

Towards Systematic Mutations for and with ATL Model Transformations^{*}

Patrick Sommer¹ and Carola Gabriel² and Martin Keiblinger³

¹ Mautner Markhof-Gasse 58/4/31, 1110 Wien
`e0925011@student.tuwien.ac.at`
MatrNr.: 0925011

² Leberweg 14/3/16, 1110 Wien
`e0825992@student.tuwien.ac.at`
MatrNr.: 0825992

³ Mustergasse 54/4/3, 1030 Wien
`matthias@tuwien.ac.at`
MatrNr.: 0426553

Abstract. Faults in model transformations will produce faults in models. The correction of the defective models is often very expensive. This result affects the quality of the end product. This is why model transformations has to be correctly tested to maintain product quality. For this mutation testing is a popular technique. The mutation testing of model transformations have to be developed and for this a suite of mutation operators for the Atlas Transformation language (ATL) is needed. In this paper a set of mutation operators are implemented and the solutions of the implementations are discussed and evaluated regarding effectiveness.

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1 Introduction

Model transformation allows to synthesize software artifacts from model definitions and ease other software engineering tasks by automating them.

This abstraction eases incremental processes like: [16]

- Reverse engineering models e.g. in the process of replacing a legacy system. The resulting artifact can be tested and if results of the legacy and the new system are found only the model has to be changed.
- Refactoring models
- et cetera

Therefore the quality of the overall software solution is determined by the quality of the models and the resulting model transformations. [7] As a consequence testing the transformations for correctness is an essential part to achieve the best possible quality of the software. [19]

To check the quality of a software it has to be tested. Software testing is a process, or a series of engineered processes to check if a program does what it is designed for and that it does not do anything unintended. [12] Model based testing (MBT) is a variant of this software testing process. Test cases are not written by the programmer directly. The programmer only creates a model of the requirements and in a second step the test cases are generated based on this model. [20]

Mutation testing or mutation analysis is a fault-based testing technique. It applies changes to the input model and creates a mutant. Every mutant represents a faulty program. In the best case these changes, which are applied by the mutator, represent mistakes a programmer would make. It has been proven that mutation testing is useful as testing approach but also as: [8]

1. Generate input models as test data.
2. Generate mutants of model transformations.

1.1 Problem

To make mutation testing an effective testing method a complete set of mutation operators and a large number of mutated model transformations has to exist. Due to the needed size of these sets it's too expensive to create them manually. Also the execution of the different models against the test data is very time-consuming.

Therefore automation is required for:

1. generation of a set of mutation operators.
2. generation of mutated model transformations.

Furthermore, the computational costs of the executions have to be lowered.

1.2 Contribution

Troya et. al. contributed three aspects.

1. They have defined a general languagecentric synthesis approach by defining a set of mutation operators based on ATL.
2. They made a concept and build a first version of a framework utilizing Higher order transformations for generating mutants. [18]
3. They integrated techniques [1] for incremental model transformation execution in their framework.

We contribute further implementations of mutation operators and small tests.

2 Background

2.1 Model transformation in MDE

This work is focused on mutation testing for model transformations. The basic idea of mutation testing in software engineering is not to test the resulting software itself but the test cases.

Good test cases should be able to identify mutants. In the jargon of mutation testing the mutations are *killed*. Killing means recognizing differing results of the original system under test (SUT) and tested mutants. [11]

The process of mutation testing consists of four components:

- *Test data* as input for the original program P and its mutants.
- The original program P
- The *mutants* of P .
- An *oracle* which is able to decide if results differ and which is therefore able to identify mutants.

The goal of the process?? is to *kill* or identify faulty versions of the original program. If a mutant outputs the same data for the same input data as the original program it's called *equivalent*. In this case this mutant has to be removed from the set of mutants under test.

The last step is to assess how good the tests are and check if they should be improved. Assume KM is the set of the killed mutants, M is the set of all mutants and EM is the set of all identified, equivalent mutants then the mutation score MS is calculated like this: [8]

$$MS = \frac{|KM|}{|M| - |EM|} \quad (1)$$

If this value is too small the tests have to be improved.

The success of this method depends on the set of mutants used in the process. Manual creation of mutants is a tedious and time consuming task. Therefore a quick, reliable and efficient creation of mutants is proposed in [19].

Troya et al. build upon ATL and higher order transformations (HOT) to create transformations to automatically generate mutants.

This report shows which additional transformations have been developed and what their goals are. The scope of this work is the mutation generation in the whole process.

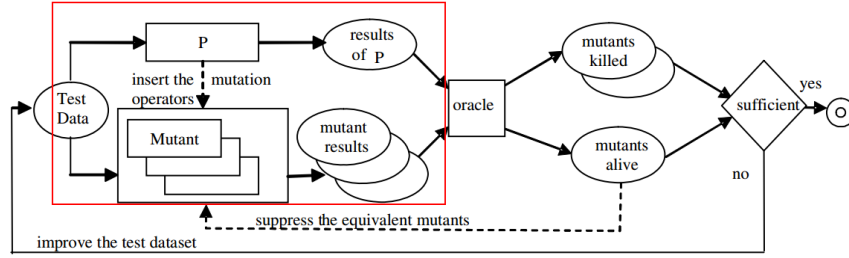


Fig. 1. The mutation testing workflow contains a feedback loop. The red marked area is the part this paper contributes to. [11]

Model transformations plays an important role in the Model Driven Engineering (MDE) approach. Developing model transformation definitions is expected to become a common task in model driven software development. [4] In this part of the paper we want to explain the basics of the requirements we needed for mutations for and with ATL Model Transformations.

2.2 Mutation Testing

Speaking in broader terms, model transformation is the process of synthesizing one or more models from one or more input models. To successfully generate output-models it needs a clear understanding of the syntax and the semantic of these models and the relationship between their different entities. Model driven engineering provides a formal framework to define this prerequisites. [16]

At the highest level two main categories of model transformations exist: [3]

1. Model to model transformations
2. Model to code transformations

Model to code transformations take models as input and generate source code as output. There exists two different approaches to synthesize the generated source code. On the one side there is the visitor based approach, which is driven by a model traverse engine which outputs code artifacts when it visits specific points in the model hierarchy. The other approach is the template based approach. Therefore a template consists of constant text and parts which dynamically generates text from the input model. The dynamically part expands iteratively. [3]

For model to model transformations there exist multiple strategies:

- The *Direct-manipulation approach* offers an internal model representation and tools to manipulate it.
- The *relational approach* uses relations, in the sense of the mathematical concept, and mapping rules. In combination with a declarative logic for defining constraints, this is used to produce executable transformations.
- The *graph-transformation-based approach* utilizes graph theory. It models entities as nodes and edges in the graph to define model transformations.
- The *structure-driven approach* provides the user with a framework to operate on a hierarchy to copy objects and their attributes.
- The *hybrid approach* is the combination of two or more of the above mentioned concepts.

ATL ATL is a model transformation language containing a mixture of declarative and imperative constructs. ATL is applied in the context of the transformation pattern shown in figure 2. In this pattern a source model Ma is transformed into a target model Mb according to a transformation definition `mma2mmb.atl` written in the ATL language. This transformation definition is a model conforming to the ATL metamodel. All metamodels conform to the MOF.

ATL is a hybrid transformation language. It is encouraged to use a declarative style of specifying transformations. The declarative style of transformation specification has a number of advantages: it is usually based on specifying relations between source and target patterns and thus tends to be closer to the way the developers intuitively perceive a transformation. This style stresses on encoding these relations and hides the details related to selection of source elements, rule triggering and ordering, dealing with traceability, etc. Therefore, it can hide complex transformation algorithms behind a simple syntax. [4]

The class metamodel is used by ATL transformations 1.1 shown in figure 4 [4]

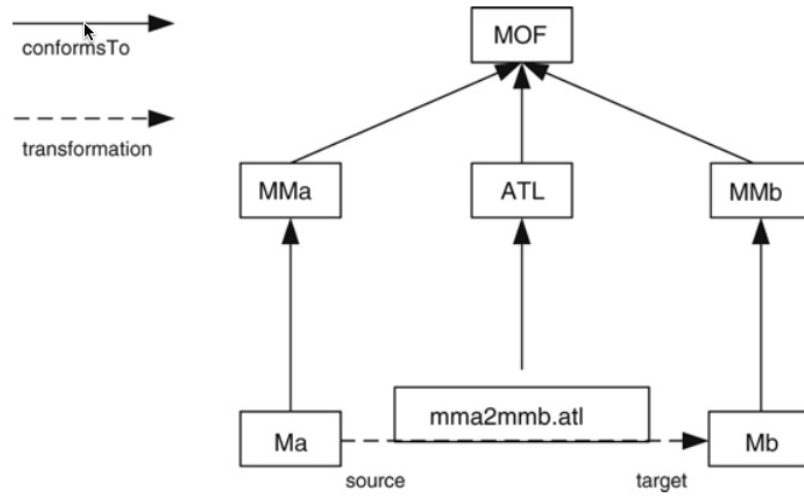


Fig. 2. Overview of the ATL transformational approach
[4]

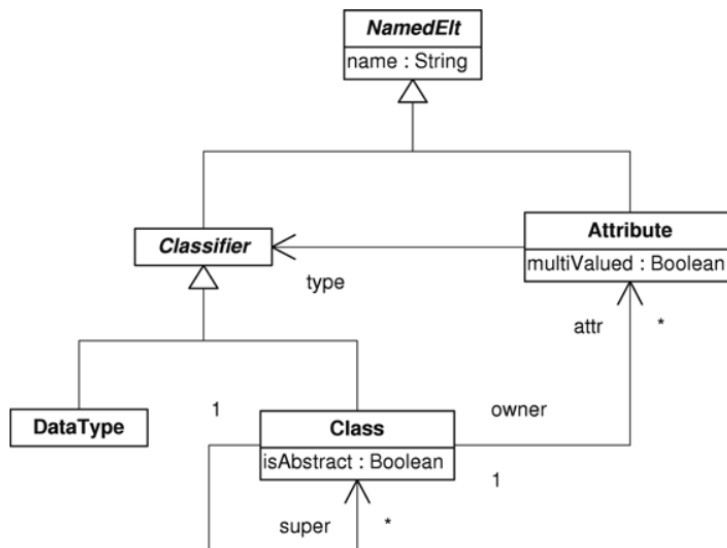


Fig. 3. Class metamodel
[4]

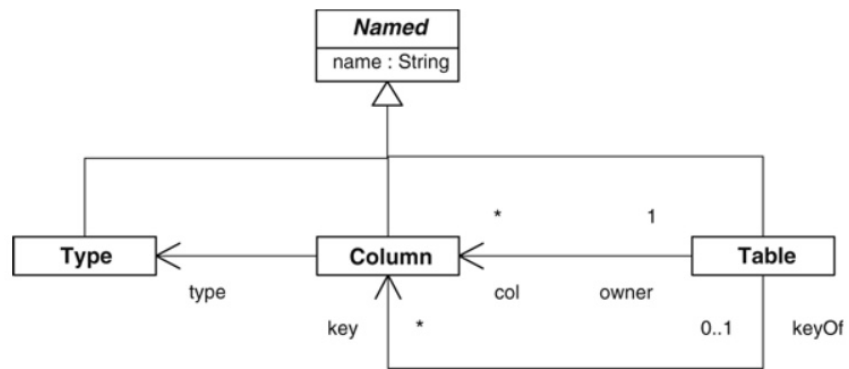


Fig. 4. Relational metamodel
[4]

In this part we want to create a transformation program for a general example that transforms simple class models to relational models. The source and the target model are presented in figure 3 and figure 4.

Listing 1.1. Simple example for a ATL transformation

```

1 //Start Program
2 module Class2Relational;
3 create OUT : Relational from IN : Class;
4
5 rule Class2Table {
6     from
7         c : Class!Class
8     to
9         out : Relational!Table (
10             name <- c.name
11         )
12 }
13 //End Program

```

The source model is the 'IN' model and the target model is 'OUT'. The rule maps the element EntityModel to FormModel.

Higher Order Transformations Higher order transformations are defined as model transformations where the input and/or the output models are transformation models themselves. [17]

Figure 5 shows a sample schema of a higher order transformation for transformation modification in ATL where you can see a good overview for the model transformation with transformation models as input and output models.

[9]

Therefore a transformation model can be:

- The input model of a higher order transformation
- The output model of a higher order transformation
- Both, the input and the output model

Tisi et. al [17] identified four transformation patterns for Higher order transformations:

- **Transformation Synthesis** These Higher order transformations generate transformations. If any input is used it is not a transformation.
- **Transformation Analysis** takes transformations as input and generates data of different types as output. The output is never a transformation.
- **Transformation (De)composition** is the integration of multiple transformations of the input and/or integration of transformations as output.
- **Transformation Modification** is defined by modifying an input transformation and generating an output transformation.

The focus of this work is on *Transformation Modifications* (short TM).

Another possibility of a Higher order transformation is a *second Higher order transformation*. That means that a Higher order transformation will also be the input/output of another transformation.

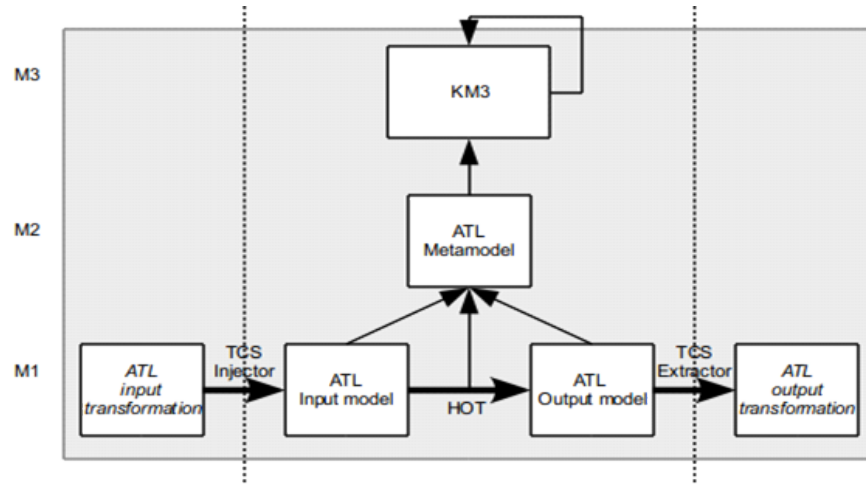


Fig. 5. Sample schema of a Higher Order Transformations for transformation modification in ATL

[9]

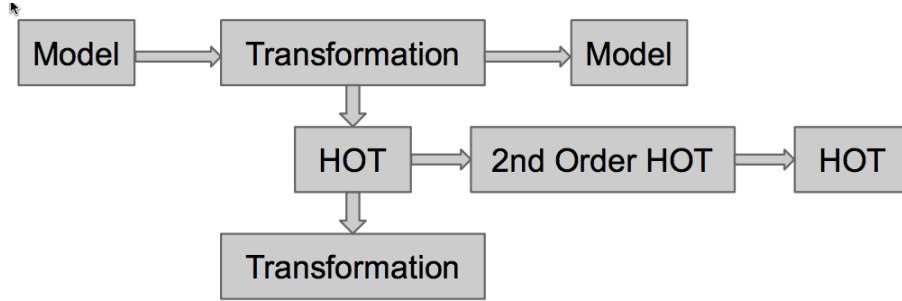


Fig. 6. Sample schema of a Second Higher Order Transformation

2.3 Mutations in Model Transformations

In order to identify the possibilities of mutations in languages we need to know about the concepts of the languages which can be mutated. This mutation possibilities are presented in the referenced paper [19]. For a better overview the following table shows the possible mutations for ATL transformations.

Concept	Mutation Operator	Consequence
Matched Rule	Addition Deletion Name Change	OA;[RA] OD;[RD]
In Pattern Element	Addition Deletion Class Change Name Change	OA;[RA] OD;[RA] OD,OA;[RD];[RA]
Filter	Addition Deletion Condition Change	OD OA OA;OD
Out Pattern Element	Addition Deletion Class Change Name Change	OA;[RA] OD;[RD] OR;[RA];[RD]
Binding	Addition Deletion Value Change Feature Change	OP;[RA] OPN;[RD] OPM;[RA];[RO]

Table 1. Mutations identified for ATL transformations [1]

In the column *Consequences* of table 1 there are some notices about the consequences of a mutation. In the referenced paper [19] the consequences are described as follows: When a transformation is mutated, it has an effect on the output model that is generated for the same input model as with the original transformation.

There can be completely new objects that were not present before (OA: Object Addition), some objects can be deleted (OD: Object Deletion), some can be replaced (OR: Object Replacement) and other objects can be modified. They are labeled as OPI: Object Property Initialized or OPN: Object Property set to Null. That means that a property of an object is initialized or set to null. Another possibility is to modify only the value of objects property (OPM: Object Property Modified). For OR: Object Replacement it is important to know that Object Replacement can also be seen as the deletion and addition of an object. Relationships between objects can also be added (RA: Relationship Added) or deleted (RD: Relationship Deleted). [19]

For our implemented solutions the consequences OPI: Object Property Initialized, OPN: Object Property set to Null, OPM: Object Property Modified, OA: Object Addition, OR: Object Replacement and OD: Object Deletion are important. In case of relationships we have to know that the modification of an object implies automatically the modifications of relationships and that is why also RA: Relationship Added or RD: Relationship Deleted are important for our implemented solutions.

3 Mutations implemented

The overall goal of this work is to implement seven transformations. The following table shows the definition of these goals and the current implementation status.

Nr.	Concept	Mutation operator	Status
1	Binding	Value change	Done
2	Binding	Value change	Done
3	Binding	Addition	
4	Binding	Deletion	Done
5	Out pattern element	Class change	
6	Out pattern element	Addition	
7	In pattern element	Deletion	Done
8	In pattern element	Class change	

Table 2. The implementation goals

3.1 Implemented binding mutations

To understand how the binding mutations work you need to know, that there are two types of bindings in the ATL metamodel:

- Primitive Expressions
- Variable Expressions

The primitive expressions, like String- or IntegerExpressions, are directly assignable in the ATL rules. Variable expressions have to be composed from the available objects in the metamodel. (See figure 7)

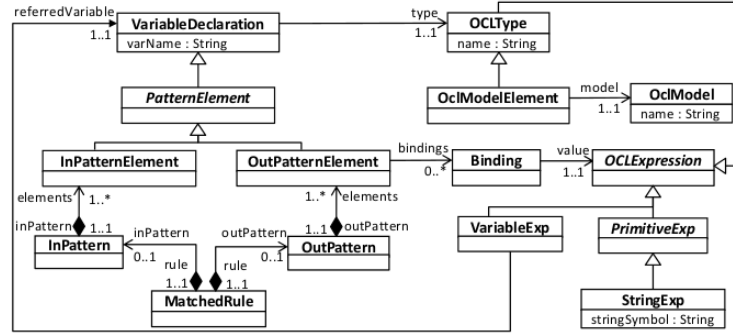


Fig. 7. Excerpt of the ATL metamodel

Bindings are used for the initialization of either *attributes* or *references*. Attributes are primitive values whereas references are relations to other models (variable expressions). Mutation 1 and 2 in table 2 are attribute binding mutations. 3 is a reference binding mutation.

Deletion Deleting a binding is the implicitly omitting of an attribute or reference assignment in the *to*-part of the ATL rule. The example in listing 1.2 demonstrates the simple structure of delete bindings.

Listing 1.2. Definition of Delete-Binding.

```
1 rule DeleteBinding{
2   from b: ATL!Binding
3   to
4 }
```

Addition The addition of a binding is the introduction of a new assignment in the *OutPatternElement*. This does not work for an arbitrary type as there are type constraints of the metamodel of the *OutPatternElement*.

Therefore the rule has to implement a type lookup to take the set of possible properties of a specific type into account. This is not possible in the HOT because the type information of the specific metamodels are missing.

Troya et al proposed in their paper [1] second order HOTs which are applied to the first order HOTs. The result of the first order HOTs transformations contain type information which is available in the second order HOTs.

This results is a two pass transformation:

1. Add a binding with a dummy name. (e.g. *NewBindingPropertyName*)
2. Lookup available bindings and replace the dummy name with an actual available one.

Additionally the rule has to take care to prevent the same *OutPatternElement* to be transformed more than once by filtering out entities which already contain the dummy binding.

This proposed algorithm is showed by listing 1.3

Listing 1.3. AddBinding-Definition

```
1 rule AddBinding{
2   from
3     ope : ATL!OutPatternElement (
4       ope.bindings -> forall( b | b.propertyName <> 'NewBindingPropertyName'
5       )
6     to
7     ope2 : ATL!OutPatternElement (
8       bindings <- ope.bindings -> append(bindingNewElement)
9     ),
10    bindingNewElement : ATL!Binding (
11      outPatternElement <- ope2,
12      propertyName <- 'NewBindingPropertyName',
13      value <- newValue
14    ),
15    newValue : ATL!StringExp (
16      stringSymbol <- 'testvalue'
17    )
18 }
```

The second order HOT does a lookup for a general supertype in the meta-model. In listing 1.4 the rule chooses an attribute, called *EStructuralFeature*, which is added to all subtypes.

Listing 1.4. AddBindingNames-Definition.

```
1 rule AddBindingNames {
```

```

2 from b : ATL!StringExp (
3   b.stringSymbol = 'NewBindingPropertyName'
4 )
5 using{
6   classes : Sequence(OUT_MM!EClass)
7   = OUT_MM!EClass.allInstancesFrom('OUT_MM')
8   -> select(c | c.getESuperTypes() -> size() <= 0);
9 }
10 to b2 : ATL!StringExp (
11   stringSymbol <- classes
12   -> first().getEStructuralFeatures() -> last().name
13 )
14 }

```

Detailed description of adding binding reference: For example there exists a simple meta model like shown in figure 8.

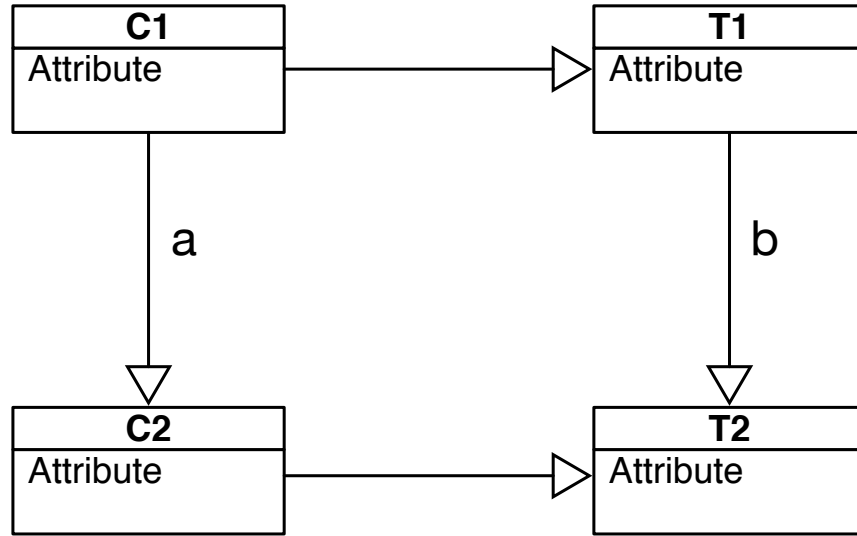


Fig. 8. Example of a simple metamodel

For the next step we want create a new binding with a reference (for example: `b1- c1.a`). First we have to search a reference from the model. For this reference it is important that there is no binding in the original transformation. Furthermore we have to store the attributes `propertyName` ('b') and `EType` ('Type2'). Then we have to search a rule from the original transformation which has as a first `OutPatternElement` one with the 'Type2' and next we have to store the type of the corresponding `InPatternElement` which is 'Class2'. For the next step we need a reference from the input metamodel which has type `Class2` and store its name ('a').

For the first implementation of the program it was not implemented to use the original transformation as input of the second order HOT. For this reason we couldn't search for a rule with the corresponding OPE in the second order HOT, but only in the first order HOT. But in the context of the first order HOT there is no access to the class names and attributes of the input and output model ('Type1', 'Type2', 'Class1', 'Class2'). For this missing link an adaption of Main.java (Line 69-77) was necessary. So the possibility to add another input model - the original transformation (AddBindingReference.atl) - was created (see listing 1.5).

Listing 1.5. Adaption of Main.java.

```

1  /** The SecondOrderHOT takes as input, one by one, each of the generic
2     HOTs (together with the input and
3     * output metamodels of the transformation we want to mutate) and
4     generates one specific mutation for each of the generic ones
5     .
6     * Since the generic HOTs (that serve as input) are rewritten by
7     the in-place SecondOrderHOT, we first copy them
8     * into the folder HOTs/specific
9     */
10 for (String hot : HOTsGenericMutations){
11     copyFile(HOTs + "temp/" + hot + ".xmi", HOTs + "specific/" +
12             hot + ".xmi");
13     TransfoRunnerEMFTVM tr = new TransfoRunnerEMFTVM();
14     tr.runTransformation(HOTs + "specific/" + hot + ".xmi", "ATL",
15                         transformation + "temp/" + trans2Mutate + ".xmi", "
16                             IN_ATL",
17                         transformation + inputMM, "IN_MM",
18                         transformation + outputMM, "OUT_MM",
19                         HOTs, "SecondOrderHOT"); //path name plus module name
20     of the transformation
21 }

```

Furthermore an adaption of TransfoRunnerEMFTVM.java and second order higher transformation (line 4: IN_ATL:IN_ATL was added) was necessary.

In the figure 9 you can see the original implementation of the program and as part b in the figure we see the missing reference which had to be added.

Value change The simplest value change mutation is changing a primitive expression like a StringExp. The example in listing 1.6 demonstrates how to change a primitive string expression to a constant ("Hello").

This is achieved by looking up all bindings with the *ATL!StringExp* type. The next step is to set it to the constant.

Listing 1.6. ValueChangeBinding-Definition.

```

1 rule ValueChangeBinding_All{
2     from
3         b : ATL!Binding (b.value.oclIsTypeOf(ATL!StringExp))
4     to
5         c : ATL!Binding (
6             value <- newStringExp
7         ),
8         newStringExp : ATL!StringExp(
9             stringSymbol <- 'hello'
10        )
11 }

```


Original implementation

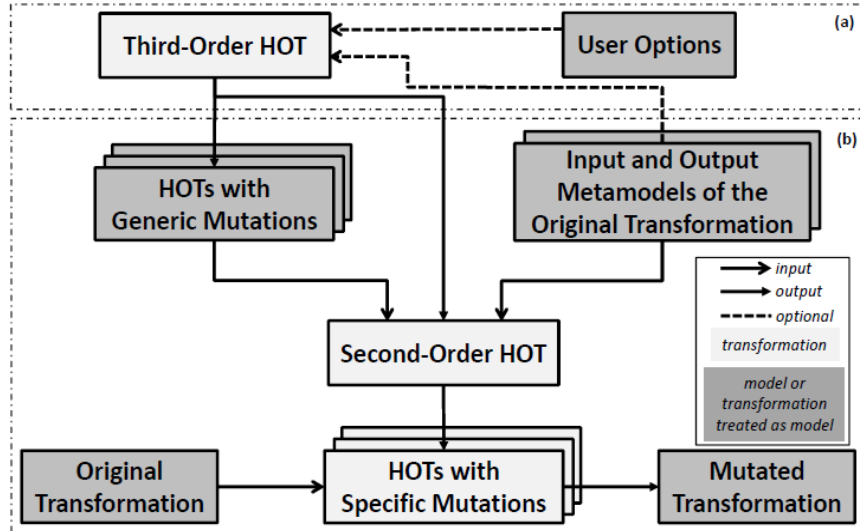


Figure shows the missing reference

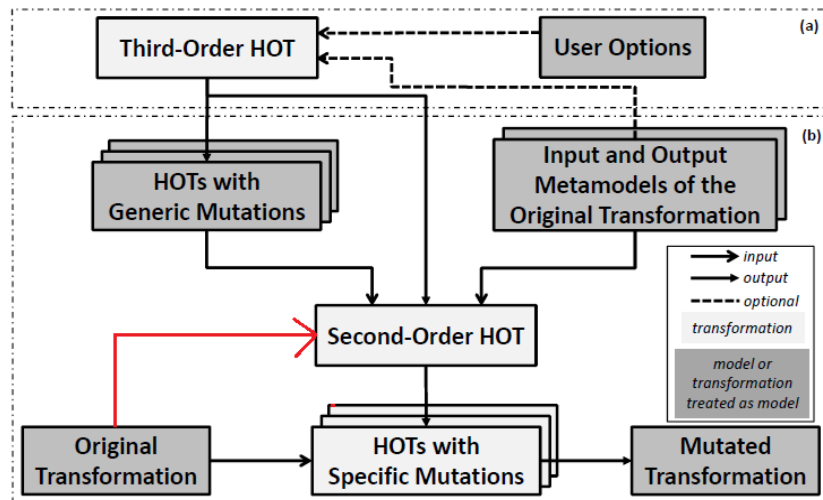


Fig. 9. AddBindingReference

A simple extension of the constant value change algorithm is to change the constant to a value of the actual model. The example in listing 1.7 changes all string expressions to the first string value of the input model. In case there's no string expression the element is ignored.

Listing 1.7. ValueChangeBinding-Definition using same constant string value.

```

1 rule ValueChangeBinding_AllSameStringValue{
2   from
3     b : ATL!Binding(
4       b.value.oclIsTypeOf(ATL!StringExp) and
5       ATL!StringExp.allInstances() -> size() > 1
6     )
7   to
8     c : ATL!Binding(
9       value <- stringexpression
10    ),
11    stringexpression : ATL!StringExp(
12      stringSymbol <- (ATL!StringExp.allInstances()
13        -> first()).stringSymbol
14    )

```

The third approach in this category was to switch the first with the last value binding. For this we first filter only the OutPatternElements which have more than one binding and have only StringExpression bindings.

As a second step we exclude the first and the last binding from the binding-list to replace them with our new bindings with the prepend and append commands. As a third step we have to create our new binding-elements.

Such a binding element needs three values: the corresponding OutPatternElement, the property name and the value.

As outPatternElement and propertyName we take the original outPatternElement and propertyName, as value, we take the value from the last binding for our new first element and the value from the first binding for our new last element.

Important to achieve correct values is, that we use the original binding list from the "from"-clause of the rule.

Listing 1.8. ValueChangeBinding-Definition using values from input models.

```

1 rule ValueChangeBinding_Switch{
2   from
3     ope : ATL!OutPatternElement (
4       ope.bindings
5       -> forAll(e | e.value.oclIsTypeOf(ATL!StringExp)) and
6       ope.bindings -> size() > 1
7     )
8   to
9     ope2 : ATL!OutPatternElement (
10      bindings <- ope.bindings -> excluding (ope.bindings -> first())
11      -> excluding (ope.bindings -> last())
12      -> prepend (bindingNewFirst)
13      -> append (bindingNewLast)
14    ),
15    bindingNewLast : ATL!Binding (
16      outPatternElement <- ope2,
17      propertyName <- (ope.bindings -> last()).propertyName,
18      value <- (ope.bindings -> first()).value
19    ),
20    bindingNewFirst : ATL!Binding (

```

```

21     outPatternElement <- ope2,
22     propertyName <- (ope.bindings -> first()).propertyName,
23     value <- (ope.bindings -> last()).value
24 )
25
26 }

```

3.2 Implemented InPatternElement mutations

Deletion The deletion of an InPatternElement requires the handling of its usage in OutPatternElement bindings.

To delete an InPatternElement (IPE) it is not enough to delete only the InPatternElement itself. You have to deal at least with one important effect. The usage of this InPatternElement in the bindings of the OutPatternElements. E.g. the rule *PNMLDocument* in listing 3.2 contains the IPE *e*. If it is deleted the usage *e* in the OutPatternElement has to be handled.

```

1 rule PNMLDocument {
2   from
3     e : PetriNet!PetriNet,
4     f : PetriNet!PetriNet
5   to
6     n : PNML!PNMLDocument
7     (
8       location <- e.location,
9       xmlns <- uri,
10      nets <- net
11    )

```

Listing 3.2 shows what would happen if the OutPatternElement isn't changed too.

```

1 rule PNMLDocument {
2   from
3     f : PetriNet!PetriNet
4   to
5     n : PNML!PNMLDocument
6     (
7       location <- .location,
8       xmlns <- uri,
9       nets <- net
10    )

```

In case the IPE is deleted the corresponding binding will contain an un-referred variable. This would void the generated model. To prevent this from happening all un-referred variable bindings have to be deleted in a second step in the HOT.

A possible implementation of an IPE is shown in listing 3.2.

```

1 rule DeleteIPE {
2   from ipe : ATL!InPatternElement (
3     ipe.inPattern.elements -> size() > 1 and
4     ipe = ipe.inPattern.elements -> last()
5   )

```

Listing 3.2 shows another binding deletion.

```

1 rule DeleteNavigationBinding{
2   from b : ATL!Binding(
3     b.value.ocIsTypeOf(ATL!NavigationOrAttributeCallExp) and
4     b.value.source.referredVariable.ocIsUndefined()
5   )
6   to
7 }
8 rule DeleteCollectionBinding{
9   from b:ATL!Binding(
10    b.value.ocIsTypeOf(ATL!CollectionOperationCallExp) and
11    b.value.source.ocIsTypeOf(ATL!NavigationOrAttributeCallExp) and
12    b.value.source.source.referredVariable.ocIsUndefined()
13  )
14  to
15 }

```

To delete really all of the occurrences of the IPE it is necessary to delete not only the simple binding itself, also more complex occurrences like in navigation expression (ATL!NavigationOrAttributeCallExp) or collection Expressions (ATL!CollectionOperationCallExp). As these complex expressions can be encapsulated it is necessary to do this deletion in some kind of recursion to cover really all occurrences.

4 Related work

In the related work [19] the authors has identified the mutations for ATL transformation language as in chapter *Mutations in Model Transformations* described. We have implemented a set of possible mutations in ATL they have identified. For the general part of the paper we read some other papers with different approaches. In another referenced work [22] the authors has researched how it is possible to support mutation testing in the atlas transformation language. The authors has defined a set of mutation operators. This operators are:

- Matched to Lazy (M2L)
- Lazy to Matched (L2M)
- Delete Attribute Mapping (DAM)
- Add Attribute Mapping (AAM)
- Delete Filtering Expression (DFE)
- Add Filtering Expression (AFE)
- Change Source Type (CST)
- Change Target Type (CTT)
- Delete Return Statement (DRS)
- Delete Use Statement (DUS)
- Change Execution Mode (CEM)

The authors approach has been validated and the results have shown that their defined operators successfully detected insufficiency in the test suite.

5 Conclusion and future work

The broader goal of this work is to create an introduction to a specific field of model driven engineering (MDE). Integral part of MDE is model transformation. [16]. In this paper we have implemented some solutions regarding mutations in ATL. The implementation of a set of mutation operators is discussed and evaluated regarding effectiveness. We have selected some mutations in ATL like Binding (Addition, Deletion and Change), In Pattern Element (Addition, Class change) and Out Pattern Element (Deletion, Class change). In the paper we have explain the effect of the mutations of transformations and we see that there are many consequences. The approach presented in this paper aims at mutation of model transformations for building trust into model transformation programs using this technique. Further work will consist in development of tools for automated mutations of model transformations. First only for ATL and second for other model transformation languages for example like QVT.

References

1. BERGMAYR, A., TROYA, J., AND WIMMER, M. From out-place transformation evolution to in-place model patching. In *Proceedings of the 29th ACM/IEEE International Conference on Automated Software Engineering* (New York, NY, USA, 2014), ASE '14, ACM, pp. 647–652.
2. BUSINESS INFORMATICS GROUP. <http://www.big.tuwien.ac.at>. Accessed: 2010-11-09.
3. CZARNECKI, K., AND HELSEN, S. Classification of model transformation approaches. In *2nd OOPSLA'03 Workshop on Generative Techniques in the Context of MDA* (Anaheim, CA, USA, 2003).
4. FRÉDÉRIC JOUAULT, FREDDY ALLILAIRE, J. B., AND KURTEV, I. Atl: A model transformation tool. *Software Engineering Group* 37, 5 (Aug 2007), 31–39.
5. HITZ, M., KAPPEL, G., KAPSAMMER, E., AND RETSCHITZEGGER, W. *UML @ Work, Objektorientierte Modellierung mit UML 2*, 3. ed. dpunkt.verlag, 2005 (in German).
6. HUEMER, C., LIEGL, P., SCHUSTER, R., AND ZAPLETAL, M. B2B Services: Worksheet-Driven Development of Modeling Artifacts and Code. *Computer Journal* 52, 2 (2009), 28–67.
7. HUTCHINSON, J., ROUNCEFIELD, M., AND WHITTLE, J. Model-driven engineering practices in industry. In *Proceedings of the 33rd International Conference on Software Engineering* (New York, NY, USA, 2011), ICSE '11, ACM, pp. 633–642.
8. JIA, Y., AND HARMAN, M. An analysis and survey of the development of mutation testing. *Software Engineering, IEEE Transactions on* 37, 5 (Sept 2011), 649–678.
9. JORDI CABOT. <http://modeling-languages.com/introducing-higher-order-transformations-hots/>. Accessed: 2015-04-15.
10. LANGER, P. Konflikterkennung in der Modellversionierung. Master's thesis, Vienna University of Technology, 2009.
11. MOTTU, J.-M., BAUDRY, B., AND LE TRAON, Y. Mutation analysis testing for model transformations. In *Proceedings of the Second European Conference on Model Driven Architecture: Foundations and Applications* (Berlin, Heidelberg, 2006), ECMDA-FA'06, Springer-Verlag, pp. 376–390.

12. MYERS, G. J., AND SANDLER, C. *The Art of Software Testing*. John Wiley & Sons, 2004.
13. OASIS. *Business Process Execution Language 2.0 (WS-BPEL 2.0)*, 2007.
14. SCHAUERHUBER, A., WIMMER, M., SCHWINGER, W., KAPSAMMER, E., AND RETSCHITZEGGER, W. Aspect-Oriented Modeling of Ubiquitous Web Applications: The aspectWebML Approach. In *Proceedings of the 14th Annual IEEE International Conference and Workshops on the Engineering of Computer-Based Systems (ECBS '07), March 26-29, Tucson, Arizona, USA* (2007), IEEE CS Press, pp. 569–576.
15. SCHWINGER, W., AND KOCH, N. Modeling Web Applications. In *Web Engineering*, G. Kappel, B. Pröll, S. Reich, and W. Retschitzegger, Eds. John Wiley & Sons, Ltd, 2006, pp. 39–64.
16. SENDALL, S., AND KOZACZYNSKI, W. Model transformation: The heart and soul of model-driven software development. *IEEE Softw.* 20, 5 (Sept. 2003), 42–45.
17. TISI, M., JOUAULT, F., FRATERNALI, P., CERI, S., AND BÉZIVIN, J. On the use of higher-order model transformations. In *Proceedings of the 5th European Conference on Model Driven Architecture - Foundations and Applications* (Berlin, Heidelberg, 2009), ECMDA-FA '09, Springer-Verlag, pp. 18–33.
18. TISI, M., JOUAULT, F., FRATERNALI, P., CERI, S., AND BZIVIN, J. On the use of higher-order model transformations. In *Model Driven Architecture - Foundations and Applications*, R. Paige, A. Hartman, and A. Rensink, Eds., vol. 5562 of *Lecture Notes in Computer Science*. Springer Berlin Heidelberg, 2009, pp. 18–33.
19. TROYA, J., BERGMAYR, A., BURGUEO, L., AND WIMMER, M. Towards systematic mutations for and with atl. In *Proc. of the Eighth IEEE International Conference on Software Testing, Verification and Validation Workshops (ICSTW); 10th International Workshop on Mutation Analysis (Mutation 2015)* (2015).
20. UTTING, M., PRETSCHNER, A., AND LEGEARD, B. A taxonomy of model-based testing approaches. *Softw. Test. Verif. Reliab.* 22, 5 (Aug. 2012), 297–312.
21. WIMMER, M. *From Mining to Mapping and Roundtrip Transformations - A Systematic Approach to Model-based Tool Integration*. PhD thesis, Vienna University of Technology, 2008.
22. YASSER KHAN, J. H. *Applying Mutation Testing to ATL Specifications: An Experimental Case Study*. IARIA, 2013.