IFJ project documentation

Project authors

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Distribution of points

- xkralo07 - 25%
- xvehov01 - 25%
- xhashm00 - 25%
- xbrabl04 - 25%

Assignment variant

Tým xkralo07, varianta TRP-izp

Division of work

- xkralo07 - recursive descent parser
- xhashm00 - tokenizer
- xvehov01 - precedence parser
- xbrabl04 - semantic analyzer, codegen

Implemented extensions

BOOLTHEN

Overall architecture of the compiler

Since we basically had two weeks to do the entire project, we chose a simple design, always preferring code simplicity and robustness over efficiency or extensibility.

The tokenizer (`tokenizer.h`) exposes a single function for loading the next token, which is not used directly by parsers, but by a token table, which is filled once before parsing, and then stays on the heap until the end of compilation. Pointers to tokens in this table can therefore be used throughout the program without fear of accessing freed memory.

The compiler doesn't use an AST to represent code internally, instead the output code is generated on-the-fly during a single (main) pass over the input code. We chose a syntax-directed compilation approach - the recursive descent parser (`rec_parser.h`) (from now on, the *main parser*) makes calls to the semantic analyzer/codegen. AST is not built even for expressions, which are also checked/generated as the precedence parser (`parser.h`) progresses.

The semantic analyzer (`sem_stmt.h`, `sem_expr.h`) and codegen are mostly implemented together, in the same functions. Splitting these into two separate modules wouldn't have a big benefit in clarity, since much code would be either duplicated or shared in a third, common module, further complicating things.

Note: in the following chapters, a corresponding module is always mentioned. Modules are pairs of `.c` and `.h` files, together forming a compilation unit. For simplicity, only the `.h` file containing the public interface of each module is mentioned.

Structure of a token

Module: `global_include.h`

A single token is composed of the following data:

- an enum representing the token's type, this is used by parsers to differentiate tokens
- a union with the token's content (only identifiers and literals have a content, the other tokens are fully described by their token type
- the token's line number, length, and pointer into the line in the source code buffer, that contains the start of the token (these are used for user-friendly error printing)

Since no error printing is a part of the requirements, one might ask why we included such an elaborate system for pretty-printing errors. This was done for two reasons: firstly, it allowed for very concise error handling. The only thing required to print an error and cleanly exit a program with the correct exit code was to call a single function, `print_error_exit`, and pass it the token itself, error type, and an error message, and the function would handle the rest. The other reason was a huge speedup in debugging, since the error function printed the whole line containing the error, underlined the token related to the error, and printed the reason why the compilation failed, instead of just returning the error code itself. This proved very useful in debugging both parsers, semantic analysis and codegen.

Tokenizer

Module: tokenizer.h

Tokenizer is implemented through a finite state machine with some deviations from the original scheme. Diagram of the state machine is available below in Attachments.

The finite state machine is divided into multiple sections in code. The main function for the tokenizer is called `get_token()` and each function call from it roughly represents one section of the state machine (literals, symbols, operators, identifiers and keywords, comments, newline and end-of-file).

Rather than the entire tokenizer being a single big state machine, the sections themselves contain smaller, more manageable FSMs. Identificators and keywords are in the same section because they are evaluated in the same way, with the final identificator being checked for being a keyword.

Some operators, like `/`, are evaluated in other sections because they share characters with unrelated lexemes (comments).

Multiline string literal is not processed in a single step, but at first, the whole string is loaded into a temporary buffer, where the mandatory offset after a new line is calculated according to the ending triple-quotes. Then the ending of the string is stripped by setting the first byte to discard to value 0. Lastly, the string content is copied into the final buffer, while discarding the spaces in offset, and substituting escape characters.

Anything unexpected is treated as an error and terminates the compiler.

Token table

Module: `token_table.h`

Token table is used for storing and accessing tokens. It first loads all tokens by calling the tokenizer, until it receives an end-of-file token. The token table discards all newline tokens, and stores information about preceding newline into the next non-newline token. This is done to simplify grammar and main parser.

After storing all the tokens in an array, it sets an internal pointer to the first token and allows operations `peek`, `next` and `previous`, through its public API. These are used by the parsers.

Recursive descent parser

Module: rec_parser.h

The parser is written according to the LL1 grammar (available below), with some exceptions. Each nonterminal is represented by a function with the same name, prefixed by `parse_`. We use some helper macros, such as `expect_token`, which fetches the current token, and checks if its type agrees with the expected type. If not, extra information about the error is printed for debugging purposes, and parsing fails with an error.

The parser makes calls to the semantic analyzer, giving it the parsed tokens, and occasionally carrying some context information further (for example, when parsing a function call, the semantic analyzer gives the parser some info about the called function, which the parser carries to the other calls to semantic analyzer, that handle function arguments).

Return analysis

The parser also does the "return analysis", which determines, whether a return statement is present in every possible path of the program inside a function. Result of the analysis is a single boolean value. The analysis runs for each statement, according to the following rules:

- sequence of statements yields `true` if at least one of the statements inside yields `true`
- if statement yields `true`, if both of its branches yield `true`
- return statement yields `true`
- any other statement yields `false`

Result of this analysis is then passed to the semantic analyzer, which decides whether the function was supposed to return a value, and checks whether this was actually satisfied.

Handling newlines

Even though a token type for newline exists, it is not used in grammar, nor in any of the parsers. It is emitted by the tokenizer, but discarded in code that fills the token table, and the information about a newline is inserted directly into the first non-newline token following the newline.

This information is then used to check if the first token of a statement was preceded by a newline. The first token is not checked, and therefore it is possible to write a whole code block with just one statement on a single line:

```
if true { write("then") } else { write("else") }
```

Exceptions to LL1 grammar

When interfacing with the precedence parser, in rules for `EXPR_OR_CALL` and `EXPR_OPT`, we must look two tokens ahead, and determine the correct rule to follow. The problem arises in the following situations:

```
return
a = 5

return
a()
```

In these cases, we need to parse nonterminal `EXPR_OPT` after finding `return`, but we cannot just look at the following token and run the precedence parser if it belongs to First(EXPR), because in these cases, the next token is `tt_ident`, which the precedence parser would parse successfully, and consume the token. After that, we would attempt to parse the rest (`= 5` or `()`), which would result in an error. This is solved by looking two tokens ahead, and if they match (`tt_ident`, `tt_assign`), or (`tt_ident`, `tt_left_paren`), we go according to the epsilon rule and don't parse an expression (which corresponds to the return statement without any expression).

In the following case, a similar problem occurs:

```
let a = b()
// vs
let a = b + c
```

after parsing `=`, we need to parse either expression, or call (nonterminal `EXPR_OR_CALL`). Here, we also need to look at first two tokens, and if they match (`tt_ident`, `tt_left_paren`), we parse this as a function call, otherwise, the precedence parser is ran.

Precedence parser

Module: parser.h

The precedence parser analyzes and ensures the correct order of execution of operations in expressions. It iteratively consumes tokens until the end of the expression is found. Subsequently, the parser checks the precedence of the incoming token and the non-expression token at the top of the stack using the precedence table. Based on the precedence of the incoming token, the parser decides whether to shift or reduce the token onto the stack, terminate the expression or return an error.

Reducing

Expression reduction follows these four rules:

1. `E -> i`
2. `E -> E!`
3. `E -> E <infix operator> E`
4. `E -> (E)`

The first rule is implemented by calling the semantic analysis function for a term and pushing the resulting expression back onto the stack. The second and third rules are similarly implemented through semantic analysis based on the operator and the resulting expression is then pushed back onto the stack. The fourth rule is addressed by removing parentheses and returning the original expression to the stack. If none of these rules are met, the parser returns an error.

Symbol names in IFJcode23

Because IFJ23 supports variable shadowing, multiple scopes need to be accessible at the same time in IFJcode23. Therefore, when one variable in IFJ23 shadows another, both need to exist alongside each other in IFJcode23. For this, we need to extend variable names in IFJcode23 beyond the original IFJ23 name.

In our compiler, variable names in IFJcode23 all have the postfix `$id`, where `id` is a program-wide unique number. For each variable, this will be generated and stored in symbol table. Numbers will be assigned sequentially, starting from zero. This means there will be an implementation limit on the number of variables in a program.

Exceptions

One exception to this rule are function parameters of built-in functions, since those are coded directly in IFJcode23, and therefore their arguments and internal variables cannot have IDs generated at compile time. This is solved by a condition in codegen, which omits IDs for built-in function parameters.

Symbol table

Modules: symtable.h (hashmap), sem_state.h (the rest)

Symbol table is implemented in two parts, hashmap in one module, and the rest of the table in another. The whole table consists of two stacks of hashmaps, representing the scopes in local and global frame. From here on, a *scope* will refer to any block of code that allows for shadowing of variables from the scope above. The symbol table module also implements an algorithm for symbol lookup, which finds the stored information about a variable with given name. The algorithm walks the current stack of scopes from the bottom up, querying each hashmap, and returning the first found result.

The data stored about each variable is the usual: whether it is initialized, whether it is mutable, the type of the variable, and also a unique ID of that variable (explained below).

Calling convention of IFJcode23

Non-variadic functions

Function labels are identical to their names, since function names are unique in IFJ23. A function call consists of the following steps:

- create new a temporary frame
- create variables inside TF named after identifiers (not names) of input parameters of called function
- call with a label identical to the function name

If a function is not void, then also:

- push special variable `$return` from TF onto the stack
- return value is available on top of the stack (as if an expression was evaluated)

Bodies of all functions are located after the end of the main program. Function code consists of the following:

- label instruction with a name identical to the function name
- pushframe instruction to move TF into new LF
- function code that uses input parameters as top-scope immutable local variables
- move returned value into a special local variable `$return`
- popframe instruction to remove the local frame into a temporary frame
- return instruction

Variadic functions (only `write` function)

Since IFJ23 doesn't allow user-created variadic functions, and the only predefined variadic function is `write`, variadic functions will not have a standalone calling convention. Instead, uses of `write` will be directly inserted (inlined) into calling code.

Function table

Module: function_table.h

Function table is represented simply by a vector of structs containing information about each function, and it is used by semantic analysis and codegen.

Finding function signatures

Module: sem_find_functions.h

Since IFJ23 supports calling functions above their definition, it is necessary to find all functions and add them to the function table before starting the main compiler pass. The other option (without building an AST) would be to log function calls and definitions into a separate table during the main (and only) pass, and check that the call signatures conform to the function definitions after finishing the pass. This would complicate the calling convention, since arguments couldn't be simply created inside TF and then moved into function's LF, because the parameter identifiers wouldn't have been known yet. That's why we chose to do a simple pass before the main pass, which simply finds each `func` keyword token in the token table, and runs a function for parsing function definition in special mode, which parses just the header, not the body. During the main pass, the function header is just parsed, without adding the function to the function table again.

Built-in functions

File: builtin_functions.c

Built-in functions are implemented directly in assembly, and inserted into the generated code at the end. The functions internally use variables prefixed with `$` not to collide with any other names. These functions are registered into the function table before the main pass starts, so that the usual code for semantic analysis and codegen of function calls can be used.

Semantic analysis

Modules: sem_stmt.h (statements), sem_expr.h (expressions)

Semantic analysis is implemented without any special structure. There are simply two modules, one for expressions, and another for statements, which both expose many functions, each to be called when any specific statement/expression is parsed. Input parameters specify the tokens which are to be passed into semantic analysis. Sometimes, information about a parsed structure (such as info about called function) must be propagated from a result of one function into the argument of another. The semantic analyzer checks for type compatibility of assignments, definitions with explicit type, conditions, function arguments, and operators inside expressions. It also performs various checks according to requirements, such as:

- no nested function definitions
- no redefinitions of variables and functions
- functions that have return type actually return value on all control paths

The semantic analyzer also changes its state through the API in `sem_state.h`, which consists of:

- adding variables to symbol table
- entering/leaving scope
- entering/leaving function

Codegen

Module: codegen.h

As mentioned, codegen itself is done in the same functions as semantic analysis, but not directly into the standard output. There is a module exposing a set of functions for outputting instructions with variadic formatting (like `printf`). These functions internally ask the semantic state module, whether the current code is function code or main code, and output to appropriate buffer.

`DEFVAR` instructions are treated differently. If there was a `DEFVAR` instruction placed inside a loop (eg. generated from a while loop), the interpreter would hit it twice and complain about variable redefinition. For this reason, all `DEFVAR` instructions are "pulled" to the start of their respective functions. This is done by outputting them to a different temporary buffer than the rest of the code, and then flushing the "defvar" buffer *before* the rest. This is probably the best worst solution one can do, without actually doing the right thing and implementing an AST.

After finishing the compilation, only if there were no errors, the main code buffer is flushed to `stdout`, then the function buffer, and last the static string containing manual implementations of built-in functions.

Memory allocator

Module: sgc.h

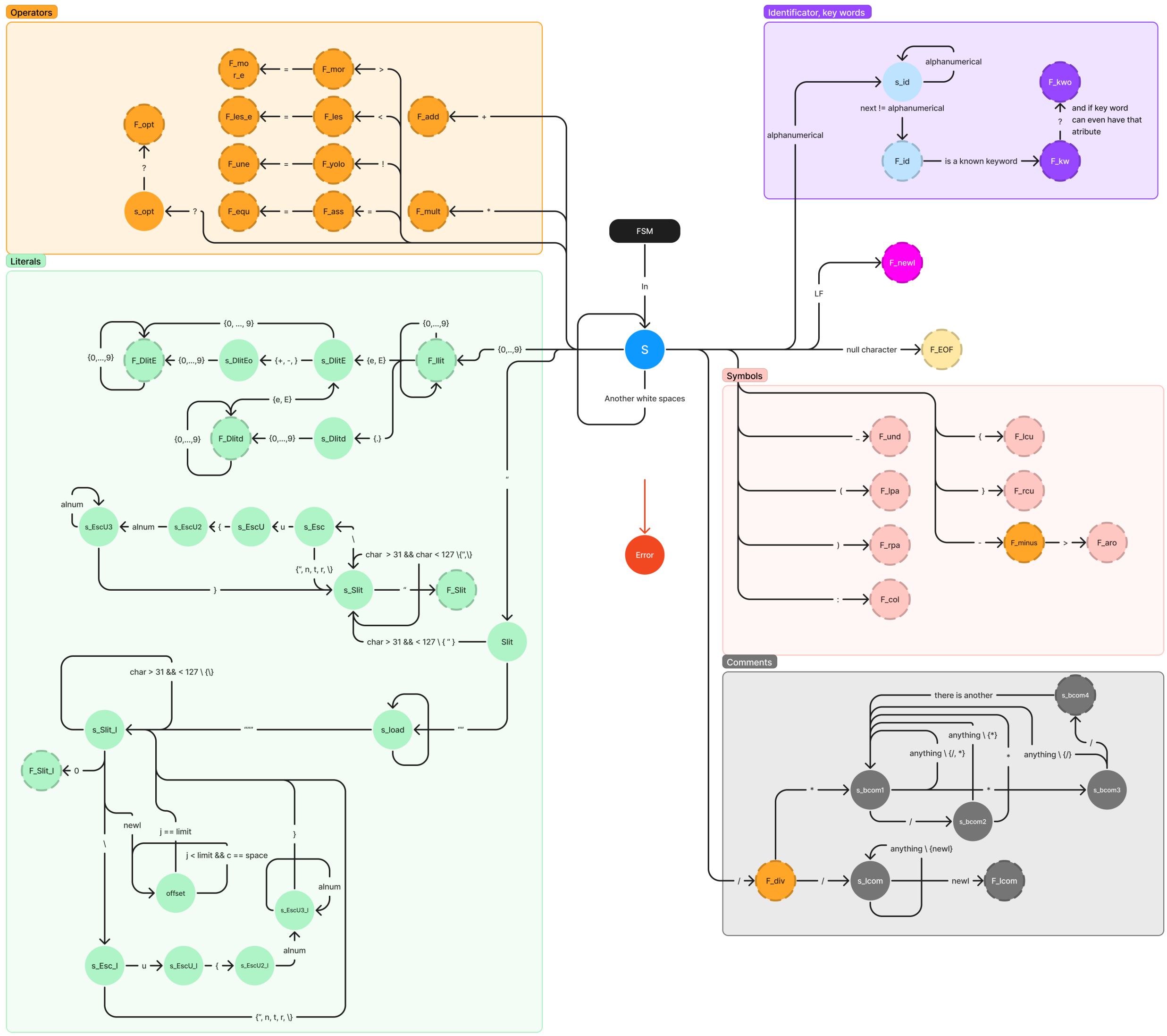
Since memory management in C is quite unpleasant, we implemented a wrapper to standard allocation functions, which logs all allocations, handles allocation errors cleanly, and allows for freeing all allocated memory with a single function call. This allows us to, at any place in code, cleanly exit the program without leaking any memory. That allows for much simpler error handling - errors are almost always resolved directly where they're encountered by shutting down the compiler, instead of propagating them to the main function. Also, there is no need to extensively check for memory leaks, since all memory will be freed even in a successful pass after finishing the compilation.

Conclusion

Even though the main work on the compiler was done in just around two weeks, we consider the code to be quite robust. We achieved this by extensive testing, and parallel work on the project using git. Communication was handled mainly on Discord, and we also used Github's issue tracking for more important problems. It also helped that merging and subsequent testing was done by a single member.

Attachments

State machine of tokenizer



LL-grammar

Nonterminals are written in capital letters, terminals are in lowercase letters and prefixed with `tt_` (they are the names of token types from `global_include.h`). Each rule has its number, these numbers are used in LL-table

```
01 EXPR_OR_CALL ::= EXPR
02 EXPR_OR_CALL ::= tt_ident CALL
03 EXPR_OPT ::= EXPR
04 EXPR_OPT ::= ε
05 FILE ::= STMT_LIST tt_EOF
06 STMT_LIST ::= ε
07 STMT_LIST ::= STMT STMT_LIST
08 TYPE ::= tt_kw_Double
09 TYPE ::= tt_kw_Double_opt
10 TYPE ::= tt_kw_Int
11 TYPE ::= tt_kw_Int_opt
12 TYPE ::= tt_kw_String
13 TYPE ::= tt_kw_String_opt
```

```
14 TYPE ::= tt_kw_Bool
15 TYPE ::= tt_kw_Bool_opt
16 STMT ::= STMT_FUNC_DEF
17 STMT ::= STMT_LET
18 STMT ::= STMT_VAR
19 STMT ::= tt_ident STMT_IDENT
20 STMT ::= STMT_IF
21 STMT ::= STMT_WHILE
22 STMT ::= STMT_RETURN
23 STMT_FUNC_DEF ::= tt_kw_func tt_ident tt_left_paren PARAM_LIST
tt_right_paren RETURN_TYPE tt_left_curly STMT_LIST tt_right_curly
24 PARAM_LIST ::= ε
25 PARAM_LIST ::= PARAM PARAM_REST
26 PARAM_REST ::= tt_comma PARAM PARAM_REST
27 PARAM_REST ::= ε
28 PARAM ::= OPT_IDENT OPT_IDENT tt_colon TYPE
29 OPT_IDENT ::= tt_ident
30 OPT_IDENT ::= tt_underscore
31 RETURN_TYPE ::= ε
32 RETURN_TYPE ::= tt_arrow TYPE
33 STMT_LET ::= tt_kw_let tt_ident DECL
34 STMT_VAR ::= tt_kw_var tt_ident DECL
35 DECL ::= tt_colon TYPE DEF
36 DECL ::= tt_assign EXPR_OR_CALL
37 DEF ::= tt_assign EXPR_OR_CALL
38 DEF ::= ε
39 STMT_IDENT ::= tt_assign EXPR_OR_CALL
40 STMT_IDENT ::= CALL
41 CALL ::= tt_left_paren ARGUMENT_LIST tt_right_paren
42 ARGUMENT_LIST ::= ε
43 ARGUMENT_LIST ::= ARGUMENT ARGUMENT_REST
44 ARGUMENT_REST ::= tt_comma ARGUMENT ARGUMENT_REST
45 ARGUMENT_REST ::= ε
46 ARGUMENT ::= tt_ident OPT_TERM
47 ARGUMENT ::= LITERAL
48 OPT_TERM ::= ε
49 OPT_TERM ::= tt_colon TERM
50 TERM ::= tt_ident
51 TERM ::= LITERAL
52 LITERAL ::= tt_lit_Int
53 LITERAL ::= tt_lit_Double
54 LITERAL ::= tt_lit_String
55 LITERAL ::= tt_lit_Bool
56 LITERAL ::= tt_kw_nil
57 STMT_IF ::= tt_kw_if IF_CONDITION tt_left_curly STMT_LIST tt_right_curly
tt_kw_else tt_left_curly STMT_LIST tt_right_curly
58 IF_CONDITION ::= EXPR
59 IF_CONDITION ::= tt_kw_let tt_ident
60 STMT_WHILE ::= tt_kw_while EXPR tt_left_curly STMT_LIST tt_right_curly
61 STMT_RETURN ::= tt_kw_return EXPR_OPT
```

LL-table

Note that we added EXPR as a terminal into LL-table. This is not a mistake, from the point of LL-grammar, the EXPR nonterminal has no rules associated with it, so in the process of constructing the LL-table, we instead considered it a terminal for better clarity.

Also, note that we didn't include all tokens in the table, just those which exist in the LL-grammar itself.

	EXPR	tt_ident	tt_EOF	tt_kw_Double	tt_kw_Double_opt	tt_kw_Int	tt_kw_Int_opt	tt_kw_String	tt_kw_String_opt	tt_kw_Bool	tt_kw_Bool_opt	tt_kw_func	tt_left_paren	tt_right_paren	tt_left_curly	tt_right_curly	tt_comma	tt_colon	tt_underscore	tt_arrow	tt_kw_let	tt_kw_var	tt_assign	tt_lit_Int	tt_lit_Double	tt_lit_String	tt_lit_Bool	tt_kw_nil	tt_kw_if	tt_kw_else	tt_kw_while	tt_kw_return
EXPR_OR_CALL	01	02																														
EXPR_OPT	03	04	04									04				04					04	04							04		04	04
FILE		05	05									05									05	05							05		05	05
STMT_LIST		07	06									07				06					07	07							07		07	07
TYPE				08	09	10	11	12	13	14	15																					
STMT		19										16									17	18							20		21	22
STMT_FUNC_DEF												23																				
PARAM_LIST		25												24					25													
PARAM_REST														27			26															
PARAM		28																	28													
OPT_IDENT		29																	30													
RETURN_TYPE															31					32												
STMT_LET																					33											
STMT_VAR																						34										
DECL																		35					36									
DEF		38	38									38				38					38	38	37						38		38	38
STMT_IDENT													40										39									
CALL													41																			
ARGUMENT_LIST		43												42										43	43	43	43	43				
ARGUMENT_REST														45			44															
ARGUMENT		46																						47	47	47	47	47				
OPT_TERM														48			48	49														
TERM		50																						51	51	51	51	51				
LITERAL																								52	53	54	55	56				
STMT_IF																													57			
IF_CONDITION	58																				59											
STMT_WHILE																															60	
STMT_RETURN																																61

Precedence table

	+-	*/	<>	!	??	(	)	i	$
+-	R	S	R	S	R	S	R	S	R
*/	R	R	R	S	R	S	R	S	R
<>	S	S	E	S	R	S	R	S	R
!	R	R	R	E	R	E	R	E	R
??	S	S	S	S	S	S	R	S	R
(	S	S	S	S	S	S	S	S	E
)	R	R	R	R	R	E	R	E	R
i	R	R	R	R	R	E	R	E	R
$	S	S	S	S	S	S	E	S	X

R = reduce, S = shift, X = end, E = error