Compiling `ParL` to `PArIR` in Rust

A report on the Rust compiler for the `ParL` programming language.

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Abstract

In this report, we discuss the implementation details of a compiler for `ParL`, an expression-based strongly typed programming langauge. Code written in `ParL` is compiled to `PArIR`, which is the proprietary assembly-like language that is used to drive the programmable pixel art displays designed by the company `PArDis`. The `ParL` compiler was written in Rust, due to its strong type system and performance characteristics. It was implemented incrementally, as to ensure each component can be run in isolation, and is working correctly before moving on to the next one.

1 Project Structure

2 Lexical Analysis

The first step in the compilation process is the lexical analysis. A recurring theme in the implementation of this compiler is the use of *abstraction* to achieve *modularity*, and simplify the implementation of the subsequent stages. The lexical analysis is no exception to this rule.

At the highest level, the lexical analysis is implemented as a `Lexer` struct, which is responsible for reading the input source code, and producing a stream (*or vector*) of tokens.

We shall start by defining the `Token` struct, which is a wrapper for the different types of tokens that can be found in a `ParL` program. The `Token` enum is defined as follows:

```
pub struct Token {
    pub kind: TokenKind,
    pub span: TextSpan,
}
```

The `TextSpan` struct is mainly used to store the lexeme of the token, and its position in the source code, which is useful for error reporting. The `TokenKind` is just an enum, which represents the different types of tokens, such as `Identifier`, `IntegerLiteral`, `If` and many more.

The actual `Lexer` struct is defined as follows:

```
pub struct Lexer<B: Stream> {
    buffer: B,
    dfsa: Dfsa,
}
```

Listing 1: The `Lexer` struct.

The `Lexer` struct is generic over the type `B`, which is a trait that abstracts out the file reading logic from the lexer. This is useful for testing purposes, as we can easily mock the file reading logic, and test the lexer in isolation. It is also useful in case the lexer is to be improved in the future, by using more efficient file reading logic, such as the double buffering technique.

The main function of the `Lexer` struct is the `next_token` function, which is responsible for reading the next token from the input stream. Not much can be said, as it has been heavily inspired by the `next_token` function in the textbook *Engineering a Compiler* [3]. We provide a wrapper around the `next_token` function, called `lex()`, which filters out comments, whitespace and newlines, and only returns the actual tokens, and if any, a list of errors that have been encountered.

We note that the `next_token` returns `Result<Token, LexicalError>` instead of just a `Token`, which is caught by the wrapper `lex()`. This feature, known as *synchronization* allows the lexer to return an error, instead of crashing. This enables the lexer to recover after an error has been encountered, such as reading a character that is not in the character table of the DFSA. It will continue reading from the next token, and find other invalid characters.

Whilst using a compiler, one would expect to be given as many errors as possible, instead of playing whack-a-mole with the compiler.

2.1 DFSA Builder

Of course, the `Lexer` that was implemented in the project, was required to be a based on a finite state automaton, with a character table. Initially, the DFSA was implemented manually, but as the number of tokens (and hence states) grew it was getting harder to keep track of the transitions.

To solve this problem, together with the `Dfsa` struct, a `DfsaBuilder` struct was implemented, which is responsible for dynamically building the DFSA from a number of chained function calls. I will describe each method of the `DfsaBuilder` struct, and how it is used, by demonstrating the effect as it is run incrementally on an empty DFSA.

The `DfsaBuilder` struct is defined as follows:

```rust
pub struct DfsaBuilder {
    pub max_state: i32,
    pub accepted_states: Vec<i32>,
    pub character_table: HashMap<char, Category>,
    pub transition_table: HashMap<(i32, Category), i32>,
    pub state_to_token: HashMap<i32, TokenKind>,
}
```

Clearly, we can see that states are represented by `i32` integers, and transitions are represented by a tuple of the current state and the category of the character that is being read. The category of a character is defined by the `Category` enum, containing variants such as `Digit`, `Letter`, `Whitespace`, and many more.

The first function is

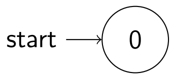
```
add_category(&mut self, range: Vec<char>, category: Category)
```

This method is used to add multiple characters to the same category. For example, we can add all the digits to the `Digit` category, by calling `add_category(’0’..=’9’, Category::Digit)`. Note that in the actual implementation, the `range` parameter is actually a more complex type, but for simplicity's sake it can be thought of a vector. It actually accepts anything that can be casted to an iterator, as to allow for more convenient usage. This is done using Rust's built in ranges like `’0’..=’9’`. As it does not have any effect on the DFSA, but only modifies the character table, a DFSA will not be shown.

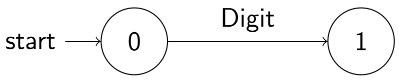
Then, we have

```
add_transition(&mut self, state: i32, category: Category, next_state: i32)
```

This method is used to add a transition from one state to another, given a category. For example, we can add a transition from state 0 to state 1, when reading a digit, by calling `add_transition(0, Category::Digit, 1)`. Note that it doesn't automatically make the state 1 an accepted state, as it is only responsible for adding transitions.



(a) The DFSA before adding calling `add_transition`



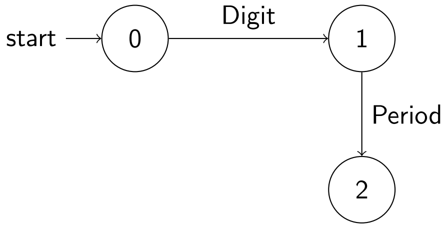
(b) The DFSA after adding calling `add_transition`

The next function is

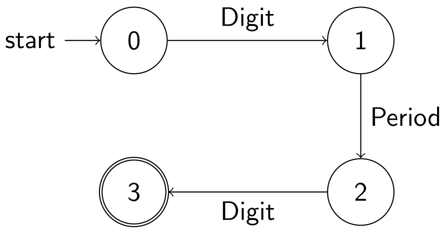
```
auto_add_transition(&mut self, state: i32, category: Category
to: Option<i32>, token_kind: TokenKind) -> i32
```

This method is used used to add a transition from `(state, category)` to the state `to`. Since `to` is an `Option`, it can be `None`, in which case the destination state is automatically set to the next state. This is useful for adding transitions to the same state, as well as constructing slightly more complicated sequences of transitions, say for tokenizing a float. The `token_kind` parameter is used to set the token kind of the state, if it is an accepted state. Similarly to the `to` parameter, it can be `None`, in which case the destination state is not an accepted state. We also note that this function returns an integer, which is the state that was just added, for further use in subsequent calls.

If we run `auto_add_transition(2, Category::Digit, None, Category::Float)`, the resultant DFSA will be as follows:

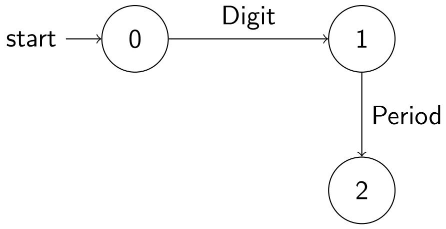


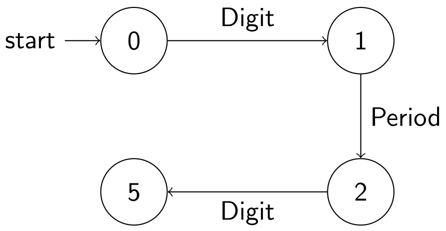
(a) Before running the function



(b) After running the function

If we run `auto_add_transition(2, Category::Digit, Some(5), None)`, the resultant DFSA will be as follows, meaning we just want to map to an auxiliary state that doesn't correspond to any token kind, (and thus is not an accepted state), the following is the resulting DFSA.



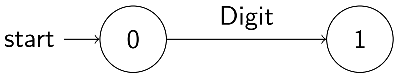


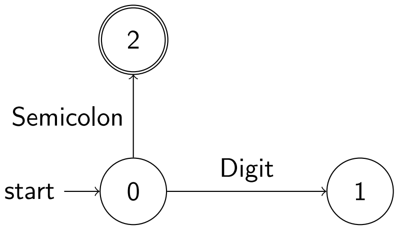
Next up, we have the function

```
add_final_character_symbol(character: char, category: Category, token_kind:
TokenKind)
```

This function is a shortcut for adding single characters that are final symbols, such as the semicolon, or the period to the character table, and the transition that follows from this to the transitions table.

Suppose we called `add_final_character_symbol(';', Category::Semicolon, TokenKind::Semicolon)`. The resultant DFSA would be as follows:





Then we have a function that does the same thing as the previous one, but is able to take in multiple tuples of the type (`char`, `Category`, `TokenKind`), and add them all at once. This function is called `add_final_character_symbols`.

Finally, we have the function `build`, which is used to build the DFSA from the builder. This function is called at the end of the chain of function calls, and returns the DFSA that was built.

Clearly, the `DfsaBuilder` has proved itself useful for an efficient and readable way to build the DFSA for the lexer. However, we still require a greater degree of freedom when it comes to making complex multi-character transitions.

> In the production rules for the `ParL` grammar, there is a slight inconsistency. There is an overlap between the `Letter` and the `Hex` symbol. This was taken into account by creating an auxiliary category called `HexAndLetter`, so that the lexer can differentiate between the two.

To be able to get around the above inconsistency, as well as to allow for the aforementioned flexibility, we can also call the `.transition()` method on the `DfsaBuilder`, and have it return an instance of the `Transition` struct. This transition automatically starts from the first unused state index, (which is kept track of in the `max_state` member of the `DfsaBuilder` struct) and gives us another set of functions we can chain to further build the transition.

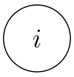
The `Transition` struct holds a reference to the `DfsaBuilder` that it was created from, the current state, the list of transitions that have been added, and the a list of final states with the token kind that they return.

```
pub struct Transition<'a> {
    dfsa_builder: &'a mut DfsaBuilder,
    current_state: i32,
    transitions: Vec<((Category, i32), i32)>,
    final_state_token: Vec<(i32, TokenKind)>,
}
```

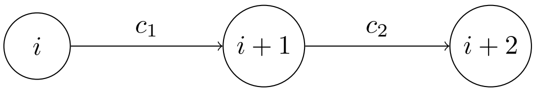
The first function that can be called on the `Transition` struct is the following:

`to(category: Category) -> Transition`

This method is used to just append a single category to the transition. Calling it multiple times, increments an internal pointer, that always points to the last state that was added. Thus, calling it multiple times creates a *chain* of states.

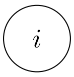


(a) The transition before adding calling `to`

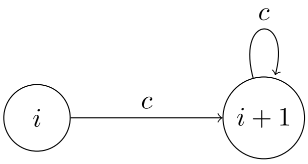


(b) The transition after adding calling `to` twice with c_1 and c_2 respectively

Then, we have the `repeated()` method, which is used to allow an indeterminate number of repetitions of the last category, think of this as the $\star$ symbol in regular expressions.



(a) The transition before adding calling `repeated`



(b) The transition after adding calling `to(c)` followed by `repeated()`

Whenever we want to make the last state an accepted state, we can thenc all the

`goes_to(token_kind:  TokenKind)`

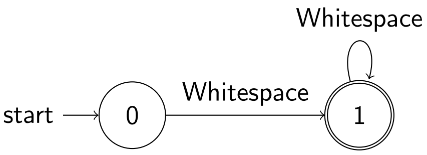
method, that simply marks the last state as an accepted state, and sets the token kind it returns to the one that was passed as an argument.

Finally, we have the `done()` method, which is used to append the transition that has been prepared to the actual DFSA from which `.transition()` was called from.

Full example

```
let mut builder = DfsaBuilder::new();
builder.add_category([' '], ['\t'], Category::Whitespace)
       .transition()
       .to([Category::Whitespace])
       .repeated()
       .goes_to(TokenKind::Whitespace)
       .done();
```

Would result in the following DFSA, with the category table already filled in with the whitespace characters.



The actual definitions of the DFSA that was used in the lexer can be found in `lexer.rs`, as part of the `Lexer::new()` function, and also in Appendix A. The final thing I must mention is how keyword are interpreted. Keywords are treated as identifiers, and then checked against a `HashMap` of reserved keywords. If the identifier is found in the map, the token kind is changed to the corresponding keyword.

3 Parsing the Token Stream

Parsing the token stream generated by the lexer is where the Rust language really shines. It allows to define an enum, called `AstNode`, which represents the different types of nodes that can be found in the abstract syntax tree of a `ParL` program. Additionally, we can mix and match different types of variants, such as ones with no data (similar to unit-like structs, like `struct Foo;`), ones with unnamed data (similar to tuple structs, like `struct Foo(i32, i32);`), and ones with named data (similar to regular structs, like `struct Foo { x: i32, y: i32 };`).

This gives us much more flexibility when defining the AST, in contrast to C or C++, where enums are basically just integers. Furthermore, I had to create a type alias from `Box<AstNode>` to `AstNodePtr`. This is because certain `AstNode` variants, have another `AstNode` as a child. The Rust compiler complains about the enum having infinite size, as it is can't be calculated at compile time. This is understandable, as for example, if the `AstNode::Expression` variant contained another `AstNode` as its member, the compiler would try to recursively visit this member to check its size, which could also be an expression, visiting the same member again, and so on. With a `Box`, the size of the enum is known at compile time, as it is just a pointer to the heap, and the compiler is happy. Lists of `AstNodes`, like parameter lists, do not need this, as a Rust `Vec` is already allocated on the heap.

The actual parser is implemented as a struct called `Parser`, which must be initialized with the list of tokens generated by the lexer. The parser privately defines all the different parsing functions. The only public function is `parse`, which is called to start the parsing process. The parser uses a recursive descent parsing algorithm, together with the Rust pattern matching feature, which is used to differentiate between the different variants of the `AstNode` enum.

Due to this, the Visitor design pattern is slightly different in Rust. With pattern matching, we avoid having every variant of the `AstNode` enum requiring it's own `accept` method. Instead we define each case in the `match` clause in the `visit` method for a given struct implementing the `Visitor` trait. Pattern matching is thoroughly used to ensure correctness and to avoid unnecessary code duplication.

A number of utility functions, such as `consume_if(kind: Tokenind)`, and `assert_token_is_any (kind: Vec<TokenKind>)`, are used to simplify the parsing process. The former consumes a token if it matches the given `TokenKind`, and returns an error otherwise. This is useful as it in allows the user to quickly identify syntax errors in the input program, with the parser suggesting what it was expecting, and announcing what it found instead. The latter function, asserts that the current token is any of the given `TokenKinds`, and returns an error if it is not. This is useful when the parser is expecting one of a number of different tokens, such as when declaring a variable, we expect either an `int`, `float`, `colour` or `bool` token kind after the semicolon. The error outputted will be more informative, as it will list all the possible token kinds that were expected.

The full list of the `AstNode` enum variants can be found in Appendix B.

3.1 Syntax Modifications

It is worth noting that the original grammar for the parser was not perfect. The precedence of the operators was not correctly defined, leading to incorrect parsing of expressions. For example, the expression

`a < b and c >= d`

was being parsed as

`a < (b and c) >= d`

which is expected from a programming language that treats the `‘and’` and `‘or’` keywords as its bitwise operators. After observing the behavior of these operators in the VM (they are indeed logical operators), the correct parsing should be

`(a < b) and (c >= d)`

The `‘and’` and `‘or’` operators were being parsed with a higher precedence than the comparison operators. Whilst researching alternative expression grammars, I stumbled upon the Lox language [1], and decided to take inspiration from it use its production rules for expressions.

The new production rules for expressions are as follows. All other rules remain the same.

⟨ Expression ⟩ ::= ⟨ Equality ⟩ { (‘and’ | ‘or’) ⟨ Equality ⟩ }
⟨ Equality ⟩ ::= ⟨ Comparison ⟩ { (‘!=’ | ‘==’) ⟨ Comparison ⟩ }
⟨ Comparison ⟩ ::= ⟨ Term ⟩ { (‘<=’ | ‘<’ | ‘>=’ | ‘>’) ⟨ Term ⟩ }
⟨ Term ⟩ ::= ⟨ Factor ⟩ { (‘+’ | ‘-’) ⟨ Factor ⟩ }
⟨ Factor ⟩ ::= ⟨ Unary ⟩ { (‘*’ | ‘/’ | ‘%’) ⟨ Unary ⟩ }
⟨ Unary ⟩ ::= (‘!’ | ‘-’) ⟨ Unary ⟩ | ⟨ Primary ⟩
⟨ Primary ⟩ ::= ⟨ Literal ⟩ | ⟨ Identifier ⟩ | ⟨ FunctionCall ⟩ | ⟨ SubExpr ⟩
| ⟨ Unary ⟩ | ⟨ PadRandI ⟩ | ⟨ PadWidth ⟩ | ⟨ PadHeight ⟩ | ⟨ PadRead ⟩

One may also notice the addition of the `%` operator, known as the modulo. Although this wasn't specified in the original grammar, it is present as an instruction in the VM, so I decided to include it. In the context of drawing pixels, it's useful for creating a wrap-around effect in loops.

4 Semantic Analysis

Semantic analysis is the process of checking the program for semantic errors, such as type errors, and ensuring that the program is well-formed. This is done after the parsing stage, where the abstract syntax tree has been constructed. The semantic analysis stage is where the compiler ensures that the program is semantically correct, and can be translated to the target language. This is done by traversing the abstract syntax tree, and checking that the program adheres to the rules of the language.

4.1 Visitor Trait

The `Visitor` trait has been mentioned in the previous section, but it is now crucial to define it and describe it properly.

```
pub trait Visitor<T> {
    fn visit(&mut self, node: &AstNode) -> T;
}
```

The `Visitor` trait is a generic trait that takes a type parameter `T` and defines a single method, `visit`, which takes a mutable reference to the struct that implements the trait, and a reference to an AST node. The method returns a value of type `T`.

The generic type parameter `T` is central to the way we will be using, or rather, re-using the visitor trait in the code generation stage. It will allow us to control the return type of the `visit` method, and thus, the type of the value that is returned when visiting a node in the abstract syntax tree. In other words, we can access different properties of an AST node, depending on the struct that implements the `Visitor` trait.

I have implemented the `Visitor` trait on a number of structs (here on referred to as Visitors), and these are:

- `Formatter`: A visitor that parses, and then *un-parses* the AST, rewriting the source in an (un-configurable) opinionated style. Similar to running `cargo fmt`.
- `TreePrinter`: A visitor mainly used for debugging the parsing stage, which prints the AST in a vertical tree-like structure.
- `SemanticAnalyser`: The visitor that performs the semantic analysis on the AST, checking for type errors, and ensuring the program is well-formed.
- `PArIRWriter`: The visitor that generates the PArIR code from the AST.

In this report I will describe the latter two, as they are part of the requirements for the project.

4.2 Type/Scope Checking

The `SemanticAnalyser`, other than being a visitor, also contains a number of structs inside of it, which are used to keep track of the current scope, and the types of variables that are in scope.

```
struct SemanticAnalyser {
    symbol_table: Vec<SymbolTable>,
    inside_function: bool,
    scope_peek_limit: usize,
    results: SemanticResult,
}
```

The `SemanticAnalyser` struct contains a vector of `SymbolTables`, which functions as a stack. Each `SymbolTable` contains a mapping of variable names (lexeme) to their types (`SymbolType`). My implementation of `SymbolType` also further differentiates between identifiers that belong to a function, array, or primitive type variable definitions. In the case of functions, I stored the entire signature, including the return type, and the types of the parameters.

Additionally, the `SemanticAnalyser` struct keeps track of whether the visitor is currently is inside a function, through the `inside_function` flag. Different behaviour is expected from the visitor when inside a function, for example, when checking for the existence of an identifier, we are only allowed to look for it in the current scope, and not in the global scope.

The `scope_peek_limit` field is used to limit the number of scopes that the visitor can look up when checking for the existence of an identifier. Used in conjunction with the `inside_function` flag, it allows the visitor to only look up to a certain number of scopes when inside a function, and all the way up to the global scope when outside of a function.

Finally, we have the `results` field, of the type `SemanticResult`. This is simply a struct that contains two lists of possible errors that can be emitted during the semantic analysis stage. We categorize these errors as `Warnings`, i.e. possible involuntary mistakes performed by the user that do not necessarily disallow the compilation of the program, and `Errors`, i.e. mistakes that must be fixed before the program can be compiled.

Variable Shadowing

This implementation of the `ParL` compiler allows for *variable shadowing*, like Rust [2]. This means that a variable can be re-declared in an inner scope, and the latter will *take over* the former for the life-time of the inner scope. Variable shadowing will produce a warning, as it can lead to confusion, but variable re-declaration in the same scope will produce an error.

Now that we know what tools the semantic analyser has at its disposal, we still have one more thing to discuss. How do we find out the types of arbitrary expressions, possibly with a mixture of literals, variables, function calls, and operations applied to them?

To answer this question we must define the type inference of operations between types in the language.

`+ - * /`	Int	Float	Colour	Boolean
Int	Int	Float	N/A	N/A
Float	Float	Float	N/A	N/A
Colour	N/A	N/A	Colour	N/A
Bool	N/A	N/A	N/A	N/A

(a) Addition, subtraction, multiplication, and division operations between types.

`== != < > <= >=`	Int	Float	Colour	Boolean
Int	Bool	Bool	N/A	N/A
Float	Bool	Bool	N/A	N/A
Colour	N/A	N/A	Bool	N/A
Bool	N/A	N/A	N/A	Bool

(b) Comparison operations between types.

`%`	Int	Float	Colour	Boolean
Int	Int	N/A	N/A	N/A
Float	N/A	N/A	N/A	N/A
Colour	N/A	N/A	N/A	N/A
Bool	N/A	N/A	N/A	N/A

(a) Modulo operation between types.

`and or`	Int	Float	Colour	Boolean
Int	N/A	N/A	N/A	N/A
Float	N/A	N/A	N/A	N/A
Colour	N/A	N/A	N/A	N/A
Bool	N/A	N/A	N/A	Bool

(b) Logical operations between types.

Every time we encounter an operation between two types, we must thus check the tables above to see if the operation is valid. If it is, we can infer the type of the operation, and continue checking the rest of the expression. If it is not, the semantic analyser must emit an error, and stop the compilation process.

Type Inference

This type inference was only possible due to the flexibility between the operations performed in the VM itself. Given the VM is implemented in JavaScript, this flexibility is warranted, as JavaScript is a dynamically typed language. Had it been done on actual hardware, the type inference would have been much more rigid, and the checking must have been more strict, possibly with more intricate conversions to achieve the desired result.

Behind the scenes, the compiler actually assigns a type to unsupported operations, namely the `Unknown` type, which by default is incompatible with any operation.

This is the general idea behind evaluating types of expressions in the `SemanticAnalyser` visitor. How do we determine however the true return type of a function declaration, or a `Block`? Well, we just traverse the AST until we hit a `Return` statement, and then we check the type of the expression that is being returned. Since we are not allowed to have functions that do not return anything, any `Block` is at first assigned the `Void` type, and if it remains so until the end of the block, an error is emitted.

Now that we know how all the type information of the program and the statements therein is gathered, the semantic analyser will check this against the type provided by the user in the function signature, or variable declaration, and will emit a type mismatch error, stating what the type it expected is (the one the user defined) and what it found, the type of the returned expression. In the case of arrays, lengths must also match.

A Lexer DFSA

```
pub fn new(input: &str, file: &Path, dfsa: Option<Dfsa>) -> Self {
    let mut dfsa_builder = DfsaBuilder::new();

    match dfsa {
        Some(dfsa) => Lexer {
            buffer: B::new(input, file),
            dfsa,
        },
        None => {
            let dfsa = dfsa_builder
                .add_category(’a’..=’f’, Category::HexAndLetter)
                .add_category(’A’..=’F’, Category::HexAndLetter)
                .add_category(’g’..=’z’, Category::Letter)
                .add_category(’G’..=’Z’, Category::Letter)
                .add_category(’0’..=’9’, Category::Digit)
                .add_final_character_symbols(vec![
                    (’\n’, Category::Newline, TokenKind::Newline),
                    (’{’, Category::LBrace, TokenKind::LBrace),
                    (’}’, Category::RBrace, TokenKind::RBrace),
                    (’(’, Category::LParen, TokenKind::LParen),
                    (’)’, Category::RParen, TokenKind::RParen),
                    (’[’, Category::LBracket, TokenKind::LBracket),
                    (’]’, Category::RBracket, TokenKind::RBracket),
                    (’;’, Category::Semicolon, TokenKind::Semicolon),
                    (’:’, Category::Colon, TokenKind::Colon),
                    (’+’, Category::Plus, TokenKind::Plus),
                    (’*’, Category::Asterisk, TokenKind::Multiply),
                    (’,’, Category::Comma, TokenKind::Comma),
                    (’\0’, Category::Eof, TokenKind::EndOfFile),
                    (’%’, Category::Percent, TokenKind::Mod),
                ])
                .add_whitespace_logic()
                .add_comment_functionality()
                .add_multi_char_rel_ops()
                .add_identifier_logic()
                .add_number_logic()
                .build();

            Lexer {
                buffer: B::new(input, file),
                dfsa,
            }
        }
    }
}
```

B Parser AST Node Enum

```rust
pub type AstNodePtr = Box<AstNode>;

#[derive(Debug)]
pub enum AstNode {
    Program {
        statements: Vec<AstNode>,
    },
    VarDec {
        identifier: Token,
        r#type: Token,
        expression: AstNodePtr,
    },
    Block {
        statements: Vec<AstNode>,
    },
    Expression {
        casted_type: Option<Token>,
        expr: AstNodePtr,
    },
    SubExpression {
        bin_op: AstNodePtr,
    },
    UnaryOp {
        operator: Token,
        expr: AstNodePtr,
    },
    BinOp {
        left: AstNodePtr,
        operator: Token,
        right: AstNodePtr,
    },
    PadWidth,
    PadRandI {
        upper_bound: AstNodePtr,
    },
    PadHeight,
    PadRead {
        x: AstNodePtr,
        y: AstNodePtr,
    },
    IntLiteral(Token),
    FloatLiteral(Token),
    BoolLiteral(Token),
    ColourLiteral(Token),
    FunctionCall {
        identifier: Token,
        args: Vec<AstNode>,
    },
    ActualParams {
        params: Vec<AstNode>,
    },
    Delay {
        expression: AstNodePtr,
    },
    Return {
        expression: AstNodePtr,
    },
    PadWriteBox {
        loc_x: AstNodePtr,
        loc_y: AstNodePtr,
        width: AstNodePtr,
        height: AstNodePtr,
        colour: AstNodePtr,
    },
    PadWrite {
        loc_x: AstNodePtr,
        loc_y: AstNodePtr,
        colour: AstNodePtr,
    },
    Identifier {
        token: Token,
    },
    If {
        condition: AstNodePtr,
        if_true: AstNodePtr,
        if_false: Option<AstNodePtr>,
    },
    For {
        initializer: Option<AstNodePtr>,
        condition: AstNodePtr,
        increment: Option<AstNodePtr>,
        body: AstNodePtr,
    },
    While {
        condition: AstNodePtr,
        body: AstNodePtr,
    },
    FormalParam {
        identifier: Token,
        param_type: Token,
        index: Option<Token>,
    },
    FunctionDecl {
        identifier: Token,
        params: Vec<AstNode>,
        return_type: Type,
        block: AstNodePtr,
    },
    Print {
        expression: AstNodePtr,
    },
    Assignment {
        identifier: Token,
        expression: AstNodePtr,
        index: Option<AstNodePtr>,
    },
    PadClear {
        expr: AstNodePtr,
    },
    VarDecArray {
        identifier: Token,
        element_type: Token,
        size: usize,
        elements: Vec<AstNode>,
    },
    ArrayAccess {
        identifier: Token,
        index: AstNodePtr,
    },
    EndOfFile,
}
```

References

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[2] *Scope and Shadowing - Rust By Example — doc.rust-lang.org*. `https://doc.rust-lang.org/rust-by-example/variable_bindings/scope.html`. [Accessed 26-05-2024].

[3] Linda Torczon and Keith Cooper. *Engineering A Compiler*. 2nd. San Francisco, CA, USA: Morgan Kaufmann Publishers Inc., 2007, pp. 86–71. ISBN: 012088478X.