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Language and IDE Modularization, Extension and Composition with MPS

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Received: date / Accepted: date

Abstract Language modularization, extension and composition is an important building block for working efficiently with DSLs. Historically, this has been a challenge because many grammar formalisms are not closed under composition, hence syntactic composition of languages is challenging. Composing static and dynamic semantics can also be hard, at least in the general case. Finally, a lot of existing work does not consider IDEs for the composed and extended languages. In this paper, I will show how the projectional language workbench JetBrains MPS solves most of these issues in a practically usable way. The main part of the paper is an extensive example that shows the various kinds of extension and modularization. The last section contains an evaluation that identifies the strong and weak aspects of modularization, composition and extension in MPS, and suggests a couple of improvements.

Keywords DSLs · language composition · language extension · JetBrains MPS · Language Workbench

1 Introduction

1.1 Approach and Structure of the paper

Language modularization, extension and composition (LME&C) is an important ingredient to the efficient use of DSLs, just like reuse in general is important to software development. We discuss the need for LME&C in the context of DSL design in [10], where we also introduce some of the terminology used in this paper. Traditionally, LME&C, including the respective IDEs, has been

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hard for various reasons, including limited composability of grammars, non-modular IDEs as well as semantic interactions. Specifically, LME&C, requires the following concerns to be considered:

– The concrete and the abstract syntax have to be combined. Depending on the kind of composition, this requires the embedding of one syntax into another one. This, in turn, requires modular grammars.
– The static semantics, i.e. the constraints and the type system have to be integrated. For example in case of language extension, new types have to be "made valid" for existing operators.
– The execution semantics have to be combined as well. In practice, this may mean mixing the code generated from the composed languages, or composing the generators.
– Finally, the IDE that provides code completion, syntax coloring, static checks and other relevant services has to be extended and composed as well.

With JetBrains MPS two of these challenges — composability of concrete syntax and modular IDEs — are a completely solved problem, as this paper will show. Modular type systems are reasonably well supported. Semantic interactions are hard to solve in general, but can be handled reasonably in many relevant cases, as we show in this paper as well. However, as we will see, in many cases, languages have to be designed *explicitly for reuse*, in order to make them reusable. After-the-fact reuse, without considering it during the design of the reusable language, is possible only in limited cases. However, this is true for reuse in software generally.

The paper is structured as follows. In Section 1.3 we outline the various kinds of LME&C as defined and explained in the [10] paper. Then we describe how projectional editors work in general, and how MPS works specifically (Section 2). Next we provide a brief overview over related tools and approaches to illustrate how MPS is different (Section 3). Then we develop the core language which acts as the basis for the extension and composition examples. We use the simplest possible language, entities, for this task. This section (Section 4) also serves as a very brief tutorial on language definition in MPS. The main part of the paper, the implementation of the various extension and composition approaches is discussed in Section 5. Finally, Section 6 looks at what works well and at what could be improved in MPS with regards to extension and composition.

1.2 Additional Resources

The example code developed for this tutorial can be found at github.com:

`https://github.com/markusvoelter/MPS-Language-Composition-Demos---For-MPS-2.0`

It is developed with MPS 2.0 M6 and should run with the final version of MPS 2.0 as well. At the point of this writing, MPS 2.0 had not yet been released and hence I couldn't test it.

A set of recorded demos (90 minutes in total) that walk through all the example code is available on Youtube. The initial video is here:

`http://www.youtube.com/watch?v=1NMRMZk8KBE`.

The others are either suggested by Youtube, or you can find them by searching for *Language Modularization and Composition with MPS (Part X)*, where X is between 1 and 8.

Note that this paper cannot be a complete MPS tutorial. MPS is very deep and powerful, so we have to focus on those aspects that are essential for LME&C. We refer to the LWC 11 MPS tutorial for a at detailed MPS tutorial:

`http://code.google.com/p/mps-lwc11/wiki/GettingStarted`

1.3 Types of Modularization

As we describe in the paper on DSL design dimensions [10], we distinguish language *combination*, *extension*, *reuse* and *embedding*.

■ *Extension.* A language B extends another language A if B contains additional language concepts. This means that for programs written in B, all concepts from A are available, plus those defined in B. Concepts in B may specialize concepts in A. This means that in B programs, the specialized concept can be used wherever A programs expect only the more general one, effectively adapting the Liskov substitution principle to language concepts. An extended language may also restrict the base language, so certain concepts are not available in the sublanguge.

■ *Combination.* If a domain is structured along different concerns, and these concerns should be implemented using separate viewpoints, then it is often useful to implement every concern as a separate DSL. When these DSL are developed from scratch, as a group, then dependencies between the concerns can be materialized as dependencies between the languages and the language concepts. A language B may depend on language A because a concept in language B references a concept in language A. The models remain separate, only cross-references connect the two.

■ *Reuse.* Reuse describes the case where a language has been developed explicitly to be used in contexts not known at the time of development of that language (this is in contrast to combination). So the language cannot have dependencies to other languages. To make it fit in with a new context, the reusable language has to be extended so it can reference concepts from languages in that context.

■ *Embedding.* Embedding is a special case of reuse, where the reused language is syntactically embedded into languages from the context. If the host language is designed with an awareness of the composed language, the host language can simply depend on the composed language and embed concepts from it. As in the case of language reuse, the composed language may have to be extended to "plug it into the context". If both the host language and the composed language have been designed independent of each other and should be combined later, then both the host language and the composed language will have to be extended.

In this paper we illustrate all of these approaches with MPS. At the center is a simple entities language. We then build additional language to illustrate LME&C. Fig. 1 illustrates these additional languages. The uispec language illustrates *combination* with entities. relmapping is an example of *reuse* with separated generated code. *rbac* illustrates reuse with intermixed generated code. uispec_validation demonstrates *extension* (of the uispec language) and *embedding* with regards to the expressions language.

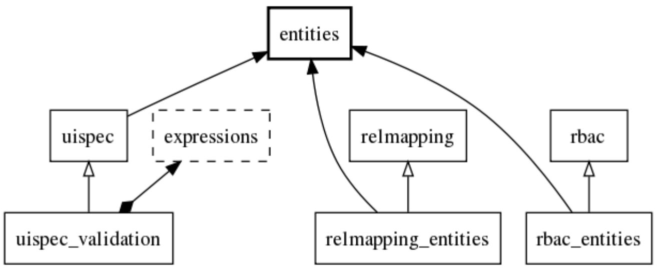


Fig. 1 entities is the central language. uispec defines UI forms for the entities. uispec_validation adds validation rules, and composes a reusable expressions language. relmapping provides a reusable database mapping language, relmapping_entities adapts it to the entities language. rbac is a reusable language for specifying permissions; rbac_entities adapts this language to the entities language.

2 How MPS works

2.1 Projectional Editing

The term Language Workbench has been coined by Martin Fowler in 2005 [3]. In his article he defines it as a tool with the following characteristics:

1. Users can freely define languages which are fully integrated with each other.
2. The primary source of information is a persistent abstract representation.
3. A DSL is defined in three main parts: schema, editor(s), and generator(s).
4. Language users manipulate a DSL through a projectional editor.

5. A language workbench can persist incomplete or contradictory information.

Note how points 2, 3 and 4 imply projectional editing. In the meantime, Martin Fowler, and the community as a whole uses the term language workbench also for tools that use (modern) parsing techniques. MPS is a projectional editor. The most important characteristic of projectional editors is that all text, symbols, and graphics are projected. Projectional editing is well-known from graphical modeling tools (UML, ER, State Charts). The model is stored independent of its concrete syntax, only the model structure is persisted, often using XML or a database. For editing purposes this abstract syntax is projected using graphical shapes. Users use mouse gestures and keyboard actions tailored to graphical editing to modify the abstract model structure directly. While the concrete syntax of the model does not have to be stored because it is specified as part of language definition and hence known by the projection engine, graphical modeling tools usually also store information about the visual layout.

Projectional editing can also be used for textual syntax. However, since the projection looks like text, users expect interaction patterns and gestures known from "real text" to work. For a projectional editor to be useful, it has to "simulate" interaction patterns known from real text. MPS achieves this quite well. How it does that is beyond the scope of this paper. The following is a list of benefits of the approach projectional editing:

– No grammar or parser is required. Editing directly changes the underlying structure. Projectional editors can handle unparsable code. Language composition is easily possible, because it cannot result in ambiguous grammars [1].
– Notations are more flexible than ASCII/ANSI/Unicode. Graphical, semi-graphical and textual notations can be mixed and combined. For example, a graphical tool for editing state machines can embed a textual expression language for editing the guard conditions on transitions.
– Because projectional languages by definition need an IDE for editing (it has to do the projection!), language definition and extension always implies IDE definition and extension. The IDE will provide code completion, error checking and syntax highlighting for all languages, even when they are composed.
– Because the model is stored independent of its concrete notation, it is possible to represent the same model in different ways simply by providing several projections. Different viewpoints of the overall program can be stored in one model, but editing can still be viewpoint-specific. It is also possible to store out-of-band data, i.e. annotations on the core model/program. Examples of this include documentation, pointers to requirements (traceability) or feature dependencies in the context of product lines.

As a side effect, language workbenches deliver on the promise of removing the difference between what is traditionally considered programming and what is traditionally considered modeling. This distinction is arbitrary anyway: as software developers we want to express different concerns of software systems with abstractions and notations suitable to that particular concern (graphical, textual, symbolic), formally enough for automatic processing or translation, and with good IDE support. Projectional language workbenches deliver on this goal.

2.2 JetBrains MPS

JetBrains Meta Programming System is an open source projectional language workbench, so all the statements on projectional editing made earlier apply to MPS. Defining a language includes (a) defining the language concepts (abstract syntax), (b) defining the editor for the concepts and (c) defining a generator (compiler). For a language whose programs should be processed with a text-oriented tools (such as existing compilers or interpreters) the generator outputs text. For higher-level languages assimilation is used: the generator transforms a program expressed in L_D (a language for the domain D, see [**?**] for details on hierarchical domains and languages, and the L_D notation) into a program at L_{D-1} (a program at a lower domain). In this case, the generators are not text generators, they transform between abstract syntax trees (this process is explained in more detail below).

Editing the tree as opposed to real text needs some getting used to. Without specific customization, every program element has to be selected from a drop-down list to be "instantiated". However, MPS provides editor customizations to enable editing that resembles modern IDEs that use automatically expanding code templates. This makes editing quite convenient and productive in all but the most exceptional cases. We will show in section 4 how to actually build a language woth MPS.

2.3 Real-World use of MPS

Web Development JetBrains's YouTrack issue tracking system is an interactive web application with many UI features known from desktop applications. YouTrack is the first JetBrains product that was developed completely with MPS. The effort for building the necessary MPS-based languages will be repaid by future applications that build on the same web platform architecture and hence use the same set of languages. Language extension is used to add product-specifics to these languages.

Web development involves many languages. In the browser, HTML, CSS, JavaScript and SVG are used. All these languages embed one another. On the Java-based server side, a set of descriptive languages is used, together with query languages (EQL, HBQL, SQL), template languages (JSP, Velocity) and of course the Java programming language at the core. JetBrains decided to wrap these platform-specific implementation languages with a set of Java language extensions. For the sake of the example, we focus on describing the extensions used in the Java-based backend. The most notable of the languages used in YouTrack are *dnq* and *webr*. *dnq* is a Java language extension for working with persistent data and queries. Almost all modern web applications store data in a database. However, database manipulation is not very well supported in general purpose languages such as Java. Developers use object relational mapping frameworks such as Hibernate, JDO or JPA to alleviate this problem. These frameworks basically map database rows to Java classes. However, because authors of these frameworks cannot change the Java language, the integration is limited, hampering developer productivity. For example:

– Entity relations which are inherently bidirectional cant be easily expressed in Java. Consider a program which models organizational structure, consisting of Departments and Employees. When an Employee is added to a Department, both, the references in Employee and Department must be updated consistently.
– Relational databases optimize queries very aggressively. In order to accomplish these optimizations, queries should be expressed in SQL. However, its much more natural to use the programming language for querying database, especially if the query language were integrated with the host language and its type system. To enable this, the programming language must be extended with query constructs and these must be translated into SQL when the program is compiled.

The *dnq* language supports the expression of relations in a more natural way: unidirectional and bidirectional relationships can be declared, distinguishing between composition and references. Programmers can access them in a way similar to accessing fields in Java. *dnq* also includes a collections language, a language which supports the manipulation of collections in a way similar to .NETs LINQ. For example, t supports code such as the following:

```
aColl.where({it=> it.val < 20 && it.val > 10}).select({it=> it*it});
```

This code is more declarative than procedural collection manipulation code which allows MPS to optimize such queries to the database.

The *webr* language is used for request handling in web applications. In web frameworks this tasks is typically accomplished by controller classes and HTML templates. To configure HTTP request handling, frameworks often use XML based descriptors. In order to process the HTML templates, template engines are used. Examples include JSP, Velocity or FreeMarker. *webr* supports this through Java language extension. Its template language combines XML and Java, relatively similar to JSP at first glance. However, based on MPS' ability to extend languages, *webr* provides much more freedom of what templates can contain. For example, in many template engines, its impossible to add new constructs to the template language. In JSP it is possible using extension tags but the XML based syntax is quite verbose. In *webr* templates, developers can choose whatever syntax they like by defining a suitable language extension. An example used in YouTrack is a UI components language that is not limited to XML syntax. *webr* also provides first-class support for controllers. For example, controllers can declare actions and attach them directly to events of UI components. Parameters are specified in special entities called template controllers. *webr* is well integrated with *dnq*, so for example, it is possible to use a persistent entities as a parameter to a page. The database transaction is automatically managed during request processing.

Embedded Development Embedded systems are becoming more and more software intensive and the software becomes bigger and more complex. Traditional embedded system development approaches use a variety of tools for various aspects of the system, making tool integration a major headache. Some of the specific problems of embedded software development include the limited capability for meaningful abstraction in C, some of C's "dangerous" features (leading to various coding conventions such as Misra-C), the proprietary and closed nature of modeling tools, the integration of models and code, traceability to requirements, long build times as well as management of product line variability. To address these issues, we propose an alternative approach based on the incremental extension of C. We have implemented a proof-of-concept language (http://mbeddr.com) that contains a set of language extensions relevant to this embedded development. A larger-scale research project is starting in July 2011 to continue the development of this approach.

For the proof-of-concept, the mbeddr project uses Lego mindstorms as the target platform together with the Osek operating system to ensure real-world relevance. The current showcase is a line follower robot. It uses a single light sensor to follow (one side of) a thick black line by changing the speed of motors that drive the two wheels. The current state of the prototype contains language modules for components, tasks, state machines, bit-level data structures, physical quantities, documentation annotations, as well a core module with basically all of C. There is a clearly defined dependency structure between those languages, with the core language at the root. We have also added a DSL for simplified control of the two-wheeled robot using commands such as accelerate, turn left, or stop. The implementation of this DSL is a model transformation down to the basic embedded languages: we generate tasks, procedures and state machines, which are then (automatically) transformed down to actual C and are compiled by GCC for the Osek target.

3 Related Tools and Approaches

MPS is not the only projectional workbench and projectional workbenches are not the only approach to language modularity and composition. For example, the Intentional Domain Workbench (IDW) [8] is another projectional editor that has been used in real projects. An impressive presentation about its capabilities can be found in this InfoQ presentation titled "Domain Expert DSL" (`http://bit.ly/10BsWa`). IDW is conceptually very similar to MPS, although quite different in many details. We will not provide more details here, partly because Intentional Software is very sensitive about publishing information about details of their technology.

MetaEdit+ (`http://metacase.com`) is an example of a purely graphical language workbench (tables and forms can also be used). Languages are defined via meta models, constraints, code generators and graphical symbols associated with the meta-model. Language concepts can be represented by different symbols in different diagrams types and elements from several languages can be used in one diagram. Elements from language A can reference elements in language B. This is not surprising since graphical language workbenches are (and have always been) projectional. Since this paper focuses mostly on textual language, we include MetaEdit+ here only for completeness.

Eclipse Xtext (`http://eclipse.org/Xtext`) supports the creation of extremely powerful text editors (with code completion, error checking and syntax coloring) from an enhanced EBNF-like grammar definition. It also generates a meta-model that represents the abstract syntax of the grammar as well as a parser that parses sentences of the language and builds an instance of the meta-model. Since it uses Eclipse EMF as the basis for its meta models, it can be used together with any EMF-based model transformation and code generation tool (examples include Xpand, ATL, and Acceleo, all at `http://eclipse.org/modeling`). Language combination is easily possible; Code completion for references into other models as well as cross-model and cross-language consistency checks in the editor are supported out of the box. Language reuse, extension and embedding are quite limited, though. It is possible to make a language extend one other language. Concepts from the base language can be used in the sub language and it is possible to redefine grammar rules defined in the base language. Creating new subtypes (in terms of the meta-model) of language elements in the base language is also possible. However, it is not possible to define different representations of the same element (except the concrete syntax of the reference) and it is not possible to embed arbitrary languages or language modules. This is mainly because the underlying parser technology is antlr (`http://antlr.org`) which is a classical two phase LL(*) parser which has problems with grammar composition [2]. While single inheritance is useful, and many interesting DSLs can be built with Xtext, single inheritance language extension is not enough in practice; it would be like object-oriented programming with only inheritance and no delegation or traits.

SDF [5] (`http://strategoxt.org/Sdf`), developed by the University of Delft, uses scannerless parsers. Consequently, languages can be embedded within each other. Code generators are implemented via term rewriting on the abstract syntax, but rendered in the concrete syntax! Currently SDF is mainly a set of command-line tools, but IDE support (with automatically generated eclipse editors) is in progress as part of Spoofax [6] (`http://strategoxt.org/Spoofax`).

Monticore(`http://monticore.org`) is another parser based language engineering environment that generates parsers, meta-models, and editors based on extended grammar. Currently, the group at RWTH works on modularizing languages [7]. Languages can extend each other and can be embedded within each other. An important idea is the ability to not have to regenerate the parsers or any of the related tools after a combined language has been defined.

FURCAS (`http://www.furcas.org/`) is a tool that is developed by SAP and the FZI Karlsruhe. FURCAS stores models in an abstract structure. However, for editing it "projects" the model into plain ASCII. So when editing the model, users actually edit ASCII text. Consequently, syntax definition also includes a definition of indentation and white space conventions, otherwise the projection could not work. Second, a lot of effort has to be put into a retaining object identity [4]. If an abstract structure is projected into text, and then for example something is moved around and saved back into the abstract structure, it has to be made sure the objects (identified by UUIDs) aren't deleted and re-created but really just moved. This is important to make sure that references between models which are based on the UUID's and not (qualified) names remain valid. By using scannerless parsers it is possible to combine different languages, however a combined grammar has to be defined and the parser has to be regenerated to be able to use the composed language. As a consequence of the projectional approach is possible to define several syntaxes for the same abstract structure or define views and subsets for a model. FURCAS also generates IDE-like editors (based on Eclipse).

Note that while parser-based approach are becoming more flexible (as illustrated by some of the tools mentioned in this section), they will not be able to work with non-parseable code, inlined tables or diagrams or annotations.

For a general overview of language workbenches, please refer to the Language Workbench Competition at `http://languageworkbenches.net`. Participating tools have to implement a standardized language and document the implementation strategy. This serves as a good tutorial of the tool, and makes them comparable. As of June 2010, the site contains 13 submissions.

4 Implementing a DSL with MPS

This section illustrates the definition of a language with JetBrains MPS. Like other language workbenches, MPS comes with a set of DSLs for language definition, a separate DSL for each language aspect. Language aspects include structure, editor, type systems, generators as well as things like quick fixes or refactorings. MPS is bootstrapped, so these DSLs are built with MPS itself.

At the center of the language extensions we will build later, we use a simple entities language. Here is an example model. *Modules* are so-called root nodes. They live as top level elements in *models*. Referring back to the terminology introduced in the DSL design paper [**?**], root nodes (and their descendants) are considered *fragments*, while the models are partitions (actually, they are XML files).

```
module company
  entity Employee {
    id : int
    name : string
    role : string
    worksAt : Department
    freelancer : boolean
  }
  entity Department {
    id : int
    description : string
  }
```

■ *Structure and Syntax.* Language definition starts with the abstract syntax. In MPS, this is defined via so-called *concepts*. Fig. 2 shows a UML diagram of the structure of the entities language. Each box represents a language concept.

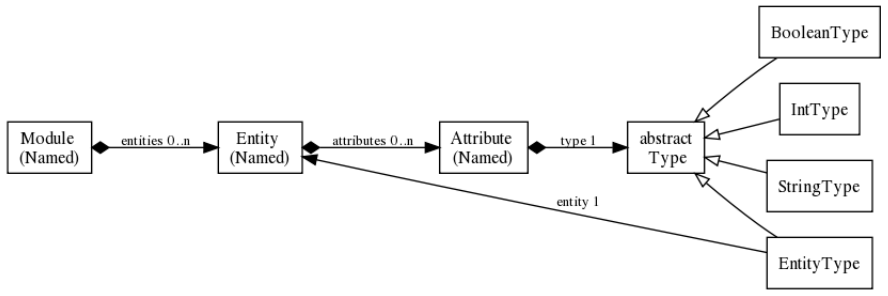


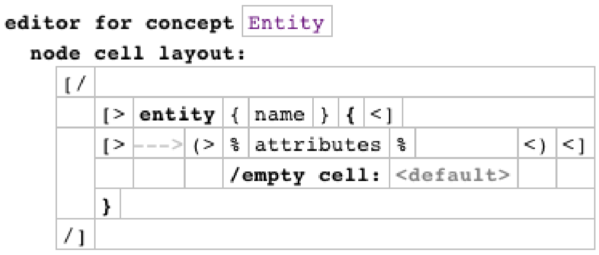
Fig. 2 The abstract syntax of the entities language. Entities have attributes, those have types and names. *EntityType* extends *Type* and references *Entity*. This "adapts" entities to types (cf. the Adapter pattern). Concepts like *EntityType* which have exactly one reference are called smart references and are treated specially by the IDE in code completion.

The following code shows the definition of the *Entity* concept[1]. *Entity* extends *BaseConcept*, the root concept, similar to *java.lang.Object* in Java. It implements the *INamedConcept* interface to inherit a *name* field. It declares a list of children of type *Attribute* in the *attributes* role. A concept may also have references to other concepts (as opposed to children).

```
concept Entity extends BaseConcept implements INamedConcept
  is root:
    true
  properties:
    << ... >>
  children:
    Attribute attributes 0..n specializes: <none>
  references:
    << ... >>
```

[1] This is not the complete definition, concepts can have more characteristics. This is simplified to show the essentials.

Editors in MPS are based on cells. Cells are the smallest unit relevant for projection. Defining an editor hence consists of arranging cells and defining their content. Different cell types are available to compose editors. Fig. 3 explains the editor for *Entity*. The editors for the other concepts are defined similarly.



```
editor for concept Entity
  node cell layout:
    [/
      [> entity { name } { <]
      [> ---> (> % attributes %       <) <]
                  /empty cell: <default>
      }
    /]
```

Fig. 3 The editor for *Entity*. The outermost cell is a vertical list. In the first line, we use a horizontal list that contains the "keyword" *entity*, the value of the name property and an opening curly brace. In the second line we use indentation and a vertical arrangements of the contents of the *attributes* collection. Finally, the third line contains the closing curly.

■ *Type System.* The MPS type system engine uses unification. Language developers specify type equations and the unification engine tries to assign values to the type variables so that all equations are satisfied. This is similar to what we know from math. Consider

```
(1) 2 * x == 10
(2) x + x == 10
(3) x + y == 2 * x + 5
```

This set of equations can be solved by `x := 5, y := 10`. The MPS type system engine works the same way, but the domain is types instead of integers. Type equations also don't just contain equations (:==:), but also equations with subtyping and other relationships.

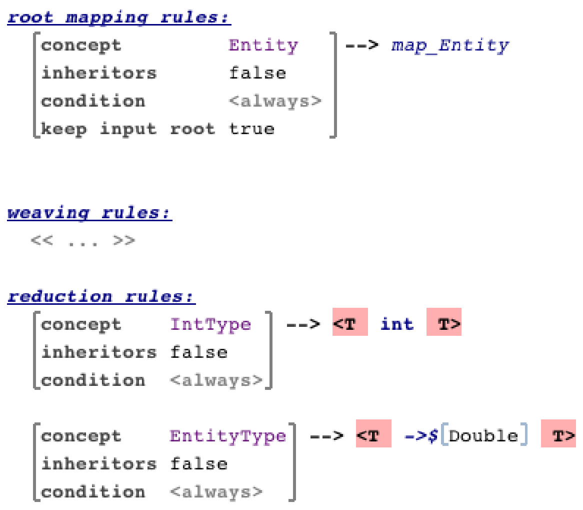
For the entities language, we specify two simple typing rules. The first one specifies that the type of the primitives (*int*, *string*) is a clone of themselves:

```
rule typeof_Type {
  applicable for concept = Type as type
  overrides false
  do {
    typeof(type) :==: type.copy;
  }
}
```

The only other typing rule is an equation that defines the type of the attribute as a whole to be the type of the attribute's *type* property, defined as `typeof(attribute) :==: typeof(attribute.type);`.

■ *Generator.* From entity models we generate Java Beans. Since Java is available in MPS as the BaseLanguage, the generation is actually a model-to-model transformation: from the entities model we generate a Java model. MPS supports several kinds of transformations. The default case is the template-based transformation which uses the concrete syntax of the target language to specify model-to-model transformations. Alternatively, one can use the node API to manually construct the target tree. Finally the textgen DSL is available to generate ASCII text (at the end of the transformation chain). Throughout this paper we use the template based approach.

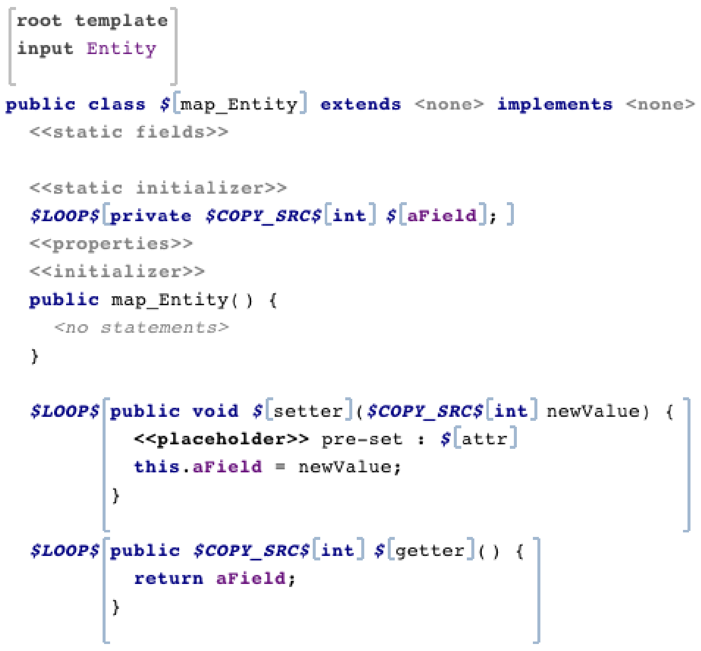
Template-based generators in MPS consist of two main building blocks: mapping configurations and templates. Mapping configurations define which elements are processed with which templates. For the entities language, we need a *root mapping rule* and *reduction rules.* Root mapping rules can be used to create new top level artifacts from existing top level artifacts (they map fragments to other fragments). In our case we generate a Java class from an entity. Reduction rules are in-place transformations. Whenever the engine encounters an instance of the specified source concept somewhere in a model tree, it removes that source node and replace it with the result of the associated template. In our case we have to reduce the various types (*int*, *string*, etc.) to their Java counterparts. Fig. 4 shows a part of the mapping configuration for the entities language.



```
root mapping rules:
  [concept          Entity    ] --> map_Entity
  [inheritors       false     ]
  [condition        <always>  ]
  [keep input root  true      ]


weaving rules:
  << ... >>

reduction rules:
  [concept     IntType ] --> <T  int  T>
  [inheritors  false   ]
  [condition   <always>]

  [concept     EntityType] --> <T  ->$[Double]  T>
  [inheritors  false     ]
  [condition   <always>  ]
```

Fig. 4 The mapping configuration for the entities language. The root mapping rule for Entity specifies that instances of *Entity* should be transformed with the *map_Entity* template. The reduction rules use inline templates. For example, the *IntType* is replaced with the Java *int* and the *EntityRefType* is reduced to a reference to the class generated from the target entity. The arrow-dollar-symbol is a so-called reference macro. It contains code (not shown) that "rewires" the reference to *Double* to a reference to the class generated from the target entity.

MPS templates work differently from normal text generation templates such as for example Xpand, Jet or StringTemplate, since they are actually model-to-model transformations. Developers first write a structurally correct example model using the target language. Then so called macros are used to change the example model to reflect the input from which we generate. Fig. 5 shows the *map_Entity* template. It generates a complete Java class — notice the complete structure of a Java class is present, because that is how BaseLanguage defines the editor for a Java class. We then generate a field for each entity *Attribute*. To do this we first create a prototype field in the class (`private int aField;`). Then we use macros to "transform" this prototype into an instance for each entity attribute. We first attach a *LOOP* macro to the whole field. It contains an expression `node.attributes;` where *node* refers to the input *Entity*. This code is entered in the Inspector window and is not shown in the screenshot. We then use a *COPY_SRC* macro to transform the type. *COPY_SRC* copies the input node (the inspector specifies the current attribute's type as the input here) and applies reduction rules. So instances of the types defines as part of the entities language are transformed into a Java type using the reduction rules defined in the mapping configuration. Finally we use a property macro (the dollar sign) to change the *name* property of the field we generate from the dummy value *aField* to the name of the attribute we currently transform (once again via an expression in the inspector).



```
[root template
 input Entity
]
public class $[map_Entity] extends <none> implements <none>
  <<static fields>>

  <<static initializer>>
  $LOOP$[private $COPY_SRC$[int] $[aField]; ]
  <<properties>>
  <<initializer>>
  public map_Entity( ) {
    <no statements>
  }

  $LOOP$[public void $[setter]($COPY_SRC$[int] newValue) {
           <<placeholder>> pre-set : $[attr]
           this.aField = newValue;
         }
        ]
  $LOOP$[public $COPY_SRC$[int] $[getter]( ) {
           return aField;
         }
        ]
```

Fig. 5 The template for creating a Java class from an entity. The running text explains the details.

5 Implementing Language Extensions with MPS

5.1 Language Combination

■ *Structure and Syntax.* We define a language uispec for defining user interface forms based on the entities. Fig. 6 shows the abstract syntax and below is an example model. Note how the form is another, separate fragment. It is a *dependent* fragment, since it references elements from another fragment (expressed in the entities language). Both fragments are *homogeneous* since they consist of sentences expressed in a single language.

```
form CompanyStructure
  uses Department
  uses Employee
  field Name: textfield(30) -> Employee.name
  field Role: combobox(Boss, TeamMember) -> Employee.role
  field Freelancer: checkbox -> Employee.freelancer
  field Office: textfield(20) -> Department.description
```

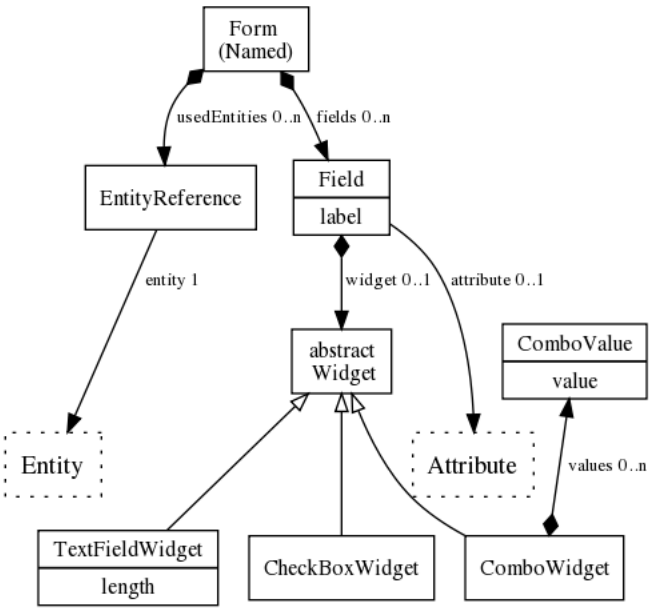


Fig. 6 The abstract syntax of the uispec language. Dotted lines represent classes from another language (here: the entities language). A *Form* contains *EntityReferences* that connect to an entities model. A form also contains *Fields*, each referring to an *Attribute* from an *Entity* and containing a *Widget*.

The uispec language extends[2] the entities language. This means, that concepts from the entities language can be used in the definition of language concepts in the uispec language. A *Form* owns a number of *EntityReferences*, which in turn reference the *Entity* concept. Also, *Field*s refer to the *Attribute* that shall be edited via the field. Here is the definition of the *Field* concept. It owns a *Widget* and refers to an *Attribute*.

```
concept Field extends BaseConcept implements <none>
  properties:
    label : string
  children:
    Widget widget 0..1 specializes: <none>
  references:
    Attribute attribute 0..1 specializes: <none>
```

■ *Type System.* There are limitations regarding which widget can be used with which attribute type. This typing rule is defined in the uispec language and references types from the entities language. The following is the code for the type check. We use a non-typesystem rule to illustrate how constraints can be written that do not use the inference engine introduced above.

```
non type system rule checkTypes {
  applicable for concept = Field as field
  overrides false
  do {
    if (field.widget.isInstanceOf(CheckBoxWidget)
         && !(field.attribute.type.isInstanceOf(BooleanType))) {
      error "checkbox can only be used with booleans" -> field.widget;
    }
    if (field.widget.isInstanceOf(ComboWidget)
         && !(field.attribute.type.isInstanceOf(StringType))) {
      error "combobox can only be used with strings" -> field.widget;
} } }
```

■ *Generation.* The defining characteristic of language combination is that the two languages only reference each other, and the instance fragments are dependent, but homogeneous. No syntactic integration is necessary in this case. In this example, the generated code exhibits the same separation. From the form definition, we generate a Java class that uses Java Swing to build the form. It *uses* the beans generated from the entities. The classes are instantiated, and the setters are called. The generators are separate but they are *dependent*, they share information. Specifically, the forms generator knows about the names of the generated entity classes, as well as the names of the setters and getters. This is implemented by defining a couple of behaviour methods on the *Attribute* concept that are called from both generators (the colon represents the node cast operator and binds tightly; the code below casts the attribute's parent to *Entity* and then accesses the *name* property).

[2] MPS uses the term "extension" whenever the definition of one language uses or referes to concepts defined in another language. This is not necessarily an example of language extension as defined in this paper.

```
concept behavior Attribute {
  public string qname() {
    this.parent : Entity.name + "." + this.name;
  }
  public string setterName() {
    "set" + this.name.substring(0, 1).toUpperCase() + this.name.substring(1);
  }
  public string getterName() {
    "get" + this.name.substring(0, 1).toUpperCase() + this.name.substring(1);
  }
}
```

The original entities fragment is still *sufficient* for the transformation that generates the Java Bean. The form fragment is not sufficient for generating the UI, it needs the entity fragment. This is not surprising since *dependent* fragments can never be sufficient for a transformation, the transitive closure of all dependencies has to be made available.

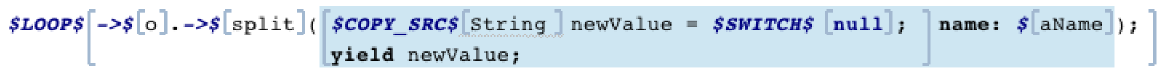
5.2 Language Extension

We will revisit language extension later for more meaningful examples of extension. For now, we extend the MPS base language with expression blocks and placeholders. These concepts make writing generators *that generate base language code* much simpler. Fig. 7 shows an Example. We use a screenshot instead of text because we use non-textual notations (the big brackets) and color.

■ *Structure and Syntax.* An expression block is a block that can be used where an *Expression* is expected [1]. The block can contain any number of statements; *yield* can be used to "return values" from within the block. So, in some sense, an expression block is an "inlined method", or a closure that is defined and called directly. The optional name property of an expression block is then used as the method name. The generator of the expression block transforms it into just this structure:

```
okButton.addActionListener(new ActionListener() {
  public void actionPerformed(ActionEvent p0) {
    Employee aEmployee = new Employee();
    aEmployee.setName(retrieve_name(aEmployee, widget0));
  }
  public String retrieve_name(Employee aEmployee, JComponent widget0) {
    String newValue = ((JTextField) widget0).getText();
    return newValue;
  }
}
```

The jetbrains.mps.baselanguage.exprblocks language extends MPS' Base-Language. The expression block is used in places where the base language expects an *Expression.* This is why an *BlockExpression* extends *Expression.* Consequently, fragments that use the exprblocks language, can now use *Block-Expressions* in addition to the concepts provided by the base language. The fragments become *heterogeneous*, because languaegs are mixed.



```
$LOOP$ ->$ o .->$ split ( $COPY_SRC$ String  newValue = $SWITCH$ null ;   name: $ aName );
                          yield newValue;
```

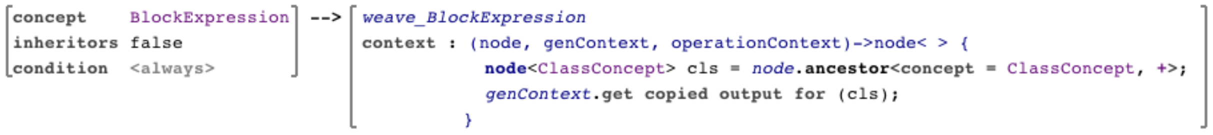
Fig. 7 Expression blocks (in blue) are basically anonymous inline methods. Upon transformation, a method is generated that contains the block content, and the expression block is replaced with a call to this method. Expression block are used mostly when implementing generators; this screenshot shows a generator that uses an expression block.

```
concept BlockExpression extends Expression implements INamedConcept
  children:
    StatementList body 1 specializes: <none>
```

■ *Type System.* The type of the *yield* statement is the type of the expression that is yielded, specified by `typeof(yield) :==: typeof(yield.result);` (the type of /verb+yield 1;+ would be *int*). Since the *BlockExpression* is used as an expression, it has to have a type as well. Since it is not explicitly specified, the type of the *BlockExpression* is the common super type of the types of all the yields. The following typing rule computes this type:

```
var resultType ;
for (node<BlockExpressionYield> y :
        blockExpr.descendants<concept = BlockExpressionYield>) {
  resultType :==: typeof(y.result);
}
typeof(blockExpr) :==: resultType;
```

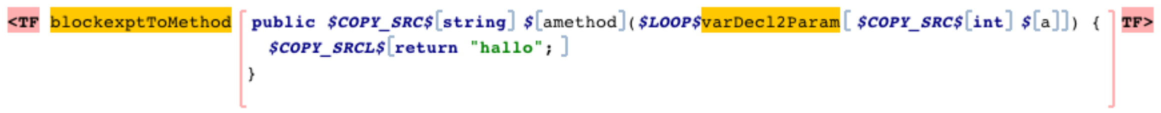
■ *Generator.* The generator for *BlockExpressions* reduces the new concept to pure base language: it performs assimilation. It transforms a heterogeneous fragment (using BaseLanguage and exprblocks) to a homogeneous fragment (using only BaseLanguage). The first step is the creation of the additional method for the block expression (Fig. 8).



```
concept    BlockExpression  --> weave_BlockExpression
inheritors false                context : (node, genContext, operationContext)->node< > {
condition  <always>                        node<ClassConcept> cls = node.ancestor<concept = ClassConcept, +>;
                                           genContext.get copied output for (cls);
                                         }
```

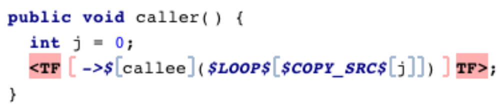
Fig. 8 We use a weaving rule to create an additional method for this. A weaving rule processes an input element (*BlockExpression*) by creating another node in a different place. The context function defines this other place. In this case, it simply gets the class in which we have defined the block expression.

The template shown in Fig. 9 shows the creation of the method. It assigns a mapping label to the created method. The mapping label creates a a mapping between the *BlockExpression* and the created method. We will use this label to refer to this generated method when we generate the method call that replaces the *BlockExpression* (Fig. 10).



```
<TF blockexptToMethod [ public $COPY_SRC$[string] $[amethod]($LOOP$varDecl2Param[ $COPY_SRC$[int] $[a]]) { ] TF>
                          $COPY_SRCL$[return "hallo"; ]
                        }
```

Fig. 9 The generator creates a method from the block expression. It uses COPY_SRC macros to replace the *string* type with the computed return type of the block expression, inserts a computed name, adds a parameter for each referenced variable outside the block, and inserts all the statements from the block expression into the body of the method. The *blockExprToMethod* mapping label is used later in the method call.



```
public void caller( ) {
  int j = 0;
  <TF [ ->$[callee]($LOOP$[$COPY_SRC$[j]]) ] TF>;
}
```

Fig. 10 Here we generate the call to the previously generated method. We use the mapping label *blockExprToMethod* to refer to the correct method (not shown; happens inside the -¿$ macro). We pass in the environment variables as actual arguments.

A second concept introduced by the exprblocks language is the *PlaceholderStatement*. It extends *Statement* so it can be used insider method bodies. It is used to mark locations at which subsequent generators want to add additional code. These subsequent generators will use a reduction rule to replace the placeholder with whatever they want to put at this location. It is a means to building extensible generators, as we will see later.

5.3 Language Reuse

Language reuse covers the case where a language that has been developed independent of the context in which it should be reused. The respective fragments remain homogeneous. In this paper, we cover two alternative cases: the first case addresses a persistence mapping language. The generated code is separate of the code generated from the entities language. The second case described a language for role-based access control. The generated code has to be ”woven into” the entities code to check permissions when setters are called.

5.3.1 Separated Generated Code

■ *Structure and Syntax.* relmapping is a reusable language for mapping arbitrary data to relational tables. The relmapping language supports the definition of relational table structures, but leaves the actual mapping to the source data unspecified. As you adapt the language to a specific reuse context, you have to specify this mapping. The following code shows the reusable part. A database is defined that contains tables with columns. Columns have (database-specific) data types.

```
Database CompanyDB
  table Departments
    number id
    char descr
  table People
    number id
    char name
    char role
    char isFreelancer
```

Fig. 11 shows the structure of the relmapping language. The abstract concept *ColumnMapper* serves as a hook: if we reuse this language in a different context, we extend this hook by context-specific code.

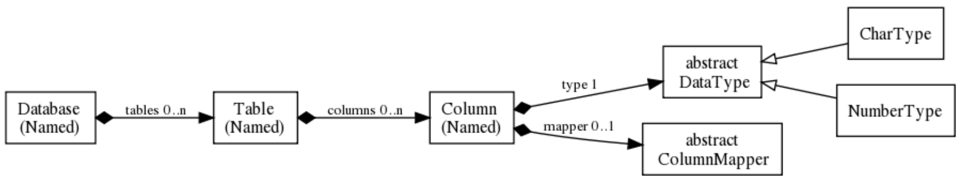


Fig. 11 A *Database* contains *Tables* which contain *Columns*. A column has a name and a type. A column also has a *ColumnMapper*. This is an abstract concept that determines where the column gets its data from. It is a hook intended to be specialized in sublanguages that are context-specific.

The relmapping_entities language extends relmapping and adapts it for reuse with the entities language. To this end, it provides a subconcept of *ColumnMapper*, the *AttributeColMapper*, which references an *Attribute* from the entities language as a means of expressing the mapping from the attribute to the column. The column mapper is projected on the right of the field definition, resulting in the following (heterogeneous) code fragment:

```
Database CompanyDB
  table Departments
    number id <- Department.id
    char descr <- Department.description
  table People
    number id <- Employee.id
    char name <- Employee.name
    char role <- Employee.role
    char isFreelancer <- Employee.freelancer
```

■ *Type System.* The type of a column is the type of its *type* property. In addition, the type of the column must also conform to the type of the column mapper, so the concrete subtype must provide a type mapping as well. This "typing hook" is implemented as an abstract behaviour method *typeMappedToDB* on the *ColumnMapper*. It is acceptable from a dependency perspective to have this typing hook, since relmapping is designed to be extensible. The typing rules then look as follows:

```
typeof(column) :==: typeof(column.type);
typeof(column.type) :==: typeof(column.mapper);
typeof(columnMapper) :==: columnMapper.typeMappedToDB();
```

The *AttributeColMapping* concept from the relmapping_entities implements this method by mapping ints to numbers, and everything else to chars.

```
public node<> typeMappedToDB()
  overrides ColumnMapper.typeMappedToDB {
  node<> attrType = this.attribute.type.type;
  if (attrType.isInstanceOf(IntType)) { return new node<NumberType>(); }
  return new node<CharType>();
}
```

■ *Generator.* The generated code is also separated into a reusable part (a class generated by the generator of the relmapping language) and a context-specific subclass of that class, generated by the relmapping_entities language. The generic base class contains code for creating the tables and for storing data in those tables. It contains abstract methods that are used to access the data to be stored in the columns. So the dependency structure of the generated fragments, as well as the depdendencies of the respective generators, resembles the dedpendency structure of the languages: the generated fragemnts are dependent, and the generators are dependent as well (they share the name (and implicitly the knowledge about the structure) of the class generated by the reusable relmapping generator). A relmapping fragment (without the concrete column mappers) is sufficient for generating the generic base class.

```
public abstract class CompanyDBBaseAdapter {

  private void createTableDepartments() {
    // SQL to create the Departments table
  }

  private void createTablePeople() {
    // SQL to create the People table
  }

  public void storeDepartments(Object applicationData) {
    StringBuilder sql = new StringBuilder();
    sql.append("insert into" + "Departments" + "(");
    sql.append("" + "id");
    sql.append(", " + "descr");
    sql.append(") values (");
    sql.append("" + "\"" + getValueForDepartments_id(applicationData) + "\"");
    sql.append(", " + "\"" + getValueForDepartments_descr(applicationData) + "\"");
    sql.append(")");
  }

  public void storePeople(Object applicationData) {
    // like above
  }

  public abstract String getValueForDepartments_id(Object applicationData);
  public abstract String getValueForDepartments_descr(Object applicationData);

  // abstract getValue methods for the People table
}
```

The subclass, generated by the generator in the relmapping_entities language implements the methods defined by the generic superclass. The interface, represented by the *applicationData* object, has to be kept generic so any kind of user data can be passed in. Note how this class references the beans generated from the entities. So the generator for entities and the generator for relmapping_entities are dependent, the information shared between the two generator is the names of the classes generated from the entities. The code generated from the relmapping language is designed to be extended by code generated from a sublanguage (the abstract getValue methods). This is acceptable, since the relmapping language itself is intended to be extended to adapt it to a new reuse context.

```
public class CompanyDBAdapter extends CompanyDBBaseAdapter {
  public String getValueForDepartments_id(Object applicationData) {
    Object[] arr = (Object[]) applicationData;
    Department o = (Department) arr[0];
    String val = o.getId() + "";
    return val;
  }
  public String getValueForDepartments_descr(Object applicationData) {
    Object[] arr = (Object[]) applicationData;
    Department o = (Department) arr[0];
    String val = o.getDescription() + "";
    return val;
  }
}
```

5.3.2 Interwoven generated code

■ *Structure and Syntax.* rbac is a language for specifying role-based access control, to specify access permissions for the entities.

```
RBAC

users:
  user mv : Markus Voelter
  user ag : Andreas Graf
  user ke : Kurt Ebert

roles:
  role admin : ke
  role consulting : ag, mv

permissions:
  admin, W : Department
  consulting, R : Employee.name
```

The structure is shown in Fig. 12. Like relmapping, it provides a hook, in this case, *Resource*, to adapt it to context languages. The sublanguge rbac_entities provides two subconcepts of *Resource*, namely *AttributeResource* to reference to an attribute, and *EntityResource* to refer to an *Entity*, to define permissions for entities and their attributes.

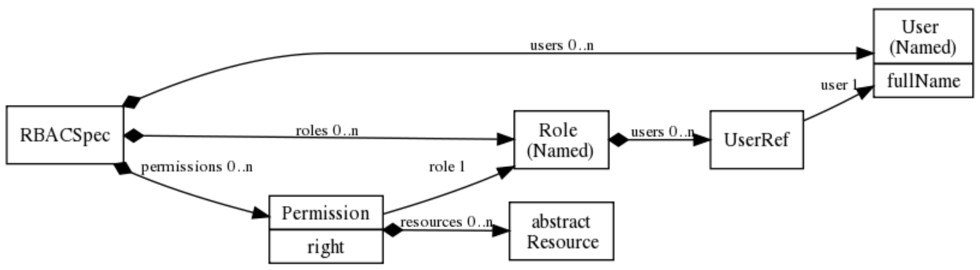


Fig. 12 Language strucrure of the rbac language. An *RBACSpec* contains *Users*, *Roles* and *Permissions*. Users can be members in several roles. A permission assigns a right to a *Resource*.

■ *Type System.* No type system rules apply here.

■ *Generator.* What distinguishes this case from the relmapping case is that the code generated from the rbac_entities language is *not* separated from the code generated from the entities. Instead, inside the setters of the Java beans, a permission check is required.

```
public void setName(String newValue) {
  // check permissions (from rbac_entities)
  if (new RbacSpecEntities().currentUserHasWritePermission("Employee.name")) {
    throw new RuntimeException("no permission");
  }
  this.name = newValue;
}
```

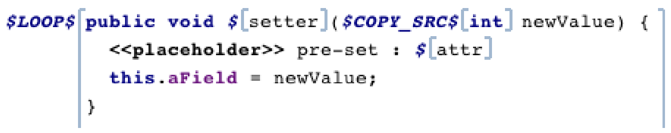
The generated fragment is homogeneous (it is all Java code), but it is *multi-sourced*, since several generators contribute to the same fragment. To implement this, several approaches are possible:

– We could use AspectJ (`http://www.eclipse.org/aspectj/`). This way, we could generate separate Java artifacts (all single-sourced) and then use the aspect weaver to "mix" them. However, we don't want to introduce AspectJ here, so we will not use this approach.
– An interceptor (`http://en.wikipedia.org/wiki/Interceptor_pattern`) framework could be added to the generated Java Beans, with the generated code contributing specific interceptors (effectively building a custom AOP solution). We will not use this approach either, since it would require the addition of a whole interceptor framework to the entities. This seems like overkill.

– We could "inject" additional code generation templates to the existing entities generator from the rbac_entities generator. This would make the generators *woven* as opposed to just dependent. Assuming this would work in MPS, this would be the most elegant solution. But it does not.
– We could define a hook in the generated Java beans code and then have the rbac_entities generator contribute code to this hook. This is the appraoch we will use. The generators remain dependent, they have to agree on the way the hook works.

Notice that only the AspectJ solution can work without any preplanning from the perspective of the entities language, because it avoids mixing the generated code artifacts (it is handled "magically" by AspectJ). All other solutions require the original entities generator to "expect" certain extensions.

In our case, we have modified the original generator in the entities language to contain a *PlaceholderStatement* (Fig. 13). In every setter, the placeholder acts as a hook at which subsequent generators can add statements. While we have to preplan *that* we want to extend the generator in this place, we don't have to predefine *how*. The placeholder contains a key into the session object that points to the currently processed attribute. This way, the subsequent generator can know from which attribute the method with the placeholder in it was generated.



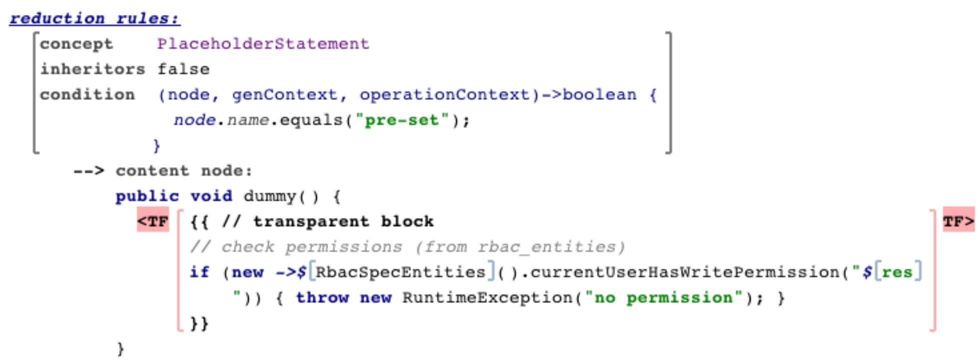
```
$LOOP$[public void $[setter]($COPY_SRC$[int] newValue) {
         <<placeholder>> pre-set : $[attr]
         this.aField = newValue;
       }                                                ]
```

Fig. 13 This generator fragment creates a setter method for each attribute of an entity. The LOOP iterates over all attributes. The $ macro computes the name of the method, and the COPY_SRC macro on the argument type computes the type. The placeholder is used later to insert the permission check.

The rbac_entities generator contains a reduction rule for *PlaceholderStatements*. So when it encounters a placeholder (that has been put there by the entities generator) it removes it and inserts the code that checks for the permission (Fig. 14). To make this work we have to make sure that this generator runs *after* the entities generator (since the entities generator has to create the placeholder) and *before* the BaseLanguage generator (which transforms BaseLanguage code into Java text for compilation). We use generator priorities, i.e. a partial ordering, to achieve this.

5.4 Language Embedding

■ *Structure and Syntax.* uispec_validation extends uispec, it is a sublanguage of the validation language. It supports writing code such as the following in



```
reduction rules:
  [concept     PlaceholderStatement                                    ]
  [inheritors  false                                                   ]
  [condition   (node, genContext, operationContext)->boolean {         ]
  [              node.name.equals("pre-set");                          ]
  [            }                                                       ]
      --> content node:
            public void dummy( ) {
              <TF [{{ // transparent block                                                    ] TF>
                  [// check permissions (from rbac_entities)                                  ]
                  [if (new ->$[RbacSpecEntities]( ).currentUserHasWritePermission("$[res]     ]
                  [    ")) { throw new RuntimeException("no permission"); }                   ]
                  [}}                                                                         ]
            }
```

Fig. 14 This reduction rule replaces *PlaceholderStatement*s with a permission check. Using the condition, we only match those placeholders whose identifier is *pre-set* (notice how we have defined this identifier in Fig. 13). The inserted code queries another generated class that contains the actual permission check. A runtime exception is thrown if the check fails.

the UI form specifications. Writing the expressions is supported by embedding a reusable expressions language. Fig. 15 shows the structure. To be able to use the expressions, the user has to use a *ValidatedField* instead of a *Field*. *ValidatedField* is also defined in uispec_validation and is a subconcept of *Field*.

```
form CompanyStructure
  uses Department
  uses Employee

  field Name: textfield(30) -> Employee.name validate lengthOf(Employee.name) < 30
  field Role: combobox(Boss, TeamMember) -> Employee.role
  field Freelancer: checkbox -> Employee.freelancer
        validate if (isSet(Employee.worksAt)) Employee.freelancer == true else
                    Employee.freelancer == false
  field Office: textfield(20) -> Department.description
```

To support the migration of existing models that use *Field* instances, we provide an intention: the user can press Alt-Enter on a *Field* and select "Make Validated Field". This transforms an existing *Field* into a *ValidatedField*, so that validation expressions can be entered. The core of the intention is the following script, which performs the actual transformation:

```
execute(editorContext, node)->void {
    node<ValidatedField> vf = new node<ValidatedField>();
    vf.widget = node.widget;
    vf.attribute = node.attribute;
    vf.label = node.label;
    node.replace with(vf);
}
```

The uispec_validation language extends the uispec language. We also extend the existing, reusable expressions language, so we can use *Expressions* in the definition of our language. *ValidatedField* has a property *expr* that contains the actual expression. As a consequence of polymorphism, we can

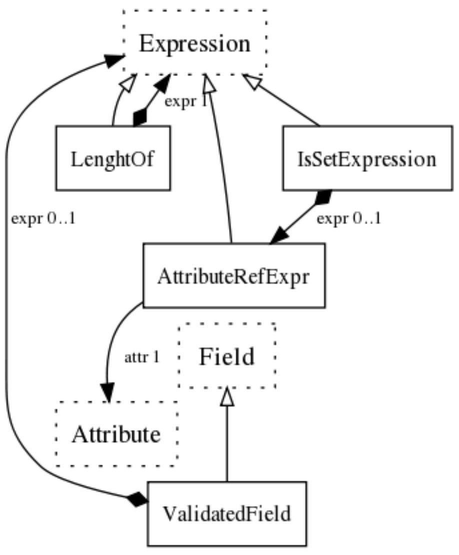


Fig. 15 The uispec_validation language defines a subtype of *uispec.Field* that contains an *Expression* from a reusable expression language. The language also defines a couple of additional expressions, specifically the *AttributeRefExpr*, which can be used to refer to attributes of entities.

use any existing subconcept of *Expression* here. So without doing anything else, we could write `20 + 40 > 10`, since integer literals and the plus operator are defined as part of the composed expressions language. However, to write anything useful, we have to be able to reference entity attributes from within expressions. To achieve this, we create the *AttributeRefExpr* as shown in Fig. 15. We also create *LenghtOf* and *IsSetExpression* as further examples of how to adapt an embedded language to its new context — i.e. the uispec and entities languages.

The *AttributeRefExpr* may only reference those attributes of those entities that used in the form within which we define the validation expression. The following is the code for the search scope:

```
(model, scope, referenceNode, linkTarget, enclosingNode)
                             ->join(ISearchScope | sequence<node< >>) {
  nlist<Attribute> res = new nlist<Attribute>;
  node<Form> form = enclosingNode.ancestor<concept = Form, +>;
  for (node<EntityReference> er : form.usedEntities) {
    res.addAll(er.entity.attributes);
  }
  res;
}
```

Notice that the actual syntactic embedding of the expressions in the uispec_validation language is no problem at all as a consequence of how projectional editors work. We simply define *Expression* to be a child of the *ValidatedField*.

■ *Type System.* The general challenge here is that primitive types such as *int* and *string* are defined in the entities language and in the reusable expression language. Although they have the same names, they are not the same types. So the two sets of types must be mapped. Here are a couple of examples. The type of the *IsSetExpression* is by definition *expressions.BooleanType*. The type of the *LengthOf*, which takes an *AttrRefExpression* as its argument, is *expressions.IntType*. The type of an attribute reference is the type of the attribute's *type* property, as in `typeof(are) :==: typeof(are.attr.type);`. However, consider now the following code:

```
  field Freelancer: checkbox -> Employee.freelancer
        validate if (isSet(Employee.worksAt)) Employee.freelancer == true else
                    Employee.freelancer == false
```

This code states that if the *worksAt* attribute of an employee is set, then its *freelancer* attribute must be *true* else it must be *false*. It uses the equals operator from the expressions language. However, that operator expects two *expressions.BooleanType* arguments, but the type of the *Employee.freelancer* is *entities.BooleanType*. In effect, we have to override the typing rules for the expressions languages's equals operator. Here is how we do it, using *Equals* as an example.

In the expressions language, we define so-called overloaded operation rules. We specify the resulting type for an *EqualsExpression* depending on its argument types. Here is the code in the expressions language that defines the resulting type to be *boolean* if the two arguments are *Equallable*:

```
operation concepts: EqualsExpression
  left operand type: new node<Equallable>()
  right operand type: new node<Equallable>()
operation type:
  (operation, leftOperandType, rightOperandType)->node< > {
    <boolean>;
  }
```

In addition to this code, we have to specify that *expressions.BooleanType* is a subtype of *Equallable*, so this rule applies if we use equals with two *expressions.BooleanType* arguments. We have to tie this overloaded operation specification into a regular type inference rule.

```
rule typeof_BinaryExpression {
  applicable for concept = BinaryExpression as binaryExpression
  overrides false

  do {
    when concrete (typeof(binaryExpression.left) as left) {
      when concrete (typeof(binaryExpression.right) as right) {
        node<> opType = operation type( binaryExpression , left , right );
          if (opType != null) {
            typeof(binaryExpression) :==: opType;
          } else {
            error "operator " + binaryExpression.concept.name +
                  " cannot be applied to these operand types " +
                  left.concept.name + "/" + right.concept.name
```

```
              -> binaryExpression; }
}  }  }  }
```

To override these typing rules to work with *entities.BooleanType*, we simply provider another overloaded operation specification in the uispec_validation language:

```
operation concepts: EqualsExpression
  one operand type: <boolean> // this is the entities.BooleanType!
operation type:
  (operation, leftOperandType, rightOperandType)->node< > {
    <boolean>;  // this is the expressions.BooleanType
  }
```

■ *Generator.* The generator has to create BaseLanguage code, which is then subsequently transformed into Java Text. To deal with the transformation of the expressions language, we can do one of two things:

– Either we can use the expression's language existing to-text generator and wrap the expressions in some kind of *TextHolderStatement.* Remember that we cannot simply embed text in BaseLanguage, since that would not work structurally. A wrapper is necessary.
– Alternatively, we can write a (reusable) transformation from expressions code to BaseLanguage code; these rules would get used as part of the transformation of uispec and uispec_validation code to BaseLanguage.

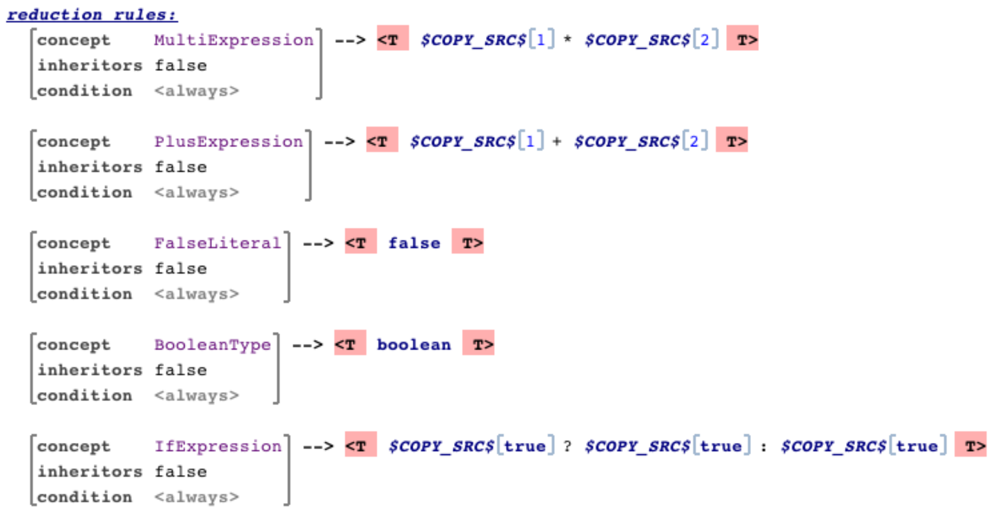
Since many DSLs will map code to BaseLangauge, it is worth the effort to write a reusable generator from uispec_validation expressions to BaseLanguage expressions. We choose this second alternative. The generated Java code is multi-sourced, since it is generated by two independent code generators.

Expression constructs from the reusable expr language and those of BaseLanguage are almost identical, so this generator is trivial. We create a new language project de.voelter.mps.expressions.blgen and add reduction rules. Fig. 16 shows some of these reduction rules.

In addition to these, we also need reduction rules for those new expressions that we have added specifically in the uispec_validation language (*AttrRefExpression, isSetExpression, LengthOf*). Those are defined in uispec_validation. As an example, Fig. 17 shows the rule for handling the *AttrRefExpression.* The validation code itself is "injected" into the UI form via the same placeholder reduction as in the case of the rbac_entities language.

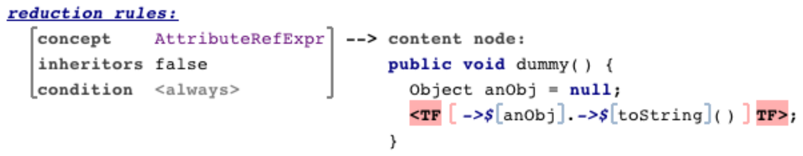
Language extension can also be used to prohibit the use of certain concepts of the base language in the sublanguage, at least in certain contexts. As a simple (but admittedly relatively useless) example, we restrict the use of certain operators provided by the reusable expression language insider validation rules in uispec_validation. This can be achieved by implementing a *can be ancestor* constraint on *ValidatedField.*

```
can be ancestor:
  (operationContext, scope, node, childConcept)->boolean {
    return !(childConcept == concept/GreateEqualsExpression/ ||
             childConcept == concept/LessEqualsExpression/);
  }
```



```
reduction rules:
 [concept    MultiExpression] --> <T $COPY_SRC$[1] * $COPY_SRC$[2] T>
 [inheritors false          ]
 [condition  <always>       ]

 [concept    PlusExpression] --> <T $COPY_SRC$[1] + $COPY_SRC$[2] T>
 [inheritors false         ]
 [condition  <always>      ]

 [concept    FalseLiteral] --> <T false T>
 [inheritors false       ]
 [condition  <always>    ]

 [concept    BooleanType] --> <T boolean T>
 [inheritors false      ]
 [condition  <always>   ]

 [concept    IfExpression] --> <T $COPY_SRC$[true] ? $COPY_SRC$[true] : $COPY_SRC$[true] T>
 [inheritors false       ]
 [condition  <always>    ]
```

Fig. 16 A number of reduction rules that map the reusable expression language to Base-Language (Java). Since the languages are very similar, the mapping is trivial. For example, a *PlusExpression* is mapped to a + in Java, the left and right arguments are reduced recursively through the COPY_SRC macro.



```
reduction rules:
 [concept    AttributeRefExpr] --> content node:
 [inheritors false           ]     public void dummy() {
 [condition  <always>        ]       Object anObj = null;
                                     <TF [->$[anObj].->$[toString]()] TF>;
                                   }
```

Fig. 17 References to entity attributes are mapped to a call to their getter method. The tempalte fragment (inside the TF) uses two reference macros (-¿$) to "rewire" the object reference to the Java bean instance, and the *toString* method call to a call to the getter.

5.5 Language Annotations

■ *Structure and Syntax.* Since in a projectional editor the visual representation of a program is not necessarily the complete information in the program, and since the program's persistence format is not the concrete syntax, it is possible to store additional data in a program, and show it optionally. The mechanism MPS uses for this is called annotations. Using this approach, we can store the mapping from entity attributes to database columns directly in the entity, resulting in the following code:

```
module company
  entity Employee {
    id : int -> People.id
    name : string -> People.name
    role : string -> People.role
    worksAt : Department -> People.departmentID
    freelancer : boolean -> People.isFreelancer
  }

  entity Department {
    id : int -> Departments.id
    description : string -> Departments.descr
  }
```

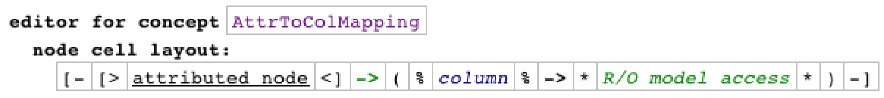
This is a heterogeneous fragment, consisting of code from the entities, as well as the annotations. From a concrete syntax perspective, the column mapping is ”embedded” in the entity description. In the underlying persistent data structure, the information is also actually stored in the entity model. However, the definition of the entities language does not know that this additional information is stored and projected ”inside” entities! No modification to the entities language is necessary whatsoever. Instead we define an additional language relmapping_annotations which extends the entities language as well as the relmapping language. In this language we define a so-called annotation link:

```
annotation link declaration colMapping
    stereotype node
    cardinality 1
    source Attribute
    target AttrToColMapping
```

This must be read as follows: we create an annotation for *Attribute* which can point to one instance of *AttrToColMapping*. *AttrToColMapping* is simply another concept that has one reference that points to a *Column*:

```
concept AttrToColMapping extends BaseConcept implements <none>
  references:
    Column column 1 specializes: <none>
```

Structurally, an annotation is a child of the node it is annotated to. So the *Attribute* has a new child of type *AttrToColMapping*, and the reference that contains the child is called *@colMapping*. However, in the editor the relationship is reversed. The editor for *AttrToColMapping* wraps the editor for *Attribute*, as Fig. 18 shows. The annotation is added via an intention (”quick fix” via Alt-Enter).



```
editor for concept AttrToColMapping
  node cell layout:
    [- [> attributed node <] -> ( % column % -> * R/O model access * ) -]
```

Fig. 18 The editor for the *AttrToColMapping* embeds the editor of the concept it is annotated to (using the *attributed node* cell). It then projects the reference to the referenced column.

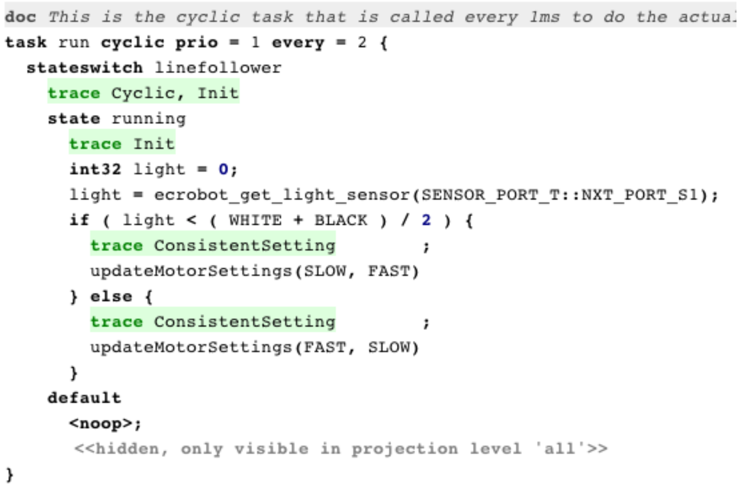
Note that it is also possible to define the annotation source to be *BaseConcept*, which means the annotation can be attached to any node. The language that contains the annotation then has no dependency to any other language. This is useful for generic "metadata" such as documentation, requirements traces or presence conditions in product line engineering. We have described this in [11] and [9].

■ *Type System.* The same typing rules are necessary as in the relmapping_entities language described above. They reside in relmapping_annotations.

■ *Generator.* The generator is also broadly similar to the above example with relmapping_entities. It takes the entities model as the input, and then uses the column mappings in the annotations to create the entity-to-database mapping code.

The annotations introduced above were typed to be specific to certain target concepts (*EntityAttribute* in this case). A particularly interesting use of of annotations includes those that can be annotated to *any* language concept (formally targetting *BaseConcept*). In this case, there is no dependency between the language that contains the annotation and the language that is annotated. This is very useful for "meta data", as well as anything that can be processed generically.

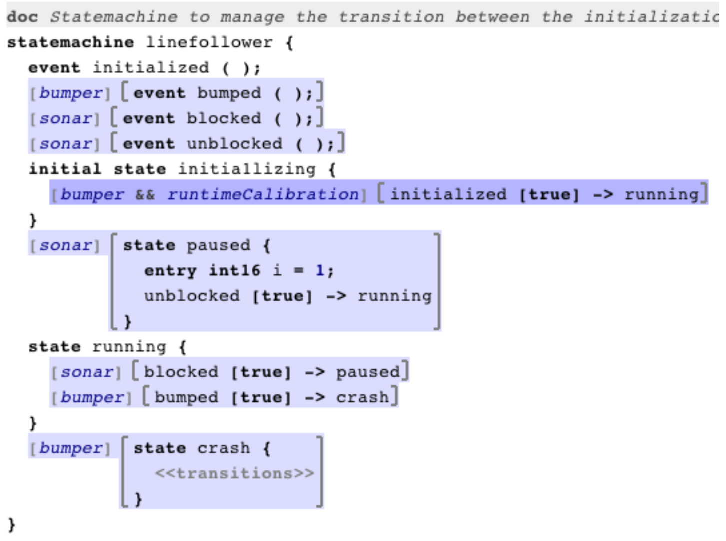
An example of the first case is traceability links (Fig. 19). This annotation can be annotated to any language concept and adds pointers (trace links) to requirements. As a consequence of the projectional approach, the program can be shown with or without the annotations, controlled by a global switch.



```
doc This is the cyclic task that is called every 1ms to do the actua
task run cyclic prio = 1 every = 2 {
  stateswitch linefollower
    trace Cyclic, Init
    state running
      trace Init
      int32 light = 0;
      light = ecrobot_get_light_sensor(SENSOR_PORT_T::NXT_PORT_S1);
      if ( light < ( WHITE + BLACK ) / 2 ) {
        trace ConsistentSetting        ;
        updateMotorSettings(SLOW, FAST)
      } else {
        trace ConsistentSetting        ;
        updateMotorSettings(FAST, SLOW)
      }
    default
      <noop>;
      <<hidden, only visible in projection level 'all'>>
}
```

Fig. 19 Requirements traces can be annotated to any arbitrary program element. The annotation is targetted to *BaseConcept*, which means there is no explicit dependency any specific language.

An example of the second case is product line variability annotations (Fig. 20). Boolean expressions over configuration switches can be annotated to any model element. Such an annotation means that the respective element is only in the program variant, if the boolean expression is true for the given setting of configuration switches. The generic transformation simply removes all elements whose annotation evaluates to false. The expressions can also be evaluated as part of the projection, showing the code for a given variant. The code is of course still editable. Details on this approach can be found in [9] and [11].



```
doc Statemachine to manage the transition between the initializatic
statemachine linefollower {
  event initialized ( );
  [bumper] [event bumped ( );]
  [sonar] [event blocked ( );]
  [sonar] [event unblocked ( );]
  initial state initiallizing {
    [bumper && runtimeCalibration] [initialized [true] -> running]
  }
  [sonar] [state paused {
            entry int16 i = 1;
            unblocked [true] -> running
          }]
  state running {
    [sonar] [blocked [true] -> paused]
    [bumper] [bumped [true] -> crash]
  }
  [bumper] [state crash {
             <<transitions>>
           }]
}
```

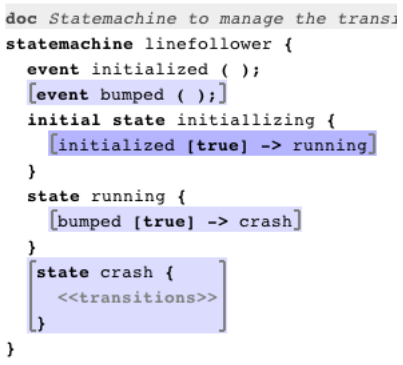
Fig. 20 Feature dependency annotations are boolean expresssions over configuration switches that determine whether the annotated program element is part of a program variant. The transformation removes all those elements for which the annotation evaluates to false.

6 Evaluation

The examples above show that meaningful LME&C is possible with MPS. Specifically, reuse and embedding of languages is possible. The challenge of grammar composition is not an issue in MPS at all, since no grammars and parsers are used. The fact that we hardly ever discuss syntactic issues in the above discussions is proof of this.

However, extensibility regarding the other aspects is a bit less well structured:

– In case of generators, language designers have to specify a partial ordering of mapping configurations using priorities. It is not easily possible to



```
doc Statemachine to manage the trans
statemachine linefollower {
  event initialized ( );
  [event bumped ( );]
  initial state initiallizing {
    [initialized [true] -> running]
  }
  state running {
    [bumped [true] -> crash]
  }
  [state crash {
    <<transitions>>
  }]
}
```

Fig. 21 This is the statemachine from Fig. 20, customized to the variant where only the *bumper* switch is turned on. The *bumper*-specific parts are highlighted.

"override" an existing generator, but generators can run *before* existing ones. Generator extension is not possible directly, this is why we use the placeholders that are put in by earlier generators to be reduced by later ones.

– The concrete syntax for elements of the base language cannot be overridden in the sublanguage, although this is supposed to change.
– Overriding of scopes is not possible; a workaround exists by factoring the code into a virtual method (and calling it from the scope).
– Typing rules cannot be overridden unless an overloaded operation rules container is used in the original language.

In my opinion, a consistent approach for extending and overriding aspects of the original language is missing. I suggest an approach called *Generic Outside, Specific Inside*. It is basically a variant of component-based design (`http://en.wikipedia.org/wiki/CBD`). All language aspects use components as the core structural building block. Components have types. The type of the component determines the kinds of facets it has. A facet is a kind of interface that exposes the (externally visible) ingredients of the component. The kinds of ingredients depend on the component type: a component of type *structure* exposes language concepts. A component of type *editor* exposes editors, type *type system* exposes type system rules, and so on. Each component type would use a different DSL for implementation. Here is the important point: a component (in a sublanguage) can specify an *advises* relationship to another component (from a super language). Then each of the facets can determine which facets from the advised component it wants to *preempt*, *enhance* or *override*. Fig. 22 shows the meta model of the approach.

This approach would provide the same way of packaging behavior for all language aspects, as well as a single, consistent way of changing that behavior in a sublanguage:

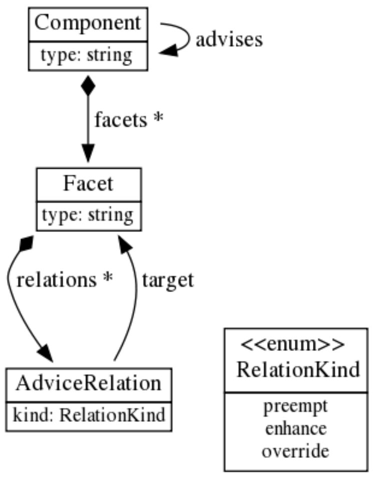


Fig. 22 Components contain facets. Facets come in different kinds and the component type determines which facets types are available. The facets export the component's contribution to a language. Facets can declare relations to other facets (preempt, enhance, override) as a generic way to change the contributions exported by components of a base language.

- *preemption* means that the respective behavior is contributed before the the behavior from the base language. A generator may use this to reduce a construct before the original generator gets a chance to reduce the construct.
- *enhancement* means that the sublanguage component is executed after the advised component from the base language. Notice that for declarative aspects where ordering is irrelevant, preempt and enhance are exchangable.
- *overriding* means that the original facet is completely shadowed by the new one. This could be used for example to define a new editor for an existing construct.

To control the granularity at which preemption, enhancement or overriding is performed, the base language designed would have to group his structures or behaviors into suitably cut facets. This amount of preplanning is acceptable: it is just as in OO programming, where behavior that should be overridable has to be packaged into its own method.

The approach could be taken further. Components could be marked as *abstract*, and define a set of parameters for which values need to be provided by non-abstract subcomponents. A language is abstract as long as it has at least one abstract component, for which no concrete subcomponent is provided. Component parameters could even be usable in structure definitions, for example as the base concept; this would make a language parametrizable regarding the base language it extends from.

In essence, the suggested approach is a bit like object orientation (components == classes, facets == methods), with a rich advise framework (as in AOP). Component parameters typed to language concepts are similar to generics. Using this approach, a powerful and consistent approach to language extensibility would be available.

7 Summary

MPS is powerful environment for language engineering. While not all of its features are unique (see Section 3), the combination of flexible composition and the notational freedom as a consequence of the projectional approach is certainly convincing. I also want to emphasize that the tool also scales to realistic program sizes, the editor is very usable, and it integrates well with existing VCS (diff and merge is provided on the level of the concrete syntax). At the very minimum, the tool is a perfect environment for language experimentation in the context of academic and industrial research.

The major drawback of MPS is its non-trivial learning curve. Because it works so differently than traditional language engineering environments, and because it addresses so many aspects of languages (incl. type systems, data flow and refactorings) mastering the tools takes a significant investment in terms of time. I hope that in the future this investment will be reduced by better documentation and better defaults, to keep simple things simple and complex things tractable. First ideas exist on how this could be done.

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