Template Metaprogramming Techniques for Concept-Based Specialization

Bruno Bachelet, Antoine Mahul, Loïc Yon

Generic Programming: Controlling Static Specialization with Concepts in C++

Bruno Bachelet [1,4], Antoine Mahul [2,5]
and Loïc Yon [3,4]

Research Report LIMOS/RR-10-18

Revised February 2012

1. bruno.bachelet@isima.fr - http://frog.isima.fr/bruno
2. antoine.mahul@clermont-universite.fr
3. loic.yon@isima.fr - http://www.isima.fr/~loic
4. LIMOS, UMR 6158-CNRS, Université Blaise Pascal, BP 10125, 63173 Aubière, France.
5. CRRI, Clermont Université, BP 80026, 63177 Aubière, France.

Abstract

In generic programming, software components are parameterized on types (and sometimes static values, as in C++) rather than dynamic values. When available, a static specialization mechanism allows building, for a given set of parameters, a more suitable version of a generic component than its primary version. The normal C++ template specialization mechanism is based on the type pattern (or sometimes the static value) of parameters, which may not be accurate enough and may lead to ambiguities or false specializations. This is mainly due to the fact that some relationships between types, which can be considered as similar in some ways, are missing. Thus, it is not always possible to determine an order of the specializations of a generic component.

Concepts can be used to introduce relationships between "similar" types: a concept represents a set of requirements for a component that among others refer to its interface and its behavior. This paper describes generic programming techniques in C++ for declaring concepts, "modeling" relationships (between a type and a concept) and "refinement" relationships (between two concepts), and for controlling template specializations based on a taxonomy of concepts. This control relies on a metaprogram that determines, in a given static specialization context, the most specialized concept of any type instantiating a template parameter.

The solution presented here is open for retroactive extension: at any time, a new concept or a new modeling/refinement relationship can be declared, or a new template specialization can be defined; and this new statement will be picked up by the specialization mechanism. The control is also improved by avoiding false specializations and many ambiguities during the specialization process.

Keywords: generic programming, template specialization, concept-based overloading/specialization, metaprogramming.

Résumé

En programmation générique, les composants logiciels sont paramétrés sur des types (et parfois des valeurs statiques, comme en C++) plutôt que sur des valeurs dynamiques. Quand il est disponible, un mécanisme de spécialisation statique permet de construire, pour un jeu de paramètres donné, une version plus adaptée d'un composant générique que sa version initiale. Le mécanisme normal de spécialisation d'un *template* en C++ repose sur le patron de type (ou parfois la valeur statique) de paramètres, ce qui n'est parfois pas assez précis et peut conduire à des ambiguïtés ou à de fausses spécialisations. Ceci est principalement dû au fait que certaines relations entre types, qui peuvent être considérés comme similaires d'une certaine manière, sont manquantes. Ainsi, il n'est pas toujours possible d'établir un ordre des spécialisations d'un composant générique.

Les concepts peuvent être utilisés pour introduire des relations entre types "similaires" : un concept représente un ensemble de spécifications pour un composant qui peuvent, entre autres, faire référence à son interface et à son comportement. Ce rapport décrit des techniques de programmation générique en C++ pour déclarer des concepts, des relations de "modélisation" (entre un type et un concept) et des relations de "raffinement" (entre deux concepts), et pour contrôler les spécialisations de *templates* à partir d'une taxonomie de concepts. Ce contrôle repose sur un métaprogramme qui détermine, dans un contexte de spécialisation statique donné, le concept le plus spécialisé de tout type instanciant un paramètre *template*.

La solution présentée ici permet une extension rétroactive : à tout moment, un nouveau concept ou une nouvelle relation de modélisation/raffinement peut être déclarée, ou une nouvelle spécialisation de *template* peut être définie ; et cette nouvelle déclaration sera prise en compte par le mécanisme de spécialisation. Le contrôle est également amélioré en évitant les fausses spécialisations et de nombreuses ambiguïtés au cours du processus de spécialisation.

Mots clés : programmation générique, spécialisation de *template*, surcharge/spécialisation basée concept, métaprogrammation.

Abstract

In generic programming, software components are parameterized on types (and sometimes static values, as in C++) rather than dynamic values. When available, a static specialization mechanism allows building, for a given set of parameters, a more suitable version of a generic component than its primary version. The normal C++ template specialization mechanism is based on the type pattern (or sometimes the static value) of parameters, which may not be accurate enough and may lead to ambiguities or false specializations. This is mainly due to the fact that some relationships between types, which can be considered as similar in some ways, are missing. Thus, it is not always possible to determine an order of the specializations of a generic component.

Concepts can be used to introduce relationships between "similar" types: a concept represents a set of requirements for a component that among others refer to its interface and its behavior. This paper describes generic programming techniques in C++ for declaring concepts, "modeling" relationships (between a type and a concept) and "refinement" relationships (between two concepts), and for controlling template specializations based on a taxonomy of concepts. This control relies on a metaprogram that determines, in a given static specialization context, the most specialized concept of any type instantiating a template parameter.

The solution presented here is open for retroactive extension: at any time, a new concept or a new modeling/refinement relationship can be declared, or a new template specialization can be defined; and this new statement will be picked up by the specialization mechanism. The control is also improved by avoiding false specializations and many ambiguities during the specialization process.

1 Introduction

Generic programming aims at providing software components, mainly algorithms and data structures, as general as possible and broadly adaptable and interoperable [8], with no loss of efficiency when the language supports generics without run-time overhead. Generic programming relies on the notion of a generic component that is a component (class, function, or method) with parameters that are types or static values, instead of dynamic values as the usual parameters of functions and methods.

1.1 Static Specialization

Similar to inheritance in object-oriented programming, which allows the specialization of classes, C++ provides a mechanism to specialize generic components (called *templates*). The decision to select a specialized version of a template is made by the compiler based on the type pattern (or static value) of parameters at instantiation. Here is a C++ example of a generic class, `ArrayComparator`, that allows comparing arrays of length `N` and containing elements of type `T`.

```
template <class T, int N> class ArrayComparator {
 public:
  static int run(const T * a, const T * b) {
   int i = 0;
   while (i<N && a[i]==b[i]) ++i;
   return (i==N ? 0 : (a[i]<b[i] ? -1 : 1));
  }
};
```

A specialization of the template with `T` = `char`, presumably more efficient than the primary version, is proposed.

```
template <int N> class ArrayComparator<char,N> {
 public:
  static int run(const char * a, const char * b) { return memcmp(a,b,N); }
};
```

1.2 Concepts

In generic programming, the instantiation of the parameters of a generic component raises two concerns: *(i)* how to ensure that a type instantiating a parameter fulfills the requirements to be properly used by the generic component (e.g., any type instantiating `T` must provide operators `<` and `==` in the `ArrayComparator` class); *(ii)* how to find the best static specialization of the generic component for a given instantiation of the parameters (e.g., if type `char` instantiates parameter `T`, then specialization `ArrayComparator<char,N>` must be selected).

To specify requirements for a type, the notion of a "concept" has been introduced [3]. When a type instantiates a parameter of a generic component, it must follow a set of requirements represented by a "concept". Among others, these requirements refer to the interface of the type (e.g., the existence of a method) and its behavior (e.g., the complexity of a method). When a type fulfills the requirements of a concept, it is said that the type "models" the concept. The notion of specialization between concepts is possible and is called "refinement": a concept "refines" a more general concept.

For instance, let us define the concept `Integral` that models the requirements of an integral number, and the concept `Numerical` that models the requirements of any kind of number. One can state that type `int` models concept `Integral`, and concept `Integral` refines concept `Numerical`.

1.3 Challenges

Concern (i) of Section 1.2 is referred to as "concept checking" [14], and its goal is to identify at compile time which types do not model the concepts required by a generic component. A concept acts like a contract between the users and the author of a generic component: the author specifies requirements on the parameters using concepts, and the users must instantiate the parameters with types that fulfill these requirements, i.e., with types that model the specified concepts.

In C++, concepts can not be defined explicitly and they are only documentation (e.g., *Standard Template Library*). This leads to late error detections, and thus to cryptic error messages [14]: for instance, let us declare the instantiation `ArrayComparator<x,10>`; if type `x` has no operator `<`, the error will be detected in method `run`, and not at the instantiation declaration. Some langages, such as Java, rely on interfaces to express requirements on parameter types. Constraints can be expressed on the parameters of a generic component in the following form: parameter `T` must be a "subtype" of `U`, where `T` is a subtype of `U` if `T` inherits from class `U`, or `T` implements interface `U`, or `T` and `U` are the same type [4].

Concern (ii) of Section 1.2 is referred to as "concept-based overloading" [9], but in this article, we propose to use the term "concept-based specialization" as we will focus more on class specialization than function overloading. The goal of concept-based specialization is to control the specialization of generic components with concepts rather than type patterns. By pattern, we mean a type or a parameterized type (e.g., `T*` or `vector<T>`), or a "template template" parameter [16] (e.g., `template <class> class U`). Specialization based on type patterns can lead to ambiguities (the compiler cannot decide between two possible specializations) or false specializations (the compiler selects the wrong specialization), as it will be presented in Section 2.

Several attempts have been made to represent concepts in C++. On one hand, implementations for concept checking have been proposed, mainly to ensure interface conformance of types instantiating template parameters [12, 14]. On the other hand, an implementation for concept-based specialization has been proposed [11]. In this solution, the specialization is based on both the SFINAE (*substitution failure is not an error*) principle [2] and a mechanism to answer the question

"does type T model concept C ?" (through the `enable_if` template). However this approach may still lead to ambiguities [6].

More recently, an attempt has been initiated to define an extension of the C++ language to support concepts [6, 13] that may be added to the C++ Standard [7]. This extension is available within the experimental compiler ConceptGCC [6, 10], and is implemented as ConceptClang in Clang, a C language family front-end for the LLVM compiler [15]. In the meantime, there seems to be no satisfactory solution directly available in standard C++ compilers for concept-based specialization that avoids ambiguities and false specializations.

1.4 Proposal

We propose here a C++ library that focuses on the concept-based specialization aspect only. Due to portability concerns, our goal was to provide a solution that could be used with any standard C++ compiler, with no need of an additional tool such as a preprocessor. Our solution enables declaring concepts, modeling relationships, and refinement relationships. Once a taxonomy of concepts has been declared, it can be used to control the specialization of generic components: to define a specialization, concepts are used instead of type patterns to constrain parameters. At instantiation time, the selection of the best specialization relies on a metaprogram that determines, in the context of a given static specialization, the most specialized concept of any type instantiating a parameter of a generic component.

Even if this proposal does not detect directly concept mismatches to provide more understandable error messages, it needs to perform some checking on concepts to control the specialization process. The checking is only based on "named conformance" [12] (i.e., checking on whether a type has been declared as modeling a given concept), and avoids "structural conformance" (i.e., checking on whether a type implements a given interface).

Following the key ideas of generic programming [8], mainly to express components with minimal assumptions, and to enable that the most specialized, and thus presumably the most efficient, form of a generic component is chosen, our proposal is open for retroactive extension:

- A new concept or new relationships (modeling and refinement) can be declared at any time. Declaring such relationships is not tightly related to the definition of types or concepts, contrary to inheritance relationships, for instance, that must be declared at the definition of classes.
- A new specialization of a generic component can be defined at any time. For instance, if a new concept is defined, the specialization of any generic component can be defined for this concept.

Section 2 discusses several issues encountered with static specialization, and shows how concepts can be used to bypass most of them. Section 3 presents our C++ library for concept-based specialization, and an example using this solution. Section 4 shows compilation performances of the library depending on the number of concepts and the number of relationships (modeling and refinement) in a program. The full source code of the library and the examples is available for download [7].

2 Issues with Static Specialization

This section presents several issues that may occur with static specialization based on type patterns, and how most of these issues can be addressed with concepts:

6. See the documentation about `enable_if` at: http://www.boost.org/doc/libs/release/libs/utility/enable_if.html
7. Source code is available at: http://forge.clermont-universite.fr/projects/show/cpp-concepts.

(i) Some types that can be considered somehow similar (e.g., with a common subset of operations in their interface) may have the same specialization, but because of different type patterns, they have different specializations.

(ii) A specialization based on type patterns may lead to false specialization, because a type pattern is not often related to the interface of the matching types.

Existing solutions that use concepts to control static specialization in C++ are discussed. It appears that refinement relationships are also necessary to address the last issue:

(iii) A type may have several suitable specializations. As there is no clear ordering between these specializations, it is not possible to choose one particularly.

2.1 Specialization Based on Type Patterns

As an example, we propose to develop a generic class, `Serializer`, to store the state of an object into an array of bytes (the "deflate" action), or to restore the state of an object from an array of bytes (the "inflate" action). The primary version of the template, which makes a bitwise copy of an object in memory, is as follows.

```
template <class T> class Serializer {
 public:
  static int deflate(char * copy, const T & object);
  static int inflate(T & object, const char * copy);
};
```

This version should not be used for complex objects, such as containers, where the internal state may have pointers that should not be stored (because these versions of the deflate and inflate actions would lead to memory inconsistency after restoring). If we consider "sequence containers" of the STL (*Standard Template Library*), such as vectors and lists, we can provide a specialized version of `Serializer`.

```
template <class T, class ALLOC, template <class,class> class CONTAINER>
class Serializer< CONTAINER<T,ALLOC> > {
 public:
  static int deflate(char * copy, const CONTAINER<T,ALLOC> & container);
  static int inflate(CONTAINER<T,ALLOC> & container, const char * copy);
};
```

This specialization is based on the type pattern of the STL sequence containers: they are generic classes with two parameters, the type `T` of the elements to be stored, and the type `ALLOC` of the object used to allocate elements.

Now, let us consider "associative containers" of the STL, such as sets and maps. Their type pattern is different from the one of sequence containers (they have at least one more parameter `COMP` to compare elements), whereas sequence and associative containers have a common subset of operations in their interface that should ideally allow defining a common specialization of `Serializer`. However, as specialization is based on type pattern for now, another specialization of `Serializer` is necessary.

```
template <class T, class COMP, class ALLOC,
          template <class,class,class> class CONTAINER>
class Serializer< CONTAINER<T,COMP,ALLOC> > { [...] };
```

Notice that this specialization of `Serializer` is only suitable for sets, and not for maps, because their type pattern is different: maps have an additional parameter `K` for the type of the keys associated with the elements of the container. The specialization `Serializer< CONTAINER<K,`

`T, COMP, ALLOC> >` is necessary for maps, whereas maps and sets have a common subset of operations in their interface and could ideally share the same specialization.

The specialization for sets has been written having only STL associative containers in mind, but any type with the same type pattern matches the specialization. Thus, there could be an unwanted match. For instance, the `std::string` class of the C++ standard library is an alias for a type that matches the type pattern of sets.

```
std::basic_string< char, std::char_traits<char>, std::allocator<char> >
```

The first two issues presented in the introduction of the section have been illustrated here. They could be addressed with concepts:

(i) "Similar" types could model a common concept, and a specialization for this concept could be defined. Thus, "similar" types with different type patterns could share a common specialization.

(ii) Concepts could avoid false specialization: with static specialization controlled by concepts, any template parameter could be associated with a concept, and only types that model this concept could instantiate the parameter. This way, only the types that satisfy the requirements of a specialization could be considered.

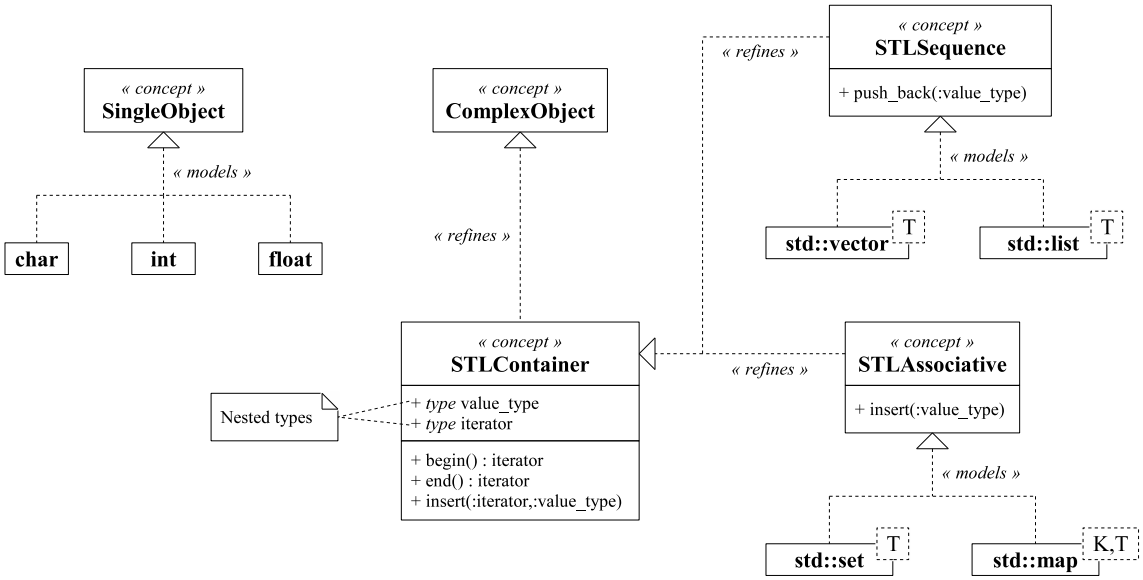

Figure 1: Taxonomy of concepts for the serialization example.

For the example of serialization discussed here, Figure 1 proposes concepts and their relationships. The `SingleObject` and `STLContainer` concepts are defined to provide two specializations for `Serializer`: one based on bitwise copy, and another one based on the common subset of operations shared by all STL containers, respectively. The `STLContainer` concept is refined into the `STLSequence` and `STLAssociative` concepts to provide specializations of `Serializer` using specific operations of sequence containers and associative containers respectively.

2.2 Existing Solutions Based on Concepts

Existing solutions for concept-based specialization in C++ [12, 11] are discussed here. They use concepts to guide the specialization of templates, and enable addressing the two first issues presented in the introduction of the section. However, about the third issue, i.e., to find the most appropriate specialization when there are several candidates, the solutions presented here are not fully satisfactory.

2.2.1 Concept-Based Dispatch

A first solution [12] implements concepts with "static interfaces" in C++, and proposes a "dispatch" mechanism to control static specialization with concepts. The solution is based on the `StaticIsA` template that provides some concept checking: `StaticIsA<T,C>::valid` is true if `T` models concept `C`. Let us assume that `StaticIsA` answers accordingly to the taxonomy of concepts of Figure 1 (see the source code for details). Here is an example of the dispatch mechanism for the specialization of the `Serializer` generic class.

```
enum { IS_SINGLE_OBJECT, IS_STL_CONTAINER, IS_STL_SEQUENCE,
       IS_STL_ASSOCIATIVE, UNSPECIFIED };

template <class T> struct Dispatcher {
 static const int which
  = StaticIsA<T,STLAssociative>::valid ? IS_STL_ASSOCIATIVE
    : StaticIsA<T,STLSequence>::valid  ? IS_STL_SEQUENCE
    : StaticIsA<T,STLContainer>::valid ? IS_STL_CONTAINER
    : StaticIsA<T,SingleObject>::valid ? IS_SINGLE_OBJECT
    : UNSPECIFIED;
};

template <class T> struct ErrorSpecializationNotFound;

template <class T, int = Dispatcher<T>::which>
class Serializer : ErrorSpecializationNotFound<T> {};

template <class T> class Serializer<T,IS_SINGLE_OBJECT> { [...] };
template <class T> class Serializer<T,STL_CONTAINER>    { [...] };
template <class T> class Serializer<T,STL_SEQUENCE>     { [...] };
template <class T> class Serializer<T,STL_ASSOCIATIVE>  { [...] };
```

The `Dispatcher` template goes through all the concepts (in a well-defined order) until its parameter `T` models a concept. The symbolic constant associated with the found concept is stored in the `which` attribute of `Dispatcher`. For instance, `Dispatcher< vector<int> >::which` is equal to `IS_STL_SEQUENCE`.

Compared to the version of the `Serializer` template based on type patterns, there is an additional parameter with a default value that is the answer of the dispatcher for parameter `T`. This value is used rather than the type pattern of `T` to define the specializations of `Serializer`. This way, it is possible to provide a specialization for any concept. For instance, `Serializer< vector<int> >` instantiates in fact `Serializer< vector<int>, IS_STL_SEQUENCE >` and matches the specialization for the `STLSequence` concept.

Notice that the primary version of the template inherits from a class that is only declared, the aim being that this version could not be instantiated. This way, compilation errors related to the fact that `T` has been instantiated with a wrong type appears at the instantiation of `Serializer`, rather than inside the code of `Serializer` where it tries to call invalid operations on `T`. This solution avoids usual error messages that could be cryptic for the user [14].

In this solution, a dispatcher (and dispatch rules) must be defined for each context of specialization, i.e., for each generic component that is specialized, which can quickly become tedious. A solution where the dispatch rules are automatically deduced, for each context of specialization, from the modeling and refinement relationships of the taxonomy of concepts should be provided.

2.2.2 Concept-Based Overloading

The second solution [11] relies on the `enable_if` template, which can be found in the Boost Library [1], and the SFINAE (*substitution failure is not an error*) principle [2] to provide some

control on static specialization with concepts. The definition of `enable_if` is as follows.

```
template <bool B, class T = void>
struct enable_if_c { typedef T type; };

template <class T> struct enable_if_c<false,T> {};

template <class COND, class T = void>
struct enable_if : enable_if_c<COND::value,T> {};
```

The idea is that if `B` is true, there is a nested type `type` inside `enable_if_c`, and thus inside `enable_if` if its parameter `COND` has an attribute `value` set to true. Let us assume that, for each concept `C` of the taxonomy of Figure 1, a template `is_C<T>` is defined so `is_C<T>::value` is true if `T` models concept `C` (see the source code for details). Here is an example of the use of `enable_if` for the specialization of the `Serializer` generic class.

```
template <class T, class = void>
class Serializer : ErrorSpecializationNotFound<T> {};

template <class T>
class Serializer<T, typename enable_if< is_SingleObject<T> >::type>
{ [...] };

template <class T>
class Serializer<T, typename enable_if< is_STLContainer<T> >::type>
{ [...] };

template <class T>
class Serializer<T, typename enable_if< is_STLSequence<T> >::type>
{ [...] };

template <class T>
class Serializer<T, typename enable_if< is_STLAssociative<T> >::type>
{ [...] };
```

The SFINAE principle is: if an invalid parameter is formed during the instantiation of a template, this instantiation is ignored. For instance, the instantiation `Serializer< vector<int> >` implies instantiating the specialization `Serializer< vector<int>, typename enable_if< is_SingleObject< vector<int> > >::type>`[8], and because `enable_if` has no member `type` in this situation, the specialization for concept `SingleObject` is not considered.

This way, only the specializations associated with a concept modeled by the instantiation of parameter `T` are considered. If more than one specialization remain, the compiler has to deal with an ambiguity: for instance, `vector<int>` models both `STLContainer` and `STLSequence` concepts. This ambiguity should be avoided: concept `STLSequence` is more specialized than concept `STLContainer`, so the specialization for `STLSequence` should be selected.

2.2.3 Conclusion

In this section, solutions have been presented to control static specialization. Concept-based dispatch allows considering refinement relationships, but the selection of the specialization is not automatic and requires some specific code for each context of specialization. At the opposite, concept-based overloading allows an automatic selection of the specialization, but is not able to deal with ambiguities that could be avoided considering refinement relationships.

8. `typename` is necessary in C++ to declare that the member `type` is actually a type and not a value.

3 A C++ Library for Concept-Based Specialization

Concepts appear to be better suited than type patterns to control static specialization, but to our knowledge, there is no solution that addresses all the issues brought up in the previous section. We propose here a C++ library that enables expressing a taxonomy of concepts, and using this taxonomy to automatically select the most appropriate specialization of a template.

Two main goals have guided our choices for this implementation: to provide a fully portable C++ code (without any additional tool such as a preprocessor), and to be open for retroactive extension (at any time, a new concept or a new modeling/refinement relationship can be declared, or a new template specialization can be defined).

3.1 Example

Let us consider the example of the `Serializer` generic class with our library. In a first step, the taxonomy of concepts of Figure 1 is defined: concepts and relationships (modeling and refinement) are declared. Then, the `Serializer` template is defined: first its primary version, and then its specializations for each concept. The library is based on template metaprogramming, and the details of its implementation are presented afterward.

Concepts Declaration

```
gnx_declare_concept(SingleObject);
gnx_declare_concept(ComplexObject);
gnx_declare_concept(STLContainer);
gnx_declare_concept(STLSequence);
gnx_declare_concept(STLAssociative);
```

Modeling and Refinement Relationships

```
template <> struct gnx_models_concept<char,SingleObject>  : gnx_true {};
template <> struct gnx_models_concept<int,SingleObject>   : gnx_true {};
template <> struct gnx_models_concept<float,SingleObject> : gnx_true {};

template <class T>
struct gnx_models_concept<std::vector<T>,STLSequence>   : gnx_true {};

template <class T>
struct gnx_models_concept<std::list<T>,STLSequence>     : gnx_true {};

template <class T>
struct gnx_models_concept<std::set<T>,STLAssociative>   : gnx_true {};

template <class K, class T>
struct gnx_models_concept<std::map<K,T>,STLAssociative> : gnx_true {};

template <>
struct gnx_models_concept<STLContainer,ComplexObject>   : gnx_true {};

template <>
struct gnx_models_concept<STLSequence,STLContainer>     : gnx_true {};

template <>
struct gnx_models_concept<STLAssociative,STLContainer>  : gnx_true {};
```

Template Primary Version

```
struct SerializerContext;

template <class T,class = gnx_best_concept(SerializerContext,T)>
class Serializer : ErrorSpecializationNotFound<T> {};
```

Template Specialized Versions

```
template <>
struct gnx_uses_concept<SerializerContext,SingleObject> : gnx_true {};

template <class T> class Serializer<T,SingleObject> { [...] };

template <>
struct gnx_uses_concept<SerializerContext,STLContainer> : gnx_true {};

template <class T> class Serializer<T,STLContainer> { [...] };

template <>
struct gnx_uses_concept<SerializerContext,STLSequence> : gnx_true {};

template <class T> class Serializer<T,STLSequence> { [...] };

template <>
struct gnx_uses_concept<SerializerContext,STLAssociative> : gnx_true {};

template <class T> class Serializer<T,STLAssociative> { [...] };
```

Concepts are declared using macro `gnx_declare_concept`. The modeling and refinement relationships are equally declared using metafunction `gnx_models_concept`. To control the specialization, a "specialization context" must be declared (`SerializerContext` in our example). Each specialization of `Serializer` based on a concept must be declared and associated with the specialization context `SerializerContext`, using metafunction `gnx_uses_concept`. The most appropriate concept for any instantiation of parameter `T` is automatically determined by the `gnx_best_concept` macro and stored in an additional parameter of the `Serializer` template, enabling static specialization based on this parameter.

3.2 Metafunctions

Some fundamental "metafunctions" are necessary to implement our library. These generic classes are common in metaprogramming libraries (e.g., in the Boost Library). A metafunction acts similarly to an ordinary function, but instead of manipulating dynamic values, it deals with "metadata", i.e., entities that can be handled at compile time in C++: mainly types and static integer values [1]. In order to manipulate equally types and static values in metafunctions, metadata are embedded inside classes, as follows [9].

```
template <class TYPE> struct gnx_type { typedef TYPE type; };

template <class TYPE, TYPE VALUE>
struct gnx_value { static const TYPE value = VALUE; };

typedef gnx_value<bool,true>  gnx_true;
typedef gnx_value<bool,false> gnx_false;
```

Template `gnx_type<T>` represents a type and provides a type member `type` that is `T` itself. The same way, template `gnx_value<T,V>` represents a static value and provides an attribute `value` that is the value `V` of type `T`. Based on template `gnx_value`, types `gnx_true` and `gnx_false` are defined to represent the boolean values.

The parameters of a metafunction, which are the parameters of the template representing the metafunction, are assumed to be metadata, i.e., to be classes with a member `type` or `value`. The

9. We chose to prefix all the metafunctions and macros of our library with "`gnx_`".

"return value" of a metafunction is implemented with inheritance: the metafunction inherits from a class representing a metadata. This way the metafunction itself has a member `type` or `value`, and can be a parameter of another metafunction. Here are metafunctions necessary for the discussion of this section.

```
template <class TYPE1, class TYPE2> struct gnx_same : gnx_false {};

template <class TYPE> struct gnx_same<TYPE,TYPE> : gnx_true {};

template <class TEST, class IF, class ELSE, bool = TEST::value>
struct gnx_if : ELSE {};

template <class TEST, class IF, class ELSE>
struct gnx_if<TEST,IF,ELSE,true> : IF {};
```

Metafunctions usually need static specialization to fully implement their behavior. Metafunction `gnx_same` determines whether two types are identical: `gnx_same<T1,T2>` inherits from `gnx_true` if `T1` and `T2` are the same type, or from `gnx_false` otherwise. Thus, the value returned by metafunction `gnx_same<T1,T2>` is stored in its `value` attribute. Metafunction `gnx_if` acts similarly to the common `if` instruction: `gnx_if<T,A,B>` inherits from `A` if `T::value` is true, or from `B` otherwise. If `A` and `B` represent metadata, then `gnx_if<T,A,B>` inherits the member nested in `A` or `B`.

3.3 Declaring Concepts

Concepts must be identified in C++. In our solution, macro `gnx_declare_concept` defines an empty structure to represent a concept. For instance, `struct STLContainer {};` declares concept `STLContainer`.

3.3.1 Typelists

Concepts also need to be stored in a container, in order to be manipulated by metafunctions, e.g., to determine the most specialized concept for a static specialization. Notably, the "typelist" technique [5, 2], based on metaprogramming, allows building a static linked list to store types, and can be defined as follows.

```
template <class CONTENT, class NEXT> struct gnx_list {
 typedef CONTENT content;
 typedef NEXT    next;
};

struct gnx_nil {};
```

Type `gnx_nil` models "no type" (`void` is not used, as it could be a valid type to be stored in a list), and is used to indicate the end of a list. For instance, to store the `STLSequence` and `STLAssociative` concepts in a list:

```
typedef gnx_list< STLSequence,
                  gnx_list<STLAssociative,gnx_nil> > mylist1;
```

Common operations on linked lists can be defined on typelists [2]. For instance, to add concept `STLContainer` in the previous list:

```
typedef gnx_list<STLContainer,mylist1> mylist2;
```

However, typelists are too static for the needs of our library: in the previous example, list `mylist1` cannot be modified to add a type, so a new list `mylist2` has to be created instead. In the following section, a solution is proposed to build a list of concepts that can be modified at compile time to add new concepts, without changing the identifier of the list. Typelists will nevertheless be useful in our library for several metafunctions where operations for merging and searching typelists are necessary.

3.3.2 Indexing Concepts

To design a list where concepts can be added at any time, a mechanism for indexing the concepts is proposed. The metafunction `gnx_concept` is defined: it has one parameter that is an integer value, and it returns the concept associated with this number. Adding a concept to the list is performed by the specialization of the metafunction.

```
template <int ID> struct gnx_concept : gnx_type<gnx_nil> {};

template <> struct gnx_concept<1> : gnx_type<STLContainer> {};
template <> struct gnx_concept<2> : gnx_type<STLSequence> {};
[...]
```

Indexing the concepts by hand is not acceptable, so a solution to get the number of concepts already in the list is needed. For this purpose, a preliminary version of the `gnx_nb_concept` metafunction is proposed. It goes through all the concepts in the list by increasing an index until finding `gnx_nil`.

```
template <int N = 0> struct gnx_nb_concept
: gnx_if< gnx_same<typename gnx_concept<N+1>::type, gnx_nil>,
          gnx_value<int,N>,
          gnx_nb_concept<N+1>
        > {};
```

For an automatic indexing of the concepts, one would use the return value of metafunction `gnx_nb_concept` to determine the next index to assign to a new concept.

```
template <> struct gnx_concept<gnx_nb_concept<>::value+1>
: gnx_type<STLContainer> {};

template <> struct gnx_concept<gnx_nb_concept<>::value+1>
: gnx_type<STLSequence> {};

[...]
```

However, this solution is not working as is, because using `gnx_nb_concept<>` infers that `gnx_concept` is instantiated from `gnx_concept<0>` to `gnx_concept<N+1>`, where `N` is the number of indexed concepts. Due to this fact, specializing `gnx_concept` for `STLContainer` and `STLSequence` in the previous example is not possible, because `gnx_concept<N+1>` has already been instantiated based on the primary version of `gnx_concept`. To eliminate this flaw, an additional parameter, called here "observer", is added to both metafunctions `gnx_concept` and `gnx_nb_concept`.

```
template <int ID, class OBS = gnx_nil>
struct gnx_concept : gnx_type<gnx_nil> {};

template <class OBS, int N = 0> struct gnx_nb_concept
: gnx_if< gnx_same<typename gnx_concept<N+1,OBS>::type, gnx_nil>,
          gnx_value<int,N>,
          gnx_nb_concept<OBS,N+1>
        > {};
```

The idea is to provide a different observer each time the concepts need to be counted to determine the next index to assign to a new concept: the new concept itself will be the observer. With this solution, counting the concepts with observer `OBS` induces the instantiation of `gnx_concept<N+1,OBS>`, so any specialization for index `N+1` with an observer other than `OBS` is still possible. Finally, concepts are indexed as follows.

```
template <class OBS>
struct gnx_concept<gnx_nb_concept<STLContainer>::value+1, OBS>
: gnx_type<STLContainer> {};

template <class OBS>
struct gnx_concept<gnx_nb_concept<STLSequence>::value+1, OBS>
: gnx_type<STLSequence> {};

[...]
```

To declare a concept in a single and easy instruction, as presented in the example at the start of the section, the `gnx_declare_concept` macro is defined.

```
#define gnx_declare_concept(CONCEPT)                          \
 struct CONCEPT {};                                           \
                                                              \
 template <class OBS>                                         \
 struct gnx_concept<gnx_nb_concept< CONCEPT >::value+1, OBS> \
 : gnx_type< CONCEPT > {}
```

To conclude, the `gnx_nb_concept` metafunction requires $O(n)$ operations, where n is the number of concepts already in the program. Hence, indexing n concepts requires $O(\sum_{i=1}^{n} i) = O(n^2)$ operations at compile time.

3.4 Modeling and Refinement Relationships

The modeling relationships between a type and a concept, and the refinement relationships between two concepts are declared equally in our library with the `gnx_models_concept` metafunction.

```
template <class TYPE_OR_CONCEPT, class CONCEPT>
struct gnx_models_concept : gnx_false {};
```

The primary version of the template returns false, and the relationships are declared through specializations of the template: if type `X` models concept `C` (or concept `X` refines concept `C`), then specialization `gnx_models_concept<X,C>` must return true.

```
template <> struct gnx_models_concept<X,C> : gnx_true {};
```

Notice that `gnx_models_concept` provides an answer for a direct relationship only. If a type `T` models a concept `C1` that refines a concept `C2`, this metafunction returns false for a relationship between `T` and `C2`. Additional metafunctions, necessary in our library to find any relationship between a type and a concept (or between two concepts), are briefly presented below (see the source code for details).

– Metafunction `gnx_direct_concepts<X>` provides a list (using the typelist technique) of all the concepts directly associated with a type (or a concept) `X`. It goes through all the concepts using their index, and checks whether `X` models (or refines) each concept using metafunction `gnx_models_concept`. Assuming that to retrieve a concept from its index (i.e., to call metafunction `gnx_concept`) is a constant time operation, `gnx_direct_concepts` requires $O(n)$ operations, where n is the number of concepts in the program.

– Metafunction `gnx_all_concepts<X>` provides a list of all the concepts directly or indirectly associated with a type (or a concept) `X`. It calls `gnx_direct_concepts` to list the concepts directly related to `X`, and recursively gets all the concepts related to each one of the direct concepts. This metafunction requires $O(n^2+rn)$ operations, where r is the number of modeling and refinement relationships declared in the program: at worst, all the n concepts are asked for their direct concepts (i.e., a call to metafunction `gnx_direct_concepts`), which requires $O(n^2)$ operations; to build the final list, at worst all the r relationships are considered, and each time the list of the currently found concepts is merged with the list of the newly found concepts, which requires $O(rn)$ operations (at worst $2n$ operations are necessary for the merging, as it avoids duplicates).
– Metafunction `gnx_matches_concept<X,C>` returns whether a type (or a concept) `X` models (or refines) a concept `C`, directly or indirectly. This metafunction searches for `C` in the list of concepts provided by metafunction `gnx_all_concepts` and requires $O(n^2 + rn)$ operations: $O(n^2 + rn)$ operations to build the list, and $O(n)$ for the search.

3.5 Specialization Based on Concepts

3.5.1 Declaring Specializations

With our library, controlling the specialization of a generic class based on the concept of one of its template parameter implies an additional template parameter. In the example, class `Serializer` has initially one parameter `T` that is used to control the specialization: based on different concepts that `T` might model, several specializations of `Serializer` are provided. For this purpose, an additional parameter is added to `Serializer`.

```
template <class T, class = gnx_best_concept(SerializerContext,T)>
class Serializer : ErrorSpecializationNotFound<T> {};
```

This additional parameter is the most specialized concept that type `T` models and that is of interest for the specialization of `Serializer`. This "best" concept is obtained using the `gnx_best_concept` macro, which eases the call to metafunction `gnx_contextual_concept`.

```
#define gnx_best_concept(CONTEXT,TYPE) \
 typename gnx_contextual_concept<CONTEXT,TYPE>::type
```

Notice that metafunction `gnx_contextual_concept` requires a "context", which is a type that represents the context of a given specialization. Each template that uses static specialization based on concepts requires its own context.

There are two main reasons for this notion of a context: (i) as seen previously, metafunction `gnx_nb_concept`, called by many metafunctions, requires an observer to perform correctly and to allow defining new concepts at any time, and this observer will be the context of the specialization; (ii) we want our solution to be portable on any standard C++ compiler, meaning we do not want to modify the C++ language itself, nor to provide a preprocessor, so to know which concepts are of interest for a given context of specialization, each one of these concepts must be associated with the context using the `gnx_uses_concept` metafunction.

```
template <>
struct gnx_uses_concept<SerializerContext,STLContainer> : gnx_true {};
```

In our example, the `SerializerContext` context has been declared for the specialization of `Serializer`. Among others, concept `STLContainer` is used to control a specialization of `Serializer`, so `gnx_uses_concept` is specialized (the same way as `gnx_models_concept`) to specify that concept `STLContainer` is used in the `SerializerContext` context.

3.5.2 Selecting the Best Specialization

Based on the list of concepts declared in a specialization context, and a taxonomy of concepts, metafunction `gnx_contextual_concept` determines the "best" concept for a type `T`, meaning the most specialized concept that `T` models and that is of interest for the context of specialization.

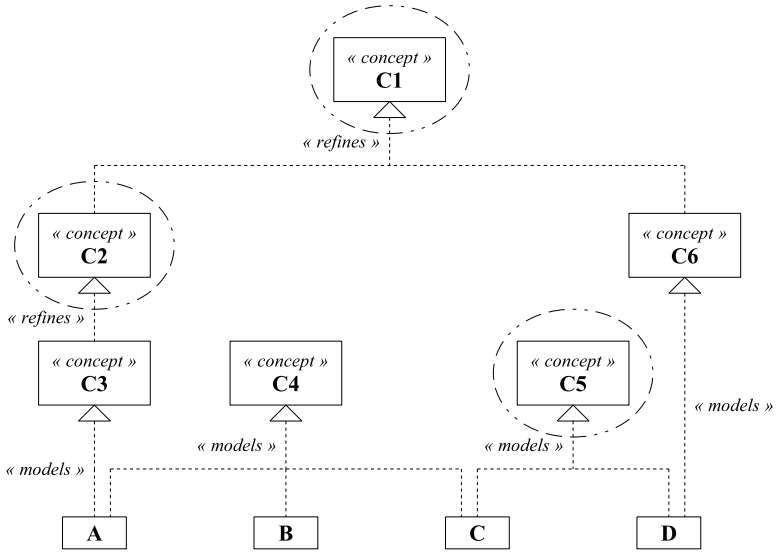

Figure 2: Example of best concept selection.

If we consider the taxonomy of concepts of Figure 2, and a context `X` that provides specializations for concepts `C1`, `C2` and `C5` in this example, the following best concepts should be selected.

- For type `A`: concept `C2`, candidates are `C1` and `C2`, but `C2` is more specialized.
- For type `B`: no concept, there is no candidate in the context's list, `gnx_nil` is returned.
- For type `C`: concept `C5`, it is the only choice.
- For type `D`: concepts `C1` or `C5`, both concepts are valid (because `D` models both), and there is no relationship between them to determine that one is more specialized than the other. The selected one depends on the implementation of `gnx_contextual_concept`. In our library, the concept with the highest index is selected. But to force the selection, one can specialize `gnx_contextual_concept`.

Metafunction `gnx_contextual_concept<X,T>` goes through the list of all the concepts modeled directly or indirectly by type `T` (provided by `gnx_all_concepts<T>`), and selects the one that does not refines directly or indirectly any other concept in the list (using metafunction `gnx_matches_concept`) and that is declared in context `X`. This metafunction requires $O(n^2 + rn)$ operations: $O(n^2 + rn)$ operations to build the list, and $O(n)$ to select the best candidate (because `gnx_all_concepts` has already achieved all the necessary `gnx_matches_concept` instantiations).

3.6 Conclusion

Several steps are necessary for concept-based specialization with our library: (i) to declare concepts and modeling/refinement relationships in order to define a taxonomy of concepts; (ii) for each context of specialization, to declare the concepts that are used to control the specialization. These steps are not monolithic, and new concepts and specializations can be defined at any time (but before the first instantiation of the affected generic component), which provides high flexibility with minimal assumptions about components.

The selection of the best specialization is fully automatic and safe as long as the modeling and refinement relationships are correct. Notice that those relationships, declared manually with our solution, could be automated using a mechanism to check structural conformance, such as the `StaticIsA` template (cf. Section 2.2.1) for instance.

```
template <class TYPE, class CONCEPT> struct gnx_models_concept
: gnx_value<bool, StaticIsA<TYPE,CONCEPT>::valid> {};
```

However, a few issues appear with our solution. First, the type pattern of any template whose specialization is controlled by concepts is altered: for each initial template parameter, an additional "hidden" parameter may be added to get its best concept. For instance, users of the `Serializer` generic class could think that this template has only one parameter, whereas it actually has two.

Secondly, the notion of an observer, which is totally hidden from the user of the generic component, has been introduced to bypass an instantiation problem with `gnx_nb_concept` (cf. Section 3.3.2). However there are very specific situations where the issue remains. For instance, the following specialization may be troublesome.

```
template <> class Serializer<int> { [...] };
```

It induces the full instantiation of `Serializer` that forces the default value of the "hidden" parameter to be instantiated, i.e., `gnx_contextual_concept<SerializerContext,int>`, which itself forces `gnx_nb_concept` to be instantiated for observer `SerializerContext`. If concepts are added after this code, another call to metafunction `gnx_contextual_concept` with context `SerializerContext` will ignore the new concepts. Hence, one should avoid to instantiate `gnx_contextual_concept` before the final use of the affected generic component. In our example, the full instantiation can be avoided as follows.

```
template <class CONCEPT> class Serializer<int,CONCEPT> { [...] };
```

4 Compilation Performance

The theoretical performance of the metafunctions of our library has been studied in this paper. We assumed some operations of the compiler to be constant time, so it is important to confirm the theoretical performance with practical experiments. The initial implementation of the library, that is presented in this paper, is meant for understanding and is not optimized for compilation. Thus, a second version of the library has been designed to optimize the compilation time. How to use the library remains unchanged with this new version.

The tests presented here have been performed with the optimized version [10] of the library on an Intel Core 2 Duo T8100 2.1 GHz with 3 GB of memory, and using GNU G++ 4.3.4 (its template recursion limit set to 1024). Instances with different numbers n of concepts and r of modeling/relationships in the whole program have been randomly generated (see the source code for details). Each compilation time presented here is expressed in seconds and is the mean of compilations of 10 different instances.

Figure 3 shows the compilation time, depending on n, for indexing concepts. As predicted by the theoretical performance analysis, there is a quadratic dependence on n (confirmed by a quadratic regression with a correlation coefficient [11] $R = 0.997$).

10. Optimized version 2011-08-25 was used for the experiments.
11. R = Pearson's correlation coefficient; the closer to 1, the more the regression fits the curve.

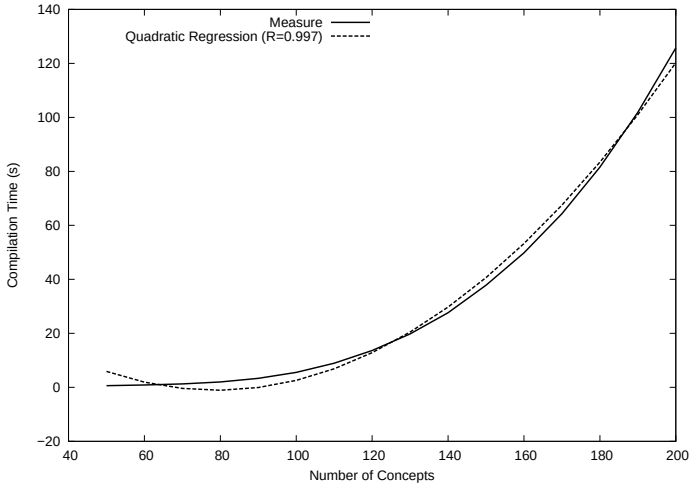

Figure 3: Compilation time for indexing concepts ($r = 100$).

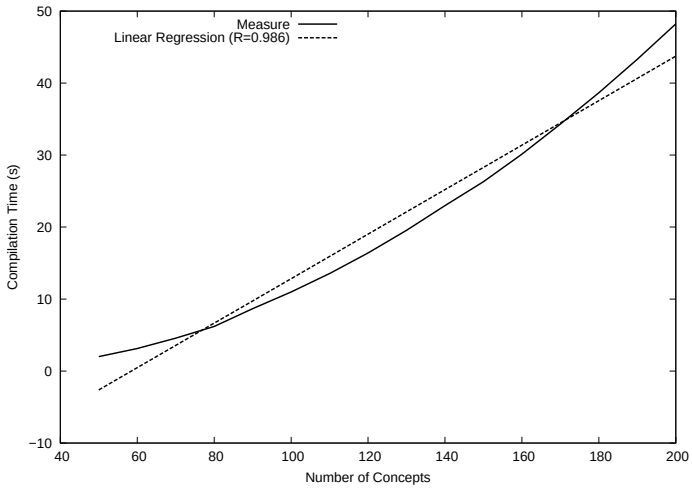

Figure 4: Compilation time for `gnx_direct_concepts` (50 instantiations, $r = 100$).

Figure 4 shows the compilation time, depending on n, of 50 instantiations of metafunction `gnx_direct_concepts` (which lists the concepts that a given type or concept directly models or refines respectively). The theoretical performance analysis predicted a linear dependence on n, but the practical results show otherwise, which we think is related to our assumption that accessing a concept through its index (i.e., a call to `gnx_concept`) was constant time. It seems that to find a specialization of a template, the compiler may require a number of operations dependent on the total number of specializations for this template. However, this non-linear dependence is not so significant, as the linear regression shows a correlation coefficient $R = 0.986$ in the range of our experiments, and the instantiations of `gnx_direct_concepts` are only one step of the whole compilation process.

Figures 5 and 6 show the compilation time, depending respectively on n and r, of 50 instantiations of `gnx_contextual_concept` (which determines the best concept of a given type in a given specialization context). The performance of each intermediate metafunction is not shown, as it is similar. As predicted by the theoretical performance analysis, there is a quadratic dependence on n (confirmed with $R = 1$), and a linear dependence on r (confirmed with $R = 0.989$).

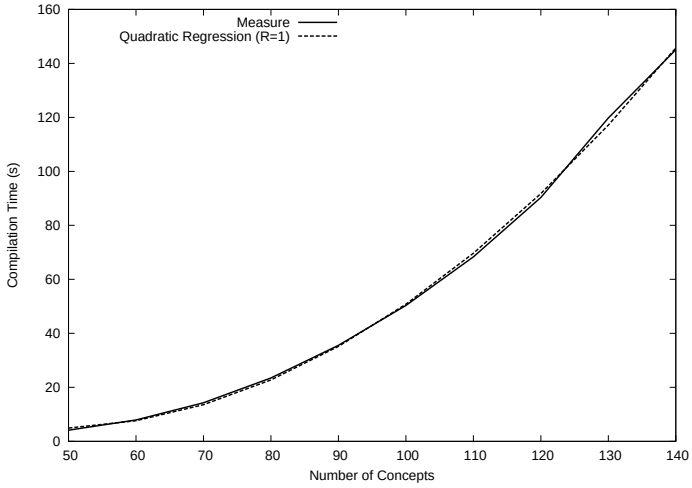

Figure 5: Compilation time for `gnx_contextual_concept` (50 instantiations, $r = 300$).

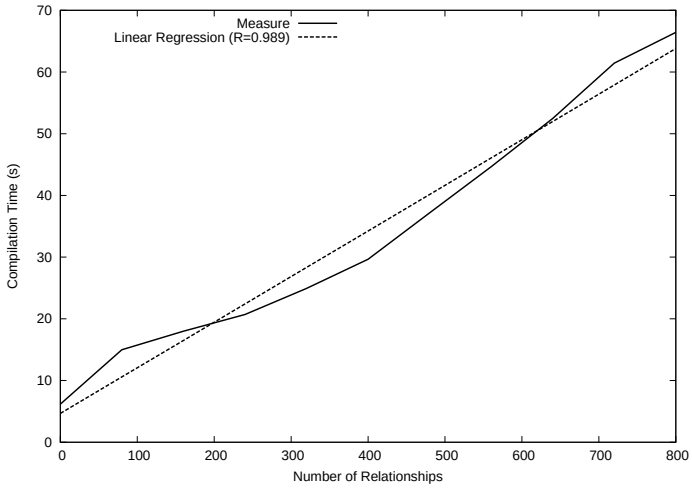

Figure 6: Compilation time for `gnx_contextual_concept` (50 instantiations, $n = 80$).

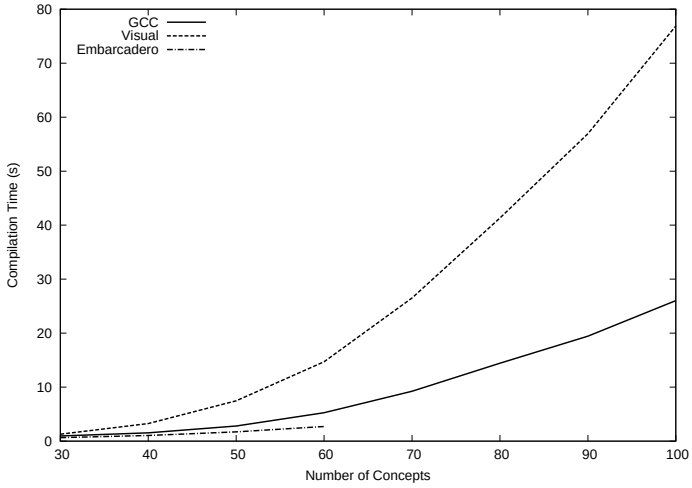

Figure 7: Whole compilation time (with 30 instantiations of `gnx_contextual_concept`, $r = 100$).

Our library has been tested successfully on several compilers: GNU GCC from 3.4.5 to 4.4.3, Microsoft Visual C++ 10, and Embarcadero C++ 6.20. Figures 7 and 8 show the time of the whole compilation process for those compilers, from indexing the concepts to finding the best concept for types in specialization contexts, depending on n and r. Notice that we were not able to test all the instances with Embarcadero's compiler, due to a hard limitation of 256 levels in the template recursion.

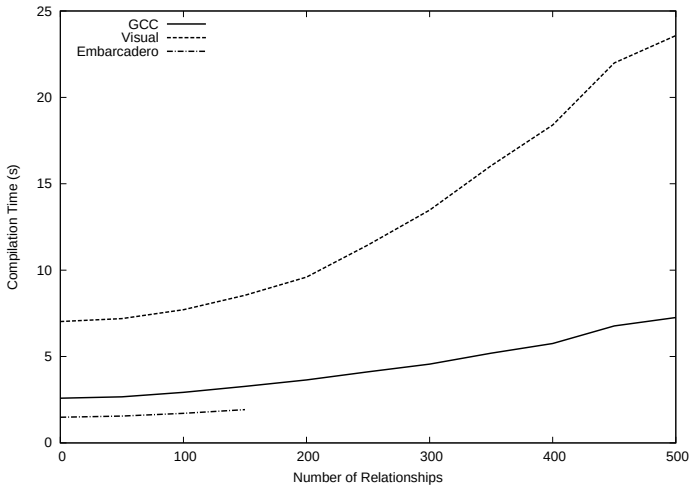

Figure 8: Whole compilation time (with 50 instantiations of `gnx_contextual_concept`, $n = 50$).

5 Conclusion

This paper describes a C++ library that enables controlling the specialization of generic components with concepts. As concepts are not part of the C++ language yet, a solution is provided to declare concepts and modeling/refinement relationships in order to define a taxonomy of concepts. It relies on an automatic indexing of the concepts that allows a retroactive extension: at any time, new concepts and modeling/refinement relationships can be declared.

The library also provides a mechanism to automatically select the most appropriate specialization of a template based on concepts. Specializations of a generic component can be defined based on the modeling of concepts, rather than the matching of type patterns, of its parameters. At instantiation time, a metafunction determines the most specialized concept of any type instantiating a template parameter, and thus guides the selection of the specialization of the template. Our solution is a bit invasive because a default parameter must be added to the template to be specialized, but after the definition of the primary version of the template, specializations based on concepts can be added non intrusively and retroactively.

The retroactive extension enabled by the library provides high flexibility with minimal assumptions about the components: the coupling between a generic component and the types that will instantiate its parameters is minimized. However, as our goal was to provide a standard C++ code (without any additional tool such as a preprocessor), we were not able to automate the identification of the concepts used to control the specialization of a given template. So the notion of a "context of specialization" is necessary and requires to explicitly declare each concept involved in the control of a specialization.

To conclude, a theoretical performance analysis and the performance of practical experiments have been presented to show the compilation time overhead of our solution. Even if a quadratic dependence on the number of concepts has been identified, the compilation time is reasonable for

many applications: compiling 50 specializations with 50 concepts and 250 modeling/refinement relationships on an average computer requires less than 5 seconds.

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