Testing model transformation programs using metamorphic testing

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Keywords

Metamorphic Testing, Model Transformation, Software Quality, Software Testing, Test Oracle

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Testing Model Transformation Programs using Metamorphic Testing *

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Abstract

Model transformations are crucial for the success of Model Driven Engineering. Testing is a prevailing technique of verifying the correctness of model transformation programs. A major challenge in model transformation testing is the oracle problem, which refers to the difficulty or high cost in determining the correctness of the output models. Metamorphic Testing alleviates the oracle problem by making use of the relationships among the inputs and outputs of multiple executions of the target function. This paper investigates the effectiveness and feasibility of metamorphic testing in testing model transformation programs. Empirical results show that metamorphic testing is an effective testing method for model transformation programs.

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1. Introduction

Model transformation, which refers to the automatic process of transforming one model into another, is a vital element of Model Driven Engineering (MDE). In MDE, model transformations are usually used to transform models between different languages or different abstraction levels. In this way, models are automatically transformed and refined until code of final software is produced. The success of MDE critically depends on the correctness of model transformation programs as an incorrect transformation will result in incorrect models and the final software.

Testing is a prevailing technique of verifying the correctness of model transformation programs. A major challenge in the testing process is the *oracle problem*: In general, it is difficult to obtain test oracles for model transformation programs [8]. We propose the technique of *Metamorphic Testing* (MT) to alleviate the oracle problem in testing model transformation programs. MT has been successfully applied to detect real-world faults [3, 5]. In MT, programs are tested against their expectedly necessary properties. A major difference between MT and all the other testing methods for model transformation is that the properties used by MT are relationships among the inputs and outputs of *multiple* executions of the target program (known as *metamorphic relations*), whereas the properties used by the other methods focus on the input and output of a *single* execution. Another difference is that when testing model transformations, metamorphic relations (MRs) can be extracted from informal specifications, whereas most of the other methods rely on formal specifications.

2. Model Transformation

Model transformation is a critical activity in MDE, which is about the generation of target models from source models. A framework of model transformation is given in Fig. 1. The *source metamodel* (MMa) and the *target metamodel* (MMb) describe the static information of models, which are manipulated by the model transformation. The *source* (Ma) and *target* (Mb) models conform to their respective metamodels. The *transformation model* (Mt) refers to an implementation (program) of the model transformation, and MMt is the metamodel of Mt. The model transformation program (Mt) takes a source model as input and produces a target model as output.

There are different transformation languages, of which a popular one is the ATLAS Transformation Language (ATL) [6]. We conducted a case study using a popular model transformation program written in ATL, namely,

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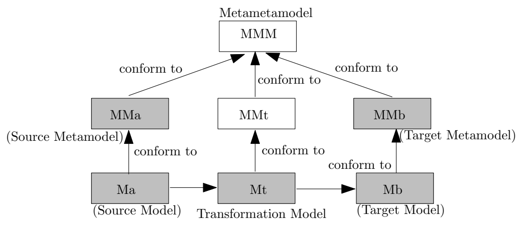
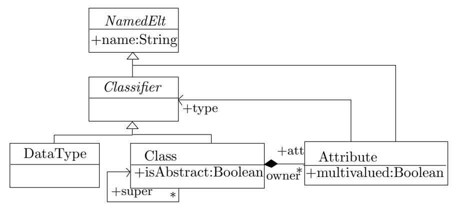
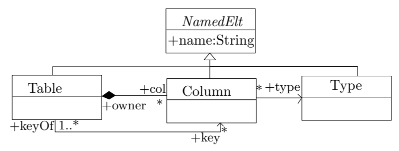


Figure 1. A framework of *model transformation*



(a) The Class metamodel



(b) The Relational metamodel

Figure 2. The metamodels of *Class2Relational*

Class2Relational, which is an "advanced example" open-sourced in the ATL Transformations Zoo [1] and is often used as a subject program by various experimentations [4].

In *Class2Relational*, *Class model* is the source model and *Relational model* is the target model. The *Class* and *Relational* models conform to the *Class* and *Relational* metamodels, respectively (see Fig. 2). In a *Class* model, each *DataType* represents a primitive data type, and each *Class* has a *name* and a set of *Attributes*, each of which can be single-valued or multi-valued and has either *DataType* or *Class* as its *type*. In a *Relational* model, each *Table* contains a *name*, a reference to its *key Columns* and a set of *Columns*, each of which is described by its *name* and *type*. The following describes the requirements of how *Class2Relational* should transform a *Class* model into a *Relational* model:
(1) For each *DataType*, a *Type* is created.
(2) For each *Class*, a *Table* (Type1) is created. Their *names* are identical. The *Table* contains a *key Column*, whose *name* is "objectId" and *type* is a specific type (In this example, it refers to *Integer*). Each *Attribute* of the *Class* is also manipulated, which is described in the following.
(3) For each single-valued *Attribute* of type *DataType*, a *Column* is created, and their *names* and *types* are identical.
(4) For each multi-valued *Attribute* of type *DataType*, a *Table* (Type2) is created. Two *Columns* of the *Table* are also created. One is the identifier *Column* (with a specific type) and the other contains *name* and *type* of the *Attribute*.
(5) For each single-valued *Attribute* of type *Class*, a *Column* is created. The *name* of the *Column* is the *Attribute*'s name +"id", and the *type* of the *Column* is a specific type.
(6) For each multi-valued *Attribute* of type *Class*, a new *Table* (Type3) is created, which has two *Columns* with specific types (one is the identifier *Column*, and the other is named *attribute*.name + "id").
(7) The name of the *Table* (Type2, Type3) is set to *str1*+ "_"+ *str2*, *str1* represents the name of the *Class* which contains the *Attribute*, and *str2* represents the name of the *Attribute*. The *Table*'s identifier *Column* is named *str1*+"id".

The model transformation program *class2relational.atl* was written according to the above requirements. An example *Class* model is given in Table 1 (left column), written in the XML Metadata Interchange (XMI) format. After executing *class2relational.atl* with this *Class* model as input, the output model, that is, the corresponding *Relational* model, is shown in Table 1 (right column). Obviously, it is not difficult to manually verify the correctness of the transformation. It should be noted that real-world models are much larger and much more complex than the above example. Checking the correctness of the transformations of real-world models is therefore a very difficult task.

3. Metamorphic Testing

Metamorphic Testing (MT) [3] is a methodology designed to alleviate the oracle problem. Different from conventional testing strategies, MT uses some specific properties known as Metamorphic Relations (MRs) involving *multiple* test cases and their outputs.

Let p be a program implementing function f. To test p, suppose a set of test cases T=$\{t_1, t_2, \ldots, t_n\}$ ($n > 0$) have been generated using some test case selection strategies (such as black-box, white-box or random testing). Test cases in T are referred to as *original test cases*. Based on the knowledge of f, some MRs can be identified. For each MR, a set of *follow-up test cases* can be generated for T. Suppose t'_i is a follow-up test case for the original test case t_i, then $(t_i,\ t'_i)$ is called a *metamorphic test group* [12]. MT runs the original and follow-up test cases and checks whether the outputs satisfy the MRs, regardless of the availability of an oracle for each individual test case.

4. Application of Metamorphic Testing to Model Transformation

The procedure is outlined as follows: First, identify MRs and construct a set of original test models. For each MR, generate follow-up test models based on the original test models. Then execute the model transformation program using both the original and follow-up test models, and

[1]http://www.eclipse.org/atl/atlTransformations

Table 1. A *Class* model (left column) and the corresponding *Relational* model (right column)

<?xml version=”1.0” encoding=”ASCII”?>	<?xml version=”1.0” encoding=”ASCII”?>
<xmi:XMI xmi:version=”2.0” xmlns:xmi=	<xmi:XMI xmi:version=”2.0” xmlns:xmi=
”http://www.omg.org/XMI” xmlns=”Class”>	”http://www.omg.org/XMI” xmlns=”Relational”>
<DataType name=”Integer”/>	<Table name=”C1” key=”/0/@col.0”>
<DataType name=”String”/>	<col name=”objectId” keyOf=”/0” type=”/2”/>
<Class name=”C1”>	<col name=”A1” type=”/3”/> </Table>
<attr name=”A1” multiValued=”false”	<Table name=”C2” key=”/1/@col.0”>
type=”/1”/>	<col name=”objectId” keyOf=”/1” type=”/2”/>
<attr name=”A2” multiValued=”true”	<col name=”A3Id” type=”/2”/> </Table>
type=”/1”/>	<Type name=”Integer”/>
</Class>	<Type name=”String”/>
<Class name=”C2”>	<Table name=”C1_A2”>
<attr name=”A3” multiValued=”false”	<col name=”C1Id” type=”/2”/>
type=”/2”/>	<col name=”A2” type=”/3”/> </Table>
<attr name=”A4” multiValued=”true”	<Table name=”C2_A4”>
type=”/2”/>	<col name=”C2Id” type=”/2”/>
</Class></xmi:XMI>	<col name=”A4Id” type=”/2”/> </Table></xmi:XMI>

collect the output models. Finally, check the relationship among the original and follow-up test models and their respective output models against the MR. Any violation of MR implies that the program under test is faulty.

A key activity in MT is the identification of MRs, which requires knowledge of the model transformation requirements. Once MRs are identified, they can be used for testing irrespective of the programming language of the model transformation software. We are now going to present some MRs for the subject program *Class2Relational*.

We will use Type1_Table, Type2_Table and Type3_Table to represent the aforementioned three kinds of *Tables* of the *Relational* model and use *Specific*_Columns to represent *Columns* whose *type* refers to the specific type. Let C_1 denote the original test model and C_2 denote the follow-up test model with T_1 and T_2 being their output models, respectively. We use *X.Y* to indicate the element *Y* of model *X*, and *X.#Y* to denote the number of *Y* of model *X*.

Based on the requirements of *Class2Relational*, the following categories of MRs can be identified:

1. Reset of values of some attributes of the test model.

MR1.1: If we modify the values of some attributes of C_1 to obtain C_2 (the modified values are legal), then

T_2.#Type1_Tables=T_1.#Type1_Table1s,

and T_2.#Types=T_1.#Types.

MR1.2: Suppose *Attr* is an *attribute* of *Class Cla* in C_1, and C_2 is constructed by reversing the value of *Attr*.multivalued.

• If *Attr*.multivalued is *true* (It is *false* in C_2), then we have:

(T_2.*Tab*.Columns $\setminus$ T_1.*Tab*.Columns) = $\{$*Col* $\mid$ *Col*.name contains *Attr*.name$\}$, where *Tab* is the *Table* whose name equals Cla.name and $\setminus$ is the set difference operator, which will be used hereafter in this paper,

T_2.#Ts_1 = (T_1.#Ts_1 $-$ 1),where Ts_1 is a set composed of *Tables* whose name contains *Attr*.name,

and T_2.#Ts_2 = (T_1.#Ts_2 $-$ 1), where Ts_2 is a set composed of *Tables* whose name contains *Cla*.name.

• If *Attr*.multivalued is *false*, then (T_1.Tab.Columns $\setminus$ T_2.Tab.Columns) = $\{$*Col* $\mid$ *Col*.name contains *Attr*.name$\}$,

T_2.#Ts_1=(T_1.#Ts_1 +1), and T_2.#Ts_2=(T_1.#Ts_2 +1).

MR1.3: Suppose *Attr* is an *attribute* of *Class Cla* in C_1, and C_2 is constructed by changing *Attr*'s *type*.

• If *Attr*.type refers to a *DataType* (*Attr*.type will refer to a *Class* in C_2), then

T_2.#Specific_Columns = (T_1.#Specific_Columns +1).

• If *Attr*.type refers to a *Class*, then we have:

T_2.#Specific_Columns = (T_1.#Specific_Columns -1).

2. Insertion of an element into the test model.

MR2.1: Construct C_2 by adding a *DataType* into C_1, then

T_2.#Columns=T_1.#Columns,

T_2.#Types= (T_1.#Types+1), and T_2.#Tables=T_1.#Tables,

MR2.2: Construct C_2 by adding a *Class* into C_1, then

T_2.#Type1_Tables= (T_1.#Type1_Tables+1),

T_2.#Columns>T_1.#Columns, T_2.#Types=T_1.#Types,

and T_2.#specific_Columns $>$ T_1.#specific_Columns.

MR2.3: Construct C_2 by adding an *Attribute* to C_1.

MR2.3.1: The added *Attribute* is a single-valued *Attribute* of *DataType*, then T_2.#Columns= (T_1.#Columns+1),

T_2.#Tables=T_1.#Tables, T_2.#Types=T_1.#Types,

and T_2.#specific_Columns=T_1.#specific_Columns.

MR2.3.2: The added *Attribute* is a multi-valued *Attribute* of *DataType*, then T_2.#Columns= (T_1.#Columns+2),

T_2.#Tables= (T_1.#Tables+1), T_2.#Types=T_1.#Types,

T_2.#Type1_Tables=T_1.#Type1_Tables,

T_2.#Type2_Tables= (T_1.#Type2_Tables+1),

and T_2.#specific_Columns= (T_1.#specific_Columns+1).

MR2.3.3: The added *Attribute* is a single-valued *Attribute* of *Class*, then T_2.#Columns= (T_1.#Columns+1),

T_2.#Tables=T_1.#Tables, T_2.#Types=T_1.#Types

and T_2.#specific_Columns= (T_1.#specific_Columns+1).

MR2.3.4: The added *Attribute* is a multi-valued *Attribute* of *Class*, then T_2.#Columns = (T_1.#Columns+2),

T_2.#Tables= (T_1.#Tables+1), T_2.#Types=T_1.#Types

T_2.#Type1_Tables=T_1.#Type1_Tables,

T_2.#Type3_Tables = (T_1.#Type3_Tables+1),

and T_2.#specific_Columns= (T_1.#specific_Columns+2).

3. Deletion of data from the test model according to the output model

MR3.1: Suppose *Col* is a *Column* of *Table Tab* (*Tab* is a *Table* of Type1) in the output mode of C_1. Construct C_2 by deleting information related to *Col* of C_1.

• If *Col* is related to a single-valued *Attribute*, then
(T_1.Tab.Columns $\setminus$ T_2.Tab.Columns) = $\{$*Col*$\}$.

• If *Col* is related to a multi-valued *Attribute*, then
(T_1.Tables $\setminus$ T_2.Tables) = $\{$*T* $|$ *T*.name = *Tab*.name+ '_'+ *Col*.name$\}$, and (T_1.Columns $\setminus$ T_2.Columns) = $\{$*Col* $|$ *Col*.name either contains *Tab*.name or *Col*.name$\}$.

MR3.2: Suppose *Tab* is a *Table* of Type1 in the output model of C_1, and C_2 is constructed by deleting information related to *Tab* of C_1. Then we have: (T_1.Tables $\setminus$ T_2.Tables) = $\{$*T* $|$ *T*.name=*Tab*.name+*str*, where *str* can be empty$\}$.

4. Interchange of data in the test model

MR4 Suppose Cla_1 and Cla_2 are two *Classes* of C_1, and $Attr_1$ and $Attr_2$ are *Attributes* of Cla_1 and Cla_2, respectively. C_2 is constructed by interchanging the data of $Attr_1$ and $Attr_2$ (that is, in C_2, $Attr_1$ becomes an *Attribute* of Cla_2 and $Attr_2$ becomes an *Attribute* of Cla_1).

• If $Attr_1$ and $Attr_2$ are both single-valued *Attributes*, then
T_2.Columns = T_1 .Columns, T_2.#Tables = T_1.#Tables,
DiffTable = (T_2.Tables $\setminus$ (T_2.Tables $\cap$ T_1.Tables)) = $\{$*Tab* $|$ *Tab*.name = Cla_1.name or Cla_2.name$\}$, where $\cap$ is the set intersection operator, which will be used throughout this paper, and *DiffTables*.size = 2, where *size* is the number of elements in the set.

• If $Attr_1$ and $Attr_2$ are both multi-valued *Attributes*, then
T_2.Columns = T_1. Columns, T_2.#Tables = T_1.#Tables,
DiffTable = (T_2.Tables $\setminus$ (T_2.Tables $\cap$ T_1.Tables)) = $\{$*Tab* $|$ *Tab*.name contains $Attr_2$.name and Cla_1.name or contains $Attr_1$.name and Cla_2.name$\}$ and *DiffTables*.size = 2.

• If one of these two *attributes* (namely, $Attr_1$) is single-valued and the other (namely, $Attr_2$) is multi-valued, then
T_2.#Columns=T_1.#Columns, T_2.#Tables=T_1.#Tables,
DiffColumns = (T_2.Columns $\setminus$ (T_2.Columns $\cap$ T_1.Columns)) = $\{$*Col* $|$ *Col*.name contains Cla_1.name$\}$ and *DiffColumns*.size =1,
DiffTable1 = (T_2.Type1_Tables $\setminus$ (T_2.Type1_Tables $\cap$ T_1.Type1_Tables)) = $\{$*Tab* $|$ *Tab*.name = Cla_1.name or *Tab*.name = Cla_2.name$\}$ and DiffTable1.size=2,
DiffTable2 = (T_2.Type2,3_Tables $\setminus$ (T_2.Type2,3_Tables $\cap$ T_1.Type2,3_Tables)) = $\{$*Tab* $|$ *Tab*.name contains $Atrr_2$.name and Cla_1.name$\}$ and DiffTable2.size=1.

5. Empirical Evaluation

5.1. Experimental procedure

We conducted empirical evaluation of MT using the model transformation program *class2relational.atl*, which has 107 lines of code and contains 6 ATL rules and 1 ATL helper. Using the MRs described in Section 4, the testing procedure consists of the following three steps:

(1) Generation of original test models. The set of original test models were generated randomly in such a way that (i) they all conform to the source metamodel, (ii) all elements of the source metamodel are covered, and (iii) different original test models have different values in the same attributes in order to maximize diversity.

(2) Construction of follow-up test models. Different MRs will result in different follow-up test models. These models were generated automatically.

(3) Verification of test results. This step was also performed automatically by our test script against the MRs.

A total of 100 *Class* models were generated as the original test models for testing the subject program *class2relational.atl*. No violation of MRs was detected. This is expected as *class2relational.atl* is a popular and open-source program. In order to evaluate the fault-detection effectiveness of MT, we then applied *mutation analysis* [7] to generate 20 non-equivalent mutants from *class2relational.atl*. Details of the mutants are shown in Table 2, where Mi denotes the i^{th} mutant.

5.2. Results of experiments

We applied MT to test every mutant using the 100 original test models. Results of experiments are summarized in Table 3 in terms of the violation ratio which is defined as the ratio of violated metamorphic test groups among all used metamorphic test groups. The last row shows the average violation ratio for each individual MR, and the last column shows the average violation ratio for each individual mutant. It is observed that every mutant has some violated metamorphic test groups. In other words, all seeded faults are detected.

Table 3 shows that the average violation ratios of MRs range from 0.00 to 0.54. This result is consistent with many other MT studies, which reported that different MRs can have very different fault-detection effectiveness. Table 3 also shows that the fault-detection effectiveness of an MR is mutant dependent. Consider MR2.3.1, for instance, it has varied violation ratios for M3, M9, M19, M20, which are 1.00, 0.08, 0.00 and 1.00, respectively.

The effectiveness of MT can be further analyzed using metamorphic test groups. For each mutant, $100 \times 12 = 1,200$ metamorphic test groups have been executed. Therefore, there is a total of $1,200 \times 20 = 24,000$ metamorphic test groups. The total number of violated metamorphic test groups is 5,240, which gives the overall effectiveness of MT (in terms of violated metamorphic test groups) to be $5,240/24,000 = 22\%$. This result shows that MT is quite effective because a failure will be revealed after running about 5 metamorphic test groups on average.

Table 2. Details of mutants of *class2relational.atl*

Mutant	Line number	Original code	New code	mutation operator
M1	42	type<-a.type	type<-a.owner	ROCC
M2	77	thisModule.objectIdType	a.type	RSCC
M3	37	a.type.oclsKindof(CLA!DataType)	a.oclKindof(CLA!DataType)	RSMD
M4	56	name<-a.owner.name+'_'+a.name	name<-a.name+'_'+a.name	RSMD
M5	88	name<-a.owner.name+'_'+a.name	name<-a.name+'_'a.name+	RSMD
M6	60	name<-a.owner.name+'Id'	name<-a.name+"Id"	RSMD
M7	56	name<-a.owner.name+'_'+a.name	name<-a.owner.name+'_'+a.owner.name	RSMA
M8	7	select(e | e.name = 'Integer')	select(e | true)	CFCD
M9	11	c:CLA!Class	c:CLA!Class(c.attr.size()>0)	CFCA
M10	29	REL!Type	REL!Table	CCCR
M11	29	REL!Type	REL!Column	CCCR
M12	21	type<-thisModule.objectIdType		CACD
M13	57	col<-Sequence{id,value}		CACD
M14	57	col<-sequence{id,value}	col<-sequence{value}	CACD
M15	61	type<-thisModule.objectIdType		CACD
M16	89	col<-Sequence(id,foreignKey)		CACD
M17	89	col<-sequence{id,foreignKey}	col<-sequence{id}	CACD
M18	7	select(e|e.name='Integer')	select(e|not(e.name='Integer'))	CFCP

M19	52,
	84
		a.type.oclIsKindOf(CLA!DataType)
		a.type.oclIsKindOf(CLA!Class)
			not a.type.oclIsKindOf(CLA!DataType)
			not a.type.oclIsKindOf(CLA!Class)
				CFCP

M20	37,
	72
		a.type.oclIsKindOf(CLA!DataType)
		a.type.oclIsKindOf(CLA!Class)
			not a.type.oclIsKindOf(CLA!DataType)
			not a.type.oclIsKindOf(CLA!Class)
				CFCP

Table 3. Results of experiments: violation ratios

	MR 1.1	**MR 1.2**	**MR 1.3**	**MR 2.1**	**MR 2.2**	**MR 2.3.1**	**MR 2.3.2**	**MR 2.3.3**	**MR 2.3.4**	**MR 3.1**	**MR 3.2**	**MR 4**	**Average violation ratio for each mutant**
M1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.73	0.06
M2	0.00	0.00	0.55	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.87	0.49	0.24
M3	0.00	0.47	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.45	0.16
M4	0.00	0.59	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.41	0.77	0.73	0.29
M5	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.25	0.00	0.63	0.19
M6	0.00	0.00	0.00	0.00	0.00	0.00	0.94	0.00	0.00	0.00	0.00	0.49	0.12
M7	0.00	0.58	0.00	0.00	0.00	0.00	0.94	0.00	0.00	0.05	0.00	0.81	0.20
M8	0.00	0.00	0.50	0.00	0.50	0.00	0.50	0.50	0.50	0.00	0.00	0.45	0.25
M9	0.00	0.00	0.00	0.00	0.54	0.08	0.08	0.08	0.05	0.03	0.00	0.55	0.12
M10	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.47	0.12
M11	0.00	0.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0.00	0.77	0.53	0.61
M12	0.00	0.00	0.00	0.00	0.49	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.07
M13	0.00	0.00	0.41	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.54	0.16
M14	0.00	0.00	0.54	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.53	0.17
M15	0.00	0.00	0.54	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.56	0.18
M16	0.00	0.00	0.60	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.50	0.18
M17	0.00	0.00	0.49	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.46	0.16
M18	0.00	0.00	1.00	0.00	1.00	0.00	1.00	1.00	1.00	0.00	0.00	0.49	0.46
M19	0.00	0.00	0.49	0.00	0.00	0.00	1.00	0.00	1.00	0.00	0.89	0.46	0.32
M20	0.00	0.00	0.48	0.00	0.00	1.00	0.00	1.00	0.00	0.00	0.87	0.44	0.32
Average violation ratio for each MR	0.00	0.10	0.33	0.10	0.18	0.10	0.47	0.23	0.33	0.04	0.20	0.54	

5.3. A further analysis of the effectiveness of MRs

Table 3 shows that the fault-detection effectiveness of different MRs can be very different: MR4 was violated by every mutant, but MR1.1 was never violated. The most effective MR is MR4. Its average violation ratio is 0.54. That is, on average, more than half of its metamorphic test groups can reveal a failure. MR4 is highly effective because it makes use of more information of the transformation requirements than the remaining MRs. MR4 checks almost all data items of the *Relational* model, taking their concrete values into consideration, instead of just comparing the numbers of some elements. The other MRs (except the worst one, MR1.1) generate follow-up test models by adding or deleting some elements, or resetting the attributes' values of some elements of the original test model. Their average violation ratios range from 0.10 to 0.47. They are less effective than MR4 because they check only certain parts of the *Relational* model. We analyzed each MR together with all the mutants that violated it. For any given pair of mutant and MR, a high violation ratio will be intuitively expected if the fault in the mutant is relevant to the MR.

MR1.1, which constructs follow-up test models by changing the values of some arbitrary attributes, was the least effective MR: It did not detect any violation. The reason for this is twofold. First, in each and every metamorphic test group generated by MR1.1, the original and follow-up test case executions are almost identical in the sense that the same statements of the subject program are exercised (and in the same sequence). The original and follow-up output models generated in this way are therefore very similar. As a result, MR1.1 is very likely to be satisfied. This observation confirms the findings of Chen el al. [2] and Cao et al. [1]: an effective MR should make the original and follow-up test case executions as different as possible. Secondly, MR1.1 checks the test results at a quite high abstraction level by ignoring many details of the output models. Consequently, even if an output model is incorrect, the incorrect data item buried in the output model is not checked by MR1.1 and hence a violation cannot be detected. This finding shows that an effective MR should look at the details of the output as much as possible.

We have obtained two useful guidelines. First, MRs whose original and follow-up test case executions are very different, are likely to have a higher chance of detecting a failure than those whose original and follow-up test case executions are similar. Secondly, an effective MR should involve detailed information from the requirements specification as much as possible and as complete as possible.

6. Discussions and Conclusion

We propose to apply Metamorphic Testing (MT) to alleviate the oracle problem in testing model transformation programs. To evaluate the effectiveness of the proposed approach, a case study has been conducted using *Class2Relational* and mutation analysis. The empirical results show that MT can effectively detect model transformation faults. We used Metamorphic Relations (MRs) involving four kinds of operations, namely, addition of elements, deletion of elements, alteration of attribute's values, and interchange of elements. We have obtained two guidelines for applying MT to model transformation programs. The first guideline is to select MRs whose original and follow-up test case executions are significantly different. The second guideline is to select MR that involves as many details of the model transformation as possible from the transformation requirements. These two guidelines are appropriate for the selection of MRs for any model transformation programs.

Many applications have a model transformation component or have been developed using model transformations. Examples of the former include software development tools that use model transformations to generate the application code [10]. Examples of the latter include context-aware pervasive systems [9] and secure XML data warehouses [11] which are developed using Model Driven Development (MDD) method. Obviously, the correctness of the model transformations will affect the quality of the final systems. MT can be used to test the model transformations in such applications.

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