CASM: Implementing an Abstract State Machine based Programming Language *

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Abstract: In this paper we present CASM, a general purpose programming language based on abstract state machines (ASMs). We describe the implementation of an interpreter and a compiler for the language. The demand for efficient execution forced us to modify the definition of ASM and we discuss the impact of those changes. A novel feature for ASM based languages is symbolic execution, which we briefly describe. CASM is used for instruction set simulator generation and for semantic description in a compiler verification project. We report on the experience of using the language in those two projects. Finally we position ASM based programming languages as an elegant combination of imperative and functional programming paradigms which may liberate us from the von Neumann style as demanded by John Backus.

1 Introduction

Most of the well known programming languages have a sequential execution semantics. Statements are executed in the order they appear in the source code of the program (imperative programming). The effects of a statement – changes to the program’s state – are evaluated before the next statement is considered. Examples of such programming languages are assembly languages, C, Java, Python and many more. Actually there are so many languages based on the imperative paradigm that it may even feel "natural".

However, there seems to be a demand for alternative programming systems. John Backus even asked whether programming can be liberated from the von Neumann style [Bac78]. John Hughes tries to convince the world that functional programming matters [Hug89]. Hudak et al. conclude that, although not used by the masses, aspects of functional programming are being incorporated into main stream imperative languages [HHPJW07]. Functional languages describe side-effect free application of functions to their arguments which makes them presumably easier to understand. They struggle to gain real-world

*This work is partially supported by the Austrian Research Promotion Agency (FFG) under contract 827485, Correct Compilers for Correct Application Specific Processors and Catena DSP GmbH.
acceptance however. While not claiming to be a representative source, but merely an indi-
cator, the popular source code repository hoster github¹ (more than 4 million repositories) lists no functional language amongst its 10 most popular ones. Actually, even assembly
languages (17th most popular) are more popular than Haskell (18th most popular with approx. 16000 projects using it) according to github’s language statistics.

In this paper we report on CASM a general purpose programming language based on Ab-
stract State Machines (ASMs). ASMs were introduced by Gurevich (originally named evolving algebras) in the Lipari Guide [Gur95]. One of the core concepts of ASM (as
the name indicates) is the state. Another core concept of ASM is the concept of a rule, which describes exactly how the state is changed by means of updates applied to the state. Application of a rule itself is side-effect free, one of the core concepts of functional pro-
gramming.

The CASM language was originally designed to describe programming language seman-
tics, a purpose for which ASMs are known to be well suited [SSB01, ZG97, Gau95, KP97,
Gle04, HS00, GH93]. We perform correctness proofs in a compiler verification project using symbolic execution. Having the ASM models of a machine language at hands it
suggests itself to reuse them for implementing an instruction set simulator [BHK10]. To
create a fast simulator we added a type system and developed a compiler for the CASM
language.

The remainder of this paper is structured as follows. Section 2 discusses previous work
on ASM based programming languages, in section 3 we describe the CASM language, section 4 briefly introduces the implemented type system, section 5 explains implementa-
tion details of the interpreter and compiler, in section 6 we report on our experience using CASM in various projects and section 7 finally concludes the paper and gives directions
for further work.

2 Related Work

The ASM method is well known and there have been quite a few efforts to create a widely
accepted framework for ASM tools. However, most of the projects ceased to exist. One
reason it seems to be so difficult to provide a generally accepted framework and language
for all ASM users may be the fact that ASM’s applications are so broad. On the one hand it is used to create very high level models [Bo03], and on the other it is used to model very
low level aspects of hardware (like we do). The demands of the users vary greatly and this
may be the reason there is quite a number of attempts to create ASM tools. In a sense this work adds to the misery, but it is driven by the very specific needs of compiler verifi-
cation (symbolic execution) and simulator synthesis (very fast performance). This section tries
to distinguish the CASM language from other ASM based languages.

Schmid introduced AsmGofer in [Sch01b]. AsmGofer is an interpreter for an ASM based
language. It is written in the Gofer² language (a subset of Haskell) and covers most of the

¹http://github.com
²http://web.cecs.pdx.edu/~mpj/goferarc/index.html
features described in the Lipari guide. The author notes however that the implementation is aimed at prototype modeling and too slow for performance critical applications.

Castillo describes the ASM Workbench in [Cas01]. Similar to CASM he added a type system to his language. The ASM Workbench is implemented in ML3 in an extensible way. Castillo describes an interpreter and a plugin for a model checker, which allows to translate certain restricted classes of abstract state machines to models for the SMV4 model checker.

Schmid also describes compiling ASM to C++ [Sch01a]. His compiler uses the ASM Workbench language as input. He proposes a double buffering technique avoiding collection update sets to increase runtime performance. There is no report of the achieved performance. CASM uses a so called pseudo state (more details are in section 5.1.3) to implement update sets efficiently.

Anlauf introduces XASM, a component based ASM language compiled to C [Anl00]. The novel feature of XASM is the introduction of a component model, allowing implementation of reusable components. XASM supports functions implemented in C using an extern keyword. CASM does not feature modularization, but can be extended using C code as well. XASM was used as the core of the gem-mex system, a graphical language for ASMs.

Farahbod designed CoreASM, an extensible ASM execution engine [FGG05]. The CoreASM project is actively maintained and early prototypes of our compiler verification proofs even used CoreASM. Unfortunately performance of the CoreASM interpreter is very poor, which ultimately lead to the development of CASM. Execution speed was increased by a factor of 3000 [LK12]. The CASM language is heavily inspired by the CoreASM language, but over time they have diverged.

3 The CASM language

In this section we introduce the most important aspects of the CASM language. The Lipari guide [Gur95] contains a formal definition of the constructs presented in this section. Also the CoreASM handbook may be a useful reference [Far] as CASM roots in the CoreASM language. In section 3.7 the most important differences between the two languages are pointed out.

3.1 State and Execution model

The state of an ASM is a so called static algebra over a set of universes (types) [Gur95]. These universes form a superuniverse X in which at least 3 distinct elements (true, false and undef) are defined. The state contains r-ary functions (mapping Xr to X) and relations

4http://www.cs.cmu.edu/~modelcheck/smv.html
(mapping \(X\) to true, false). For all locations of a function, unless not explicitly defined otherwise, the value undef is assigned. CASM programs describe a (potentially infinite) sequence of state changes by alternating calculation and application of update sets.

The state of a CASM program is formed by a number of functions (possibly 0). An example is given in listing 1.

```
function foo : -> Boolean
function bar : Int -> Int
```

Listing 1: A state

Function foo is a 0-ary function, and is very similar to a global boolean variable in common programming languages. Function bar is a 1-ary function, mapping an Int to another Int. This can be interpreted as an array, although there are no bounds and the function may be only partially defined. The special value undefined will be returned for all locations where bar is undefined. In that sense a 1-ary CASM function is more like a hash-map. The arguments to a function are called a location.

CASM programs are formulated as a set of rules. There is a top-level rule which will be executed repeatedly until the program terminates itself. A rule can’t change the state while being executed, which implies that all calculations are side-effect free. The rule returns the changes to the state, as a so called update set. An update set is a set of updates, each of which describes a function, a location and the new value. Update sets are applied to the state whenever the top-level rule concludes (returns). Listing 2 shows an example of a rule (and the state it operates on).

```
function x : -> Int
function y : -> Int
function z : -> Int

rule swap = {
  x := y
  y := x
}
```

Listing 2: Parallel swap

Assuming an initial state of \(\{x = 3, y = 2, z = 1\}\) the calculated update set of a (single) invocation of swap is \(\{(x, 2), (y, 3)\}\). The update is then applied to the state, yielding \(\{x = 2, y = 3, z = 1\}\).

When a function is assigned different values (for the same location) the update set is said to be inconsistent. In CASM a non-revocable runtime error is raised when an update set becomes inconsistent. Listing 3 shows an example for a rule triggering a runtime error.

```
function b : -> Boolean

rule inconsistent = {
  b := true
  b := false
}
```

Listing 3: Inconsistent update set - runtime error
3.1.1 Update Rule and Function Signatures

The previous examples informally introduced the update rule (:=) and function signatures. A function signature defines the types of the function arguments (comma-separated between : and ->) and the type the function maps to (after ->).

The general form of an update rule is \( f(l) := v \), where \( f \) is a function and \( l \) a location. A location has to match the argument types of the function signature. \( v \) is an expression of the function’s type which will be evaluated and assigned to the function at the given location. The state will not be changed when the update rule is executed, but the effects of the update will be added to the update set of the environmental rule. Only the update rule can change the state (or more precisely, add updates to an update set).

3.1.2 Types, Composition and Enumerations

CASM offers 3 built-in primitive types. They are Boolean for boolean values (true, false), Int for integer values and String for character strings.

An enumeration can be defined using the enum keyword. Each enumeration defines a new type with the same name as the enumeration. Each member of the enumeration becomes a new globally unique identifier of the enumeration’s type. An example is given in listing 4.

```plaintext
enum MyEnum = { one, two, three }  
function x : -> MyEnum    
rule example =  
  x := three
```

Listing 4: Enumeration Type

CASM offers two kinds of type composition. A List is a sequence of zero or more elements of equal type. The Tuple is a sequence with a fixed number of elements of possibly different type. CASM disallows user-provided recursive data types in the current version. An example is given in listing 5.

```plaintext
function stack : -> List(Int)  
function aMapping : -> List(Tuple(String,Int))
```

Listing 5: Composition Type

3.2 Expressions, Variables and Derived Values

For Int types the usual set of operators is provided via built-ins. Expressions are very similar to the C programming language (without any side-effects however).

CASM does not offer a notion of local state, so there are no local variables in the common sense. There is however the possibility to bind expressions to a local name using the let rule. In contrast to CoreASM let rules are statically scoped.
Some expressions may be used extensively in a program and in more than one rule. Such expressions can be declared globally using the derived keyword. A derived accepts typed arguments, just like functions, and is a single expression. Listing 6 gives an example of a derived and nested let rules (assigning true to function foo at location 18).

3.3 Block Rule and Control Flow

The block rule, syntactically expressed by curly brackets, combines the update sets of all enclosed rules into one single update set. Each of the enclosed rules is invoked on the same state and because all rules are side-effect free the order in which the rules are invoked does not matter. The resulting update set is formed by applying the union operator on all calculated update sets. When merging is performed inconsistent updates need to trigger a runtime error. Listing 2 already made use of the block rule.

The CASM language offers an if-then-else rule (an example can be seen in listing 11). In the context of an ASM based language it is an if-then-else rule (not a statement). Thinking of if-then-else as a rule also helps to comprehend the semantics. if-then-else produces an update set (like any other CASM rule does). The update set is either the update set produced by the rule in the if-branch or the one in the else-branch, depending on the boolean value of the expression following the if keyword.

There also is a switch-case statement, with the usual semantics and an optional default case label.

The call rule invokes another rule. There are two flavors of the call rule, a direct and an indirect one. In the direct case the rule to be invoked is known statically and directly coded in the source file, while in the indirect case the rule to be invoked is calculated by an expression of type RuleRef. A RuleRef can be produced by the @ operator (similar to C’s & operator). Listing 7 shows a direct and an indirect call (note the additional brackets
around the expression). One can also see that rules can have typed arguments. CASM’s call rule differs from the definition given in the Lipari guide, see section 3.7 for more details.

### 3.4 Sequential Block Rule

Some problems can naturally be described by imperative programming. CASM supports sequential programming by means of the seqblock rule. Statements enclosed by a seqblock are executed in exactly the specified order. Additionally the state change induced by previous rules is visible to subsequent ones. The update set of a seqblock rule is calculated by subsequently merging the update sets of the enclosed rules. Two updates to the same function and location from different rules do not conflict however, the later overwrites the previous one. Effectively the update set describes what would have happened if the rules were applied using a sequential semantics.

It is important to note that the state is not actually changed. The rules are evaluated using the state which would result from applying the previous update sets. A temporary state is created and each calculated update set is applied to it. This temporary state is discarded at the end of the seqblock.

Listing 8 shows an implementation of swap using a seqblock rule. Please note the use of the temporary variable \( t \), because the update to \( x \) is visible to the second update rule (compare to listing 2). Again assuming an initial state of \{ \( x = 3, y = 2, z = 1 \) \} the update set of the first update rule is \{ \( (x, 2) \) \}. This update set is applied to the initial state resulting in the temporary state \{ \( x = 2, y = 2, z = 1 \) \}. The second update rule results in the update set \{ \( (y, 3) \) \}. Applying to the temporary state the gives \{ \( x = 2, y = 3, z = 1 \) \}, this state is discarded however. Merging the update sets gives the update set of the seqblock rule itself, it is \{ \( (x, 2), (y, 3) \) \}. This final update set will be applied to the state when the swap rule concludes.

```plaintext
function x : -> Int
function y : -> Int
function z : -> Int

rule swap =
  let t = x in
  seqblock
    x := y
    y := t
  endseqblock
```

Listing 8: Sequential swap
3.5 Forall and Iterate

The *forall* rule is used in combination with an iterate-able expression (e.g. a range of integers, an enumeration). For each element of the iterate-able expression the rule given in the body is invoked. The *update sets* produced by the body are understood to be executed in parallel. An example is given in listing 9 where it is used to create a list of 4 elements.

```plaintext
function x : -> Int
rule create =
    forall i in [0..3] do
        x(i) := i
Listing 9: Forall
```

The *iterate* rule on the other hand repeatedly invokes its rule body until the produced *update set* is empty. Each invocation is understood to be executed in a sequential manner, so each rule is invoked using the *temporary state* produced by the previous iteration. An example is given in listing 10 where the rule is used to atomically perform a fold operation (using addition) on a list. The update set returned by the *iterate* rule is \{(i,10),(f,45)\}.

```plaintext
function a : Int -> Int initially { 0->0, 1->1, /* skipped */ , 9->9 }
function i : -> Int initially { 0 }
function f : -> Int initially { 0 }
rule fold =
    iterate
        if i < 10 then {
            i := i + 1
            f := f + a(i)
        }
Listing 10: Iterate
```

3.6 Stacks and Lists

There are rules and built-in functions which can be used with *List* types. Rules *pop* and *push* are used to implement stacks. The built-in functions *cons*, *peek* and *tail* construct and consume lists. There also is a *nth* function to access the nth element of a list (or tuple). These functions are (parametric) polymorphic in their nature and need to be handled correctly by the type system. Listing 11 gives an example.

```plaintext
function list : -> List(Int)
rule foo =
    seqblock
        push 3 into list
        if peek(list) != 3 then assert false
        let x = nth(list, 1) in list := cons(x, list)
    endseqblock
Listing 11: List built-ins and rules
3.7 Differences to other ASM based languages

CASM differs in two major aspects from other ASM based programming languages (i.e. CoreASM).

The Lipari guide defines rule arguments to be passed-by-name. Passing by-name has some interesting features, but is difficult to be implemented efficiently [BG93]. In CASM the semantics of the call rule specify arguments to be passed by-value. Please note that pass-by-value is semantically equivalent to pass-by-name when all arguments are constants. Therefore the restricted call rule of CASM can be simulated by evaluating all argument expressions (e.g. using a let rule) before invoking an unrestricted call. We merely enforce this policy on the CASM programmer by performing this evaluation before invoking the called rule.

The other difference is the scope of variables introduced by the let rule. CoreASM installs variable names into an environment passed to rules invoked by a call rule. So listing 12 is valid in CoreASM, but not in CASM. Environments are not passed to rules invoked by a call rule in CASM. The main reason for this is that the type inference and type checking would be unable to handle this.

```plaintext
function y : -> Int
rule callee = y := x
rule caller =
  let x = 3 in
  call callee()
```

Listing 12: Only valid in CoreASM

4 CASM Type System

CASM is a static\(^5\), strongly typed language and no implicit type conversion is performed. To reduce the often redundant notation of types the programmer is allowed to omit the type if it can be deduced automatically. CASM only demands types for the arguments of functions, rules and derived as well as for a function’s type. Optionally the programmer can provide type information for the type of a derived and a named expression type bound via a let rule. This may improve readability of the source code and may be needed to guide the type inference system in some corner cases. These corner cases often result from the special value of `undef` which is compatible to every type.

```plaintext
function assign : -> List(Int)
rule foo =
  let uList : List(Int) = undef in
  let uElem = nth(1, uList) in
  assign := [ uElem ]
```

Listing 13: Type Annotation needed

\(^5\)except indirect calls
Listing 13 shows an example the CASM type system implementation can not handle without annotation. The first let binds the name uList to the value undef. The second let binds the name uElem to the nth (1st in this case) element of a list or tuple. nth (a built-in function) returns undef if any of its arguments is undef. uElem’s type could not be computed (locally) when no additional type information would be provided by the programmer. Although limitations in the implementation of the type system exist, they very rarely occur in real world programs.

To specify the argument types of rules and deriveds may be superfluous, but increases readability and documentation. But especially for derived it prevents parametric polymorphism, which may be a useful feature after all. We are considering to change this in a future version of CASM.

5 Interpreter and Compiler

We have developed an interpreter and a compiler for CASM. The interpreter is capable of concrete and symbolic execution of CASM programs. We have also developed a compiler generating C++ code.

The CASM interpreter is a simple abstract syntax tree (AST) interpreter. For creating the parser traditional compiler tools like lex and yacc have been used. Type inference and type checking is performed on the AST. The program is rejected if any types can’t be calculated or any type mismatch is detected.

During symbolic execution some (or all) values of the state can hold symbolic instead of concrete values. Evaluation of operators then depends on whether all operands are concrete values or if there is at least one symbolic one. As long as all operands have concrete values the operator is evaluated as usual. But if there is at least one symbolic operand the operator itself returns a new symbol. This returned symbol is linked to the fact that it had been calculated by applying the operator to the specific operands. E.g. an addition of the symbol s3 and the concrete value 23 will result in a new symbol s4. s4 will be linked to the fact s4 := s3 + 23. Should s4 ever be used as an operand a new symbol will be created as result, linked to the fact that s4 was used as an operand. Any symbol appearing as the result of a program can that way be traced back to an initial symbol provided as input to the program.

Things get interesting when control flow branches on a symbolic value [Kin76]. For the sake of brevity we only consider if-then-else rules here. The conditional expression must be of Boolean type in CASM, so it can only have two possible values (true, false). When the boolean value is symbolic, both possible values need to be considered. The program forks assuming the expression to be true in one case and false in the other one. These assumptions become part of the facts known about the symbols. The sum of all facts learnt about symbols along a path of execution is called path condition. Path conditions can be used to automatically generate test cases [VPK04]. The CASM interpreter does not directly support this, but it can easily be implemented by using the generated trace files.
5.1 Compilation scheme and efficient runtime

The typed AST is also used to compile the CASM program to C++. Our current CASM compiler implementation performs only a limited set of optimizations to keep the generated C++ files small. The runtime system makes heavy use of C++ template mechanism and inlining and hence the generated machine code is therefore quite compact resulting in satisfying performance for common CASM code patterns.

5.1.1 Efficient Memory Allocation

During evaluation of a rule a number of updates and update sets have to be generated dynamically. The lifetime of these objects is limited however. All update sets and the updates they contain can safely be deleted when the top-level rule has concluded and all updates have been committed to the state. We therefore allocate these objects in a dump memory area. When the top-level rule concludes, the dump memory is reset and all objects it contained are invalid. New updates are allocated overwriting the old ones. This technique reduces overhead for dynamic memory allocation to almost zero.

5.1.2 Optimization for very small update sets

For the workloads we operate on we observed that most update sets are very small (\(\leq 4\) in most cases). Our current implementation for update sets therefore use a small number (4) of pre-allocated slots. Only after all pre-allocated slots of an update set are occupied a hash-map is used to store any additional updates part of the update set. A hash-map needs to be used as update sets are frequently tested for membership (to detect conflicting updates).

5.1.3 Pseudo State

Handling of the update sets is crucial for the performance of the compiled code. CASM uses hash-maps to implement update sets. The underlying assumption justifying this design decision is that update sets are small and the global state is large. A concept called pseudo state is used to realize temporary states needed to implement sequential execution semantics (see section 3.4). When reading a state function from within a seqblock the update set is queried first. If there has been an update to that function (and location) by a preceding rule, the value from the update set is returned. Otherwise the value is read from the global state. All rules return the update set produced according to their semantics (described in section 3). Using this mechanism the update sets only needs to be applied to the state when the top-level rule concludes. Merging and querying hash-maps is efficient as long as they are reasonably small.
6 Evaluation of the CASM language

6.1 Hardware modeling

We successfully used CASM in two projects to model CPU architectures and will briefly report the results here. Details can be found in the cited papers.

One project focused on fast design space exploration synthesizing cycle-accurate simulators from a CASM model of a microprocessor. The microprocessor model is proven to be coherent to the CASM specification of its instruction set architecture. We were able to model the instruction set and two variants of pipelined MIPS processors in just a few hundred lines of code. This is in size similar to a MIPS model formulated in a specialized hardware description language and demonstrates the expressiveness of the CASM language. The synthesized simulator is capable of executing benchmark programs of the SPECInt suite with a very satisfying peak performance of 1 MHz. This roughly translates into 15 million (basic) CASM rules to be executed per second. More details are reported in [LK13].

In a compiler verification project CASM is used to model a complex (non-interlocking) DSP processor. Combining parallel and sequential execution modes emerged as the crucial feature to describe cycled circuits. All hardware blocks are described in a parallel execution block, whereas their internal operations are described by a sequential execution block. We primarily use symbolic execution to perform simulation proofs in a translation validation approach. Some details are reported in [LK12].

6.2 Functional and Imperative programming style

In the introduction it was claimed that ASM based languages in a way combine imperative and functional programming styles. This property of the CASM language proved to be very useful in our experience. In this section we want to point out this property giving an illustrative example.

Börger and Bolognesi give a recursive ASM version of quicksort in [BB03]. Their implementation is very short and concise, like it is in most functional languages, but is not in-place as well. Imperative implementations swap elements directly (in-place) in the array avoiding copies of the whole input data. Functional languages need to construct a new list containing the resulting array (they can not destroy the input data) which induces $O(n)$ additional space requirements. ASM based languages calculating quicksort in one computation step return an update set describing the new state of the array. This update set also uses $O(n)$ additional space. We present an in-place, non-recursive version of quicksort.
Listing 14 shows the state needed to perform the algorithm. It uses a `stack` to keep track of the parts of the `array` still to be sorted. The `quicksort` rule pops a new part to be sorted of the `stack` and stores the left and right indices into `l` and `r`. Line 48 tests if there is still further work to do and if so lines 49-45 contain the necessary initializations. The CASM idiom in line 57 terminates the whole computation. As long as a part of the array still needs to be sorted the rule `quicksort_one_step` will be executed. The rule `partition` will be called until a partition has been found. If the remaining parts are not trivial small they are pushed onto the `stack` and a new part needs to be popped from the stack `need_pop`.

The `partition` rule initially determines a pivot element (the last element of the part to be
sorted here) and either swaps two elements of the array (rule partition_one_step) or swaps
the pivot element to its final position $p$. Because the partition_one_step rule concludes
after swapping two elements of the array the resulting update set is size bound and not
dependent on the input data. Otherwise the update sets would need up to $O(n)$ memory
(i.e. on input $y_0, y_1, \ldots, y_n, x_0, x_1, \ldots, x_m, p : y_i < p \land x_j > p : 0 \leq i \leq n, 0 \leq j \leq m$).
To keep the observable computations small and the program simpler partition_one_step
utilizes the iterate rule in lines 4 and 7 when searching for elements to be swapped. Oth-
erverswise it would need to keep track of the search similar to need_partition.

An ASM based language shares many features of a functional programming language.
Large parts of the program are executed side-effect free, and while executing them the
global state is read-only. One could think of the state as an explicit argument to each rule,
the returned update set would then be the result of a functional application. The state only
changes between invocations of the top-level rule, so the assumed implicit state argument
changes for the next invocation. In that sense each single application of an ASM top-level
rule is functional.

By combining parallel and sequential execution modes a programmer can chose the gran-
ularity of the computations steps seen by an observer of the program. This can, as demon-
strated, be used to implement an in-place version of quicksort while basically program-
mapping a functional style.

The beauty of ASM based languages is the clear separation of invoking rules and applying
changes to the state. They closely resemble what Backus called an applicative state transi-
tion system (AST system), on a much smaller scale though. What he calls a formal system
for functional programming (FFP system) correspond to a rule and his SYSTEM state is
just the state of the program.

7 Conclusion and Further Work

In this paper we presented CASM, a general purpose programming language based on the
abstract state machine (ASM) method. We presented core features of the language and
described how we are able to efficiently compile CASM to C++. The CASM compiler
was successfully used to generate an instruction set simulator for the MIPS architecture
capable of executing SPECInt benchmark with a peak performance of 1 MHz. We also
developed an interpreter capable of symbolic execution which is successfully used in an
ongoing compiler verification project.

The CASM language in a way combines functional and imperative programming aspects.
We found this feature very useful and convenient and tried to showcase it using a small
example.

While using the language common programming pattern arise which lead to new rules be-
ing implemented and new built-in functions being added. We are also working on a faster
compilation and runtime implementation further increasing the performance of generated
simulators.
References


