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Master of Science

A Very Long and Impressive Thesis Title with a Forced Line Break

Dissertation plan submitted in partial fulfillment
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⟨month⟩, ⟨year⟩

Abstract

The dissertation must contain two versions of the abstract, one in the same language as the main text, another in a different language. The package assumes that the two languages under consideration are always Portuguese and English.

The package will sort the abstracts in the appropriate order. This means that the first abstract will be in the same language as the main text, followed by the abstract in the other language, and then followed by the main text. For example, if the dissertation is written in Portuguese, first will come the summary in Portuguese and then in English, followed by the main text in Portuguese. If the dissertation is written in English, first will come the summary in English and then in Portuguese, followed by the main text in English.

The abstract shoul not exceed one page and should answer the following questions:

- What's the problem?
- Why is it interesting?
- What's the solution?
- What follows from the solution?

Keywords: Keyword 1, Keyword 2, Keyword 3, ...

Resumo

Independentemente da língua em que está escrita a dissertação, é necessário um resumo na língua do texto principal e um resumo noutra língua. Assume-se que as duas línguas em questão serão sempre o Português e o Inglês.

O *template* colocará automaticamente em primeiro lugar o resumo na língua do texto principal e depois o resumo na outra língua. Por exemplo, se a dissertação está escrita em Português, primeiro aparecerá o resumo em Português, depois em Inglês, seguido do texto principal em Português. Se a dissertação está escrita em Inglês, primeiro aparecerá o resumo em Inglês, depois em Português, seguido do texto principal em Inglês.

O resumo não deve exceder uma página e deve responder às seguintes questões:

- Qual é o problema?
- Porque é que ele é interessante?
- Qual é a solução?
- O que resulta (implicações) da solução?

E agora vamos fazer um teste com uma quebra de linha no hífen a ver se a LaTeX duplica o hífen na linha seguinte...

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-lhe zzz zzzz zzz zzzz

Sim! Funciona! :)

Palavras-chave: Palavra-chave 1, Palavra-chave 2, Palavra-chave 3, ...

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p4	Pre-Processor-Pretty-Printer	9
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Chapter 1

Introduction (20/01/2021)

1.1 Context

Users face bugs on a daily basis, whether in their instant messaging application or a game, bugs currently permeate our lives, they are mostly harmless as such applications are not critical, resulting in some unsent messages or texture glitches.

However, in areas as systems programming, one of the most demanding domains in computer science, bugs and their respective consequences come at a high cost to both service providers and consumers. There are reports from several industries where bugs lead to huge monetary losses and even death.

In 2014, the Heartbleed [11] bug, caused due to a missing bound check, compromised the security of any OpenSSL user, enabling the theft of critical information (e.g. cryptographic keys). In 2018, a bug in Coinbase (a popular cryptocurrency exchange) allowed for account balance manipulation [41]. In 2019 and 2020, after several crashes [2], the Boeing 737 Max was grounded to fix existing problems, while grounded, more software-related issues were found [24, 23], delaying its re-certification. In 2020, as the number of COVID-19 grew, contact tracing apps were deployed as a mitigation strategy. The UK's National Health Service app failed to ask users to self-isolate due to a bug [19].

The previous examples are not isolated incidents, the language and nature of the bugs is different for each case, to put it simply, there is no silver bullet and the next best alternative is to do our best to mitigate them by building tools and abstractions which allow developers to increase their code's safety.

```java
Scanner s = new Scanner(System.in);          // open the stream
s.nextLine();                                // read
s.close();                                   // close the stream
s.nextLine();                                // IllegalStateException
```

Listing 1.1 – Java's `Scanner` misuse example.

1.2 Problem

Languages like C/C++ have dominated the systems programming landscape for years and one of the main problems with both is the lack of memory management. Leaving such responsibility to the developer has proven to be *a less than ideal* solution, with 70% of bugs in projects like Chromium [20] and Microsoft products [21] being due to memory management.

To address such problem, several tools and languages have been and continue to be developed, so far, Rust has been the only one to achieve *mainstream* status. Rust aims to provide memory safety without affecting performance or productivity, to achieve such ambitious goal, Rust validates code with the borrow checker, which then enforces memory safety rules, targeting the problem at its root.

Addressing memory safety is not enough though, languages which side-step the problem of having manual management through the use of a garbage collector (e.g. Java and Go) still suffer from other kinds bugs. As discussed in the end of Section 1.1, we can only mitigate their occurrence, and so we are required to reach out to new mechanisms.

Typestates are an approach which aims to tame stateful computations, to do so typestates lift the concept of state to the type level, this enables the compiler to reason about state and provides the developer with information of the expected computation state at runtime.

Consider Java's `Scanner`, its API allows the developer to write code like Listing 1.1, which will compile without issuing any errors or warnings (even with the `-Xlint:all` flag). The example in Listing 1.1 will crash during runtime, since it is not possible to read from a closed source, the thrown exception is `IllegalStateException`. Informing the user that the attempted operation is illegal for the current object state, ideally we want such illegal states to be detected at compile time.

If we consider a typestated language, as in Listing 1.2, the code allows us to trace the state of the object, but even better, the compiler is now able to tell us there is an error during compilation.

1.3 State of the Art

As it stands, current mainstream languages do not provide first-class support for behavioral types, leaving developers to write their own abstractions over the language type-system. These abstractions will usually be built on top of existing meta-programming

```
Scanner[Open] s = new Scanner(System.in);    // open the stream
s.nextLine();                                // read
Scanner[Closed] s = s.close();               // close the stream
s.nextLine();                                // compile-time error
```

Listing 1.2 – Typestated `Scanner` example. Notice how the compiler is able to detect the error.

capabilities offered by the language, or with the help of external tools in an ad-hoc fashion. The latter is the most common approach as it allows the built tool to take advantage of other existing tools. This is Mungo's case [15, 42], a language which generates a Java API skeleton along with a typestate specification from a Scribble [46] protocol.

In Rust's ecosystem a crate providing typestated futures exists, the `state_machine_future` crate [9], it also provides some state machine related guarantees, such as that every state is reachable from the start start, there are no states unable to reach the final state and all state transitions are invalid. Furthermore, these guarantees are provided at compile-time, invalid state transitions, for example, fail to compile. The crate, however, revolves around futures, requiring a runtime and thus making it unsuitable for other kinds of applications. Other crates exist, they focus on finite state machines but are unable to provide static guarantees.

Amidst the previous topics, Scribble and Rust's crates, there exists a third alternative, rooted in session types. The work done by [14, 22] introduces bi-directional session types to Rust, since then, this line of work has been expanded by [18], extending it to multiparty session types.

Finally, regarding typestates, languages like Plaid [1] and Obsidian [**Coblenz2020a**, 3] put typestates to use. Plaid in an object-oriented context while Obsidian makes use of typestates and linear types to provide more safety when writing blockchain smart contracts.

1.4 Objectives & Contributions

In this thesis I try to bridge the gap between typestates and Rust, aiming for an elegant and usable solution, allowing for effective usage of typestates in Rust. To achieve such solution I expect to develop an embedded Rust DSL, enabling the flexibility of a dedicated language without leaving the Rust ecosystem.

To this effect I expect the contributions of this thesis to be a typestate specification DSL to be embedded in Rust, shipped as a crate (i.e. library), as well as a small survey over the usability of the DSL.

1.5 Report Organization

This document is organized as follows:

- Chapter 2 provides a review over existing systems programming languages (Section 2.1), the Rust programming language (Section 2.2) and behavioral types (Section 2.3).
- Chapter 3 describes existing work regarding language preprocessing (Section 3.1), Rust macros (Section 3.2) and existing approaches to behavioral types (Section 3.3).
- Chapter 4 illustrates the development roadmap of this project, detailing the required work to achieve the goals proposed in Section 1.4.

Chapter 2

Background (03/02/2021)

2.1 Systems Programming Languages

2.1.1 C & C++

2.1.2 Ada

Ada was developed in a standardization effort for USA's Department of Defense, unifying projects spanning over 450 programming languages [35]. Its main focus was the development of embedded application, currently the Ada language is mostly used in the critical domain due to its strong emphasis on safety, some Ada success stories are the Metro Victoria Line and the Paris Metro Line [30]. Ada is also used in several other domains, such as aviation, space vehicles, financial systems and more [8].

2.1.3 Go

The Go programming language (or `golang`) is a Google project, according to its tale, it was designed by the authors while they waited for their C++ code to compile. Go tried to address several of the criticisms to C, namely memory management, which it solved by using a garbage collector. While it has made a name for itself in the network and distributed systems sector, being the main language behind projects like Docker [6] and Kubernetes [17], its position as a systems programming language can be discussed.

Since its binaries carry a runtime and make use of garbage collection, its performance may not be enough in some cases. This was the case for Discord, the popular internet voice server company, as demand increased, Go was not able to meet the expected performance requirements and the company replaced it with Rust [12]. Regardless of discussion, Go has proven to be a viable alternative to its counterparts, compromising extreme performance in name of safety and simplicity.

2.2 The Rust Language

Rust is a fairly recent systems programming language, its main focus revolves around memory safety, effectively removing classes of such bugs (e.g. *use-after-free* and *double-free*). Another one of Rust's focus, is on productivity, aiming to provide the safety mechanisms necessary to remove the previous class of bugs, while trying to provide a pleasant and productive development experience.

To achieve its goals, Rust makes use of a borrow checker and an ownership system, in conjunction, they're responsible for guaranteeing correct memory usage. At its core, the borrow checker is a lightweight theorem prover, it tries to prove that the code does not break safety rules.

Its rules can be distilled down to the following intuition, only one entity can hold a reference to mutable data at a time, several entities may hold references to immutable data. This also enables Rust to also provide mechanisms which help deal with concurrency, allowing for developers to write data-race free code [38].

2.2.1 What makes Rust different?

2.3 Behavioral Types

2.3.1 Session Types

2.3.2 Typestates

> *... traditional strong type checking was enhanced with **typestate checking** a new mechanism in which the compiler guarantees that for all execution paths, the sequence of operations on each variable obeys a finite state grammar associated with that variable's type. — Typestates as described by [34]*

The first language to make use of typestates was NIL [34], afterwards languages like Hermes [33] and Plaid [1] extended the concept with new techniques.

The case for typestates

As discussed in Section 1.1, bugs in systems programming are costly, thus, bugs must be minimized. Several tools, such as static analyzers, fuzzers, testing frameworks and others, aid in this purpose, if we have all these external tools, why should we not try and leverage the programming language itself?

Moving towards better languages. Programming languages allow the programmer to express a set of actions to be taken by the computer, they are tools which enable us to achieve a goal. Being essential to our work, better tools enable developers to be more productive and achieve higher quality work. The remaining question is *"why do we not create better languages?"*. Even when considering languages to be cheap to develop,

```
1 public class Mult {
2     public static void main(String[] args) {
3         Scanner s = new Scanner(System.in);
4         s.nextLine();
5         s.close();
6         s.nextLine();
7     }
8 }
```

Listing 2.1 – The `Mult` program, which reads two integer and multiplies them together.

the amount of work between a *working* language to be *production ready* is not cheap. Furthermore, while adopting a new language for a hobby project is easy, the same does not apply for enterprise level projects, requiring several developers to know the ins and outs of the language.

Static typed languages. The current trend is to move from dynamically typed languages, to statically typed ones, or at the very least, add typing support to existing dynamic languages. Typescript [39], Reason [27] and PureScript [25] are all examples of languages built to bridge the gap between static type systems and JavaScript. Python and Ruby, two popular dynamic languages, have also pushed for type adoption with the addition of type hint support in recent releases [40, 29].

Where do typestates fit? Typestates are a complex subject, able to be adopted at several levels, just like type hints, they can be partially used in some languages, through tools such as Mungo [42], by contract-style assertions as in Ada2012, Eiffel or pre-0.4 Rust, or finally by leveraging the existing type system to write typestate enabled code as it is possible in Rust [7].

Why use typestates? By leveraging the state to the typesystem, the compiler is able to aid the programmer during development, a given set of transitions will be impossible by default, since the types do not implement them. By reducing the need for developers to check for a certain set of conditions through the use of typestates, it becomes possible to reduce the number of runtime assertions and completely eliminate the need for illegal state exceptions since illegal transitions are checked at compile time.

Typestates in action

As a simple example, consider the Java application in Listing 2.1 which simply takes two numbers and multiples them together. The application will throw an exception on line 6, since the programmer closed the `Scanner` in line 5. In this example, the error is simple to catch, the program is short and the `Scanner` can either be open or closed, however, real-world applications are not that simple.

In the case of *typestated* programming, the type system will provide the programmer with better tools to express state, furthermore, the compiler will then catch errors

```
public class Mult {
    public static void main(String[] args) {
        Scanner[Open] s = new Scanner(System.in);
        s.nextLine();
        Scanner[Closed] s = s.close();
        s.nextLine(); // compiler error
    }
}
```

Listing 2.2 – The `Mult` program, written in a typestated fashion.

regarding state, such as the previous *use-after-close*.

Listing 2.2 shows the `Mult` program written in a typestated fashion, notice that the `Scanner` type is now augmented with its state and the compiler is able to catch the misuse of the `Scanner[Closed]` interface.

Plaid is a typestate-oriented programming language [1], instead of `class`es users write `typestate`s. Each typestate represents a class in its possible states, its methods and behavior change during runtime as state changes, in contrast with other languages (e.g. Java) where public methods and fields are always available.

This property allows the typesystem to enforce certain properties at compile time, such as certain methods will never be called in a given state since it is not possible by design (i.e. they are not available in the interface).

Rust. As discussed in Section 2.2, Rust takes its commitment with safety with seriousness, providing the necessary tools to users. While Rust does not support first-class typestates, it is possible to emulate them using its type system (as demonstrated in [7]), this is discussed in further sections of this document.

Embedded Rust. As any systems programming language, Rust penetrated the embedded development space. Its features are most adequate and the community has put great effort into making Rust a viable language for embedded systems.

The Embedded Rust Book's [36] Chapter 4 is dedicated to static guarantees, introducing programmers to the concepts of typestate in Section 4.1, and their usage in embedded systems.

As for real-world usage, typestates are abundantly used in the area (not just discussed in the book), under [31] one finds several repositories (suffixed with `-hal`) which implement typestates (e.g. `gpio.rs` from `stm32h7xx-hal`).

Obsidian is a language targeting Hyperledger Fabric [10], among other features it makes use of typestates to reduce the amount of bugs when dealing with assets.

In [3] an empirical study tested and proved Obsidian claims, when compared with Solidity, the leading blockchain language, users inserted fewer bugs and were able to start developing safer code faster.

Chapter 3

Related Work (10/02/2021)

3.1 Language Preprocessors

Language preprocessors are a mechanism which runs during compilation, some languages will apply the preprocessor during different compilation stages while others will only apply the preprocessor in a single stage.

3.1.1 OCaml

The OCaml ecosystem currently uses OCaml PPX, however, previous to version 4.02, OCaml made use of p4.

We briefly review both p4 and PPX.

Camlp4

Camlp4 is a parsing library which provides extensible grammars, its main goal is to allow users to extend OCaml syntax, Camlp4 is also able to redefine the core syntax, OCaml even introduced a revised syntax [26] to enable Camlp4.

The library has been deprecated due to being confusing to users and tools alike. Users were required to learn the revised OCaml syntax which complicates the development process. These criticisms are found throughout documents which discuss Camlp4 [43].

In a nutshell, the Camlp4 library would allow developers to develop an extension syntax, when the compiler would pass the source code as text to the preprocessor, which, in turn would generate valid OCaml source code.

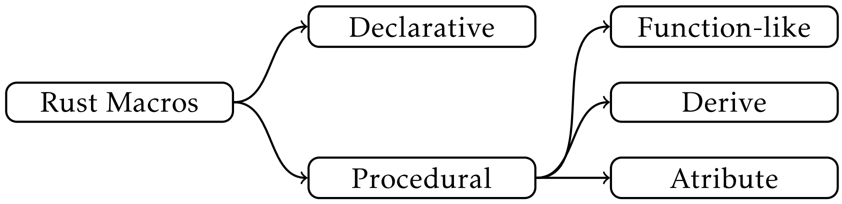

Figure 3.1 – Rust macro's family tree

PPX

3.1.2 Java

As other languages, Java is also capable of source code processing during compile time, we review two existing approaches, annotations and the ExtendJ compiler.

Java Annotation Processor

Java annotations were first introduced in Java 5 [5], they are a form of metadata which can be added to Java source code. Annotations can be used in conjunction with several components of the Java language, such as classes, interfaces, documentation and others. These are processed by build-time tools or by run-time libraries to achieve new semantic effects, a popular example of such library would be the compile-time dependency injection framework Dagger 2 [4].

ExtendJ & JastAdd

3.1.3 Kotlin

Kotlin Compiler Plugins

3.2 Rust Macros

Just like its predecessors, C & C++, Rust offers macros as part of the language. In essence, Rust macros are just like other languages macro's, running during compile-time to generate code. In Rust, macros refer to a family of features (see Figure 3.1), *declarative* macros and *procedural* macros.

3.2.1 Declarative Macros

Declarative macros (also known as *macros-by-example*) can be declared with `macro_rules!` and are called with function syntax (see Listing 3.1).

> *Each macro by example has a name, and one or more rules. Each rule has two parts: a matcher, describing the syntax that it matches, and a transcriber, describing the syntax that will replace a successfully matched invocation. Both the matcher*

> *and the transcriber must be surrounded by delimiters. Macros can expand to expressions, statements, items (including traits, impls, and foreign items), types, or patterns. — [37, Section 3.1]*

Transcribing. When a macro is invoked, the macro expander loops through the declared rules, transcribing the first successful match. It transcribes the first successful match; if this results in an error, then future matches are not tried. An error is thrown if the compiler cannot determine unambiguously how to parse the macro [37, Section 3.1 - Transcribing].

Metavariables. To specify a macro a user first declares a pattern which will match a given form of syntax. *Metavariables* are used to achieve such goal, they are declared with "`$ name : fragment-specifier`" in the macro matcher and can match thirteen different kinds of syntax fragments [37, Section 3.1 - Metavariables]. In Listing 3.1, the metavariable `n` is of kind `literal` which will match literals such as `'E'`, `"Elite"` and `420` [37, Section 8.2.1].

Repetitions are indicated by placing the tokens to be repeated inside `$(...)`, followed by a repetition operator, optionally with a separator token between. This is valid both for the matcher and the transcriber. Repetition operators are the same as the regular expression ones:

- `*` — indicates zero or more repetitions.
- `+` — indicates at least one repetition.
- `?` — indicates zero or one repetition.

Hygiene works by attaching an invisible *syntactic context* to all identifiers [44]. Identifiers are compared over two pieces of information, the *textual value* and their *syntactic context*. The textual value consists of the variables name (e.g. `four`), the syntactic context is a kind of scope added to variables declared inside the macro, this is done to keep the macro declared variables from interfering with existing ones.

When expanding a declarative macro[1] variables declared inside the macro belong in a different scope, consider the macro declared in Listing 3.2 and the respective expansion in Listing 3.3. As illustrated by Listing 3.3, line 2 is considered to be in a different context than the rest of the expanded code. This will rightfully raise an error (shown in Listing 3.4), since line's 3 `a` will not exist due to not being in the same syntactic context as line 2.

3.2.2 Procedural Macros

Rust also has another macro mechanism, *procedural macros*, these can take three forms: *function-like macros*, *derive macros* and *attribute macros*. In a nutshell, procedural macros allow users to run code at compile time, consuming and producing Rust syntax.

[1] The same mechanism does not apply to procedural macros, which are not hygienic. Their output will interfere with existing code if precautions are not taken [16].

```
macro_rules! say_hello {
    ($n:literal) => {
        for 0..$n {
            println!("Hello, world!");
        }
    }
}
fn main() {
    say_hello!(5);
}
```

Listing 3.1 – Example macro_rules! usage. When executed, the code above will print “Hello, world!” five times.

```
1 macro_rules! using_a {
2     ($e:expr) => {
3         {
4             let a = 42;
5             $e
6         }
7     }
8 }
9 let four = using_a!(a / 10);
```

Listing 3.2 – Definition of the using_a macro and usage. The macro simply declares a variable a, set to 42 and then writes an expression which was passed in.

```
1 let four = {
2     let a = 42;
3     a / 10
4 };
```

Listing 3.3 – Listing 3.2 line 9’s macro expansion. Declarations with a blue background will be placed in a different *scope* than the others, thus the a for lines 2 and 3 will not be considered the same.

```
error[E0425]: cannot find value `a` in this scope
  --> src/main.rs:13:21
   |
 9 | let four = using_a!(a / 10);
   |                     ^ not found in this scope
```

Listing 3.4 – The expansion in Listing 3.3 will result in an error during compile time since the as in line 2 and 3 are considered to belong to different contexts.

```
html! {
    h1 { "Hello, world!" }
    p.intro {
        "This is an example of the "
        a href="https://github.com/lambda-fairy/maud" { "Maud" }
        " template language."
    }
}
```

Listing 3.5 – HTML DSL embedded in Rust. Example taken from [45].

Function-like Macros

Function-like macros and declarative macros are similar regarding invocation, being indistinguishable from each other, and output, completely replacing the original call. However, the similarities stop there as their implementation methods are completely different.

Definition. Function-like macros are defined by a public function with the `proc_macro` attribute and a signature of type `(TokenStream) -> TokenStream`. Everything contained inside the call delimeters of the macro invocation is input to the function, as previously referred, the output will completely replace the macro call.

Domain Specific Languages. While the macros discussed next also provide their contribution for domain specific languages in Rust, function-like macros provide the necessary tools to write an embedded DSL. The Rust ecosystem developers have developed HTML DSLs [45, 32] (see the example in Listing 3.5) and the possibility to run Python inside Rust[13].

Derive Macros

Derive macros likely are the most common kind of procedural macro in Rust, they are usually used to *derive* a `trait` implementation from a `struct` (see Listing 3.6). They define new inputs for the `derive` attribute, and can also create new items given the token stream of a `struct`, `enum` or `union`.

Definition. Just like function-like macros, derive macros are defined as a public function with the `proc_macro_derive` attribute and a signature of `(TokenStream) -> TokenStream`. The input is a token stream of the item with the `derive` attribute, the output is a set of items that are appended to the module or block where the input token stream is in. In Listing 3.6 the `Debug` implementation will be appended to the end of the structure.

Helper Attributes. Derive macros are also able to add additional attributes to the scope of the current item. Such attributes are called *derive macro helper attributes* and they are *inert*, that is, they are not processed by themselves but rather serve as annotations (see Listing 3.7).

```
#[derive(Debug)]
struct Coordinate {
    x: f32,
    y: f32,
    x: f32,
}
```

Listing 3.6 – Example usage of #[derive(...)], in this case deriving Debug enables the structure to be printed with "println!("{:?}", coord)".

```
#[derive(Error)]
enum CoordinateError {
    #[error("Invalid coordinates {0}")]
    InvalidCoordinates(Coordinates),
}
```

Listing 3.7 – Example usage of a derive macro with helper attributes, in this case the error(...) defines an error message with a Coordinates parameter.

```
#[get("/hello/<name>/<age>")]
fn hello(name: String, age: u8) -> String {
    format!("Hello, {} year old named {}!", age, name)
}
```

Listing 3.8 – Attribute macros are commonly used in web frameworks to provide an easy way to declare an endpoint. In this example (taken from [28]) the user declares that GET requests to hello/ have two path parameters (name and age) and should be handled by the hello function.

Attribute Macros

Attribute macros define new outer attributes, in contrast to the attributes discussed in Listing 3.2.2, attribute macros are processed as independent units and not as an annotation. They can be attached to items (see [37, Section 6]), including items in extern blocks, inherent and trait implementations, and trait definitions.

Definition. Like its counterparts, attribute macros are also declared by a public function with the proc_macro_attribute, however, their function signature takes two parameters instead of one, being (TokenStream, TokenStream) -> TokenStream.

The first parameter is the token tree following the attribute name, for example, in Listing 3.8 it would contain the token tree of ("/hello/<name>/<age>"), in the case the attribute is written as a bare attribute name (e.g. #[attribute]), the token tree is empty.

The second parameter is the token tree of the item the macro is attached to, the function output will *replace* such item with the return item or items.

Macro Type	Input Processing	Output Processing	Invocation
Declarative	Pattern Matching	Replace	`macro!`
Function-like	User programmed	Replace	`macro!`
Derive	User programmed	Append	`#[derive(...)]`
Attribute	User programmed	Replace	`#[attribute]`

Table 3.1 – Rust macros properties summary.

3.2.3 Summary

In summary, Rust enables metaprogramming through macros, the same can be divided into two categories, declarative macros, with work through pattern matching, and procedural macros. Procedural macros can be further subdivided into three categories, being *function-like*, *derive* and *attribute* macros. Their characteristics are summarized in Table 3.1.

3.3 Approaches to Behavioral Types

3.3.1 Papers do NOW (Ancona)

3.3.2 Mungo

3.3.3 Session Types in Rust

Chapter 4

Planning (17/02/2021)

4.1 The DSL

4.1.1 Objectives

What the DSL should achieve

4.1.2 Architecture

How it achieves it

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