# Problem Statement

Multithreading is often problematic in that effects of timing and scheduling may lead to nondeterministic behavior. This again leads to race conditions and limits testability of the system, in a manner that might not be acceptable for critical systems.

The possibility of making a programming language with multithreading semantics more suitable to critical systems should be explored.

The student shall:

1. Provide a short summary of systematic approaches to multithreading
2. Define a language with syntax and semantics that support writing high-reliability, real-time multithreaded programs
3. Make a prototype implementation of this language

# Preface

This report describes a master thesis done as a part of the MSc Engineering Cybernetics course at NTNU. The master thesis represents 30 ECTS points. It was written in the spring semester of 2015.

It assumes that readers have prior experience working with programming languages and knows some common nomenclature.

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# Abstract

This report presents a programming language with deterministic multithreading and its compiler. The language demonstrates that when making IO and inter-thread communication sequential, most problems with multithreaded programming disappears, while most of the architectural and some of the performance benefits of multithreading are preserved. Much difficulty in modern programming is a result of insufficient abstraction, and while the popular embedded programming languages are unlikely to be replaced anytime soon, effort still has to be made to figure out the next step in the language evolution. In the language presented, there are also other changes meant to aid in the programming of critical systems besides determinism: Threads are written much like functions, dependencies between functions not contained in each other are explicit and arguments are distinguished by name, not sequence. Finally, threads and objects shared between threads are all visible in a single place.



# Sammendrag

Denne rapporten omhandler et programmerinsspråk med deterministisk multitråding og dette språkets kompilator. Språket demonstrerer at når en gjør IO og intertråd kommunikasjon sekvensielt, så forsvinner de fleste problemer med multitråding, mens de fleste arkitekturmessige og noen av de ytelsesmessige fordelene forblir. Mange av problemene i moderne programmering er et resultat av manglende abstraksjon, og selv om de populære språkene for mikrokontrollere ikke ser ut til å bli erstattet med det første, må vi fremdeles gjøre en innsats for å finne det neste steget i språkutviklingen. I det presenterte språket er det også andre forandringer ment å lette programmeringen av kritiske systemer: Tråder skrives som funksjoner, avhengigheter mellom funksjoner som ikke er erklært i hverandre er uttalt og argumenter er skilt fra hverandre ved navn, ikke relativ posisjon. Til slutt er tråder og objekter delt mellom tråder synlig på ett sted.

# Contents

# Chapter 1

# Introduction

It is commonly understood that writing software is hard and that writing multithreaded software is even harder. This report concerns itself with a new language - Fumurt - with a functional, though incomplete, compiler. This language is intended as a viability test of some new language semantics and a starting point for further development. The semantics of the language are intended to ease development of multithreaded real-time and reactive applications and produce programs which require less testing and have fewer bugs than the existing state of the art.

Specifying a language and implementing a compiler are inherently difficult tasks. The former is an exercise in subjective judgment and trade-offs and the latter is a challenging exercise in software engineering. When starting to work with this thesis, a language was envisioned that made manual scheduling of threads easier than before, but it was decided that this placed too heavy of a burden on the programmer. The ideas that culminated in this report are the result of several weeks of reconsideration.

Fumurt is a language built with the intention that the programmer shall never be surprised. It strives to make the least possible demands on programmers ability to build mental models and memorize. Therefore Fumurt strives to imbue its syntax with as much meaning as possible and to concentrate declaration of concurrent code in one place (fork-join concurrency not affected). Language design inherently necessitates compromise and Fumurt compromises minimally on readability and predictability, sacrificing instead keyboard typing and rapid iteration. It favors predictability over performance and explicitness over terseness.

## 1.1 Report Structure

The report is divided into chapters as follows:

- The Background chapter contains information needed to understand the rest of the report and a summary of the state of the art
- The specification loosely outlines how the language should look and behave

- Analysis and Design discusses the high-level choices taken during implementation and the limitations of the current design
- Implementation documents how the compiler is written
- Testing contains examples of input source code and resulting error messages or runtime behavior
- Conclusion, Discussion and Future Work evaluates and reflects on the work done and presents recommendations for future work

The appendices are as follows:

- System manual describes how to compile and run the compiler from source
- User manual describes how to run the compiler from Java bytecode
- Code listing contains the source code

The report layout adheres to a recommendation by University College London[4], modified in consultation with supervisor.

The citation style is that of the Association for Computing Machinery.

# A Note on Terminology

During the writing of this report, a word that described both statements and definitions was needed, and it was decided to call them both expressions, despite this not being the usual way to use that word.

# Chapter 2

# Background

## 2.1 Author's Prior Knowledge

The inner workings of the compiler are heavily influenced by a course the author took on compilers at the Technische Universität Berlin under Peter Pepper and Judith Rohloff. While no code is reused, the structure of the compiler is very similar.

## 2.2 Concurrency Paradigms

It is commonly understood that writing software is hard. The development of programming languages is a response to this problem. The common pattern is that flexible features that are easily used to write code that is hard to reason about are replaced by, often several, less flexible features. After all, the less flexible a feature is, the more predictable its use is. Three examples:

- goto replaced by sequence, selection and iteration [8]
- pointers replaced by indexes and references
- mutable variables replaced by immutable values

Interestingly, one can observe that as each feature becomes easier to reason about, the total number of features increase. For example, to eliminate mutation, one needs to also eliminate iteration. One way to do this is by using recursion, which is a full replacement for iteration. But recursion, while allowing immutability, is often harder for humans to understand [22]. To ameliorate this problem, a variety of mechanisms have been implemented, for example map and fold, which performs common functions previously performed utilizing iteration. In this manner, the number of features often increase in the interest of analyzability. Is this generally true? And if so, at what point does the drawbacks of increasing feature number outweigh the benefit of increased analyzability and predictability? Answering

these questions is outside the scope of this report. Much progress has been made in making programs easier to understand and analyze in this fashion, yet there is always room for improvement. In later years, one feature in particular has risen to notability: Concurrency. In the past, concurrency has not been an issue for most programmers but as multi-processor (or multi-core) systems have gone mainstream, so has multithreaded programming[24]. The problems inherent to concurrency can roughly be divided into two categories: Communication and scheduling; making sure the correct information is shared between threads in a correct way and making sure tasks are done at correct times, respectively. One possibility is to let the programmer deal with these problems in an application-specific way. This is notoriously error-prone, however. Several abstractions have been devised for dealing with the two concurrency problems in a systematic manner, to the author's knowledge:

- Actors [16]
- Communicating sequential processes [17]
- Transactional memory[15]
- Synchronous programming[6]

**Actors** Actors are nondeterministic by definition. Each actor has a function that processes incoming messages. This function can run on its own thread, or a more lightweight system can be used. Regardless, the only way actors can exchange information is through messages. Each actor has a queue and each message received ends up at the back of this queue. When there is a message to process, the actor springs to life, processing messages (in the process probably sending some messages of its own) until its queue is empty again. Actors are similar to computers; actors are like processors with running software, and queues are like network buffers. This means that there is no need to adjust the actor system when there is a desire to spread the actors over several machines; communication over the network and communication over shared memory can both be abstracted away by the actor system. The two mainstream implementations of actors are Akka and Erlang.

**Communicating Sequential Processes** Communicating sequential processes (CSP) are also based on messages. The crucial difference is that in CSP there's no queue; the sending process blocks until the receiving process has received the message and, depending on whether this is desired, responded to the message. A very elegant property of CSP is that calling a function can be implemented as sending a message; the same syntax can be used for both. Two mainstream implementations of CSP are Go and Rust.

**Transactional memory** Transactional memory is implemented both in hardware and software, but hardware implementations are not widely available for consumer systems yet. The essence of transactional memory is the same that that of mutexes and locks - that is, shared memory where one prevent concurrent processes from accessing shared memory objects. The difference is that, where mutexes and

locks assume that there will be memory collisions, transactional memory assumes that the normal state of the system is that no two threads write to the same memory at the same time. From the perspective of a thread, it looks like this:

1. The thread locks the variable (O), and makes a read copy (C1)
2. The thread performs whatever calculations it wants to perform with the variable
3. If the calculation involves writing to the variable, then the result is written to a write copy (C2)
4. Now the thread locks the variable (O), and checks whether it is equal to the read copy (C1). If $O == C1$, then the result from the calculation is still valid. If $O! = C1$ then the thread deletes the copies (C1 and C2) and reverts to step 1.
5. If the calculation involved writing to the variable (O), then the write copy is assigned to the variable($O \leftarrow C2$)
6. The thread now unlocks the variable (O)

For big structures, such as arrays, the copies made are usually only of the read (read-set) and written (write-set) parts of the variable, which reduces copying, and lets several threads modify the same variable at the same time as long they do not affect the same parts of the variable. In transactional memory, it is desired to hold locks in as short time intervals as possible. Assuming the calculation takes a long time and no other thread tries to write to the same variables, the performance gains can be significant. And since protecting variables like this has such a low cost except under write contention, this technique can be applied to all memory the threads share. Transactional memory has many popular implementations, but it is particularly heavily used in Haskell and Clojure.

**Synchronous Programming** Synchronous programming provides a synchronicity abstraction, the same as is used for logical circuits: Time is discretized and all operations during a time step are done instantly and computed from memory as it was at the beginning of the time step. Notice that the operations done in a time step does not affect each other. Synchronous programming is thus *deterministic*. Synchronous programming is a rarity and the most mainstream implementation is Esterel, which is proprietary.

**The Decision Made for This Thesis** In the end a decision was made in favor of using a variation on the synchronous programming paradigm. There are trade-offs associated with choosing synchronous programming, but they were determined to be preferable to the alternatives. The main problems with synchronous programming are

1. Difficulty in scaling beyond one physical machine. The cost of global synchronization grows with latency.

2. Performance loss due to processing resources idling as the synchronization abstraction requires all operations to use the same amount of time.

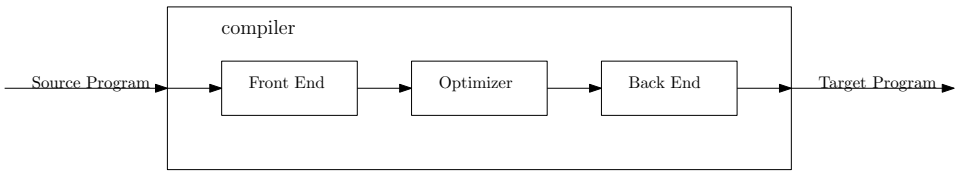
Synchronous programming therefore has substantial problems, yet for single-machine systems it presents a way to achieve near-multi-threaded performance and multi-threaded architecture but with single-threaded predictability and therefore debugability. While the other abstractions place some of the responsibility for correct concurrent behavior on the programmer, synchronous programming takes care of all of that and replaces it with the responsibility for performance, as the program performs best if all threads has an equal amount of work. Let us discuss the problems of the other abstractions:

- Actors assume infinite message queues, with the failure mode being a loss of information. In a producer-consumer relationship, producer actors can overwhelm consumer actors. Actors are designed to mimic distributed systems and create a unified abstraction over these, with the limited guarantees that requires. Distributed systems have to correctly handle hardware failures, so loss of information is an acceptable failure mode for actors. However, this makes actors unsuitable for real-time systems as recovering from data loss and unpredictable memory usage are unacceptable trade-offs. Ordering of IO is also unpredictable.
- CSP systems use synchronous communication and therefore avoid the message queue problem of actors entirely. In exchange, they are open to deadlock, and the ordering of IO is unpredictable. CSP therefore requires brute force search for deadlocks, and debugging is harder than for single-threaded systems. Despite this, it is regarded as a solid choice for real time systems.
- Transactional memory, though it makes it look as if thread communication is easy, has its own problems. The unpredictability of the sequence of writing is a problem, as well as the unpredictable time it takes. Again, IO order is unpredictable.

## 2.3 Compilers

A compiler is a program (one may regard it as a function) that accepts a program in a source format and outputs a corresponding program in a target format. The source and target format may differ in terms of encoding, language and any other way one may imagine.

This figure, reconstructed from [10], illustrates the structure of a typical compiler:




Consider the steps:

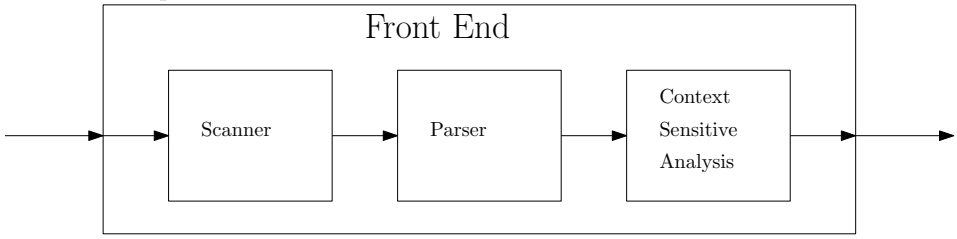
1. The front end accepts source text and transforms it into an intermediate representation that is easier to work with. It is generally independent of the target format.

2. The optimizer improves the code as encoded in the intermediate representation. The improvement is usually done with regards to performance, code size or memory usage .

3. The back end accepts the intermediate representation and outputs the the program encoded therein translated to the target format. It can be independent of the source format, depending on how general and flexible the intermediate representation is.

Since the Fumurt compiler (described in chapter 5) does not deal with optimization and conversion to binary itself, but rather outsources this to a C++ compiler, all of the difficult material on instruction selection, scheduling and register allocation is of no relevance. The parts of relevance to this report is the front end and a relatively simple back end.

Consider the parts of the front end:




- Scanner: Transforms source text into a list of tokens (simple objects), possibly ignoring some symbols (such as spaces, comments, indentation etc.)

- Parser: Transforms a list of tokens into an intermediate representation, usually an abstract syntax tree. In the process, it checks whether the syntax of the program is correct.

- Context Sensitive Analysis: Checks the correctness of program semantics. Most interpreted languages skip this step and deal with semantic errors at runtime. The correct time to do semantic analysis is not a settled matter, but in a static compiler such as the one for Fumurt it is done at compilation. This step may or may not emit a modified intermediate representation, but a case in which it would be expected to do so would be when the language has type inference.

The back end is composed of successive passes, of which every step transform the input intermediate representation into an output that is closer to the target format. The number of passes required vary greatly and depend on the differences between the source and output formats. In the trivial case, where the input and output format is identical (for example C to C), the number of necessary passes would be zero.

## Grammars

A grammar is a formal and complete description of the syntax of a language. It is mostly used for programming languages. It consists of the confusingly named "production rules". The standard used here is the Extended Backus-Naur Form of ISO/IEC 14977[25].

**Example:** Consider that a lower case letter can be described like this:

```
lower case letter = "a" | "b" | "c" | "d" | "e" | "f" | "g" | "h" |
    "i" | "j" | "k" | "l" | "m" | "n" | "o" | "p" | "q" | "r" | "s" |
    "t" | "u" | "v" | "w" | "x" | "y" | "z" ;
```

Where "=" signify the division of the two sides of the production rule, "|" signify alternation (intuitively "or"), quotes signify a string and ";" signify the end of the rule. Let us expand the example by describing a lower case word:

```
lower case word = lower case letter, {lower case letter};
```

Note that the correctness of the word as it pertains to English is ignored. The comma signify a sequence, and contents of curly brackets can be repeated from zero up to an infinite amount of times. A lower case word, as it has been defined here, is simply one lower case letter, followed by zero or more lower case letters. Next, the same is done for sentences, again ignoring rules for English:

```
lower case sentence = lower case word, {(", ", lower case word) | ("
    ", lower case word)}, ". ";
```

A lower case sentence is here a lower case word followed either by a comma plus space or just space, both followed by a new word. This is repeated as many times as desired and terminated by a period and a space.

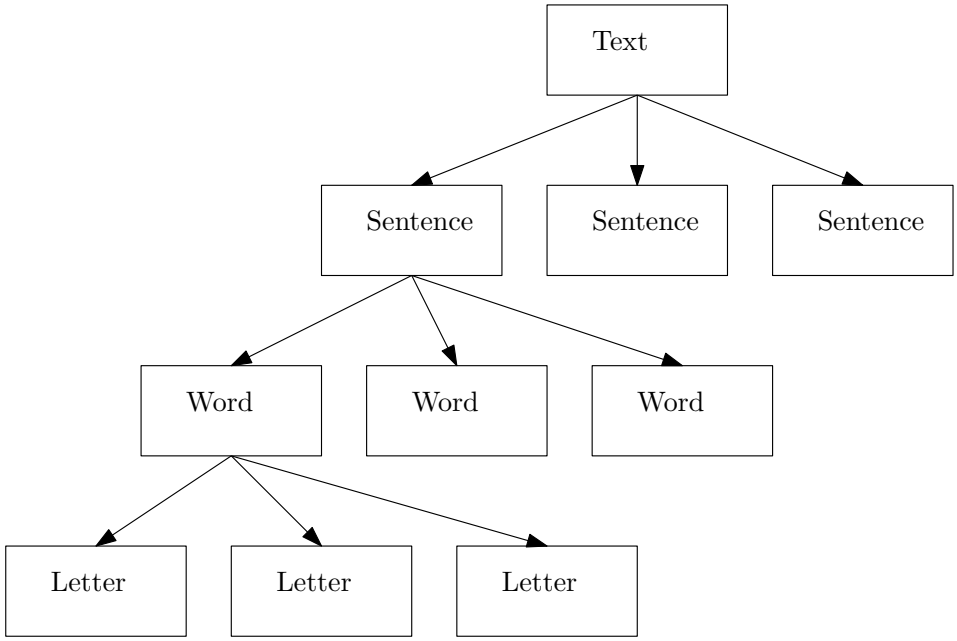
Parentheses allows grouping of sequences. Here, it allows us to alternate between sequences of symbols rather than just single symbols. Finally:

```
lower case text = lower case sentence, {lower case sentence};
```

The result is a very simple grammar, which allows us to partition up a text into sentences and words.

## Abstract Syntax Trees

Now suppose it was desired to systematize a string of characters according to the grammar above. A data structure corresponding to the grammar would be appropriate. Consider the following figure:




This is an abstract syntax tree, often abbreviated AST. An abstract syntax tree is a tree, in the computer science sense, that represents the production of the source string from the grammar. In code:

```
1 class Text(val sentences:List[Sentence])
2 class Sentence(val words:List[Word])
3 class Word(val letters:List[Char])
```

## 2.4 Parser Combinators

A parser combinator is a higher order function that accepts parsers as input and returns a new parser[13]. The overall effect is similar to a domain specific language for constructing recursive descent parsers.

A parser is a function that converts one data structure to a more sensible data structure. Usually, the output data structure is more restricted and systematic than the input one.

**Example:** Consider a function that accepts the string "=" and returns an object of class equalToken or, if the string it is given is not "=", returns an error object. Such a function is then a parser. Such parsers can be combined to form a larger parser that can work as a scanner, that is a parser that converts a list of characters to a list of tokens (very simple objects). Let the previously discussed function be called the equalParser. Let a parser that works exactly the same, save for exchanging "=" for "-" be called the minusParser and let it return a minusToken upon success. Consider combining the equalParser with the minusParser using

an *alternate parser combinator* (the "|" operator in 2.4.1). The resulting function would then first try the equalParser, and if that returned an error object, it would try the minusParser, returning an error object if both of these parsers fail. This new parser would not need to return a minusToken or equalToken, but can process the results from equalParser and minusParser into something new. In this example, two parsers have been formed and combined into a new parser using a parser combinator. This new parser can be part of a scanner. Indeed, the Fumurt scanner is formed like this (see **??**).

**A Note on Conflicting terminology:** Unfortunately there is a case of conflicting terminology concerning the term "parser". The parser is referred to in two senses:

1. The parser as defined above. A function that converts one data structure to a more sensible data structure.

2. A parser as a compilation step that converts a list of tokens into an abstract syntax tree

### 2.4.1 The Scala Standard Parser Combinator Library

All the information here is also available at [2].

The Scala Standard Parser Combinator Library introduces many parser combinators, most of whom are formulated as operators.

Let's discuss these operators:

- ~ is used to combine parsers sequentially
- ~> is used to combine parsers sequentially but ignore the result of the left parser
- ~! is used to combine parsers sequentially but disallow backtracking.
- * applies the parser to the left as many times as it is successful, moving on at failure
- + applies the parser to the left as many times as it is successful, moving on at failure. Must be applied at least once
- ? applies the parser to the left zero or one time
- | used to combine parsers in a manner similar to logical "||". Tries to apply the left parser first. If the left parser fails, it will backtrack and attempt the right parser. If none work then an error is returned.
- ^^ is used to apply a function to the successful result of the parser.
- ^^^ is used to apply a function to the result of the parser, successful or not.

## 2.5 A Quick Tour of Scala, the Compiler Implementation Language

In order to understand the code in the compiler, which is included in appendix C, it is helpful to understand the language it is written in. This section gives a quick introduction to Scala.

### 2.5.1 Execution

There are three ways to execute Scala code:

1. In a read-evaluate-print loop (REPL).
2. Interpreted as a script.
3. As compiled Java bytecode.

The compiler is executed as compiled Java bytecode. Scala can look somewhat different when it is compiled versus when it is interpreted, due to the requirements imposed by the Java bytecode. As a result, methods need to be contained in an object if the code is intended for compilation, but in the REPL and in a script there are no such restrictions. In the REPL and script, statements are evaluated starting from the top, while a main method is required if the program is supposed to be compiled. This report uses only code meant to be compiled or code as it would look in a REPL. The two are easily distinguished by the latter's use of the "scala>" command prompt.

### 2.5.2 Hello World

A simple Hello World example illustrates some main concepts.

- A singleton is called an "object". These are sometimes called static classes in other languages
- Scope is demarcated using curly braces
- A method is defined using the "def" keyword
- Arguments are given using parentheses (separated by commas and identified by relative position)
- Types of values are written after the object name, separated with ":"
- Unit, as a return type, means the method returns nothing
- Some types are container types, such as List[Int] or Array[String]. These can hold any type through generics. In this case the square brackets means that args is an object of type Array, which in this case holds String. In other words, args is an array of strings.

- There are sequences, like Array or List
- lines need not be terminated with ";" (but it is optional)

```
object HelloWorld
{
  def main(args:Array[String]):Unit =
  {
    println("Hello, world!")
  }
}
```

### 2.5.3 Creating and Using Objects

- All values are objects, even native types
- Functions are objects, but methods are not
  - Internally, functions are objects that implement an interface, for example Function1 for functions with one argument. This interface has a method "apply" where the actual "function", in the C sense of the word, is stored. This is completely transparent to the programmer, however.
- Var lets you create mutable references to objects
- Val lets you create immutable references to objects

```
scala> def int1 = 3
int1: Int

scala> val int2 = 2
int2: Int = 2

scala> var int3 = 7
int3: Int = 7

scala>//reassignment to a def is illegal

scala> int1 = int1+1
<console>:8: error: value int1_= is not a member of object $iw
       int1 = int1+1
       ^

scala>//so is reassignment to val

scala> int2 = int2+1
<console>:8: error: reassignment to val
       int2 = int2+1
            ^

scala>//reassignment to var is completely ok

scala> int3 = int3+1
```

```
int3: Int = 8

scala> int1+int2+int3
res0: Int = 13

scala>//all values are objects

scala> int1.+(int2.+(int3))
res1: Int = 13

scala>//even functions

scala> val square = ((x:Int) => x*x)
square: Int => Int = <function1>

scala> square(3)
res2: Int = 9

scala> square.toString
res3: String = <function1>

scala>//methods are not objects

scala> def cube(x:Int) = x*x*x
cube: (x: Int)Int

scala> cube(3)
res4: Int = 27

scala> cube.toString
<console>:9: error: missing arguments for method cube;
follow this method with '_' if you want to treat it as a partially
    applied function
              cube.toString
              ^
```

### 2.5.4 Classes and Pattern Matching

- Classes work much like they do in Java
- Case classes are different than normal classes.
  - Their constructors can be used like normal functions. The "new" keyword is not necessary
  - Their constructor parameters are exported
  - One can use pattern matching on them. Pattern matching allows one to test which type an object has and extract its values, a reference to it or both.
    - Pattern matching looks like this:

```
val x:String = input match
{
  case TypeA("specific string") => "specific string"
```

```
    case TypeB(anystring, otherstring) => anystring + " "
        + otherstring
    case TypeB(_,otherstring) => "only care about
        "+otherstring
    case TypeB(_,_) => "only care about type"
    case reference:TypeA => "the object looks like this:
        "+reference.toString
    case reference @ TypeA(str) => "both the reference and
        the constructor parameter"
}
```

- The wildcard "_" can be used to represent anything. In pattern matching it can be used much like "else" would in an if statement

```
scala>//classes in scala function much like classes in Java

scala> class A(int:Int, str:String)
defined class A

scala> val a = new A(3,"a string")
a: A = A@66ae2a84

scala>//case classes, on the other hand, have more functionality.
    Their constructors are called like normal functions

scala> case class B(str:String, int:Int)
defined class B

scala> val b = B("other string", 5)
b: B = B(other string,5)

scala>//and one can pattern match on them

scala> case class C(double:Double, int:Int)
defined class C

scala> val c = C(3.0, 3)
c: C = C(3.0,3)

scala> def matchfunc(in:Any):Unit = in match
     | {
     |   case B(string,integer) => println(string + integer.toString)
     |   case x:C => println(x.double.toString+x.int.toString)
     |   case _ => println("unknown type")
     | }
matchfunc: (in: Any)Unit

scala> matchfunc(b)
other string5

scala> matchfunc(c)
3.03
```

### 2.5.5 Inheritance

- A trait is like an interface, a class with only abstract methods, but one that can also have default implementations of methods
- Classes and trait inherit from each other using "extends [first super] with [second super] with [third super]"
- A class can inherit multiple traits. In the case where two traits have the same signature for different method implementations, the last trait to be inherited is the one whose implementation will be used. Inheriting two classes is not allowed.

```
scala> trait Super
defined trait Super

scala> trait Side
defined trait Side

scala> trait Side2
defined trait Side2

scala> case class Sub(int:Int) extends Super with Side with Side2
defined class Sub
```

Inheritance is used very sparingly in this thesis.

### 2.5.6 Iteration

- While works like C while loops
- For is a sequence comprehension which works much like in Python.
  - The indices of sequences are represented by 32 bit integers so "for(x <- -1 until Int.MaxValue){println(x)}" won't work since "-1 until Int.MaxValue" is a range with Int.MaxValue +1 elements. Put differently, the last element's index in this case is higher than the maximum value of 32-bit integers, which is not allowed.
  - It is possible to iterate over any sequence with the for syntax
- FoldLeft, foldRight and fold allow combination of a sequence's elements, going left to right, right to left and in an undefined direction, respectively
- Map and flatMap allows transformation of one sequence to another by applying a function to all elements. FlatMap allows the function to additionally eliminate elements whose results will thereby not be a part of the resulting list.

```
scala> var int = 0
int: Int = 0

scala> while(int<10){println(int); int=int+1}
0
1
2
3
4
5
6
7
8
9

scala> for(x <- 0 until 10){println(x)}
0
1
2
3
4
5
6
7
8
9

scala> val list = List(0,1,2,3,4,5,6,7,8,9)
list: List[Int] = List(0, 1, 2, 3, 4, 5, 6, 7, 8, 9)

scala> for(x <- list){println(x)}
0
1
2
3
4
5
6
7
8
9
```

Fold, foldLeft, foldRight, map and flatMap examples:

- fold is supplied with a function which produces a single value from two input values, all three of the same type, fold repeatedly uses this to produce a single value from a list. It takes two arguments using currying syntax; the first is the starting value and the second is the function used to fold two elements into one. It can be executed in parallel.

```
scala> (0 to 2).fold(0)((left,right) => left+right)
res1: Int = 3

scala> (0 to 2).par.fold(0)((left,right) => left+right)
res2: Int = 3
```

If the fold is executed in parallel, having the starting argument be non-zero or otherwise have consequence in application will give unexpected results:

```
scala> (0 to 2).fold(1)((left,right) => left+right)
res1: Int = 4

scala> (0 to 2).par.fold(1)((left,right) => left+right)
res3: Int = 6

scala> (0 to 2).par.fold(1)((left,right) => left+right)
res2: Int = 5
```

This is generally true: Mixing necessarily sequential operations and parallel collections is a bad idea, and a highly unfortunate pitfall for newcomers to Scala.

- foldLeft and foldRight are equivalent, except that the iteration over the list goes in opposite directions. In contrast to fold, the input and output types can be unequal. These can not be done in parallel.

```
scala> (0 to 9).foldLeft("numbers")((string,number) =>
    string+number.toString)
res1: String = numbers0123456789

scala> (0 to 9).foldRight("numbers")((number,string) =>
    number.toString+string)
res2: String = 0123456789numbers
```

- map

```
scala> (0 to 9).map(x=>x*x)
res1: scala.collection.immutable.IndexedSeq[Int] = Vector(0, 1,
    4, 9, 16, 25, 36, 49, 64, 81)

scala> (0 to 9).par.map(x=>x*x)
res2: scala.collection.parallel.immutable.ParSeq[Int] =
    ParVector(0, 1, 4, 9, 16, 25, 36, 49, 64, 81)
```

- flatMap

```
scala> (0 to 9).flatMap(x=>if(x%2==0){None}else{Some(x)})
res1: scala.collection.immutable.IndexedSeq[Int] = Vector(1, 3,
    5, 7, 9)

scala> (0 to 9).flatMap(x=>if(x%2==0){None}else{Some(x*x)})
res2: scala.collection.immutable.IndexedSeq[Int] = Vector(1, 9,
    25, 49, 81)
```

Together:

```
scala> (0 to 9).par.flatMap(x=>if(x%2==0){None}
    else{Some(x*x)}).fold(0)((left,right)=>left+right)
res1: Int = 165
```

### 2.5.7 Container Types

Scala has several container types, some more exotic than others.

- Option allows handling of values which may or may not have any content. Both "Some(3)" and "None" can be passed as a parameter of type Option[Int]. Options can be mapped, in which case the unwrapping of the contents and subsequent re-wrapping is handled automatically.

- Either allows handling of values which are one of two types. It's applicability is therefore a superset of that of Option. Left(3) and Right("str") can be passed as a parameter of type Either[Int, String]

- Sets are somewhat similar to arrays in that their size is fixed. However, each element can have a unique fixed type. So "(3, "str", 5.0)" is a set with type (Int, String, Double). specific places in the set are accessed using "set._n", where n is the 1-indexed index.

```
scala>//Option:

scala> def maybeSquare(in:Option[Int]):Option[Int] = in.map(x => x*x)
maybeSquare: (in: Option[Int])Option[Int]

scala> maybeSquare(Some(3))
res0: Option[Int] = Some(9)

scala> maybeSquare(None)
res1: Option[Int] = None

scala>//Either:

scala> def squareOrCube(in:Either[Int,Int]) = in match
     | {
     |   case Left(x) => x*x
     |   case Right(x) => x*x*x
     | }
squareOrCube: (in: Either[Int,Int])Int

scala> squareOrCube(Left(3))
res2: Int = 9

scala> squareOrCube(Right(3))
res3: Int = 27

scala>//set:

scala> def change(in:(Int, String, Double)):(Int, String, Double) =
    (in._1*in._1, in._2+"ing", in._3)
change: (in: (Int, String, Double))(Int, String, Double)

scala> change((3, "str", 5.0))
res4: (Int, String, Double) = (9,string,5.0)
```

## 2.6 C++11

This section covers only the features needed in order to understand the C++ code the compiler generates. The features listed below may or may not have additional capabilities to those mentioned:

- std::atomic provides atomic transactions for integral types, boolean and pointers. This means a load and a store operations to this variable will never happen concurrently.
- std::mutex is a traditional mutual exclusion lock.
- std::condition_variable provides a variable that threads can wait on. Subsequently, one or all threads waiting can be awakened. A thread that wishes to use it must hold a unique_lock first. Also allows timeouts on waiting.
- std::unique_lock allows more sophisitcated use of locks. It is not a mutex, but instead provides more ways to acquire and release locks on mutexes, including timed attempts at gaining locks and releasing locks when leaving the scope of the unique_lock.
- std::thread provides a standardized wrapping around Pthread and similar OS-specific thread libraries.

## 2.7 Regular Expressions

Regular expressions are programs used to match strings of text. More specifically, they are finite automata capable of parsing regular languages. In practice, what is called "regular expressions" are often capable of parsing more than just regular languages due to extra features. The IEEE POSIX standard specifies their syntax.

The following explains enough to understand their use in this thesis:

- Square brackets match a single character if that character is inside the square brackets. For instance, "[ab]" matches either "a" or "b", while "[a-z]" matches all Latin lower case characters.
- A question mark ("?") signifies that the preceding element can be matched one or zero times.
- Parentheses marks a subexpression.
- Backward slash ("\") escapes the following character, allowing characters that would usually be interpreted as operators to be interpreted as actual character and vice versa. For instance, "\." matches a period, while "\d" matches any digit.
- A plus sign ("+") signifies that there are one or more of the preceding element
- A star ("*") signifies that there are zero or more of the preceding element

- A vertical bar ("|") signify that either the character to the left or the right is matched

### Example

Integers are matched with this regular expression: "[-+]?(0|[1-9]\d*)". First, there can optionally be a plus or minus sign, then comes the characters in the parenthesis: Either 0 or a number between 1 and 9 followed by a string of digits. "00201" will not match, but "201" and "-201" will match.

## 2.8 Deterministic Multithreading

All material here is based on [20] unless otherwise stated. This section is to be understood as a discussion of contemporary approaches to multithreading determinism - they have not influenced this thesis because their determinism models are generally less strict.

Deterministic multithreading is an active area of research. Two components are necessary for determinism:

- A deterministic logical clock, which orders synchronization operations deterministically
- A deterministic memory consistency model, which ensures unsynchronized load operations have deterministic results

### 2.8.1 Deterministic Logical Clock

There are two main approaches to this:

- Round-robin scheduling
- Instruction-count based scheduling[23]

Both concern themselves with which thread's turn it is to do synchronization calls. In normal pthread systems, it is the thread which calls first that, say, acquires the lock. Round robin scheduling means that it is the thread that has gotten it last that will get it next. In instruction-count scheduling, the next recipient of the lock is determined by which thread has completed the least amount of instructions, with a tie-breaker. Notice that in the latter model, synchronization call order is not necessarily robust in the face of changing inputs, as some inputs may require more instructions to be performed than others.

### 2.8.2 Deterministic Memory Consistency Model

The memory consistency model concerns itself with making guarantees about the determinism of memory access. Total Store Order (TSO) guarantees that all writes are globally visible in deterministic order, yet makes no guarantees about when.

In both Dthreads and Consequence described below, synchronization of memory is done whenever there is a synchronization (for example *lock()*) operation, which ensures determinism since the position of these operations are determined by the logical clock. This read determinism is then a result of implementation; TSO does not require it. Alternatives to TSO (for example DRF0[12] and LRC[19]) relax the total store order requirements to guaranteeing that a write with respect to a synchronization object is only visible to the next thread that holds the synchronization object. While the computational result is the same, the total store order requires less memory than relaxed models, since all shared memory needs only one copy and thread-local writes will always be applied and memory freed. In relaxed models, memory copies will have to be made whenever a thread releases a synchronization object and freed when the synchronization object is locked by a new thread. This means memory use scales with the amount of synchronization objects. That said, relaxed models can be faster than TSO since individual threads can be isolated until they need updates, even while other threads synchronize memory among themselves.

### 2.8.3 Dthreads

Dthreads[18] is a deterministic replacement for Pthreads, using round-robin scheduling and total store order. DTHREADS work by giving each thread, as declared in C/C++, its own process and then cleverly hiding this by reimplementing functions such as *getpid()* to give the same answer for all processes that make up the program. All threads do work in a parallel phase, and upon an event that triggers synchronization, for instance the acquisition of a lock, a serial phase is entered. The updates that any single thread applies to shared memory will be applied in deterministic order in the serial phase.

### 2.8.4 Consequence

Consequence[20] is, like Dthreads, an deterministic implementation for C/C++. It uses instruction-count based scheduling and provides total store order. Instruction-count based scheduling allows Consequence to be faster than Dthreads. The downside is that Consequence is nondeterministic in the face of changing input and also changes behavior when inserting debugging operations like print-statements. Consequence relies on Conversion, a kernel-implemented version control system, for the memory consistency model. Like in Dthreads, each thread is actually run in its own process.

## 2.9 Related Work

There are related work which also tries to make multithreaded programs easier to work with, using custom compilers or languages extensions. Among these are CoreDet and Deterministic Parallel Java. CoreDet is a custom compiler for C/C++ made by modifying LLVM. Deterministic Parallel Java is a language extension for

Java. Given that they are about making multithreading easier they are worth mentioning, even though they have not influenced this thesis.

### 2.9.1 CoreDet

CoreDet is "[a] compiler and runtime system that runs arbitrary multithreaded C/C++ POSIX Threads programs deterministically"[5].

### 2.9.2 Deterministic Parallel Java

DPJ extends Java with a deterministic features. It is built on the idea of *regions.* The programmer divides memory into regions by annotating classes, and thereafter annotates methods with effect summaries stating which regions are read and written by a method. "The compiler uses the class types and method effect summaries to check that all concurrent (read, write) and (write, write) pairs of accesses to the same region are disjoint" [7][1].

# Chapter 3

# Specification

It was decided that an approach belonging to the tradition of synchronous programming would be the best choice for this thesis, as described in the background chapter. Given the importance of a familiar superficialities for language adoption[21], it was decided that the language should have a familiar C/Algol-style syntax, rather than invent or adopt something less common.

#### A Note on the Finality of This Specification

Much of what has been specified has not been implemented. While everything has been given thought, this thought has not been distributed equally, but concentrated on the basic things and that which has been implemented. Everything herein, especially that which is left unimplemented, is to be considered preliminary. Future work should not give this specification undue consideration.

## 3.1 Language Design Goals

It is the goals of Fumurt to aid in producing correct programs suitable for real-time applications in general, and such multithreaded programs in particular.

## 3.2 Runtime Execution Model

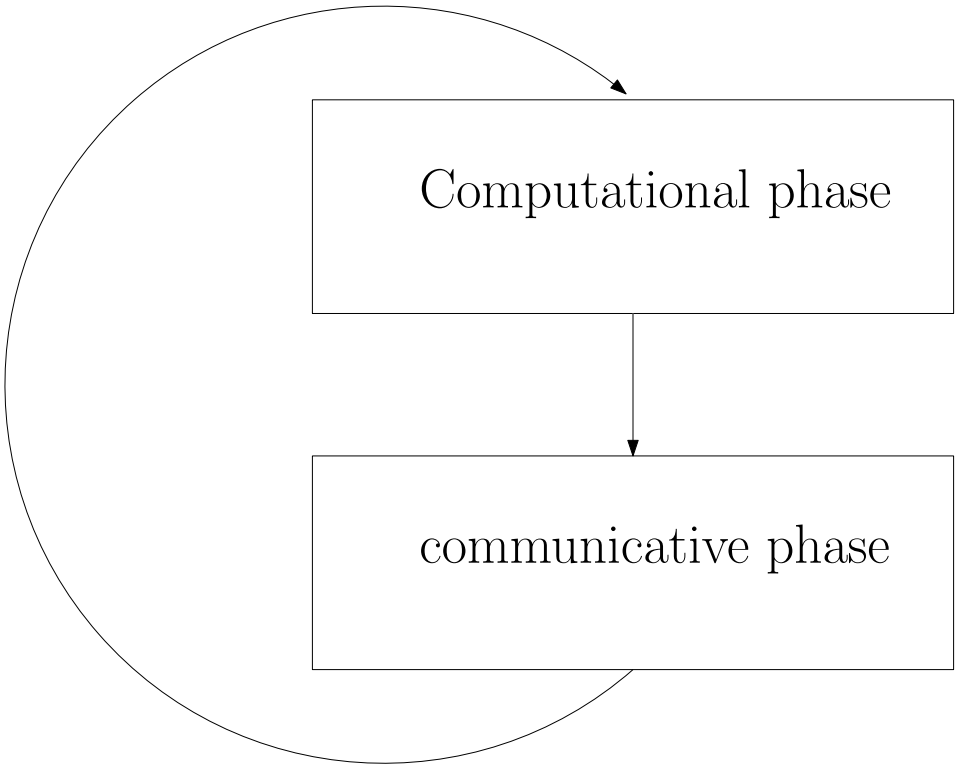
The goal of the programming language is to make a multithreaded program behave as predictably as were it single-threaded and, more generally, to help create reliable applications. A corollary of this is that only changes of state that are visible to a single thread can happen concurrently. All IO and inter-thread communication are required happen in a statically determined sequence. One way to do this is to have the program have two alternating phases:

- Computational phase: In which computations local to a thread are performed.

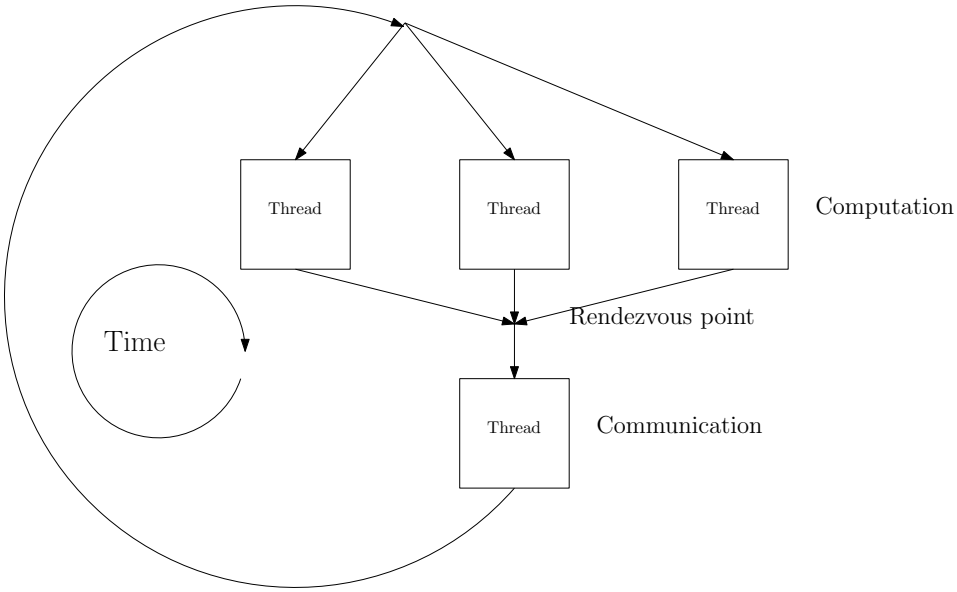
- Communicative phase: In which IO is effected and shared variables are updated, all in a single-threaded manner.

In the computational phase, the order in which computations are performed on the processor is irrelevant as nothing is shared between the thread and the rest of the world. Since the threads have no effect on each other or the outside world in this phase, the only difference between concurrent execution and sequential execution is speed. In the communicative phase, however, execution has to be single threaded. This is similar to Dthreads[18], except here IO sequence is also deterministic and only one thread per synchronized variable have write rights to a synchronized variable. Having only one thread have write privileges means last-writer-wins semantics are avoided, in which everything but the last write since the start of the computational phase will never be visible to other threads. This seems like it would very rarely be the programmer's intended behavior.

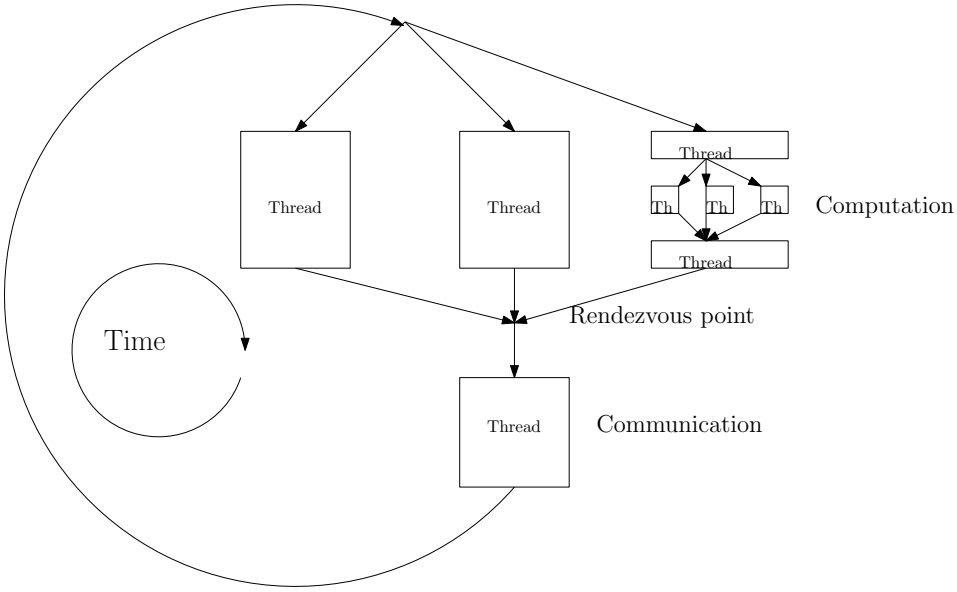
Using this scheme, the application appears to be single threaded both to itself and to the rest of the world, all the while enabling separation of concerns and better utilization of multi-core systems. The following figure illustrates the principle:




In terms of the actual execution a more detailed figure is offered:




Observe that in the computational stage parallel list transformations like map and fold or even futures can be made available, without affecting the outward behavior of the system, except for performance:




Futures and parallel list comprehensions are together applicable to all problems which can be divided into subproblems that can be done in parallel without communication. Futures are a bit of extra work to deal with, but the map-and-fold pattern, sometimes called mapReduce[11], is easy to use and widely applicative to many problems.[9] Indeed, map-and-fold is intensely used in the Fumurt com-

piler. Supporting map-and-fold and futures reduces the performance problems of all threads waiting on each other significantly as long as it can be applied to the most time-consuming task.

The overall effect of this execution model is that phases per second becomes an important measure of responsiveness of the system.

## 3.3 Inter-thread communication

Inter-thread communication is provided by synchronized variables. These are variables to which one thread has write rights, while all threads has read rights. The writes to a synchronized variable are effected so that all threads can read them during the communication phase. Having only one thread have write rights circumvents the entire problem of store order, and makes sure the programmer doesn't have to worry about the order in which a synchronized variable is written to by the different threads.

## 3.4 Input and Output

Input and output sequence must be deterministic. To achieve this, output requests are placed in a queue, and are written to the output devices during the communicative phase. Whenever input is desired, the thread will immediately pause and wait for the communicative phase, during which the input will be returned to the thread. In the case where several pieces of input and output do not depend on each other, they can be combined to a composite IO action, whose effects will be performed in the same communicative phase. The syntax for this is left unspecified.

## 3.5 Syntax

Syntax is by definition somewhat arbitrary but, as Brainfuck demonstrates, some syntaxes are better than others. The following goals were decided upon:

- Look modern and familiar. This is supposed to make it easier to learn, as well as more appealing to someone evaluating whether to learn it.
- Be simple. For ease of implementation.
- Be predictable, and aid the programmer in the understanding of the program.

A language made as part of a master thesis is simple by necessity. The two other goals require more explanation:

### 3.5.1 Modern and Familiar

Fumurt adopts several conventions from contemporary languages:

- Separating expressions with line endings instead of special characters (for example semicolon).
- Employ “instanceOfType:Type” instead of “Type instanceOfType” when declaring the type of something.
- “=” is used to perform definitions and mark the boundaries of blocks with brackets

This results in syntax with a distinctly modern look:

```
function integerIdentity(x:Integer):Integer = {x}
```

One might wish for brackets to be optional in such one-liners, though,

### 3.5.2 Predictable and Helpful

Although modern languages and their type systems have made the use of functions safe, the syntax of modern languages insufficiently aid the programmer in understanding what a function does, as it is called:

- Functions that perform IO or mutate shared variables are called actions and their names must begin with “action”, like so:

```
action actionPrintFoo:Nothing =
{
  actionPrint("  FOO   ")
}
```

  Similarly thread names begin with “thread” and synchronized variable names begin with “synchronized”. This means that one can observe much about the properties of a call or a variable where it is used without looking up the definitions.

- Function arguments, if there are more than one, are distinguished not by relative position, but by name (as is optionally available in Python). Here is presented a call to the if function and some calls to the toString function:

```
if(condition=true, then=toString(1), else=toString(0))
```

  Type classes are an alternative to named arguments, the idea being that you have one type per role a variable can play. There are multiple problems with this:

  - It’s unnecessarily verbose. Worst case, you’ll end up with one type class declaration per argument.
  - Because it’s unnecessarily verbose, the temptation will be to use the same type class everywhere or just use a base class (like Integer) instead. Which would mean that we’re back at square one.

## 3.6 Scope

Among the goals of this programming language is to help the programmer understand the program. One way this is done is to make dependencies between functions explicit via *inclusions*. It is common among languages for changes in one function to affect the correctness of seemingly unrelated parts of the program. In the following example, changing the definition of function c affects the output of function a:

```
action actionA:Nothing =
{
  b()
}
action actionB:Nothing =
{
  c()
}
action actionC:Nothing =
{
  actionPrint("string")
}
```

While the above example is a bit contrived, it illustrates the problem. Using inclusions, the dependencies become explicit:

```
action actionA(b:Inclusion, c:Inclusion):Nothing =
{
  b(c=c)
}
action actionB(c:Inclusion):Nothing =
{
  c()
}
action actionC:Nothing =
{
  actionPrint("string")
}
```

Note that inclusions are not functions as arguments - the passed function and the name of the inclusion must have the same name; it is simply there to make dependencies between functions explicit.

In keeping with the goal of being modern and familiar, definitions of functions inside other definitions of functions are allowed. Recursive function definitions, that is. This means that developers can hide functions inside other functions when they are not needed outside them. Inclusions are not needed when functions are defined inside each other, as dependence is implied.

## 3.7 Pointers

There are no pointers in the language. Any pointers required by C++ is to be hidden by Fumurt. This is because pointers are colloquially as well as formally[22] known to be hard to understand. Programmers should be able to specify specific

memory ranges that can later be written to with functions. These are intended to be used only when the programmer needs to store data to specific addresses.

## 3.8 Operators

Operators are functions with two arguments and the function name in between the arguments. There are multiple problems with them:

1. Convention suggests that their names should be information-anemically short, often one character. This is obviously problematic

2. It can be hard to figure out what role the different arguments have

3. Operator precedence for user-defined operators is tricky. For math operators there's convention, but for user-defined ones this may be confusing for users of those operators

A prime example of unhelpful operator names can be found in section 2.4.1.

Any good solutions to this have not been found, to the author's knowledge, but it's hard to argue with the convenience of operators. Some predictability to operators are provided by enforcing the following rules:

1. Either the types of the two arguments has to be the same or one of the types have to be a container type of the other. For example Int and Int or List[Int] and Int.

2. There's no operator precedence, it has to be defined on a use-by-use basis using parentheses. Ambiguous use of operators are not allowed.

## 3.9 Immutability

Mutable variables are a major source of bugs, and even experienced developers create bugs when a variable that would have held the correct information previously no longer holds that information. At the same time mutable variables are needed in order to share information across threads. Therefore mutable variables are disallowed, except the synchronized variables that are shared across threads.

### 3.9.1 Loops

Loops are familiar for many people, yet are usually not included in languages with only immutable values, because their utility is pretty limited. However, they are convenient and they are equivalent to tail-recursion. The major advantages of tail recursion over looping is that the assignment and dependencies are explicit. And yet loops are far easier to understand[22]. Loops that are as safe as tail recursion while being almost as friendly as common loops are possible:

```
value y:Int = 5

value x:Int = loop(y=y,x=y)
{
  if(
  condition=(y>0),
  then=
  {
  x = x*y
  y = y-1
  continue
  },
  else=break)
}
```

All variables passed to the loop would then need to be copied. In the example above, the y modified inside the loop cannot be the same that is defined outside it. Such scoping of variables are common in function calls, and a similar mechanism can be used for loops.

An additional benefit of loops is that their use has constant memory consumption independent of number of iterations. While the same can be achieved for recursion using tail recursion with optimizing compilers, such compilers are still not the norm. Mutual tail recursion optimization is particularly rare. Since optimizations are not an immediate goal for the Fumurt compiler, loops would offer an important guarantee for the programmer.

## 3.10 Types

### 3.10.1 Classes

In trying to be familiar, it is desirable to provide types along with their popular object oriented nomenclature. So classes are present, just that they are immutable. They are defined by their constructors, optionally with extra static methods:

```
class IntAndString(int:Integer, string:String) =
{
  function combine:String = {concatenate(left=toString(int),
      right=string)}
}

value x = IntAndString(int=3, string="something")
actionPrint(x.combine)
actionPrint("==")
actionPrint(concatenate(left=toString(x.int), right=x.string))
```

Fumurt does not have inheritance, because while inheritance means you get code reuse, it also obscures the class that inherits. When one class inherits from a hierarchy, one needs to understand not only what's written about that class but also the entire hierarchy in order to understand the end result.

In order to aid the programmer in understanding their own and others' code, the names of types always lead with a capital letter. Conversely, leading with a

capital letter for anything else is illegal.

### 3.10.2 Interfaces

All classes are interfaces, but one can also create interfaces that aren't classes using the "interface" keyword. When implementing an interface one explicitly have to note what interfaces the class is implementing.

```
interface IntAndString(int:Integer, string:String)
//or
class IntAndString(int:Integer, string:String)

class IntAndStringAndBool(int:Integer, string:String, bool:Boolean)
    implements IntAndString
```

### 3.10.3 Modules

Modules are singletons containing only immutable values, actions and functions. They can therefore serve as libraries. Their scope is handled the same way functions' scope is. This avoids the problem where singletons are global entities and functions' dependence on them are completely obscure.

## 3.11 Program Declaration

The program declaration is meant to give a high level overview of the behavior of the program. It declares what threads are spawned, in what sequence their IO should be enacted, which synchronized variables exist and which threads have write permission to which variable.

## 3.12 Built-in Functions

Fumurt provides the following built-in functions:

- toString(x) gives a string representation of x
- actionPrint(x) prints the string x
- actionMutate(variable, newValue) assigns the newValue to the synchronized variable
- if(condition, then, else) returns result of *then* if *condition* is true and returns *else* if it is not
- plus(left, right) returns $left + right$
- minus(left, right) returns $left - right$
- divide(left, right) returns $\frac{left}{right}$

- multiply(left, right) returns $left * right$
- equal(left, right) returns $left == right$

# Chapter 4

# Analysis and Design

## 4.1 Choice of Intermediate Target

For easy debugging and wide selection of binary targets it was decided to first compile to an intermediate language and then let an external compiler perform the final transformation to binary form. This is a well-trodden path[14], and C is often used. Though many modern languages would be suitable for this, a wish list of features determined which language to choose:

1. No garbage collection or other other source of run-to-run variability.
2. Wide selection of final targets, including embedded.
3. Low overhead, whether in performance or memory.
4. A solid set of features to make transformation into the language easier.
5. Mature standard that is unlikely to break backwards compatibility.
6. One, preferably more, good and mature open source implementations available.
7. Possibility of running without an operating system.

C++ seems to satisfy all these criteria, and were therefore selected as the intermediate language. Its main competitor, C, has too few features, which means a compiler would have to make more difficult transformations and/or things like linked lists would have to be manually implemented. Such difficulties seem unnecessary.

## 4.2 Choice of Compiler Implementation Language

Scala was chosen as the implementation language for the compiler partly because it's what the author used in the TU Berlin compiler bau course (see 2.1) and already had lots of experience in, but it also has some highly attractive qualities for making a compiler:

- Solid type checking which makes the code easier to work with, especially when refactoring
- A wide selection of functional abstractions, which allows compact code and eliminates simple but irritating bugs as well as access to imperative constructs like loops etc. when this is more convenient
- A parser combinator library
- Fast execution time

Other languages under consideration were C, C++ and Haskell. C has inadequate abstractions and lackluster type checking. While C++ has much better abstractions, its type checking is still not strict enough to prevent many of the errors that would undoubtedly have been made during development. Haskell has all the features necessary, but the author had previously had problems learning it. It was also a concern that Haskell does not provide non-functional mechanisms, even when these are the best solution to a problem.

## 4.3 Choice of C++ Compiler

There were two compilers under consideration: GCC and Clang. While Clang is in many ways the better compiler, GCC is installed by default on most Unix systems. That leaves Windows. After some trial and error, it was found that installing a C++11 compliant standard library was difficult on Windows, and that the by far easiest solution on Windows is to install Visual Studio and use the Microsoft Visual C++ compiler. In the end it was decided that the Fumurt compiler will compile the C++ code using GCC, unless it is run on Windows, in which case it will ask the user to compile the C++ code using Visual C++ manually. This is quite clearly the lesser evil, rather than a particularly good solution.

## 4.4 Synchronization Mechanisms in The Intermediate Language

Our execution model formulated in 3.2 needs to be formulated in the compiled C++ code.

- Each thread gets its own printList (type std::list<std::string>), and actionPrints are translated into printList.push_back. The same principle can be used for future output as well. When the threads are finished with the computational phase, the last thread to finish will print printList.pop_front until the printList is empty. The thread started first in the program statement gets its printList emptied first, and so on.
- A rendezvous pattern is used:

1. A macro NUMTOPTHREADS, with the number of threads defined in the program statement is defined
2. A static std::atomic<int> rendezvousCounter, which holds the number of threads that have arrived at the rendezvous point is defined.
3. A static std::mutex rendezvousSyncMutex and a static std::condition_variable cv are defined.
4. For each synchronized variable in the source code, one variable which holds the global state of this variable and one which holds the local state of this variable in the thread that is allowed to write to it is defined.
5. A [[noreturn]] static void threadName() is defined for each thread, holding its values. All arguments to thread in the source code are converted to static global variables. If the platform is Windows, "__declspec(noreturn)" is used instead of "[[noreturn]]", since Microsoft Visual C++ does not support C++11 syntax for attributes.
6. A main function is defined, inside of which:
   (a) rendezvousCounter is set to 0, threads (std::thread) are started with the thread functions (defined in previous step) as arguments and finally the main function enters a loop executing std::this_thread::sleep_for( std::chrono::seconds(1) ).
7. static void waitForRendezvous(std::string name) which a thread calls when it is ready to wait, is defined. Inside of which:
   (a) The thread locks the rendezvousSyncMutex
   (b) Increments the rendezvousCounter
   (c) If the value in the rendezvousCounter is less than NUMTOPTHREADS, the thread waits using cv.wait, at which point rendezvousSyncMutex will be automatically unlocked. If the rendezvousCounter equals NUMTOPTHREADS, the thread prints all strings held in the printLists as described above, sets any global synchronized variables to its writer-local values, sets rendezvousCounter to 0 and finally notifies all other threads using cv.notify_all before exiting the function. rendezvousSyncMutex is unlocked on function exit. Example of a generated waitForRendezvous function:

```
1  static void waitForRendezvous(std::string name)
2  {
3    std::unique_lock<std::mutex> lk(rendezvousSyncMutex);
4    ++rendezvousCounter;
5    if(rendezvousCounter.load() < NUMTOPTHREADS)
6    {
7      cv.wait(lk);
8    }
9    else if (rendezvousCounter.load() == NUMTOPTHREADS)
10   {
11     while(!printthreadPrintHello.empty())
12     {
13       std::cout << printthreadPrintHello.front();
```

```
14          printthreadPrintHello.pop_front();
15      }
16          /*similarly for other thread print lists*/
17      synchronizedNumber = writeSynchronizedNumber;
            //where synchronizedNumber is the name of a
            synchonized variable
18          //similarly for other synchronized variables
19      rendezvousCounter.store(0);
20      cv.notify_all();
21    }
22    /*abnormal situation diagnostics mechanism here*/
23  }
```

## 4.5 A Need for Annotation

Technically, the finished code can always be determined directly from the AST, but it was discovered that in order to do this in the Fumurt case, the same rules would have to be encoded into the code in several different places. In the current state of implementation, there are two rules that require annotation. The first was the rule for determining the C++ names of function and the second is the rule for naming arguments to threads. In both cases, Fumurt's semantics are very different from C++'s. There are four aspects to the naming:

1. Actions and functions that are in other functions need to get new names because the hierarchy needs to be flattened
2. Actions need to be demultiplexed, as the C++ code they contain needs to be different depending on which thread calls that action. For instance, an actionPrint needs to be transformed to a push to a list whose name depends on the calling thread
3. Function calls need to be changed so they refer to the new names
4. Arguments to threads need to have new C++ names that will be globally unique.

This can be accomplished by doing two passes over the AST. In the first pass, all function definitions and thread arguments are annotated with their C++ names. In the last pass, all function calls are annotated with the C++ name of the function they call, copying from the annotation done in pass one.

## 4.6 Limitations

While the specification and design is satisfactory, there are many ways in which it could be improved:

- There are no compound statements, except in the right hand side of definitions

- Definition right hand demarcation of the begin..end [function/x] type (for example begin..end loop) should be optional, as it can be helpful when reading and writing deeply nested expressions, where exactly what it is that is ending can often be unclear.

- Performance of the current execution model may be a concern for some applications. Allowing programmer-defined synchronization intervals would allow for greater performance without sacrificing predictability. The programmer could then specify that computation-heavy threads participate in only every Nth communication phase. In cases where the appropriate performance and responsiveness requires sacrifices to predictability, it seems prudent to evaluate the possibility of using an instruction-based logical clock system when the programmer specifies it. Systems such as Consequence[20] may make it possible to obtain greater performance in cases where the programmer can allow predictability requirements to be relaxed. Likewise, software transactional memory could be interesting, particularly when a thread needs to wait on input from an unpredictable source, like a human, while the rest of the threads needs to be responsive.

- The design of Fumurt centers around predictability, but in order to guarantee any predictability we have to assume correctness of the underlying hardware. Fumurt is by design not fault-tolerant, because fault tolerance deals with, and causes, unpredictability. This is in many cases insufficient. It would be beneficial if it was possible to construct some system wherein multiple computers or chips running Fumurt code could be coordinated by a system that does deal with fault-tolerance. Erlang with OTP is often used for such applications, but no study has been carried out regarding how to combine Erlang and Fumurt.

- As it is, the design of Fumurt has some, but very little empirical underpinnings. User surveys concerning how the various aspects of the language are received , particularly by novice programmers, would shed light on whether all the ideas introduced in this report are actually good ideas.

- There is no appropriate response in the cases where the IO buffers can no longer fit in memory. A solution which would degrade performance but otherwise work well, would be to pause all threads trying to put IO into a full memory while letting the thread whose IO are to be effected first write directly to IO. Once that first thread is finished, the second thread whose IO shall be effected can write directly to IO and so on until all threads are ready to enter the communicative phase. This will serialize execution, which can degrade performance. In those cases where responsiveness is more important than strict IO sequentiality, special mechanisms may be provided whereby the programmer can specify that in such cases IO buffers shall be emptied to IO during the computational phase.

- Recursion can cause a stack overflow, leading to a segmentation fault. With the exception of the recursion happening when a thread recurses on itself,

no recursion is optimized away. This is problematic in a critical-application system. Some types of recursion are easy to optimize away, some less so. The appropriate behavior for the compiler towards recursion it can't optimize away is undetermined.

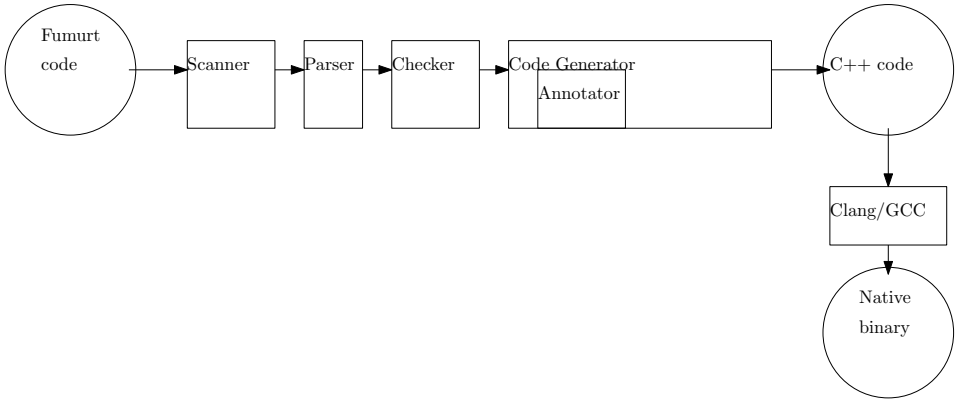
- There is no mechanism for direct access to memory, which is often needed in embedded programming
- There are no lists, arrays or similar sequences. Likewise, loops, values, operators and user-defined types are missing.

# Chapter 5

# Implementation

## 5.1 Overview

The compiler consists of four parts: The scanner, parser, checker and code generator. There is no optimizer, although the requirement for no dynamic destruction or creation of threads allows us to use a loop in threads instead of just recursion. This is necessary because neither Clang nor GCC could correctly optimize that tail recursion into a loop in testing, leading to an inevitable stack overflow.




Consider the steps taken by the compiler:

1. The code is scanned. If there is an error it's printed and compilation ended. Note that neither scanner nor parser are advanced enough to detect more than one error at a time.

2. The tokens from the scanner is parsed. If there is an error it's printed and compilation ended.

3. The AST from the parser is handed to the checker, which looks for any semantic errors. If there are any, they are printed out and compilation ended.

4. The AST from from the parser is given to the code generator, which produces C++ code conforming to the C++11 standard.

5. GCC is used to compile the C++ code to native binaries.

## 5.2 Scanner

Scanners, it should be noted, are sometimes called lexers. Drawing on experience from the TU Berlin course (see 2.1), the Scala Standard Parser Combinator Library was chosen.

Parsers for individual tokens are formed like this:

```
def intParser: Parser[IntegerT] = positioned( new
    Regex("""(0|[1-9]\d*)""") ^^ {x => IntegerT(x.toInt)} )
def equalParser: Parser[EqualT] = positioned( new Regex("=") ^^ {x =>
    EqualT()} )
```

The parsers are then combined into the final scanner using the alternate operator ("|")[2].

It all goes into a list of tokens. The tokens are defined like this:

```
abstract class Token() extends Positional
abstract class DefDescriptionT() extends Token
abstract class BasicValueT() extends Token
abstract class SyntaxT() extends Token

case class TrueT() extends BasicValueT {override def toString =
    "true"}
```

Positional[3] is a trait that gives the token a Position. The "positioned" call in the parsers assigns the Position to the token. This is all inherited from the parser combinator library, so it's hard to understand what's going on from looking at the source alone. The "positioned" call assigns the source code position of the input text to the token object produced by the parser, which allows us to output really nice error messages later on.

### Function List

- *scan(in:String):Either[NoSuccess, List[Token]]* takes the source file as a string and either outputs a list of tokens or an error message
- *scanInternal:Parser[Token]* is the internal scanner. The parser combinator library will use this to create a parser to serve as scanner at compile time
- x*Parser: Parser[XT]* parses that particular type of token, for example *newlineParser: Parser[NewlineT]*

### Classes

- The scanner uses token classes. These are held in Ast.scala

## 5.3 Parser

Like in the scanner, the Scala Standard Parser Combinator Library was used. Unfortunately, the tasks of the parser is a bit more complicated than those of the scanner, and the code reflects this.

### 5.3.1 Grammar

The grammar serves as a formal definition of the language. Though not needed in order to understand the language, it is included for completeness. Here's the EBNF ([25]) for the grammar, as implemented:

```
prog = paddedDef, {paddedDef}, EoF;
paddedDef = {"\n"}, def, {"\n"};
def = deflhs, "=", {"\n"}, defrhs;
deflhs = defdescription, id, args, ":", type;
args = ("(", id, ":", type, {subsequentArg}) | "";
subsequentArg = ",", id, ":", type;
defrhs = "{", {"\n"}, expression, {("\n", {"\n"}, expression)},
    {"\n"}, "}";
expression = def | statement;
statement = functionCall | basicStatement | identifierStatement;
callargs = "(", (namedcallargs|callarg), ")";
callarg = statement | "";
namedcallargs = namedcallarg, subsequentnamedcallarg,
    {subsequentnamedcallarg};
subsequentnamedcallarg = ",", namedcallarg;
namedcallarg = id, "=", callarg;
functionCall = id, callargs;
identifierStatement = id;
defdescription = "program" | "action" | "thread" | "function" |
    "value";
basicStatement = boolean | string | integer | float;
float = integer, ".", digit, {digit};
integer = "0" | (digit excluding zero, {digit});
digit excluding zero = "1" | "2" | "3" | "4" | "5" | "6" | "7" | "8"
    | "9" ;
digit = "0" | digit excluding zero ;
upper case = "A" | "B" | "C" | "D" | "E" | "F" | "G" | "H" | "I" |
    "J" | "K" | "L" | "M" | "N" | "O" | "P" | "Q" | "R" | "S" | "T" |
    "U" | "V" | "W" | "X" | "Y" | "Z" ;
lower case = "a" | "b" | "c" | "d" | "e" | "f" | "g" | "h" | "i" |
    "j" | "k" | "l" | "m" | "n" | "o" | "p" | "q" | "r" | "s" | "t" |
    "u" | "v" | "w" | "x" | "y" | "z" ;
id = lower case, {(upper case | lower case)}
type = upper case, {(upper case | lower case)}
```

For help understanding this, see section 2.3.

### 5.3.2 Code

This is where the grammar is encoded into the program:

```
def progParser: Parser[List[Definition]] = (paddedDefParser.+) <~
    eofParser
```

```
def paddedDefParser:Parser[Definition] = { newlineParser.* ~>
    defParser <~ newlineParser.* }
/*more here*/
```

The relevant values are extracted from the result by using the "._x" methods, where x is a number. This is because the result of several consecutive parsers are combined into sets. "._1" is then the first value of the set, etc. The structure of these sets are sometimes not immediately obvious. For the operators refer back to 2.4.1.

There are also a number of somewhat less exciting helper parsers, of which an example is provided:

```
def equalParser:Parser[Token] = accept(EqualT())
def basicStatementParser:Parser[BasicValueStatement] =
    accept("expected string, integer, boolean or float", {
case StringT(value) => StringStatement(value);
case IntegerT(value)=> IntegerStatement(value)
case TrueT() => TrueStatement()
})
```

This shows how the parser error messages are generated.

The entirety produces an abstract syntax tree. Both the checker and the code generator operates on this AST, and it is the centerpiece of the implementation. Without understanding the AST, the rest of the implementation will appear cryptic at best:

```
class Expression() extends Positional
trait Callarg extends Positional
trait Statement extends Expression
trait BasicValueStatement extends Statement with Callarg with
    aCallarg with aStatement

case class Definition(val leftside:DefLhs, val rightside:DefRhs)
    extends Expression
case class DefLhs(val description:DefDescriptionT, val id:IdT, val
    args:Option[Arguments], val returntype:TypeT)
case class Arguments(val args:List[Argument])
case class Argument(val id:IdT, val typestr:TypeT)
case class DefRhs(val expressions:List[Expression] )
case class Empty();
case class DefDescription(val value:Token)
case class NamedCallarg(id:IdT, argument:Callarg) //extends Callarg
case class NamedCallargs(val value:List[NamedCallarg])
case class NoArgs() extends Callarg with aCallarg

case class StringStatement(val value:String) extends
    BasicValueStatement
case class IntegerStatement(val value:Int) extends BasicValueStatement
case class DoubleStatement(val value:Double) extends
    BasicValueStatement
case class TrueStatement() extends BasicValueStatement
case class FalseStatement() extends BasicValueStatement
case class IdentifierStatement(val value:String) extends Statement
    with Callarg with aCallarg with aStatement
```

```
23 case class FunctionCallStatement(val functionidentifier:String, val
       args:Either[Callarg,NamedCallargs]) extends Statement with Callarg
```

**Function List**

- *parse(in:List[Token]):Either[NoSuccess, List[Definition]]* takes a list of tokens and returns either an error message or an AST
- *progParser: Parser[List[Definition]]* is the first of the parsers, from which the parser combinator library will generate the final parser
- x*Parser:Parser[X]* parses that particular kind of AST node, for example *defParser:Parser[Definition]*. Can often be a bit indirect. For example, *paddedDefParser:Parser[Definition]* parses a definition with newlines around it, but uses *defParser:Parser[Definition]* to parse the definition part of that.

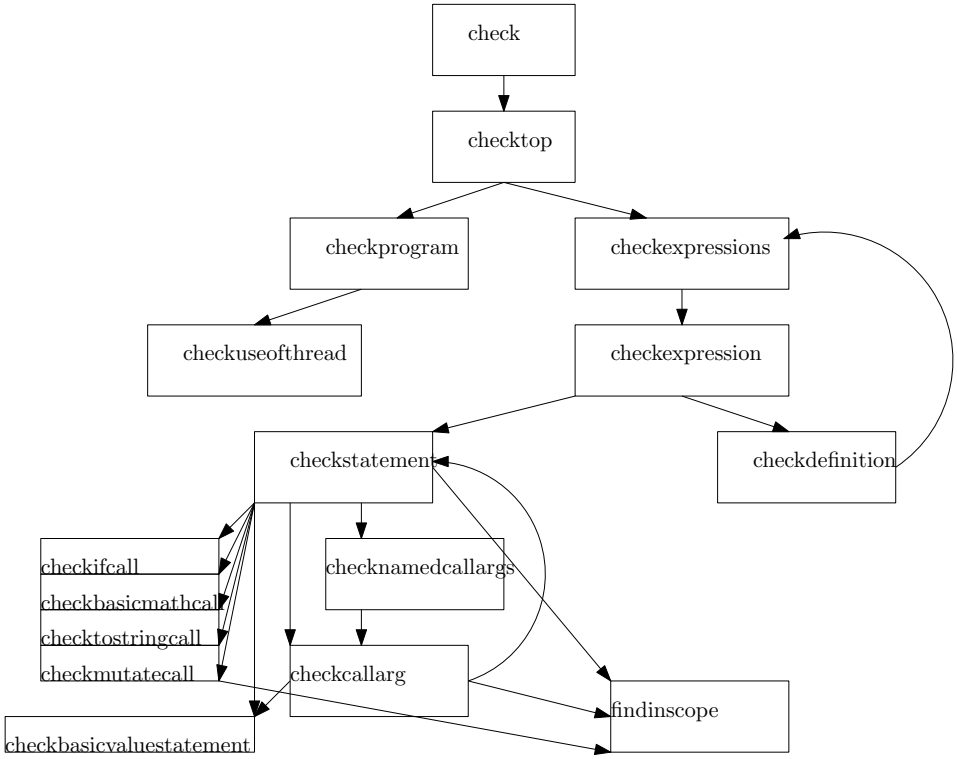
**Classes**

- *Class TokenReader* is a wrapping around the list of tokens. It is required by the parser combinator library and implements the Reader interface. It has the following functions:
  - *atEnd* which returns true if the list of tokens is empty
  - *first*, which returns the current first element in the list
  - *pos*, which returns the source text position of the first element in the list
  - *rest*, which returns a new TokenReader wrapping all elements except the first in the list
- The parser uses AST and token classes. These are in the Ast.scala file.

## 5.4 Checker

The checker, contrary to its in-source name (FumurtTypeChecker) checks more than types. It does not modify, annotate or otherwise change the abstract syntax tree. It simply returns errors found or returns nothing. When the implementation of the checker began it was envisaged that the basic functions would be treated equally with user defined functions, but due to the lack of generics and other abstraction mechanisms, most of the basic functions still needed special treatment, with “actionPrint” being the notable exception.

This graphic illustrates how the functions in the checker call each other:




**Function List**

- *check* is the interface to the rest of the program. Takes in an AST and returns a list of errors, if there are any.
- *checktop* checks the top level of the program. The top is special because it contains threads and the program statement, though only the program statement need special treatment.
- *checkprogram* checks the program statement. Uses *checkuseofthread* and checks whether there are any calls to non-threads or definition of non-synchronized variables.
  - *checkuseofthread* checks that the thread given is actually called in the program statement. Declaring a thread and failing to call it is an error.
- *checkexpressions* checks a list of expressions, such as might be found in the right-hand side of a definition. Uses *indexleft* to get new in-scope definitions and passes them to *checkexpression*
- *checkexpression* checks an individual expression. Determines if the expression is a statement or a definition, and subsequently uses *checkstatement* and *checkdefinition*

- *checkstatement* checks a statement. If it's an identifierStatement, checks that its return value is as expected. Uses *checkbasicvaluestatement* for the same for basic values. If it's a function call, then it either uses special case functions, such as *checkifcall* or finds the function in scope and uses a general approach using checknamedcallargs and/or checkcallarg

- *checkifcall* checks calls to if. Makes sure the return type of then and else is the same and that condition is a boolean. Also checks naming.

- *checkmutatecall* checks that the variable is a synchronized variable and otherwise has the same type as the new value

- *checkbasicmathcall* checks the four basic math operators, with special attention to the return type when double and int are mixed

- *checktostringcall* checks that there is only one argument and that the expected type is String

- *checknamedcallargs* checks named call arguments. Checks that the correct names are used, that the correct number of arguments are given and uses *checkCallarg* to check each argument individually.

- *checkCallarg* checks a call argument. Makes sure the type is correct. Uses checkbasicvaluestatement and checkstatement.

- *checkbasicvaluestatement* checks that the type of the basic value is correct.

- *checkdefinition* checks a definition. makes sure the return type is the one specified, that an action is not defined or used from inside a function etc.

- *indexlefts(in:List[Expression]):List[DefLhs]* takes a list of expressions and returns a list of all the left sides of definitions in that list.

- *findinscope* finds a left side of the definition in the current scope with the same name as that which is searched for.

## 5.5 Code generator

The code generator can best be explained step by step:

1. First the C++ include statements are determined. These are currently handwritten.

2. We scan the program declaration and find the threads that will be started in the main thread. The statements for those are found in the program declaration.

3. The main function is determined from the list of thread statements and their arguments

4. The print list declarations are determined from the list of thread statements.
5. The NUMTHREADS macro is determined from the length of the list of threads.
6. The abstract syntax tree and a list of the threads are passed to the annotator, which returns an annotated tree.
   (a) The definitions are annotated with their C++ names, and actions called by several threads are demultiplexed into one per calling thread. Inclusion arguments are removed from the signatures. Thread arguments are annotated with their C++ names.
   (b) The calls to functions and actions are annotated with the correct C++ name, and inclusion call arguments are removed.
7. The C++ equivalent of the threads, actions and functions are constructed along from the annotated tree, along with their forward declarations.
8. The global synchronization variables for use in the runtime (for example rendezvousCounter) are generated. This is currently handwritten.
9. The synchronized variables are found in the program declaration and the C++ equivalents are later determined. These are later put in the global scope of the C++ program.
10. The synchronizer function (waitForRendezvous) is constructed from the synchronized variables and the thread list.

**Function List**

- *generate* generates the final C++ code from the Fumurt AST
- *getAnnotatedTree* Returns an annotated version of the supplied AST. This version has the final C++ names for functions and their arguments and function calls
- *getCallsAnnotatedTreeInternal* returns an annotated version of the AST with final C++ names for function calls. Requires that function names have been annotated first
- *annotateFunctionCall* annotates a single function call
  - annotateCallargs annotates that function calls call arguments. Since call arguments can be function calls, this is often recursive.
  - *removeInclusions* removes inclusion arguments from functions, since these have no purpose in C++
- *indexlefts* indexes DefLhs's like in the checker, but with the annotated types.

- *findinscope* same as the version in the checker, but with annotated types.
- *getAnnotatedTreeInternal* returns an AST with with final C++ names for functions
- *getFunctionDeclarations* gets the functions, in C++, from the annotated AST
  - *actfunrecursivetranslate* gets function body and signature of a function corresponding to the arguments as well as all functions defined in the body of the definition.
  - *changeNamesToCppOnes* changes all identifiers which are arguments to a thread to their C++ names throughout the thread.
- *getFunctionSignature* constructs a C++ function signature from the arguments
  - *argtranslator* translates an argument as used in defining a function
- *typetranslator* translates Fumurt types to their C++ equivalents. Currently there are no user-defined types, so only basic types need to be translated.
- *callargTranslator* translates a call argument to the C++ equivalent
- *functioncalltranslator* translates function calls to C++ syntax
- *basicmathcalltranslator* translates calls to plus, minus, divide and multiply into +,-,/, and *
- *gettopthreadstatements* gets the C++ statements spawning the threads.
- *getprintlistdeclarations* gets the printList declarations. These are lists in which strings to be printed are kept. One for each thread
- *getmain* gets the main function. The main function only spawns the threads and then goes to sleep
- *getsynchronizerfunction* gets the mostly static and hand-written function that performs all actions during the communication phase
- *getGlobalSynchVariableDeclarations* gets the C++ declarations of the synchronized variables
- *getsynchronizedvariables* gets the definitions of the synchronized variables, so that they can later be used in *getGlobalSynchVariableDeclarations*

**Classes** The generator uses classes needed to annotate the AST, for example *class aDefinition(val leftside:aDefLhs, val rightside:aDefRhs).* Existing AST classes are used unless extra information needs to be held or it is a parent of such a class. The most dramatic example is *class aDefLhs(val description:DefDescriptionT, val id:IdT, val cppid:IdT, val callingthread:String, val args:Option[Arguments], val returntype:TypeT).* Here, we see the new C++ name, as well as which thread is meant to call the function. These are in the Ast.scala file.

## 5.6 Not Implemented

Considering the nature of languages, the amount left undone could very well be infinite. The following list are for things that make the current implementation feel incomplete.

- Loops
- User-defined types
- Boolean functions
- Comparison functions (beside equal)
- Exit function. This is not particularly important, as the systems Fumurt is made for are not expected to ever exit
- A check that only the thread with write rights to a synchronized variable is allowed to write to that variable
- Some checks for the *equal* function
- Any other IO than print to console

# Chapter 6

# Testing

## 6.1 Hello World

A simple repeating Hello World is written like this:

```
program helloworld:Nothing =
{
  threadPrintHelloWorld()
}

thread threadPrintHelloWorld:Nothing =
{
  actionPrint("Hello World\n")
  threadPrintHelloWorld()
}
```

Which prints Hello World forever:

```
Hello World
Hello World
Hello World
Hello World
Hello World
Hello World
/*and so on*/
```

## 6.2 Multithreaded Hello World

A dualthreaded hello World is written like this:

```
program helloworld:Nothing =
{
  threadPrintHello()
  threadPrintWorld()
}

thread threadPrintWorld:Nothing =
```

```
{
  actionPrint("World\n")
  threadPrintWorld()
}

thread threadPrintHello:Nothing =
{
  actionPrint("Hello ")
  threadPrintHello()
}
```

Which also prints Hello World forever:

```
Hello World
Hello World
Hello World
Hello World
Hello World
Hello World
/*and so on*/
```

Note there is absolutely no performance benefits to dualthreading this, as the IO is sequential and this program does nothing but IO.

## 6.3 Synchronized Integer

Synchronized variables are the same in all threads, and mutations are published in the communicative phase.

```
program helloworld:Nothing =
{
  synchronized variable synchronizedCounter:Integer =
      {synchronized(variable=0, writer=threadC)}
  threadA(synchronizedCounter)
  threadB(synchronizedCounter)
  threadC(synchronizedCounter)
}

thread threadA(synchronizedCounter:Integer):Nothing =
{
  actionPrint(toString(synchronizedCounter))
  actionPrint(" == ")
  threadA(synchronizedCounter)
}

thread threadB(synchronizedCounter:Integer):Nothing =
{
  actionPrint(toString(synchronizedCounter))
  actionPrint("\n")
  threadB(synchronizedCounter)
}

thread threadC(synchronizedCounter:Integer):Nothing =
{
  actionMutate(newValue=plus(left=synchronizedCounter, right=1),
      variable=synchronizedCounter)
```

```
  threadC(synchronizedCounter)
}
```

And we can see that the number is consistent across threads:

```
0 == 0
1 == 1
2 == 2
3 == 3
4 == 4
5 == 5
6 == 6
7 == 7
8 == 8
9 == 9
/*and so on*/
```

## 6.4 Functions, Actions, Recursion and the Limitations of Integers

An example with a single thread, a square and a factorial function and an action is presented below.

```
program helloworld:Nothing =
{
  threadA(d=1.0, i=1, actionPrintSquare=actionPrintSquare)
}

thread threadA(d:Double, i:Integer,
    actionPrintSquare:Inclusion):Nothing =
{
  function factorial(i:Integer):Integer =
  {
    if(condition=equal(left=1, right=i), then=1,
        else=multiply(left=i, right=factorial(minus(left=i,
        right=1))))
  }
  actionPrint("The factorial of ")
  actionPrint(toString(i))
  actionPrint(" is ")
  actionPrint(toString(factorial(i)))
  actionPrint("    ")
  actionPrintSquare(d)
  threadA(d = plus(left=d, right=0.5), i = plus(left=i, right=1),
      actionPrintSquare=actionPrintSquare)
}

action actionPrintSquare(d:Double):Nothing =
{
  function square(x:Double):Double = {multiply(left=x, right=x)}
  actionPrint("The square of ")
  actionPrint(toString(d))
  actionPrint(" is ")
  actionPrint(toString(square(d)))
```

```
  actionPrint("\n")
}
```

When run, this example gives the following output:

```
The factorial of 1 is 1    The square of 1.000000 is 1.000000
The factorial of 2 is 2    The square of 1.500000 is 2.250000
The factorial of 3 is 6    The square of 2.000000 is 4.000000
The factorial of 4 is 24    The square of 2.500000 is 6.250000
The factorial of 5 is 120    The square of 3.000000 is 9.000000
The factorial of 6 is 720    The square of 3.500000 is 12.250000
The factorial of 7 is 5040    The square of 4.000000 is 16.000000
The factorial of 8 is 40320    The square of 4.500000 is 20.250000
The factorial of 9 is 362880    The square of 5.000000 is 25.000000
The factorial of 10 is 3628800    The square of 5.500000 is 30.250000
The factorial of 11 is 39916800    The square of 6.000000 is 36.000000
The factorial of 12 is 479001600    The square of 6.500000 is
    42.250000
The factorial of 13 is 1932053504    The square of 7.000000 is
    49.000000
The factorial of 14 is 1278945280    The square of 7.500000 is
    56.250000
The factorial of 15 is 2004310016    The square of 8.000000 is
    64.000000
The factorial of 16 is 2004189184    The square of 8.500000 is
    72.250000
The factorial of 17 is -288522240    The square of 9.000000 is
    81.000000
The factorial of 18 is -898433024    The square of 9.500000 is
    90.250000
The factorial of 19 is 109641728    The square of 10.000000 is
    100.000000
The factorial of 20 is -2102132736    The square of 10.500000 is
    110.250000
The factorial of 21 is -1195114496    The square of 11.000000 is
    121.000000
The factorial of 22 is -522715136    The square of 11.500000 is
    132.250000
The factorial of 23 is 862453760    The square of 12.000000 is
    144.000000
The factorial of 24 is -775946240    The square of 12.500000 is
    156.250000
The factorial of 25 is 2076180480    The square of 13.000000 is
    169.000000
The factorial of 26 is -1853882368    The square of 13.500000 is
    182.250000
The factorial of 27 is 1484783616    The square of 14.000000 is
    196.000000
The factorial of 28 is -1375731712    The square of 14.500000 is
    210.250000
The factorial of 29 is -1241513984    The square of 15.000000 is
    225.000000
The factorial of 30 is 1409286144    The square of 15.500000 is
    240.250000
The factorial of 31 is 738197504    The square of 16.000000 is
    256.000000
The factorial of 32 is -2147483648    The square of 16.500000 is
    272.250000
```

```
The factorial of 33 is -2147483648    The square of 17.000000 is
    289.000000
The factorial of 34 is 0    The square of 17.500000 is 306.250000
The factorial of 35 is 0    The square of 18.000000 is 324.000000
/*and so on*/
```

Here we see a problem with relying on integers of limited size. 32-bit integer is clearly inadequate for the factorial calculation. As for the eventual answer to the factorial calculation being zero, this seems to be a result of the C++ compiler's optimizations. No optimization gives the stack overflow we expect; running the binary results in a segmentation fault when compiled with GCC with -O0 or -O1 or Clang with -O0. Though there are problems with integer wrap-around and stack overflow, a recursive factorial function is a classic way to demonstrate the syntax of a language.

## 6.5 Full Program Test With C++ Intermediate

The following Fumurt code:

```
program p:Nothing =
{
  synchronized variable synchronizedNumber:Integer =
      {synchronized(variable=0, writer=threadPrintHello)}
  threadPrintHello(synchronizedNumber)
  threadPrintWorld(synchronizedNumber)
  threadPrintBaz(actionPrintFoo=actionPrintFoo, counter=0.0,
      integerIdentity=integerIdentity)
}

thread threadPrintWorld(synchronizedNumber:Integer):Nothing =
{
  actionPrint("world ")
  actionPrint(toString(synchronizedNumber))
  threadPrintWorld(synchronizedNumber)
}

thread threadPrintHello(synchronizedNumber:Integer):Nothing =
{
  actionPrint(toString(synchronizedNumber))
  actionPrint(" Hello ")
  actionMutate(variable=synchronizedNumber,
      newValue=plus(left=synchronizedNumber, right=1))
  threadPrintHello(synchronizedNumber)
}

thread threadPrintBaz(actionPrintFoo:Inclusion,
    integerIdentity:Inclusion, counter:Double):Nothing =
{
  action actionPrintBaz(counter:Double):Nothing =
  {
    actionPrint("  BAZ ")
    actionPrint(toString(counter))
    actionPrint("   ")
  }
```

```
32
33    actionPrintBaz(counter)
34    actionPrintFoo(integerIdentity)
35    threadPrintBaz(counter=minus(right=1.0, left=counter),
          actionPrintFoo=actionPrintFoo, integerIdentity=integerIdentity)
36  }
37
38  action actionPrintFoo(integerIdentity:Inclusion):Nothing =
39  {
40    action actionPrintFooo:Nothing =
41    {
42      actionPrint("  FOOO  ")
43    }
44    actionPrint("  FOO   ")
45    actionPrintFooo()
46    actionPrint(toString(integerIdentity(5)))
47    actionPrint("  ")
48    actionPrint(if(condition=true, then=toString(6), else=toString(3)))
49    actionPrint("\n")
50  }
51
52  function integerIdentity(x:Integer):Integer = {x}
```

The program gets compiled to the following C++11 code:

```
1   #include <iostream>
2   #include <thread>
3   #include <string>
4   #include <atomic>
5   #include <condition_variable>
6   #include <list>
7   #include <chrono>
8
9
10  #define NUMTOPTHREADS 3
11
12  [[noreturn]] static void threadPrintWorld();
13  [[noreturn]] static void threadPrintHello();
14  [[noreturn]] static void threadPrintBaz();
15  void actionPrintBaz$threadPrintBaz(double counter);
16  int integerIdentity$(int x);
17  void actionPrintFoo$threadPrintBaz();
18  void actionPrintFooo$threadPrintBazactionPrintFoo();
19
20  static int synchronizedNumber = 0;
21  static int writeSynchronizedNumber = 0;
22  static std::list<std::string> printthreadPrintHello;
23  static std::list<std::string> printthreadPrintWorld;
24  static std::list<std::string> printthreadPrintBaz;
25  static std::atomic<int> rendezvousCounter;
26  static std::mutex rendezvousSyncMutex;
27  static std::condition_variable cv;
28  static double threadPrintBaz$counter;
29  static void waitForRendezvous(std::string name)
30  {
31    std::unique_lock<std::mutex> lk(rendezvousSyncMutex);
32    ++rendezvousCounter;
33    if(rendezvousCounter.load() < NUMTOPTHREADS)
```

```
34    {
35      cv.wait(lk);
36    }
37    else if (rendezvousCounter.load() == NUMTOPTHREADS)
38    {
39      while(!printthreadPrintHello.empty()){
40  std::cout << printthreadPrintHello.front();
41  printthreadPrintHello.pop_front();
42  }
43  while(!printthreadPrintWorld.empty()){
44  std::cout << printthreadPrintWorld.front();
45  printthreadPrintWorld.pop_front();
46  }
47  while(!printthreadPrintBaz.empty()){
48  std::cout << printthreadPrintBaz.front();
49  printthreadPrintBaz.pop_front();
50  }
51  synchronizedNumber = writeSynchronizedNumber;
52
53      {
54        rendezvousCounter.store(0);
55        cv.notify_all();
56      }
57    }
58    else
59    {
60      std::cout << "error in wait for " << name << ". Rendezvouscounter
          out of bounds. RedezvousCounter = " <<
          rendezvousCounter.load() << "\n";
61      exit(0);
62    }
63  }
64
65
66
67  [[noreturn]] static void threadPrintWorld()
68  {while(true)
69  {
70    printthreadPrintWorld.push_back("world ");
71    printthreadPrintWorld.push_back(std::to_string(synchronizedNumber));
72    waitForRendezvous("threadPrintWorld");
73    continue;
74  }
75  }
76
77  [[noreturn]] static void threadPrintHello()
78  {while(true)
79  {
80    printthreadPrintHello.push_back(std::to_string(synchronizedNumber));
81    printthreadPrintHello.push_back(" Hello ");
82    writeSynchronizedNumber = (synchronizedNumber + 1);
83    waitForRendezvous("threadPrintHello");
84    continue;
85  }
86  }
87
88  [[noreturn]] static void threadPrintBaz()
```

```
{while(true)
{
  actionPrintBaz$threadPrintBaz(threadPrintBaz$counter);
  actionPrintFoo$threadPrintBaz();
  waitForRendezvous("threadPrintBaz");
threadPrintBaz$counter = (threadPrintBaz$counter - 1.0);

  continue;
}
}

void actionPrintBaz$threadPrintBaz(double counter)
{
  printthreadPrintBaz.push_back("  BAZ ");
  printthreadPrintBaz.push_back(std::to_string(counter));
  printthreadPrintBaz.push_back("   ");
}

int integerIdentity$(int x)
{
  return x;
}

void actionPrintFoo$threadPrintBaz()
{
  printthreadPrintBaz.push_back("  FOO   ");
  actionPrintFooo$threadPrintBazactionPrintFoo();
  printthreadPrintBaz.push_back(std::to_string(integerIdentity$(5)));
  printthreadPrintBaz.push_back("  ");
  printthreadPrintBaz.push_back(std::to_string(6));
  printthreadPrintBaz.push_back("\n");
}

void actionPrintFooo$threadPrintBazactionPrintFoo()
{
  printthreadPrintBaz.push_back("  FOOO  ");
}


int main()
{
rendezvousCounter.store(0);

threadPrintBaz$counter = 0.0;
std::thread tthreadPrintHello (threadPrintHello);
std::thread tthreadPrintWorld (threadPrintWorld);
std::thread tthreadPrintBaz (threadPrintBaz);
while(true)
{
std::this_thread::sleep_for(std::chrono::seconds(1));
}
}
```

When run in a terminal, this results in the following output:

```
0 Hello world 0  BAZ 0.000000     FOO     FOOO  5  6
1 Hello world 1  BAZ -1.000000     FOO     FOOO  5  6
2 Hello world 2  BAZ -2.000000     FOO     FOOO  5  6
```

```
3 Hello world 3   BAZ -3.000000      FOO      FOOO  5  6
4 Hello world 4   BAZ -4.000000      FOO      FOOO  5  6
/*and so on...*/
```

## 6.6 Error messages

Error messages are useful to detect errors in the program at compile time. Changing the source in 6.5 to the following erroneous program allow us to test them:

```
program p:Nothing =
{
  synchronized variable synchronizedNumber:Integer =
      {synchronized(variable=0, writer=threadPrintHello)}
  threadPrintWorld(synchronizedNumber)
  threadPrintLol(actionPrintFoo=integerIdentity,
      integerIdentity=integerIdentityyy)
}

thread threadPrintWorld(synchronizedNumber:Integer):Nothing =
{
  actionPrint("world ")
  actionPrint(toString(synchronizedNumber))
  threadPrintWorld(synchronizedNumber)
}

thread threadPrintHello(synchronizedNumber:Integer):Nothing =
{
  actionPrint(synchronizedNumber)
  actionPrint(" Hello ")
  actionMutate(variable=synchronizedNumber,
      newValue=plus(left=synchronizedNumber, right=1))
  threadPrintHello(synchronizedNumber)
}

thread threadPrintLol(actionPrintFoo:Inclusion,
    integerIdentity:Inclusion):Nothing =
{
  action actionPrintLol:Nothing =
  {
    actionPrint("  LOL   ")
  }

  actionPrintLol()
  actionPrintFoo(integerIdentity)
  threadPrintLol(actionPrintFoo=actionPrintFoo,
      integerIdentity=integerIdentity)
}

function printFoo(integerIdentity:Inclusion):Nothing =
{
  action actionPrintFooo:Nothin =
  {
    actionPrint("  FOOO  ")
  }
  actionPrint("  FOO   ")
```

```
  actionPrintFooo()
  actionPrint(toString(integerIdentity(5.0)))
  actionPrint("  ")
  actionPrint(if(condition=0, then=6, else=toString(3)))
  actionPrint(toString(if(condition=false, then=6, else=3)))
  actionPrint("\n")
}

function integerIdentity(x:Integer):Integer = {multiply(left=x,
    right=1.0)}
```

This causes the Fumurt checker produces the following errors:

```
0.0: thread threadPrintHello is declared but not used
global position
^

5.33: Passed inclusion must be the same as the one referenced inside
    the function
  threadPrintLol(actionPrintFoo=integerIdentity,
      integerIdentity=integerIdentityyy)

                                  ^

5.66: integerIdentityyy not found
  threadPrintLol(actionPrintFoo=integerIdentity,
      integerIdentity=integerIdentityyy)

                                                                  ^

17.15: Expected type String. Got Integer
  actionPrint(synchronizedNumber)

              ^

31.3: actionPrintFoo not found
  actionPrintFoo(integerIdentity)

  ^

32.33: actionPrintFoo not found
  threadPrintLol(actionPrintFoo=actionPrintFoo,
      integerIdentity=integerIdentity)

                                  ^

39.5: Expected return type Nothin. Got Nothing
    actionPrint("  FOOO  ")

    ^

37.3: actions cannot be defined in  functions
  action actionPrintFooo:Nothin =

  ^

42.3: Expected return type Nothing. Got Nothin
  actionPrintFooo()
```

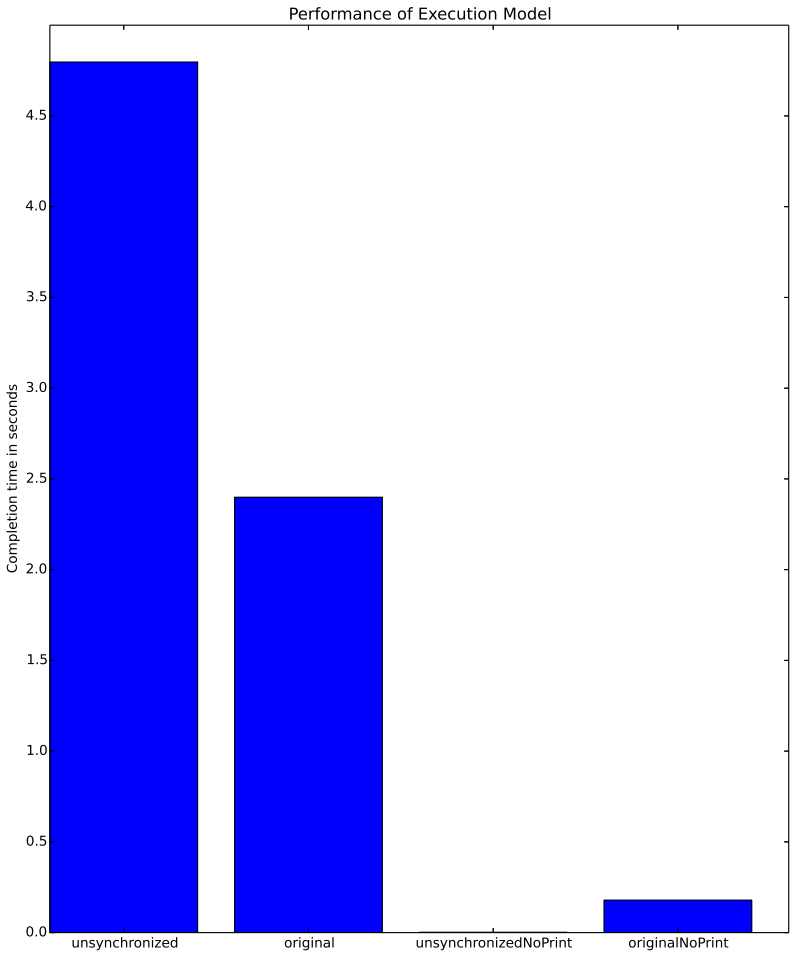
```
42
43    ^
44
45  43.40: Call argument type should be Integer. Call argument type was
        Double
46    actionPrint(toString(integerIdentity(5.0)))
47
48                                            ^
49
50  45.28: Call argument type should be Boolean. Call argument type was
        Integer
51    actionPrint(if(condition=0, then=6, else=toString(3)))
52
53                               ^
54
55  45.36: Call argument type should be String. Call argument type was
        Integer
56    actionPrint(if(condition=0, then=6, else=toString(3)))
57
58                                        ^
59
60  50.48: This call to multiply returns a Double not an Integer
61  function integerIdentity(x:Integer):Integer = {multiply(left=x,
        right=1.0)}
62
63                                                      ^
64
65  13 errors found
```

## 6.7 Performance

In order to understand the cost of the synchronization in the execution model, a test was performed. The C++ code generated in 6.5 was modified to exit when synchronizedNumber was equal to or bigger than 20000. Let this be the *original*. Then all synchronization mechanisms was removed. Let this be the *unsynchronized*. Then the print statements of both was removed, as if the original Fumurt program had had no calls to actionPrint. Let these be *originalNoPrint* and *unsynchronizedNoPrint*. The times taken until completion was then measured using the Unix *time* utility. The optimizations used were "-O3 -march=native" on an Intel i5-2500 CPU. The results were very interesting:

| Code | Time until completion (in seconds) |
|---|---|
| original | 2.399 |
| unsynchronized | 4.797 |
| originalNoPrint | 0.179 |
| unsynchronizedNoPrint | 0.002 |

The same results are visualized in the plot below:




Two things can be concluded from these measurements:

1. The execution model incurs considerable cost
2. The execution model can achieve superior performance compared to an unsynchronized model when the program is dominated by access to terminal output. One may speculate that this is due to resource contention and applies equally to all inherently sequential IO

# Chapter 7

# Conclusion, Discussion and Further Work

## 7.1 Conclusion

During the writing of this thesis, a deterministic multithreaded language has been designed and a compiler has been built for it. In this report it has been shown that creating a programming language that eliminates almost all of the difficulties of multithreaded programming is possible, while maintaining some of the architectural and performance benefits of multithreading. Fumurt also presents some new ideas regarding the ways in which code should be structured, possibly making it easier to maintain large software projects. Yet Fumurt is not near being a usable language, and many questions remain unanswered.

## 7.2 Discussion

In hindsight, the code generator could have been better written. Adding an additional two steps with the annotator was a fairly late decision, and the architecture of the module suffered for it. There's also numerous bugs and lacking features, as well as corner cases where the appropriate behavior simply has not been determined. The various features of the language included with the intent of easing the maintenance of large programs are not rooted in empirical studies, which is clearly unfortunate. In the case where a computational phase runs for a long time, the IO buffers may grow to be too large to be stored in memory. While this is not an issue for desktop and laptop computers where filling up the memory takes so long that the program's unresponsiveness is the bigger issue, it's a bigger problem for microcontrollers. Fixing this problem means that the sequential IO and inter-thread communication abstraction which the programming language provides can in extreme cases require that the execution itself becomes sequential. It seems intuitively possible that this is simply a necessity when providing such an abstraction.

In situations where performance is more important than predictability, mechanisms need to be provided to the programmer so that determinism requirements can be relaxed. Similarly, some kinds of recursion have memory use requirements which are hard to optimize away. The correct way to handle this is yet to be determined.

More fundamentally, the literature concerning multithreading seems divided over what should be required to be deterministic by the language and what should require programmer intervention if a deterministic sequence is required. It is unclear whether this thesis has the best approach.

## 7.3 Suggestions for Future Work

It is common for programming languages to need a decade of intensive development by several contributors before it is ready for serious usage. It is therefore not hard to come up with ways in which Fumurt could be improved. For ideas, see section 4.6 and 5.6. But not all improvements to Fumurt are of academic interest; much of the work is simply implementation of pretty mundane things. Improvements to the execution model might be more interesting. There are many ideas in section 4.6 about how the model might be refined. Investigating solutions to employing deterministic Fumurt or Fumurt-like systems while accommodating hardware faults and distributed systems is another possibility. An Erlang/OTP system might be able to serve as a supervisor for several networked systems running deterministic code. Lastly, there seems to be little empirical work when it comes to programming language design. Performing empirical studies among programmers investigating what programming language ideas are actually helpful seems like a good idea.

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# Appendix A

# System manual

To avoid confusion when discussing compiling the compiler, the Fumurt compiler will be referred to as "the program".

To compile this code you need the Simple Build Tool (SBT), available at `http://www.scala-sbt.org/`. SBT will download the dependencies required including the compiler and the parser combinator library. It will also allow you to run the program. Depending on the way you install SBT and on which platform, you may have to install a Java runtime environment in order to run SBT

To compile the code using SBT, a certain directory hierarchy is required. The directory in which you run SBT must be the same directory that the "build.sbt" file and "src" directory is in. "build.sbt" holds dependency and compilation options for SBT. The "src" directory holds all the source code for the project in a structure. Since there's only Scala code in this project, the source files shall be in "src/main/scala".

Once SBT is installed and the directory structure conforms to SBT rules, SBT can be started in the directory by using the "sbt" command in a terminal in the directory holding "build.sbt" file and "src". SBT will then download the files needed to compile and run the program. This usually takes a long while, depending on your Internet connection. Once this is done, SBT will present a command prompt. The program can then be compiled and run from this SBT command prompt using the "run [name of Fumurt file]" command. The compilation (of the compiler) also usually takes a while. Note that the Fumurt source file must be in the same directory that you launch SBT in, as the the Fumurt compiler does not handle file paths in its input.

The Fumurt compiler uses GCC, and GCC must therefore be installed. If GCC is not installed, the user may compile the generated C++ from the generated "generated.cpp" file. The options "-pthread" and "-std=c++11" are required when using Clang/GCC on Linux, but not using the Microsoft Visual C++ compiler on Windows.

If everything goes well, the output will be a binary executable named "generated", with "-O3" and "march=native" options.

Example:

```
$ ls
build.sbt src test.fumurt
$ sbt
[info] /*current sbt state*/
> run test.fumurt
[info] Running fumurtCompiler.Main test.fumurt
[success] Total time: 2 s, completed May 29, 2015 5:42:18 PM
> /*ctrl+c*/
$ ls
generated.cpp build.sbt generated src test.fumurt
$ ./generated
/*program output here*/
```

# Appendix B

# User manual

You need to have Scala installed (`http://www.scala-lang.org/download/`) to run the Fumurt compiler from compiled bytecode. The current directory must be the one *above* the ".class" bytecode files. Because the starting point of the program is function "main" in object "Main" in package "fumurtCompiler", the folder containing the bytecode files must be "fumurtCompiler" (i.e. the name of the package), and the command to run must be "scala fumurtCompiler.Main [fumurt source file here]".

The Fumurt compiler uses GCC, and GCC must therefore be installed. If GCC is not installed, the user may compile the generated C++ from the generated "generated.cpp" file. The options "-pthread" and "-std=c++11" are required when using Clang/GCC on Linux, but not using the Microsoft Visual C++ compiler on Windows.

Example:

```
$ ls
fumurtCompiler  test.fumurt
$ ls fumurtCompiler
aCallarg.class
FumurtParser$$anonfun$subsequentArgsParser$1$$anonfun$apply$11.class
ActionT.class
FumurtParser$$anonfun$subsequentArgsParser$1.class
ActionT$.class
FumurtParser$$anonfun$subsequentArgsParser$2.class
/*more bytecode files here*/
$
$ scala fumurtCompiler.Main test.fumurt
$ ./generated
/*program output here*/
```

# Appendix C

# Code listing

## C.1 build.sbt

```
name := "solution"

organization := "NTNU ITK"

version := "0.1.0"

scalaVersion := "2.11.6"

scalacOptions ++= Seq("-feature", "-optimise", "-Xlint",
    "-Xfatal-warnings", "-deprecation", "-Ywarn-unused",
    "-Ywarn-infer-any", "-Ywarn-unused-import", "-Ywarn-dead-code",
    "-Ywarn-inaccessible", "-Ywarn-numeric-widen",
    "-Ywarn-nullary-override", "-Ywarn-nullary-unit",
    "-Ywarn-adapted-args")

libraryDependencies ++= Seq( "org.scala-lang.modules" %%
    "scala-parser-combinators" % "1.0.3")
```

## C.2 Main.scala

```
package fumurtCompiler

import scala.io.Source._
import scala.util.parsing.input.Positional

object CompileTypeOption extends Enumeration
{
  type CompileTypeOption = Value
  val compiledToGo, compiledToC, compiledToCpp, interpreted = Value
}

import CompileTypeOption._
```

```
13
14  object Main
15  {
16    def main(args: Array[String]) :Unit ={
17      if(args.length <1)
18      {
19          println("no file found in arguments\n")
20      }
21      else
22      {
23        val parts = args(0).split("""\.""")
24        if(parts.length==2)
25        {
26          if(parts(1)=="fumurt")
27          {
28            compile(getOptions(args.drop(1), args(0)))
29          }
30          else
31          {
32            println("unknown file ending: " + parts(1) + "\n")
33          }
34        }
35        else
36        {
37          println("too many arguments\n")
38        }
39      }
40    }
41
42    def getOptions(args:Array[String],file:String): Options =
43    {
44      //println(args.toString)
45      new Options(CompileTypeOption.interpreted, true, file)
46    }
47
48    def compile(opts:Options):Unit =
49    {
50      //println("Now compiling!")
51      val sourcestring = fromFile(opts.file).mkString
52      FumurtScanner.scan(sourcestring) match
53      {
54        case Left(error) => println("Error in scanner: " +
              error.toString)
55        case Right(tokens) =>
56        {
57          //println("successful scan. Tokens: "+tokens.toString+"\n")
58          FumurtParser.parse(tokens) match
59          {
60            case Left(error) => println("Error in parser: " +
                  error.toString)
61            case Right(ast) =>
62            {
63              //println("Success in parser: " + ast.toString)
64              FumurtTypeChecker.check(ast) match
65              {
66                case Some(errors) =>
67                {
```

```
68                  errors.map(x=>println(x))
69                  val errornum:String = errors.length match
70                  {
71                    case 1 => "one"
72                    case 2 => "two"
73                    case 3 => "three"
74                    case 4 => "four"
75                    case 5 => "five"
76                    case 6 => "six"
77                    case 7 => "seven"
78                    case 8 => "eight"
79                    case 9 => "nine"
80                    case x => x.toString
81                  }
82                  val singularplural:String = if(errors.length==1){"
                        error"}else{" errors"}
83                  println(errornum.capitalize + singularplural + "
                        found")
84                }
85                case None =>
86                {
87                  //println("\nNo errors in checker")
88                  val generatedcode = FumurtCodeGenerator.generate(ast)
89                  //println("\ncode generated: \n" + generatedcode)
90                  import java.nio.file.{Paths, Files}
91                  import java.nio.charset.StandardCharsets
92                  val outname = "generated"
93                  val fileending = ".cpp"
94                  Files.write(Paths.get("./"+outname+fileending),
                        generatedcode.getBytes(StandardCharsets.UTF_8))
95                  val options = " -pthread -std=c++11 -O3 -march=native"
96                  //println("\n\n===Starting GCC cpp compilation===")
97                  //println("options = " + options)
98                  import scala.sys.process._
99                  val command = "g++ " + outname + fileending + options
                        + " -o " + outname
100                 //println(command)
101                 if( System.getProperty( "os.name"
                        ).startsWith("Windows") )
102                 {
103                   println("OS identified as Windows. Please use the
                          Microsoft Visual C++ compiler (included in
                          Visual Studio) to compile the generated
                          \"generated.cpp\" file")
104                 }
105                 else
106                 {
107                   (command).!
108                 }
109               }
110             }
111           }
112         }
113       }
114     }
115
116 }
```

```
117
118 }
119
120 class Options(val compileTypeOption:CompileTypeOption, val
        debug:Boolean, val file:String)
```

## C.3 Ast.scala

```
1  package fumurtCompiler
2
3  import scala.util.parsing.input.Positional
4
5
6  abstract class Token() extends Positional
7  abstract class DefDescriptionT() extends Token
8  abstract class BasicValueT() extends Token
9  abstract class SyntaxT() extends Token
10
11 case class EmptyT() extends Token
12 case class TrueT() extends BasicValueT {override def toString =
       "true"}
13 case class FalseT() extends BasicValueT {override def toString =
       "false"}
14 case class ProgramT() extends DefDescriptionT {override def toString
       = "program"}
15 case class ActionT() extends DefDescriptionT {override def toString =
       "action"}
16 case class ThreadT() extends DefDescriptionT {override def toString =
       "thread"}
17 case class FunctionT() extends DefDescriptionT {override def toString
       = "function"}
18 case class ValueT() extends DefDescriptionT {override def toString =
       "value"}
19 case class SynchronizedVariableT() extends DefDescriptionT {override
       def toString = "synchronized variable"}
20 case class OpenParenthesisT() extends SyntaxT {override def toString
       = "\"(\""}
21 case class CloseParenthesisT() extends SyntaxT {override def toString
       = "\")\""}
22 case class OpenCurlyBracketT() extends SyntaxT {override def toString
       = "\"{\""}
23 case class CloseCurlyBracketT() extends SyntaxT {override def
       toString = "\"}\""}
24 case class DoubleT(val value:Double) extends BasicValueT {override
       def toString = "decimal number"}
25 case class IntegerT(val value:Int) extends BasicValueT {override def
       toString = "integer"}
26 case class EqualT() extends SyntaxT {override def toString = "\"=\""}
27 case class ColonT() extends SyntaxT {override def toString = "\":\""}
28 case class CommaT() extends SyntaxT {override def toString = "\",\""}
29 case class NewlineT() extends SyntaxT {override def toString =
       "newline"}
30 case class IdT(val value:String) extends Token {override def toString
       = "identifier(\""+value+"\")"}
```

```
31 case class TypeT(val value:String) extends Token {override def
       toString = "type(\""+value+"\")"}
32 case class StringT(val value:String) extends BasicValueT {override
       def toString = "string"}
33 case class SpaceT() extends SyntaxT
34 case class DummyT() extends Token
35 case class EofT() extends SyntaxT {override def toString = "end of
       file"}
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54 class Expression() extends Positional
55 trait Callarg extends Positional
56 trait Statement extends Expression
57 trait BasicValueStatement extends Statement with Callarg with
       aCallarg with aStatement
58
59 case class Definition(val leftside:DefLhs, val rightside:DefRhs)
       extends Expression
60 case class DefLhs(val description:DefDescriptionT, val id:IdT, val
       args:Option[Arguments], val returntype:TypeT)
61 /*case class Arguments(val id:IdT, val typestr:TypeT, val
       args2:Option[Arguments2])
62 case class Arguments2(val id:IdT, val typestr:TypeT, val
       args2:Option[Arguments2])*/
63 case class Arguments(val args:List[Argument])
64 case class Argument(val id:IdT, val typestr:TypeT)
65 case class DefRhs(val expressions:List[Expression] )
66 case class Empty();
67 case class DefDescription(val value:Token)
68 case class NamedCallarg(id:IdT, argument:Callarg) //extends Callarg
69 case class NamedCallargs(val value:List[NamedCallarg])
70 case class NoArgs() extends Callarg with aCallarg
71
72 case class StringStatement(val value:String) extends
       BasicValueStatement
73 case class IntegerStatement(val value:Int) extends BasicValueStatement
74 case class DoubleStatement(val value:Double) extends
       BasicValueStatement
75 case class TrueStatement() extends BasicValueStatement
76 case class FalseStatement() extends BasicValueStatement
```

```
77 case class IdentifierStatement(val value:String) extends Statement
       with Callarg with aCallarg with aStatement
78 case class FunctionCallStatement(val functionidentifier:String, val
       args:Either[Callarg,NamedCallargs]) extends Statement with Callarg
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95 trait aExpression
96 trait aCallarg extends Callarg with aStatement
97 trait aStatement extends aExpression
98
99 case class aDefinition(val leftside:aDefLhs, val rightside:aDefRhs)
       extends aExpression
100 case class aDefLhs(val description:DefDescriptionT, val id:IdT, val
       cppid:IdT, val callingthread:String, val args:Option[aArguments],
       val returntype:TypeT)
101 case class aArguments(val args:List[aArgument])
102 case class aArgument(val id:IdT, cppid:IdT, val typestr:TypeT)
103 case class aDefRhs(val expressions:List[aExpression] )
104 case class aNamedCallarg(id:IdT, argument:aCallarg) //extends Callarg
105 case class aNamedCallargs(val value:List[aNamedCallarg])
106
107 case class aFunctionCallStatement(val functionidentifier:String, val
       cppfunctionidentifier:String, val
       args:Either[aCallarg,aNamedCallargs], val returntype:String)
       extends aStatement with aCallarg
```

## C.4 Scanner.scala

```
1
2
3  package fumurtCompiler
4
5  import scala.language.implicitConversions
6  import scala.util.parsing.combinator.RegexParsers
7  import scala.util.matching.Regex
8  import scala.language.postfixOps
9  //import scala.util.parsing.combinator.lexical._
10 import scala.util.parsing.input.Positional
11
12 object FumurtScanner extends RegexParsers /*with Parsers*/
```

```
{
  override val skipWhitespace = false

  def scan(in:String):Either[NoSuccess, List[Token]] =
  {
    //println(in)

    parseAll((scanInternal*), in) match
    {
      case Success(result, _) =>
      {
        val tokens = result.filter(x=>x match{case SpaceT() => false;
            case _ => true}) :+ EofT()
        Right(tokens)
      }
      case f:Failure => Left(f)
      case e:Error => Left(e)
      //case Failure(message, reader) => Left(new
          FumurtError(reader.pos, "Failure: "+message,"\n" +
          in.lines.toList(reader.pos.line) +"\n"))
      //case Error(message,_) => Left(new FumurtError(Global, "Error:
          " + message, ""))
    }

  }



  def spaceParser:Parser[SpaceT] = positioned( new Regex(""" """) ^^
      {x => /*println("scanned space");*/SpaceT()} )
  def programStrParser: Parser[ProgramT] = positioned( new
      Regex("program ") ^^ {x => /*println("scanned program
      "+x.toString);*/ProgramT()} )
  def functionParser: Parser[FunctionT] = positioned( new
      Regex("function ") ^^ {x => /*println("scanned function
      "+x.toString);*/FunctionT()} )
  def threadParser: Parser[ThreadT] = positioned( new Regex("thread
      ") ^^ {x => /*println("scanned thread
      "+x.toString);*/ThreadT()} )
  def synchronizedVariableParser: Parser[SynchronizedVariableT] =
      positioned(new Regex("synchronized variable ") ^^ {x =>
      /*println("scanned synchronized variable "+x.toString);*/
      SynchronizedVariableT()})
  def valueParser: Parser[ValueT] = positioned( new Regex("value ")
      ^^ {x => /*println("scanned unsafe value
      "+x.toString);*/ValueT()} )
  def actionParser: Parser[ActionT] = positioned( new Regex("action
      ") ^^ {x => /*println("scanned action
      "+x.toString);*/ActionT()} )
  def trueParser: Parser[TrueT] = positioned( new Regex("true") ^^ {x
      => /*println("scanned true "+x.toString);*/TrueT()} )
  def falseParser: Parser[FalseT] = positioned( new Regex("false") ^^
      {x => /*println("scanned false "+x.toString);*/FalseT()} )
  def openParenthesisParser: Parser[OpenParenthesisT] = positioned(
      new Regex("""\(""") ^^ {x => /*println("scanned (
      "+x.toString);*/OpenParenthesisT()} )
```

```
47    def closeParenthesisParser: Parser[CloseParenthesisT] = positioned(
          new Regex("""\)""") ^^ {x => /*println("scanned )
          "+x.toString);*/CloseParenthesisT()} )
48    def openCurlyBracketParser: Parser[OpenCurlyBracketT] = positioned(
          new Regex("""\{""") ^^ {x => /*println("scanned {
          "+x.toString);*/OpenCurlyBracketT()} )
49    def closeCurlyBracketParser: Parser[CloseCurlyBracketT] =
          positioned( new Regex("""\}""") ^^ {x => /*println("scanned }
          "+x.toString);*/CloseCurlyBracketT()} )
50    def doubleParser: Parser[DoubleT] = positioned( new
          Regex("""[-+]?[0-9]*\.[0-9]+""") ^^ {x => /*println("scanned
          double "+x.toString);*/DoubleT(x.toDouble)} )
51    def intParser: Parser[IntegerT] = positioned( new
          Regex("""[-+]?(0|[1-9]\d*)""") ^^ {x => /*println("scanned
          integer "+x.toString);*/IntegerT(x.toInt)} )
52    def equalParser: Parser[EqualT] = positioned( new Regex("=") ^^ {x
          => /*println("scanned = "+x.toString);*/EqualT()} )
53    def colonParser: Parser[ColonT] = positioned( new Regex(":") ^^ {x
          => /*println("scanned : "+x.toString);*/ColonT()} )
54    def commaParser: Parser[CommaT] = positioned( new Regex(",") ^^ {x
          => /*println("scanned , "+x.toString);*/CommaT()} )
55    //def emptyParser: Parser[EmptyT] = new Regex("") ^^ {x =>
          println("scanned empty");EmptyT()}
56    def newlineParser: Parser[NewlineT] = positioned( new Regex("\n")
          ^^ {x => /*println("scanned newline ");*/NewlineT()} )
57    def idParser: Parser[IdT] = positioned( new
          Regex("[a-z]+[a-zA-Z]*") ^^ {x => /*println("scanned id
          "+x.toString);*/IdT(x.toString)} )
58    def stringParser: Parser[StringT] = positioned( new
          Regex("""("[^"]*")""") ^^ {x => /*println("scanned string
          "+x.toString);*/StringT(x.toString)} )
59    def typeParser: Parser[TypeT] = positioned( new
          Regex("[A-Z][a-zA-Z]*") ^^ {x => /*println("scanned type
          "+x.toString);*/TypeT(x.toString)} )
60
61
62    def scanInternal: Parser[Token] =
63    {
64      (
65        spaceParser                |
66        programStrParser           |
67        threadParser         |
68        actionParser               |
69        synchronizedVariableParser  |
70        functionParser             |
71        trueParser                 |
72        falseParser                |
73        openParenthesisParser      |
74        closeParenthesisParser     |
75        openCurlyBracketParser     |
76        closeCurlyBracketParser    |
77        doubleParser               |
78        intParser                  |
79        equalParser                |
80        colonParser                |
81        commaParser                |
82        //emptyParser                |
```

```
      newlineParser             |
      stringParser              |
      idParser                  |
      typeParser
    )
  }


}
```

## C.5 Parser.scala

```
package fumurtCompiler

//import scala.util.parsing._
import scala.language.postfixOps
import scala.language.implicitConversions
import scala.util.parsing.input._
import scala.util.parsing.combinator._
//import scala.util.parsing.combinator.PackratParsers.PackratReader
//import scala.util.parsing.combinator.syntactical._
import scala.util.parsing.combinator.PackratParsers

object FumurtParser extends Parsers //with PackratParsers
{
  override type Elem = Token
  //type Tokens = Token
  //type Token = Elem

  def parse(in:List[Token]):Either[NoSuccess, List[Definition]]=
  {
    //val ast = parseAll((progParser), in)
    val res = progParser(new TokenReader(in))
    res match
    {
      case ns:NoSuccess=>
      {
         println(res+"\n")
         //Left(new FumurtError(ns.next.pos, ns.msg, ""))
         Left(ns)
      }
      case _=>
      {
        val ast = res.get
        //println("\n")
        //println(ast.toString+"\n")
        Right(ast)
      }
    }
  }


  def progParser: Parser[List[Definition]] = (paddedDefParser.+) <~
      eofParser
```

```
42    def paddedDefParser:Parser[Definition] =
          {/*println("paddeddefparser");*/ newlineParser.* ~> defParser
          <~ newlineParser.* }
43    def defParser: Parser[Definition] = {/*println("defparser");*/
          positioned((deflhsParser <~ equalParser ~! newlineParser.*) ~!
          defrhsParser ^^ {x=>Definition(x._1,x._2)}) }
44    def deflhsParser: Parser[DefLhs] = {/*println("deflhsparser");*/
          (defdescriptionParser ~ idParser ~ argsParser ~! (colonParser
          ~> typeParser)) ^^ {x=>DefLhs(x._1._1._1, x._1._1._2, x._1._2,
          x._2)} }
45    def argsParser: Parser[Option[Arguments]] =
          {/*println("argsparser");*/ openParenthesisParser ~> ((idParser
          <~ colonParser) ~ typeParser ~ subsequentArgsParser.*) <~
          closeParenthesisParser ^^{x=>Some(Arguments( (Argument(x._1._1,
          x._1._2) +:
          x._2).sortWith((left,right)=>left.id.value<right.id.value) ))}
          | emptyParser ^^ {x=>None} }
46    def subsequentArgsParser: Parser[Argument] =
          {/*println("args2parserparser");*/  commaParser ~> (idParser <~
          colonParser) ~ typeParser ^^{x=>Argument(x._1, x._2)} }
47
48    def defrhsParser: Parser[DefRhs] = {/*println("-defrhsparser");*/
          (openCurlyBracketParser ~ newlineParser.* ~> expressionParser ~
          (newlineParser.+ ~> expressionParser).*) <~ newlineParser.* ~
          closeCurlyBracketParser ^^{x=>DefRhs(x._1 +: x._2)} }
49    def expressionParser: Parser[Expression] =
          {/*println("expressionparser");*/ positioned(defParser |
          statementParser) }
50    /*
51    def defrhsParser: Parser[DefRhs] = {println("-defrhsparser");
          (openCurlyBracketParser ~> expressionParser.+) <~
          newlineParser.* ~ closeCurlyBracketParser ^^{x=>DefRhs(x)} }
52    def expressionParser: Parser[Expression] =
          {println("expressionparser"); newlineParser.+ ~>
          positioned(defParser | statementParser) }
53    */
54    def statementParser: Parser[Statement] =
          {/*println("statementparser");*/ functionCallParser |
          basicStatementParser  | identifierStatementParser }
55    def callargsParser: Parser[Either[Callarg,NamedCallargs]] =
          {/*println("callargsparser");*/ openParenthesisParser ~>
          (namedcallargsParser | callargParser) <~ closeParenthesisParser
          ^^{x=>x match{case x:Callarg => Left(x); case
          x:NamedCallargs=>Right(x)}} }
56    def callargParser: Parser[Callarg] = {/*println("callargparser");*/
          positioned(functionCallParser | identifierStatementParser |
          basicStatementParser | success(NoArgs())) }
57    def namedcallargsParser: Parser[NamedCallargs] =
          {/*println("namedcallargsparser");*/ namedcallargParser ~
          subsequentnamedcallargsParser.+ ^^ {x => NamedCallargs((x._1 +:
          x._2).sortWith((left,right)=>left.id.value<right.id.value))} }
58    def subsequentnamedcallargsParser: Parser[NamedCallarg] =
          {/*println("subsequentnamedcallargsParser");*/ (commaParser ~!
          success(Unit)) ~> namedcallargParser }
59    def namedcallargParser:Parser[NamedCallarg] =
          {/*println("namedcallargparser");*/ (idParser <~ equalParser) ~
          callargParser ^^ {x=>NamedCallarg(x._1, x._2)} }
```

```
60    def functionCallParser:Parser[FunctionCallStatement] =
          {/*println("functioncallparser");*/ idParser ~ callargsParser
          ^^ {x=>FunctionCallStatement(x._1 match{case IdT(str)=>str},
          x._2)} }
61
62    /*
63    def argsParser: Parser[Option[Arguments]] = {println("argsparser");
          openParenthesisParser ~> ((idParser <~ colonParser) ~
          typeParser ~ args2Parser) <~ closeParenthesisParser
          ^^{x=>Some(Arguments(x._1._1, x._1._2, x._2))} | emptyParser ^^
          {x=>None} }
64    def args2Parser: Parser[Option[Arguments2]] =
          {println("args2parserparser");  commaParser ~> (idParser <~
          colonParser) ~ typeParser ~ args2Parser
          ^^{x=>Some(Arguments2(x._1._1, x._1._2, x._2))} | emptyParser
          ^^^{None} }
65    */
66
67
68    def equalParser:Parser[Token] = accept(EqualT())
69    def colonParser:Parser[Elem] = accept(ColonT())
70    def commaParser:Parser[Elem] = accept(CommaT())
71    def newlineParser:Parser[Elem] = accept(NewlineT())
72    def emptyParser:Parser[Empty] = success(Empty())
73    def openParenthesisParser:Parser[Elem] = accept(OpenParenthesisT())
74    def closeParenthesisParser:Parser[Elem] =
          accept(CloseParenthesisT())
75    def openCurlyBracketParser:Parser[Elem] =
          accept(OpenCurlyBracketT())
76    def closeCurlyBracketParser:Parser[Elem] =
          accept(CloseCurlyBracketT())
77    def programStrParser:Parser[Elem] = accept(ProgramT())
78    def actionParser:Parser[Elem] = accept(ActionT())
79    def threadParser:Parser[Elem] = accept(ThreadT())
80    def functionParser:Parser[DefDescription] = accept("function",
          {case FunctionT() => DefDescription(FunctionT())})
81    def eofParser:Parser[Elem] = accept(EofT())
82    def idParser:Parser[IdT] = accept("identifier", {case IdT(value) =>
          {/*println("idparser accepted "+value);*/IdT(value)}})
83    def trueParser:Parser[Elem] = accept(TrueT())
84    def falseParser:Parser[Elem] = accept(FalseT())
85    def identifierStatementParser:Parser[IdentifierStatement]
          ={/*println("identifierstatementparser");*/
          accept("identifier", {case
          IdT(str)=>{/*println("identifierstatementparser accepted
          "+str);*/ IdentifierStatement(str)}}) }
86    def basicStatementParser:Parser[BasicValueStatement] =
          accept("expected string, integer, boolean or float", {case
          StringT(value) => StringStatement(value);
87
88
```

```
89
90
91
92    def typeParser:Parser[TypeT] = accept("expected type. Types are
          written with a leading capital letter", {case x:TypeT => x})
93    def intParser:Parser[Elem] = accept("integer", {case x:IntegerT =>
          x})
94    def doubleParser:Parser[Elem] = accept("double", {case x:DoubleT =>
          x})
95    def defdescriptionParser: Parser[DefDescriptionT] =
          {/*println("defdescriptionParser");*/ accept("expected
          function, action, thread or program", {case x:DefDescriptionT
          => x}) }
96
97
98
99
100
101
102
103   class TokenReader(in:List[Token]) extends Reader[Elem]
104   {
105     def atEnd:Boolean = in.isEmpty
106     def first:Elem = in.head
107     def pos:Position = in.head.pos;
108     def rest = new TokenReader(in.tail)
109   }
110 }
```

## C.6 Typechecker.scala

```
1  package fumurtCompiler
2  import scala.collection.mutable.ListBuffer
3
4  object FumurtTypeChecker
5  {
6    def check(in:List[Definition]):Option[List[FumurtError]] =
7    {
8      val print = DefLhs(ActionT(), IdT("actionPrint"),
           Some(Arguments(List(Argument(IdT("toPrint"),
           TypeT("String"))))), TypeT("Nothing"))
9      val basicfunctions = List(print)
10
11
12     //all standard library functions available everywhere (maybe also
           actions).
13     //checkexpression(in, DefLhs(UnsafeActionT(), IdT(""), None,
           TypeT("Nothing")), None, List(List():List[Definition]),
           basics, List():List[DefLhs], List():List[FumurtErrors])
```

```
14
15      //println()
16      val errors = checktop(in, basicfunctions)
17      //println()
18      if (errors.isEmpty)
19      {
20        None
21      }
22      else
23      {
24        Some(errors)
25      }
26    }
27
28    def checktop(in:List[Definition], basicFunctions:List[DefLhs]):
          List[FumurtError]=
29    {
30      val topdefs = indexlefts(in)
31      val programs = in.filter(x=>(x.leftside.description match {case
            ProgramT() => true; case _=> false}))
32      val implicitargs = topdefs.filter(x=>(x.description match {case
            ProgramT() => false; case _=> true}))
33      //println("\nimplicitargs is: "+implicitargs)
34      val programerrors = if(programs.length==1)
35      {
36        checkprogram(programs(0), implicitargs, basicFunctions)
37      }
38      else {List(FumurtError(Global, "There must be exactly one program
            definition. "+programs.length+" program definitions
            detected"))}
39      val program = programs(0)
40      //val synchronizedvars = program.rightside.expressions.filter(x=>
            x match {case
            Definition(DefLhs(SynchronizedVariableT(),_,_,_),_)=>true;
            case _=>false}):List[Definition]
41      val synchronizedvars = program.rightside.expressions.flatMap(x=>
            x match
42        {
43          case deff:Definition=>if(deff.leftside.description ==
                SynchronizedVariableT()) {Some(deff.leftside)} else
                {None};
44          case _=>None
45        }
46      ):List[DefLhs]
47      val nonProgramDefs = in.filter(x=>(x.leftside.description match
            {case ProgramT() => false; case _=> true}))
48      val othererrors = checkexpressions(nonProgramDefs, None,
            Some(implicitargs++synchronizedvars), basicFunctions)
49
50       programerrors++othererrors
51    }
52
53    def checkprogram(program:Definition, topleveldefs:List[DefLhs],
          basicFunctions:List[DefLhs]): List[FumurtError]=
54    {
55      def checkuseofthread(program:Definition,
            thread:DefLhs):List[FumurtError]=
```

```
56      {
57        thread.description match
58        {
59          case ThreadT() => program.rightside.expressions.find(y=>y
                match{case FunctionCallStatement(thread.id.value, _) =>
                true; case _=>false})
60            match
61            {
62              case Some(_)=> List();
63              case None=> List(FumurtError(Global, "thread
                    "+thread.id.value+" is declared but not used"))
64            }
65          case _=> List()
66        }
67      }
68      val unusedthreaderrors:List[FumurtError] =
            topleveldefs.foldLeft(List():
            List[FumurtError])((x:List[FumurtError], y:DefLhs)=>
69        x++checkuseofthread(program,y)
70      ):List[FumurtError]
71
72      val lefts = indexlefts(program.rightside.expressions)
73      val unsuitableexpressions =
            program.rightside.expressions.foldLeft(List():
            List[FumurtError])( (x,y)=>
74        y match
75        {
76          case z:Definition=>
77          {
78            z.leftside.description match
79            {
80              case SynchronizedVariableT() =>
81              {
82                if(z.rightside.expressions.length !=
                      1){x++List(FumurtError(z.pos, "only single call to
                      synchronized permitted"))}
83                else
84                {
85                  val synchcall = z.rightside.expressions(0)
86                  val signatureerror =
87                  synchcall match
88                  {
89                    case FunctionCallStatement( "synchronized",
                          Right(NamedCallargs(List(
                          NamedCallarg(IdT("variable"),
                          variablearg:Callarg),
                          NamedCallarg(IdT("writer"),writerarg:
                          Callarg))))) =>
90                    {
91                      x++checkCallarg(z.leftside.returntype,
                            variablearg, IdT("variable"),
                            program.leftside, None, basicFunctions,
                            List()) //TODO: make sure that writer is a
                            thread that exists.
92                    }
93                    case _=>x++List(FumurtError(synchcall.pos, "must be
                          call to synchronized with \"variable\" and
```

```
                    \"writer\" arguments"))
94                }
95                x++signatureerror
96              }
97
98            }
99            case _=> x++List(FumurtError(z.pos,"Do not define
                  functions, actions or unsynchronized values in
                  Program"))
100         }
101       }
102       case z:FunctionCallStatement=>
103       {
104         if(!z.functionidentifier.startsWith("thread")) {x ++
              List(FumurtError(z.pos, "Only threads can be called in
              Program"))}
105         else
106         {
107           x++checkstatement(z, program.leftside, None,
                basicFunctions, lefts++topleveldefs, TypeT("Nothing"))
108         }
109
110       }
111       case z:Expression=>x++List(FumurtError(z.pos, "Only
            definitions and thread start statements allowed in
            Program"))
112     }
113   )
114   //println(program.rightside.expressions)
115   //println("unsuit "+(unusedthreaderrors ++
          unsuitabledefinitions.toList))
116
117   (unusedthreaderrors ++
          unsuitableexpressions.toList):List[FumurtError]
118 }
119
120 def checkexpressions(tree:List[Expression],
      containingdefinition:Option[Definition],
      containingdefinitionarguments:Option[List[DefLhs]],
      basicFunctions:List[DefLhs]):List[FumurtError]=
121 {
122   val insamedefinition = indexlefts(tree)
123   //println("\nin checkexpressions:   insamedefinition is
          "+insamedefinition+" containingdefinition is
          "+containingdefinition)
124   tree.foldLeft(List():List[FumurtError])((x,y) =>x
          ++checkexpression(y, containingdefinition,
          containingdefinitionarguments, basicFunctions,
          insamedefinition))
125 }
126
127 def checkexpression(tocheck:Expression,
      containingdefinition:Option[Definition],
      arguments:Option[List[DefLhs]], basicFunctions:List[DefLhs],
      inSameDefinition:List[DefLhs]):List[FumurtError] =
128 {
```

```
129     //println("\nIn checkexpression:   tocheck:
            "+tocheck+"containingdefinition: "+containingdefinition+"
            arguments: "+arguments)
130     tocheck match
131     {
132       case x:Definition=>
133       {
134         val (newargs, argpropagationerrors) = x.leftside.args match
135         {
136           case None => (List(), List())
137           case Some(Arguments(args)) =>
138           {
139             val hits = arguments match
140             {
141               case Some(contargs) => args.flatMap(arg =>
                      (contargs++inSameDefinition).find(y =>
                      y.id.value==arg.id.value))
142               case None => args.flatMap(arg =>
                      inSameDefinition.find(y =>
                      y.id.value==arg.id.value))
143             }
144             if (hits.length == args.length)      //used to be !=.
                    Don't know why. bug?
145             {
146               (hits, List())
147             }
148             else
149             {
150
151               //(hits, List(FumurtError(x.pos,"One or more arguments
                      not found in local scope"))) TODO: Find better
                      solution than just abandoning compile time
                      dependent checking. Checking for each function call
                      might be possible...
152               (hits,List())
153             }
154           }
155         }
156         checkdefinition(x, containingdefinition.map(x=>x.leftside),
                Some(newargs), basicFunctions) ++ argpropagationerrors
157       }
158       case x:Statement => containingdefinition match
159       {
160         case None => List(FumurtError(x.pos, "Statements must be
                enclosed in either Program or another definition"))
161         case Some(contdef) => /*println("\n"+x);*/ checkstatement(x,
                contdef.leftside, arguments, basicFunctions,
                inSameDefinition, contdef.leftside.returntype)
162       }
163     }
164   }
165
166   def checkstatement(tocheck:Statement, containingdefinition:DefLhs,
          arguments:Option[List[DefLhs]], basicFunctions:List[DefLhs],
          inSameDefinition:List[DefLhs], expectedreturn:TypeT):
          List[FumurtError]=
167   {
```

```
168     //println("\nIn checkstatement:   tocheck:
            "+tocheck+"containingdefinition: "+containingdefinition+"
            arguments: "+arguments)
169     tocheck match
170     {
171       case b:BasicValueStatement=>
              checkbasicvaluestatement(expectedreturn, b, "Return")
172       case b:IdentifierStatement=>
173       {
174         val statedvalue = findinscope(arguments, inSameDefinition,
                basicFunctions, Some(containingdefinition), b.value)
175         statedvalue match
176         {
177           case Left(string) => List(FumurtError(b.pos, /*"in
                  checkstatement "+*/string))
178           case Right(deflhs) =>
179           {
180             if(containingdefinition.returntype.value !=
                    deflhs.returntype.value)
181             {
182               List(FumurtError(b.pos, "expected: "
                      +expectedreturn.value+ ". Got: "
                      +deflhs.returntype.value))
183             }
184             else
185             {
186               List()
187             }
188           }
189         }
190       }
191       case y:FunctionCallStatement=>
192       {
193         //println("found "+y)
194         if (y.functionidentifier=="if")
195         {
196           checkifcall(y, expectedreturn, containingdefinition,
                  arguments, basicFunctions, inSameDefinition)
197         }
198         else if (y.functionidentifier=="plus" ||
                  y.functionidentifier=="minus" ||
                  y.functionidentifier=="multiply" ||
                  y.functionidentifier=="divide")
199         {
200           checkbasicmathcall(y, expectedreturn, containingdefinition,
                  arguments, basicFunctions, inSameDefinition)
201         }
202         else if (y.functionidentifier=="toString")
203         {
204           checktostringcall(y, expectedreturn, containingdefinition,
                  arguments, basicFunctions, inSameDefinition)
205         }
206         else if (y.functionidentifier=="actionMutate")
207         {
208           checkmutatecall(y, expectedreturn, containingdefinition,
                  arguments, basicFunctions, inSameDefinition)
209         }
```

```
210           else if (y.functionidentifier=="equal")
211           {
212             val reterror = if(expectedreturn!=TypeT("Boolean"))
                    {List(FumurtError(tocheck.pos, "Call to equal always
                    returns boolean, not
                    "+expectedreturn.value))}else{List()}
213             val argerrors = y.args match
214             {
215               case Right(NamedCallargs(List(NamedCallarg(IdT("left"),
                      leftargument), NamedCallarg(IdT("right"),
                      rightargument)))) =>
216               {
217                 List()
218               }
219
220               case _=>List(FumurtError(tocheck.pos, "Call to equal
                      requires two arguments named left and right"))
221             }
222             reterror++argerrors
223           }
224           /*else if (y.functionidentifier=="lessThan" || "biggerthan")
225           {
226             val reterror = if(expectedreturn!=TypeT("Boolean"))
                    {List(FumurtError(ifcall.pos, "Call to
                    "+y.functionidentifier+" always returns boolean, not
                    "+expectedreturn.value))} else{List()}
227           }
228           else if (y.functionidentifier=="not")
229           {
230             val reterror = if(expectedreturn!=TypeT("Boolean"))
                    {List(FumurtError(ifcall.pos, "Call to not always
                    returns boolean, not "+expectedreturn.value))}
                    else{List()}
231           }*/
232           else
233           {
234             findinscope(arguments, inSameDefinition, basicFunctions,
                    Some(containingdefinition), y.functionidentifier) match
235             {
236               case Left(string) => List(FumurtError(y.pos, /*"in
                      checkstatement_2 "+*/string))
237               case Right(calledfunction) =>
238               {
239                 val argumenterrors:List[FumurtError] = y.args match
240                 {
241                   case Left(NoArgs()) => calledfunction.args match
242                   {
243                     case None => List()
244                     case Some(_) => List(FumurtError(y.pos, "expected
                            arguments, but none were given"))
245                   }
246                   case Left(callarg) => calledfunction.args match
                          //checkCallarg(, callarg, containingdefinition,
                          arguments, basicFunctions, inSameDefinition)
247                   {
248                     case Some(Arguments(args)) =>
249                     {
```

```
250                     if (args.length != 1) { List(FumurtError(y.pos,
                            "expected "+args.length+" arguments, but only
                            one was given")) }
251                     else { checkCallarg(args(0).typestr, callarg,
                            args(0).id, containingdefinition, arguments,
                            basicFunctions, inSameDefinition) }
252                   }
253                   case None => List(FumurtError(y.pos, "expected no
                          arguments, but some were given"))
254                 }
255                 case Right(NamedCallargs(value)) =>
256                 {
257                   //println("checking namedcallargs "+value)
258                   checknamedcallargs(calledfunction, value,
                          containingdefinition, arguments,
                          basicFunctions, inSameDefinition)
259                 }
260               }
261               val returnerror:List[FumurtError] = if (expectedreturn
                      != calledfunction.returntype)
262               {
263                 List(FumurtError(y.pos, "Expected return type
                        "+expectedreturn.value+". Got
                        "+calledfunction.returntype.value/*+".
                        containingdefinition is"+containingdefinition*/))
264               }
265               else {List()}
266               returnerror ++ argumenterrors
267             }
268           }
269
270         }
271       }
272     }
273   }
274
275   def checkifcall(ifcall:FunctionCallStatement, expectedtype:TypeT,
          containingdefinition:DefLhs, arguments:Option[List[DefLhs]],
          basicFunctions:List[DefLhs],
          inSameDefinition:List[DefLhs]):List[FumurtError] =
276   {
277     ifcall.args match
278     {
279       case Left(callarg) => List(FumurtError(ifcall.pos, "Call to if
              needs three arguments"))
280       case Right(NamedCallargs(arglist))=>
281       {
282         if (arglist.length != 3)
283         {
284           List(FumurtError(ifcall.pos, "Call to if needs three
                  arguments"))
285         }
286         else
287         {
288           ( if(arglist(0).id.value !=
                  "condition"){List(FumurtError(ifcall.pos, "Call to if
                  needs a condition argument"))} else {List()} )++
```

```
289           ( if(arglist(1).id.value !=
                  "else"){List(FumurtError(ifcall.pos, "Call to if needs
                  an else argument"))} else {List()} )++
290           ( if(arglist(2).id.value !=
                  "then"){List(FumurtError(ifcall.pos, "Call to if needs
                  a then argument"))} else {List()} )++
291           checkCallarg(TypeT("Boolean"), arglist(0).argument,
                  IdT("condition"), containingdefinition, arguments,
                  basicFunctions, inSameDefinition)++
292           (checkCallarg(expectedtype, arglist(1).argument,
                  IdT("else"), containingdefinition, arguments,
                  basicFunctions, inSameDefinition))++
293           (checkCallarg(expectedtype, arglist(2).argument,
                  IdT("then"), containingdefinition, arguments,
                  basicFunctions, inSameDefinition))
294         }
295       }
296     }
297   }
298
299   def checkmutatecall(call:FunctionCallStatement, expectedtype:TypeT,
        containingdefinition:DefLhs, arguments:Option[List[DefLhs]],
        basicFunctions:List[DefLhs],
        inSameDefinition:List[DefLhs]):List[FumurtError] =
300   {
301     //println("mutate call "+call)
302     call.args match
303     {
304       case Left=>List(FumurtError(call.pos, "call to mutate requires
              both a variable, and a new value to assign to that
              variable"))
305       case Right(NamedCallargs(List(value:NamedCallarg,
              variable:NamedCallarg)))=>
306       {
307         val firstnameerror = if(value.id.value !=
                "newValue"){List(FumurtError(call.pos, "call to mutate
                requires argument \"newValue\""))} else{List()}
308         val lastnameerror = if(variable.id.value !=
                "variable"){List(FumurtError(call.pos, "call to mutate
                requires argument \"variable\""))} else{List()}
309         val variabletypeerror = variable.argument match
310         {
311           case z:IdentifierStatement=>
312           {
313             findinscope(arguments, inSameDefinition, basicFunctions,
                    Some(containingdefinition), z.value) match
314             {
315               case Left(str) => List(FumurtError(z.pos, str))
316               case Right(defl)=>
317               {
318                 (if (defl.description != SynchronizedVariableT())
                        {List(FumurtError(call.pos, "Variable must be
                        synchronized"))}else{List()})++
319                 (checkCallarg(defl.returntype, value.argument,
                        IdT("variable"), containingdefinition, arguments,
                        basicFunctions, inSameDefinition))
320               }
```

```
321             }
322           }
323           case z:Expression=>List(FumurtError(call.pos, "variable
                  argument must be an identifier"))
324         }
325
326         firstnameerror++lastnameerror++variabletypeerror
327       }
328     }
329   }
330
331   def checkbasicmathcall(call:FunctionCallStatement,
        expectedtype:TypeT, containingdefinition:DefLhs,
        arguments:Option[List[DefLhs]], basicFunctions:List[DefLhs],
        inSameDefinition:List[DefLhs]):List[FumurtError] =
332   {
333     //println("in checkbasicmathcall. Call is "+call)
334     call.args match
335     {
336       case Left(callarg) => List(FumurtError(call.pos, "Call to
              "+call.functionidentifier+" needs two arguments"))
337       case Right(NamedCallargs(arglist))=>
338       {
339         if (arglist.length != 2)
340         {
341           List(FumurtError(call.pos, "Call to
                  "+call.functionidentifier+" needs two arguments"))
342         }
343         else
344         {
345           val leftinterrors = checkCallarg(TypeT("Integer"),
                arglist(0).argument, IdT("left"), containingdefinition,
                arguments, basicFunctions, inSameDefinition)
346           val rightinterrors = checkCallarg(TypeT("Integer"),
                arglist(1).argument, IdT("right"),
                containingdefinition, arguments, basicFunctions,
                inSameDefinition)
347           val leftdoubleerrors = checkCallarg(TypeT("Double"),
                arglist(0).argument, IdT("left"), containingdefinition,
                arguments, basicFunctions, inSameDefinition)
348           val rightdoubleerrors = checkCallarg(TypeT("Double"),
                arglist(1).argument, IdT("right"),
                containingdefinition, arguments, basicFunctions,
                inSameDefinition)
349           val (lefterrors, leftdouble) = if (leftinterrors.length <
                leftdoubleerrors.length){(leftinterrors,false)} else
                {(leftdoubleerrors,true)}
350           val (righterrors, rightdouble) = if (rightinterrors.length
                < rightdoubleerrors.length){(rightinterrors,false)}
                else {(rightdoubleerrors,true)}
351           val returnsdouble = leftdouble || rightdouble
352           ( if(arglist(0).id.value !=
                "left"){List(FumurtError(call.pos, "Call to
                "+call.functionidentifier+" needs a left argument"))}
                else {List()} )++
353           ( if(arglist(1).id.value !=
                "right"){List(FumurtError(call.pos, "Call to
```

```
              "+call.functionidentifier+" needs a right argument"))}
              else {List()} )++
          ( lefterrors )++
          ( righterrors )++
          ( expectedtype match
            {
              case TypeT("Double")=>List();
              case TypeT("Integer") =>
                  if(returnsdouble){List(FumurtError(call.pos, "This
                  call to "+call.functionidentifier+" returns a
                  Double not an Integer"))} else{List()}
              case TypeT(str)=>
              {
                if(returnsdouble){List(FumurtError(call.pos, "This
                    call to "+call.functionidentifier+" returns a
                    Double not "+str))}
              else{List(FumurtError(call.pos, "This call to
                  "+call.functionidentifier+" returns an Integer
                  not "+str))}
              }
            }
          )
        }
      }
    }
  }

  def checktostringcall(call:FunctionCallStatement,
      expectedtype:TypeT, containingdefinition:DefLhs,
      arguments:Option[List[DefLhs]], basicFunctions:List[DefLhs],
      inSameDefinition:List[DefLhs]):List[FumurtError] =
  {
    call.args match
    {
      case Left(callarg) =>
      {
        val integererrors = checkCallarg(TypeT("Integer"), callarg,
            IdT("none needed as not user defined and single
            argument"), containingdefinition, arguments,
            basicFunctions, inSameDefinition)
        val doubleerrors = checkCallarg(TypeT("Double"), callarg,
            IdT("none needed as not user defined and single
            argument"), containingdefinition, arguments,
            basicFunctions, inSameDefinition)
        val argumenterrors = if(integererrors.length <
            doubleerrors.length){integererrors} else{doubleerrors}
        val outerrors = expectedtype match{ case
            TypeT("String")=>List(); case
            TypeT(str)=>List(FumurtError(call.pos, "toString returns
            String not "+str))}
        argumenterrors++outerrors
      }
      case Right(NamedCallargs(arglist))=>List(FumurtError(call.pos,
          "Call to toString needs one argument"))
    }
  }

```

```
388   def checknamedcallargs(calledfunction:DefLhs,
          namedcallargs:List[NamedCallarg], containingdefinition:DefLhs,
          arguments:Option[List[DefLhs]], basicFunctions:List[DefLhs],
          inSameDefinition:List[DefLhs]):List[FumurtError] =
389   {
390     calledfunction.args match
391     {
392       case None => List(FumurtError(namedcallargs(0).id.pos, "No
              arguments expected, but "+namedcallargs.length+" were
              given"))
393       case Some(Arguments(defargs)) =>
394       {
395         if (defargs.length != namedcallargs.length)
396         {
397           List(FumurtError(namedcallargs(0).id.pos, "expected
                "+defargs.length+" arguments. Got
                "+namedcallargs.length+" arguments"))
398         }
399         else
400         {
401           if( !namedcallargs.groupBy(x => x.id.value).filter(y =>
                y._2.length>1).isEmpty ) //ensure uniqueness of
                arguments
402           {
403             List(FumurtError(namedcallargs(0).id.pos, "two or more
                  arguments were given with the same name"))
404           }
405           else
406           {
407             val individualargumenterrors =
                    ListBuffer():ListBuffer[FumurtError]
408             for(i<-0 until namedcallargs.length)
409             {
410               individualargumenterrors ++=
                      (if(namedcallargs(i).id.value !=
                      defargs(i).id.value)
411                 {
412                   //println("FOUND INCORRECT NAMES")
413                   List(FumurtError(namedcallargs(i).id.pos, "Wrong
                        argument name. Argument in definition named
                        "+defargs(i).id.value+". In calling named
                        "+namedcallargs(i).id.value ))
414                 }
415                 else
416                 {
417                   checkCallarg(defargs(i).typestr,
                        namedcallargs(i).argument, defargs(i).id,
                        containingdefinition,
                        arguments:Option[List[DefLhs]],
                        basicFunctions:List[DefLhs],
                        inSameDefinition:List[DefLhs])
418                 }
419               )
420             }
421
422             //println("individualargumenterrors.toList:
                    "+individualargumenterrors.toList)
```

```
423             individualargumenterrors.toList
424           }
425         }
426       }
427     }
428   }
429
430   def checkCallarg(expectedtype:TypeT, arg:Callarg, id:IdT,
        containingdefinition:DefLhs, arguments:Option[List[DefLhs]],
        basicFunctions:List[DefLhs],
        inSameDefinition:List[DefLhs]):List[FumurtError] =
431   {
432     //println("in checkCallarg. arg is "+arg)
433     arg match
434     {
435       case c:BasicValueStatement=>
            checkbasicvaluestatement(expectedtype, c, "Call argument")
436       case c:NoArgs =>
437       {
438         println("NoArgs got checked by checkCallarg. This is better
              checked in checkstatement"); scala.sys.exit()
439       }
440       case c:IdentifierStatement =>
441       {
442         findinscope(arguments, inSameDefinition, basicFunctions,
              Some(containingdefinition), c.value) match
443         {
444           case Left(str) => List(FumurtError(c.pos, /*"in
                checkcallarg "+*/str))
445           case Right(thingdef) =>
446           {
447             if(expectedtype.value == "Inclusion")
448             {
449               if(thingdef.id.value != id.value)
450               {
451                 List(FumurtError(c.pos, "Passed inclusion must be the
                      same as the one referenced inside the function"))
452               }
453               else{List()}
454             }
455             else if(expectedtype.value != thingdef.returntype.value)
456             {
457               List(FumurtError(c.pos, "Expected type
                    "+expectedtype.value+". Got
                    "+thingdef.returntype.value))
458             }
459             else {List()}
460           }
461         }
462
463       }
464       case c:FunctionCallStatement =>
465       {
466         //check that call end result is correct
467
468         //check that call itself is correct
```

```
469         val callerrors = checkstatement(c, containingdefinition,
                arguments, basicFunctions, inSameDefinition, expectedtype)
470         callerrors //++ resulterrors
471       }
472     }
473   }
474
475   def checkbasicvaluestatement(expectedtype:TypeT,
        basicstatement:BasicValueStatement,
        role:String):List[FumurtError] =
476   {
477     basicstatement match
478     {
479       case c:StringStatement => {if (expectedtype.value != "String")
            List(FumurtError(c.pos, role+" type should be
            "+expectedtype.value+". "+role+" type was String")) else
            List()}
480       case c:IntegerStatement => {if (expectedtype.value !=
            "Integer") List(FumurtError(c.pos, role+" type should be
            "+expectedtype.value+". "+role+" type was Integer")) else
            List()}
481       case c:DoubleStatement => {if (expectedtype.value != "Double")
            List(FumurtError(c.pos, role+" type should be
            "+expectedtype.value+". "+role+" type was Double")) else
            List()}
482       case c:TrueStatement => {if (expectedtype.value != "Boolean")
            List(FumurtError(c.pos, role+" type should be
            "+expectedtype.value+". "+role+" type was Boolean")) else
            List()}
483       case c:FalseStatement => {if (expectedtype.value != "Boolean")
            List(FumurtError(c.pos, role+" type should be
            "+expectedtype.value+". "+role+" type was Boolean")) else
            List()}
484     }
485   }
486
487   def checkdefinition(tocheck:Definition,
        containingdefinition:Option[DefLhs],
        arguments:Option[List[DefLhs]], basicFunctions:List[DefLhs]):
        List[FumurtError]=
488   {
489     //println("\nIn checkdefinition:   tocheck:
          "+tocheck+"containingdefinition: "+containingdefinition+"
          arguments: "+arguments)
490     val undererrors = checkexpressions(tocheck.rightside.expressions,
          Some(tocheck), arguments, basicFunctions)
491     val threadenderror:List[FumurtError] =
          tocheck.leftside.description match
492     {
493       case ThreadT() => tocheck.rightside.expressions.last match
494       {
495         case FunctionCallStatement(functionidentifier,_) =>
496         {
497           if(functionidentifier != tocheck.leftside.id.value)
498           {
499             List(FumurtError(tocheck.rightside.expressions.last.pos,
                  "A thread must recurse on itself (at least until
```

```
                exit() is implemented)"))
500           }
501           else
502           {
503             List()
504           }
505         }
506         case _ =>
              List(FumurtError(tocheck.rightside.expressions.last.pos,
              "A thread must recurse on itself (at least until exit()
              is implemented)"))
507       }
508       case _ => List()
509     }
510     val nameerror = tocheck.leftside.description match
511     {
512       case ActionT() =>
            if(!tocheck.leftside.id.value.startsWith("action"))
            {List(FumurtError(tocheck.pos, "Name of action is not
            prefixed with \"action\""))} else{List()}
513       case ThreadT() =>
            if(!tocheck.leftside.id.value.startsWith("thread"))
            {List(FumurtError(tocheck.pos, "Name of thread is not
            prefixed with \"thread\""))} else{List()}
514       case FunctionT() => List()
515       case ValueT() => List()
516       case ProgramT() => println("Program got checked by
            checkdefinition. This is better checked in checkprogram");
            scala.sys.exit()
517     }
518     val permissionerror = tocheck.leftside.description match
519     {
520       case ActionT() => containingdefinition match
521       {
522         case None=>List()
523         case Some(DefLhs(ValueT(),_,_,_))=>
              List(FumurtError(tocheck.pos, "actions cannot be defined
              in values"))
524         case Some(DefLhs(FunctionT(),_,_,_))=>
              List(FumurtError(tocheck.pos, "actions cannot be defined
              in  functions"))
525         case Some(something) => List()
526       }
527       case ThreadT() => containingdefinition match{ case None =>
            List(); case Some(_)=>List(FumurtError(tocheck.pos,
            "threads must be defined on top "+containingdefinition))}
528       case FunctionT() => containingdefinition match{ case
            Some(DefLhs(ValueT(),_,_,_)) =>
            List(FumurtError(tocheck.pos, "functions cannot be defined
            in values")); case _=> List()}
529       case SynchronizedVariableT() => List(FumurtError(tocheck.pos,
            "synchronized variables must be defined in Program
            definition"))
530       case ValueT() => List()
531       case ProgramT() => println("Program got checked by
            checkdefinition. This is better checked in checkprogram");
            scala.sys.exit()
```

```
532       }
533
534       undererrors.toList ++ nameerror ++ permissionerror ++
              threadenderror
535     }
536
537
538     def indexlefts(in:List[Expression]):List[DefLhs]=
539     {
540       in.foldLeft(List():List[DefLhs]) ((list,y)=> y match
541         {
542           case Definition(leftside, _)=>list :+ leftside;
543           case _:Statement=> list
544         }
545       )
546     }
547
548     def findinscope(arguments:Option[List[DefLhs]],
          inSameDefinition:List[DefLhs], basicfunctions:List[DefLhs],
          enclosingDefinition:Option[DefLhs],
          searchFor:String):Either[String, DefLhs]=
549     {
550       val argsres = arguments match{ case
              Some(args)=>args.filter(y=>y.id.value==searchFor); case
              None=>List():List[DefLhs]}
551       val inscoperes = inSameDefinition.filter(x=>x.id.value==searchFor)
552       //println()
553       //println(basicfunctions)
554       //println()
555       val basicfunctionres =
              basicfunctions.filter(x=>x.id.value==searchFor)
556
557       val enclosingres = enclosingDefinition match
558       {
559         case None => List()
560         case Some(deff) => if (deff.id.value == searchFor) {List(deff)}
                else {List()}
561       }
562
563       val res = argsres ++ inscoperes ++ basicfunctionres ++
              enclosingres
564
565       if(res.length == 1)
566       {
567         Right(res.head)
568       }
569       else if(res.length>1)
570       {
571         Left("Ambiguous reference to "+searchFor)
572       }
573       else if(res.length == 0)
574       {
575         enclosingDefinition match
576         {
577           case None=>Left(searchFor+" not found" /*+" arguments is:
                  "+arguments+". insamedefinition is "+inSameDefinition*/)
578           case Some(DefLhs(_,_,Some(Arguments(internalargs)),_))=>
```

```
579           {
580             internalargs.find(x=>x.id.value==searchFor) match
581             {
582               case Some(Argument(id, TypeT("Inclusion")))=>
                      Left(searchFor+" not found" /*+" arguments is:
                      "+arguments+". insamedefinition is
                      "+inSameDefinition*/)
583               case Some(Argument(id, typestr))=>
                      Right(DefLhs(ValueT(),id,None,typestr))
584               case None=>Left(searchFor+" not found" /*+" arguments is:
                      "+arguments+". insamedefinition is
                      "+inSameDefinition*/)
585             }
586           }
587           case Some(_)=> Left(searchFor+" not found" /*+" arguments is:
                  "+arguments+". insamedefinition is "+inSameDefinition*/)
588       }
589     }
590     else
591     {
592       Left("error in search for "+searchFor)
593     }
594   }
595
596 }
597
598
599
600
601 //TODO: add type for synchronized variables and use it to pass them
      around, so that it can be controlled that a thread calling
      actionMutate has write rights
```

## C.7 CodeGenerator.scala

```
1  package fumurtCompiler
2
3  import scala.collection.mutable.ListBuffer
4
5  object FumurtCodeGenerator
6  {
7    def generate(ast:List[Definition]):String =
8    {
9      val includestatement = "#include <iostream>\n#include
           <thread>\n#include <string>\n#include <atomic>\n#include
           <condition_variable>\n#include <list>\n#include
           <chrono>\n\n\n"
10     val topthreads = gettopthreadstatements(ast)
11     val atree = getAnnotatedTree(ast, topthreads)
12     //println(atree)
13     val numtopthreads = topthreads.length
14     val synchronizationGlobalVars = "static std::atomic<int>
           rendezvousCounter;\nstatic std::mutex
           rendezvousSyncMutex;\nstatic std::condition_variable cv;"
```

```
15      val main = getmain(topthreads, atree)
16      val synchvars = getsynchronizedvariables(ast)
17      val syncfunc = getsynchronizerfunction(synchvars, topthreads)
18      val synchvardeclarations =
            getGlobalSynchVariableDeclarations(synchvars)
19      val printdecs = getprintlistdeclarations(topthreads)
20      //val topthreaddeclarations = gettopthreaddeclarations(ast)
21      val (funSignatures, funDeclarations) =
            getFunctionDeclarations(atree)
22      val staticthreadargs =
            getStaticThreadArgs(atree:List[aExpression])
23      val topThreadNumMacroln = "#define NUMTOPTHREADS " +
            numtopthreads.toString + "\n"
24
25      //println(funSignatures)
26
27      includestatement + topThreadNumMacroln + funSignatures + "\n" +
            synchvardeclarations + printdecs + "\n" +
            synchronizationGlobalVars + staticthreadargs + syncfunc +
            "\n\n" /*+ topthreaddeclarations*/ + "\n"+ funDeclarations +
            "\n\n" + main
28    }
29
30
31    def getAnnotatedTree(ast:List[Expression],
          topthreadcalls:List[FunctionCallStatement]):List[aExpression] =
32    {
33      val treeWithAnnotatedDefinitions =
            getAnnotatedTreeInternal(ast,topthreadcalls,"", None)
34      getCallsAnnotatedTreeInternal(treeWithAnnotatedDefinitions,
            List(), None)
35    }
36
37    def getCallsAnnotatedTreeInternal(ast:List[aExpression],
          arguments:List[aDefLhs],
          containingDefinition:Option[aDefinition]):List[aExpression] =
38    {
39      val inSameDefinition = indexlefts(ast)
40
41      ast.flatMap(node=>node match
42        {
43          case deff @ aDefinition(aDefLhs(desc, id, cppid,
                callingthread, args, returntype), aDefRhs(expressions))=>
44          {
45            val argumentsToDef = args match
46            {
47              case None => List()
48              case Some(aArguments(arglist)) => arglist.flatMap(arg =>
49                  {
50                    val fromargs =
                          arguments.find(x=>x.id.value==arg.id.value)
51                    val fromSame = inSameDefinition.find(x =>
                          x.id.value == arg.id.value)
52                    fromargs match
53                    {
54                      case Some(_)=>fromargs
55                      case None=>fromSame
```

```
56                  }
57                }
58              )
59          }
60          //println("\n{deff: "+deff+"\nargumentsToDef:
                "+argumentsToDef+"\nargs: "+args+"\n\nast:
                "+ast+"\n\narguments: "+arguments+"}\n\n\n")
61          val aexpressions =
                getCallsAnnotatedTreeInternal(expressions,
                argumentsToDef, Some(deff))
62          Some(aDefinition(aDefLhs(desc, id, cppid, callingthread,
                args, returntype), aDefRhs(aexpressions)))
63        }
64        case call @ aFunctionCallStatement(fid,_,args,_) =>
              Some(annotateFunctionCall(call, arguments,
              inSameDefinition, containingDefinition))
65        case z:IdentifierStatement=>Some(z)
66        case z:BasicValueStatement=>Some(z)
67      }
68    )
69  }
70
71  def annotateFunctionCall( functioncall:aFunctionCallStatement,
      arguments:List[aDefLhs], inSameDefinition:List[aDefLhs],
      containingDefinition:Option[aDefinition] ):
      aFunctionCallStatement=
72  {
73
74    def annotateCallargs(args: Either[aCallarg,aNamedCallargs],
        arguments:List[aDefLhs], inSameDefinition:List[aDefLhs],
        containingDefinition:Option[aDefinition]):
        Either[aCallarg,aNamedCallargs] =
75    {
76      args match
77      {
78        case Left(callarg)=>callarg match
79        {
80          case z:aFunctionCallStatement=>Left(annotateFunctionCall(z,
                arguments, inSameDefinition, containingDefinition))
81          case z:aStatement=>Left(z)
82        }
83        case Right(aNamedCallargs(callargs)) =>
              Right(aNamedCallargs(callargs.map(namedcallarg =>
              namedcallarg.argument match
84          {
85            case z:aFunctionCallStatement =>
                  aNamedCallarg(namedcallarg.id,
                  annotateFunctionCall(z, arguments, inSameDefinition,
                  containingDefinition))
86            case aCallarg=>namedcallarg:aNamedCallarg
87          }
88        )))
89      }
90    }
91
92    val fid = functioncall.functionidentifier
93    val args = functioncall.args
```

```
94      if(fid=="actionPrint" || fid=="toString" || fid=="actionMutate")
95      {
96        val newargs = annotateCallargs(args, arguments,
              inSameDefinition, containingDefinition)
97        aFunctionCallStatement(fid,fid,newargs,"Nothing")
98      }
99      else if(fid=="plus" || fid=="minus" || fid=="multiply" ||
            fid=="divide")
100     {
101       val newargs = annotateCallargs(args, arguments,
              inSameDefinition, containingDefinition)
102       aFunctionCallStatement(fid,fid,newargs,"Number") //TODO: Find
              actual type like in typechecker. As it is, it only matters
              if it is Nothing or not.
103     }
104     else if(fid=="equal" || fid=="lessThan")
105     {
106       val newargs = annotateCallargs(args, arguments,
              inSameDefinition, containingDefinition)
107       aFunctionCallStatement(fid,fid,newargs,"Boolean")
108     }
109     else if(fid=="if")
110     {
111       val newargs = annotateCallargs(args, arguments,
              inSameDefinition, containingDefinition)
112       aFunctionCallStatement(fid,fid,newargs,"Something") //TODO:
              Find actual type like in typechecker. As it is, it only
              matters if it is Nothing or not.
113     }
114     else
115     {
116       def removeInclusions(args: Either[aCallarg,aNamedCallargs],
              ldeffargs:Option[aArguments]):
              Either[aCallarg,aNamedCallargs] = args match
117       {
118         case Left(callarg)=>
119         {
120           ldeffargs match
121           {
122             case Some(aArguments(defargs))=>
123             {
124               if(defargs.head.typestr.value == "Inclusion")
                      {Left(NoArgs())}
125               else
126               {
127                 args
128               }
129             }
130             case None=>Left(NoArgs())
131             //case _=>Left(NoArgs())
132           }
133         }
134         case Right(aNamedCallargs(namedcallargs))=>
135         {
136           ldeffargs match
137           {
138             case Some(aArguments(defargs))=>
```

```
139             {
140               val mnewargs = ListBuffer():ListBuffer[aNamedCallarg]
141               for(i<-0 until defargs.length)
142               {
143                 if(defargs(i).typestr.value!="Inclusion")
144                 {
145                   mnewargs += namedcallargs(i)
146                 }
147               }
148               Right(aNamedCallargs(mnewargs.toList))
149             }
150             case None=>println("in
                    getCallsAnnotatedTreeInternal");scala.sys.exit()
151             //case _=>Left(NoArgs())
152           }
153         }
154       }
155       val ldeff = findinscope(Some(arguments), inSameDefinition,
              containingDefinition.map(x=>x.leftside), fid)
156       val newargs = annotateCallargs(removeInclusions(args,
              ldeff.args), arguments, inSameDefinition,
              containingDefinition)
157       //println("ldeff.cppid.value: "+ldeff.cppid.value)
158       aFunctionCallStatement(fid, ldeff.cppid.value, newargs,
              ldeff.returntype.value)
159     }
160   }
161
162   def indexlefts(in:List[aExpression]):List[aDefLhs]=
163   {
164     in.foldLeft(List():List[aDefLhs]) ((list,y)=> y match
165       {
166         case aDefinition(leftside, _)=>list :+ leftside;
167         case _=> list
168       }
169     )
170   }
171
172   def findinscope(arguments:Option[List[aDefLhs]],
          inSameDefinition:List[aDefLhs],
          enclosingDefinition:Option[aDefLhs], searchFor:String):aDefLhs=
173   {
174     val argsres = arguments match{ case
            Some(args)=>args.filter(y=>y.id.value==searchFor); case
            None=>List():List[aDefLhs]}
175     val inscoperes = inSameDefinition.filter(x=>x.id.value==searchFor)
176
177     val enclosingres = enclosingDefinition match
178     {
179       case None => List()
180       case Some(deff) => if (deff.id.value == searchFor) {List(deff)}
              else {List()}
181     }
182
183     val res = argsres ++ inscoperes ++ enclosingres
184
```

```
185     if(res.length==0){println("{arguments:
            "+arguments+"\n\ninSameDefinition:
            "+inSameDefinition+"\n\nenclosingDefinition:
            "+enclosingDefinition+"\n\nsearchFor:
            "+searchFor+"}\n\n\n");scala.sys.exit()}
186     res.head
187   }
188
189   def getAnnotatedTreeInternal(ast:List[Expression],
          topthreadcalls:List[FunctionCallStatement], hierarchy:String,
          callingthread:Option[String]):List[aExpression] =
190   {
191     val topactions:List[aExpression] =
192     {
193       if(hierarchy=="")
194       {
195         val mess = topthreadcalls.map(threadcall=>threadcall.args
              match
196           {
197             case Left(IdentifierStatement(argname)) =>
198             {
199               val deff = ast.filter(x => x match {case
                      Definition(DefLhs(ActionT(), IdT(thisargname), _,
                      _),_) =>argname==thisargname; case _=> false})
200               getAnnotatedTreeInternal(deff, List(),
                      threadcall.functionidentifier,
                      Some(threadcall.functionidentifier)):
                      List[aExpression]
201             }
202             case Left(_)=> List():List[aExpression]
203             case Right(NamedCallargs(namedargs))=>
204             {
205               val deffs = namedargs.flatMap(namedarg=>
206                 namedarg match
207                 {
208                   case NamedCallarg(_,IdentifierStatement(argname))=>
209                   {
210                     ast.find(y=>y match{case
                            Definition(DefLhs(ActionT(),
                            IdT(thisargname), _, _) ,_) => argname ==
                            thisargname; case _=> false})
211                   }
212                   case _=>None
213                 }
214               )
215               getAnnotatedTreeInternal(deffs,List(),
                      threadcall.functionidentifier,
                      Some(threadcall.functionidentifier)):
                      List[aExpression]
216             }
217           }
218         ):List[List[aExpression]]
219
220         mess.foldLeft(List(): List[aExpression])((x,y) => x++y):
              List[aExpression]
221       }
222       else
```

```
223       {
224         List()
225       }
226     }
227     val rest:List[aExpression] = ast.flatMap(x=>x match
228       {
229         case Definition(DefLhs(ThreadT(), id, args, returntype),
                DefRhs(expressions)) =>
230         {
231           val aexps = getAnnotatedTreeInternal(expressions,
                topthreadcalls.filter(x => x.functionidentifier ==
                id.value), id.value, Some(id.value))
232           //println("\n"+args+"\n\n")
233           val newargs =
                args.map(args=>aArguments(args.args.map(arg=>arg match
234             {
235               case Argument(id, TypeT("Inclusion")) =>
                    aArgument(id, id, TypeT("Inclusion"))
236               case Argument(argid, typee) =>
237               {
238                 if (argid.value.startsWith("synchronized"))
239                 {
240                   aArgument(argid, argid, typee)
241                 }
242                 else
243                 {
244                   aArgument(argid, IdT(id.value+"$"+argid.value),
                        typee)
245                 }
246               }
247             }
248           )
249         )
250       )
251       //println(newargs+"\n\n\n")
252       Some(aDefinition(aDefLhs(ThreadT(), id, id, id.value,
            newargs, returntype),aDefRhs(aexps)))
253       }
254
255       case Definition(DefLhs(FunctionT(), id, args, returntype),
            DefRhs(expressions)) =>
256       {
257         val aexps = getAnnotatedTreeInternal(expressions,
              topthreadcalls, hierarchy+id.value, callingthread)
258         val newargs = args.map(args=>aArguments(args.args.map(arg
              => aArgument(arg.id, arg.id, arg.typestr))))
259         Some(aDefinition(aDefLhs(FunctionT(), id,
              IdT(id.value+"$"+hierarchy), "shouldn't matter",
              newargs, returntype), aDefRhs(aexps)))
260       }
261       case Definition(DefLhs(ProgramT(),_,_,_),_) => None //we
            don't really care about it...
262       case Definition(DefLhs(ActionT(), id, args, returntype),
            DefRhs(expressions)) =>
263       {
264         if(hierarchy=="")
265         {
```

```
266             None
267           }
268           else
269           {
270             val aexps = getAnnotatedTreeInternal(expressions,
                    topthreadcalls, hierarchy+id.value, callingthread)
271             val newargs = args.map(args=>aArguments(args.args.map(arg
                    => aArgument(arg.id, arg.id, arg.typestr))))
272             Some(aDefinition(aDefLhs(ActionT(), id,
                    IdT(id.value+"$"+hierarchy), callingthread match
                    {case Some(z)=>z; case None=>"not found"}, newargs,
                    returntype), aDefRhs(aexps)))
273           }
274         }
275         case FunctionCallStatement(fid,args)=>
276         {
277           def annotateCallarg(callarg:Callarg):aCallarg=
278           {
279             callarg match
280             {
281               case z:aCallarg => z
282               case FunctionCallStatement(fid,args)=>
283               {
284                 val newargs:Either[aCallarg,aNamedCallargs] = args
                        match
285                 {
286                   case Left(arg)=>Left(annotateCallarg(arg))
287                   case Right(NamedCallargs(arglist)) =>
                          Right(aNamedCallargs(arglist.map(x =>
                          aNamedCallarg(x.id,
                          annotateCallarg(x.argument)) )))
288                 }
289                 aFunctionCallStatement(fid,"not filled
                        out",newargs,"not filled out")
290               }
291             }
292           }
293           Some(annotateCallarg(FunctionCallStatement(fid, args))):
                  Option[aExpression]
294         }
295         case z:IdentifierStatement=>Some(z)
296       }
297     ):List[aExpression]
298     rest++topactions
299
300   }
301
302   def getFunctionDeclarations(ast:List[aExpression]):(String,String) =
303   {
304     def actfunrecursivetranslate(cppid:IdT, callingthread:String,
          args:Option[aArguments], returntype:TypeT,
          expressions:List[aExpression]):Option[(String,String)] =
305     {
306       val signature = getFunctionSignature(cppid, args, returntype)
307       val functionstart = signature+"\n{"
308       val functionend = "\n}\n"
309       val generals = expressions.flatMap(
```

```
310         y=> y match
311         {
312           case aDefinition(leftside, rightside)=>None
313           case z:aFunctionCallStatement =>
314           {
315             if(z.returntype!="Nothing")
316             {
317               Some("return "+functioncalltranslator(z, callingthread)
                      + "; //returntype: "+z.returntype)
318             }
319             else
320             {
321               Some(functioncalltranslator(z, callingthread) + ";")
322             }
323
324           }
325           case IdentifierStatement(value) => Some("return "+value+";")
326           case StringStatement(value) => Some("return "+value+";")
327           case IntegerStatement(value) => Some("return
                  "+value.toString+";")
328           case DoubleStatement(value) => Some("return
                  "+value.toString+";")
329           case TrueStatement() => Some("return true;")
330           case FalseStatement() => Some("return false;")
331           //case _=> "not implemented" //println("Error in
                  gettopthreaddeclarations. Not implemented.");
                  scala.sys.exit()
332         }
333       ).foldLeft("")((x,y)=>x+"\n  "+y)
334       val underfunctions = getFunctionDeclarations(expressions)
335       val body = functionstart+generals+functionend
336       //Some((signature+";",body))
337       Some((signature+";"+underfunctions._1, body+underfunctions._2))
338     }
339
340     val list = ast.flatMap(node=>node match
341       {
342         case aDefinition(aDefLhs(ThreadT(), id, cppid, _, args, _),
                aDefRhs(expressions)) =>
343         {
344           val attributeNoreturn = if(
                  System.getProperty("os.name").startsWith("Windows") )
                  {"__declspec(noreturn)"} else{"[[noreturn]]"}
                  //Microsoft Visual C++ does not support C++11 attribute
                  syntax
345           val signature = attributeNoreturn+" static void
                  "+cppid.value+"()"
346           val functionstart = signature+"\n{"
347           val functionend = "\n}\n"
348           val (tailrecursestart, tailrecurseend) = ("while(true)\n{",
                  "\n}")
349
350           def changeNamesToCppOnes(in:aCallarg,
                  threadargs:Option[aArguments]):aCallarg = in match
351             {
352               case call:aFunctionCallStatement=>
353               {
```

```
354                     val newargs:Either[aCallarg,aNamedCallargs] =
                            call.args match
355                     {
356                       case Left(callarg) =>
                              Left(changeNamesToCppOnes(callarg,
                              threadargs))
357                       case Right(aNamedCallargs(namedcallargs)) =>
                              Right(aNamedCallargs(namedcallargs.map(
                              namedcallarg =>
                              aNamedCallarg(namedcallarg.id,
                              changeNamesToCppOnes(
                              namedcallarg.argument, threadargs )))) )
358                     }
359                     aFunctionCallStatement(call.functionidentifier,
                            call.cppfunctionidentifier, newargs,
                            call.returntype)
360                   }
361                   case IdentifierStatement(value)=>
362                   {
363                     threadargs match
364                     {
365                       case None => IdentifierStatement(value)
366                       case Some(aArguments(arglist)) =>
367                       {
368                         val arg = arglist.find(arg=>arg.id.value ==
                                value) match{case Some(x)=>x;case None =>
                                println("error in
                                functioncallargmodifier");
                                scala.sys.exit()}
369                         IdentifierStatement(arg.cppid.value)
370                       }
371                     }
372                   }
373                   case _=>in
374                 }
375
376             val generals = expressions.flatMap(
377               y=> y match
378               {
379                 case aDefinition(leftside, rightside)=>None
380                 case aFunctionCallStatement(id.value,_, callargs,_) =>
381                 {
382                   val updates = args match
383                   {
384                     case None => ""
385                     case Some(aArguments(List(aArgument(argid,
                            cppargid, _)))) =>
386                     {
387                       callargs match
388                       {
389                         case Left(callarg) =>
390                         {
391                           val newvalue = callargTranslator(callarg,
                                  id.value)
392                           if (argid.value.startsWith("synchronized"))
393                           {
```

```
394                         if( argid.value!=newvalue){"\nwe haven't
                                figured out the correct way to handle
                                this yet"}
395                         else{""}
396                       }
397                       else{"\n"+cppargid.value+" =
                              "+callargTranslator(
                              changeNamesToCppOnes(callarg, args),
                              id.value )+";\n"}
398
399                     }
400                     case Right(_)=>"error in generating updates1"
401                   }
402                 }
403                 case Some(aArguments(defargslist)) =>
404                 {
405                   callargs match
406                   {
407                     case Right(namedcallargs) =>
408                     {
409                       namedcallargs.value.foldLeft("\n")((l,r)=>
410                         {
411                           val newvalue =
                                callargTranslator(r.argument,
                                id.value)
412                           if( r.id.value.startsWith( "synchronized"
                                ) )
413                           {
414                             if (r.id.value.startsWith(
                                  "synchronized" ) && r.id.value !=
                                  newvalue) {l + "\nwe haven't
                                  figured out the correct way to
                                  handle this yet"}
415                             else{l}
416                           }
417                           else
418                           {
419                             val defarg = defargslist.find(defarg =>
                                  defarg.id.value == r.id.value)
                                  match{case Some(x) => x; case None
                                  => println("error in generating
                                  updates3"); scala.sys.exit()}
420                             l+defarg.cppid.value +" = "+
                                  callargTranslator(
                                  changeNamesToCppOnes( r.argument,
                                  args ) , id.value) + ";\n"
421                           }
422                         }
423                       )
424                     }
425                     case Left(_)=>"error in generating updates2"
426                   }
427                 }
428               }
429               Some("waitForRendezvous(\""+ cppid.value+"\");"
                      +updates+ "\n  continue;")
430           }
```

```
431                 case z:aFunctionCallStatement =>
432                 {
433                   val modified = changeNamesToCppOnes(z, args) match
434                   {
435                     case a:aFunctionCallStatement => a
436                     case _=> println("eror when modifying function
                            call");scala.sys.exit()
437                   }
438                   Some(functioncalltranslator(modified, id.value) + ";")
439                 }
440                 //case z:aFunctionCallStatement =>
                        Some(functioncalltranslator(z, id.value) + ";")
441                 //case _=> "not implemented" //println("Error in
                        gettopthreaddeclarations. Not implemented.");
                        scala.sys.exit()
442               }
443             ).foldLeft("")((x,y)=>x+"\n  "+y)
444             val underfunctions = getFunctionDeclarations(expressions)
445             val body = functionstart + tailrecursestart + generals +
                    tailrecurseend + functionend
446             Some((signature+";"+underfunctions._1,
                    body+underfunctions._2))
447
448           }
449           case z:aFunctionCallStatement=>None
450           case z:IdentifierStatement=>None
451           case aDefinition(aDefLhs(ActionT(), id, cppid, callingthread,
                  args, returntype), aDefRhs(expressions)) =>
                  actfunrecursivetranslate(cppid, callingthread, args,
                  returntype, expressions)
452           case aDefinition(aDefLhs(FunctionT(), id, cppid,
                  callingthread, args, returntype),aDefRhs(expressions)) =>
                  actfunrecursivetranslate(cppid, callingthread, args,
                  returntype, expressions)
453       }
454     ):List[(String,String)]
455     list.foldLeft(("",""))((x,y)=>(x._1+"\n"+y._1,x._2+"\n"+y._2))
456   }
457
458
459
460
461   def getFunctionSignature(cppid:IdT, optargs:Option[aArguments],
          returntype:TypeT):String =
462   {
463     def argtranslator(arg:aArgument):String=
464     {
465       typetranslator(arg.typestr)+" "+arg.id.value
466     }
467     val argsString = optargs match
468     {
469       case None=>""
470       case Some(aArguments(List(arg)))=>
471       {
472         if(arg.typestr.value!="Inclusion")
473         {
474           argtranslator(arg)
```

```
475         }
476         else{""}
477       }
478       case Some(aArguments(args))=>argtranslator(args.head) +
              args.tail.foldLeft("")((x,y)=>
479         if(y.typestr.value!="Inclusion"){x+", "+argtranslator(y)}
              else{x}
480       )
481
482     }
483
484     typetranslator(returntype)+" "+cppid.value+"("+argsString+")"
485   }
486
487   def typetranslator(in:TypeT):String =
488   {
489     in.value match
490     {
491       case "Integer"=>"int"
492       case "Double"=>"double"
493       case "String"=>"std::string"
494       case "Nothing"=>"void"
495       case "Inclusion"=>"shouldn't be here"
496       case "Boolean"=>"bool"
497       case _=>"not implemented"
498     }
499   }
500
501   def callargTranslator(callarg:aCallarg,
          callingthread:String):String =
502   {
503     callarg match
504     {
505       case StringStatement(value)=>value
506       case IntegerStatement(value)=>value.toString
507       case DoubleStatement(value)=>value.toString
508       case TrueStatement()=>"true"
509       case FalseStatement()=>"false"
510       case IdentifierStatement(value)=>value
511       case call:aFunctionCallStatement =>
            functioncalltranslator(call: aFunctionCallStatement,
            callingthread:String)
512       case NoArgs()=>""
513     }
514   }
515
516   def functioncalltranslator(call:aFunctionCallStatement,
          callingthread:String):String =
517   {
518     //println("in functioncalltranslator. call is "+call)
519     //if(call.functionidentifier=="plus"){println("found")}
520     //println("\n\n"+call)
521     call match
522     {
523       case aFunctionCallStatement("actionPrint",_,
            Left(StringStatement(value)),_) => "print" + callingthread
            + ".push_back(" + value + ")"
```

```
524         case aFunctionCallStatement("actionPrint",_,
                Left(IdentifierStatement(value)),_) => "print" +
                callingthread + ".push_back(std::to_string(" + value + "))"
525         case aFunctionCallStatement("actionPrint",_,
                Left(x:aFunctionCallStatement),_) => "print" +
                callingthread + ".push_back(" +
                functioncalltranslator(x,callingthread) + ")"
526         case aFunctionCallStatement("toString",_,
                Left(x:aFunctionCallStatement),_) => "std::to_string(" +
                functioncalltranslator(x,callingthread) + ")"
527         case aFunctionCallStatement("toString",_,
                Left(IdentifierStatement(value)),_) => "std::to_string(" +
                value + ")"
528         case aFunctionCallStatement("toString",_,
                Left(IntegerStatement(value)),_) => "std::to_string(" +
                value.toString + ")"
529         case aFunctionCallStatement("toString",_,
                Left(DoubleStatement(value)),_) => "std::to_string(" +
                value.toString + ")"
530         case aFunctionCallStatement("toString",_,
                Left(TrueStatement()),_) => "true"
531         case aFunctionCallStatement("toString",_,
                Left(FalseStatement()),_) => "false"
532         case aFunctionCallStatement("equal", _,
                Right(aNamedCallargs(List(aNamedCallarg(IdT("left"),
                IntegerStatement(left)), aNamedCallarg(IdT("right"),
                IdentifierStatement(right))))), _) => left.toString +" ==
                "+ right.toString
533         case aFunctionCallStatement("equal", _,
                Right(aNamedCallargs(List(aNamedCallarg(IdT("left"),
                IdentifierStatement(left)), aNamedCallarg(IdT("right"),
                IntegerStatement(right))))),_) => left.toString +" == "+
                right.toString
534         case aFunctionCallStatement("equal", _,
                Right(aNamedCallargs(List(aNamedCallarg(IdT("left"),
                StringStatement(left)), aNamedCallarg(IdT("right"),
                IdentifierStatement(right))))), _) => left.toString +" ==
                "+ right.toString
535         case aFunctionCallStatement("equal", _,
                Right(aNamedCallargs(List(aNamedCallarg(IdT("left"),
                IdentifierStatement(left)),
                aNamedCallarg(IdT("right"),StringStatement(right))))),_) =>
                left.toString+" == "+right.toString
536         case aFunctionCallStatement("equal", _,
                Right(aNamedCallargs(List(aNamedCallarg(IdT("left"),
                IdentifierStatement(left)), aNamedCallarg(IdT("right"),
                IdentifierStatement(right))))),_) => left.toString+" ==
                "+right.toString
537
538         case aFunctionCallStatement("equal", _,
                Right(aNamedCallargs(List(aNamedCallarg(IdT("left"),
                IntegerStatement(left)), aNamedCallarg(IdT("right"),x:
                aFunctionCallStatement)))),_) => left.toString+" ==
                "+functioncalltranslator(x, callingthread)
539         case aFunctionCallStatement("equal", _,
                Right(aNamedCallargs(List(aNamedCallarg(IdT("left"), x:
                aFunctionCallStatement), aNamedCallarg(IdT("right"),
```

```
            IntegerStatement(right))))), _) =>
            functioncalltranslator(x, callingthread) +" == "+
            right.toString
540       case aFunctionCallStatement("equal", _,
            Right(aNamedCallargs(List(aNamedCallarg(IdT("left"),
            StringStatement(left)),  aNamedCallarg(IdT("right"),
            x:aFunctionCallStatement)))), _) => left.toString+" ==
            "+functioncalltranslator(x, callingthread)
541       case aFunctionCallStatement("equal", _,
            Right(aNamedCallargs(List(aNamedCallarg(IdT("left"),
            x:aFunctionCallStatement), aNamedCallarg(IdT("right"),
            StringStatement(right))))), _) => functioncalltranslator(x,
            callingthread) +" == "+ right.toString
542       case aFunctionCallStatement("equal", _,
            Right(aNamedCallargs(List(aNamedCallarg(IdT("left"),
            x:aFunctionCallStatement), aNamedCallarg(IdT("right"),
            IdentifierStatement(right))))), _) =>
            functioncalltranslator(x, callingthread) +" == "+
            right.toString
543       case aFunctionCallStatement("equal", _,
            Right(aNamedCallargs(List(aNamedCallarg(IdT("left"),
            IdentifierStatement(left)), aNamedCallarg(IdT("right"),
            x:aFunctionCallStatement)))),_) => left.toString+" ==
            "+functioncalltranslator(x, callingthread)
544       case aFunctionCallStatement("equal", _,
            Right(aNamedCallargs(List(aNamedCallarg(IdT("left"),
            x:aFunctionCallStatement), aNamedCallarg(IdT("right"),
            y:aFunctionCallStatement)))),_) =>
            functioncalltranslator(x, callingthread) +" == "+
            functioncalltranslator(y, callingthread)
545
546       case aFunctionCallStatement("lessThan", _,
            Right(aNamedCallargs(List(aNamedCallarg(IdT("left"),
            IntegerStatement(left)), aNamedCallarg(IdT("right"),
            IntegerStatement(right))))),_) => left.toString +" <
            "+right.toString
547       //TODO: Make better solution for commutative functions
548       //TODO: add more types that the comparison functions can accept
549       case aFunctionCallStatement("actionMutate", _,
            Right(aNamedCallargs(List(aNamedCallarg(IdT("newValue"),
            IdentifierStatement(newval)),
            aNamedCallarg(IdT("variable"),
            IdentifierStatement(vari))))),_) => vari + " = " + newval
550       case aFunctionCallStatement("actionMutate", _,
            Right(aNamedCallargs(List(aNamedCallarg(IdT("newValue"),
            x:aFunctionCallStatement), aNamedCallarg(IdT("variable"),
            IdentifierStatement(vari))))), _) =>
551       {
552         "write" + vari.capitalize + " = " + functioncalltranslator(x,
              callingthread)
553       }
554       case aFunctionCallStatement("plus",_,_,_) =>
            basicmathcalltranslator(call, callingthread)
555       case aFunctionCallStatement("minus",_,_,_) =>
            basicmathcalltranslator(call, callingthread)
556       case aFunctionCallStatement("multiply",_,_,_) =>
            basicmathcalltranslator(call, callingthread)
```

```
557       case aFunctionCallStatement("divide",_,_,_) =>
              basicmathcalltranslator(call, callingthread)
558       case aFunctionCallStatement("if",_,
              Right(aNamedCallargs(List(aNamedCallarg(IdT("condition"),
              condstat), aNamedCallarg(IdT("else"), elsestat),
              aNamedCallarg(IdT("then"), thenstat)))), _) =>
559       {
560         def translator(in:aStatement):String=
561         {
562           in match
563           {
564             case TrueStatement()=>"true"
565             case FalseStatement()=>"false"
566             case StringStatement(value)=>value
567             case IntegerStatement(value)=>value.toString
568             case DoubleStatement(value)=>value.toString
569             case IdentifierStatement(value)=>value //Correct
                    behaviour? .....
570             case z:aFunctionCallStatement=>functioncalltranslator(z,
                    callingthread)
571           }
572         }
573         condstat match
574         {
575           case TrueStatement()=>translator(thenstat)
576           case FalseStatement()=>translator(elsestat)
577           case _=>
578           {
579             translator(condstat)+" ? "+translator(thenstat)+" :
                    "+translator(elsestat)
580           }
581         }
582       }
583       case aFunctionCallStatement(funcid,cppfuncid,args,_) =>
584       {
585         val argstr = args match
586           {
587             case Left(callarg)=>callargTranslator(callarg,
                    callingthread)
588             case Right(aNamedCallargs(args)) =>
589             {
590               val first = callargTranslator(args.head.argument,
                      callingthread)
591               val subsequent = args.foldLeft("")((x,y)=>x+",
                      "+callargTranslator(y.argument, callingthread))
592               first+subsequent
593             }
594           }
595         cppfuncid+"("+argstr+")"
596       }
597       case _=> "not implemented"
598     }
599   }
600
601   def basicmathcalltranslator(call:aFunctionCallStatement,
          callingthread:String):String=
602   {
```

```
603     val operator = if(call.functionidentifier=="plus"){" + "}else
            if(call.functionidentifier=="minus"){" - "}else
            if(call.functionidentifier=="multiply"){" * "}else
            if(call.functionidentifier=="minus"){" / "}
604     call match
605     {
606       case aFunctionCallStatement(_,_,
              Right(aNamedCallargs(callargs)),_) =>
607       {
608         val argstr = callargs.map(arg=>
609           {
610             arg match
611             {
612               case aNamedCallarg(_, IdentifierStatement(value)) =>
                      value
613               case aNamedCallarg(_, IntegerStatement(value)) =>
                      value.toString
614               case aNamedCallarg(_, DoubleStatement(value)) =>
                      value.toString
615               case aNamedCallarg(_, f:aFunctionCallStatement) =>
                      functioncalltranslator(f, callingthread)
616             }
617           }
618         ):List[String]
619         "(" + argstr(0) + operator + argstr(1) + ")"
620       }
621     }
622   }
623
624
625
626   def gettopthreadstatements(ast:List[Definition]):
          List[FunctionCallStatement] =
627   {
628     ast.find(x => (x.leftside.description match {case ProgramT() =>
          true; case _=> false})) match
629     {
630       case None => println("Error in getthreads. Should be caught by
              checker."); scala.sys.exit()
631       case Some(res) =>
632       {
633         res.rightside.expressions.flatMap(x => x match
634         {
635           case x:FunctionCallStatement => if
                  (x.functionidentifier.startsWith("thread")) {Some(x)}
                  else {None}
636           case _ => None
637         })
638       }
639     }
640   }
641
642   def getprintlistdeclarations(topthreads:
          List[FunctionCallStatement]): String=
643   {
644     val topthreadnames = topthreads.map(x=>x.functionidentifier)
645     var out = ""
```

```
646     for(i<-topthreadnames)
647     {
648       out += "\nstatic std::list<std::string> print"+i+";"
649     }
650     out
651   }
652
653   def getStaticThreadArgs(atree:List[aExpression]):String =
654   {
655     atree.flatMap(exp=>exp match
656       {
657         case aDefinition(aDefLhs(ThreadT(), _, _, _,
                Some(aArguments(args)), _), _) => Some(args.flatMap(arg =>
658             if (arg.typestr.value == "Inclusion" ||
                    arg.id.value.startsWith("synchronized"))
659             {
660               None
661             }
662             else
663             {
664               Some("static "+typetranslator(arg.typestr)+"
                        "+arg.cppid.value+";\n")
665             }
666           ).fold("")((l,r)=>l+r)
667         )
668         case _=> None
669       }
670     ).fold("\n")((l,r)=>l+r)
671
672   }
673
674   def getmain(topthreads:List[FunctionCallStatement],
        atree:List[aExpression]):String =
675   {
676     val threaddefls:List[aDefLhs] = atree.flatMap(exp=>exp match
677       {
678         case aDefinition(a @ aDefLhs(ThreadT(),_,_,_,_,_,_),_) =>
              Some(a)
679         case _=>None
680       }
681     )
682
683     val threadargsSet:String = topthreads.map(topthreadcall =>
684       {
685         val threaddefl = threaddefls.find(threaddefl =>
              threaddefl.id.value == topthreadcall.functionidentifier)
              match {case Some(x)=>x; case None=>println("error in
              getmain");scala.sys.exit()}
686         topthreadcall.args match
687         {
688           case Left(callarg) =>
689           {
690             threaddefl.args match
691             {
692               case None=>List("")
693               case Some(aArguments(List(defarg)))=>
694               {
```

```
695                 if (defarg.typestr.value == "Inclusion" ||
                        defarg.id.value.startsWith("synchronized"))
696                 {
697                   List("")
698                 }
699                 else
700                 {
701                   val modcallarg:aCallarg = callarg match
702                   {
703                     case a:aCallarg => a
704                     case _=>println("error in getmain2(should be
                            forbidden)");scala.sys.exit() //function
                            calls in assignment in program statement
                            doesn't make much sense and should be
                            forbidden
705                   }
706                   List(defarg.cppid.value+" =
                          "+callargTranslator(modcallarg:aCallarg,
                          "shouldn't be here")+";")
707                 }
708
709               }
710               case _=>println("error in getmain3");scala.sys.exit()
711             }
712           }
713           case Right(NamedCallargs(namedarglist)) =>
714           {
715             val defarglist = threaddefl.args match
716             {
717               case None => println("error in
                      getmain4");scala.sys.exit()
718               case Some(aArguments(defarglist))=>defarglist
719             }
720             namedarglist.foldLeft(List():List[String])((list,
                    namedarg)=>
721               {
722                 val modcallarg:aCallarg = namedarg.argument match
723                 {
724                   case a:aCallarg => a
725                   case _=>println("error in getmain5(should be
                          forbidden)");scala.sys.exit() //function calls
                          in assignment in program statement doesn't make
                          much sense and should be forbidden
726                 }
727                 val defarg = defarglist.find(defarg =>
                        defarg.id.value==namedarg.id.value) match {case
                        Some(x)=>x; case None=>println("error in
                        getmain6");scala.sys.exit()}
728                 if (defarg.typestr.value == "Inclusion" ||
                        defarg.id.value.startsWith("synchronized"))
729                 {
730                   list
731                 }
732                 else
733                 {
734                   list :+ (defarg.cppid.value+" =
                          "+callargTranslator(modcallarg:aCallarg,
```

```
                        "shouldn't be here")+";")
                }
              }
            )
          }
        }
    ).fold(List(): List[String]) ((llist,rlist) => llist ++
        rlist).foldLeft("\n") ((str,sublist) => if(sublist!="")
        {str+"\n"+sublist} else{str})

    var threadsStart = ""

    for(i<-topthreads)
    {
      threadsStart = threadsStart + "\n" + "std::thread t" +
          i.functionidentifier + " (" + i.functionidentifier + ");"
    }

    "int main()\n{\nrendezvousCounter.store(0);" + threadargsSet +
        threadsStart + "\nwhile(true)\n {\n
        std::this_thread::sleep_for(std::chrono::seconds(1)); \n}" +
        "\n}"
  }

  def getsynchronizerfunction(synchvariables:List[Definition],
      topthreads:List[FunctionCallStatement]):String=
  {
    var synchvariablestrings = ""

    for(i<-synchvariables)
    {
      val name = i.leftside.id.value
      synchvariablestrings += name + " = write" + name.capitalize +
          ";\n"
    }

    var printstatements = ""
    for(i<-topthreads)
    {
      val currentprintqueuename = "print" + i.functionidentifier
      printstatements += "while(!"+currentprintqueuename+".empty())
          {\nstd::cout << "+currentprintqueuename + ".front();
          \n"+currentprintqueuename+".pop_front(); \n}\n"
    }

    ("""static void waitForRendezvous(std::string name)
{
  std::unique_lock<std::mutex> lk(rendezvousSyncMutex);
  ++rendezvousCounter;
  if(rendezvousCounter.load() < NUMTOPTHREADS)
  {
    cv.wait(lk);
  }
  else if (rendezvousCounter.load() == NUMTOPTHREADS)
  {
    """
```

```
781       + printstatements + synchvariablestrings + """
782     {
783       rendezvousCounter.store(0);
784       cv.notify_all();
785     }
786   }
787   else
788   {
789     std::cout << "error in wait for " << name << ". Rendezvouscounter
          out of bounds. RedezvousCounter = " <<
          rendezvousCounter.load() << "\n";
790     exit(0);
791   }
792 }""")
793   }
794
795   def getGlobalSynchVariableDeclarations(synchvariables:
          List[Definition]): String=
796   {
797     var synchdeclares = ""
798     for(i<-synchvariables)
799     {
800       val fumurttype = i.leftside.returntype.value
801       val initialValue = i.rightside.expressions(0) match
802       {
803         case FunctionCallStatement(functionidentifier, args) => args
              match
804         {
805           case Right(namedcallargs) =>
                namedcallargs.value(0).argument match
806           {
807             case IntegerStatement(value) => value
808             //case DoubleStatement(value) => value
809             case _=> println("Error in
                  getGlobalSynchVariableDeclarations. Should be caught
                  by checker."); scala.sys.exit()
810           }
811           case _=> println("Error in
                getGlobalSynchVariableDeclarations. Should be caught by
                checker."); scala.sys.exit()
812         }
813         case _=> println(i.rightside.expressions(0).toString);
              println("Error in getGlobalSynchVariableDeclarations.
              Should be caught by checker."); scala.sys.exit()
814       }
815       if (fumurttype == "Integer")
816       {
817         synchdeclares += "\nstatic int " + i.leftside.id.value + " =
              " + initialValue + ";"
818         synchdeclares += "\nstatic int write" +
              i.leftside.id.value.capitalize + " = " + initialValue +
              ";"
819       }
820     }
821     synchdeclares
822   }
823
```

```
824   def getsynchronizedvariables(ast: List[Definition]):
          List[Definition] =
825   {
826     ast.find(x => (x.leftside.description match {case ProgramT() =>
          true; case _=> false})) match
827     {
828       case None => println("Error in getthreads. Should be caught by
            checker."); scala.sys.exit()
829       case Some(res) =>
830       {
831         res.rightside.expressions.flatMap(x => x match
832         {
833           case x:Definition => x.leftside.description match {case
                SynchronizedVariableT() => Some(x); case _=> None}
834           case _=> None
835         })
836       }
837     }
838   }
839
840 }
```

## C.8 Error.scala

```
1  package fumurtCompiler
2
3  import scala.util.parsing.input.Position
4  //import scala.util.parsing.input.NoPosition
5
6  case object Global extends Position
7  {
8    def column:Int = 0
9    def line:Int = 0
10   protected def lineContents:String = "global position"
11 }
12 case class Source(val line:Int, val column:Int, val
       lineContents:String) extends Position
13
14 case class FumurtError(val position:Position, val message:String)
15 {
16   override def toString:String=
17   {
18     position.toString + ": " + message + "\n" + position.longString +
         "\n"
19   }
20 }
```