A Compiler for Natural Semantics

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Abstract. Natural semantics is a formalism used for specifying both semantics and implementations of programming languages. Until recently, no practical implementation of the formalism existed. We have defined the Relational Meta-Language, RML, as an executable specification language for natural semantics. After a brief outline of the language, we describe the compilation strategy used by our `rm12c` compiler: transformations are applied to minimize non-determinism, and a continuation-passing style form is produced and simplified. Finally the CPS is emitted as low-level C code, using an efficient technique for implementing tailcalls. We also present performance measurements that support our choice of compilation strategy.

Keywords: natural semantics, determinacy, continuations, tailcalls.

1 Introduction

Natural Semantics is a successor to Structural Operational Semantics that has become a popular tool for specifying type systems, dynamic (interpretive) semantics, and compilation [9, 18, 20, 25]. Until recently, the only implementation of the formalism was the Typol language in the Centaur programming environment [10, 17]. However, that implementation is both very inefficient, and does not support stand-alone executables.

We have defined a meta-language for Natural Semantics, RML, with the intention of producing a practical compiler for it. Efficient code was the foremost goal, followed by the ability to produce code that could be combined with other code, hand-written or generated, to form stand-alone applications.

In this paper we describe the main aspects of the `rm12c` compiler, which compiles RML to efficient C code. Our contributions are:

- We outline the features of Natural Semantics and the RML specification language.
- We describe a reasonably straightforward compilation strategy for RML that has proven to be very effective for several non-trivial specifications.
- Compiling tailcalls to C code is a problem faced by many compilers for high-level languages; we describe a new strategy that is both correct and efficient.

Section 2 starts by giving a brief overview of natural semantics and RML. Section 3 then discusses the compilation strategy, and some alternatives, followed in section 4 by a description of the high-level transformations employed in the

first compilation phase. Then follows section 5 with a brief discussion of the continuation-passing style intermediate representation used. The back-end emits low-level C code, but in doing so needs to emulate *tailcalls*. Section 6 starts with a brief overview of known techniques, before detailing a new solution we have developed. Then follows a summary of our benchmark results in section 7. Section 8 compares this with related work, and section 9 concludes.

2 Overview of Natural Semantics and RML

Natural semantics is a formalism frequently used to specify programming languages in general, type systems, special properties, and transformations between representations [9, 18, 20]. Specifications consist of three parts: declarations of the types of objects involved (typically in the form of abstract syntax), declarations of the judgements (logical formulas) involved, and axioms and inference rules defining those judgements. The end result is a Gentzen-style natural deduction system (a *sequent calculus* [12]) for an application-specific logic.

The Relational Meta-Language, RML, is a straightforward realization of the description above. Data type declarations are identical to those found in Standard ML, and ‘relations’ (our terminology for groups of related inference rules) are written textually almost as they are on paper. An ML-like polymorphic type system is present for static type checking. The operational interpretation of specifications is roughly as in Prolog. To prove a judgement, a top-down search through the program is performed to find a relevant inference rule. Then a left-right execution of the premises of that rule is done, after which the judgement is considered ‘proved’. As in Prolog, we refer to relations as *procedures* when taking an operational view.

In contrast to Prolog, the search rule is defined to be *determinate*, which means that once a proof is found for a judgement, no attempts will be made to find alternative proofs. The full power of backtracking is still present *during* proof construction.

A small example specification is listed in figure 1. It contains type declarations for *expressions* and *environments*, and a relation `eval(env, exp) => int` describing the relationship between environments, expressions, and values. Pragmatically, we use the relation to *evaluate* expressions in order to retrieve their values.

3 Implementation Strategy

The compilation process is a multi-stage pipeline, with appropriate optimizations applied at each level:

1. Source code is translated to a form reminiscent of first-order logic, FOL. A left-factoring transformation is applied to reduce the usually enormous amount of non-determinism present in specifications.

```

datatype Exp = INT of int
             | VAR of string
             | ADD1 of Exp
             | IF of Exp * Exp * Exp

type Env = (string * int) list
relation lookup =
  (* rules defining lookup(env,var) => val *)
end

relation eval =
  (* eval(env, exp) => int *)
  axiom eval(env, INT i) => i

  rule lookup(env, x) => i
  -----
  eval(env, VAR x) => i

  rule eval(env, exp) => i &
  int_add(i, 1) => i'
  -----
  eval(env, ADD1 exp) => i'

  rule eval(env, cond) => 1 & (* if-true *)
  eval(env, then) => v
  -----
  eval(env, IF(cond,then,else)) => v

  rule eval(env, cond) => 0 & (* if-false *)
  eval(env, else) => v
  -----
  eval(env, IF(cond,then,else)) => v
end

```

Fig. 1. Small RML example

2. Then the FOL form is translated to a continuation-passing style functional form, CPS. Inlining of procedures and continuations is performed, as is constant propagation and other simple optimizations.
3. A low-level *Code* representation is produced in which continuations are replaced by concrete data structures, and data structure creation is made explicit. A *copy-propagation* optimization is applied to remove some redundancies introduced by the code to pass parameters when tailcalls are emulated.
4. The final step prints the low-level form as C code, compiles it, and links with a small (≈ 2600 lines) runtime system.

The compiler is written in 11569 lines of Standard ML.

Absent from this description is any mention of Warren's Abstract Machine (WAM) [2], which is a standard starting point for logic programming language

implementations. There are two reasons for this. First, its instructions are very low-level, which means that high-level optimizations would be difficult to express for it, and it is not certain that they would be effective. Second, the instructions are complex, hiding many smaller operations inside. This in turn prevents useful *low-level* optimizations.

In an earlier paper [22], we showed that a continuation-passing style denotational semantics for RML has operational properties that correspond closely to the WAM. In essence, we make use of a WAM-like model of the control and trail stacks, but ignore its instruction set.

4 Improving Determinacy

Many natural semantics specifications describe deterministic processes, e.g. type checking, evaluation, or translation. However, neither the formalism nor RML has local control-flow operators such as conditionals. Choices have to be expressed as separate inference rules.

Consider for instance the expression evaluator in figure 1, in particular the two rules defining IF-expressions. Interpreted naively, the first rule calls for the pattern-matching of the arguments, followed by evaluation of the predicate. If the predicate is not true (1), the first rule fails, backtracking takes us to the next rule, and the pattern-matching and evaluation is done all over. Obviously, this can be very inefficient.

While rules like these can be rewritten to be more efficient, this is not something we want specification writers to have to deal with. Instead, the compiler performs a *left-factoring* transformation that converts these rules into the obvious conditional.

4.1 Left-factoring

We call this transformation left-factoring because execution of relations is much like top-down parsing, and the transformation is similar to left-factoring of context-free grammars.

After type checking, relations are translated into a form that is a disjunctive-normal form of a kind of first-order logic; we call it FOL. First, every inference rule becomes a conjunction of its explicit and implicit goals. For instance, the first rule for the conditional above would become (we use Lisp-like notation for these forms):

```
(and (match [(arg1 env)
             (arg2 (IF cond then else))])
      (and (call eval [env cond] [result1])
            (and (match [(result1 1)])
                  (and (call eval [env then] [result2])
                        (and (match [(result2 v)])
                              (return v)))))))
```


This form no longer contains any explicit disjunctions. Later on, the pattern-match compiler will discover that there is no overlap between the cases in the inner `case`, so the implicit disjunction there is also eliminated. The result is completely deterministic code.

4.2 Implementation

Our compiler uses a term-rewriting system with 17 rules to specify these and related transformations. Of the rules, 11 perform useful work, while the remaining ones make sure the terms are in a right-linear form recognizable by the useful rules.

The code, which is only 105 lines of Standard ML, also includes support for a limited form of higher-order unification. Some rules need to compare terms for equality, but equality must ignore the actual names of bound variables. Hence renamings must be performed *on-the-fly*.

4.3 Limitations

As indicated by the performance evaluation presented later, the left-factoring phase is very effective in removing unnecessary *non-determinism*. However, the purely syntactic nature of the transformations causes some cases to be missed.

Some primitive language operators are known to be mutually exclusive. For instance, two rules, one containing $x < y$ and one containing $x \geq y$, must be mutually exclusive. The current implementation knows nothing of primitive operators, and so will not be able to introduce a conditional in this case. This problem, while not frequent, does occur occasionally.

Also, even if two user-defined relations happen to be mutually exclusive, the compiler will not notice this since it never inspects the definitions of called relations. Luckily, typical specifications do not seem to suffer from this.

5 Intermediate Code

After the left-factoring optimizations, the FOL representation is translated into a continuation-passing style (CPS) representation. At the same time, a pattern-match compiler [21] is used to expand pattern-matching constructs into appropriate combinations of data structure inspections and tests.

Since RML has backtracking, the CPS transformation introduces *two* kinds of continuations, success and failure continuations. The former are used for normal calls and returns, while the latter are introduced at disjunctions as handles for backtracking [22]. Apart from this, the CPS representation is fairly conventional.

Our reasons for using CPS are several:

1. We obviously need to model and optimize both ordinary calls and returns, and backtracking. Continuations provide us with an easy way to do so.

2. CPS has nice pragmatic features for compiler writers. It has a simple structure, and, being a λ -calculus, makes some optimizations (inlinings, constant and copy propagations) easy. Other lower-level optimizations can be left for the back-end, which in our case is a C compiler.
3. Although CPS is high-level, it has a simple interpretation in terms of machine resources. This makes the final translation to low-level code straightforward.

Our compiler only applies simple optimizations to its CPS representation, mainly constant propagation, copy propagation, and inlining of those continuations and procedures that have single unique invocation points. No static analysis is performed, except a simple per-module reference count analysis.

We refer the reader to the literature for further details concerning the practical issues involved [3, 19, 22, 27, 28].

6 Tailcalls in C

Implementations of high-level languages must often deal with *tailcalls*. A tailcall is a function call that occurs as the last action (the ‘tail’) in a function body. An implementation is *properly tail-recursive* if tailcalls do not cause net growth in stack usage. In effect, tailcalls are *gotos* that pass arguments.

Functional and logic languages typically have no primitive iteration constructs: instead recursive procedures and tailcalls are used to *synthesize* a variety of iteration schemes.

Some compilers, including `rm12c`, use a continuation-passing style representation of programs. In this representation, *all* non-local control transfers are tailcalls.

In both of these cases, it is important to implement tailcalls both efficiently and correctly, i.e. properly tail-recursively.

For portability reasons, many compilers choose to compile to low-level C code instead of machine code. This causes problems, since C’s function calls are not guaranteed to be implemented tail-recursively³.

6.1 Earlier solutions

A number of techniques for implementing tailcalls have been proposed over the years, especially in the functional and logic programming communities; we summarize them below. We do not concern ourselves with approaches that do not guarantee proper tail-recursion.

In this section the term *module* is often used. By this we mean *an individual compilation unit*, usually just a single file with a set of declarations. In RML, a module is a language construct which simultaneously defines a number of types and relations, and declares the externally visible interface.

³ Some C compilers recognize trivial cases, but the great majority never do anything special about tailcalls.

In the plain dispatching technique, every label becomes a single function. When a label terminates with a tailcall, it returns the label to which control is to be transferred. A dispatcher is given an initial label. It calls the label, receives as the return value the next label to call, and loops ad infinitum. While this preserves tail-recursion, parameter passing cannot be done in a natural way. Instead, global variables are used to communicate arguments from caller to callee. This technique has been used many times [24, 27, 28].

To eliminate the high overhead for parameter passing and control flow in the previous scheme, some compilers collect *all* code into a single C function [13]. This allows parameters to be located in local C function variables, perhaps even registers, and known control transfers become simple `gotos`. For unknown control transfers, a big `switch` statement is used⁴. This scheme is not really practical though, since it makes separate compilation impossible. Also, gathering all code into a single function makes that function extremely large, which in turn negatively affects compilation times and the C compiler's ability to perform register allocation.

Some use the first-class labels in the Gnu C compiler to `goto` from one function to another, e.g. the Erlang and Mercury compilers [15, 26]. All code for a module is collected into a single C function. Known calls within this module use ordinary `gotos`. A label is exported by exporting its address (a GCC extension). To branch to *any* unknown label, a `goto` is done to the address of that label (a GCC extension). Unfortunately, to make this work, severe restrictions have to be placed on the generated C code. In particular, local C variables are banned: all computations must use only global variables. This has a very negative effect on the performance of the code.

The `wamcc` Prolog-to-C compiler [7] uses an idea similar to the previous one, but without being GCC-specific. On some RISC processors, calling a function does not in itself cause stack growth. Rather, it is the callee that extends the stack in its function prologue. The `wamcc` approach is to insert an assembly label at the start of every function body, and then declare a C function of that name. A function call to this label will therefore bypass the prologue, and hence not cause stack growth. Unfortunately, this elegant idea only works on some systems; on many others, the `wamcc` compiler has to insert system-dependent assembly code, making the idea inherently non-portable.

Baker [5] has proposed that tailcalls *should* be implemented by actual recursion. To prevent unbounded stack growth, the stack size is checked at the start of every function. When it has grown to some limit, a non-local `goto` (`longjmp`) is performed to back the stack up to an earlier point, then the aborted function is re-invoked. Also, since the C stack actually behaves like the allocation arena of a garbage collector, memory allocation can be performed simply by declaring local C variables of appropriate types. When the stack overflows, the garbage collector copies live data to a 'proper' heap. Unfortunately, the performance of this elegant scheme is *extremely* sensitive to the chosen stack size. Also, our measurements have indicated that it is slower than other schemes.

⁴ The first-class labels of GCC allow this to be implemented by a jump table.

6.2 Our solution: ‘dispatching switches’

One disadvantage of the plain dispatching technique is that *all* calls go through the dispatcher loop, even when the target is known to be in the same module as the caller.

It is possible to compile all code in a module to a single function, and only use the dispatcher when going from one module to another, this is called ‘block compilation’. Although this allows known intramodular calls to be very fast, no system we know of [6, 11] tries to make *unknown* intramodular calls efficient. Source-level ‘returns’ are one common source of unknown calls. In the code generated by `rm12c`, about 40% of all calls are unknown intramodular.

Our contribution here is a technique for efficiently testing whether an unknown call is intra- or intermodular.

First suppose that each module is compiled into a single C function. A label is represented as a record containing two fields: a pointer to the C function, and an integer tag. The C function takes the tag as an argument, and branches to the corresponding piece of code using a `switch` statement.

One strategy is to compile an unknown tailcall into a test, followed by separate code sequences for the intra- and intermodular cases. This has two problems: code size increase, and the fact that the test itself takes time. The test can be implemented either by comparing the function pointer of the target label with the current function, or by requiring different modules to use disjoint ranges of tags. The first problem can be avoided, but the test remains a bottleneck.

Our technique is the following: Let each module have a private *bitmask* variable. When the module is entered, its bitmask is set to all-ones, and when it is exited, the bitmask is set to zero. Also let label records have a third field, which is a pointer to its module’s bitmask.

Recall that the labels are given integer tags, and that a `switch` is used to branch to the code when the module is entered. We reserve tag zero as a kind of *trap handler*. To perform an unknown tailcall, arguments are evaluated as if it was a known intramodular call, then the `switch` is used to branch to the bitwise ‘and’ of the label’s tag and its bitmask variable. The code below exemplifies:

```
struct label {
    struct label *(*module)(unsigned);
    unsigned tag;
    unsigned *bitmask;
};

/* my_module.c */
static unsigned my_bitmask = 0;
struct label *my_module(unsigned); /*forward*/
struct label my_label_N = { my_module, N, &my_bitmask };
struct label *my_module(unsigned tag)
{
    struct label *label;
```

```

    my_bitmask = ~0; /* we are active */
dispatch:
    switch(tag) {
    case 0: break; /* intermodular; leave module */
    ...
    case K:
        /* make an unknown call: */
        label = <expr>;
        tag = label->tag & *(label->bitmask);
        goto dispatch;
    ...
    case N:
    ...
    }
    my_bitmask = 0; /* we are not active */
    return label;
}

```

If the unknown call was intramodular, the bitmask is all-ones, and so the `switch` will branch to the correct label. The overhead compared to a *known* intramodular call is two memory loads, one ‘and’, and the `switch`⁵. If the call was intermodular, case zero is invoked, and the module can move parameters to global variables and return the label to the dispatcher.

This scheme has the advantage of allowing both known and unknown intramodular calls to be efficient. This is important, because of the high frequency of these cases.

6.3 Copy-propagation

As a consequence of tailcall emulation, global variables are used for parameter passing between modules. Even though our intermediate CPS representation is assignment-free, assignments are introduced in the translation to low-level code.

It turns out that in many label bodies, when they tailcall some other label, one or more of the outgoing (global) argument variables will have the same values as they had on entry to the label. A simple *copy-propagation* [1] optimization can discover when this happens, and eliminate some of the unnecessary loads and stores. (A C compiler can in general not do this optimization, since any recursive call, say to a runtime primitive, may modify any global location.)

7 Evaluation

To evaluate the `rml2c` compiler, we have performed a large number of benchmarks on several combinations of machines and C compilers [23].

⁵ Usually implemented by a jump table if GCC is used.

Our benchmark suite consisted of three RML specifications: an interpreter for a normal-order functional language applied to a prime numbers program (*mf*), a type checker for most of the Standard ML core language applied to a number of function definitions and a pathological expression with more than 4000 schematic type variables (*miniml*), and a multi-stage translator for a Pascal-like language to low-level C applied to a 2300 line program (*petrol*). These specifications represent three common application areas for natural semantics.

We have implemented four different strategies for tailcalls in *rm12c*. In table 1, 'switch' is our dispatching switches strategy, 'plain' is the plain dispatching strategy, 'pushy' is Baker's recursive scheme, and 'warped' is the Erlang/Mercury use of GCC's labels. In the other dimension is listed the machines we used. Most of these are standard Unix workstations, using either their vendor's standard compiler or gcc 2.7.0/2.6.3. The 'ppc' target is a single PowerPC 601 processor in a 128-processor Parsytec GC/PP.

To do these comparisons, we had to allow the size of the 'pushy' scheme's stack buffer to vary, because of its great sensitivity to this parameter. To be fair, we also varied the size of the allocation arena used by the other schemes. In table 1, the size was varied from 1K to 128K words, each benchmark was run at each step, and the sum of the execution times was computed for each tailcall scheme. Then these times were normalized with respect to the 'switch' entry.

As is evident from table 1, our dispatching switches scheme is a clear winner on all machines we have used. It is also clear that the 'pushy' scheme loses big, because of its sensitivity of the size of the stack. (Space restrictions do not allow us to report all results from this benchmark. However, our 'switch' scheme *always* won, and 'plain' always beat both 'pushy' and 'warped'.)

To evaluate the effectiveness of the optimizations implemented in *rm12c*, we re-ran the benchmarks but with some optimizations turned off. Tables 2, 3, and 4 list the results. In the Oall column, all optimizations are enabled. In the no-Ofol column, the FOL optimizations are disabled, and in the no-Ocps column, no optimizations were applied to the CPS level. In the last column, no-Ocode, the low-level copy propagation optimization was not performed. It is clear that optimizations applied to higher level representations, earlier in the compiler, are significantly more important for good performance than are lower-level optimizations.

To compare *rm12c* with the obvious alternatives, Typol and Prolog, we wrote Typol and Prolog versions of one of the benchmarks, viz. the *mf* interpreter for the normal-order functional language. In table 5 we see that Typol's performance is several orders of magnitude worse than *rm12c*'s. Typol obviously was not implemented with efficiency in mind.

In table 6, we compare the same benchmark against two popular commercial Prolog compilers (both in native-code mode). *rm12c* generates code that is about ten times faster than that produced by these Prolog compilers.

The *petrol* compiler is a natural semantics specification of a language that has been used in our department's undergraduate compiler course. We compared the performance of our *rm12c* generated compiler with the existing one, which

	switch	plain	pushy	warped
alpha-cc	1.00	1.17	3.40	n/a
alpha-gcc	1.00	1.34	3.00	1.62
hp-cc	1.00	1.56	1.95	n/a
hp-gcc	1.00	1.59	2.03	1.62
i586-cc	1.00	1.18	2.07	n/a
mips-cc	1.00	1.13	1.45	n/a
mips-gcc	1.00	1.15	1.30	1.54
ppc-cc	1.00	1.27	1.97	n/a
ppc-gcc	1.00	1.27	1.88	1.40
sparc-cc	1.00	1.17	3.20	n/a
sparc-gcc	1.00	1.20	1.50	1.41
average	1.00	1.28	2.16	1.52

Table 1. Normalized time as a function of tailcall strategy

Oall	no-Ofol	no-Ocps	no-Ocode
1.00	2.93	1.35	1.06

Table 2. Normalized time as a function of optimization level

is written in Sun Pascal. As table 7 shows, even though the Pascal version was compiled with all optimizations enabled, it is actually 39% *slower* than the generated compiler.

8 Related Work

There are extremely few implementations of compilers for natural semantics specifications. We have already mentioned the most well-known one, the Typol compiler in the Centaur programming environment. This compiler works by translating Typol to Prolog. As our benchmarks have shown, this implementation is not efficient enough for practical use.

Oall	no-Ofol	no-Ocps
1.00	2.25	2.08

Table 3. Normalized #calls as a function of optimization level

Oall	no-Ofol	no-Ocps
1.00	2.00	1.51

Table 4. Normalized max stack as a function of optimization level

primes	RML	TYPOL	T/R
3	0.0026	13	5000
4	0.0037	72	19459
5	0.0063	1130	179365

Table 5. MF, RML vs. TYPOL, time in seconds

Recently, Attali and Parigot [4] have described a system that translates a sub-class of natural semantics into strongly non-circular attribute grammars. By then using the FNC-2 system's compiler for this class, they are able to improve performance by a factor of 10 compared to Typol.

A description of an early prototype of `rml2c` was published in [22]. At that time, the language had a full Prolog-like search rule, but no attempts were made to reduce non-determinism. Both the left-factoring transformations and the new implementation technique for tailcalls are later extensions.

Transformations similar to our left-factoring ones have been described before, e.g. by da Silva [8], Hannan [14], and others. As far as we know, no one has made use of them in an actual implementation before.

9 Conclusion

We have described a simple yet very effective compilation strategy for natural semantics. We have shown the great importance of applying high-level determinacy-improving optimizations early in the compiling process.

We have also shown that using a continuation-passing style intermediate

primes	RML	SICStus	S/R	Quintus	Q/R	machine
18	0.45	5.0	11.1	4.5	10.0	Sun 4/470
18	0.22	2.20	10.0			Sun 10/40
30	0.87	11.20	12.9			Sun 10/40

Table 6. MF, RML vs. Prolog, time in seconds

RML	Pascal	P/R
1.06	1.47	1.39

Table 7. Petrol, RML vs. Pascal, time in seconds

representation can be both practical and effective in a compiler for a logic-programming language.

A new technique, ‘dispatching switches’, for compiling tailcalls to efficient C code has been described. Our benchmarks indicate that this technique is better than several known portable and non-portable alternatives.

Our benchmarks show that `rml2c` generates much better code than some commercial Prolog compilers, and even better code than one commercial Pascal compiler. This clearly supports our choice of compilation strategy.

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