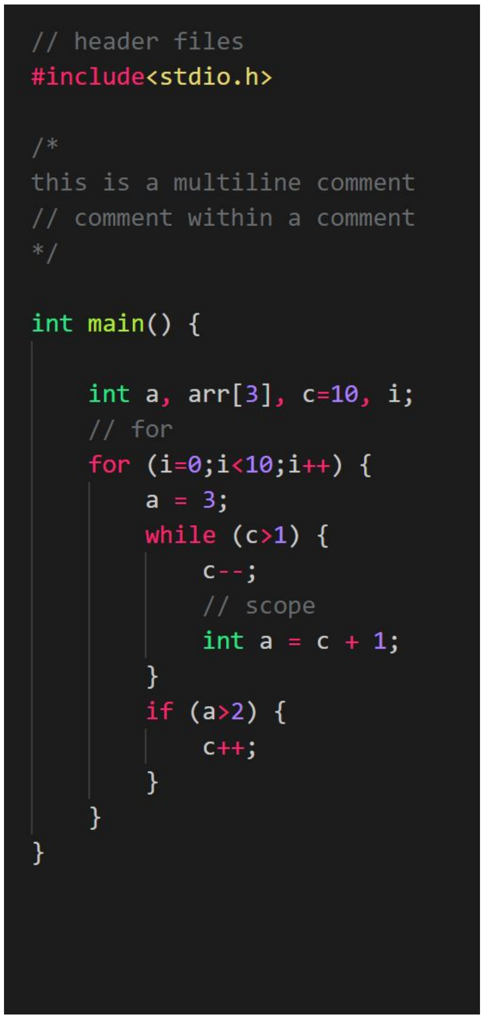
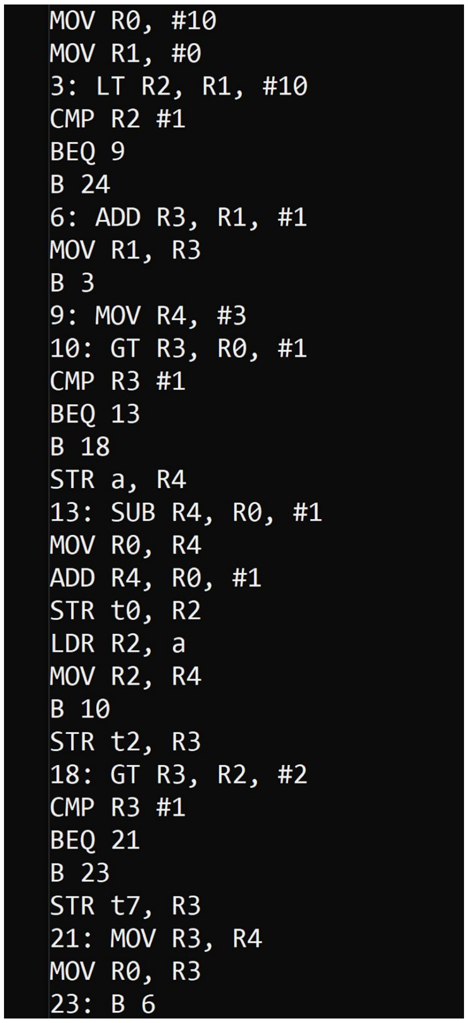
Introduction

This project is a Mini C Compiler, written in the language C. Lex and Yacc were the main tools which were used to build this. The project was implemented through a series of stages such as generation of the symbol table, creation of the abstract syntax tree, generation of intermediate code, optimization of this intermediate code and finally the conversion of this code to assembly code. The mini C compiler is capable of efficiently compiling the given input C code, while catching any errors that might be present in the source code.
Below, in *Fig.1* is a sample input that was taken and the corresponding assembly code that was generated as output.



```
// header files
#include<stdio.h>

/*
this is a multiline comment
// comment within a comment
*/

int main() {

    int a, arr[3], c=10, i;
    // for
    for (i=0;i<10;i++) {
        a = 3;
        while (c>1) {
            c--;
            // scope
            int a = c + 1;
        }
        if (a>2) {
            c++;
        }
    }
}
```



```
MOV R0, #10
MOV R1, #0
3: LT R2, R1, #10
CMP R2 #1
BEQ 9
B 24
6: ADD R3, R1, #1
MOV R1, R3
B 3
9: MOV R4, #3
10: GT R3, R0, #1
CMP R3 #1
BEQ 13
B 18
STR a, R4
13: SUB R4, R0, #1
MOV R0, R4
ADD R4, R0, #1
STR t0, R2
LDR R2, a
MOV R2, R4
B 10
STR t2, R3
18: GT R3, R2, #2
CMP R3 #1
BEQ 21
B 23
STR t7, R3
21: MOV R3, R4
MOV R0, R3
23: B 6
```

Sample Input

Sample output

Figure 1. A sample input along with its corresponding final output

Architecture of the language

The implemented mini-compiler handles the syntax and semantics of the C language's grammar. It identifies the syntax errors present in the input program and provides useful error messages along with the line numbers. This helps in faster error correction. It identifies errors such as missing semicolons, unidentified tokens, using undeclared variables, mismatched brackets, redeclaration within a scope, etc. The compiler is also capable of ignoring all forms of valid comments that may be present in the code. Invalid comments of the C language are identified as errors and returned accordingly.
The mini-compiler handles the following constructs:

1. If condition
2. For loops
3. While loops

Thus the semantics and syntactical usage of these constructs will be taken care of as and when they appear in the input program.

Literature Survey

To get started with writing the grammar and using tools such as Lex and Yacc, we used the following material -

1. LEX & YACC Tutorial [1]

For building the symbol table and handling of scopes, we took help from the following -

1. Compiler Design - Symbol Table [2]
2. Symbol Table [3]
3. C++ Program to implement Symbol Table [4]

To generate the abstract syntax tree,

1. Abstract syntax tree [5]
2. Let's Build A Simple Interpreter. Part 7: Abstract Syntax Trees [6]

For generating the intermediate code, the following proved to be useful

1. Compiler - Intermediate Code Generation [7]
2. Intermediate Code Generation in Compiler Design [8]

Optimizations of the intermediate code was performed after referring to the following links

1. Constant folding [9]
2. Dead Code Elimination [10]

For converting the optimised intermediate code to assembly code for the ARM instruction set architecture, we referred to the following articles -

1. Code Generation [11]
2. Final Code Generation - General approach [12]

3. Architectures | Instruction Set Architecture [13]
4. ARM Information Center [14]

Context Free Grammar

A **program** is divided into 4 major portions, the optional header files and macros section followed by the optional global variable and function declarations and definitions. It then has the main function again followed by the optional global variable and function declarations and definitions.
Every **statement** in the body of the functions contain expressions, variable declarations, updation, function calls, return statements, if conditions, while loops and for loops.
If conditional statements execute a block of statements based on the result evaluated by an expression as the condition. This construct has an optional "else" portion .
An **expression** is a combination of logical, relational and arithmetic operations, evaluated by the grammar according to the correct precedence and associativity.
While loops, similarly have an expression based on which a block of statements are executed.
For loops have an optional initialization, condition and updation based on which a block of statements are executed. The initialisation is an optional variable declaration and initialisation phase. The condition can be any expression. A the updation can be either unary updation or normal variable assignment operations.
Basic **array and pointer** functionality like declaration and initialisation is also handled at the respective statements.
Function declarations and definitions are syntactically checked. But function definitions and calls are not checked with their corresponding function declarations, as this would require a context sensitive grammar to achieve this.
Once the working grammar is completely framed, the L and S attributes are added to generate the Intermediate code etc.

Design Strategy

Symbol Table Creation
The compiler maintains a different symbol table for every scope encountered. Everytime the compiler comes across an increase in the scope while parsing through the program, a new symbol table is created to hold all variables that are present in the current scope. This helps identify errors such as redeclaration of a variable within a scope. All the scope tables are stored with the help of a stack, which is implemented by the use of a structure. Individually, each table is also defined as a structure, essentially making it a structure of structures. Data is stored in the symbol tables using a hashing technique. Values are found in the symbol table recursively by searching through all lower level symbol tables as well.

Error Handling

The compiler is capable of processing multiple errors. On the detection of an error the compiler outputs a description of the error along with the line number where error was found. It then moves on to execute the rest of the program. This is achieved by generating an error keyword in cases of an error, ensuring that the compiler continues to execute the rest of the program, ignoring that line.

Abstract Syntax Tree

As and when the grammar tokens are being derived, nodes are created for them. They are then linked together to form a binary tree structure. This represents the flow of the program. A pre-order traversal of this tree gives the entire traversal of the grammar for the input program.

Intermediate Code Generation

The implemented intermediate code here is 3 address code and a quadruple format. A check for data-type compatibility is made before proceeding forward. The temporary variables that are created on the fly while generating the ICG are of the form **t0**, **t1** etc. The code generation begins by evaluating the length of the line since it indicates the type of instruction that has been encountered. With this information, the line of code can be classified into categories such as arithmetic, logical expressions etc. We then implement backpatching to resolve forward branches and jumps that are present in the code that have been previously framed, majorly consisting of goto statements and if-else conditions.

Code Optimization

Implementation of several machine independent code optimizations techniques was done in this phase. The techniques were applied onto the intermediate code generated in the previous phase. The following optimizations were implemented -

1. **Constant folding** - The process of recognizing and evaluating constant expressions at compile time rather than computing them at runtime.
2. **Constant propagation** - The process of replacing the occurrences of targets of direct assignments with their values. A direct assignment is an instruction of the form x = y, which simply assigns the value of y to x .
3. **Elimination of common subexpressions** - It replaces instances of identical expressions (i.e., they all evaluate to the same value) with a single variable holding the computed value
4. **Dead code elimination** - It removes code which does not affect the program results or is unreachable.

Target Code Generation

The Optimized Intermediate Code obtained from the previous stage is converted into assembly language for the ARM instruction set architecture. Every line of the intermediate code is classified into categories like expressions, assignment expressions, branching statements, etc based on the token present in it. The next step involves further classification of expressions, if present, to find out if there are any numerals present in the expression. If they are, them immediates can be used to store the value(Eg-#10). For the variables and temporaries, registers are used. The MOV instruction is then used for storing the values.

For if and goto statements, the CMP and B instruction is introduced into the output machine code to take care of when and where to branch to. Variable reuse is done by employing the Least Recently Used policy wherein due to the limited number of registers available in the instruction set architecture, everytime we run out of registers, we store the least recently used variable into memory and use the freed register to store the new variable.

Implementation Details

Symbol Table Creation
Data Structures - Hash table, structure of structures
Implementation

1. An entry in the symbol table consists of a structure which has fields such as the matched lexeme, the value of the lexeme, the associated data type, storage required for the lexeme and the line number where it was first declared in the code.
2. Jenkins Hash Function was used as a hashing function
3. Creating a symbol table, adding entries to the table, searching through the table are taken care of by separate functions

Abstract Syntax Tree
Data Structures - Nodes represented in the form of a structure
Implementation

1. Irrespective of whether the node is a leaf node or non leaf node, a single structure was used to represent it. The first field acts as a flag and is used to decide if the node is a leaf or not.
2. The second field is used to store the name or the operator that the node represents (Eg - Identifier / ’+’ / Number etc)
3. There are fields to the store a pointer to the symbol table entry (in case of an identifier), value (in case of a numerical constant), string value (in case of a character constant). These fields are active when the node acts as a leaf.
4. There are also two pointers to the left and right children which are active if the node acts as a non leaf node. These pointers are used for creating a binary tree structure.

Intermediate Code Generation
Data Structures - String vectors, Structures
Implementation

1. The intermediate code is represented in the form of 3 address code and quadruple format.
2. Vectors are dynamic arrays with the ability to resize itself automatically when an element is inserted or deleted, with their storage being handled automatically by the program.
3. 5 Vectors are used, all of them residing under a structure
4. The vectors contain blocks of code that are updated dynamically based on the evaluation of conditions.

5. The struct has the name **content_t** , the vectors are: **truelist**, **falselist**, **nextlist**, **breaklist**, **continuelist**. For example, **falselist** will contain the blocks of code that need to be executed once a condition is evaluated as false.
6. The variables **lhs** and **rhs** store the values on either side of the assignment operator while making temporary variables
7. Different functions have been implemented for different types of expressions, such as relational expressions and logical expressions and mathematical expressions.
8. Backpatching is used to update those values in the code that have been declared above and have been assigned values at later points, recursively.

Code Optimization
Data Structures - Python lists and dictionaries
Implementation (Implemented in Python)

1. The optimizations performed were constant propagation, constant folding, elimination of common subexpressions and finally dead code removal
2. Constant Folding and Constant Propagation - Identify the assignment statements which have numerical constants, keep track of which temporaries/variables are associated with those expressions, evaluate the expression if possible, replace the expression with the result throughout the code wherever applicable
3. Eliminating Common Subexpressions - Identify the first temporary or variable associated with the expression, if found later, substitute the temp/variable instead of expression, wherever applicable
4. Dead Code removal - Identify the useful temporaries/variables, identify the LHS temporaries/variables, subtract the two lists to get those that have to be removed
5. Helper functions to ensure that the handling of line numbers is taken care of when certain lines of intermediate code are eliminated in favour of increasing efficiency.

Assembly Code Generation
Data Structures - Python lists, sets, dictionaries
Implementation (Implemented in Python) for the ARM instruction set architecture

1. Split every line into tokens and identify the type of each line with the help of tokens like ‘if’, “goto”, “=”
2. Keep track of the registers used for each temporary or variable. If registers are available they are used and it is ensured that frequently used registers are given an incrementally higher value ensuring that the least recently used policy works suitably.
3. If a register is not available, the least recently used variable is stored into memory by using STR instruction and the freed register is then used.
4. For assignment statements, check if the expression contains numbers or variables, use immediates (Eg - #10) if numeric constants are encountered, use registers (Eg - R0) if variables are found.
5. Instructions like MOV are used to assign values, expressions are converted to instructions based on the operators found in them.
6. Relational operators and branch statements are taken care of using instructions like CMP, B.

Error Handling
Implementation

1. Error keyword generation in that yacc phase to prompt to execute yyerror without exiting the code

Instructions to run the code

The first step is to compile the lex and the yacc files

```
$ lex lex.l
$ yacc -d yacc.y -v
```

Compile and generate an executable from the C files generated by the lex and yacc compilers

```
$ g++ -std=c++11 -g y.tab.c -ly -ll -o icg
```

Run the executable to generate the symbol table and intermediate code for the input file provided as an argument in the command line

```
$ ./icg input.c
```

Next, the optimisation can performed by running the corresponding python script

```
$ python optimization.py ICG.code
```

Finally, the assembly code is generated by running the corresponding python script

```
$ python assembly.py ICG_opt.code
```

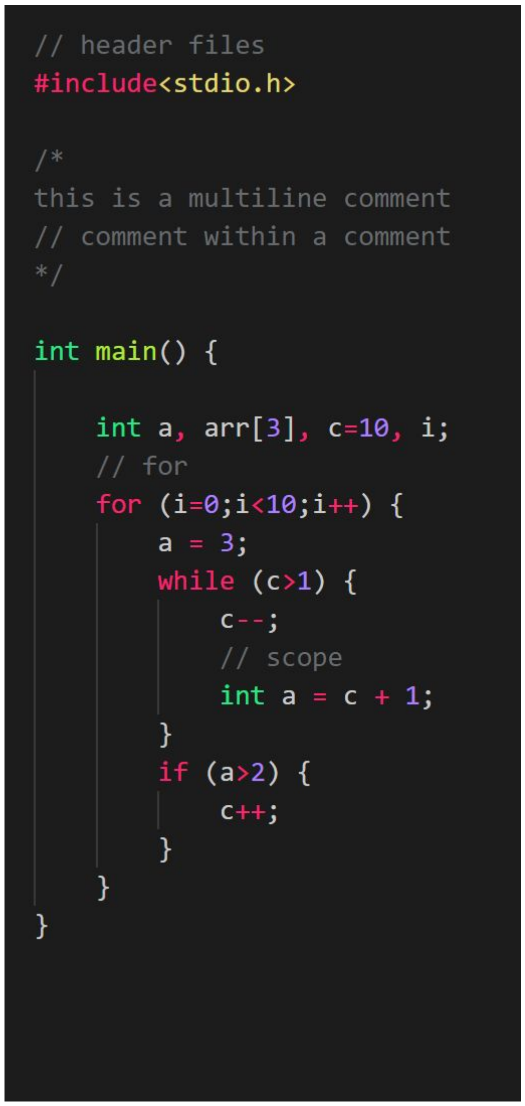
Results and short-comings of the mini-compiler

The mini compiler works as any other compiler would, on the provided constraints. It is able to efficiently compile input C code, while catching any error that might be present in the source code, be it runtime, logical, syntactic or semantic. The intermediate stages of the compiler can be seen since it has been broken down into phases. The 1st phase gives an abstract syntax tree as the output. The preorder traversal is printed by the compiler, to give the user a better idea of how the source code is being processed. The 2nd phase gives the intermediate code as the generated output. This is in accordance with other compilers of the C language. The intermediate code is represented in the form of 3 address code. The compiler shows the quadruple format of the 3 address code as the output. In the next phase, this intermediate code is then optimised using various optimization techniques. Finally, since this code is still in the high level form, it needs to be converted to machine level code for the computer to understand. Thus lastly, the compiler converts the above obtained optimised intermediate code to machine level code as the final output.

Shortcomings of the compiler include the fact that in the end it’s still a mini compiler. It is not capable of handling each and every construct of the C language as it currently stands, and will require significant changes to do so, beginning from the context free grammar that was used.

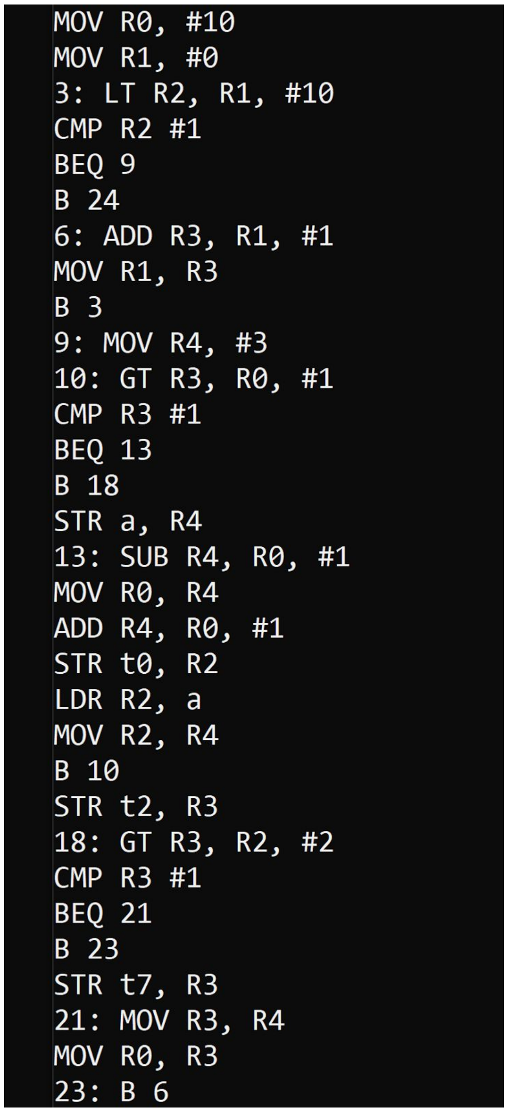
Snapshots of output

The overall process (as shown in the introduction also) is outlined through *Fig. 2*.



```
// header files
#include<stdio.h>

/*
this is a multiline comment
// comment within a comment
*/

int main() {

    int a, arr[3], c=10, i;
    // for
    for (i=0;i<10;i++) {
        a = 3;
        while (c>1) {
            c--;
            // scope
            int a = c + 1;
        }
        if (a>2) {
            c++;
        }
    }
}
```

Sample Input



```
MOV R0, #10
MOV R1, #0
3: LT R2, R1, #10
CMP R2 #1
BEQ 9
B 24
6: ADD R3, R1, #1
MOV R1, R3
B 3
9: MOV R4, #3
10: GT R3, R0, #1
CMP R3 #1
BEQ 13
B 18
STR a, R4
13: SUB R4, R0, #1
MOV R0, R4
ADD R4, R0, #1
STR t0, R2
LDR R2, a
MOV R2, R4
B 10
STR t2, R3
18: GT R3, R2, #2
CMP R3 #1
BEQ 21
B 23
STR t7, R3
21: MOV R3, R4
MOV R0, R3
23: B 6
```

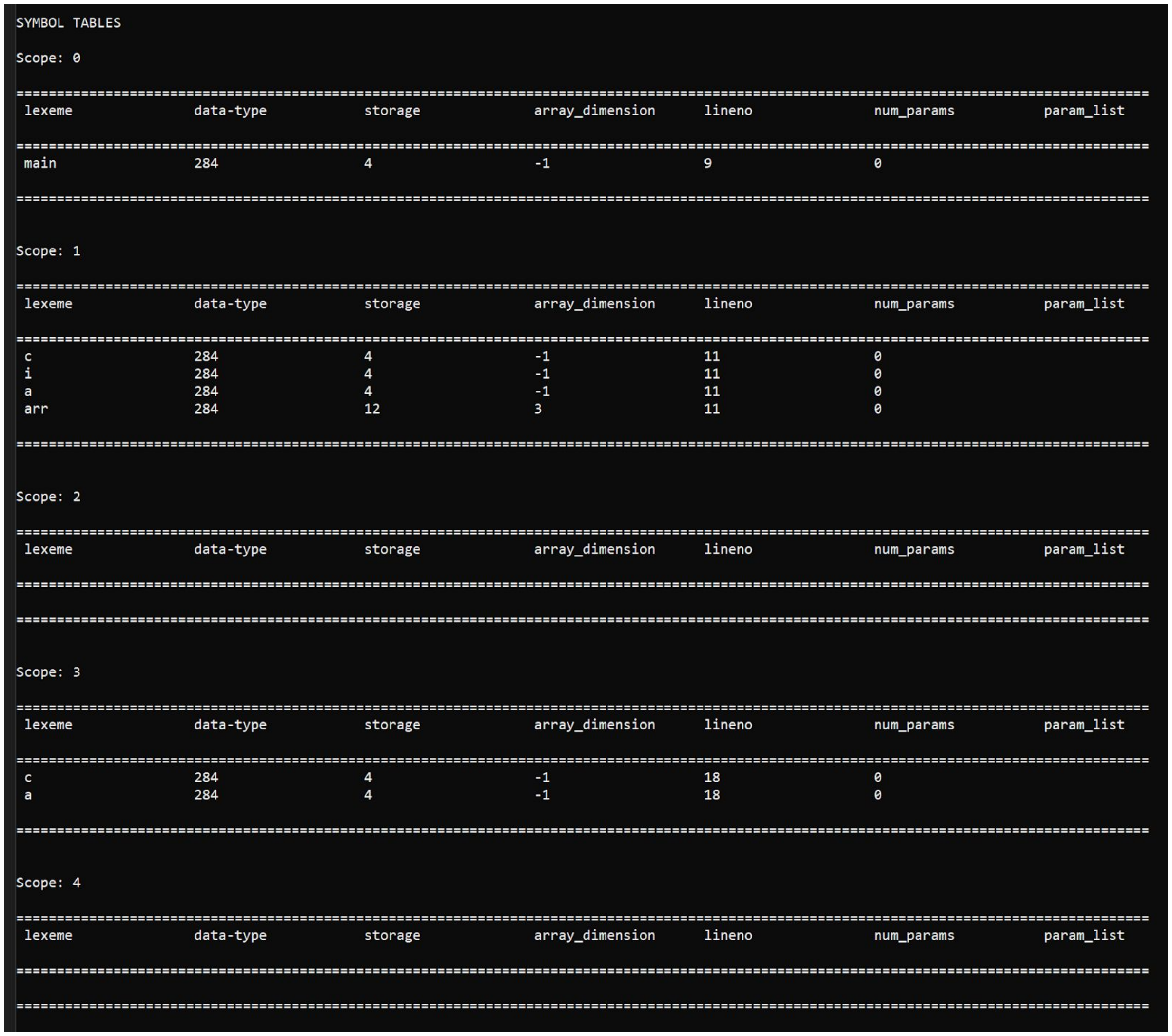
Sample output

Figure 2. A sample input along with its corresponding final output

The following portion of this section shows the stepwise intermediate outputs generated at each stage.

Symbol Table

In the following *Fig. 3*, the symbol table generated for the sample input is shown.

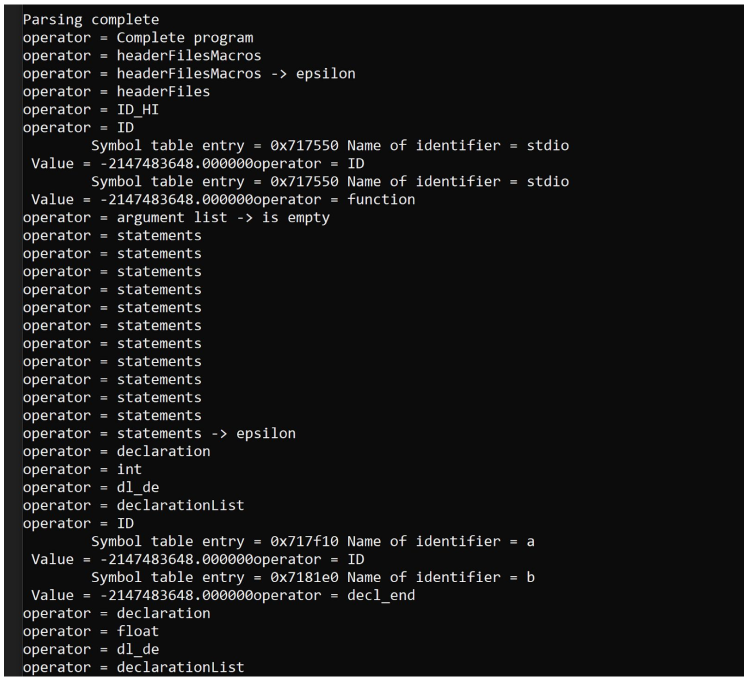


```
SYMBOL TABLES

Scope: 0

=====================================================================================================================================
 lexeme              data-type           storage             array_dimension     lineno              num_params          param_list

=====================================================================================================================================
 main                284                 4                   -1                  9                   0

=====================================================================================================================================


Scope: 1

=====================================================================================================================================
 lexeme              data-type           storage             array_dimension     lineno              num_params          param_list

=====================================================================================================================================
 c                   284                 4                   -1                  11                  0
 i                   284                 4                   -1                  11                  0
 a                   284                 4                   -1                  11                  0
 arr                 284                 12                  3                   11                  0

=====================================================================================================================================


Scope: 2

=====================================================================================================================================
 lexeme              data-type           storage             array_dimension     lineno              num_params          param_list

=====================================================================================================================================

=====================================================================================================================================


Scope: 3

=====================================================================================================================================
 lexeme              data-type           storage             array_dimension     lineno              num_params          param_list

=====================================================================================================================================
 c                   284                 4                   -1                  18                  0
 a                   284                 4                   -1                  18                  0

=====================================================================================================================================


Scope: 4

=====================================================================================================================================
 lexeme              data-type           storage             array_dimension     lineno              num_params          param_list

=====================================================================================================================================

=====================================================================================================================================
```

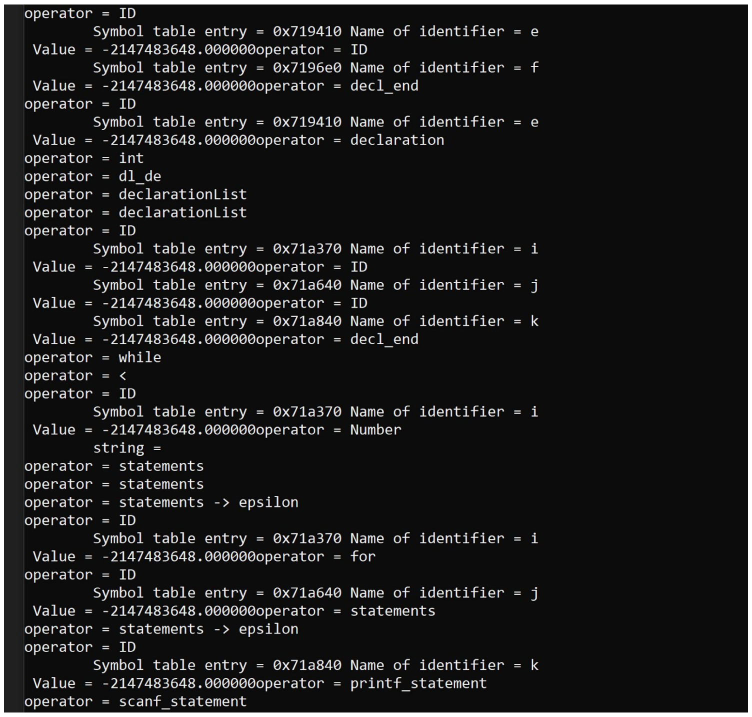
Figure 3. The Symbol Table generated for the sample input

Abstract Syntax Tree

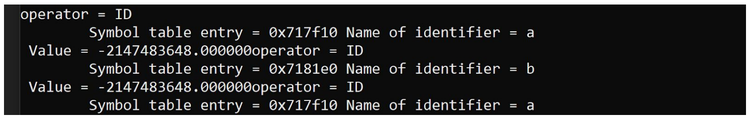
In the following *Fig. 4*, the abstract syntax tree for the sample input is shown.



```
Parsing complete
operator = Complete program
operator = headerFilesMacros
operator = headerFilesMacros -> epsilon
operator = headerFiles
operator = ID_HI
operator = ID
        Symbol table entry = 0x717550 Name of identifier = stdio
 Value = -2147483648.000000operator = ID
        Symbol table entry = 0x717550 Name of identifier = stdio
 Value = -2147483648.000000operator = function
operator = argument list -> is empty
operator = statements
operator = statements
operator = statements
operator = statements
operator = statements
operator = statements
operator = statements
operator = statements
operator = statements
operator = statements
operator = statements
operator = statements -> epsilon
operator = declaration
operator = int
operator = dl_de
operator = declarationList
operator = ID
        Symbol table entry = 0x717f10 Name of identifier = a
 Value = -2147483648.000000operator = ID
        Symbol table entry = 0x7181e0 Name of identifier = b
 Value = -2147483648.000000operator = decl_end
operator = declaration
operator = float
operator = dl_de
operator = declarationList
```



```
operator = ID
        Symbol table entry = 0x719410 Name of identifier = e
 Value = -2147483648.000000operator = ID
        Symbol table entry = 0x7196e0 Name of identifier = f
 Value = -2147483648.000000operator = decl_end
operator = ID
        Symbol table entry = 0x719410 Name of identifier = e
 Value = -2147483648.000000operator = declaration
operator = int
operator = dl_de
operator = declarationList
operator = declarationList
operator = ID
        Symbol table entry = 0x71a370 Name of identifier = i
 Value = -2147483648.000000operator = ID
        Symbol table entry = 0x71a640 Name of identifier = j
 Value = -2147483648.000000operator = ID
        Symbol table entry = 0x71a840 Name of identifier = k
 Value = -2147483648.000000operator = decl_end
operator = while
operator = <
operator = ID
        Symbol table entry = 0x71a370 Name of identifier = i
 Value = -2147483648.000000operator = Number
        string =
operator = statements
operator = statements
operator = statements -> epsilon
operator = ID
        Symbol table entry = 0x71a370 Name of identifier = i
 Value = -2147483648.000000operator = for
operator = ID
        Symbol table entry = 0x71a640 Name of identifier = j
 Value = -2147483648.000000operator = statements
operator = statements -> epsilon
operator = ID
        Symbol table entry = 0x71a840 Name of identifier = k
 Value = -2147483648.000000operator = printf_statement
operator = scanf_statement
```

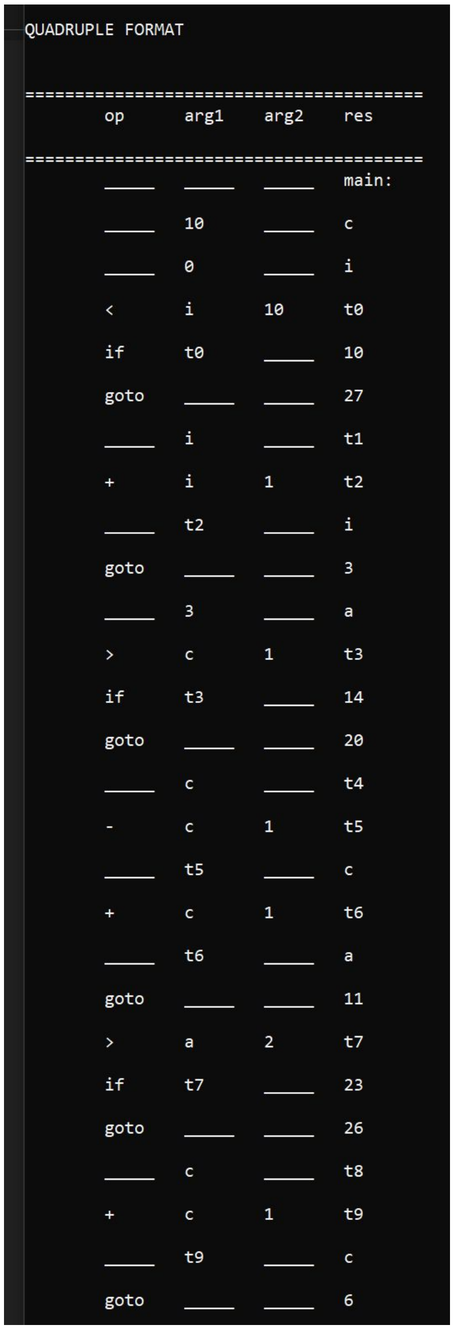


```
operator = ID
        Symbol table entry = 0x717f10 Name of identifier = a
 Value = -2147483648.000000operator = ID
        Symbol table entry = 0x7181e0 Name of identifier = b
 Value = -2147483648.000000operator = ID
        Symbol table entry = 0x717f10 Name of identifier = a
```

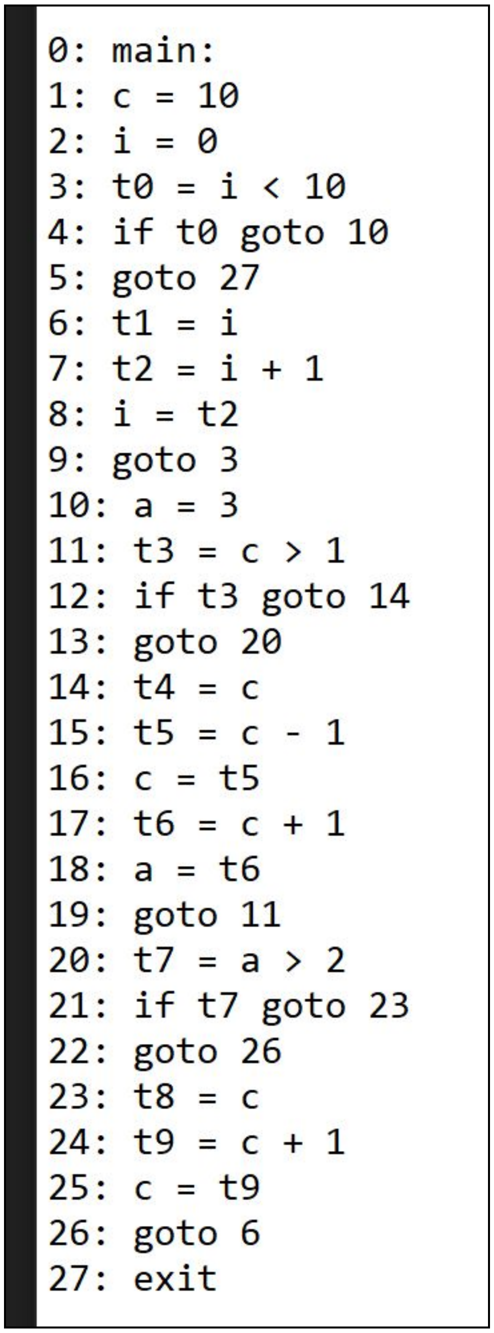
Figure 4. The Abstract Syntax Tree generated for the sample input

Intermediate Code

In the following *Fig. 5*, the intermediate code for the sample input is shown.



```
QUADRUPLE FORMAT


========================================
        op      arg1    arg2    res

========================================
        _____   _____   _____   main:

        _____   10      _____   c

        _____   0       _____   i

        <       i       10      t0

        if      t0      _____   10

        goto    _____   _____   27

        _____   i       _____   t1

        +       i       1       t2

        _____   t2      _____   i

        goto    _____   _____   3

        _____   3       _____   a

        >       c       1       t3

        if      t3      _____   14

        goto    _____   _____   20

        _____   c       _____   t4

        -       c       1       t5

        _____   t5      _____   c

        +       c       1       t6

        _____   t6      _____   a

        goto    _____   _____   11

        >       a       2       t7

        if      t7      _____   23

        goto    _____   _____   26

        _____   c       _____   t8

        +       c       1       t9

        _____   t9      _____   c

        goto    _____   _____   6
```



```
0: main:
1: c = 10
2: i = 0
3: t0 = i < 10
4: if t0 goto 10
5: goto 27
6: t1 = i
7: t2 = i + 1
8: i = t2
9: goto 3
10: a = 3
11: t3 = c > 1
12: if t3 goto 14
13: goto 20
14: t4 = c
15: t5 = c - 1
16: c = t5
17: t6 = c + 1
18: a = t6
19: goto 11
20: t7 = a > 2
21: if t7 goto 23
22: goto 26
23: t8 = c
24: t9 = c + 1
25: c = t9
26: goto 6
27: exit
```

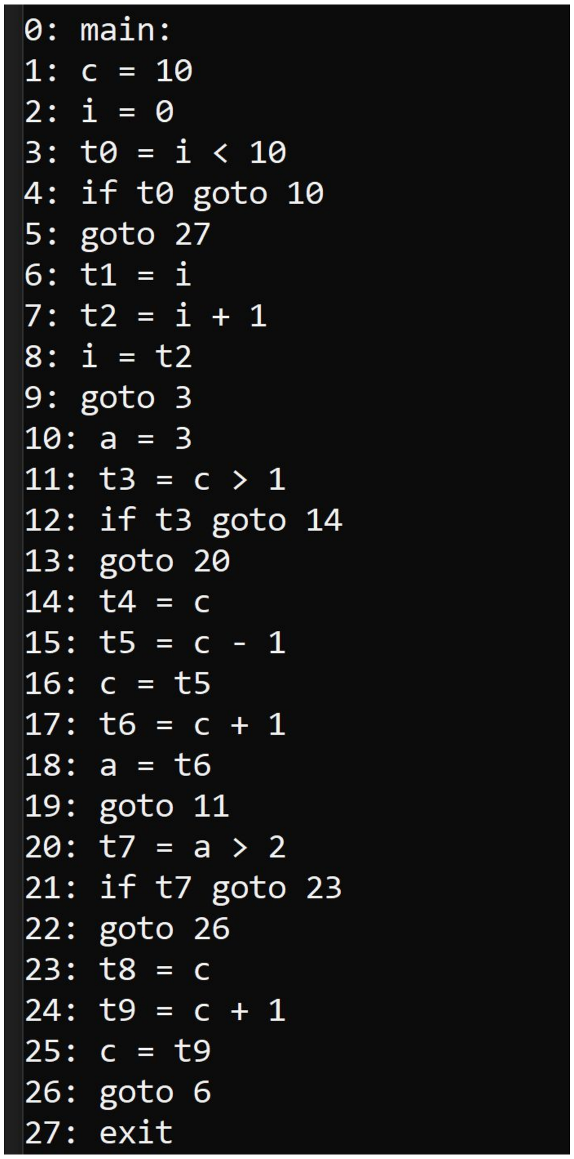
Quadruple Format

Intermediate Code

Figure 5. The Intermediate Code generated for the sample input

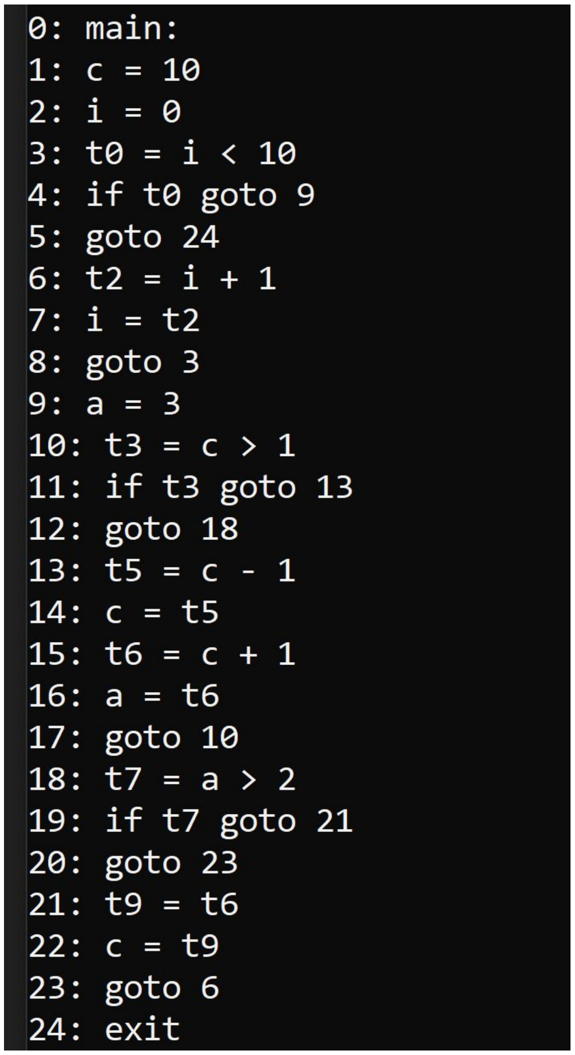
Code Optimization

In the following *Fig. 6*, the optimized code generated for the sample input is shown.



```
0: main:
1: c = 10
2: i = 0
3: t0 = i < 10
4: if t0 goto 10
5: goto 27
6: t1 = i
7: t2 = i + 1
8: i = t2
9: goto 3
10: a = 3
11: t3 = c > 1
12: if t3 goto 14
13: goto 20
14: t4 = c
15: t5 = c - 1
16: c = t5
17: t6 = c + 1
18: a = t6
19: goto 11
20: t7 = a > 2
21: if t7 goto 23
22: goto 26
23: t8 = c
24: t9 = c + 1
25: c = t9
26: goto 6
27: exit
```

Unoptimized



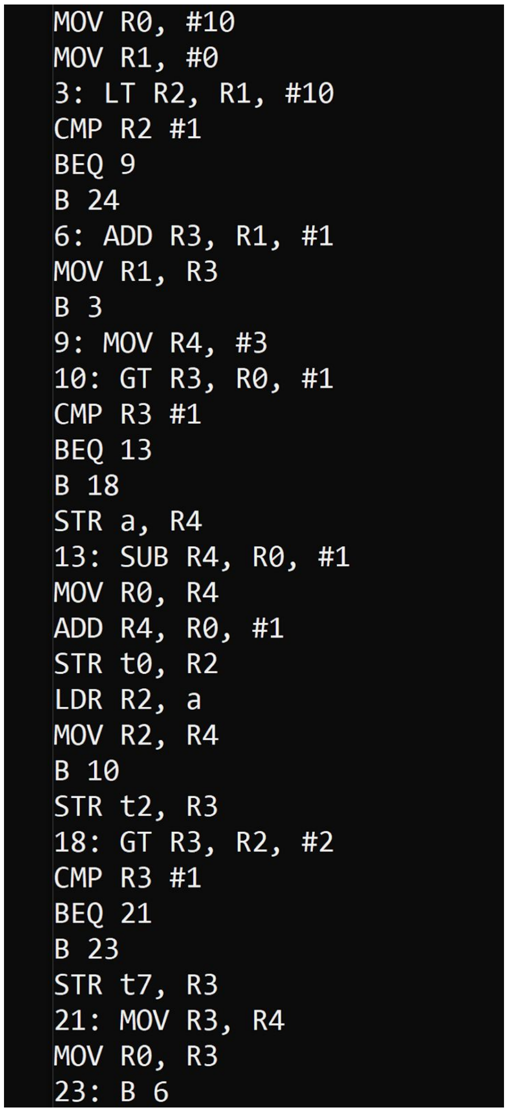
```
0: main:
1: c = 10
2: i = 0
3: t0 = i < 10
4: if t0 goto 9
5: goto 24
6: t2 = i + 1
7: i = t2
8: goto 3
9: a = 3
10: t3 = c > 1
11: if t3 goto 13
12: goto 18
13: t5 = c - 1
14: c = t5
15: t6 = c + 1
16: a = t6
17: goto 10
18: t7 = a > 2
19: if t7 goto 21
20: goto 23
21: t9 = t6
22: c = t9
23: goto 6
24: exit
```

Optimized

Figure 6. The Optimized Code generated for the sample input

Assembly Code Generation

In the following *Fig. 7*, the assembly code generated for the sample input is shown.



```
MOV R0, #10
MOV R1, #0
3: LT R2, R1, #10
CMP R2 #1
BEQ 9
B 24
6: ADD R3, R1, #1
MOV R1, R3
B 3
9: MOV R4, #3
10: GT R3, R0, #1
CMP R3 #1
BEQ 13
B 18
STR a, R4
13: SUB R4, R0, #1
MOV R0, R4
ADD R4, R0, #1
STR t0, R2
LDR R2, a
MOV R2, R4
B 10
STR t2, R3
18: GT R3, R2, #2
CMP R3 #1
BEQ 21
B 23
STR t7, R3
21: MOV R3, R4
MOV R0, R3
23: B 6
```

Figure 7. The Assembly Code generated for the sample input

Further Enhancements

1. Add in error productions for providing better error messages to the users. Like handling misspelt keywords such as "ofr" instead of "for", "whiel" instead of "while", "fi" instead of "if" etc.

2. The number of constraints that were handled can be increased. For example, switch case statements, structures, etc can be added.

3. An increase to the efficiency can be made with additional development, specifically in the storage of the scoped symbol tables.

4. An efficient approach can be used for implementing the register allocation algorithm by implementing other graph algorithms.

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