Classification of Model Transformation Approaches

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Abstract

The Model-Driven Architecture is an initiative by the Object Management Group to automate the generation of platform-specific models from platform-independent models. While there exist some well-established standards for modeling platform models, there is currently no matured foundation for specifying transformations between such models. In this paper, we propose a possible taxonomy for the classification of several existing and proposed model transformation approaches. The taxonomy is described with a feature model that makes the different design choices for model transformations explicit. Based on our analysis, we propose a few major categories in which most model transformation approaches fit.

1 Introduction

The Model-Driven Architecture (MDA) [MDA, Fra03] is an initiative by the Object Management Group (OMG) to define an approach to software development based on modeling and automated mapping of models to implementations. The basic MDA pattern involves defining a platform-independent model (PIM) and its automated mapping to one or more platform-specific models (PSMs).

The MDA approach promises a number of benefits including improved portability due to separating the application knowledge from the mapping to a specific implementation technology, increased productivity due to automating the mapping, improved quality due to reuse of well proven patterns and best practices in the mapping, and improved maintainability due to better separation of concerns and better consistency and traceability between models and code.

While the current OMG standards such as the Meta Object Facility (MOF) [MOF] and the UML [UML] provide a well-established foundation for defining PIMs and PSMs, no such well-established foundation exists for transforming PIMs into PSMs [GLR+02]. In 2002, in its effort to change this situation, the OMG initiated a standardization process by issuing a Request for Proposal (RFP) on Query / Views / Transformations (QVT) [QVT]. This process will eventually lead to an OMG standard for defining model transformations, which will be of interest not only for PIM-to-PSM transformations, but also for defining views on models and synchronization between models. Driven by practical needs and the OMG's request, a large number of approaches to model transformation have recently been proposed.

In this paper, we propose a feature model to compare different model transformation approaches and offer a survey and categorization of a number of existing approaches

- published in the literature: GreAT [AKS03], UMLX [Wil03], ATOM [ATOM], VIATRA [VVP02], BOTL [BM03, MB03], ATL [BDJR03], and proposals based on relations [AK02], and object-oriented logic-programming [GLR+02];
- submitted in response to the OMG's QVT RFP in the revised submission round: [QVTP], [CDI], [AST+], [IOPT], [CS];

- implemented in open-source MDA tools: Jamda [JAM], AndroMDA [AND], JET, FUUT-je and GMT [FUU]); and
- implemented in commercial MDA tools: OptimalJ [OTPJ], ArcStyler [AS], XDE [XDE], Codagen Architect [CA], b+m Generator Framework [B+M]

The feature model makes the different possible design choices for a model transformation approach explicit, which is the main contribution of this paper. We do not give the detailed classification data for each individual approach mainly because the details of the individual approaches are a moving target. Instead, we give examples of approaches for each of the discussed design choices. Furthermore, we propose a clustering of the existing approaches into a few major categories that capture their different flavors and main design choices.

The paper is organized as follows. Section 2 presents our feature model of model transformation approaches. Section 3 presents the major categories of existing transformation approaches. Section 4 concludes the paper with some remarks on the practical applicability of the different categories.

2 Design Features of Model Transformation Approaches

This section is the result of applying domain analysis to existing model transformation approaches. Domain analysis is concerned with analyzing and modeling the variabilities and commonalities of systems or concepts in a domain [Cza02]. We document our results using feature diagrams [KCH+90, Cza98], which are a common notation in domain analysis. Fig. 1 shows the top-level feature diagram, where each subnode represents a major point of variation. Further explanation of the notation is given in the legend of Fig. 2.

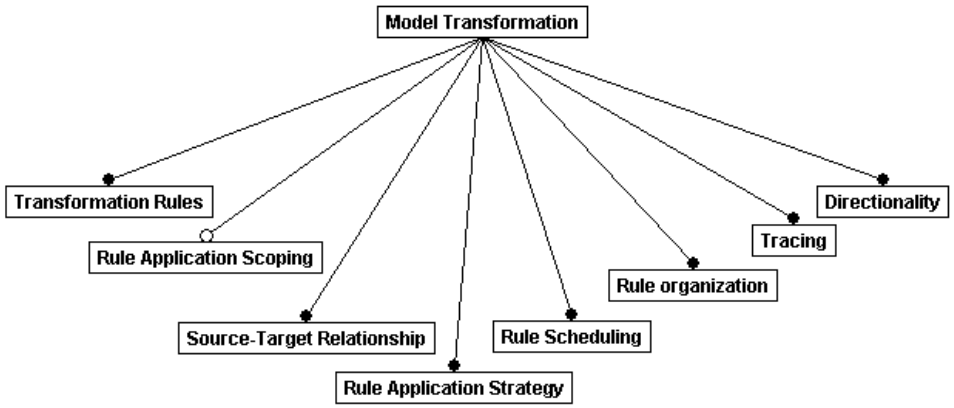

Fig. 1 Feature diagram representing the top-level areas of variation[1]

Essentially, a feature diagram defines a taxonomy. We should note that we do not aim for this taxonomy to be normative. Unfortunately, the relatively new area of model transformations has many overloaded terms, and many of the terms we use in our taxonomy are often used with different meanings in the original descriptions of the different approaches. However, we provide the definitions of the terms as we use them.

[1] The feature diagrams in this paper have been created using CaptainFeature, a feature modeling tool available from http://cvs.sourceforge.net/cgi-bin/viewcvs.cgi/captainfeature/

Each of the following subsections elaborates on one major area of variation from Fig. 1 by giving its feature diagram, describing the different choices in the text, and providing examples of approaches supporting a given feature. The combination of feature diagrams and the additional information is referred to as a *feature model*. Please note that our feature model treats model-to-model and model-to-code approaches uniformly. We will distinguish between these categories later in Section 3.

2.1 Transformation Rules

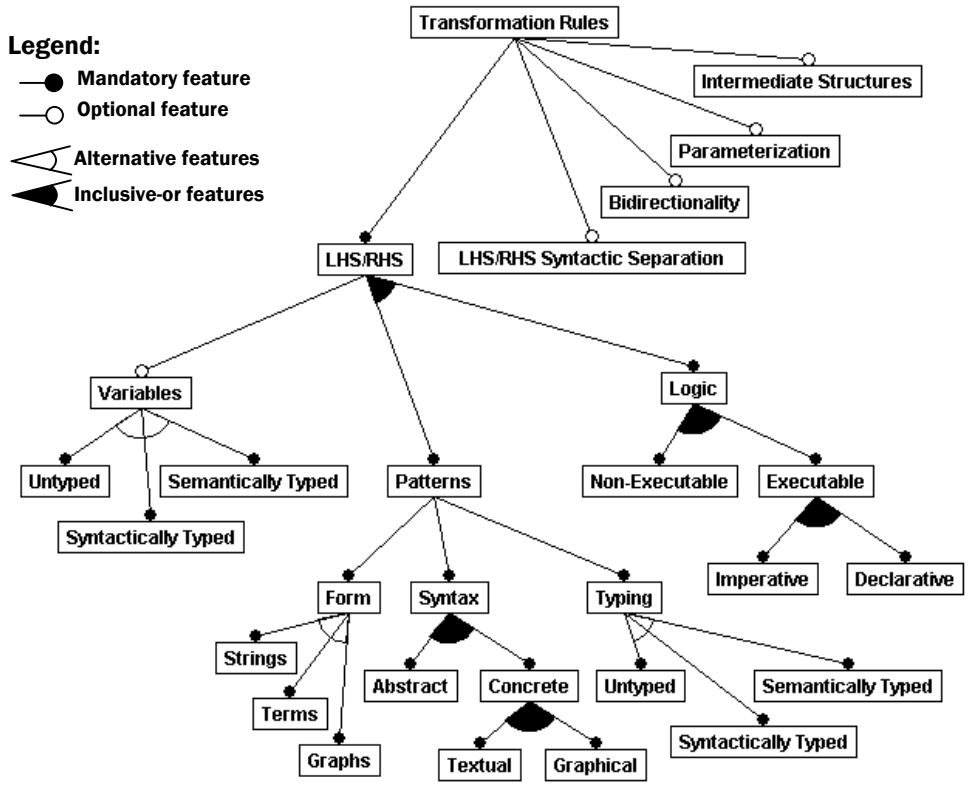

Fig. 2 Features of transformation rules

A transformation rule consists of two parts: a left-hand side (LHS) and a right-hand side (RHS).[2] The LHS accesses the source model, whereas the RHS expands in the target model. Both LHS and RHS can be represented using any mixture of the following:

- *Variables*: Variables hold elements from the source and/or target models (or some intermediate elements). They are sometimes referred to as *metavariables* to distinguish them from variables that may be part of the transformed model (e.g., Java variables in transformed Java programs).
- *Patterns*: Patterns are model fragments with zero or more variables.[3] We can have string, term, and graph patterns. String patterns are used in textual templates (see Section 3.1.2).

[2] We view templates (see Section 3.1.2) as a special case of transformation rules. The LHS may be as minimal as a parameter list, but may also contain some logic to access the source model. The RHS contains at least a pattern, but may also include additional logic performing pattern composition.

Model-to-model transformations usually use term or graph patterns (see Section 3.2.2 and 3.2.3). Patterns can be represented using abstract or concrete syntax of the corresponding source or target model language, and the syntax can be textual and/or graphical (see Section 3.2.3).

- *Logic*: Logic expresses computations and constraints on model elements. Logic may be non-executable or executable. Non-executable logic is used to specify a relationship between models (e.g., [QVTP]). Executable logic can take a declarative or imperative form. Examples of the declarative form include OCL-queries [OCL] to retrieve elements from the source model (e.g., XDE) and the implicit creation of target elements through constraints (e.g., [CDI]). Imperative logic has often the form of programming language code calling repository APIs to manipulate models directly. For instance, the Java Metadata Interface [JMI] provides a Java API to access models in a MOF repository. In the context of the QVT standardization effort, the UML Action Semantic [UAS] can be used to specify imperative logic in a form that can be automatically mapped to different programming languages.

Both variables and patterns can be untyped, syntactically typed, or semantically typed. In the case of syntactic typing, a variable is associated with a metamodel element whose instances it can hold. Semantic typing allows stronger properties to be asserted. For example, the syntactic type of a variable could be "expression," whereas its semantic type could be "expression evaluating to an integer value." The latter is not available in the current model transformation languages, but is supported in some metaprogramming languages such as MetaML and MetaOcaml [MML, MOML]. We included semantic typing in the feature model to indicate possible future development.

Four other aspects of transformation rules are:

- *Syntactic Separation*: The RHS and LHS may or may not be syntactically separated. In other words, the rule syntax may specifically mark RHS and LHS as such (as in classical rewrite rules), or there might be no syntactic distinction (as in a transformation rule implemented as a Java program; see Section 3.2.1).
- *Bidirectionality*: A rule may be executable in both directions (see also Section 2.8).
- *Rule parameterization*: Transformation rules may have additional control parameters allowing configuration and tuning.
- *Intermediate structures*: Some approaches (e.g., VIATRA and GreAT) require the construction of intermediate model structures. This is particularly relevant when the model transformation happens in-place within a model (see Section 2.3).

2.2 Rule Application Scoping

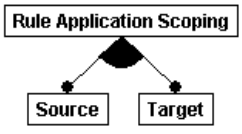

Fig. 3 Features of rule application scoping

[3] Some approaches (e.g., [IOPT]) use the term *pattern* to denote any abstract specification of some constellation of model elements in a model. This interpretation encompasses both patterns and declarative logic in our terminology.

Rule application scoping allows a transformation to restrict the parts of a model that participate in the transformation. Some approaches support flexible source model scoping (e.g. XDE and GreAT), where a scope smaller than the entire source model can be set. The latter can be important for performance reasons. The target scope is the scope of the target model, in which the RHS will be expanded (e.g., XDE).

2.3 Relationship between Source and Target

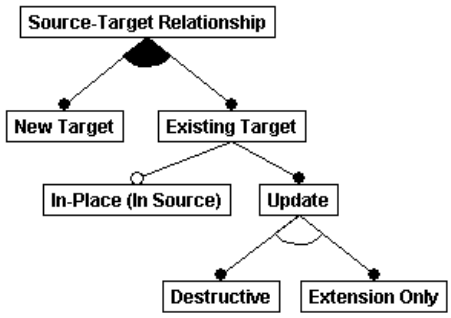

Fig. 4 Features of the relationship between source and target

Some approaches mandate the creation of a new target model that has to be separate from the source (e.g., [CDI]). In some other approaches, source and target are always the same model, i.e., they only support in-place update (e.g., VIATRA, GreAT). Yet other approaches (e.g., XDE) allow the target model to be a new model or an existing one, which could be the original source model. The latter implies in-place update. Furthermore, an approach could allow a destructive update of the existing target or an update by extension only, i.e., where existing model elements cannot be removed. Approaches using non-deterministic selection and fixpoint iteration scheduling (see Section 2.5) may restrict in-place update to extension in order to ensure termination (e.g., VIATRA).

2.4 Rule Application Strategy

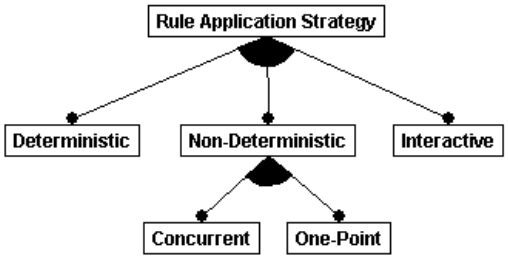

Fig. 5 Features of rule application strategy

A rule needs to be applied to a specific location within its source scope. Since there may be more than one match for a rule within a given source scope, we need an application strategy. The strategy could be deterministic, non-deterministic or even interactive. For example, a deterministic strategy could exploit some standard traversal strategy (such as depth-first) over the containment hierarchy in the source. Stratego [STR] is an example of a term rewriting language with rich mechanisms to express traversal in tree structures. Examples of non-deterministic strategies include one-point application, where a rule is applied to one non-deterministically selected location, and concurrent application, where one rule is applied concurrently to all

matching locations in the source (e.g., VIATRA). Sometimes, rule application is determined interactively (e.g. XDE).

The target location for a rule is usually deterministic. In the case of in-place update, the source location becomes the target location (e.g. VIATRA or GreAT). In an approach with separate source and target models, traceability links can be used to determine the target (e.g. [CDI]): A rule may follow the traceability link to some target element that was created by some other rule and use the element as its own target.

2.5 Rule Scheduling

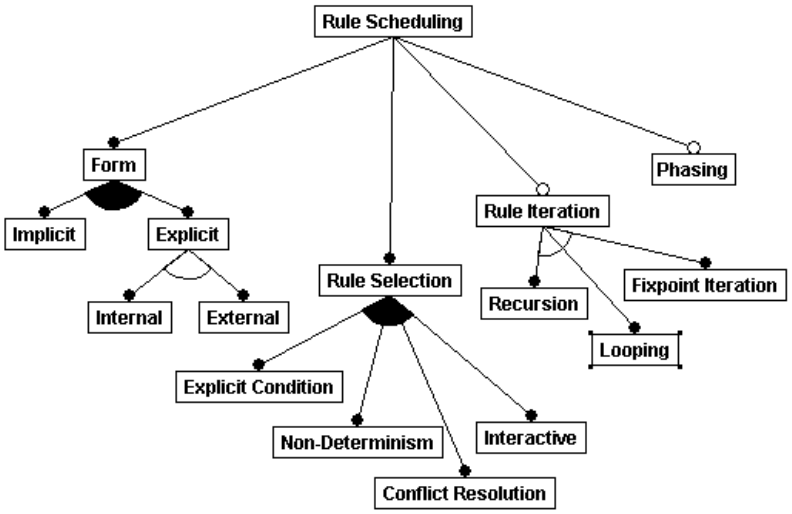

Fig. 6 Features of rule scheduling

Scheduling mechanisms determine the order in which individual rules are applied. The scheduling mechanism can vary in four main areas:

- *Form*: The scheduling aspect can be expressed implicitly or explicitly. Implicit scheduling implies that the user has no explicit control on the scheduling algorithm defined by the tool (e.g., BOTL and OptimalJ). The only way a user can influence the system-defined scheduling algorithm is by designing the patterns and logic of the rules to guarantee certain execution orders. For example, a given rule could check for some information that only some other rule would produce. Explicit scheduling has dedicated constructs to explicitly control the execution order. Explicit scheduling could be internal or external. In external scheduling, there is a clear separation between the rules and the scheduling logic (e.g., in VIATRA, rule scheduling is provided by an external finite state machine). In contrast, internal scheduling would be a mechanism allowing a transformation rule to directly invoke other rules (e.g., [CDI], Jamda and most template approaches in Section 3.1.2, which offer a way to call other templates).
- *Rule selection*: Rules can be selected by an explicit condition (e.g. Jamda). Some approaches allow non-deterministic choice (e.g. BOTL). Alternatively, a conflict resolution mechanism based on priorities could be provided (although none of the investigated approaches implement conflict resolution). Interactive rule selection is also possible (e.g. XDE).
- *Rule iteration*: Rule iteration mechanisms include recursion, looping, and fixpoint iteration (i.e., repeated application until no changes detected).

- *Phasing*: The transformation process may be organized into several phases, where each phase has a specific purpose and only certain rules can be invoked in a given phase. For example, structure-oriented approaches such as OptimalJ and [IOPT] (see Section 3.2.4) have a separate phase to create the containment hierarchy of the target model and a separate phase to set the attributes and references in the target.

2.6 Rule Organization

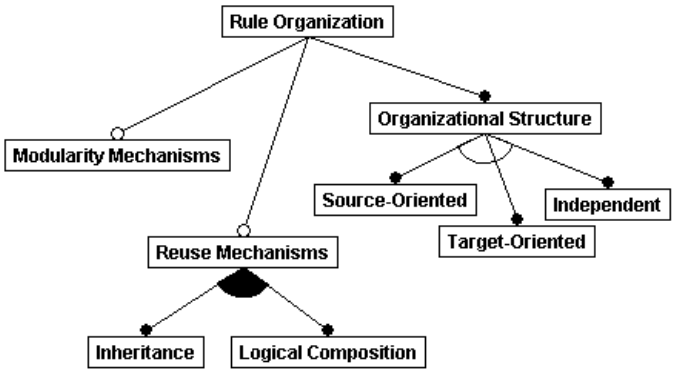

Fig. 7 Features of rule organization

Rule organization is concerned with composing and structuring multiple transformation rules. We consider three areas of variation in this context:

- *Modularity mechanisms*: Some approaches allow packaging rules into modules (e.g., [AST+] and VIATRA). A module can import another module to access its content.
- *Reuse mechanisms*: Reuse mechanisms offer a way to define a rule based on one or more other rules. In general, scheduling mechanisms can be used to define composite transformation rules; however, some approaches offer dedicated reuse mechanisms such as inheritance between rules (e.g. rule inheritance in [AST+], derivation in [IOPT], extension in [CDI], specialization in [QVTP]), inheritance between modules (e.g., unit inheritance in [AST+]), and logical composition (e.g. [QVTP]).
- *Organizational structure*: Rules may be organized according to the structure of the source language (as in attribute grammars, where actions are attached to the elements of the source language) or the target language, or they may have their own independent organization. An example of the organization according to the structure of the target is [IOPT]. In this approach, there is one rule for each target element type and the rules are nested according to the containment hierarchy in the target metamodel. For example, if the target language has a package construct in which classes can be nested, the rule for creating packages will contain the rule for creating classes (which will contain rules for creating attributes and methods, etc.).

2.7 Traceability Links

Transformations may record links between their source and target elements. These links can be useful in performing impact analysis (i.e., analyzing how changing one model would affect other related models), synchronization between models, model-based debugging (i.e., mapping the stepwise execution of an implementation back to its high-level model), and determining the target of a transformation (see Section 2.4).

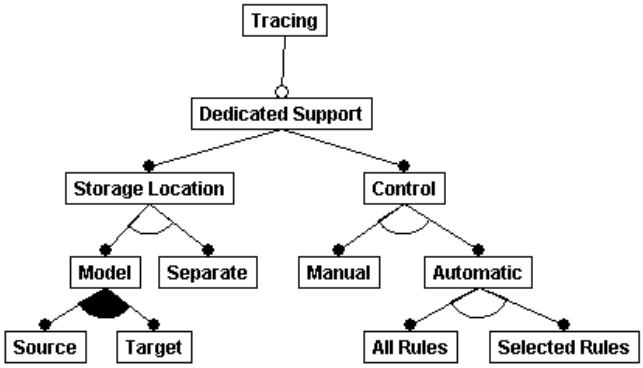

Fig. 8 Features of tracing

Some approaches provide dedicated support for traceability (e.g., [CDI], [IOPT]), while others expect the user to encode traceability using the same mechanisms as for adding any other kinds of links in models (e.g., VIATRA, GreAT). Some approaches with dedicated support for traceability require developers to manually encode the creation of traceability links in the transformation rules (e.g., [CDI]), while other create traceability links automatically (e.g., [IOPT]). In the case of automated support, the approach may still provide some control over how many traceability links get created (in order to limit the amount of traceability data). Finally, there is the choice of location where the links are stored, e.g., in the source and/or target, or separately. A preferable approach is to store a GUID in each model element and store the traceability information separate from the source and target.

2.8 Directionality

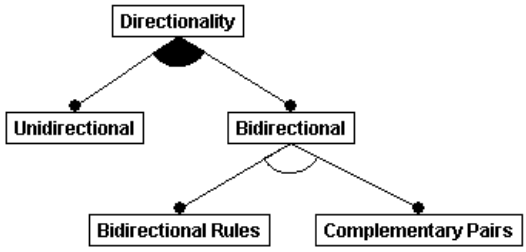

Fig. 9 Directionality

Transformations may be unidirectional or bidirectional. Unidirectional transformations can be executed in one direction only, in which case a target model is computed (or updated) based on a source model. Bidirectional transformations can be executed in both directions, which is useful in the context of synchronization between models. Bidirectional transformations can be achieved using bidirectional rules or by defining two separate complementary unidirectional rules, one for each direction.

Transformation rules are usually designed to have a functional character: given some input in the source model, they produce a concrete result in the target model. A declarative rule (i.e., one that only uses declarative logic and/or patterns) can often be applied in the inverse direction, too. However, since different inputs may lead to the same output, the inverse of a rule may not be a function. In this case, the inversion could enumerate a number of possible solutions (this could

theoretically be infinite), or just establish part of the result in a concrete way (because the part could be the same for all solutions) and use variables, defaults, or values already present in the output for the other parts. The invertibility of a transformation depends not only on the invertibility of the transformation rules, but also on the invertibility of the scheduling logic. Inverting a set of rules may fail to produce any result due to non-termination.

Most of the investigated approaches do not provide for bidirectionality. Notable exceptions are [AK02], [CS], and [QVTP]. The latter does not provide for general bidirectionality. Instead, a transformation can be described at different levels of abstraction, where one level is invertible and another is not.

3 Major Categories

At the top level, we distinguish between model-to-code and model-to-model transformation approaches. In general, we can view transforming models to code as a special case of model-to-model transformations; we only need to provide a metamodel for the target programming language. However, for practical reasons of reusing existing compiler technology, code is often generated simply as text, which is then fed into a compiler. For this reason, we distinguish between model-to-code transformation (which would be better described as model-to-text since non-code artifacts such as XML may be generated) and model-to-model transformation. Several tools offer both model-to-model and model-to-code transformations (e.g., Jamda, XDE, and OptimalJ).

In the model-to-code category, we distinguish between visitor-based and template-based approaches. In the model-to-model category, we distinguish among direct-manipulation approaches, relational approaches, graph-transformation-based approaches, structure-driven approaches, and hybrid approaches.

3.1 Model-To-Code Approaches

3.1.1 Visitor-Based Approaches

A very basic code generation approach consists in providing some visitor mechanism to traverse the internal representation of a model and write code to a text stream. An example of this approach is Jamda, which is an object-oriented framework providing a set of classes to represent UML models, an API for manipulating models, and a visitor mechanism (so called CodeWriters) to generate code. Jamda does not support the MOF standard to define new metamodels; however, new model element types can be introduced by subclassing the existing Java classes that represent the predefined model element types.

3.1.2 Template-Based Approaches

The majority of currently available MDA tools support template-based model-to-code generation, e.g., b+m Generator Framework, JET, FUUT-je, Codagen Architect, AndroMDA, ArcStyler, OptimalJ and XDE (the latter two also provide model-to-model transformations). AndroMDA reuses existing open-source template-based generation technology: Velocity [VELO] and XDoclet [XD].

A template usually consists of the target text containing splices of metacode to access information from the source and to perform code selection and iterative expansion (see [Cle01] for an introduction to template-based code generation). According to our terminology, the LHS uses executable logic to access source; the RHS combines untyped, string patterns with executable logic for code selection and iterative expansion; and there is no syntactic separation between the

LHS and RHS. Template approaches usually offer user-defined scheduling in the internal form of calling a template from within another one.

The LHS logic accessing the source model may have different forms. The logic could be simply Java code accessing the API provided by the internal representation of the source model (e.g., JMI), or it could be declarative queries (e.g., in OCL or XPath [XP]). The b+m Generator Framework propagates the idea of separating more complex source access logic (which might need to navigate and gather information from different places of the source model) from templates by moving them into user-defined operations of the source-model elements.

Compared to a visitor-based transformation, the structure of a template resembles more closely the code to be generated. Templates lend themselves to iterative development as they can be easily derived from examples. Since the template approaches discussed in this section operate on text, the patterns they contain are untyped and can represent syntactically or semantically incorrect code fragments. On the other hand, textual templates are independent of the target language and simplify the generation of any textual artifacts, including documentation.

A related technology is frame processing, which extends templates with more sophisticated adaptation and structuring mechanisms (Bassett's frames [Bas97], XVCL [XVCL], FPL [FPL], XFramer [Emr03], ANGIE [ANG]). To our knowledge, FPL, XFramer, and ANGIE have been applied to generate code from models.

3.2 Model-To-Model Approaches

Model-to-model transformations translate between source and target models, which can be instances of the same or different metamodels. All of these approaches support syntactic typing of variables and patterns.

Most existing MDA tools provide only model-to-code transformations, which they use for generating PSMs (in this case being just the implementation code) from PIMs. Why are model-to-model transformations needed? When bridging large abstraction gaps between PIMs and PSMs, it is easier to generate intermediate models rather than go straight to the target PSM. For example, when going from a class diagram to an EJB implementation, tools such as OptimalJ would generate an intermediate EJB component model, which contains all the necessary information to produce the actual Java code from it. This makes the transformations more modular and maintainable. Also, intermediate models may be needed for optimization and tuning, or at least for debugging purposes. In addition to PIM-to-PSM transformation, model-to-model transformations are useful for computing different views of a system model and synchronizing them.

3.2.1 Direct-Manipulation Approaches

These approaches offer an internal model representation plus some API to manipulate it. They are usually implemented as an object-oriented framework, which may also provide some minimal infrastructure to organize the transformations (e.g., abstract class for transformations). However, users have to implement transformation rules and scheduling mostly from scratch using a programming language such as Java. Examples of this approach include Jamda and implementing transformations directly against some MOF-compliant API (e.g., JMI).

3.2.2 Relational Approaches

This category groups declarative approaches where the main concept is mathematical relations (e.g., [AK02], [QVTP], [CDI], declarative approaches in [GLR+02], and mapping rules in [AST+]).

The basic idea is to state the source and target element type of a relation and specify it using constraints. In its pure form, such specification is non-executable (e.g., [AK02], relations in [QVTP], and mapping rules in [AST+]). However, declarative constraints can be given executable semantics, such as in logic programming. In fact, logic programming with its unification-based matching, search, and backtracking seems a natural choice to implement the relational approach, where predicates can be used to describe the relations. In [GLR+02], Gerber et al. explore the application of logic programming (in particular Mercury, a typed dialect of Prolog, and F-logic, an object-oriented logic paradigm) to implement transformations. The QVT proposal in [CDI] was inspired by the F-logic approach. The approach in [QVTP] distinguishes between relations, which in their framework are bi-directional, non-executable specifications of transformations, and mappings, which are executable, unidirectional transformations implementing relations.

All of the relational approaches are side-effect-free. They often support backtracking (e.g., [GRL+02] and [QVTP]) and, in contrast to the imperative direct manipulation approaches in Section 3.2.1, create target elements implicitly (e.g., [GRL+02] and [CDI]). Relational specifications (e.g. [AK02], relations in [QVTP], and mapping rules in [AST+]) can be interpreted bi-directionally. Logic-programming-based approaches also naturally support bi-directionality. But some approaches fix the direction for executable transformations (e.g. [CDI] and mappings in [QVTP]). Logic-programming-based approaches (e.g., [GRL+02] and [CDI]) require strict separation between source and target models, i.e., they do not allow in-place update.

3.2.3 Graph-Transformation-Based Approaches

This category of model transformation approaches draws on the theoretical work on graph transformations. In particular, these approaches operate on typed, attributed, labeled graphs [AEH+96], which is a kind of graphs specifically designed to represent UML-like models. Examples of graph-transformation approaches to model transformation include VIATRA, ATOM, GreAT, UMLX, and BOTL.

Graph transformation rules consist of a LHS graph pattern and a RHS graph pattern. The graph patterns can be rendered in the concrete syntax of their respective source or target language (e.g., in VIATRA) or in the MOF abstract syntax (e.g., in BOTL). The advantage of the concrete syntax is that it is more familiar to developers working with a given modeling language than the abstract syntax. Also, for complex languages like UML, patterns in a concrete syntax tend to be much more concise than patterns in the corresponding abstract syntax (see [MB03] for examples). On the other hand, it is easy to provide a default rendering for abstract syntax that will work for any metamodel, which is useful when no specialized concrete syntax is available.

The LHS pattern is matched in the model being transformed and replaced by the RHS pattern in place. The LHS often contains conditions in addition to the LHS pattern, e.g., negative conditions. Some additional logic (e.g., in string and numeric domains) is needed in order to compute target attribute values (such as element names). GreAT offers an extended form of patterns with multiplicities on edges and nodes. In most approaches, scheduling has an external form and the scheduling mechanisms include non-deterministic selection, explicit condition, and

iteration (including fixpoint iterations). Fixpoint iterations are particularly useful for computing transitive closures.

Similar to relational approaches, graph-transformation approaches are capable of expressing model transformation in a declarative manner. However, the provision of specialized facilities such as graph patterns and graph pattern matching differentiates graph-transformation approaches from the relational ones.

3.2.4 Structure-Driven Approaches

Approaches in this category have two distinct phases: the first phase is concerned with creating the hierarchical structure of the target model, whereas the second phase sets the attributes and references in the target. The overall framework determines the scheduling and application strategy; users are only concerned with providing the transformation rules.

An example of the structure-driven approach is the model-to-model transformation framework provided by OptimalJ. The framework is implemented in Java and provides so-called incremental copiers that users have to subclass to define their own transformation rules. The basic metaphor is the idea of copying model elements from the source to the target, which then can be adapted to achieve the desired transformation effect. The framework uses reflection to provide a declarative interface. A transformation rule is implemented as a method with an input parameter whose type determines the source type of the rule, and the method returns a Java object representing the class of the target model element. Rules are not allowed to have side effects and scheduling is completely determined by the framework.

Another structure-driven approach is [IOPT]. A special property of this approach is the target-oriented rule organization, where there is one rule per target element type and the nesting of the rules corresponds to the containment hierarchy in the target metamodel. The execution of this model can be viewed as a top-down configuration of the target model.

3.2.5 Hybrid Approaches

Hybrid approaches combine different techniques from the previous categories.

The Transformation Rule Language (TRL) [AST+] is a composition of declarative and imperative approaches. It could be also classified in the relational category, but we decided to classify it separately because of its stronger imperative component. Similar to [QVTP], it distinguishes between specification and implementation. A mapping rule in TRL declares a relationship between source and target elements that is constrained by a set of invariants. They are similar to relations in [QVTP] and fit into the relational category (Section 3.2.2). Operational rules in TRL represent executable transformation rules. In contrast to mapping rules, operational rules explicitly state whether a rule creates, updates, or deletes elements. Scheduling is explicit in internal form, where a rule explicitly calls other rules in its body. Rule inheritance is supported. Rules can be organized into modules (called *units*). Inheritance between modules (with overriding) is also supported.

The Atlas Transformation Language (ATL) [BDJR03] is also a hybrid approach, which has some similarities to TLR. A transformation rule in ATL may be fully declarative, hybrid, or fully imperative. The LHS of a fully declarative rule (so-called *source pattern*) consist of a set of syntactically typed variables with an optional OCL constraint as a filter or navigation logic. The RHS of a fully declarative rule (so-called *target pattern*) contains a set of variables and some declarative logic to bind the values of the attributes in the target elements. In a hybrid rule, the

source and/or target pattern are complemented with a block of imperative logic, which is run after the application of the target pattern. A fully imperative rule (so-called *procedure*) has a name, a set of formal parameters, and an imperative block, but no patterns. Rules are unidirectional and support rule inheritance. ATL strictly separates source and target models; however, in-place transformation can be simulated thanks to an automatic copy mechanism. ATL provides both implicit and explicit scheduling. The implicit scheduling algorithm starts with calling a rule that was designated as an entry point, which may call further rules. After completing this first phase, it automatically checks for matches on the source patterns and executes the corresponding rules. Finally, it executes a designated exit point. Explicit, internal scheduling is supported by the ability to call a rule from within the imperative block of another rule.

XDE is an example of a highly hybrid approach. XDE supports model-to-model transformation through its pattern mechanism. The original motivation for patterns in XDE was to provide automated application of The-Gang-of-Four design patterns [GHJV95]. Consequently, the basic concept of the XDE pattern mechanism is a parameterized collaboration, which is the UML mechanism to model design patterns. With general model-to-model transformations as a subsequent goal, the basic pattern mechanism evolved into a highly hybrid and rather complex approach. A pattern is represented as a package containing the parameterized collaboration and a number of other models that can be automatically customized and copied and/or merged into the target using imperative Java callouts. Upon pattern application, parameters can be bound interactively through a wizard, or they also can be bound automatically. The automatic selection of source elements may be achieved declaratively through OCL queries or trough imperative Java callouts. Repeated pattern application is supported through collection-typed parameters. Each pattern application gets recorded together with all its parameter bindings, and the record can be used to later reapply the pattern with the original parameter bindings. XDE does not put any constraints on the relationship between source and target, i.e., creation of a new target, in-place update, and update of another existing target model are possible. Scheduling is supported through pattern nesting. More sophisticated scheduling has to be programmed in Java. Patterns can be associated with JSP-like code templates (so-called *scriptlets*) in order to perform model-to-code transformation.

3.2.6 Other Model-To-Model Approaches

At least two more approaches should be mentioned for completeness: the transformation framework defined in the OMG's Common Warehouse Metamodel (CWM) Specification [CWM] and transformation implemented using XSLT [XSLT].

The CWM transformation framework provides a mechanism for linking source and target elements, but the derivation of the target elements has to be implemented in some concrete language, which is not prescribed by CWM. Effectively, CWM gives a general model, but no actual mechanism to implement model transformations.

Since models can be serialized as XML using the XML Metadata Interchange (XMI) [XMI], implementing model transformations using XSLT, which is a standard technology for transforming XML, seems very attractive. Unfortunately, this approach has severe scalability limitations. Manual implementation of model transformations in XSLT quickly leads to non-maintainable implementations because of the verbosity and poor readability of XMI and XSLT. A solution to overcome this problem is to generate the XSLT rules from some more declarative rule descriptions, as demonstrated in [PBG01, PZB00]. However, even this approach suffers from poor efficiency because of the copying required by the pass-by-value semantics of XSLT and the poor compactness of XMI.

4 Related Work

In their review of the different OMG QVT RFP submissions, Gardner et al. [GGKH03] propose a unified terminology to enable a comparison of the different proposals. Since their scope of comparison is considerably different from ours, there is not much overlap in terminology. While Gardner et al. focus on the 8 initial QVT submissions, we discuss a wider range of approaches: in addition to the revised QVT submissions, we also discuss other approaches published in the literature and available in tools. Another difference is that Gardner et al. discuss model queries, views, and transformations, whereas we focus on transformations in more detail. The terms defined in [GGKH03] that are also relevant for our classification are model transformation, unidirectional, bidirectional, declarative, imperative, and rules.

In addition to providing the basic unifying terminology, Gardner et al. discuss practical requirements on model transformations such as requirements scalability, simplicity, and ease of adoption. Among others, they discuss the need to handle transformation scenarios of different complexities, such as transformations with different origin relationships between source and target model elements (e.g., 1:1, 1:n, n:1, and n:m). Finally, they make some recommendations for the final QVT standard. In particular, they recommend a hybrid approach, supporting declarative specification of simpler transformations, but also allowing for an imperative implementation of more complex ones.

5 Discussion

Model transformation is a relatively young area. Although it is related to and builds upon the more established fields of program transformation and metaprogramming, the use of graphical modeling languages and the application of object-oriented metamodeling to language definition set a new context.

While there are satisfactory solutions for transforming models to text (such as template-based approaches), this is not the case for transforming models to models. Many new approaches to model-to-model transformation have been proposed over the last two years, but little experience is available to assess their effectiveness in practical applications. In this respect, we are still at the stage of exploring possibilities and eliciting requirements. Modeling tools available on the market are just starting to offer some model-to-model transformation capabilities, but these are still very limited and often ad hoc, i.e., without proper theoretical foundation. Most of these tools target the generation of EJB applications and the model transformations they offer were specifically developed to support that goal.

In this paper, we classified the existing model-to-model transformation approaches into direct manipulation approaches, relational approaches, graph-transformation-based approaches, structure-driven approaches, and hybrid approaches. In the remainder of this section, we offer some comments on the practical applicability of the different flavors of model transformation. These comments are based on our intuition and the application examples published together with the approaches. Because of the lack of controlled experiments and extensive practical experience, these comments are not fully validated, but we hope that they will stimulate discussion and further evaluation.

- Direct manipulation is obviously the most low-level approach. It offers the user little or no support or guidance in implementing transformations. Basically all work has to be done by the user. In the long run, this approach will become impractical.

- The structure-driven category groups pragmatic approaches that were developed in the context of (and seem particularly well applicable to) certain kinds of applications such as generating EJB implementations and database schemas from UML models. These applications require a strong support for transforming models with a 1-to-1 and 1-to-n (and sometimes n-to-1) correspondence between source and target elements. Also, in this application context, there is typically no need for iteration (and in particular fixpointing) in scheduling, and the scheduling can be system-defined. It is unclear how well these approaches can support other kinds of applications.
- Graph-transformation-based approaches are inspired by heavily theoretical work in graph transformations. These approaches are powerful and declarative, but also the most complex ones. The complexity stems from the non-determinism in scheduling and application strategy, which requires careful consideration of termination of the transformation process and the rule application ordering (including the property of confluence). There is a large amount of theoretical work and some experience with research prototypes. However, experience with practical applications of these approaches is still limited. It remains to be seen how well the complexities of these approaches will be received in practice.
- Relational approaches seem to strike a well balance between flexibility and declarative expression. They provide flexible scheduling and good control of non-determinism. Three of the five current QVT submissions fit into this category ([CDI], [QVTP], and partly [AST+]).
- Hybrid approaches allow the user to mix and match different concepts and paradigms depending on the application. Practical approaches are very likely to have the hybrid character.

Evaluation of the different design options for a model transformation approach will require more experiments and practical experience. Establishing of a comprehensive collection of benchmark problems would be a valuable next step in that direction.

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