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Functional Extensions to the Boost Metaprogram Library

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**Abstract**

More and more C++ applications use template metaprograms directly or indirectly by using libraries based on that. Given the complexity of template metaprogramming, developers need supporting libraries. The most widely used one is the Boost template metaprogramming library. It implements commonly used compile time algorithms and meta-data structures in an extensible and reusable way. Despite the well- known commonality of template metaprogramming and the functional programming paradigm, boost::mpl lacks a few important features directly supporting the functional style. In this paper we evaluate how and in what degree boost::mpl supports functional programming and present new elements it can be improved with.

*Keywords:* C++, boost::mpl, template metaprogramming, functional programming

# Introduction

Templates are key elements of the C++ programming language [[3](#_bookmark7)]. Apart from their primary role – capturing commonalities of abstractions without performance penalties at runtime – they form the base of *template metaprogramming*. In 1994 Erwin Unruh used C++ templates and template instantiation rules to write a pro- gram that is “executed” as a side effect of compilation [[21](#_bookmark19)]. It turned out that cleverly designed C++ code is able to utilise the type-system of the language and force the compiler to execute a desired algorithm [[23](#_bookmark23)]. These compile time programs are called C++ template metaprograms and template metaprogramming later have been proved to form a Turing-complete sub-language of C++ [[4](#_bookmark9)].

Today programmers write metaprograms for various reasons, like implement- ing *expression templates* [[24](#_bookmark24)], where runtime computations can be replaced with compile time activities to enhance runtime performance; *static interface checking*,

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which increases the ability of the compiler to check the requirements against tem- plate parameters at compile time, i.e. to form constraints on template parameters [[13](#_bookmark16),[18](#_bookmark20)]; *active libraries* [[26](#_bookmark25)], acting dynamically at compile time, making decisions and optimizations based on programming contexts. Other applications involve em- bedded domain specific languages such as the Ararat system [[5](#_bookmark10)] for a type-safe SQL interface and boost:xpressive [[29](#_bookmark29)] for regular expressions.

In the last fifteen years major efforts were put into creating the foundations of template metaprogramming including meta data structures and algorithms. Boost is one of the most important C++ library collections. The libraries are used by a wide range of C++ users and application domains. Boost makes extensive use of templates and has been a source of extensive work and research into metapro- gramming in C++. Boost has a template metaprogramming library [[27](#_bookmark27)] providing tools to build template metaprograms in a structured way. The library implements commonly used utilities and algorithms in an extensible and reusable way. It helps reducing the amount of boilerplate code in C++ template metaprograms.

C++ template metaprogramming follows the functional paradigm [[14](#_bookmark17)], thus experience gained in the field of functional programming can be reused in C++ template metaprogramming. When developers intentionally follow the functional paradigm, they can easily apply the techniques developed over the years.

To follow the functional paradigm directly, the tools have to be developed with functional programming in mind. We have developed a complex template metapro- gramming library, that depends heavily on the functional paradigm. We were using the boost metaprogramming library. We have missed a number of tools that are commonly used in functional languages but are not yet available for C++ template metaprogramming. In this paper we evaluate some functional aspects of the boost metaprogramming library and propose new elements providing more direct support of functional programming. We have implemented these new elements and have used in the complex template metaprogramming library we built. [[30](#_bookmark30)] [[16](#_bookmark18)]

In this paper we introduce some extensions to the boost metaprogram library following the functional paradigm. In Section [2](#_bookmark1) we discuss lazy evaluation of compile time selection, in Section [3](#_bookmark2) we implement (meta)function composition, and Section [4](#_bookmark3) overviews currying. Related works are found in Section [5](#_bookmark4) and we summarize our results in Section [6](#_bookmark5).

# Laziness

When there is a selection in a metaprogram, such as a boost::if or boost::eval if, one path of execution is selected based on the condition of the selection. Evaluating functions on the other path may lead to an error. In these situations being able to evaluate expressions lazily is critical. We’ll examine how boost::mpl supports lazy evaluation in the selection constructs and how they could be improved.

A nullary metafunction is a metafunction taking 0 arguments [[1](#_bookmark6)], it is the im- plementation of thunks [[8](#_bookmark12)] in C++ template metaprogramming. Unfortunately the

value of a nullary metafunction can only be accessed explicitly. When someone accesses the value of a nullary metafunction, he has to access a nested type of the nullary metafunction. This nested type is called type. The first time the nested type is accessed, the C++ compiler evaluates the metafunction. This value is reused every time the nested type is accessed again later, during the same compilation. For example, here is a simple value:

struct infinite {};

and here is a nullary metafunction:

struct always\_infinite

{

typedef infinite type;

};

There is no other way to access the value of a nullary metafunction, but by using its nested type. An argument of a template metafunction can be a value or a nullary metafunction, but only one of them. Thus, a metafunction can’t support lazily and eagerly evaluated arguments at the same time, only one of them.

Classes representing data in template metaprogramming can be designed to be flexible by adding a nested type member to them. This nested type member evaluates to the class itself. For example:

struct infinite

{

typedef infinite type;

};

This class can be passed to template metafunctions expecting a nullary metafunc- tion: this class is a data-value and a nullary metafunction at the same time. This class as a nullary metafunction evaluates to itself, thus it represents itself when it is evaluated as a nullary metafunction. Wrappers of static constants, such as int , bool support this: they have a nested type called type that is a typedef of the wrapper class itself. These classes can be passed to metafunctions expecting eagerly evaluated arguments, because these classes represent data values. These classes can also be passed to metafunctions expecting lazily evaluated arguments, because these classes are nullary metafunctions evaluating to themselves.

A nullary metafunction can be created from any template metafunction by ap- plying it on some arguments but not accessing the nested ::type. For example

template <class x> struct identity;

is a metafunction taking one argument,

identity<infinite>

is a nullary metafunction.

Nullary metafunctions can implement lazy evaluation in C++ template metapro- gramming because they are not evaluated until their nested type class is used. We

can enforce eager evaluation by directly accessing the nested type class. As an example, here are the lazy and eager evaluations of the same function:

identity<infinite> // Lazy evaluation identity<infinite>::type // Eager evaluation

When we do lazy evaluation, we don’t access the metafunction’s nested type called type. We do it, when we need to force eager evaluation. When we access the nested type called type, we force the C++ compiler to evaluate the metafunction.

Let’s look at a more complex example.

struct infinite {};

template <class a, class b> struct divide :

if\_<

typename equal\_to<int\_<0>, b>::type, infinite,

typename divides<a, b>::type

>

{};

We use the infinite class for representing the infinite value and a divide function which divides its two operands. When the second operand is zero, the division is invalid. In this case our function evaluates to infinite. This code doesn’t work. For example divide<int <3>, int <0> >::type doesn’t evaluate to infinite, it breaks the compilation. The reason why the compiler generates an error is that the second case of if is evaluated eagerly. if takes values as arguments, it expects eager evaluation of both cases.

boost::mpl tackles this problem with eval if, which takes nullary metafunc- tions as arguments for the true and false cases. eval if evaluates only the selected branch, avoiding instantiation of invalid templates. Here is the correct version of the above example using eval if:

struct infinite {};

template <class a, class b> struct divide :

eval\_if<

typename equal\_to<int\_<0>, b>::type, identity<infinite>,

divides<a, b>

>

{};

infinite had to be passed to identity because infinite is a value, not a nullary metafunction. One way of transforming a value into a nullary metafunction is passing it to identity. A value can be built in a special way, that it is not only

a value, but a nullary metafunction evaluating to itself as well. We could add a nested type called type to infinite, which is a typedef of infinite to make it a value and a nullary metafunction:

struct infinite

{

typedef infinite type;

};

Now both functions expecting a nullary metafunction and functions expecting a value accept it, and it behaves as expected in both situations.

The two ideas can be combined:

struct infinite : identity<infinite> {};

Now infinite is a value and a nullary metafunction evaluating to itself at the same time. We reused the identity metafunction in the implementation of infinite.

The advanced infinite simplifies the definition of divide: template <class a, class b>

struct divide :

eval\_if<

typename equal\_to<b, int\_<0> >::type, infinite,

divides<a, b>

>

{};

We didn’t have to pass infinite to identity, because it’s a nullary metafunction evaluating to itself.

Consider a more complicated, but still simple example:

template <class a, class b> struct some\_calculation :

eval\_if<

typename equal\_to<b, int\_<0> >::type,

// ....,

eval\_if< typename less<

typename divides<a, b>::type, int\_<10>

>::type,

// ...,

// ...

>

>

{};

In this metafunction we need to make a decision based on the quotient of the two

arguments. When the second argument is zero, the division can not be performed, thus we have to handle that case separately. This is what the outer eval if is for. The code above doesn’t work when the second argument, b is zero because even though the branches of eval if are evaluated lazily, its condition isn’t. Thus the condition of the nested eval if is instantiated when some calculation is instan- tiated, regardless of the value of the outer eval if’s condition. When the value of b is zero, instantiation of the nested eval if’s condition generates an error.

One possible solution is moving the inner eval if to another template meta- function, such as

template <class a, class b> struct some\_calculation\_helper :

eval\_if<

typename less<typename divides<a, b>::type, int\_<10> >::type,

// ...,

// ...

>

{};

The implementation of some calculation is:

template <class a, class b> struct some\_calculation :

eval\_if<

typename equal\_to<b, int\_<0> >::type,

// ....,

some\_calculation\_helper<a, b>

>

{};

some calculation helper is evaluated lazily. When the condition in some calculation evaluates to false, some calculation helper is not instanti- ated, thus the invalid division is not evaluated and does not break the compilation. The problem with this solution is that we have to pollute the namespace with new classes and the code of some calculation is defined in multiple metafunctions.

A solution is needed, where the nested conditions don’t have to be factored out to other metafunctions.

The problem can be solved by evaluating the condition of eval if lazily. We propose a completely lazy version of eval if, which takes a nullary metafunction as its condition. Its implementation is straight forward:

template <class condition, class true\_case, class false\_case> struct lazy\_eval\_if :

eval\_if<typename condition::type, true\_case, false\_case>

{};

Using lazy eval if, the last example we’ve seen can be solved as well:

template <class a, class b>

struct some\_calculation : eval\_if<

typename equal\_to<b, int\_<0> >::type,

// ....,

lazy\_eval\_if<

apply<less<divides<a, \_1>, int\_<10> >, b>,

// ...,

// ...

>

>

{};

The nested lazy eval if evaluates its condition only when the lazy eval if it- self is evaluated. When the condition of the outer eval if evaluates to true, lazy eval if it not evaluated, thus its condition is not evaluated either. It guar- antees, that when b is 0, the invalid division in the condition of lazy eval if is not evaluated and does not break the compilation.

We have considered implementing this solution in a more generic way using a template that makes the arguments of a metafunction lazy. Unfortunately this can not be done. Such a solution could delay the evaluation of the arguments until the metafunction is evaluated. All arguments of it would have to be evaluated at the same time. It means evaluating the condition and the true and false branches of the selection. This would evaluate the unused branch as well and when the evaluation of that branch leads to an error, it would break the compilation.

Vesa Karvonen wrote a fully lazy version of the standard template library as a proof of concept [[11](#_bookmark14)]. In his library every template metafunction evaluates its arguments lazily. When someone has to pass a class without a nested type class pointing to itself as argument to a template metafunction, he has to wrap it with a template adding this capability. Only a proof-of-concept implementation of this library is available.

We’ve seen that in some cases it is essential for template metafunctions to evalu- ate their arguments lazily. boost::mpl doesn’t do it in all cases. We’ve implemented an addition that covers cases that are not supported by the library in its current form.

# Function composition

Suppose we have to write a metafunction taking a number in the range [*−π, π*] as its argument and returning the square of the tangent of that number or a special class called not a number when the argument is *±π* . Real world examples can be found in [[30](#_bookmark30)]. They are more complicated, thus we use this artificial example for the demonstration of the problem.

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Assume we have template metafunctions to calculate the absolute value (abs) and the tangent (tan) of a number. tan breaks the compilation when evaluated with a number the tangent of which is not defined. The following solution doesn’t

work

template <class deg> struct square\_tangent :

eval\_if<

typename equal\_to<

typename abs<deg>::type, divides<pi, int\_<2> >::type

>::type, not\_a\_number,

square<typename tan<deg>::type>

>

{};

when the argument is *±π*

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because the evaluation of the true and false cases of

eval if happens lazily, but square takes a value as its argument, not a nullary metafunction, thus tan has to be evaluated eagerly by accessing its type member, and eager evaluation happens when square tangent is instantiated.

In case the function we use in the true or false case of an eval if doesn’t take nullary metafunctions as arguments, its arguments need to be evaluated prior to the evaluation of the function itself and the enclosing eval if. In our example the false case of the eval if is the evaluation of square with the value of tan<deg> as its argument. square doesn’t accept nullary metafunctions as arguments, we have to evaluate tan<deg> before evaluating square. We embedded square in an eval if expression, thus we have to evaluate tan<deg> before evaluating eval if. It means that we have to calculate the tangent of a value before we could check if it’s a valid operation or not.

If every template metafunction took nullary metafunctions as arguments we wouldn’t have this problem. Requiring all metafunctions to take nullary metafunc- tions as arguments would solve the problem, but we can’t ensure that. For example we can’t affect third-party libraries. When building template metaprograms, we should be able to use libraries expecting us evaluating our functions in a eager way. We could factor the code of the branches out to external classes. In this case only the chosen branch is instantiated, thus only that metafunction is evaluated.

The other, invalid branch is not instantiated and does not break the compilation.

template <class deg>

struct square\_tangent\_impl : square<

typename tan<deg>::type

>

{};

template <class deg> struct square\_tangent :

eval\_if<

typename equal\_to<

typename abs<deg>::type,

typename divides<pi, int\_<2> >::type

>::type, not\_a\_number,

square\_tangent\_impl<deg>

>

{};

This solution works, but in this case the business logic of the function is scattered in multiple metafunctions which makes it difficult to understand. The more selection points a function has the more splits it requires.

A third solution is building anonymous template metafunctions in place, so we don’t have to move parts of the business logic to external classes. We can do it by using boost::mpl’s lambda expressions. The lambda expression is then evaluated lazily by eval if. The lambda-based implementation of our example metafunction

template <class deg> struct square\_tangent :

eval\_if<

typename equal\_to<

typename abs<deg>::type, divides<pi, int\_<2> >::type

>::type, not\_a\_number,

apply<square<tan<\_1> >, deg>

>

{};

solves the problem and keeps the business logic at one place. This was a simple example. When we have to deal with template metafunction classes [[1](#_bookmark6)] instead of template metafunctions, it has a large syntactical overhead. When square and tan are template metafunction classes, this solution gets more difficult to write, understand and maintain. This is how the square tangent would look like, if square and tan were template metafunction classes:

template <class deg> struct square\_tangent :

eval\_if<

typename equal\_to<

typename abs<deg>::type, divides<pi, int\_<2> >::type

>::type, not\_a\_number,

apply<square::apply<tan::apply<\_1> >, deg>

>

{};

We can use the apply metafunction of the boost metaprogramming library only in the outermost call of the false branch of eval if, otherwise the square and

tan functions are evaluated eagerly. When we’re developing higher order metafunc- tions, and the metafunction classes are arguments of our metafunctions it gets more complicated.

We had to use complex tools to solve a rather simple problem which is applying a chain of functions on an argument. It is so common that functional languages often have a special operator for it in the language or the standard library. Due to the functional nature of C++ template metaprograms introducing it in template metaprogramming could reduce the complexity of the code of metaprograms.

We propose a compose metafunction for function composition. It takes any number of metafunction classes as arguments and evaluates to an anonymous meta- function class implementing the chain of the arguments. Its implementation requires variadic templates. The current C++ standard hasn’t got variadic template [[6](#_bookmark11)] sup- port, but there are workarounds we can use with the current compilers [[28](#_bookmark28)] and the upcoming standard, C++0x will have variadic template support. A future work is implementing compose using this new feature. This metafunction can be im- plemented by boost lambda expressions or manually as well, its implementation is straight forward. Here is an example implementation for a fixed number of functions to compose:

template <class f1, class f2> struct compose2

{

template <class a> struct apply

{

typedef typename

apply<f1, typename apply<f2, a>::type>::type type;

};

};

compose3, compose4, etc. can be implemented similarly, their implementation can be automatically generated using the boost preprocessor metaprogramming library [[28](#_bookmark28)]. A compose function can be written to call one of the above:

struct unused {};

template <

class f1 = unused, class f2 = unused, class f3 = unused, class f4 = unused

>

struct compose;

template <class f1, class f2>

struct compose<f1, f2, unused, unused> : compose2<f1, f2>

{};

template <class f1, class f2, class f3> struct compose<f1, f2, f3, unused> :

compose3<f1, f2, f3>

{};

template <class f1, class f2, class f3, class f4> struct compose<f1, f2, f3, f4> :

compose4<f1, f2, f3, f4>

{};

It uses default template arguments and template specialisation to detect the number of arguments and choose the right version of composen. By using compose we get a cleaner implementation of our sample function:

template <class deg> struct square\_tangent :

eval\_if<

typename equal\_to< typename abs<deg>::type,

divides<pi, int\_<2> >::type

>::type, not\_a\_number,

apply<compose<square, tan>, deg>

>

{};

Here we used compose to build the composition of the two metafunctions we have to apply on deg. compose is a metafunction class we can apply deg on to apply the functions on deg. It is evaluated lazily, the functions are applied only when the condition of eval if evaluates to false, thus the functions are not applied when it would lead to a compilation error.

Compose is easy to use and reduces the syntactical complexity of template metaprograms. It encourages developers to follow the functional paradigm in tem- plate metaprogramming.

# Currying

Currying is supported by several functional languages. When we have a function taking *n* arguments, we can apply one argument on it and get a function taking *n −* 1 arguments. We can continue doing it until *n* reaches 1. When we have a function taking only 1 argument and we apply one argument on it, we get the value

of the function. This is a special form of partial function application which can be simulated using lambda expressions provided by the metaprogramming library of boost. Lambda expressions are difficult to use and have limitations.

Given the functional nature of C++ template metaprograms [[14](#_bookmark17)] solutions to problems available in functional languages could be ported to C++ template metaprograms. When we’re porting code written in a functional language, keep- ing the logic the original code follows helps debugging and later improvement of the code. A number of functional libraries make heavy use of currying, it should be supported in C++ template metaprograms as well. We propose a solution for extending metaprograms with currying support without changing existing code.

We’re going to use the following example to demonstrate what currying means in C++ template metaprogramming. Consider a function that calculates the area of a rectangle.

template <class x1, class y1, class x2, class y2> struct area :

multiplies< minus<x2, x1>, minus<y2, y1>

> {};

This function takes 4 numbers as arguments: two opposite points of the rectangle. It takes 4 arguments in one step and calculates the result immediately. If this function was using currying, it would be a function accepting one number. The value of this function would be an anonymous function taking 1 number as argument. The value of that function would be another anonymous function taking 1 argument. The value of that function would be the area of the rectangle. It would be something like the following template metaprogram:

template <class x1> struct area

{

struct type

{

template <class y1> struct apply

{

struct type

{

template <class x2> struct apply

{

struct type

{

template <class y2> struct apply :

multiplies< minus<x2,x1>, minus<y2,y1>

>

{};

};

};

};

};

};

};

As you can see adding currying to a function by hand has a large syntactical over- head. It leads to writing a large amount of boilerplate code. We propose a template metafunction taking a template metafunction as argument and building the curried version automatically. The generated metafunction maintains a compile time list internally and every time a new argument is passed to it, it stores the argument in the list. When all of the arguments are available, it applies the full argument list on the original template metafunction.

We need a function that collects its arguments in a compile time list. The func- tion takes the function to curry and the argument list collected so far as arguments. It has to take the number of arguments left as an argument as well.

template <

class UnpackedMetafunctionClass, class ArgumentsLeft,

class ArgumentList

>

struct curryImpl : eval\_if<

typename equal\_to<ArgumentsLeft, int\_<0> >::type, apply<UnpackedMetafunctionClass, ArgumentList>, nextCurryingStep<

UnpackedMetafunctionClass, ArgumentsLeft, ArgumentList

>

> {};

This template metafunction takes the function to curry as its first argument, UnpackedMetafunctionClass, the number of arguments to collect as its second argument, ArgumentsLeft and the list collected so far as its third argument, ArgumentList. It’s important, that the function to curry expects one argument, all arguments of the function in a compile time list. We have to use a helper meta- function class:

template <

class UnpackedMetafunctionClass,

class ArgumentsLeft, class ArgumentList

>

struct nextCurryingStep { typedef nextCurryingStep type;

template <class T>

struct apply : curryImpl< UnpackedMetafunctionClass,

typename minus<ArgumentsLeft, int\_<1> >::type, typename push\_back<ArgumentList, T>::type

> {};

};

It handles one currying step. It implements the metafunction class taking the next currying argument and stores it in the list.

Using these functions we can implement our curry functions. These functions take metafunctions as arguments and build a curried version of them. Template metafunctions are template classes, thus the argument of the curry functions will be templates. Unfortunately we have to create different curry functions to handle template metafunctions taking different number of arguments. We call the curry function handling a template metafunction with n arguments curryn. For example the curry function handling template metafunctions with 4 arguments is called curry4. As an example, here is the implementation of it:

template <template <class, class, class> class F> struct curry4 :

curryImpl<unpack\_args<quote4<T> >, int\_<4>, deque<> >::type {};

We had to use helper functions from boost::mpl. We used quote4 because curryImpl expects template metafunction classes while we had a template meta- function, thus we had to generate a metafunction class from it. We used unpack args because curryImpl passes the arguments of the metafunction as a compile time list to the metafunction class we call it with.

The rest of the curry functions, such as curry1, curry2 are implemented in a similar way. We can use the boost preprocessor library [[28](#_bookmark28)] to generate them automatically. The implementation of curry0 is special, since a metafunction taking 0 arguments evaluates to its value directly. It doesn’t take any arguments, thus currying doesn’t change anything in this special case. It is supported to make the interface complete:

template <class T> struct curry0 : T {};

Using the curry functions, the above example can be generated from the simple

area metafunction we presented at the beginning of this section:

curry4<area>

When we need currying, curry is a tool we can use to avoid writing a large amount of boilerplate code. It makes heavy use of automatic code generation in C++. In situations where we can’t change the implementation of a metafunction because other codes rely on it or because it’s coming from a third party library, external currying support is the only option and in such cases this tool can do the hard work.

# Related work

Todd Veldhuizen demonstrated how to implement non-trivial C++ template metaprograms [[25](#_bookmark26)]. He didn’t present the functional aspects of template metapro- gramming.

Andrei Alexanderscu uses template metaprogramming tools in his library called Loki [[2](#_bookmark8)]. He builds compile time lists called Typelists and uses them as a source of code generation. He doesn’t mention functional aspects.

FC++ [[12](#_bookmark15)] is a C++ library providing runtime functional programming support for C++. Template metaprograms are always evaluated at compile time. The development of template metaprograms is different from runtime programs, thus they need different supporting tools to develop software following the functional paradigm.

Bartosz Milewski pointed out the commonalities of functional programming and C++ template metaprogramming in his talk and on his blog [[14](#_bookmark17)]. He demonstrates the capabilities of C++ and C++0x to support the functional paradigm in template metaprograms but he doesn’t consider the tools of the boost metaprogramming library and compatibility with those tools.

In [[19](#_bookmark21)] a tool transforming a simple language based on lambda expressions was presented. Lambda expressions form an NP-complete language [[9](#_bookmark13)]. The lambda ex- pression based syntax reduced the syntactical overhead of C++ template metapro- grams.

In [[20](#_bookmark22)] a transformation tool was presented which transforms code written in a simplified version of Clean, called E-Clean to C++ template metaprograms. The generated code was more efficient than the hand-written C++ template metapro- gram for the same problem.

Vesa Karvonen built a fully lazy version of the boost template metaprogramming library. [[11](#_bookmark14)] It was only a proof of concept implementation, the boost library is still not fully lazy, however it would make it usable in many situations.

# Summary

C++ template metaprogramming can save development and maintenance effort when used appropriately. Given that it’s naturally following the functional paradigm [[14](#_bookmark17)], we’ve evaluated how the most widely used C++ template metaprogramming library, boost::mpl supports development in a functional style. We’ve seen that its support for lazy evaluation is good and proposed an addition for further im- provement. Explicit support of function composition is missing, we’ve proposed an

implementation of it. We’ve also presented a way of externally adding currying support to template metafunctions and metafunction classes. The complexity of template metaprograms can be simplified using the tools presented in this paper by eliminating unnecessary helper metafunctions and moving the entire business logic of a metafunction to one location.

We’ve found that the boost library helps following the functional paradigm. We’ve presented ways for improving this support further. We’ve implemented these additions and used in the construction of complex template metaprograms. [[30](#_bookmark30)]

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