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EClean - An Embedded Functional Language

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Abstract

C++ template metaprogramming is often regarded as a functional language, however, nowadays metapro- gram libraries are not implemented in functional programming style. In this paper we discuss a compile-time graph-rewriting engine based on the properties of the functional language Clean. The most important prop- erty imported from the functional paradigm is the lazy evaluation strategy. With the help of the engine it is possible to embed lazy functional-style code into C++ programs, and transform it into template metaprograms. We present the implemented lazy evaluation strategy by examples including also infinite lists.

*Keywords:* C++, template metaprogramming, language embedding, functional languages

# Introduction

Template metaprogramming is an emerging new direction in C++ programming for executing algorithms in compilation time. The relationship between C++ tem- plate metaprograms and functional programming is well-known: most properties of template metaprograms are closely related to the principles of the functional pro- gramming paradigm. On the other hand, C++ has a strong heritage of imperative programming (namely from C and Algol68) influenced by object-orientation (Sim- ula67). Furthermore the syntax of the C++ templates is especially ugly. As a result, C++ template metaprograms are often hard to read, and hopeless to maintain.

Ideally, the programming language interface has to match the paradigm the program is written in. *Meta*<*Fun*> is a running project at the Department of Pro- gramming Languages and Compilers at the Eo¨tv¨os Lora´nd University, Budapest. The long-term goal of the project is to define and implement a clear and maintan- able, purely functional-style interface for C++ template metaprograms. For this purpose, template metaprograms are written in a functional language and embedded

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in C++ programs. This code is translated into classical template metaprograms by a translator. The result is a native C++ program complies with the ANSI standard [[3](#_bookmark9)].

*Clean* is purely functional lazy programming language [[11](#_bookmark13)]. In our approach we explore Clean’s main features including uniqueness types, higher order functions, and the powerful constructor-based syntax for generating data structures. Clean also supports infinite data structures via delayed evaluation. We defined *EClean* as a subset of the Clean language. EClean is used as an embedded language for writing template metaprograms. The Clean code will be executed by a graph-rewriting engine. The parser recognizes only a subset of the Clean language, as our aim was to create an embedded language aiding programmers in writing metaprograms, and not the implementation of a fully capable Clean compiler. This subset includes:

* recursion, conditional expression
* function definitions
* basic built-in types (int, bool, etc) and their lists
* arithmetic operations and comparisons

In this article we overview the most important properties of the functional paradigm, and evaluate their possible translation techniques into C++ metapro- grams. The graph-rewriting system of Clean has been implemented as a C++ template metaprogram library. With the help of the engine and the corresponding parser, EClean programs can be translated into C++ template metaprograms – as clients of this library – and can be evaluated in a semantically equivalent way. Delayed evaluation of infinite data structures are also implemented and presented by examples.

The paper is organized as follows: in section [2](#_bookmark1) we discuss C++ template meta- programming, and its relationship with functional programming. Lazy data struc- tures, evaluation, and the template metaprogram implementation of the graph rewriting system of the Clean functional language is described in section [3](#_bookmark2). In section [4](#_bookmark3) the transformation process of the EClean system is discussed in detail, section [5](#_bookmark6) discusses future work, and related work is presented in section [6](#_bookmark7).

# C++ Template Metaprogramming

*Templates* are key elements of C++ programming language [[23](#_bookmark16)]. They enable the implementation of data structures and algorithms that can be parameterized by types, thus capturing commonalities of abstractions in compile time without loos- ing performance in runtime [[27](#_bookmark17)]. *Template metaprogramming* is a generative pro- gramming style [[6](#_bookmark11)] utilizing the C++ template facilities for executing algorithms in compile-time. Recursions are created by forcing the compiler into executing a chain of instantiations of the same template. On the other hand, compile-time con- ditional statements can also be created with the help of template specializations. With these two constructs available, TMP is *Turing-complete* [[30](#_bookmark18)], in theory its expressive power is equivalent to that of a Turing machine (and of most modern

programming languages). The most important applications of metaprograms are the implementation of *concept checking* [[33](#_bookmark19)] (testing for certain type-properties of in compile-time), the implementation of data structures containing types in compile- time (e.g. *typelist* [[2](#_bookmark8)]), the construction of *active libraries* [[7](#_bookmark12)], and many others.

Despite all of its advantages TMP is not yet widely used in the software industry due to the lack of coding standards, and software tools. A common problem with TMP is the tedious syntax, and long code. Libraries like boost::mpl help the pro- grammers by hiding implementation details of certain algorithms and containers, but still a big part of coding is left to the user. Due to the lack of a standard- ized interface for TMP, naming and coding conventions vary from programmer to programmer, which causes comprehensibility problems.

Template metaprograms are many times regarded as a pure functional language programs. The common properties include referential transparency (metaprograms have no side-effects) and the lack of variables, loops, and assignments. One of the most important functional properties of TMP is the immutability of defined entities,

i.e. in case we define constants, enumeration values, types their value or meaning can not be changed. Metaprograms does not contain assignments. Instead of them recursions and specializations are used in order to implement loops since the value of any loop variable can not be changed. Immutability – as in functional languages – has a positive effect too: unwanted side effects do not occur in metaprograms.

The similarities between the two programming paradigms require a more thor- ough examination, as the metaprogramming realm could benefit from the introduc- tion and library implementation of more functional techniques. In our view two methods are possible for integrating a functional interface into C++: either modi- fying the compiler to extend the language itself, or creating a library-level solution by using a preprocessor or macros. The first approach is probably quicker, eas- ier, and more flexible, but at the same time a language extension is undesirable in the case of a standardized, widely used language like C++. Our approach is the aforementioned second one. We re-implement the graph-rewriting engine of the Clean language as a compile-time metaprogram library using only ANSI standard compliant C++ language elements. The goal is to implement in TMP the laziness property of functional languages. Our approach has many advantages, like:

* + independent translation of the Clean code fragments into C++ template metapro- grams by separating the user written embedded code from the graph-rewriting engine.
  + easy usage, since the engine follows the graph-rewriting rules of the Clean lan- guage as it is defined in [[5](#_bookmark10)], the semantic of the translated code is as close to the programmers intension as possible.
  + high portability of the introduced library, as our solution uses only standard C++ elements.

The above advantages will be presented the following by detailed examples. First we describe the implemented laziness.

# Lazy Evaluation Strategy

As lazy evaluation is one of the most characteristic features of the functional lan- guage Clean, our research focuses on lazy evaluation and its application in C++ template metaprograms. In order to present the analogies between the lazy evalua- tion strategies and the behaviour of template metaprograms, we modeled the purely functional lazy language Clean in TMP.

Clean programs are represented by an expression graph in the compiler. This graph is *rewritten* automatically in several phases in runtime. The rewriting process is starting when the main function expression on the right side of the *Start* symbol is evaluated.

One of the basic data structures in Clean is the list. A list in Clean is defined as a linked list [[11](#_bookmark13)]. In the following we will describe lists as a head element and the ”tail”, as they are regarded in functional programs by the pattern matching mechanisms. The constructor handling these two parts of the list is called Cons. For example the list [2,3,4] is written as Cons 2 Cons 3 Cons 4 Nil, with Nil representing the end of the list.

The *lazy* evaluation strategy means *”a redex is only evaluated when it is needed to compute the ﬁnal result”* [[17](#_bookmark15)]. This laziness enables us to specify lists that contain an infinite number of elements, e.g. the list of natural numbers: [1..]. A classic example for the usage of lazy lists is the *Eratosthenes sieve* algorithm producing the first arbitrarily many primes.

Our running example uses EnumFrom. We defined the EnumFrom constructor to create an infinite list starting at a certain number. The list [2..] can thus be written as EnumFrom 2 (or [2..]). Of course to acquire the head element of a list we need to rewrite this expression to Cons 2 EnumFrom 3 (or [2,EnumFrom 3]),

i.e. this is a list containing 2 and [3..].

In the following we present a simple Clean program calculating the first 10 primes. (The symbols R1..R6 are line numberings)

(R1) take 0 xs = []

(R2) take n [x,xs] = [x, take n-1 xs]

(R3) sieve [prime:rest] = [prime : sieve (filter prime rest)] (R4) filter p [h:tl] | h rem p == 0 = filter p tl

= [h : filter p tl]

(R5) filter p [] = []

(R6) Start = take 10 (sieve ([2..]))

Clean follows the *left-right outermost* rewriting strategy. The first examined expres- sion is the Start expression. Clean first tries to apply one of the rewriting rules to the examined expression by substituting the current parameters with the rule’s pa- rameters. If it does not succeed, the arguments of every expression (subexpression) are examined recursively starting from left to right. If any of the subexpressions can be rewritten, the evaluation returns to the outermost expression. The evaluation process terminates, when none of the rules is applicable to any of the subexpressions. In our example the first examined expression is (F1). Since none of the rules’

left sides takes the form of (F1), Clean examines the first argument in (F1). It is 10, for which we have no rewriting rule, and this expression has no subexpressions either. The other argument sieve (EnumFrom 2) cannot be rewritten either. On the other hand the argument EnumFrom 2 is equivalent to [2, EnumFrom 3], and this is the substitution rule that takes place in this case.

As a rewriting rule has been applied, we return to the outermost expression which is now (F2). Again, neither this whole expression, nor its first argument can be rewritten, thus the second argument sieve [2, EnumFrom 3] is examined. The (R3) rule can be applied here with prime=2 and rest=EnumFrom 3 respectively.

The outermost expression now takes the form of (F4), which is the expression we return to. Now (R2) can be directly applied with n=10, x=2, and xs=sieve (filter 2 EnumFrom 3).

(F1) take 10 (sieve [2..])

(F2) take 10 (sieve [2, [3..]])

(F3) take 10 ([2, sieve (filter 2 [3..])])

(F4) [2, take 9 (sieve (filter 2 [3..]))]

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| (F5) | [2, | take | 9 | (sieve [3, filter | 2 | [4..])] |
| (F6) | [2, | take | 9 | [3, sieve (filter | 3 | (filter 2 [4..]))]] |

(F7) [2, 3, take 8 (sieve (filter 3 (filter 2 [4..])))]

...

The above example presents very well the applied lazy evaluation strategy. In order to simulate the inner workings of the lazy functional programming language Clean, the rewriting algorithm was implemented using TMP. The rewriting is effec- tuated by our engine, described in the next section.

# The Implementation of the Graph-rewriting Engine

In the following we present via examples the transformation method of an EClean program into C++ templates. Our EClean system consists of two main parts: a *parser* – responsible for transforming EClean code into metaprograms–, and the *en- gine* – executing of the functional code. In this paper we discuss the implementation of the latter.

The evaluation of the EClean code parts when a mixed C++ program is compiled is done in the following steps (see Figure [1](#_bookmark4)):

* The C++ preprocessor is invoked in the execution of the necessary header file inclusions and macro substitutions. The EClean library containing the engine and supporting metaprograms is also imported at this point, at the beginning.
* The original source code is divided into C++ parts and EClean parts.
* The EClean parts are transformed by the parser of the EClean into C++ metapro- gram code snippets.
* This transformed source code is passed to the C++ compiler.
* The C++ compiler invokes the instantiation chain at the code parts where the

Start expression is used, thus activating the EClean engine.

* The engine emulates Clean’s graph rewriting, and thus executes the EClean pro- gram snippets.
* When no further rewriting can be done, the finished expression’s value is calcu- lated, by demand.

ECLEAN

parser

standard C++

compiler

C++

ECLEAN

ECLEAN

ECLEAN

engine in TMP

translated ECLEAN code in TMP

eclean.h

compiled C++

Fig. 1. EClean transformation and compilation process

* 1. *The sieve program*

In the following we describe the above transformation procedure carried out by the parser to create metaprograms from the original EClean functional code written in section [3](#_bookmark2).

The EClean expressions are represented by types and typedefs. In this approach the Start expression of our example has the form take<mpl::int <10>,sieve<EnumFrom<mpl::int <2> > > >. Here take, sieve, and EnumFrom are all struct templates having the corresponding signatures.

The graph rewriting process can be emulated with the C++ compiler’s instan- tiation process. When a template with certain arguments has to be instantiated, the C++ compiler chooses the narrowest matching template of that name from the specializations. Therefore the rules can be implemented with template partial spe- cializations. Each partial specialization has an inner typedef called right which represents the right side of a pattern matching rule. At the same time the tem- plate’s name and parameter list represent the left side of a pattern matching rule, and the compiler will choose the most suitable of the specializations of the same name. Let us consider the following example, which describes the sieve rule (sieve [prime:rest] = [prime : sieve (filter prime rest)]).

template <class prime, class ys> struct sieve<Cons<prime,ys> >

{

typedef Cons<prime,sieve<filter<prime,ys> > > right;

};

The sieve template has two parameters, prime and ys. This template describes the workings of (R3) in our Clean example. In case a subexpression has the form sieve<Cons<N,T> > where N and T are arbitrary types, the previously defined sieve specialization will be chosen by the compiler as a substitute for the subexpression. Note that even though N and T are general types, the sieve template expects N to be a mpl::int , and T a list of mpl::int types.

However, in order to be able to apply this rewriting rule, an exact match is needed during the rewriting process. For example in (F1) during the evaluation process the previous sieve partial specialization will be considered as applicable when rewriting the subexpression sieve [2..].

The problem is that the argument [2..] (EnumFrom 2) does not match the sieve partial specialization parameter list, which is expecting an expression in the form Cons<N,T> with types N and T. During the compilation the C++ compiler will instantiate the type sieve<EnumFrom<mpl::int <2> > >. However this is a pattern matching failure which has to be detected. Therefore each function must implement a partial specialization for the general case, when none of the rules with the same name can be applied. The symbol NoMatch is introduced, which signs that even though this template has been instantiated with some parameter xs, there is no applicable rule for this argument. NoMatch is a simple empty class.

template <class xs> struct sieve

{

typedef NoMatch right;

};

The previously introduced filter function’s case distinction is used to deter-

mine in compile-time whether x is divisible by p, and depending on that decision either of the two alternatives can be chosen as the substitution. The C++ trans- formation of filter utilizes mpl::if for making a compile-time decision:

template <int p, class x, class xs >

struct filter<boost::mpl::int\_<p>, Cons<x,xs> >

{

typedef typename boost::mpl::if\_

<

typename equal\_to

<

typename modulus<x,p>::type, boost::mpl::int\_<0>

>::type, filter<p,xs>, Cons<x,filter<p,xs> >

>::type right;

};

The mpl::if construct makes a decision in compile-time. The first type pa-

rameter is the if condition, which in our case is an equal to template, whose inner type typedef is a mpl::bool . Depending on this bool ’s value, either the first, or the second parameter is chosen.

The working of the transformed EnumFrom is similar to the one of Clean: if a rewriting is needed with EnumFrom, a new list is created consisting of the list’s head number, and an EnumFrom withe the next number of the list.

template <class r> struct EnumFrom

{

typedef Cons<r,EnumFrom<boost::mpl::int\_<r::value+1> > > right;

};

All other functions of the EClean example of the Section [3](#_bookmark2) can be translated

into templates using analogies with the previous examples.

In the following we present the rewriting engine recognizing EClean expressions, and transforming them into TMP using the previous rules.

* 1. *The graph-rewriting engine*

Until now we have translated the Clean rewriting rules into C++ templates, by defining their names, parameter lists (the rule’s partial specialization), and their right sides. These templates will be used to create types representing expressions thus storing information in compile-time. This is the first abstraction layer. In the following we present the next abstraction level, that uses this stored information. This is done by the library’s core, the partial specializations of the Eval struct template, which evaluate a given EClean expression.

Since the specialization’s parameter is a template in itself (representing an ex- pression), its own parameter list has to be defined too. Because of this constraint, separate implementations are needed for the evaluation of expressions with different arities. In the following we present one version of Eval that evaluates expressions with exactly one parameter:

* + 1. template <class T1, template <class> class Expr>
    2. struct Eval<Expr<T1> >
    3. {
    4. typedef typename
    5. if\_c<is\_same<typename Expr<T1>::right,
    6. NoMatch>::value,
    7. typename
    8. if\_c<!Eval<T1>::second,
    9. Expr<T1>,
    10. Expr<typename Eval<T1>::result>
    11. >::type,
    12. typename Expr<T1>::right
    13. >::type result;

14

1. static const bool second =
2. !(is\_same<typename Expr<T1>::right,NoMatch>::value &&
3. !Eval<T1>::second);

18 };

The working mechanism of Eval is as follows: Eval takes one argument, an expression Expr with one parameter T1. The type variable T1 can be any type, e.g. int, a list of integers, or a further subexpression. The return type result defined in line 13 contains the newly rewritten subexpression, or the same input expression if no rule can be applied to the expression and its parameters.

When the template Expr has no partial specialization for the parameter T1, the compiler chooses the general template as described in Section [4.1](#_bookmark5). The compile-time if c in line 5 is used to determine whether this happened.

* If this is the case, the Expr<T1>::right is equal to NoMatch. Now another if c is invoked. In line 8 T1, the first (and only) argument is evaluated, with a recursive call to Eval. The boolean second determines whether T1 or any of its parameters could be rewritten. If no rewriting has been done among these children, Eval’s return type will be the original input expression. Otherwise the return type is the input expression with its T1 argument substituted with Eval<T1>::result, which means that either T1 itself, or one of its parameters has been rewritten. This mechanism is similar to type inference.
* On the other hand, if a match has been found (the if c conditional statement returned with a false value), the whole expression is rewritten, and Eval returns with the transformed expression (line 12).

The aforementioned boolean value second is defined by each Eval specialization (line 15). It is the logical value signaling whether the expression itself, or one of its subexpressions has been rewritten.

The implementation of Eval for more parameters is very similar to the previous example, the difference being that these parameters also have to be recursively checked for rewriting.

As our expressions are stored as types, during the transformation process the expression’s changes are represented by the introduction of new types. The process of the transformation is the very same as with the Clean example. The following types are created as right typedefs:

take<10,sieve<EnumFrom<2> > > take<10,sieve<Cons<2,EnumFrom<3> > > > take<10,Cons<2,sieve<filter<2,EnumFrom<3> > > > > Cons<2,take<9,sieve<filter<2>,EnumFrom<3> > > > Cons<2,take<9,sieve<3,filter<2,EnumFrom<4> > > > > Cons<2,take<9,Cons<3,sieve<filter<3,EnumFrom<4> > > > > > Cons<2,3,take<8,filter<3,filter<2,EnumFrom<4> > > > >

...

(Note that in the example all mpl::int prefixes are omitted from the int values

for the sake of readability.) The above steps demonstrates the implementation and the working mechanisms of the evaluation engine. The last step taken by the engine is given in the next subsection.

* 1. *Final rewriting of the expression*

In the factorial example we have seen that the finished expression after the in- stantiation process will be: times<mpl::int <5>, times<mpl::int <4>, times<mpl::int <3>, times<mpl::int <2>, mpl::int <1> > > > >. With a simple iteration it is now easy to multiply the values of list member mpl::int types with each other, thus giving the final answer in the form of an int value.

# Future work

One of the most interesting questions in our hybrid approach is to distinguish be- tween problems that can be dealt with by EClean alone (e.g. factorial computation), and those that do require template metaprogramming and compiler support. The EClean parser could choose function calls that can be run separately and their result computed without the transformation procedure and the invocation of the C++ compiler. On the other hand, references to C++ constants and types could be placed within the EClean code, and used by the EClean function in a callback-style. This would result in much greater flexibility and interactivity between EClean and C++.

Our proof-of-concept demo version of the EClean parser handles only the int elementary type and lists of integers. Other built-in types can be analogously used. In the future we will include support for more scalar types (bool, long, etc) besides the implemented Int, and the list construct. User defined composed types may require more complex solutions. Another interesting direction is the introduction of special EClean types like Type representing a C++ type, Func representing a C++ function or even a function pointer.

The parser will be extended with many error detections and recovery features, which can be easily implemented. The helpful error messages will aid the program- mer in using EClean and writing metaprograms.

The priority of EClean rewriting rules cannot be explicitly defined as opposed to Clean. In the EClean code if factorial 1 = 1 alternative is defined under the general factorial n = n\*factorial (n-1), then the specialized alternative will never match. However, in template form, due to the nature of the template instantiation mechanism, the Factorial<mpl::int <1> > alternative will match even if defined below the general Factorial. At this moment neither the parser nor the engine are capable of handling multiple matching. However, it is an important and interesting future development direction.

# Related Work

Functional language-like behavior in C++ has already been studied. *Functional C++* (FC++) [[12](#_bookmark14)] is a library introducing functional programming tools to C++, including currying, higher-order functions, and lazy data types. FC++, however, is a runtime library, and our aim was to utilize functional programming techniques in compile-time.

The boost::mpl library is a mature library for C++ template metaprogram- ming. Boost::mpl contains a number of compile-time data structures, algorithms, and functional-style features, like *Partial Metafunction Application* and *Higher- order metafunctions*. However, boost::mpl were designed mainly to follow the interface of the C++ Standard Template Library. There is no explicit support for lazy infinite data structures either.

# Conclusion

In this paper we discussed the Meta<Fun> project which enhances the syntactical expressivity of C++ template metaprograms. EClean, a subset of the general- purpose functional programming language Clean is introduced as an embedded lan- guage to write metaprogram code in a C++ host environment. The graph-rewriting system of the Clean language has been implemented as a template metaprogram library. Functional code fragments are translated into classical C++ template metaprograms with the help of a parser. The rewritten metaprogram fragments are passed to the rewriting library. Lazy evaluation of infinite data structures is im- plemented to demonstrate the feasibility of the approach. Since the graph-rewriting library uses only standard C++ language features, our solution requires no language extension and it is highly portable.

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<http://www.boost.org/regression-logs/cs-win32_metacomm/doc/html/boost_staticassert.html>