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# Compiler construction home exam

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## 1. SYNTAX

The answers in this home exam has been answered using the Operational Semantics document, see (van Bakel, 2002), as a reference to ENBF and SOS grammar.

### 1.1 Give an as complete as possible EBNF grammar for your language

*Program* = { *Function* };

*ArithOp* = "+" | "-" | "\*" | "/";

*LogicOp* = "&&" | "||";

*AssignOp* = "==" | "+=" | "-=" | "/=";

*RelOp* = "==" | "!=" | ">=" | "<=" | ">" | "<"

*Var* = ? Rust String ?;

*Num* = ? Rust i32 ?;

*Bool* = "true" | "false";

*Type* = "i32" | "bool" | "void";

*Parens* = "(", *expr*, ")";

*Block* = "{", {*lhs*, ";"}, "}";

*Input\_Param* = *var*, ":", *type*;

*Params* = "(", { *param* { , *param* } }, ")";

*Return* = "return", [ *expr* ];

*If* = "if", *expr*, *block*;

*While* = "while", *expr*, *block*;

*Let* = "let", *var*, ":", *var\_type*, *expr*;

*Let\_func* = "let", *var*, ":", *var\_type*, *var*, "(", *input\_param*, ")";

*Function* = "fn", *var*, *params*, *block*;

*LHS* = *let* | *var\_op* | *if* | *while* | *func\_call* | *return*;



*Expr = num | var | bool | bin\_op | func\_call | parens;*

## 1.2 Give an example that showcases all rules of your EBNF. The program should "do" something as used in the next exercise.

---

```
fn testfn1() -> i32 {  
  let a: i32 = 1;  
  let b: i32 = a;  
  let c: i32 = b;  
  return c;  
};  
  
fn testfn2() -> i32 {  
  let b: bool = true && true;  
  if b {  
    return 50;  
  };  
  return 1;  
};  
  
fn main() -> i32 {  
  let a: i32 = testfn1();  
  let b: i32 = testfn2();  
  return b;  
};
```

---

## 1.3 If you support pointers, make sure your example covers pointers as well.

There is no pointer support in the language at the moment.

## 1.4 Compare your solution to the requirements (as stated in the README.md). What are your contributions to the implementation.

The parser is implemented using the "Nom, eating data byte by byte" parser combinators library. The parser can handle operator precedence as well as parenthesized sub expressions for both integer and boolean expressions.



## 2. SEMANTICS

### 2.1 Give an as complete as possible Structural Operational Semantics (SOS) for your language

Expressions are represented as  $e_i$ , numbers as  $n_i$ , boolean as  $b_i$ , where  $i = 1, 2, 3, \dots$ . Further, stored programs are represented as  $\sigma$ .

#### 2.1.1 i32

$$\langle e, \sigma \rangle \Downarrow n \quad (1)$$

#### 2.1.2 Bool

$$\langle e, \sigma \rangle \Downarrow b \quad (2)$$

#### 2.1.3 Var-assignment

$$\overline{\langle x := n, \sigma \rangle \Downarrow \sigma[x := n]} \quad (3)$$

#### 2.1.4 Addition

$$\frac{\langle e_1, \sigma \rangle \Downarrow n_1 \quad \langle e_2, \sigma \rangle \Downarrow n_2}{\langle e_1 + e_2, \sigma \rangle \Downarrow n_1 + n_2} \quad (4)$$

#### 2.1.5 Subtraction

$$\frac{\langle e_1, \sigma \rangle \Downarrow n_1 \quad \langle e_2, \sigma \rangle \Downarrow n_2}{\langle e_1 - e_2, \sigma \rangle \Downarrow n_1 - n_2} \quad (5)$$

#### 2.1.6 Multiplication

$$\frac{\langle e_1, \sigma \rangle \Downarrow n_1 \quad \langle e_2, \sigma \rangle \Downarrow n_2}{\langle e_1 \cdot e_2, \sigma \rangle \Downarrow n_1 \cdot n_2} \quad (6)$$

#### 2.1.7 Division

$$\frac{\langle e_1, \sigma \rangle \Downarrow n_1 \quad \langle e_2, \sigma \rangle \Downarrow n_2}{\langle \frac{e_1}{e_2}, \sigma \rangle \Downarrow \frac{n_1}{n_2}} \quad (7)$$



## 2.2 Logical operators

### 2.2.1 And

$$\frac{\langle b_1, \sigma \rangle \Downarrow \text{false} \langle b_2, \sigma \rangle \Downarrow \text{true}}{\langle b_1 \& \& b_2, \sigma \rangle \Downarrow \text{false}} \quad (8)$$

$$\frac{\langle b_1, \sigma \rangle \Downarrow \text{true} \langle b_2, \sigma \rangle \Downarrow \text{false}}{\langle b_1 \& \& b_2, \sigma \rangle \Downarrow \text{false}} \quad (9)$$

$$\frac{\langle b_1, \sigma \rangle \Downarrow \text{false} \langle b_2, \sigma \rangle \Downarrow \text{false}}{\langle b_1 \& \& b_2, \sigma \rangle \Downarrow \text{false}} \quad (10)$$

$$\frac{\langle b_1, \sigma \rangle \Downarrow \text{true} \langle b_2, \sigma \rangle \Downarrow \text{true}}{\langle b_1 \& \& b_2, \sigma \rangle \Downarrow \text{true}} \quad (11)$$

### 2.2.2 Or

$$\frac{\langle b_1, \sigma \rangle \Downarrow \text{false} \langle b_2, \sigma \rangle \Downarrow \text{true}}{\langle b_1 || b_2, \sigma \rangle \Downarrow \text{true}} \quad (12)$$

$$\frac{\langle b_1, \sigma \rangle \Downarrow \text{true} \langle b_2, \sigma \rangle \Downarrow \text{false}}{\langle b_1 || b_2, \sigma \rangle \Downarrow \text{true}} \quad (13)$$

$$\frac{\langle b_1, \sigma \rangle \Downarrow \text{true} \langle b_2, \sigma \rangle \Downarrow \text{true}}{\langle b_1 || b_2, \sigma \rangle \Downarrow \text{true}} \quad (14)$$

$$\frac{\langle b_1, \sigma \rangle \Downarrow \text{false} \langle b_2, \sigma \rangle \Downarrow \text{false}}{\langle b_1 || b_2, \sigma \rangle \Downarrow \text{false}} \quad (15)$$

## 2.3 Relational operators

### 2.3.1 Equal

$$\frac{\langle e_1, \sigma \rangle \Downarrow n_1 \langle e_2, \sigma \rangle \Downarrow n_2}{\langle e_1 == e_2, \sigma \rangle \Downarrow n_1 == n_2} \quad (16)$$

### 2.3.2 Not equal

$$\frac{\langle e_1, \sigma \rangle \Downarrow n_1 \langle e_2, \sigma \rangle \Downarrow n_2}{\langle e_1 == e_2, \sigma \rangle \Downarrow n_1 == n_2} \quad (17)$$

### 2.3.3 Lesser than

$$\frac{\langle e_1, \sigma \rangle \Downarrow n_1 \langle e_2, \sigma \rangle \Downarrow n_2}{\langle e_1 < e_2, \sigma \rangle \Downarrow n_1 < n_2} \quad (18)$$

### 2.3.4 Greater than

$$\frac{\langle e_1, \sigma \rangle \Downarrow n_1 \langle e_2, \sigma \rangle \Downarrow n_2}{\langle e_1 > e_2, \sigma \rangle \Downarrow n_1 > n_2} \quad (19)$$



### 2.3.5 Lesser than equal

$$\frac{\langle e_1, \sigma \rangle \Downarrow n_1 \langle e_2, \sigma \rangle \Downarrow n_2}{\langle e_1 \leq e_2, \sigma \rangle \Downarrow n_1 \leq n_2} \quad (20)$$

### 2.3.6 Greater than equal

$$\frac{\langle e_1, \sigma \rangle \Downarrow n_1 \langle e_2, \sigma \rangle \Downarrow n_2}{\langle e_1 \geq e_2, \sigma \rangle \Downarrow n_1 \geq n_2} \quad (21)$$

## 2.4 If-statement

$$\frac{\langle b, \sigma \rangle \Downarrow true \langle c, \sigma \rangle \Downarrow \sigma''}{\langle \text{if } b \text{ then } c, \sigma \rangle \Downarrow \sigma''} \quad (22)$$

$$\frac{\langle b, \sigma \rangle \Downarrow false \langle c, \sigma \rangle \Downarrow \sigma''}{\langle \text{if } b \text{ then } c, \sigma \rangle \Downarrow \sigma''} \quad (23)$$

## 2.5 While-statement

$$\frac{\langle b, \sigma \rangle \Downarrow false}{\langle \text{while } b \text{ do } c, \sigma \rangle \Downarrow \sigma} \quad (24)$$

$$\frac{\langle b, \sigma \rangle \Downarrow true \langle c, \sigma \rangle \Downarrow \sigma' \langle \text{while } b \text{ do } c, \sigma' \rangle \Downarrow \sigma''}{\langle \text{while } b \text{ do } c, \sigma \rangle \Downarrow \sigma''} \quad (25)$$

## 2.6 Function call

$$\frac{\langle c, \sigma \rangle \Downarrow \sigma'}{\langle \text{call } c, \sigma \rangle \Downarrow \sigma'} \quad (26)$$

## 2.7 Return

$$\frac{\langle c, \sigma \rangle \Downarrow \sigma'}{\langle \text{return } c, \sigma \rangle \Downarrow \sigma'} \quad (27)$$



## 2.8 Explain (in text) what an interpretation of your example should produce, do that by dry running your given example step by step. Relate back to the SOS rules. You may skip repetitions to avoid cluttering.

Looking at the example, see 1.2, the code can be explained using SOS. The example program starts from the "main" function by going through the AST and executing each function before it returns the value of said functions.

### 1. testfn1()

- (a) A variable "a" is assigned to 1, see eq. 3.
- (b) A variable "b" is assigned to a, see eq. 3.
- (c) A variable "c" is assigned to b, see eq. 3.
- (d) Finally variable "c" is returned, see eq. 27.

### 2. testfn2()

- (a) A variable "a" is assigned to true, see eq. 3.
- (b) The if-statement check is the value of var "b" is true, see eq. 22
- (c) Then a value of 50 is returned, see eq. 27.
- (d) Else a value of 1 is returned, see eq. 27.

### 3. main()

- (a) A variable "a" is assigned to the return value of testfn1(), see eq. 3.
- (b) A variable "b" is assigned to the return value of testfn2(), see eq. 3.
- (c) Finally the value of "b" is returned, see eq. 27.

## 2.9 Compare your solution to the requirements (as stated in the README.md). What are your contributions to the implementation.

The interpreter should be able to interpret any code following the SOS documentation stated above and otherwise panic.



## 2.10 Typechecker

### 2.10.1 Arithmetic operations

$$\frac{\Gamma e_1 : i32 \quad \Gamma e_2 : i32}{\Gamma e_1 + e_2 : i32} \quad (28)$$

$$\frac{\Gamma e_1 : i32 \quad \Gamma e_2 : i32}{\Gamma e_1 - e_2 : i32} \quad (29)$$

$$\frac{\Gamma e_1 : i32 \quad \Gamma e_2 : i32}{\Gamma e_1 \cdot e_2 : i32} \quad (30)$$

$$\frac{\Gamma e_1 : i32 \quad \Gamma e_2 : i32}{\frac{\Gamma e_1}{e_2} : i32} \quad (31)$$

### 2.10.2 Logical operations

$$\frac{\Gamma e_1 : bool \quad \Gamma e_2 : bool}{\Gamma e_1 \&\& e_2 : bool} \quad (32)$$

$$\frac{\Gamma e_1 : bool \quad \Gamma e_2 : bool}{\Gamma e_1 || e_2 : bool} \quad (33)$$

### 2.10.3 Relational operations

$$\frac{\Gamma e_1 : i32 \quad \Gamma e_2 : i32}{\Gamma e_1 \leq e_2 : bool} \quad (34)$$

$$\frac{\Gamma e_1 : i32 \quad \Gamma e_2 : i32}{\Gamma e_1 < e_2 : bool} \quad (35)$$

$$\frac{\Gamma e_1 : i32 \quad \Gamma e_2 : i32}{\Gamma e_1 \geq e_2 : bool} \quad (36)$$

$$\frac{\Gamma e_1 : i32 \quad \Gamma e_2 : i32}{\Gamma e_1 == e_2 : bool} \quad (37)$$

$$\frac{\Gamma e_1 : i32 \quad \Gamma e_2 : i32}{\Gamma e_1 == e_2 : bool} \quad (38)$$

$$\frac{\Gamma e_1 : bool \quad \Gamma e_2 : bool}{\Gamma e_1 == e_2 : bool} \quad (39)$$

$$\frac{\Gamma e_1 : i32 \quad \Gamma e_2 : i32}{\Gamma e_1 != e_2 : bool} \quad (40)$$

$$\frac{\Gamma e_1 : bool \quad \Gamma e_2 : bool}{\Gamma e_1 != e_2 : bool} \quad (41)$$





#### 2.10.4 Assignment

$$\frac{\Gamma x : \text{bool} \quad \Gamma e : i32}{\Gamma x := e : i32} \quad (42)$$

$$\frac{\Gamma x : \text{bool} \quad \Gamma e : \text{bool}}{\Gamma x := e : \text{bool}} \quad (43)$$

#### 2.10.5 If-statement

$$\overline{\Gamma b : \text{bool}} \quad (44)$$

#### 2.10.6 While-statement

$$\overline{\Gamma b : \text{bool}} \quad (45)$$

#### 2.10.7 Func arguments and parameters

$$\frac{\Gamma p : i32}{\Gamma a : i32} \quad (46)$$

$$\frac{\Gamma p : \text{bool}}{\Gamma a : \text{bool}} \quad (47)$$

#### 2.10.8 Func return types

$$\frac{\Gamma p : i32}{\Gamma r : i32} \quad (48)$$

$$\frac{\Gamma p : \text{bool}}{\Gamma r : \text{bool}} \quad (49)$$

### 2.11 Demonstrate the cases of ill formed borrows that your borrow checker is able to detect and reject.

#### 2.11.1 Arithmetic operations

---

```
let a = 1 + 2; // has the type Num
let b = 1 - 2; // has the type Num
let c = 1 * 2; // has the type Num
let d = 1 / 2; // has the type Num
let e = 1 + bool; // panics
```

---



---

### 2.11.2 Logical operations

---

```
let a = true && true; // has the type Bool
let b = true || false; // has the type Bool
let c = true || 5; // panics
```

---

### 2.11.3 Relational operations

---

```
let a = true == true; // has the type Bool
let b = true != false; // has the type Bool
let c = 1 < 2; // has the type Bool
let d = 1 > 2; // has the type Bool
let e = 1 <= 2; // has the type Bool
let f = 1 >= 2; // has the type Bool
let g = 1 == true; // panics
```

---

### 2.11.4 Assignment

---

```
let a: i32 = 1 // has the type Num
let b: bool = true // has the type Bool
```

---

### 2.11.5 If-statement

---

```
if true { ... } // runs the code inside the scope
if false { ... } // does not runs the code inside the scope
if (1 < 2) { ... } // runs the code inside the scope
```

---

### 2.11.6 while-statement

---

```
while true { ... } // runs the code inside the scope
while false { ... } // does not runs the code inside the scope
while (1 < 2) { ... } // runs the code inside the scope
```

---

### 2.11.7 Function declaration

---

```
fn testfn(a: i32, b: bool) { ... } // runs the code inside the scope if correct type args.
```

---



### 2.11.8 Function declaration

---

```
return 1; // returns a value Num(1)
return true; // returns a value Bool(true)
```

---

### 2.12 Compare your solution to the requirements (as stated in the README.md). What are your contributions to the implementation.

The type checker will detect if the input-program is valid according to the type rules. However, the program will simply panic and tell the user the program did not compile if it's invalid. Specific information about where and what went wrong is not detailed.



### 3. BORROW CHECKER

#### 3.1 Give a specification for well versus ill formed borrows.(What are the rules the borrow checker should check)

The borrow checker's main task is to verify if a variable is mutable or non-mutable. There can be as many references as you'd like, since none of them are writing. However, as we can only have one `&mut` at a time it is impossible to get a data race, which is the reason Rust prevents such issues to occur at compile time. Further, it should also check that the reference does not outlive the reference of the variable, see (Steve Klabnik, 2018).

#### 3.2 Compare your solution to the requirements (as stated in the README.md). What are your contributions to the implementation?

Neither borrow checker or references has been implemented in this project.

### 4. LLVM

#### 4.1 Let your backend produces LLVM-IR for your exam-ple program

```
define i32 @testfn1() {
entry:
    %c = alloca i32
    %b = alloca i32
    %a = alloca i32
    store i32 1, i32* %a
    %a1 = load i32, i32* %a
    store i32 %a1, i32* %b
    %b2 = load i32, i32* %b
    store i32 %b2, i32* %c
    %c3 = load i32, i32* %c
    ret i32 %c3
}

define i32 @testfn2() {
entry:
    %b = alloca i32
    store i1 true, i32* %b
    %b1 = load i32, i32* %b
    br i32 %b1, label %then, label %cont

then:
    ret i32 50
    br label %cont

cont:
    %iftmp = phi i32 [ 0, %then ], [ 0, %cont ]
    ret i32 1
}
```



```
}  
  
define i32 @main() {  
entry:  
  %b = alloca i32  
  %a = alloca i32  
  %testfn1 = call i32 @testfn1()  
  store i32 %testfn1, i32* %a  
  %testfn2 = call i32 @testfn2()  
  store i32 %testfn2, i32* %b  
  %b1 = load i32, i32* %b  
  ret i32 %b1  
}  
llvm-result: 50  
eval = Ok(  
  (),  
)
```

#### 4.1.1 Describe where and why you introduced allocations and phi nodes?

Phi node allocations are performed for function declarations and let-statements when compiled. LLVM places a "alloca"-instruction at the start of each block within a let-statement belongs. With function declarations the "alloca"-instruction is position at the start of the function scope. No phi nodes were added.

#### 4.1.2 If you have added optimization passes and/or attributed your code for better optimization (using e.g., noalias

No optimization passes have been added.

#### 4.1.3 Compare your solution to the requirements (as stated in the README.md). What are your contributions to the implementation?

LLVM is able to handle the same code going through the type-checker and interpreter. However, no optimization has been performed. Code from Per Lindgren and Inkwells kaleidoscope example, see (TheDan64, 2020) has been used to complete this part of the project.

## 5. OVERALL COURSE GOALS AND LEARNING OUTCOMES

I've learnt how to build a parser in order to put together an abstract syntax tree, an interpreter, a type-checker and how to put together a working LLVM back-end. My knowledge about EBNF and SOS is on the other hand very limited. However, this is very understandable as only a small portion of the course was spent on this.



## 6. REFERENCES

- Steve Klabnik, C. N. (2018). *The rust programming language*. Retrieved from <https://doc.rust-lang.org/1.8.0/book/README.html> (2020-12-16)
- TheDan64, s. (2020). *Inkwell, kaleidoscope*. Retrieved from <https://github.com/TheDan64/inkwell/tree/master/examples/kaleidoscope> (2020-12-16)
- van Bakel, S. (2002). *Operational semantics*. Department of Computing Imperial College of Science, Technology and Medicine. Retrieved from <http://www.doc.ic.ac.uk/~svb/AssuredSoftware/notes.pdf> (2020-11-21)