



FAKULTÄT FÜR INFORMATIK

DER TECHNISCHEN UNIVERSITÄT MÜNCHEN

Master Thesis in Informatics

Adding C++ Support to MBEDDR

Zaur Molotnikov





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C++ Unterstützung für MBEDDR

Author: Zaur Molotnikov
Supervisor: Dr. Bernhard Schätz
Advisor: Dr. Daniel Ratiu
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Ich versichere, dass ich diese Masterarbeit selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel verwendet habe.

München, den 16. September 2013

Zaur Molotnikov

Acknowledgments

If someone contributed to the thesis... might be good to thank them here.

Abstract

An abstracts abstracts the thesis!

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1 Introduction

In embedded programming the C++ programming language is widely spread, [1]. Being a general purpose programming language, C++ does not provide, however, any special support for embedded systems programmers.

By changing the language itself, together with a tool set for it, it is possible to get a better environment for a dedicated domain, for example, specifically for embedded programming. There are two known approaches to change the language itself.

The first possible approach is dropping some language features, to get the language, which is simpler. As an example, a subset of C++, called *Embedded C++* can be brought, [2]. The approach taken in *Embedded C++* is omitting very many core features of C++ like virtual base classes, exceptions, namespaces and templates. It allows for a higher degree of optimizations by compiler possible.

Embedded C++ was intended to ensure higher software quality through better understanding of the limited C++ by programmers, higher quality of compilers, through simplicity, better suitability for the embedded domain, through memory consumption considerations [3].

The approach taken in *Embedded C++*, however, has been criticized by the C++ community, specifically for the inability of the limited language to take advantage of the C++ *Standard Template Library (STL)*, which requires the C++ language features, absent in *Embedded C++*, [4]. As a response for it *Extended Embedded C++* has appeared, which includes many of the omitted by *Embedded C++* language features and a memory-aware version of *STL*, [5].

The second approach to modify a language in order to get it more suitable for embedded development consists of extending the language with constructions specific to the domain. Such approach is taken, for example, in the *mbeddr*, to improve on the C programming language, [6].

Specific extensions may represent some often met idioms in the domain, for example, behavior of a device under control is often described by a state table or a state machine diagram in the device specification. Such notions can be incorporated into language, providing a higher abstraction level, compared to the core language constructs.

Moreover, higher level extensions induce some higher level semantics, which could be checked for correctness on the programming stage. For example, a given decision table could be checked for completeness of choices and their consistency, [7]. Such checks can improve quality of the software under development.

Extensions to C language developed in *mbeddr* include state machines and decision tables, together with analyses for them.

A special language engineering environment, *JetBrains MPS*, is used to support modular and incremental language development in *mbeddr*. The language under development is split in a special class-like items, called *concepts*, representing the *Abstract Syntax Tree (AST)* node types. As an example of a *concept* an expression can be taken. It is possible to describe

in *JetBrains MPS* different expression kinds, similar to object oriented class hierarchy, allowing the objects to reference each other, and enabling polymorphism, in a way when any descendant can be used instead of its ancestor, e.g. binary minus expression can be used wherever an expression (any expression) is required. After various expression types were described to the language engineering environment as *concepts*, the environment provides a chance to instantiate concrete expressions and edit them, acting as an editor for the language created.

Over the inheritance mechanisms, it is possible to extend languages, providing new concepts as descendants of the existing ones. For example, expression concept can be extended to support new sort of expressions, like decision tables. Thus language modularity is achieved and incremental development is made to be possible.

Modularity is achieved as well, when one language is enabled to interact with another one. For example, expressions, described independently as a language, can be reused in any language, which has a need in expressions, like language with statements of a programming language, because statements include expressions naturally.

Having in mind the opportunities, the language modularity in *JetBrains MPS* brings, it makes sense to recreate a general purpose programming language in *JetBrains MPS*. Building the general purpose programming language brings a basis to develop domain specific extensions to the well-known general purpose language. The editor for the general purpose language comes almost “for free”, as a side product.

Later, from the code in the implemented general purpose language a text code can be generated for further processing, compiling, deployment. The language extensions, of-course, are not known to the existing tools which process the language. But they usually can be reduced to the base general purpose programming language statements, presenting a regular syntax to the further tool chains as an outcome. Thus the general purpose programming language is getting enhanced, remaining compatible with all the existing tools to process it further.

Additionally to the language modification itself, an *Integrated Development Environment (IDE)* can be improved to support the domain specific development.

Various analyses¹ can be built in into the code editor in order to detect inconsistencies, or, simply, “dangerous” constructs, and inform the programmer. Certain code formatting, or standard requirements could be enforced as well. The *IDE* can be enhanced with various automations, like support for code generation and refactorings.

As the new *IDE* works internally with *AST* described through the node types, or *concepts*, in order to perform code analysis, generation, or transformation, there is no need to invoke parsers for the code, which is advantageous.

A mixture of the two approaches is used in this work in an attempt to achieve a modular C++ language, a suitable base for the further language engineering, including the specialization of C++ for embedded development, and even more general, for later extension, to specialize the common base C++ language to any domain of choice. A special *IDE* is created together with a new C++ language flavor, which supports the C++ programmer.

During the creation of the C++ programming language in the way described, the language modularity in general is analyzed, and caveats of it are described together with the ways to avoid them.

¹analyses not only for extensions, but for the base language itself

The newly created *IDE* features analyses. The question of their computational complexity for such analyses is raised in general, together with the practical outcomes of it.

The new language together with the new *IDE* can later serve as a basis for extending the C++ programming language with domain specific constructs for embedded programming. Creation of these extensions lies out of scope for this Master Thesis, and is left for further research.

The approach taken in this work goes further into exploring the language modularity on the basis of *JetBrains MPS*. While building the C++ programming language itself with the goal of embedded domain specific extensions in mind, the C++ itself is being built itself as an extension to the C programming language, provided by the *mbeddr*. The C++ implemented in *JetBrains MPS* and discussed in this work I call the *Projectional C++*.

Although C++ is a separate from C language, the high degree of similarity allows to make use of the C programming language, implemented by the *mbeddr* as a foundation. Not only reuse of the basic C is achieved, but also the embedded extensions from the *mbeddr* are immediately supported by the newly built C++.

The ultimate goal during the reuse of *mbeddr* as a base for C++ is keeping *mbeddr* not modified towards the C++ programming language only, but instead, making, when needed, *mbeddr* more extensible in general, so that both resulting C++ and the base for it, *mbeddr*, can develop further being disjoint to a high degree. This independence of *mbeddr* on C++ extension ensures, that the *mbeddr project* can develop further without looking back on C++, making the C++ support an independent task.

The task of such a one-side-aware only extension is a challenge for the whole language modularity concept, provided by *JetBrains MPS* and used in *mbeddr*. This work explores further the support, provided by *JetBrains MPS* for the modular language construction, [7], and reviews it from the architectural point of view.

The C++ programming language is provided with a number of automations and analyses for it. The automations include code generation and structuring. They are designed to compensate on some caveats of C++, or lack of support for some aspects, like coding style. The analyses are intended to increase the understanding of the constructed code by a novice to C++ programmer, or to provide a quick information to an experienced C++ professional. Both analyses and automations are provided to achieve an improvement in quality, security and understanding of the pure C++ code. The automations and analyses are mostly implemented as a programming on the *AST* in a Java-like programming language.

As analyses and automations grow in complexity and quantity, the question of their computational complexity arises. In the *JetBrains MPS Application Programming Interface (API)* it is not explicitly defined, when the analyses provided for the language take place, how much of the computational resource they can take advantage of. This however may affect the overall *IDE* performance, as the analyses complexity may be high. The question of analyses run-time and complexity is raised and discussed in this work in general and in particular, taking one of the C++ specific analyses and researching on its complexity. Extensions to the *JetBrains MPS API* are proposed to get a better control over the analyses run-time.

Finally, it is fair to say, that some practical foundations for the *Projectional C++* have been already grounded, before the start of this work by the *mbeddr* team. Some of them, were kept (reference type, templates partially) and just described and analyzed here, some of

them were considerably reworked (classes, inheritance, encapsulation and polymorphism). Couching from the *mbeddr* team made me changing some of the implementation aspects, as from I planned originally (namespaces, operator overloading partially). And some parts were built, of-course, new from scratch and were not (at least yet) anyhow influenced by *mbeddr* team at all (analyzes, construction and copying, some more). The evaluation of the experience, gained by me during the practical implementation part, which results into the extensibility analysis, research on complexity of cheks and the run-time for them, and general projectional guidelines represent my own theoretical focus and comittment.

2 Foundations

Before describing the technologies on which the current work is based, as well as the work itself, it makes sense to describe more general foundations and principles, around which the technology is built.

In the Section 2.1 I describe two approaches to create an *IDE* for a certain language, and mainly the projectional approach, which originates from the area of building new *Domain Specific Languages (DSLs)*.

In the Section 2.2 I describe the modular approach towards language engineering and extending, intensively used with the projectional approach to construct languages.

2.1 Building DSLs and IDEs

This section compares the traditional approach to build textual editors for the program code with the projectional approach, bringing up motivation for the least.

2.1.1 Traditional Approach

Traditionally programming languages are used in a textual form in text files, forming programs. However the textual nature is not typical for the structure of programs themselves, being rather a low-level code representation, especially when talking about syntax, which is only necessary for parsers to produce correct results, and not for the program intended semantics.

Parsers are used to construct so-called *ASTs* from the textual program representation. *ASTs* are structures in memory, usually graph-alike, reminding a control flow graph, where nodes are different statements and edges are the ways control passes from one statement to the next one.

For the developer, using an editor, the degree to which the editor can support the development process is important. For this, the editor has to recognize the programming language constructions and provide possible assistance. Among such assistance can be code formatting, syntax validation, source code transformations (including refactoring support), code analyses and verification, source code generation and others. Many of these operation rely indeed on the higher than text level notions related to program such as a method, a variable, a statement. A good editor has to be aware of these higher level program structures, to provide meaningful automations for the operations mentioned above.

Nowadays, most of the editors work with text, and, to provide assistance to a programmer, integrate with a parser/compiler front-end for the programming language. Such way to extract the program structure during editing is not perfect for several reasons.

First of all, the program being edited as text is not syntactically correct at every moment, being incomplete, for example. Under such circumstances the parsing front-end can not

be successfully invoked and returns error messages which are either not related to the program, when the code is completed, or false-positive warning and errors.

Secondly, after a minor editing of the code, usually the whole text file has to be processed again. Such compiler calls are usually computationally expensive, they slow down, sometimes significantly, the performance of the developer machine. Various techniques exist to speed it up, including partial and pre- compilation, but the problem is still relevant to a large extent.

Moreover, the textual nature of the code complicates certain operations additionally. As an example, we can take a refactoring to rename a method. Every usage of the method, being renamed, has to be found and changed. To implement it correctly an editor must take into account various possible name collisions, as well as presume a compilable state of the program prior to the start of the refactoring.

Not to mention the parsing problem itself. Parsing a program in a complex language like C++ is a difficult problem, it involves the need to resolve correctly scoping and typing, templates and related issues, work with pre-processor directives incorporated in the code. In this regard different compilers treat C++ in a different way, creating dialects, which may represent obstacles for the code to be purely cross-platform.

Listing 2.1: Closing several blocks

```
class MyClass {  
    void doSomething() {  
        while(true) {  
            try {  
                // ...  
            }  
            catch(Exception e) {  
            }  
        }  
    }  
};
```

The textual representation of program code, involves the need in formatting and preserving syntax. These both tasks, indeed, have nothing to do with the functionality program, and additionally load the developer, reducing productivity. As an example, here I can mention the need to close several blocks ending at the same point correctly, indenting the closing brace symmetrically to opening one. The Listing 2.1 demonstrates it in the last few lines.

2.1.2 Projectional Approach

Another approach which can be taken in the organization of an editor for a programming language is called *projectional approach*. Projectional editors do not work with a low-level textual representation of a program, but rather with a higher level concept, *ASTs*. This approach is especially useful and used when constructing new *DSLs*.

Working with *ASTs* directly has several advantages over the conventional textual code editing.

Firstly, all syntax errors are no longer possible, as there is no syntax.

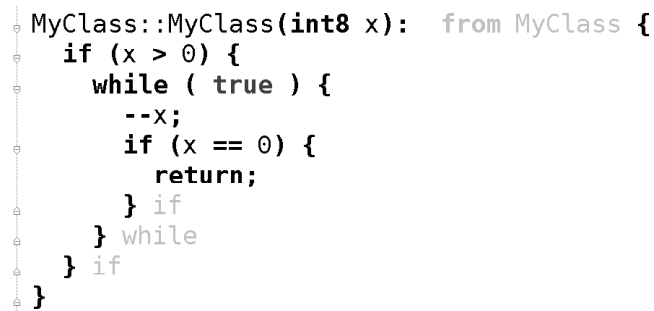
Secondly, there is no need to format the code on the level of indentation and look, since it is only needed for textual code.

Thirdly, all features, which in textual approach require parsing, can be implemented without a parser involved, because *AST* is always known to the editor.

Additionally, as the compilers still expect a code in a textual form, code generation is used to convert the *AST* into the text code for the further use. The code generation step can be customized to provide support for a variety of compilers, when the compilers differ.

Projectional editors have to display the *AST* to the developer, in order for him/her to work with it. Such visualization of an *AST* is called “projection”, giving a name to the editor class.

The model of code is stored as an *AST* in the projectional editor. As in the Model-View-Controller pattern the view for the model can be implemented separately, [8]. Thus the code may be presented in a number of different ways to the user. For example, the *AST* can be visualized as a graph, similar to control flow graph. This visualization, however, is not always advantageous being sometimes not compact and complicated to overview.



```

MyClass::MyClass(int8 x):  from MyClass {
    if (x > 0) {
        while ( true ) {
            --x;
            if (x == 0) {
                return;
            } if
        } while
    } if
}

```

Figure 2.1: Example projection of an *AST*, “source code” view

One of the well-accepted way to visualize *AST* is by visualizing its textual representation, as if it would be written as a text code in the programming language, see Figure 2.1. There can be in principle many such textual visualizations, supporting different ways the code looks. Normally in the traditional approach this has to be achieved by reformatting, and thus changing, the source code. This is performed for the code to look similar across the developed software, and standards or coding guidelines are written to enforce the way to format the text code. Compare to the projectional approach, where such formatting guidelines are not needed, when arguing about the low-level code formatting, like indentation.

The textual projection of the *AST* looks similar to the text code. However the projectional nature of it has certain outcomes, which may be unusual for a programmer, who is used to editing the code as text.

The statements in the projectional editor are only selected as whole. There is now way to just select the “while” word for cut or copy, without selecting the condition and the block belonging to the statement. This behavior represents the position of the condition

and `while-body` in the *AST* as children of the `while` statement. The statement can be selected all together only, including all of its children. Alternatively, one could select just an expression in the condition part.

Every block delimiters are just a part of the block visualization. They are organized in a proper way automatically, and there is no way to delete or confuse them, as well as to type them initially. Each closing brace can marked with the parent statement name (through implementing such behavior in the *AST* visualization), enhancing navigation through the displayed code.

As one can see, the textual projection of the *AST* looks almost the same, as a text code in a conventional textual editor. This can cause some confusion for the developer at first, as attempts to edit this textual visualization as a real text will sometimes fail.

Eventually, however, advantages of such visualization overwhelm the disadvantages. Among the benefits of the textual projection over text code are quicker code construction after short learning, better way to select code fragments, since not individual characters or lines, but rather *AST* nodes or groups of nodes are selected, plus, all the advantages, the projectional editing brings by itself, as discussed above.

I discuss additionally the projectional approach and some of its basic principles, which I consider to be of practical value in the Section 5.2.

2.2 Modular Language Engineering

2.2.1 Describing a Language in Projection

When building a projectional editor for a language, the language must be given as a certain description of the *AST*. As *AST* represent a graph, the nodes and edges types, as well as their possible relationships must be described¹.

The nodes of the *AST* are described through giving their types. The node type in projectional editing is called a *concept*. *Concepts* are very similar to classes in object oriented programming languages. They feature inheritance, they can implement interfaces, they can have internal data, similar to member fields, and they can feature behavior, similar to member functions. The difference with classes, however, is that the member fields are not usually encapsulated.

The edges of the *AST* are not described on their own, but instead as a properties of nodes. A node can have children, or can reference other nodes. An example of child relationship, can be a condition expression of the `if` statement. An example of reference relationship can be a local variable usage, referencing the declaration of the local variable. Child and reference relationships can have different cardinality, with minimal border from 0 or 1, to the maximal border of 1 or N, where N stands for just “many”, or several.

The cardinality itself, is not usually enough, to restrict as desirable node relationships. Special constraints can be added and checked for each relationship, which describe precisely, or provide procedure to check, the validity of a relationship being established. The

¹Compare this with the textual approach, where a grammar for the language must be built, which is generally speaking complex, and some times even not a possible task, which leads to the increasing parser complexity, known problem in particular in the C++ area

projectional editor must inform the user, every time, the constraint was not satisfied, so that the user has a chance to correct the code, to match a valid *AST* description.

For the user to be able to manipulate the *AST* for each node *concept* an editor has to be created. The editor defines, how a node of a given *concept* should be represented to the user, which editing operations, and how, the user may perform on the node.

The minimal set of data was described above, which has to be defined for a language, to enable the projectional editing for it.

Additionally, constraints may be refined, involving some usual for typed languages type restrictions and checks. Generators can be added to transform *ASTs* given in a language. Text generators can be defined to generate a text code from an *AST*.

Behavior can be defined for a concept, to provide some method-like functionality to it. Additionally, some user-invokable functions can be described, to perform manipulations with the *AST*.

The process of defining a modular language in the *JetBrains MPS* environment is described additionally with practical details in the Section 3.1.

2.2.2 Language Modularity

As *concepts* feature inheritance, it is possible² to use a child concept at a place where a parent concept could be used.

The inheritance works over the language borders, allowing to create the child concept in a language L2, separate from the language L1, where the original parent concept has been described. Thus the language L2 can be seen as a modular extension to the language L1.

The modular *DSL* creation is discussed in [9], [10]. The language modularity, in a context of *JetBrains MPS* is described in [7], [11].

The main focus of this work is a construction of the C++ programming language on top of the *mbeddr* C implementation. Thus the modularity in the language engineering plays a key role in the work.

While extending the C language of the *mbeddr* with C++ specific *concepts*, all the aspects of the language description (see previous subsection) have to be extended. The newly introduced *concepts* for nodes of the *AST*, typical for C++, must inherit from some *concepts* of the original *mbeddr project* C language. Not only new nodes and edges are introduced, but also constraints and other language description aspects have to be made incorporating the newly introduced concepts. The practical side of the language modularity and extensibility is discussed throughout this work.

²to some extent, the extensibility is described separately in one of the following chapters

3 Technologies in Use

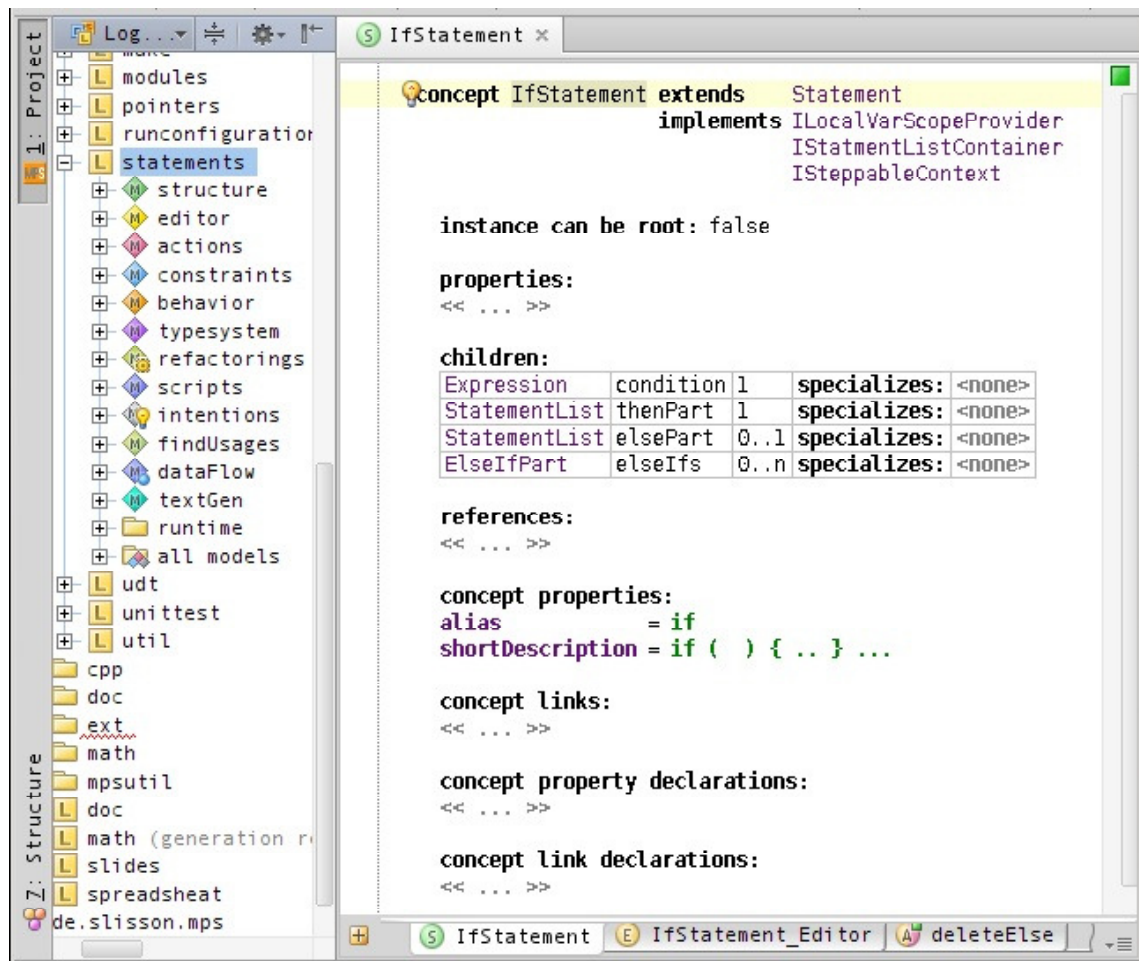
The C++ programming language developed through out this Master Thesis is based on two technologies, which are introduced in this chapter. The first technology is the *JetBrains MPS* language engineering environment, which provides the core foundations and means for incremental language construction. The second technology is the *mbeddr project*.

3.1 Jetbains MPS

JetBrains MPS stands for JetBrains Meta Programming System. In this *IDE*-like software it is possible to develop *DSLs*. The approach taken in the *JetBrains MPS* is rather unique, and it is considered to be advantageous in many ways, [12].

In general, the way the language is describe in *JetBrains MPS* coresponds to the way, described in the Section 2.2. Here I will describe the process in practical details, as it is crucial for understanding the practical part of this Master Thesis.

In this section I will go through a definition of one *concept*, describing the facilities, *JetBrains MPS* provides to support it. Each *concept* is described by several views on it.

Figure 3.1: JetBrains MPS User Interface, *if* Statement Concept

Among such views there are *concept* declaration (or language structure) view, editor view, behavior view, constraints view, type system view, generator view and few more views. As a language consists mostly of the included in it concepts, the whole language is presented by the mentioned views as well, where each view on the language contains all views of the kind on each language *concept*. Left part of the Figure 3.1 demonstrates the views on the *statements* language.

The representation of a new language created in concepts and views to them, present a seamless approach to creating a new language with a projectional editor for it.

The *mbeddr project* is a software, separate from *JetBrains MPS* but based on it, representing an extensible C language implementation with extensions. I will use *concepts* from the *mbeddr project* throughout this section as examples to demonstrate MPS. Different C language parts are going to be decomposed into *concepts* and these concepts are going to be defined using *JetBrains MPS*. The reader should not confuse though the *mbeddr project* and *JetBrains MPS* itself: the former is a software, developed in the latter and is used to demonstrate the latter.

3.1.1 Concept Declaration

Concepts, as it is described in the Section 2.2 represent a class-like types for nodes of an AST. This terminology is kept in *JetBrains MPS* and MPS concept has the same meaning as *concept* term used in the Section 2.2. I use the term “concept” both in general, to describe an AST node type, and in particular referring to an MPS concept.

The Figure 3.1 on the right part demonstrates a declaration of `IfStatement` concept from the *mbeddr statements* language. It corresponds to the `if` statement of the C language.

At first, the *concept* is named, and a *base concept* is defined. The `IfStatement` *concept* inherits from the `Statement` *concept*. This allows the `IfStatement` to be used at any place at which the `Statement` could be used, and inherits like in object oriented programming all data and behavior of the `Statement`.

Next, it is defined, which interfaces the *concept* is going to implement. For example, by implementing `ISteppableContext`, the `IfStatement` supports the *mbeddr* debugger when stepping in the body of the `IfStatement`.

The “instance can be root” property defines, if it is meaningful, to create a *concept* without a parent *concept* for it. In the case of the `IfStatement` it does not make sense, as the statement should belong to some block. The `true` value can be used, e.g. for modules, as they do not have any outer concepts, and can be seen as a document in *JetBrains MPS*.

The “properties” part defines if the described *concept* instances should have some primitive type data fields (string, boolean, int). An example of a property could be a `name` property of a variable declaration. The `IfStatement` *concept* does not specify any properties, neither does it inherit any from the `Statement` *concept*.

The “children” section describe which nodes can be children on the AST of the `IfStatement`. Each child is assigned with a role and cardinality. For example, the `IfStatement` should have exactly one child of *concept* `Expression`, it has a role “condition”.

The “references” section describes in the similar way as in the “children” section, which nodes could be referenced by the node of a given *concept*. Referencing can be used, to bind a given node, to a node, located somewhere else on the AST. As an example, a variable

usage in expression shall reference the variable declaration, to express precisely, which variable is used.

Finally, some attributes of a *concept* follow, which do not have a primary importance for the discussion here. The “alias” is used to name a *concept* in a short way, to allow for quick instantiation in the editor. The “short description” is shown to hint a programmer on the alias meaning. A *concept* can be made abstract in the “concept properties” section. Abstract *concepts* are purely used in inheritance to create other non-abstract concepts with a common parent.

JetBrains MPS separately allows to define so-called *interface concepts*. Interface concepts are *concepts* which can not be instantiated, but which serve as a base for inheritance and implementing and interfaces as Java classes do. A *concept* can have only one base concept, but can inherit from/implement many interface concepts.

3.1.2 Editor View

The editor view, Figure 3.2, is designed to give a look for a node of a *concept*, and a way to input it. This is where the projection of an *AST* node is defined. As editors are mostly defined to look like text, a program in the C++ programming language implemented in *MPS* looks almost like a regular C++ code.

In the editor view one defines an editor for a *concept*. *JetBrains MPS* introduces here a bit confusing terminology, calling one editor for a given *concept* concept an “editor concept”. Thus an error message “An editor concept not found for a concept X” would mean that no editor has been defined for the *concept* X in the editor view for it. In this work I call the content in the editor view for a *concept* X an “editor for the *concept* X”. The same terminology applies to all the following views related to a single *concept*.

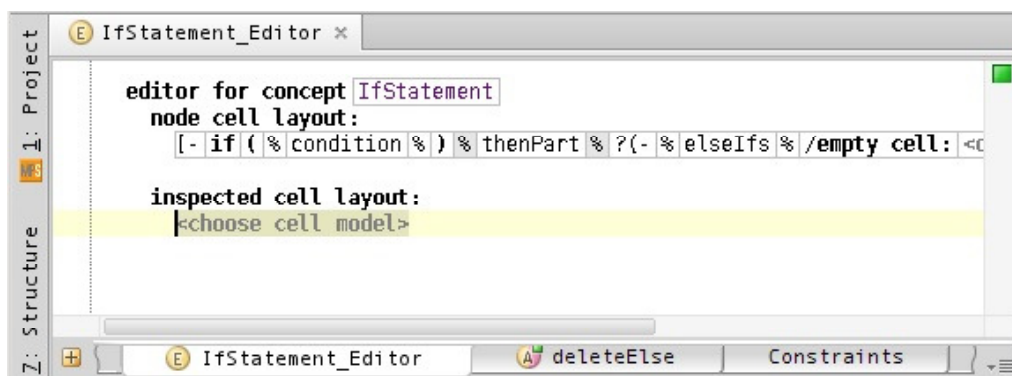


Figure 3.2: Editor View for the *IfStatement Concept*

The editor for a *concept* defines the visual representation for a node of the concept, using special syntax. For example, Figure 3.2 defines an editor for the *IfStatement*. At first the “constant” non-changeable by a programmer text is given, which is “if” and “(”. Then the child *condition* is referenced, so that after the “if(” the user will be able to input an expression for the condition of the *if* statement. The editor can be configured to show or hide some parts of a node, depending on some condition, e.g. hiding *else* part of the *if*

statement, if it is not defined anyhow. Editor are also responsible for all the interaction, a user experiences when editing a code in *JetBrains MPS*.

3.1.3 Behavior View

The behavior view, can be used to define certain behavioral methods for a concept. A concept is represented there similar to a Java class, and it is possible to define the methods in a Java-like language. *Concept* inheritance is taken into account like in Java.

A *concept* constructor can be defined there to initialize by default a newly created node of a *concept*.



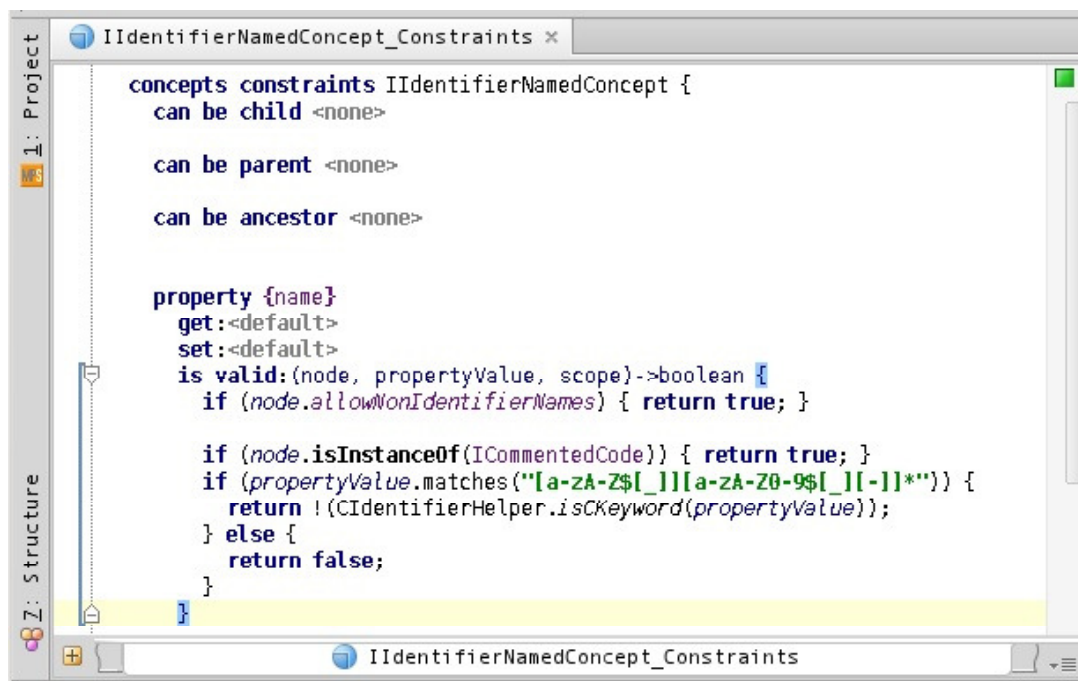
Figure 3.3: Behavior View for the LocalVarRef Concept

The Figure 3.3 shows the behavior of the `LocalVarRef` concept. This concept represents in the *mbeddr project C* language an expression, referencing a local variable. The local variable declaration is stored as a reference `var` in the *concept* nodes.

Two convenience methods are defined for the `LocalVarRef` concept, to get an easy access to the local variable properties.

3.1.4 Constraints View

The constraints view can be used, to limit in a desirable way *concept* property values and relationships, a node of the *concept* can have to other nodes.

Figure 3.4: Editor View for the *IfStatement Concept*

The Figure 3.4 shows constraints defined for a property name of the `IIdentifierNamedConcept` interface concept. All concepts which have a name, which must confirm to the identifier naming restrictions, can implement the `IIdentifierNamedConcept`, to immediately get the desired characteristic.

The name property is programmatically restricted by the use of Java-like code snippet, Figure 3.4. In a similar way relationships to children and referents can be restricted.

It is possible to create a pure Java class withing an *JetBrains MPS* language, and use it in almost any concept view in the *JetBrains MPS*. In the `IIdentifierNamedConcept` interface concept constraints the `CIdentifierHelper` class was used to check the name property on collision with the C language keywords.

3.1.5 Type System View

JetBrains MPS has a special support for creation of typed languages. Types are mainly used in expressions. An expressions may count on a certain sub-expression to have a given type, or a type, compatible with it. Whenever the expectation does not meet the reality, a warning or error can be displayed to a programmer.

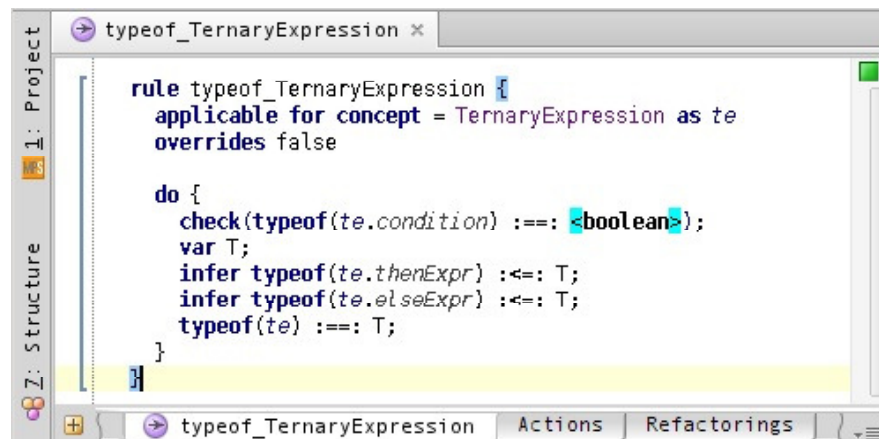


Figure 3.5: Type System View for the TernaryExpression Concept

A *concept* representing nodes which can have type in *mbeddr* inherits from `ITyped` interface concept. In the type system view certain rules must be defined with the use of a special language, which define the type or type comparison rules for a *concept*. Moreover, the type system language can be used to infer a type for a given node, Figure 3.5.

The Figure 3.5, demonstrates the use of the *JetBrains MPS* type system language to infer a type of the `TernaryExpression` Concept node. The syntax is on the one hand self-explanatory when reading, but on the other hand could be rather confusing when crafting.

3.1.6 TextGen View

To make use of the code in the projectional editor, further tools must be invoked on it, e.g. parser, compiler, etc. Normally they work with a textual representation of the same code. In order to obtain the textual code from the *AST* in the projectional editor generators are invoked.

Generators can be of two kinds. The kind of generator is dedicated to transform an *AST* in one *DSL* into another *AST* represented in a, usually, lower-level language. The second kind of generators is dedicated to transform an *AST* into text. Such generators are called “*TextGens*” in *JetBrains MPS*.

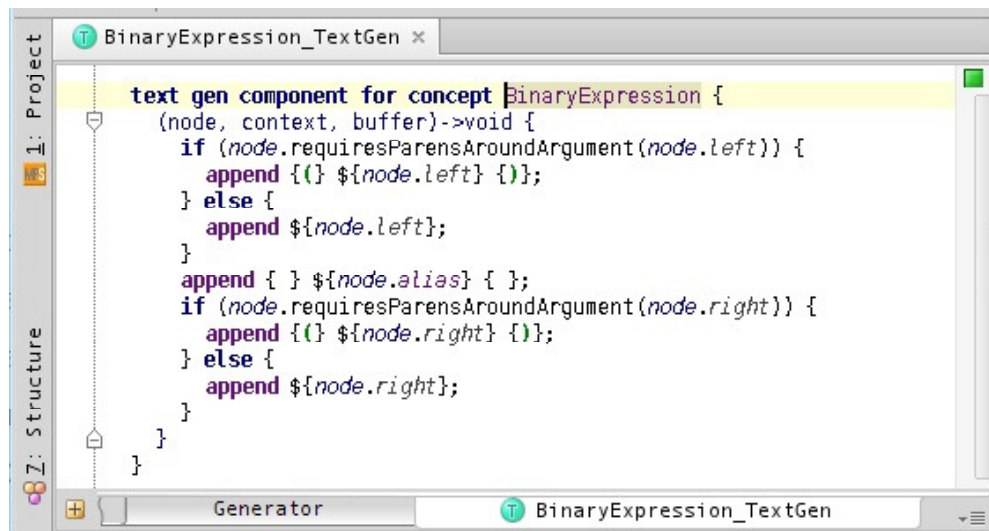


Figure 3.6: TextGen View for the `BinaryExpression` Concept

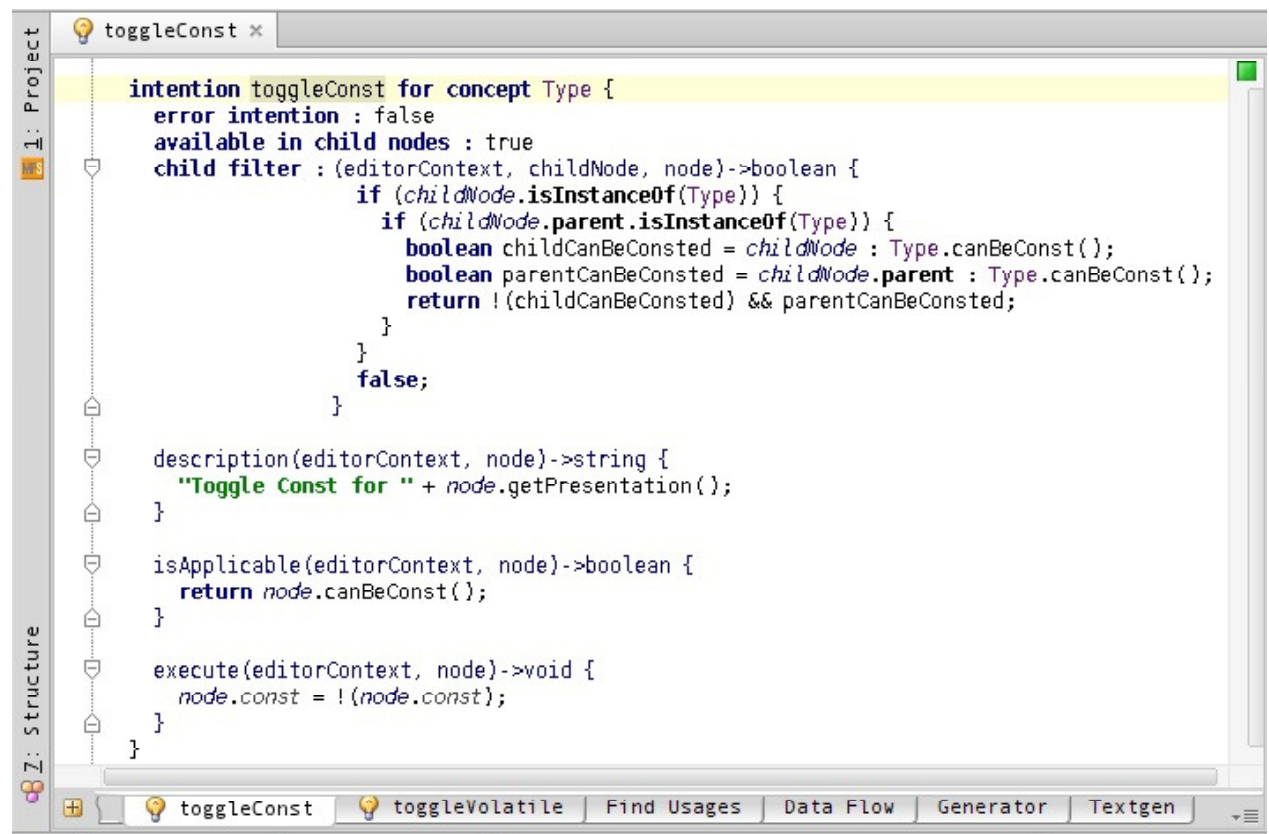
The Figure 3.6 demonstrates how a node of a `BinaryExpression` Concept is converted to text. It is noteworthy to say, that when rendering to text the left and right sub-expressions, the corresponding *TextGens* are invoked, making the text generation recursive.

3.1.7 Generator View

The generator view is one of the most complex *JetBrains MPS* views. It serves the transformation purposes of one *JetBrains MPS* language into another one. This view does not have a strong connection to the present work, as the generation of the projectional C++ programming language is mostly performed by *TextGens*.

3.1.8 Intentions

JetBrains MPS intentions are special procedures which can be used for automatic manipulations on the AST with a node of a given *concept*.

Figure 3.7: Toggle Const Property for a Type *Intention*

The Figure 3.7 demonstrates an intention, used to modify the `const` property of a given type.

For an *intention* to be defined, one has to name it, specify a *concept*, to which the *intention* is applicable, provide a textual description for it, and finally specify the desired effect.

Intentions are accessible in the projectional editor from a context menu, when focused on a target node. They represent a useful mechanism to support a programmer with various automations, including automatic code generation.

3.1.9 Other MPS Instruments

JetBrains MPS provides other instruments to enhance languages.

Actions are used to automate node deletions or editing. For example, deleting an array indexing expression, could be made to provide a substitution, an array expression itself. Such behavior may seem more natural to a programmer, used to text editing.

JetBrains MPS provides a special support for refactorings. Special code snippets in the Java-like language can automate routine operations. As an example, factoring out a local variable from an expression can be taken.

3.2 MBEDDR Project

The *mbeddr project* is a software built with the use of *JetBrains MPS*.

The *mbeddr project* represent mainly an implementation of the C programming language in the *JetBrains MPS* environment. Having embedded systems and software for them as the main focus, *mbeddr* provides certain language extensions to empower the programmer in the mentioned domain [13], [12].

Being a different language the C++ programming language shares a lot of commonality with the C programming language. As *JetBrains MPS* allows, to some extent, see 2.2.2, incremental language construction, the *mbeddr project* represents a suitable basis for the C++ programming language implementation in *JetBrains MPS*.

The use of *mbeddr* however, could not be purely incremental, and required some changes to the *mbeddr* itself. The changes were introduced however, in a way to make *mbeddr* simply more extensible in general, and not by adopting it to the current work needs.

In this section I describe the *mbeddr project*, as the current work is based on it.

No matter the *mbeddr project* has (one) C language with extensions as an outcome, internally, as a *JetBrains MPS* software it is represented as several *JetBrains MPS* languages. In *JetBrains MPS* a language corresponds to a module.

All *mbeddr* languages are named starting from *com.mbeddr*. name part. In this document I usually omit it, keeping the last word of the name only. E.g. *com.mbeddr.expressions* is called simply *expressions* here.

3.2.1 mbeddr Expressions Language

The *expressions* language contains definitions for all expressions, possible in the *mbeddr* C language. As in object oriented programming languages *concepts* of the *expressions* language form inheritance hierarchies. *JetBrains MPS* is capable of showing a given *concept* in a hierarchy.

Figure 3.8: *Concept* Hierarchy Example

The Figure 3.8 shows a hierarchy for the `MinusExpression` *concept*. In a similar way all expressions of the C programming language are implemented in the *expressions* language.

Whenever there is a need in the C++ programming language to extend the C programming language with a new expression kind, like object member reference, *new* expression and so on, a point of inheritance has to be found in the *mbeddr expressions* language to base a new *concept* on it.

Additionally, the *expressions* language defines C language types.

Figure 3.9: *mbeddr* Type Hierarchy Example

All *concepts* corresponding to C types are based (directly or indirectly) on the `Type` *concept*. For example, the hierarchy of `IntType` *concept* is demonstrated in Figure 3.9.

In order to add a type to *mbeddr* C language, one should inherit from the `Type` *concept* as well. Such inheritance automatically allows the new type to appear at all places, where a type in general can be found in the C language or its extensions.

3.2.2 mbeddr Statements Language

mbeddr statements language contains definitions for C language statements. The `Statement` *concept* serves as the base for inheritance, and represent by itself an empty line, or no-statement.

In order to create a new statement, like `delete` statement in C++, the inheritance should start from the `Statement` *concept*.

```
int16 abs(int16 x) {  
    if (x >= 0) {  
        return x;  
    } else {  
        return -x;  
    } if  
} abs (function)
```

Figure 3.10: Example of Multiple Languages Used Together

The *statements* language actively uses the *expressions* language, Figure 3.10. In the *mbeddr* code snippet the nodes coming from *statements* language are marked green, and the nodes, coming from *expressions* language are marked yellow¹. As the example shows, `if` statement and `return` statement are coming from the *statements* language, but inside they contain as children expressions. This is an example of language modularity in *JetBrains MPS*, used by *mbeddr*.

3.2.3 Modules in mbeddr

In C (and in C++ as well) there is no clear concept of a module. The *mbeddr project* improves on it, defining modules, [12]. A C module is a *concept*, from which the header and the `.c` files are generated in *mbeddr*. Flagging an object (function, variable, structure, etc.) in a module as `exported` causes the declaration of the object to appear in the header, and thus the object starts to be accessible by other modules.

An issue with the C programming language is that there is one and only global namespace. The *mbeddr project* improves on it by introducing so-called name mangling. All names of the module contents are prefixed with the module name, when generated to the C text code. Thus the object with the same name but from different modules do not cause a name clash.

The implementation of modules in *mbeddr* can be found in the *modules* language. Functions are described there as well, for the `Function` concept example, see the Figure 3.10, not marked with colors part.

Modules are further included into *JetBrains MPS models*, which correspond to one single *JetBrains MPS* file unit. Each model should have a node of `TypeSizeConfiguration` and `BuildConfiguration` concepts. In the former, the sizes for types must be given, in the latter, all directives needed to compile the generated from the *model* text.

3.2.4 Pointers and Arrays in mbeddr

In the *pointers* language array access and pointer dereferencing expressions are defined as *concepts*. Similar syntax to them have overloaded operators with classes. Thus this language could also be extended by the *Projectional C++*, if some reuse is possible there as well. This is discussed in detail in the Section 4.3.

¹not marked with color is an instance of the *Function* concept, which comes from the *modules* language

3.3 The C++ Language

This work is basically an implementation of the C++ programming language in *JetBrains MPS*. No matter, the whole work is about the C++ implementation, it is infeasible to describe the language in detail itself here. Thus I give a references to literature about the language in this chapter only. Certain aspects of C++ are raised during the description of the C++ implementation in *JetBrains MPS* itself in the Chapter 4.

Various literature is available, to get acquainted with the language closer. The most complete guide to the language, covering *STL* as well is [14]. The more easy-to-read and more suitable for beginners book on C++ is [15]. A newer book, oriented towards intermediate level C++ programmers and updated to the recent C++11 standard, [16], and describing *STL* as well, [17].

The collection of techniques to get more effective C++ programs is [18]. Templates are explained in detail and researched in, [19]. The book dedicated to ad hoc polymorphism and advanced template meta programming can be also of interest as an approach to language engineering in a certain sense, [20].

4 Projectional C++ Implementation

4.1 C and C++

Initially C++ appeared to be an extension to the C language, called “C with Classes” [21]. Till now the high degree of commonality can be found between the two languages. Mainly, the most of the C code is going to be valid C++ code.

Some differences exist however, I introduce them here, together with the way they are adopted in the *Projectional C++*.

4.1.1 Reference Type and Boolean Type

Among primitive types and operations there are two major differences relevant to practice. They are discussed in the following subsections.

Reference Type

The reference type is basically a new construction in C++ which represent the old notion of pointer in C with a different syntax. Infact behind the reference type stands a pointer to the base type, and it is dereferenced when needed.

The syntax for a variable of type T can be used with the variable of type reference to T , or $\&T$ as it is designated in C++. Thus the programmer benefits from the shorter syntax in comparison to the pointer dereferencing.

It comes especially handy when passing arguments to methods by reference, which avoids creating a copy of an object to pass by value, and still preserves the short syntax without pointer dereferencing.

Listing 4.1: Reference Type in a Copy Constructor

```
class MyClass {  
    MyClass( const MyClass& original );  
};
```

The value of the reference type in C++ is bigger however, than just a new syntax for pointers. A constant reference to a class object has to be used in a constructor to give it a special meaning of the copy constructor for the class, as the Listing 4.1 demonstrates. This changes the whole semantics of the class, making it copyable. It is discussed in detail in 4.2.1.

The reference type itself is implemented rather straightforward and similar to the pointer type of *mbeddr*. It inherits the *Type concept* of *mbeddr* as described in the 3.2.1, and has a base type as a child.

Boolean Type

The C++ programming language has a special `bool` type to represent the two logical values. There is no such type in C.

No matter, the `bool` type is not present in C, for the convenience of the user the *mbeddr* C implementation introduced a type `bool`, which is translated to `int8_t`, together with `true` and `false` values, converting to 1 and 0 respectively. This implementation can arguably be considered better than the original C++ `bool` type present in the generated code, because the C++ programming language standard does not define explicitly the size of the `bool` type [16]. This can be suitable for the embedded domain better, conforming to the *mbeddr* spirit.

In the context of embedded systems, which *mbeddr* targets, it is often very important to know precisely, with which type the user is operating, as the limited resources are important to consider. Substituting the `bool` type with the `int8_t` type ensures that the size of the `bool` variables is known. Also, it can be changed as needed in the `TypeSizeConfiguration` in each model created with *mbeddr* separately, see 3.2.3.

The C++ standard explicitly allows the `bool` type to participate in integer promotions. This ensures further the compatibility of the custom-written text code, which may use actual `bool` type, with the code generated with substitution of `bool` to `int8_t`, as the user `bool` will be promoted.

Among limitations of this approach one can take as an example `std::vector<bool>`. Since the word “bool” itself is never generated, it is not possible to use the specialization of the template, which ensures storage optimization, through, though, higher processing load when extracting a value from such a `vector`.

The `bool` type from *mbeddr* is kept in the *Projectional C++*. This decision is arguable, and can, of-course, be changed in the future.

4.1.2 Modules and C++

The C++ programming language is an improvement over the C language by itself. There is, however, no concept of a module, which can bring certain advantages and disadvantages. As a disadvantage can be named a potential disorder in placing implementations for classes and functions, as the language itself does not enforce a clear one place for them. Potential name clashes are also disadvantageous. As an advantage, conditional compilation can be used in C++ to include different files with different implementations, which is often used to create cross-platform code. Additionally, classes can be used analogously to modules.

The name clash problem is solved in C++ by introducing the namespaces. The programmer defines a namespace and then places there all the exported code. The nodes with equal names from different namespaces do not clash.

C++ however does not elaborate on the disadvantage of having declarations and implementation not organized in one place, and being fully disjoint. *mbeddr* compensates on it, 3.2.3.

After comparing the two approaches of *mbeddr* and of the C++ programming language to improve on C, the hybrid approach has been picked. Firstly, the C++ implementation modules have been introduced. And secondly, the namespaces can be defined and used.

In *Projectional* C++ modules are program modular elements, where a programmer declares and implements C++ classes, and the .h and .cpp files are automatically generated from them. This eliminates the need to create and control two files for each logical program element, like a class, and keep them synchronized with each other. For example, changing an interface of a class would require at first opening the header file, and introducing the changes in the declaration, and then rewriting the corresponding part of the .cpp file in strong correspondence with the header. This work decrease in order to change an interface can improve productivity.

Namespaces are introduced in the *Projectional* C++ to avoid inter-modular name clashes, they work similar to the namespaces in C++.

As auto-completion works very effective in the projectional editor, the need in the `using` directive does not emerge the same strong as in plain text editors. Long names of namespaces are appended to the end of method definitions for classes, to be exact about the namespace, but the declarations are kept looking short, with only the last namespace shown, Figure 4.1.

```
namespace MyNamespace {
    namespace MyInnerNamespace {
        class A /copyable and assignable/ {
            public:
                void DoSomething()
        }
        void A::DoSomething() from MyNamespace::MyInnerNamespace::A {
        }
    }
}
```

Figure 4.1: Example of Nested Namespaces

In general, the generator is responsible in generating correct namespace resolution, and the projectional C++ programmer can benefit from short and clear namespace presentations, which are also quite handy to input.

4.1.3 Memory Allocation

In the C programming language memory (de-)allocation on the heap is happening via calls to the dedicated library functions. C++ instead introduces separate language construction for memory allocation and de-allocation.

The `new` and `delete` together with their array versions are simply an expression and a statement correspondingly, which perform the required operations.

Creating them is relatively easily possible by inheriting from the Expression and Statement concepts, and introducing the corresponding typing.

When a segment of memory is allocated as an array, it has to be de-allocated as an array either. As it is stated in the C++ standard ([16]) the behavior of simple de-allocation of an memory segment, allocated as an array, results into undefined behavior. A simple check is introduced in order to control this, see the Section 4.5.6.

4.2 C++ Object-Oriented Programming

The C++ programming language is a multi-paradigm programming language. The ability to support the object-oriented programming, is incorporated via classes.

A class represents a new type in the C++ programming language. Each class may have data in the form of fields, and behavior in the form of methods. Two types of methods are special for C++ - constructors and destructors, they have special meaning and syntax.

Encapsulation is enabled via governing access permissions to fields and methods of a class. The access control is governed with the creation of `public`, `protected` and `private` class sections.

Inheritance is implemented in C++ via allowing for each class to have one, or even many base classes. Inheritance from a base class is performed under a certain access control modifier. There is no pure notion of an interface, but rather abstract classes are introduced.

Polymorphism is implemented via pointer-to-class type compatibility over inheritance-connected classes.

The implementation of these C++ features in a projectional editor environment is discussed in the following chapters.

4.2.1 Class declaration

The C++ programming language is a mature language, with long traditions, and high flexibility, [22] can serve as an example. Although the language is also famous for being complex. It will not be possible to simplify language, removing features from it, which will restrict the language use. In this work I try to research, how the editor can be more supportive for the user, to eliminate usual mistakes made while programming, as well as provide help in structuring the code.

Visibility Sections

Instead of declaring visibility type for individual class members, visibility sections are created in C++.

The sections can be opened with a string `private:`, `protected:` or `public:` within a class declaration, and closed when another section is opened or when the class declaration ends. This allows the user to open and close the same section multiple times and declare sections without any particular order.

Various coding guidelines ([23], [24]) exist to enforce some restrictions on the visibility sections.

In particular, the sections are allowed to be opened only once. This ensures, the reader of the code will see interface of the class (public section) in one place, “contents” of the class (private section) in one place, and opportunities to access members in the inheriting class (protected section) in one place, without the need to scroll through through the whole class declaration.

Another typical requirement in coding standards, is the order of the section. Usually the public section is required to be first, for the class users to see immediately the public interface, the class provides.


```
class WebPage {  
    public:  
        explicit WebPage() (constructor)  
        WebPage(const WebPage& original) (copy constructor)  
        boolean loadFromFile(string path)  
        string getHtml()  
    private:  
        int32 visits  
    protected:  
        string html  
}
```

Figure 4.2: Sample class type declaration

The Figure 4.2, shows an example class declaration implemented in the projectional editor. The class concept has the visibility sections as children. Each section is given a separate role, and can appear 0 or 1 times. The editor for the class concept orders the visibility sections so, that the public section always comes first, followed by the private and protected sections.

The creation of a section is made with the use of so called *intention* in MPS. The user uses *Alt+Enter* combination on the class declaration to create visibility sections. It should be more practical and fast for the user, compared to typing the keyword, colon and indenting the result.

A question arises on how to support another way to represent a class, so that it will reflect requirements from a different coding standard. And as a way to resolve it a definition of another editor for a class concept can be offered, Unfortunately, the current version of *JetBrains MPS 2.5* does not support a definition of multiple editors for the same concepts. This limitation however is addressed in the newer 3.0 version.

Constructors

Constructors are special methods of a class, used to construct the class instances.

Constructors have special syntax and no return type, being similar to class methods. Additional value, however, the constructors gain, when participating in type transformations. Namely, when a constructor of a class B exist from a type T, instances of the type T can be used whenever the B class instance is required. The constructor will be *implicitly* called and a temporary object of class B is going to be created as a mediator.

Thus constructors extend the type system. Since this type extension can not be easily observed, it is highly possible to get various *run-time* errors or unexpected behavior.

Listing 4.2: Example of an Implicit Constructor Error

```
#include<iostream>  
using namespace std;  
  
/*  
 * API definition
```

```
*/

class Circle{
private:
    int r;
public:
    Circle(int radius){
        r = radius;
    }

    float getPerimeter(){
        return 2*3.14*r;
    }
};

void print(Circle c) {
    cout << "The perimeter is: " << c.getPerimeter();
}

/*
 * Use case by user of the API
 */

int main(){
    print(5); //Prints "The perimeter is: 31.4"
    return 0;
}
```

The Listing 4.2 demonstrates a simplified use case where the function `print()` is invoked on `int` without any compiler error, and the resulting behavior is unexpected.

To avoid similar, it is possible to deprecate participation of a constructor in type conversions, adding a word `explicit` to the constructor declaration.

The described problematic motivated the following decision. When a new constructor is created, it is by default declared to be explicit, the user must intentionally change it to get the type conversion behavior. Such behavior is safer by default.

Copying

In the C++ programming language the programmer controls memory allocation fully on his/her own. This affects the way of copying the object. In C++ a programmer should define two methods for a class: a copy constructor and an assignment operator. These two methods work when assignment like `a = b` happens, when instances of a class are passed by value to a function, when one object is initialized with a value of another object and so on.

C++ serves here sometimes dangerously generating default copy constructor and assignment operator, which by default represent a bitwise cloning of an object. This can lead

to problems.

Listing 4.3: Need in a Custom Copy constructor

```
class Resource{
    int* r;
public:
    Resource(){
        r = new int(0);
    }
    ~Resource(){
        delete r;
    }
};

int main(){
    Resource a;
    Resource b = a; // b.r is the same address as a.r
    return 0;
}
```

The Listing 4.3 demonstrates a program which crashes upon execution as destructors of `a` and `b` are deallocating memory with the same address, after default copy-constructor copies the address from `a` into `b`.

To avoid the described problem, the programmer has to either define proper copy-constructor or forbid copying of the objects of the class. The same applies to the assignment operator. Many standards require the two functions to be implemented in sync, [25]. This can be performed by implementing the assignment operator first and reusing it in the copy-constructor. To simplify the first, specialized macros exist, for example `DISALLOW_COPY_AND_ASSIGN` or `Q_DISABLE_COPY`, [24], [26].

The use of macros in C++ appears often in similar cases, in order to perform some language-engineering tasks to add the missing features to the language. Macros bear pure textual nature, and are processed by the pre-processor. Some negative effects may come out: need to pre-process reduces the speed of compilation and hides the resulting code from a programmer, macros lead to error prone programming, as no type checks are possible, macros make code less analyzable by automatic analyzers.

```
class A /copyable and assignable/ {  
public:  
    explicit A() (constructor)  
    A& operator = (const A& original ) (makes class assignable)  
    A(const A& original) (copy constructor)  
    int16 getX()  
private:  
    int16 x  
}
```

Figure 4.3: Hinting about Copyable and Assignable Class Properties

The projectional editor allows for another solution, different from macros. In order to provide some support for the programmer regarding the copying issue, the projectional C++ implementation hints on the class declaration its assignable and copyable properties, Figure 4.3, and generates by default the declarations of copy-constructor and assignment operator.

The copy constructor and the assignment operator are detected automatically. Two intentions are provided on the Class concept to forbid or allow copying. The forbidding intention imitate the macros mentioned above, but displaying and explaining the implementation to the user Figure 4.4. The implementation consists of moving the declarations of two functions to the private section of the class. Implementation is not required for such functions.

```
class A /neither copyable nor assignable/ {  
public:  
    explicit A() (constructor)  
    int16 getX()  
private:  
    int16 x  
    A& operator = (const A& o ) (makes class not assignable)  
    A(const A& o) (makes class not copyable)  
}
```

Figure 4.4: Class Made not Copyable by the *Forbid Copying* Intention

The *JetBrains MPS* supports the implementation by providing read-only model accesses, special parts of editor concept, by which the hinting is implemented. The intentions allowed manipulations on a class, which made it possible to automate the allowing or forbidding of copying/assignment, making the implementation clear to the user, without the use of macros. The whole work to forbid copying and assignment contains of a call to an intention, one key-stroke. There is no need to include a header file with macros, and look up the documentation for them (symmetric macro requires exactly one parameter - the class name, and it has to go in the private class section).

4.2.2 Encapsulation and Inheritance

Encapsulation and inheritance are considered here together, because from the language-engineering point of view, they just decide the access for class members. In other words, the projectional C++ implementation has to track encapsulation and inheritance related definitions and provide access to the class members accordingly.

Various Cases of Access Control

In the C++ programming language exists a number of ways to govern access control to class members. Before discussing the implementation of them in a projectional C++, I briefly review them with an example.

All members, a class has, are either declared in the class, or inherited from its base classes.

The members can be accessed in a number of different locations in the code, which differ by the level of access they have to the class members. Among these locations are the class methods, friend functions, belonging to the class and external to the class code.

Each member can be declared with a certain visibility/access type, and the inheritance of the member can happen with one of the three inheritance modifiers.

The access depends on the object, on which the member is requested, and on its type as well.

```
class A /copyable and assignable/ {
    public:
        int8 valAPublic
    private:
        int8 valAPrivate
    protected:
        int8 valAProtected
    friends:
        friend compare (boolean compare(const A& a1, const A& a2))
}

class B : public A /copyable and assignable/ {
    public:
        B(const B& original) (copy constructor)
}
```

Figure 4.5: Declaration of two classes with a friend function

The Figure 4.5 shows a declaration of two classes. The class A has all three public, protected and private fields. A function `compare()` is declared to be a friend function. The visibility plays no role for the friend function declarations, that is why a decision was made to create a special section for friends, it is not generated anyhow in the resulting C++ textual code.

The class B in the Figure 4.5 is inheriting publicly from A, which means, that public members of A remain being public in B. The class B declares a copy constructor.

Such declaration can be utilized as shown in the figure Figure 4.6.

```
B::B(const B& original) from B {
    this->valAPublic = original.valAPublic;
    this->valAProtected = original.valAProtected;
    this->valAPrivate;
}

boolean compare(const A& a1, const A& a2) {
    return a1.valAPrivate >= a2.valAPrivate;
} compare (function)

void external() {
    B b;
    cout << b.valAPublic;
    cout << b.valAProtected;
    cout << b.valAPrivate;
} external (function)
```

Figure 4.6: Visibility resolution

In the copy-constructor the visibility resolution happens after `this` pointer and after the `original` object. Arrow expression and dot expression are used for this. The first and second lines are making use of public and protected fields of the base class `A`. The use of the private field is however not possible, since private fields of a class are only accessible to methods of the same class and friend functions.

It is even not possible to input the not-allowed member, as the projectional editor does not bind the text to anything, and it remains red, invalid, not usable further.

The `compare()` function is declared in advance (Figure 4.5) to be a friend function of the class `A`. Thus, it is not a problem for this function to access even private fields of `A`, for comparison purposes in this example case.

The function `external()` is not related anyhow to classes declared. Thus, it represent “external” from the class point of view code. Only public members are accessible, but not protected or private. The attempt to input them, simply fails, they are highlighted red, and not bound to anything.

Expressions to Address Class Members

Members are usually accessed relatively to some object. The object can be designated as an expression of type class or a pointer to class, in particular, `this` expression. The resulting access represent nothing else, but expression itself. One of the greatest ideas in *JetBrains MPS* to allow extensibility is concept inheritance. Once a need to create a new concept arises, serving as a concept known before, the new concept has to inherit from the existing one, and this is almost all what has to be done. Thus inheriting the `OoDotOrArrowExpression` concept from the `Expression` concept, we get the ability to use the expression, designed for member access, wherever an expression can be used.

The abstract concept `OoDotOrArrowExpression` serves as a parent for `OoDotExpression` and `OoArrowExpression`. The commonality between the two, is that an object is accessed in the left part, and a member is selected in the right part, as well as the way to decide the

access to members. The access is defined then, which left part is going to be possible in such expressions.

Within the class methods it is also possible in C++ to address class members as local variables. In the projectional implementation described, it is not possible. Instead, `this` expression has to be used. It makes typing a little bit slower, but allows to easily distinguish between members of the class and other variables or functions.

4.2.3 Polymorphism

There are several ways to achieve polymorphic behavior in C++. The purists of the language differentiate between the polymorphism based on virtual functions or on templates. More general opinion can include in the notion of the polymorphism also functions overloading and operator overloading, also called *ad hoc* polymorphism. Occasionally various operations with `void *` are also classified as the polymorphic programming.

In this section I am writing only about the class-related virtual functions polymorphism.

Virtual Functions Polymorphism in C++

Starting the description of the projectional implementation, I find it good to spend some time describing the way, the polymorphism is implemented in the C++ programming language itself.

Dislike many other popular object-oriented programming languages in the C++ there is no pure notion of an interface. Instead, a base class is used as an interface declaration for its descendants. Functions designated to be a part of the interface must be declared `virtual` and they can be overloaded in the subclasses.

The virtual functions in the base-interface class can be implemented as well, providing some “default” implementation. Otherwise they are left *pure virtual*, meaning that no implementation is provided and the pointer to the function in the table of pointers to virtual functions is zeroed. The syntax for pure virtual functions is rather not obvious, when not knowing about the zero pointer semantics, and a bit cumbersome requiring to type one reserved word, one punctuation sign and one number to express simple fact of pure virtuality or, simply, absence of implementation, Listing 4.4.

Listing 4.4: Pure Virtual Function Syntax Example

```
class Animal
{
public:
    virtual void voice() = 0;
};
```

Such approach is more flexible compared to languages with the notion of interface directly introduced. In C++ it is possible to create partially implemented base classes, what can not be done when implementing and interface in Java or C#, where the approach is “all or none” regarding the implementation of interface functions.

In order to implement a declared in a base class function the descendant must declare and implement a virtual function, matching the full (with return type) signature of the declared function, Listing 4.6. The connection to the “interface” function declaration stays subtle, and it is not immediately clear, whether the declared implementation is an override or a new independent declaration. This knowledge affects the changing process greatly, as the override should change from the interface, together with all the implementation. The absence of a clear override syntax I call here “override syntax absence”.

Whenever a class and all of its ancestors does not provide an implementation of a certain virtual function, created as a pure virtual in the declaring class, the class is called *abstract*. It is not possible to construct instances of abstract classes. C++ however does not have any special syntax for abstract classes, Listing 4.4. The programmer usually has to be aware (from documentation, implementation, or, the worst case, compilation errors) whether a given class is abstract. I will call this phenomenon as “abstract class syntax absence”.

When the overriding a function interface is a active action of the programmer, and is initiated by the programmer, the abstract property of the class, oppositely, can be deduced from the analysis on the base classes automatically, by editor.

In order to use an interface declared in some class, the using code has to get a pointer to instance of any implementing the interface descendant class instance. Thus typing system has to allow a pointer to the descendant to be treated in the way as a pointer to the base would be. The same should hold normally for the reference types, but it is not used very often on practice, and omitted in the implementation. As this typing rule represents the core of polymorphic behavior, I will start from it, describing further the projectional C++ implementation.

Pointer to Class Special Typing

The problem solved here is enabling the usage of pointers to descendants instead of pointers to ancestors, Listing 4.5.

Listing 4.5: Example Usage of a Pointer to Descendant Class

```
class Shape {};  
  
class Circle: public Shape {};  
  
void draw(Shape * shape){  
    // ...  
}  
  
int main(){  
  
    Circle* c = new Circle();  
  
    // Call with a Circle* parameter instead of the declared Shape*  
    draw(c);  
}
```



```
    return 0;
}
```

The pointer type is implemented in a separate language in *mbeddr*. Following the goal of non-invasive changes to *mbeddr* the C++ implementation needs to add the typing rules for pointer *to classes* without changing the pointer *mbeddr* language, where the typing system for pointer type is defined.

In the case when a type of a pointer to a base class is expected, a pointer to a subclass should also be accepted. The type system of the pointer language will try to check the compatibility of the two pointer types. It will fail to do so, as the *mbeddr* languages are not aware of the C++ extensions by design.

When none of the existing type system rules can resolve the given situation, the so called replacement rule can be invoked in MPS. The C++ extension provides a replacement rule, which checks, whether a class pointed to, is a passing descendant of the class required by an expression, where the pointer was used.

In the Section 5.3 I discuss more on the approach taken here, its limitations and the potential ways to overcome them.

Overriding a Virtual Function

The Listing 4.6 demonstrates, how overriding of a virtual function happens in C++. The function `getArea()` is initially defined in the class `Shape` and is then overridden in the class `Circle`. The Listing 4.6 demonstrates as well the “override syntax absence” in C++.

Listing 4.6: Example of an Overridden Function - Text Code

```
class Shape {
    public:
        Shape();
        virtual double getArea();
};

class Circle : public Shape {
    public:
        Circle(double r);
        virtual double getArea();
    private:
        double mRadius;
};
```

In the Figure 4.7 the same example is demonstrated, but in the projectional C++ implementation. Indeed, the Listing 4.6 is the generation result part from the demonstrated projectional sample.

When a method declaration is created, it can be set to be an override of a method in a base class. Only when an empty method declaration is created, it can be set to be an

override, so that the only thing which stays, is to pick a method from a base class to be overridden. The override is automatically named, the parameters and the return type are set accordingly, the `virtual` property is immediately set.

After the override has been linked to the overridden method, the projectional editor checks, if the override full signature stays precisely the same as the one of the overridden method. The overridden method is shown next to the override declaration Figure 4.7, which compensates on the override syntax absence.

```
class Shape /copyable and assignable/ {
public:
    Shape() (constructor)
    virtual double getArea()
}

class Circle : public Shape /copyable and assignable/ {
public:
    Circle(double r) (constructor)
    virtual double getArea() overrides Shape::getArea()
private:
    double mRadius
}
```

Figure 4.7: Example of an Overridden Function - Projection

The additional syntax on the projectional view, should not confuse the reader. It is only present in the projectional editor, and, when the AST is generated into code, the regular C++ syntax is achieved. However in this case the AST stores *more* than needed to generate and compile the C++ code. This subsection demonstrates, why it can be useful.

Pure Virtual Functions

In the example above one improvement to the code can be made. As the `getArea()` for a random shape can not be determined, it makes sense to make the `getArea()` function pure virtual. A pure virtual function has no implementation in the declaring class, and serves only overriding purpose. Semantically in C++ it sets the pointer in `vptr` to 0 and thus has reflecting this syntax, see the similar example in Listing 4.4.

This syntax can be seen as not obvious, as it reflect more the under-the-hood implementation of the mechanism, rather than the original programmer intention to build a basis for an overrides chain.

Additionally, as discussed above, declaring a pure virtual function requires a significant amount of the syntactical overhead.

In the projectional C++ implementation, one intention is reserved to make a function pure virtual. The intention automatically sets the needed pure virtual and virtual flags of the function declaration, and the projection changes. That is why out of the statement `virtual double getArea() = 0;` the programmer has to input only the name `getArea`, pick the type `double`, and toggle the pure virtual intention for the declaration.

The result of the intention work in projection can be seen in the Figure 4.8.

```
pure virtual double getArea() = 0
```

Figure 4.8: Example of a Pure Virtual Method - Projection

The word `pure` is added by the projection editor. This makes the reading of the code easy and natural. The `= 0` part is preserved for the C++ programmer, used to this syntax. And, as in many other cases, the semicolon is omitted as it is nothing but syntactic help to the compiler, which does not have to appear in the projection.

Abstract Classes

If any of the pure virtual functions in the inheritance chain leading to a class is not implemented by this chain, or inside the class itself, the class is called abstract. It is not possible to construct an instance of an abstract class, as such classes are partially implemented. The programmer has to know which classes are abstract, and are intended for inheritance and further implementation only.

Above I discuss the absence of the abstract class syntax in C++. It leads to the need for the programmer to determine somehow him/herself if a given class is abstract.

And editor can however perform an analysis and determine if the class is abstract. In the case of the projectional editor, this analysis is especially computationally efficient, as the AST is readily available, and the quick analysis can be performed by a simple recursive algorithm on the inheritance chains.

After an abstract class is determined, it is possible to modify the editor representation for it, and show that it is abstract, Figure 4.9.

In this example a typical class hierarchy is created to support user interface programming. A user of this API, when searching for a button, could try using the `Button` class, which is designed to be abstract, and serve as a base for the further implementation, e.g. `PushButton` in the example, or check boxes, radio buttons and similar, later.

```
abstract class Widget /copyable and assignable/ {
public:
    explicit Widget(Widget* parent) (constructor)
    pure virtual Size getDimensions() = 0
}

abstract class Button : public Widget /copyable and assignable/ {
public:
    Button() (constructor)
    pure virtual boolean isPressed() = 0
}

class PushButton : public Button /copyable and assignable/ {
public:
    PushButton() (constructor)
    virtual Size getDimensions() overrides Widget::getDimensions()
    virtual boolean isPressed() overrides Button::isPressed()
}
```

Figure 4.9: Determining Abstract Classes

The projectional editor, however, checks on the fly, if a certain class is abstract, adding a special `abstract` word in front of its declaration. This makes the reading easier, and allows for quicker understanding of the code.

Additionally, the creation and usage of abstract class instances is checked, and forbidden by type analysis. This is described separately in the Section 4.5.

4.3 Operator Overloading

4.4 Templates

4.5 Advanced Editor Functionality

As the projectional editor work directly with an AST, it is possible to provide some programming on the AST to improve the user experience. I call this additional programming as advanced editor functionality, and discuss it in this chapter.

4.5.1 Renaming Refactoring

Directly from the nature of the projectional editor, without any additional effort, comes a feature to perform the renaming refactorings.

If a node of an AST gets to be referenced somewhere else, it is referenced by the use of its unique identifier. The name of the node is a property of the node, which is not playing any role in the referencing the node from somewhere else. Thus renaming, dislike the way it is performed in text editors, does not involve replacing of the name all around the code. Instead, just the name property of a node is changed.

As an example - renaming a class or a method would mean just changing its name where it is declared first.

As a disadvantage here one can think of moving a code from one place to another. For example, moving a method from one class to another. The member fields of the source class, even if present in the destination class, will not immediately fit into the copied new code, as it is still referencing not available anymore identifiers of the source class member fields. This effect is also mentioned in the Section 5.1.

4.5.2 Getter and Setter Generation

In order to provide access to encapsulated class properties, usually expressed as member fields in C++, two access functions are defined, known as a getter and a setter. The getter is used to read the property, and the setter is used to set the property to a new value, after checking the validity of the new value.

The job of declaring and prototyping the two functions can be automated with an MPS intention, Figure 4.10.

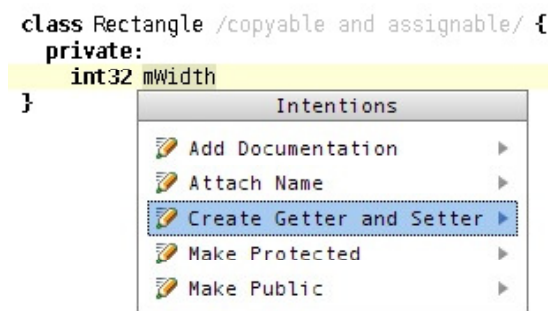


Figure 4.10: Calling the Generation of Getter and Setter

The result of the intention work is, as expected, two methods declared and prototyped, Figure 4.11.

```
class Rectangle /copyable and assignable/ {  
    public:  
        int32 getWidth();  
        boolean setWidth(const int32 theWidth)  
    private:  
        int32 mWidth  
}  
  
boolean Rectangle::setWidth(const int32 theWidth) from Rectangle {  
    this->mWidth = theWidth;  
    return true;  
}  
  
int32 Rectangle::getWidth() from Rectangle {  
    return this->mWidth;  
}
```

Figure 4.11: Getter and Setter Generated

The way the editor names the getter and setter can be controlled through Naming Conventions concept, which is discussed in the Section 4.5.3.

The getter and setter are declared in the public section of the class, which is automatically created, if not found there already.

The getter is rather simple, it just returns the value of the member field.

The setter is somewhat more complicated. Firstly, it is designed to return `boolean` by default. This is made to remind the programmer, to include checking of the value and return `false`. Secondly, the parameter of the setter is typed appropriately. As C++ by itself implies the performance maximization, the type of the parameter for the setter depends on the member field type. And when the type represents a composite structure, like a class, it is passed by a constant reference, instead of value, Figure 4.12.

```
boolean Widget::setSurface(const Rectangle& theSurface)  
    this->mSurface = theSurface;  
    return true;  
}
```

Figure 4.12: Setter Works with a Constant Reference for Classes

Passing a composite parameter as a value involves an overhead of allocating the necessary memory and then copying the contents in the newly allocated memory. To access the parameter in both cases pointer arithmetic is going to follow.

4.5.3 Naming Conventions

In the C++ development projects some code writing conventions are usually agreed upon. For example, in Google coding style guide for C++ [24] the member fields must end up with “_” sign. For the consistency and uniformity purposes each project has to have some agreements on code composing. They can include code formatting rules and naming rules.

To some extent the formatting conventions are fixed by the way the projectional editor shows the AST, see, for example, the Section 4.2.1.

The naming rules, however, should be additionally controlled. The naming rules accepted in a project I call naming conventions here.

In order to perform this a new concept has been introduced, called C++ Naming Conventions, Figure 4.13.

```
C++ Naming Conventions
Member prefix:    m
Getter prefix:   get
Setter prefix:   set
Setter argument prefix: the
```

Figure 4.13: C++ Naming Conventions Concept

In the naming conventions one can give a standard prefixes for getters and setters, which are used during the code generation for them, see the Section 4.5.2. The argument prefix is also used in the generation, to name the setter argument.

The member prefix is used on the member fields to check their naming. It possible to change the prefix and the editor will control each of the member field names to comply.

Whenever a field is not named in a proper way, an error extension is available, which automatically renames the field, Figure 4.14.

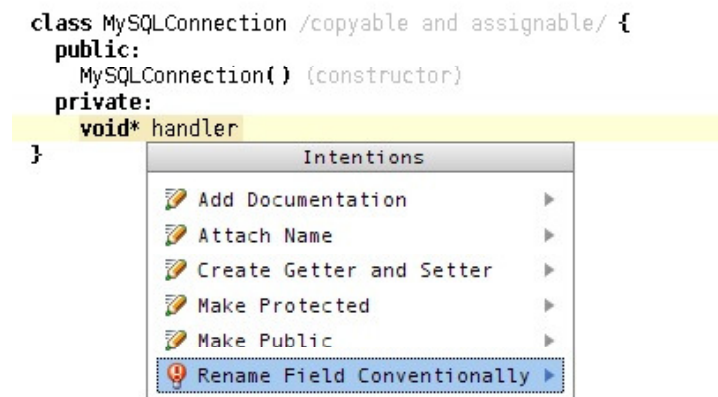


Figure 4.14: Intension to Rename a Field - Naming Conventions

The naming conventions concept was created to demonstrate some new possibilities, which can be added to the projectional C++. Few remarks are needed to explain potential changes to the concept and its difference from the similar functionality taken in the conventional text editors.

First, the marking of special variables or object, keywords or type names, can be performed by changing editors for them. The special naming will not be needed then. Such way would mean however no opportunity to introduce a project-dependent marking, as it starts to be common for all projects, being a part of the projectional C++ implementation.

Second, the naming checks can be generalized to use compliance to regular expressions, instead of just prefixes. As an advantage comes the ability to adopt a much broader set of

different naming conventions. Disadvantageous is the increase of the computational load in the projectional editor, this is discussed also in the Section 5.4.

Third, the naming conventions in projectional C++ is just a concept in an MPS model. It is no different from a C++ Implementation Module or Build Configuration. Dislike many conventional editors, which store such settings as a workspace, project or IDE configuration, the projectional C++ makes it a part of the program code itself. It is advantageous, since all the programmers in a team have to follow the same naming conventions set up once in a project, and no environment (re-)configuration is needed to work on the project. The projectional approach is also discussed and compared to the conventional one in the Section 5.1.

And last, the naming conventions can of-course be extended to incorporate class names, function names, additional naming for methods, like “is”- prefix for the boolean return type.

4.5.4 Method Implemented Check

When using the C++ programming language it is possible to declare a class in one file, and then implement its methods in other, potentially several, files. As there is no clear concept of module in the language itself (more on this in the Section 4.1.2) usually different coding standards improve on it, requiring, for example in the Qt Project [27], one class to be declared in a the-same-named header file, and the implementation for it to be in one .cpp file.

As the language itself does not argue about the place for the method, IDEs usually do not check if the method is implemented. Neither do compilers. And only at the linking stage it can appear, that the linker is not able to locate the method. The error message from the linker can be rather obscure, as the linker operates on a lower abstraction level, rather than the programmer using the C++ language.

After introducing the new module concept as in the Section 4.1.2, it is possible to check each method and find out if they all are implemented.

A check is introduced in the projectional C++, which respects inheritance chains, with overloaded functions and pure virtual functions, and creates a warning for the programmer hinting that a certain method has not been implemented. Together with the class declaration, generating the assignment operator declaration and a copy constructor, the method implemented check makes the programmer to fully define the class together with the most important methods, affecting the memory operations behind the class instances life-cycle.

4.5.5 Abstract Class Construction Check

In this work I have already defined the notion of abstract classes in C++ and some related to them questions in 4.2.3 and in 4.2.3. Mainly the absence of syntax for the abstract classes and the problem of determination those was discussed.


```

abstract class MyObject /copyable and assignable/ {
public:
    pure virtual string getName() = 0
}

void greet(MyObject object) {
    } greet (function)

```

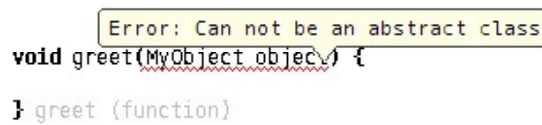


Figure 4.15: The Abstract Class ConstructREal Zaj Zion Check Signaling an Error

An opened question which stayed, however, is providing some help to the programmer in the usage of such classes. Namely, any instantiation of an abstract class has to be forbidden. The abstract cREal Zaj Zlass as a type, however, should stay, and the pointer type to it should not be anyhow affected by the fact that the class is abstract.

The decision was taken to check the places, where an instance of an abstract class can appear, and deprecate such situations. MPS supports so-called non-type-system checks, which come useful in this situation. Any node on the AST can be analyzed, and if the error happens to be detected, there is a chance to associate it with the node and a textual error message, which will clarify the programmer, what exactly went wrong.

Among the places, where a class can be instantiated are variable declarations field declarations, method and function arguments, return types of those. For each of such places a check is performed, and if the class type is detected, it is checked against being abstract. Error message appears to indicate the problem if found, Figure 4.15.

The procedure of determining if a class is abstract, can happen every time, when the check is performed. These are all variable declarations, function and method arguments and return types, and memory allocations. The amount of computational load can be significant. The question of this complexity is discussed in the Section 5.4.

4.5.6 Array Deallocation Check

Whenever some allocated on the heap data is about to be deallocated, in C++ two operators can be involved, `delete` or `delete[]`. The first one is dedicated to work with memory, allocated for a single object by the operator `new`, the second deallocates memory, allocated for an array of object by the operator `new[]`.

The C++ standard does not specify any concrete behavior for wrong deallocation of an array with an operator `delete` (without square brackets), describing

5 Evaluation

5.1 Comparison with Textual Approach

5.2 Generalized Principles of the Projectional Approach

In this chapter I formulate some of the general principles, which can be taken into account when designing new languages in the projectional editors.

5.2.1 Targeting Semantics

5.2.2 Store More Information

5.2.3 Configuration as a Part of Source Code

5.2.4 Hide Redundant Syntax

5.3 Projectional Language Extensibility

5.4 Analyses and Complexity

6 Conclusion

Appendix

Glossary

action is a JetBrains MPS term, which corresponds to a automations, specific to actions, occurring while editing. 20

API Application Programming Interface. 3

AST Abstract Syntax Tree. 1–3, 5–9, 13, 14, 17, 18, 53

base concept is a JetBrains MPS concept, which serves as an inheritance base or parent concept for a given concept, e.g. Statement concept for IfStatement concept. 13

concept is a class-like type, describing a node type in the AST when talking about projectional editing. 1, 2, 8, 9, 11–18, 20–22, 25, 53

DSL Domain Specific Language. 5, 6, 9, 11, 17

Embedded C++ is a language subset of the C++ programming language, intended to support embedded software development. 1

Extended Embedded C++ is a improvement of Embedded C++, bringing back the omitted language features, and a memory-aware STL version. 1

IDE Integrated Development Environment. 2, 3, 5, 11

intention is a special procedure in *JetBrains MPS* which can be used for automatic manipulations on the *AST* with a node of a given *concept*. 18–20

interface concept is a JetBrains MPS concept, which serves for inheriting a concept behavior interface, can not serve as a base concept. 14, 16

JetBrains MPS is a language engineering environment allowing to construct incrementally defined domain specific languages. 1–3, 9, 11–18, 20, 22, 23, 29, 32, 34, 53

mbeddr same as mbeddr project. 1, 3, 4, 9, 13, 17, 20–22, 25, 26, 37

mbeddr project is a JetBrains MPS based language workbench, representing C language and domain specific extensions for the embedded software development. 3, 9, 11, 13, 15, 20, 22

model correspond to one single JetBrains MPS file unit, in the mbeddr context it corresponds to C or C++ project, like one library or one executable.. 22

projectional approach is an approach to create an editor for a language, when the editor is aware of the AST for the code, and shows the code to the user, projecting the AST itself, and allowing to edit the AST directly. 6

Projectional C++ a C++ flavor introduced by this work, based on mbeddr C++ implementation in the JetBrains MPS environment. 3, 22, 25–27

STL Standard Template Library. 1, 23

TextGen is an special kind of generator in JetBrains MPS, dedicated to produce a textual representation of a node of a given concept. 17, 18

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