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PEDRO, Luis, et al.

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Developing Domain-Specific Modeling Languages by Metamodel Semantic Enrichment and Composition: a Case Study

Luis Pedro
D’Auriol Asset Management
Lausanne, Switzerland
luis@dauriol.ch

Matteo Risoldi and Didier Buchs
University of Geneva
Geneva, Switzerland
{name.surname}@unige.ch

Vasco Amaral
Universidade Nova de Lisboa
Lisbon, Portugal
vasco.amaral@di.fct.unl.pt

ABSTRACT
Designing a DSML implies binding the syntactical concepts of the problem domain with the semantics of a solution domain. Previous work presented a formal framework for language composition where language syntactical patterns (expressed by metamodels) along with their semantics (expressed by transformation models) are combined as small reusable building blocks in a constructive manner, in order to achieve the desired expressiveness for DSMLs. This article refines the framework, as well as showing its application through a case study led in collaboration with CERN (European Organization for Nuclear Research).

Keywords
DSML, Transformation, Composition, Metamodel, Semantics

1. INTRODUCTION
The main purpose of Domain-Specific Modeling Languages (DSMLs) is to make it easier for expert of a given domain to describe models. This is achieved by using domain-specific terms and concepts. Designing a DSML involves analysing the domain, defining an abstract syntax, and mapping the syntax to semantics. This mapping can be done in several ways; among others, by transforming models to some other language for which semantics are already well-defined.

We previously defined a formal framework [11] for making these operations modular. The goal of this article is refining the framework and illustrating its concrete application on a real world case study. It is shown how a DSML for prototyping graphical user interfaces (GUIs) for control systems was built by composing smaller DSML blocks. This case study was led in collaboration with CERN (Switzerland).

The remainder of this Section will talk about related and previous work. Section 2 resumes the formal framework for DSML composition. Section 3 illustrates the case study. Section 4 draws conclusions and discusses perspectives.

1.1 Related Work
Works [6] in the area of metamodeling and DSML engineering show that basic patterns exist that repeat across different DSMLs. These patterns, or domain concepts, can be composed to describe complex domain models. The techniques available so far are either tackling the problem purely at the syntactical level (e.g. [9]), or are too abstract (e.g. [8]) to be applied to DSMLs with a certain level of complexity. Other approaches (e.g. model extension by package merge in UML2 specifications) are too bound to the technology for which they have been defined.

In [5] a technique is presented that allows “anchoring” semantics to a metamodel. This technique uses Abstract State Machines and the Graph Rewriting And Transformation language (GReAT) [1] as instruments in the Generic Modeling Environment (GME). Semantic units are defined by attaching a transformation to each metamodel defined in the GME. Both [5] and our work use a model transformation language to provide semantics.

1.2 Previous Work and Goals
Previous work by the authors [10, 11] formally defined a framework to add semantics to metamodels by transforming them to other languages. Via transformations, domain concepts are prototyped, and their behaviour validated. Composition of domain concepts was achieved via metamodel composition at the syntactical level, and transformation composition at the semantic level. The approach extended the work presented in [2]. This article achieves two goals. First, it refines the formal framework with simpler and more correct definitions. Second, it gives a more pragmatical view by applying the approach to a real world case study.

2. FORMAL FRAMEWORK FOR DSML COMPOSITION
The composition framework is based on domain concepts. A domain concept is a block comprised of: 1) a metamodel, and 2) a transformation to one or more target domains. Transformations are operations that provide semantics to domain concepts. They map concepts to models for which semantics are already defined.

For defining modular DSMLs by composition of domain concepts, the syntax and semantics of these domain concepts must be composed. This is done by parameterizing each domain concept with other domain concepts. The parameterization means that a domain concept is partially or totally replaced by another domain concept. The latter may be richer, more refined, or have a different transformation template.
A transformation is a function \( Tr : \text{im} \rightarrow \text{im}' \), where \( \text{im} \) is an instance model of the source metamodel and \( \text{im}' \) an instance model of the target metamodel. Given the metamodel of a domain concept \( \text{mm} \), transformations are defined for it. Each transformation may be a set of other simpler transformations: \( T_{\text{mm}} = \{ T_{\text{mm}}^1, \ldots, T_{\text{mm}}^n \} \). Each \( T_{\text{mm}} \) corresponds to rules which transform elements of a source model into elements of a target model.

Domain concepts are parameterized by defining the elements that serve as parameters and the ones that replace them. The parameterization happens at two levels: syntactical, concerning the metamodel composition; and semantic, concerning transformation composition.

At the metamodel (syntactical) level, a parameterization is defined as

\[
\text{mm}' = \text{mm}[fp \leftarrow ep, F_{fp}]
\]  

(1)

where \( \text{mm}, \text{mm}' \), \( fp \) (formal parameter) and \( ep \) (effective parameter) are metamodels; \( ep \supset \varphi(fp) \) re-defines, at least, all the elements in \( fp \); and \( F_{fp} \) is a set of formulae representing conditions satisfied by \( fp \). The parameterization can be instantiated iff \( ep \models \varphi(F_{fp}) \) - meaning that the conditions satisfied by \( fp \) must be satisfied by \( ep \). The \( \varphi \) is a total function that maps elements of \( fp \) and \( ep \).

Fig. 1 illustrates a simplified diagram of the metamodel parameterization. It shows that a DSML metamodel is extended by substituting its formal parameter \( fp \) with an effective parameter \( ep \).

Figure 1: Metamodel extension by parameterization

At the transformation (semantic) level, a parameterization is defined on the transformations associated to the metamodel (syntactical) level. A parameterization is defined as:

\[
T_{\text{mm}} = T_{\text{mm}}[T_{fp} \leftarrow \psi, T_{ep}]
\]  

(2)

where:

- \( \text{mm}' \) is the metamodel resulting from the \( \text{mm} \) metamodel parameterization;
- \( T_{fp} \) is the template transformation defined for \( fp \);
- \( T_{ep} \) is the template transformation defined for \( ep \);
- \( \varphi \) is the source mapping function: \( \text{Dom}(T_{fp}) \rightarrow \text{Dom}(T_{ep}) \)
  where \( \text{Dom} \) stands for \( \text{Domain} \) of a transformation;
- \( \psi \) is the target mapping function: \( \text{Cod}(T_{fp}) \rightarrow \text{Cod}(T_{ep}) \)
  where \( \text{Cod} \) is the \( \text{Co-Domain} \) of a transformation;

\[\text{and the transformation instantiation is: } tm = T_{\text{mm}}'(m') \]

where \( m' \) is an instance of \( \text{mm}' \) and \( tm \) is an instance of the metamodel of the target language.

From an operational point of view, \( \psi \) defines which transformations in \( fp \) are replaced by which transformations in \( ep \).

3. APPLICATION: THE COSPEL DSML

The CMS Tracker at CERN is a complex high-energy physics apparatus. It is comprised of several hundred components which have to be monitored for diagnostics. GUIs for this task demand a great effort of development. However, if one had a tool that automated the GUI development, most of the information needed can be found in existing engineering data describing the system, its logic and its input/output. This spawned interest in researching a way to automatically prototype the GUI by reusing this existing information. The first step towards this solution was to model system information in a way that is understandable by users of the system.

A DSML named Cospel [12] was designed to model complex control systems. The language models a system’s structure, behavior and communication, as well as interface-related features like user and task models. An associated framework transforms the language into an executable system simulator and a user interface prototype.

Cospel has been designed using the compositional framework defined here and in [11]. Its metamodel is modular, and formed by the composition of several domain concepts. This article shows how we achieved the composition of a few of these concepts. For each concept, a metamodel and an associated transformation are shown. We compose these domain concepts into a more complex language until we have enough information to generate a simple GUI prototype from it. The final result shown in this article constitutes the essential of the Cospel language. There were further extensions to Cospel, described in [12], however discussing those is out of the scope of this article.

3.1 Target Languages

The framework supports multi-formalism approaches. In the deployment of Cospel, it was chosen to use Concur-
CO-OPN is a formal language that allows the generation of executable specifications. It is an object-oriented formal specification language based on synchronized algebraic Petri nets. The main reasons why CO-OPN was chosen as a target language are the possibility to perform formal verification on models, and the possibility to generate executable Java code from the models.

While in the context of this article the reader should not be concerned with the details of CO-OPN, a brief overview is in order to understand the transformations. CO-OPN specifications are made of three module types: ADTs (algebraic Abstract Data Types), Classes, and Contexts:

- **ADTs** represent data and their associated operations;
- **Classes** are an encapsulation of algebraic Petri nets that allows to describe both structure and component’s behavior. A CO-OPN class can have methods, gates (events with parameters) and typed places;
- **Contexts** are a higher level of encapsulation which defines the contextual coordination between class instances or other contexts.

SQL was also used as a target language since part of the information in a Cospel model is meant to be stored in a relational database. In the context of the article, this provides an example of how different target languages can be supported at once.

### 3.2 Transformation Framework

The formal framework is general with respect to the choice of a transformation framework. In the context of Cospel development, the ATLAS Transformation Language (ATL) framework was used. The remainder of the article will explain transformations using snippets of ATL rules, skipping lengthy details of the code.

### 3.3 Generic Cospel DSML

The starting point for the modular creation of Cospel was defining a “core” language, providing abstractions that define a generic control system. Fig. shows the metamodel of the Generic Cospel DSML. It includes the concepts of Object, Type, FSM (Finite State Machine), EventGen, GeometryGen and Coordinates. These describe, respectively, the objects in the system, their common features, their behaviour, the events of the system, the geometry of the system, and the coordinates of each object in space. Some of these concepts (e.g., GeometryGen, EventGen) are very generic and need to be specified further to describe a concrete system. To build the full Cospel language we added details in a sequence of metamodel and transformation compositions. The resulting metamodel is shown in Fig. where classes and relationships affected by compositions are in a darker color.

Without going into too much detail of the CO-OPN code, Generic Cospel models are transformed to CO-OPN models as follows. Types are transformed into CO-OPN Classes.

http://www.eclipse.org/m2m/atl/
by substituting the EventGen class in mmCospelgen with the Event class in mmEvent. The Conditions class and all related associations are brought over as part of mmEvent.

Using the definitions presented in Section 3.2 we can express this substitution as follows. Let mmEvent be the metamodel in Fig. 4 and mmCospelgen the Generic Cospel metamodel of Fig. 2. The metamodel of the new DSML with the event extension is defined by:

- \( f_{p1} = \) the metamodel corresponding to EventGen of mmCospelgen;
- \( e_{p1} = \) a subset of mmEvent \{Event, Condition, ownedConditions, triggerEvent\};
- \( \varphi_1 = \{(\text{EventGen}, \text{Event})\} \)

A new metamodel \( mm\text{Cospel}_{\text{event}} \) is the result of the application of definition (3):

\[ mm\text{Cospel}_{\text{event}} = \text{mmCospel}_{\text{gen}}[f_{p1} \ circ_{\varphi_1} e_{p1}, \text{true}] \]

The bottom-left part of Fig. 3 (the Event and Condition classes) shows the result of the composition. \( F_{fp} \) constraints are empty in this example.

For the transformation composition, rules for the formal parameter (i.e., \( T_{fp1} \)) are replaced by those for the effective parameter (i.e., \( T_{ep1} \)). No restrictions on \( T_{fp1} \) and \( T_{ep1} \) are specified (i.e., the whole \( T_{fp1} \) is substituted by the whole \( T_{ep1} \)). Fig. 5 shows the transformation composition.

A new transformation, \( T_{\text{mmCospel}_{\text{event}}} \) is the result of the application of definition (4):

\[ T_{\text{mmCospel}_{\text{event}}} = T_{\text{mmCospel}_{\text{event}}}[T_{fp1} \ circ_{\varphi_1} T_{ep1}] \]

Let ie be the models conforming to the \( mm\text{Cospel}_{\text{event}} \) metamodel, and if the models in the target language(s). The transformation application is: \( \psi_1(T_{\text{mmCospel}_{\text{event}}}(ie)) \). Fig. 4 resumes how the mmEvent and \( mm\text{Cospel}_{\text{gen}} \) metamodels are composed into the \( mm\text{Cospel}_{\text{event}} \) metamodel, and how the composed transformation \( T_{\text{mmCospel}_{\text{event}}} \) includes the transformation rules from \( T_{\text{mmEvent}} \).

### 3.5 Hierarchical Model Extension of Cospel

A common feature in complex control systems is they are built as hierarchies of objects. To model this concept, we use a Hierarchy metamodel \( mm\text{Hierarchy} \), shown in Fig. 7 in which the Object class has a children association to itself (0-* cardinality) as well as an opposite parent association (0-1). Transforming this to CO-OPN, the CO-OPN Context of a “parent object” will contain references to the CO-OPN Contexts of the “children objects”.

The result of the previous composition \( mm\text{Cospel}_{\text{event}} \) has been composed with \( mm\text{Hierarchy} \). The Object class in \( mm\text{Cospel}_{\text{event}} \) was substituted with the one in \( mm\text{Hierarchy} \). The resulting metamodel of Cospel enriched with the event and hierarchy extensions, \( mm\text{Cospel}_{\text{eventHierarchy}} \) is defined by:

- \( f_{p2} = \) the metamodel of the Object class of \( mm\text{Cospel}_{\text{event}} \);
- \( e_{p2} = \) a subset of \( mm\text{Hierarchy} \) \{Object, children, parent\};
- \( \varphi_2 = \{(\text{Object}, \text{Object})\} \)

At the transformation level, \( mm\text{Hierarchy} \) has two rules.
for transforming objects to CO-OPN; one for objects without children (ruleObject) and one for objects with children (ruleObjectWithChildren). When composing transformations of \textit{mmHierarchy} and \textit{mmCospelEvent}, we do not want to replace the latter's rule for \textit{Objects} (also called ruleObject), as this would destroy information about the associations of \textit{Object} which are present in \textit{mmCospelEvent} but not in \textit{mmHierarchy}. Thus, when defining the \(\psi_2\) function for this composition, instead of using the whole \(Tr_{fp_2}\) as a parameter, we use

\[(Tr_{fp_2} - TE) \cup (Tr_{fp_2}[TF])\]

where \(TE\) is a subset of \(Tr_{fp_2}\) formed by all \(Tr_{fp_2}'\) such that \(\exists Tr_{fp_2}' : Dom(Tr_{fp_2}') = \varphi_2(Dom(Tr_{fp_2}))\) for any \(i, j\). In other terms, all rules in \(Tr_{fp_2}\) who have a corresponding rule in \(Tr_{fp_2}\) with the same domain after parameterization. \(TF\) is a subset of \(Tr_{fp_2}\) formed by all the \(Tr_{fp_2}''\) as just defined; \((Tr_{fp_2} - TE)\) is the rules in \(Tr_{fp_2}\) minus those in \(TE\); and \((Tr_{fp_2}[TF])\) is the subset of \(Tr_{fp_2}\) including only the rules in \(TF\). In layman's terms, \((Tr_{fp_2} - TE)\) excludes from the composition the rules we don't want use as replacements; instead, we keep the rules for \(fp_2\) which are in \((Tr_{fp_2}[TF])\). In this case, \((Tr_{fp_2} - TE)\) is \(\{\text{ruleObjectWithChildren}, \text{ruleContextUse}\}\) and \((Tr_{fp_2}[TF])\) is \(\{\text{ruleObject}\}\).

The transformation composition is shown in Fig. 8. Rules in black are those which will be kept in the result.

Composition of \textit{mmGeometry} with the previous \textit{mmCospelEventHierarchy} substitutes the \textit{GeometryGen} class with the new abstract \textit{Geometry} class (the Box, Sphere, Cylinder and GeomFile classes are brought over too). The metamodel of the resulting DSML with the geometry extension is defined by:

- \(fp_3\) = the metamodel of the \textit{GeometryGen} class of \textit{mmCospelEventHierarchy};
- \(ep_3\) = a subset of \textit{mmGeometry} \{\text{Geometry, GeomFile, Box, Cylinder, Sphere}\};
- \(\varphi_3 = \{\text{GeometryGen, Geometry}\}\)

For the transformation composition in this case, the codomains of \(Tr_{fp_3}\) and \(Tr_{ep_3}\) are different: \(Tr_{fp_3}\) creates models conforming to the CO-OPN MetaModel, while \(Tr_{ep_3}\) creates models conforming to sql4Cospel. The composition is shown in Fig. 10.

However, in our case study there was a catch with this transformation composition. To satisfy the requirements, we had to store in the database a record stating that a certain object was associated to a certain geometry. This was not necessary pre-composition, as everything was done in CO-OPN; and unfortunately, there is nothing in the \textit{mmGeometry} transformation that allows automatic creation of this insert statement. In this case, we had to add a \textit{a posteriori} an ATL helper which made the association. This goes to show that in some cases composition can not be fully automatized.

After this last composition, the resulting metamodel is the one we had previously shown in Fig. 9. It has enough information to build a first prototype of the GUI for visualizing a control system structure and state. The GUI is a 3D dynamic representation of the system structure and state. It loads the database created by the transformations of Section 3.6. 

### 3.6 Geometry Model extension of Cospel

A useful concept for modeling physical systems is a collection of geometrical primitive shapes which can be parameterized quickly to represent the various shapes of objects.

The \textit{mmCospelGen} metamodel and the further extensions we made until now, however, only model geometry as the URL of a file containing geometrical data (vertices and faces).

To refine geometry, we use a simple metamodel \textit{mmGeometry} shown in Fig. 9 with an abstract \textit{Geometry} class. It has several classes (Box, Sphere, Cylinder and GeomFile) implementing it. The particularity of this transformation is that it has a different codomain from the rest of Cospel. This is because the Cospel framework does not store this geometrical information in the CO-OPN model, but rather in a database. The database is then used by a GUI prototyping engine to load a 3D scene. Instances of this metamodel are thus transformed into a set of SQL queries using a simplified SQL metamodel called \textit{sql4Cospel} with Strings representing queries. For each \textit{Geometry}, an INSERT statement is made in the appropriate table (according to the kind of primitive).
4. CONCLUSION AND FUTURE WORK

We presented the application of a methodology which allows a language designer to compose metamodels and transformations. There is a main advantage coming from the fact that the framework is defined formally: it is possible to ensure that the properties of transformations are preserved in composition. This is not the case when composition is done by hand. Other advantages lay in the facilitation of incremental language development with a reduced re-factoring effort and increased re-use. Also, this methodology is suitable not only to engineer DSMs in a modular and incremental fashion, but also to particularize a DSML into more specific ones [11].

Limitations of the methodology include that not everything can be composed easily. The work proposed here is not a silver bullet – difficulties often arise, especially at the transformation level. Transformation blocks must have compatible domains, and while extending the work of the case study we met some patterns which were not trivial to tackle. We found that imperative transformations in particular introduce difficulties. These can be so hard that in pathological cases the effort of performing composition might be comparable or even higher than simply rewriting the transformations by hand. Even when composition is feasible, manual work may be required to complete it, as we saw in the example of the mmGeometry metamodel. This has all sort of implications on preserving properties in composition: non-trivial compositions may require further steps to re-check models.

For some of these limitations, an editor which detects problematic compositions could help. In this perspective, a thorough classification of composition problems should be done. Another limitation is that this work obviously applies only to the cases where it makes sense to compose transformations, i.e., where available domain concepts fit the desired result rather well. If the development of a DSML from modular domain concepts requires a radical rewriting of all associated transformations, there is no particular advantage in using this methodology.

Another relevant limitation is more pragmatical. It comes from the fact that the success of this method is heavily dependent on the creation and maintenance of a solid base of domain concepts, as well as tools which implement the theoretical framework. Similar conclusions [7] were found for situational method engineering, a similar approach for designing modular methodologies. Again, we don’t think this proposal is a one-size-fits-all solution. It is rather one of many practices that can improve the process of language design. Its usage should be guided by a critical analysis of the case and of available metamodels and transformations.

Future work includes further studies on satisfying constraints of ep over fy; traceability of ep in order to automatically reflect its modifications in the composed DSMs; versioning of transformations and of transformation compositions allowing backward compatibility of subsequent versions of the DSMs.

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5. REFERENCES


