Electronic Communications of the EASST
Volume 4 (2006)

Proceedings of the Second International Workshop on Graph and Model Transformation (GraMoT 2006)

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13 pages

Guest Editors: Gabor Karsai, Gabriele Taentzer
Managing Editors: Tiziana Margaria, Julia Padberg, Gabriele Taentzer
ECEASST Home Page: http://www.easst.org/eceasst/ ISSN 1863-2122

PML: a Transformation Language for Platform Modeling

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Abstract: Modeling the computational platforms is necessary to analyze the execution characteristics of systems developed using a model-based approach. In this paper, we introduce a novel platform modeling language: PML that is based on (a) transformational concepts borrowed from graph transformation languages, and (b) generative concepts from platform modeling, like 'kernel skeleton'. PML relies on higher-level, compact constructs that represent a special case of model transformations, and which are then used to specify platform semantics. The paper also illustrates how PML constructs can be compiled into lower-level constructs of more traditional model transformational languages, such as GReAT.

Keywords: Graph Transformation, Model Transformation, Platform Modeling

1 Introduction

During the implementation of component-based software systems, high-level system models are mapped onto *platform primitives*, just like programs in high-level languages are *compiled* into machine code instruction sequences. *Platform* is defined in the general sense as a collection/abstraction of hardware, software, or middleware primitives and services used to implement the design. The notion of platform is flexible — even within a particular design one can define multiple levels of "platform" abstractions.

For a software engineer, a platform could be an operating system (offering services/primitives such as processes and shared memory), or the CPU with its machine instruction set. For an Internet applications designer, the TCP/IP protocol or XMLRPC might be an useful platform abstraction. For a component-based software system, a component framework, like real-time CORBA can be chosen.

By designing for the right platform abstraction, designers take advantage of existing *platform implementations*, reducing the required implementation effort. This definition of the platform concept is discussed by Sangiovanni-Vincentelli and Grant in [SM01].

For design-time analysis, one constructs the *analysis model* of the system being designed. The design-time analysis model captures the implementation's behavior. Obviously, in platform-based design, the properties of the platform implementation influence the system's behavior, thus platform properties have to be considered when formulating the analysis model. Analysis models usually rely on formalisms allowing *formal verification*, such as *timed automata* [AD94].

We assume that a design expressed in a domain-specific modeling language (DSML). Then generating a platform-specific analysis model takes two steps:

1. *DSML→Platform* translation (the "compiler")

2. *Platform→Analysis model* translation

The first step maps platform-independent design models into platform-level models. The second step maps these latter models composed of platform-level primitives onto analysis model structures. For example, this step might generate timed automata models for CPU-level instructions, so that the temporal behavior of the implementation on a particular CPU can be analyzed. Note that the first stage is reusable if CPU-s with the same instruction sets are used, but the second stage must be different if the timing properties of the same instruction are different across CPU-s.

This paper introduces a language for *explicit platform modeling*. With this approach, analysis models are generated at design time, based on the analytical models of different implementation platforms and the design model of the application. Using explicit platform models, designers can evaluate their system's behavior over multiple platform implementation candidates before committing themselves to one particular implementation.

The Platform Modeling Language described below assists in specifying these platform models; specifically the Platform→Analysis mapping.

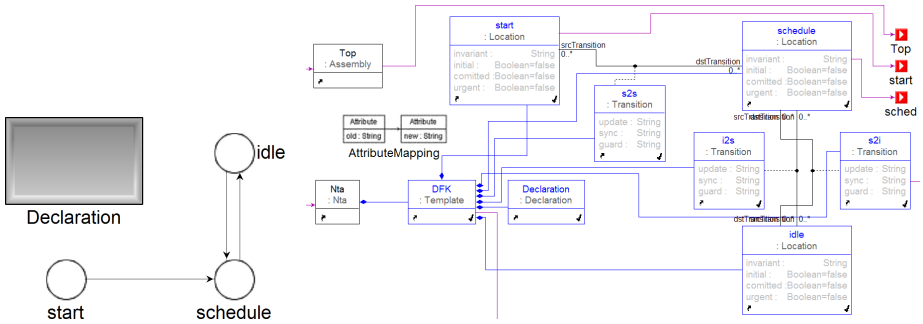
In the following text, *output model* refers to the analysis model. *DSM* is the domain-specific model (or design model), also known as the *platform-independent model* or *PIM*. *PSM* is the *platform-specific model*, which is a refinement of the PIM with platform-specific implementation details.

For example, the DSM can describe an image processing system in a high-level design language. The PSM describes the system as implemented over a particular dataflow hardware. The analysis model then captures the behavior of this PSM in a (timed or untimed) finite transition system formalism (such as Timed Automata or SPIN [Hol97] model).

2 Previous work

The need for a language to capture *explicit* platform models was first outlined in [SK04], where we argued for the automatic generation of analysis models in design-time. In the above paper, we specified a DSML→Analysis mapping using the GME [LBM+01] modeling environment and the GReAT [KASS03][GZS+05] graph transformation language.

In GME, one defines a modeling language via a *metamodel* specified using an UML-like formalism. Then, the *modeling paradigm* is established by configuring GME with this metamodel to enable working with model instances. GReAT is a graph transformation tool in the GME environment. When GReAT transformations are modeled, one imports the source and target metamodels into the modeling tool to establish the pattern language. Rewriting rules are formulated at the metamodel level. GReAT provides context propagation (i.e. subsequent rules can refer to objects matched earlier). Additionally, GReAT offers sophisticated control structures for rule sequencing, such as test/case, parallel execution, iteration and recursion.



(a) The Kernel skeleton in UPPAAL

(b) Creating the Kernel skeleton in a GReAT rule

Figure 1: Creating an analysis model fragment in GReAT

In [SK04], both the DSM and analysis models were defined via their respective UML metamodels. Then, GReAT was used to specify transformation rules at the metamodel level. This way, the analysis model, describing the behavior of the system as implemented over a given platform, was obtained from the DSM in one, rather complex, transformation step.

The above paper demonstrated *implicit* platform modeling: the analysis model of the platform was embedded in the transformation specification. The demonstrated transformation was very complex. Since it was specified as a DSML→Analysis mapping, it (implicitly) contained both DSML→Platform and Platform→Analysis mappings. Furthermore, the general-purpose graph transformation language used was a poor fit for some of the recurring transformation tasks, as discussed below.

In the demonstrated example, the platform was a dataflow network. Each actor was mapped onto a timed automaton in the analysis model. These automata were synchronized by an automaton modeling the scheduler for the network: the *Kernel* automaton.

Building the analysis model for a platform actor consisted of two steps:

1. Creating a generic "skeleton" timed automaton with generic states and transitions, such as *start* and *idle*. This "skeleton" was the same for all actors.

2. Extending this "skeleton" with details (states, transitions and conditions) specific to the actor being mapped.

As Fig. 1 shows, the GReAT rule creating a simple FSM is rather complex and hard to read. This is due to the fact that GReAT rules operate at the metamodel level. For example, creating a simple transition (connection) requires 7 objects in the GReAT rule: {source, destination, connector object, parent object and 3 associations}. Furthermore, it is often the case that switching to a different (e.g. more detailed) analysis model requires changes to the "skeletons" only. Since these are implicitly encoded in the transformation, the changes also require editing the transformation itself.

As mentioned above, GReAT also supports different control structures for rule sequencing that enable its use in many different graph transformation scenarios. The price one pays is the complex (and often awkward) way bound objects (i.e. the context) are passed between rules.

Sophisticated rule sequencing constructs are typically needed in DSML→Platform ”compiler” transformations, as these tend to be complex (examples for such transformations can be found in [TS06] and related publications). Platform→Analysis transformations are usually much simpler: These transformations typically map each platform “component” (e.g. dataflow actor) onto a corresponding fragment of the analysis model. The basic structure of the platform-level model and the analysis model is the same, thus a less generic transformation language suffices. Using a less generic language for these transformations could result in simpler, more concise transformation specifications.

The PML language, discussed in the following section, was designed with these considerations in mind.

3 PML: the Platform Modeling Language

PML is a simple, declarative language to specify the *Platform→Analysis model* mapping outlined above. The language supports the building of analysis (target) models by inserting, customizing and composing target model fragments (called “skeletons”) into the model being built. These skeletons model platform-level structures. PML uses graph patterns to identify, locate and insert these skeletons in the source and target models. Furthermore, PML includes a simple declarative graph transformation language for the composition and customization of these skeletons (“mappings language”).

A PML model consists of 4 basic parts:

1. The UML metamodels for the source (platform) and target (analysis) models that establish a visual language for patterns over models. PML provides an import tool to include GME metamodels into platform models. Additionally, PML models may contain optional *crosslinks* definitions. Crosslinks are associations that link model elements across different metamodels (i.e. source and target. They are used to simplify subsequent pattern matching by ”marking” certain elements and to maintain state information about the transformation.

2. The construction of the output model starts with the instantiation of the *Kernel model* (given as a partial analysis model). This model provides the basic structure of the output model being built. During the construction of the analysis model, this skeleton is extended by attaching PSM-specific elements or modifying attributes.

3. Next, *components* are identified in the source (PSM) model via pattern matching. A target model skeleton is associated with each component in the output model, and instantiated and then customized. The destination within the target model for the copy operation is also designated by a pattern. Crosslinks are automatically generated to link the source component with the corresponding target model structure copied.

4. Finally, the rules in the *mappings language* further customize and extend the analysis model.

The following sections discuss the *component* concept and the mappings language.

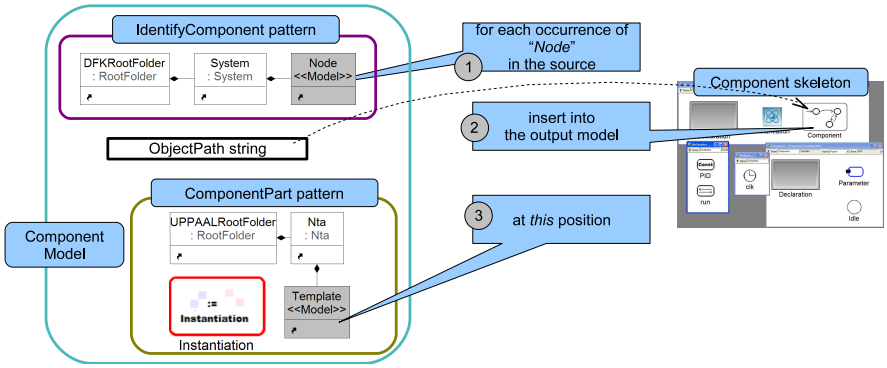


Figure 2: Visualization of the ComponentModel concept

3.1 Component Skeletons

The concept of a *component* is central to PML. Components are a related group of elements in the source model, identifiable by a pattern. The pattern designates a single element to represent the component. Components are mapped onto corresponding structures in the output model. This concept is modeled through *ComponentModels* in PML. ComponentModels contain:

- A reference to an analysis model, containing the skeleton.
- A pattern to locate the component within the source model (*IdentifyComponent*)
- Definitions of one or more target model fragments, onto which the component is mapped in the analysis model (*ComponentParts*).

The idea of a ComponentModel is visualized in Figure 2. In the figure, components are defined as *Node* objects within a *System*. In the skeleton model, a FSM fragment is designated by the *ObjectPath* identifier. This fragment is copied into the output model (as a *Template* object hierarchy) within the *Nta* container (*ComponentPart* pattern). Here, the *Instantiation* code box can be used to set the attributes of the newly instantiated elements.

3.1.1 Identifying Components

Components in the source (platform) model are identified by an *IdentifyComponent* pattern. This pattern defines what a component is in terms of source metamodel elements. The pattern also designates a representative element for the component (shaded in the visual language – *Node* in the figure). The transformation creates associations between this representative element and the corresponding analysis fragments. Thus, for each analysis fragment the originating source component can be found at a later stage.

3.1.2 Component Parts

A single component might map to corresponding elements or structures at multiple locations in the analysis model. For example, each dataflow actor has a timed automaton, and it also has

corresponding constants or states in the automaton modeling the platform scheduler. In order to facilitate this, ComponentModels may contain one or more *ComponentParts*. ComponentParts define the following:

- The location of the fragment within the component skeleton model (*ObjectPath* attribute)
- The destination of the fragment in the analysis model being built.

The destination within the target model is defined by a pattern. The pattern is formulated over target model elements, and designates a single element (shaded grey in the visual language). During the mapping process, this element is created within the target model, and the skeleton is copied into it. In Fig. 2, a *Template* is created for each *Node* and the contents of the skeleton model (shown on the right) are copied into it. The ComponentPart pattern might also contain a procedural code fragment (*Instantiation* box), that computes and sets the attributes of the inserted fragments.

Using this approach, the "skeletons" forming the backbone of the analysis model can be comfortably edited and reviewed within the analysis paradigm.

3.2 Mappings

In addition to the skeleton instantiation language, PML also features a simple graph transformation language (*Mappings*). This language facilitates fine-grained customization of the analysis model, after the skeleton instantiations have taken place.

The language uses rewriting rules based on graph patterns. The patterns are UML class diagram-like graph patterns. Typing is implemented by the nodes being references to metamodel elements.

A PML mapping identifies PSM patterns through *filter patterns* (the left-hand side, LHS), and maps them onto analysis structures as specified by *action patterns* (the right-hand side, RHS). Filter patterns can be annotated by C++ code snippets as boolean-valued *guard* functions over the attribute values of pattern elements.

A filter pattern is *satisfied* if it matches a sub-graph of the input model and the optional guard expression evaluates true. Filters are assumed to be side-effect free.

With the associated filter(s) satisfied, an action could get *executed*, creating the elements specified in the *action pattern* and setting attribute values as specified in optional *SetAttribute* C++ code fragments.

Filters and actions contain two kinds of pattern elements:

1. *MetaClasses* are metamodel element references to be matched (in filters) or created (in actions).
2. *MatchReferences* refer to elements matched by previous filters, implementing context propagation (more about filter hierarchy in the next section).

Pattern matching always starts from top-level model containers (in our case, *RootFolders*). Matched objects can be propagated "downstream" to subsequent patterns, as explained in the next section.

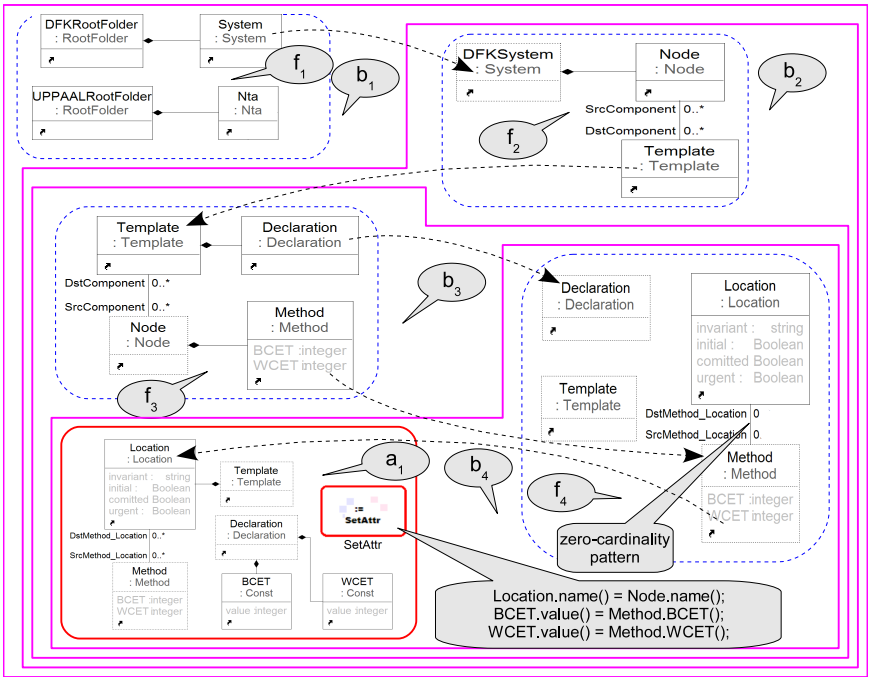


Figure 3: Example PML Block hierarchy

3.3 PML block hierarchy

Mapping blocks can be organized into hierarchy to simplify filter patterns. Figure 3 illustrates this (filters are named f_i, actions a_j and blocks b_k):

The topmost filter f_1 (in block b_1) matches *Systems*. Sub-block b_2's filter f_2 refers to the *System* matched using a *MatchReference* object, and matches all *Nodes* within the system, along with their associated Template objects. (*SrcComponent* → *DstComponent* associations were created by component skeleton instantiations).

Inside b_2, sub-block b_3's filter (f_3) matches the Template's *Declarations* block and all *Methods* within. f_4 matches all such Methods with no Location associated by a zero-cardinality pattern, marked in the Figure. Action a_1 creates the Location and maps the Method's BCET and WCET values onto constant declarations within the Template.

Filter conditions in sub-blocks use *MatchReferences* (dashed frame), which refer to to elements matched by the immediate parent block's filter. This enables breaking up filter patterns into simpler ones. (Some – not all – MatchReferences are visualized by dashed arrows in Fig. 3). A *mapping block* has one filter condition, and zero or more actions.

Note that the hierarchy does not imply scheduling for *action execution*, it is only to aid logical organization. Action execution order is discussed in the following section.

3.4 Mappings semantics

3.4.1 Global Filter Condition

For each action a_i, a *Global Filter Condition*(GFC_i) can be constructed by composing associated filter conditions along the block hierarchy:

Definition 1 Global Filter Condition Let f_i be the filter of the block containing a_i. Let f_{i-1} be the filter of the immediate parent block (i.e. one level up in the hierarchy). $Comp(f_i, f_{i-1})$ is a filter obtained by joining f_i and f_{i-1} together as follows:

1. the *glue graph*, $Glue(f_i, f_{i-1})$ is the set of elements of f_{i-1} referenced in f_i (dotted frame in the diagrams) along with the associations internal to the set. Start the composition with the glue graph, $c_0 = Glue(f_i, f_{i-1})$.
2. construct $c_1 = Attach(c_0, f_i \setminus Glue(f_i, f_{i-1}))$: add the rest of f_i and attach the associations between f_i and the glue graph.
3. $c_2 = Attach(c_1, f_{i-1} \setminus Glue(f_i, f_{i-1}))$: add the rest of f_{i-1} and attach the dangling associations between c_2 and the rest of f_{i-1}.
4. $Comp(f_i, f_{i-1}) = c_2$.

Then, let us define the composition of filters along the block hierarchy as:

$$Comp(f_i, f_{i-1}, \ldots, f_0) = Comp(Comp(Comp(f_i, f_{i-1}), f_{i-2}), \ldots), f_0)$$

and the global filter condition for action a_i as

$$GFC_i = Comp(f_i, f_{i-1}, \ldots, f_0)$$

where f_i is the filter associated with action a_i.

For example, $GFC_1 = Comp(f_4, f_3, f_2, f_1) = Comp(Comp(Comp(f_4, f_3), f_2), f_1)$ in Fig. 3 for action a_1.

3.5 Execution semantics for actions

The execution semantics for actions is shown in Algorithm 1:

Algorithm 1 Action execution semantics

while $\exists i$ such that (GFC_i) is *true* **do**
  Execute $action_i$
end while

If there are multiple actions eligible for execution, one is selected non-deterministically. There is no explicit ordering. Implicit ordering can be established by referring to elements to be created by "previous" actions.

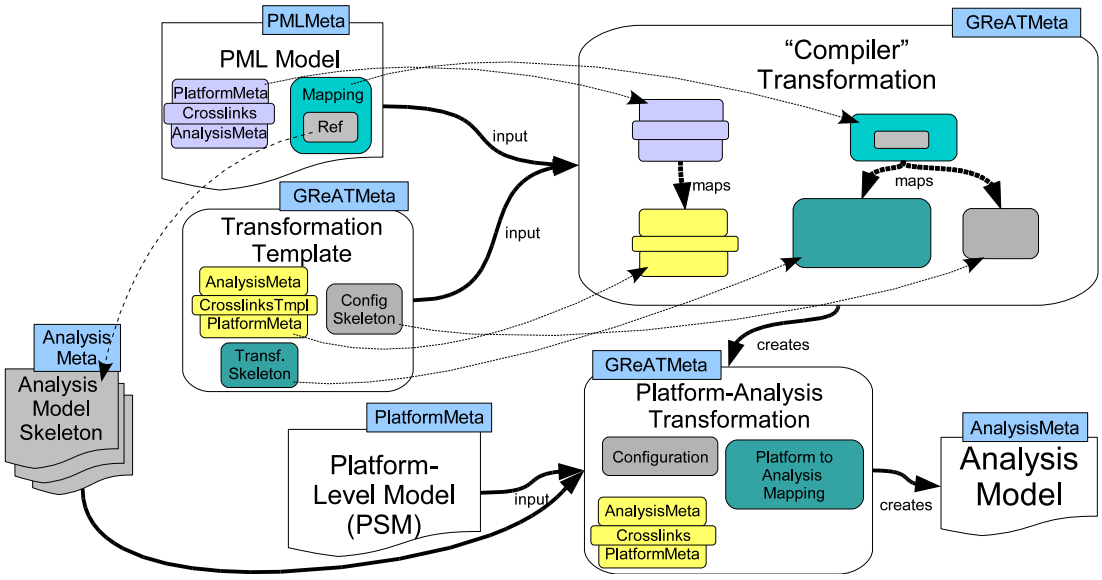


Figure 4: High-level overview of the PML→GReAT transformation

4 Implementing PML over GReAT

GReAT is a general-purpose graph transformation language sharing key concepts with PML, thus implementing PML over GReAT is a straightforward idea. The implementation is done by mapping (translating) a PML specification into an equivalent GReAT transformation — by a "compiler" transformation, specified also in GReAT.

Figure 4 provides a high-level overview: Each component in the figure is a model, and the corresponding metamodel's name is written above the model in a rectangle. The "compiler" takes a PML model (referred as $\mathscr{M}_i$ in the following discussion) and a GReAT Platform→Analysis transformation template. During compilation, this template is extended with rules generated based on $\mathscr{M}_i$.

$\mathscr{M}_i$ contains the UML-style metamodels (using an encoding suitable for PML) of the source and target models (platform, analysis), and optional crosslinks. Most importantly, it also contains the
Platform→Analysis mapping definition, with references to external analysis model fragments (skeletons), which are used in Kernel and Component mappings.

The "compiler" GReAT transformation inputs $\mathscr{M}_i$ and a GReAT template. This template contains the appropriate metamodels, and skeletal configuration and transformation specifications (rule-blocks). The "compiler" works by extending these configuration and rule-block skeletons to implement the mapping given in $\mathscr{M}_i$.

This creates a GReAT transformation, which is the Platform→Analysis transformation at the bottom of the Figure 4. The generated transformation inputs the platform-level model (PSM), the analysis model skeletons, as specified in $\mathscr{M}_i$, and creates the corresponding analysis model. The resulting analysis model captures the behavior of the PSM as implemented over the platform

modeled in $\mathscr{M}_i$.

The PML→GReAT "compiler" transformation has the following major phases:

1. Mapping metamodels and crosslinks. Ultimately, the transformation maps PML patterns onto GReAT patterns. Thus, the "compiler" first associates the PML and GReAT metamodels, as both $\mathscr{M}_i$ and the GReAT template contain them, in different formats.

2. Extending the template transformation's configuration such that the appropriate component skeletons are read and input by the main transformation block, as specified in $\mathscr{M}_i$.

3. The template rule block `Components` (on the right side of Fig. 4, within block "GReAT Transformation") is extended to implement the mapping of components captured in the PML model.

4. The template rule block `Mappings` (block next to is `Components`) is extended to implement the mappings defined in the PML model.

5 Evaluation

As a case study, we repeated the DSML→Analysis transformation discussed in [SK04]. For DSML the SMOLES language was used, the DFK dataflow package was the implementation platform, and the analysis model was given in UPPAAL (these languages are discussed in [SK04]). This time, with the platform level explicitly present, two transformations were specified (both in GReAT):

1. The SMOLES→DFK implementation mapping (DSML→Platform)

2. The DFK→UPPAAL analysis transformation (Platform→Analysis)

Then, the analysis mapping was also specified using PML. The following table gives a rough complexity comparison of the DFK→UPPAAL mapping in PML and in GReAT. The columns give the counts of GME modeling elements in the models containing the mapping specifications. Both approaches model the "pattern to be matched" (the key concept) almost identically to each other. Thus, the patterns take up approximately the same number of modeling elements. The rest is the overhead required by the language.

Transformation	Atoms	Models	Connections	Total
Hand-optimized GReAT	162	43	936	1142 (100%)
PML	77	59	642	778 (68%)
PML compiled into GReAT	567	86	2760	3413 (299%)

As we can see, the PML model is more compact than even a hand-optimized GReAT solution. The reason behind the larger number of atoms and connections in the GReAT transformation is GReAT's more complex context passing mechanism: where PML uses a simple *MatchReference*, GReAT uses *In* and *Out* ports and a propagation connections. For this example, the number of models (containers) is larger in the PML model. This is mainly due to the separation of LHS / RHS patterns: in GReAT, they can be combined into a single rule.

The last row shows the number of elements in the GReAT transformation generated by the PML→GReAT compiler. This compiler is only a prototype, "proof-of-concept" implementation, and it is far from optimal.

6 Related efforts

OMG's QVT RFP [Gro03] and the proposals it solicited (esp. the ATL [BDJ+03] language) were influential during the specification of PML. Due to practical considerations, we chose UML over the MOF modeling favored by OMG. Due to its limited scope, PML – unlike ATL – includes no imperative rules, thus it is not a *hybrid* approach. This makes formal arguments on transformation properties easier.

The idea of using UML model transformations in order to obtain analysis models is demonstrated by the VIATRA [CHM+02] approach. VIATRA does not have the concept of *platform*, thus leveraging on existing DSML→Platform "compiler" implementations is more problematic.

With pattern-based languages, expressing the *lack of* structures is an important question. The AGG [Tae03] approach (and VIATRA as well) uses *negative application conditions (NACs)*. PML uses *zero-cardinality patterns* (with certain limitations) which is a less powerful concept, but so far it seems to be sufficient.

Similar efforts to our platform modeling research were recently published in the middleware community ([SGSS05] and related publications). The authors compose timed automata fragment to model middleware structures. These results are very important as they come from domain experts. They provide generic "recipes" for the formulation and composition of the analysis model fragment. Our research offers a systematic, comprehensive and automated framework.

7 Conclusions

The introduced language, PML keeps and leverages the most useful concepts of general-purpose graph transformation languages (such as GReAT). Such concepts include the UML-inspired visual language and constructing the patterns over metamodel elements, enforcing correctness. At the same time, PML is clean and simple. LHS and RHS are separated, the execution semantics is straightforward, context passing is intuitive.

Using the skeleton concept, key output model elements can be edited in their native modeling environments. This allows analysis experts to focus on the details of the analysis model, instead of trying to map them into complex transformation rules, like the one in Fig. 1.

The output is generated as a GME model, conforming to the analysis language metamodel. This model can be exported into various tool-specific concrete syntaxes, such as UPPAAL, HyTech [HHW97] etc.

As the evaluation shows, using PML also results in simpler, more compact and easier to maintain models for the Platform→Analysis mapping than a general-purpose graph transformation language. The PML→GReAT compiler is an important and interesting result, as it shows the maturity of the GReAT language.

8 Acknowledgements

The NSF ITR on ”Foundations of Hybrid and Embedded Software Systems” has supported, in part, the activities described in this paper. This material is based upon work supported by the National Science Foundation under Grant No. 0509098

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