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Static Type Checking of Model Transformation Programs

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Abstract: Model transformation is seen as a promising approach to automate software development and verification, thus improving quality and reducing production costs significantly. However, errors of transformation programs can propagate into the generated artifacts complicating the detection of errors. The current paper proposes a static type checking approach for early detection of typing errors of partially typed transformation programs. The approach describes type safety as constraint satisfaction problems, and uses a dedicated back-annotation mechanism for error feedback.

Keywords: model transformations, type checking, constraint satisfaction problems

1 Introduction

Model-driven development (MDD) has become a key technique in system and software engineering. MDD facilitates the systematic use of models from a very early phase of the design procedure using high-level, engineering models (such as UML, SysML or AADL - Architecture Analysis & Design Language). During development model transformations are used to generate appropriate mathematical models for formal analysis, deployment descriptors and source code.

Validating these model transformations is critical, as errors can invalidate the analysis results or might propagate into the target application. However, as the complexity of developed model transformations grows, ensuring the correctness of transformation programs becomes increasingly difficult. Several different methods and frameworks are already available for the verification of model transformation programs, including different testing strategies [LZG05, KGZ09], model checking [RD06, LBA10] and static analysis [BW07, BCH$^+$09]. However, there are many more formal techniques used to support the development and validation of traditional programming languages, and their application to model transformation programs can raise the maturity of the technology.

In dynamically typed languages (that check type safety only during runtime) type errors are common, and sometimes hard to trace (e.g., instead of an error message, incorrect output is produced). Such errors are also common in partially typed transformation languages, such as VIATRA2 [VB07], using a statically typed (checked at compile time) graph transformation rules with a dynamically typed control structure. However, for type checking there is usually limited support in transformation development environments.

The current paper presents a static analysis approach for the early detection of type errors in partially typed model transformation programs. Type safety is described using finite domain

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constraint satisfaction problems (CSP), where type constraints are created from every statement of the transformation program based on the language specification. If these CSPs are unsatisfiable, a type error is detected and back-annotated to the transformation program.

The rest of the paper is structured as follows. Section 2 gives a brief overview of the technologies used in the paper. Section 3 details our approach with regards to identifying the type system, and creating constraint satisfaction problems that represent the type safety of the transformation programs. In Section 4 we demonstrate and evaluate the static type checking approach using an implementation in the VIATRA2 framework. Section 5 assesses the related work, and finally, Section 6 concludes our paper by evaluating the presented analysis approach and suggesting possible future research directions.

2 Preliminaries

In order to introduce our approach the current section briefly outlines the basics of the techniques used throughout the paper. Section 2.2 gives an introduction to metamodeling, followed by the basics of model transformations in Section 2.3. Then a quick overview is given to typing problems in Section 2.4, and finally, in Section 2.5 the basics of CSP solving is described.

2.1 Running Example: Simulation of Petri nets

In the current paper we will use the simulation of Petri nets as a model transformation problem to demonstrate the technicalities of our approach.

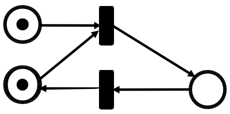


Figure 1: A Sample Petri net

Petri nets are bipartite graphs with two disjoint set of nodes: *Places* and *Transitions*. *Places* can contain an arbitrary number of *Tokens*, that represents the state of the net (marking). The process called *firing* changes this state: from every input *Place* of a *Transition* a *Token* is removed (if there is none to remove, the *Transition* must not fire), then to every output *Place* a *Token* is added. A sample Petri net model is depicted in Figure 1.

2.2 Foundations of Metamodeling

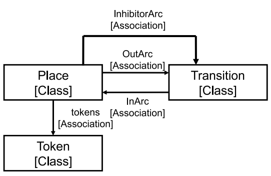
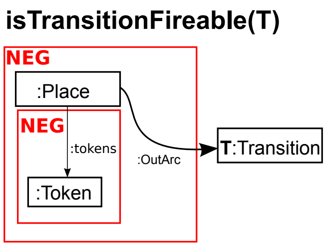


Figure 2: The Petri net metamodel

Metamodeling provides a structural definition (e.g. abstract syntax) of modeling languages. Formally, a *metamodel* can be represented by a type graph. Nodes of the type graph are called *classes*. *Associations* define connections between classes with possible *multiplicity* constraints on both ends declaring the number of objects that may participate in the association. A metamodel for Petri net models is depicted in Figure 2.

2.3 Graph Patterns and Graph Transformations

Graph patterns are often considered as atomic units of model transformations [VB07]. They represent conditions (or constraints) to be fulfilled by a part of models required for some manipulation steps on the model.



(a) Graphical Notation

```
pattern isTransitionFireable(Transition) = {
 PetriNet.Transition(Transition);
 neg pattern notFireable(Transition) = {
  PetriNet.Place(Place);
  PetriNet.Transition(Transition);
  PetriNet.Place.OutArc(OutArc, Place, Transition);
  neg pattern placeToken(Place) = {
   PetriNet.Place(Place);
   PetriNet.Place.Token(Token);
   PetriNet.Place.tokens(X, Place, Token);
  }
 }
}
```

(b) Textual Notation

Figure 3: The Firing Condition of Petri nets

A basic graph pattern consists of graph nodes and edges corresponding to the metamodel. *Negative application conditions* (NAC) are an extension to this formalism, defining a negative subpattern to forbid contextual conditions for the original pattern in case of a successful match, or *alternate patterns* where the pattern if fulfilled if any alternate pattern matches.

It is possible to reuse existing patterns using *pattern composition* - if such calls are present, the caller pattern holds only if the called pattern also holds with the specific graph nodes.

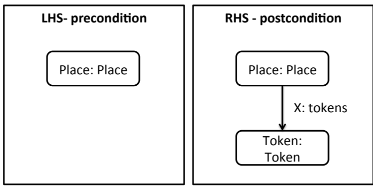
Example 1 *As an example, the firing enabled condition of the Petri net simulator program is displayed in Figure 3 as a graph pattern in the notation used in* VIATRA2. *The pattern uses nested negative application conditions to express that a* Transition *is enabled if every input* Place *instance collected to the* Transition *instance has at least one* Token *instance associated. In the example, the double negation is used to express the universal quantification with double negation of existence.*

Graph Transformation (GT) [Roz97] provides a high-level rule and pattern-based manipulation language for graph models. GT rules can be specified using a left-hand side (LHS or precondition) graph (pattern) to decide the applicability of the rule, and a right-hand side (RHS or postcondition) graph (pattern) which declaratively specifies the result model after the rule application. To achieve this, the rule application removes all elements, that are only present in the LHS, creates all elements that are only present in the RHS, and every other element remain unchanged.

Example 2 *As an example Figure 4 shows a GT rule that specifies how to add a token to a place. The precondition pattern* place *represents a single place, while the postcondition pattern* placeWithToken *describes a* Token *connected to the* Place. *When this rule is applied, a* Pattern *is found, and a new* Token *with the corresponding association is created.*

Control Language Complex model transformation programs can be assembled from elementary graph patterns and graph transformation rules using some kind of control language. In our examples, we use abstract state machine (ASM) [BS03] for this purpose as available in the VIATRA2 framework.

ASMs provide complex model transformations with all the necessary control structures in-



(a) Graphical Notation

```
gtrule addToken(in Place) = {
 precondition pattern place(Place) = {
   PetriNet.Place(Place);
 }
 postcondition pattern placeWithToken(Place, Token) = {
   PetriNet.Place(Place);
   PetriNet.Place.Token(Token);
   PetriNet.Place.tokens(X, Place, Token);
 }
}
```

(b) Textual Notation

Figure 4: The Add Token GT Rule

```
rule fireTransition(in T) = seq {
 /* perform a check to confirm that the transition is fireable */
 if (find isTransitionFireable(T))
 seq {/* remove tokens from all input places */
  forall Place with find inputPlace(T, Place)
   do apply removeToken(T, Place); // GT rule invocation
  /* add tokens to all output places */
  forall Place with find outputPlace(T, Place)
   do apply addToken(T, Place);
 }}
```

Figure 5: The Fire Transition ASM rule

cluding the sequencing operator (`seq`), ASM rule invocation (`call`), variable declarations and updates (`let` and `update` constructs), `if-then-else` structures, non-deterministically selecting (`random`) constructs, iterative execution (applying a rule as long as possible, `iterate`), the simultaneous application at all possible matches (locations) (`forall`) and single rule application on a single match (`choose`).

Example 3 *The example code in Figure 5 demonstrates how a transition can be fired in this language. At first the code determines whether the input parameters is fireable using the previously defined* `isTransitionFireable` *pattern. Then in a sequence calls the* `removeToken` *GT rule for each* `inputPlace`*, then the* `addToken` *GT Rule for every* `outputPlace`*.*

2.4 Type checking

A type system of a language can be defined as "a tractable syntactic framework for proving the absence of certain program behaviours by classifying phrases according to the kinds of value they compute" [Pie02]. In other terms, the type system defines a categorization for statements of the program (typically for variables and terms). The categories (types) are then used to write conditions (or constraints) determining the allowed types of the statement parameters in programs.

For *statically typed* languages these constraints are enforced before execution (e.g. during compile time), either by the verification of user-defined types (called *type checking*) or by calculating the proper types of variables using their uses and definitions (*type inference*).

Dynamically typed languages postpone the constraint validation until runtime. In these languages type constraints are often kept simple to avoid costly runtime validation, allowing some typing errors to give incorrect output instead of an error message. This can make such errors hard to identify, emphasizing the need for an efficient compile-time verification technique. It is important to note that dynamic typing allows constructs that are hard to analyze statically (e.g. the type associated to a variable can be changed during runtime).

The type system of transformation programs consists of (*i*) built-in types of the transformation language (e.g. string or integer) and (*ii*) the metamodels of the input and output models.

Graph patterns or graph transformation rules are statically bound to the metamodel with user-defined types, while the control structure might use dynamic typing (such as ASM rules in VIATRA2[VB07]). This allows efficient type checking, as type information from graph patterns can be propagated to the control structure, helping type inference.

2.5 Constraint Satisfaction Problems for Variables over Finite Domains

A CSP(FD) is a problem composed of a finite set of variables, each of which is associated with a finite domain, and a set of constraints that restricts the values the variables can simultaneously take. In a more precise way a constraint satisfaction problem is a triple: (Z,D,C) where Z is a finite set of variables $x_1,x_2,\ldots,x_n$; D is a function which maps every variable in Z to a set of objects of arbitrary type; and C is a finite (possibly empty) set of constraints on an arbitrary subset of variables in Z. The task is to assign a value to each variable satisfying all the constraints. Solutions to CSPs are usually found by (i) *constraint propagation* a reasoning technique to explicitly forbid values or domains for variables by predicting future subsequent constraint violations and (ii) *variable labeling* searching through the possible assignments of values to variables already restricted by the (propagated) constraints.

3 Type Checking of Model Transformation Programs

3.1 Overview of the Approach

Our constraint-based type checking process is depicted in Figure 6. The input of the static analysis is the transformation program and the metamodel(s) used by the program, while its output is a list of found errors. It is important to note that the instance models (input of the transformation program) are not used at all in the static analysis process. Our analysis process consists of the following steps:

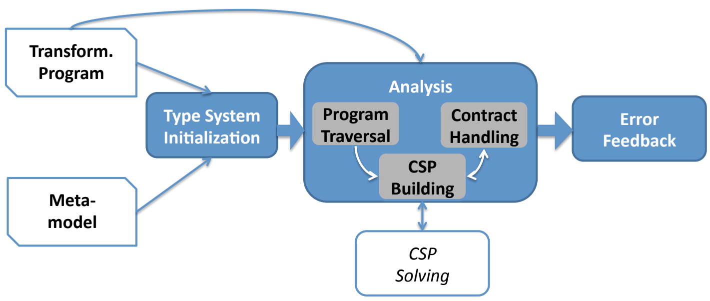


Figure 6: Overview of the Approach

Type System Initialization creates a representation of the type system of the transformation program, and makes it available for the analysis step, as described in Section 3.2.

Analysis The analysis phase can be split into three co-operating tasks:

Transformation Program Traversal processes every statement in every possible execution path of the transformation program. This task is carried out by a simple tree traversal algorithm operating on the abstract syntax tree of the transformation programs.

CSP Building creates constraints from every program statement, and calls a CSP solver to evaluate the generated problem. This step is detailed in Section 3.3.

Contract Handling is used to store (and return) partial analysis results as contracts. This task is described in Section 3.4.

Error Feedback back-annotates the analysis results to the transformation program to provide error messages to the transformation developer. For details see Section 3.5.

3.2 Type System Initialization

The first step of the analysis process is the identification of the type system (TS) of the transformation, and initializing it for the CSP solver library. As transformations often deal only with a selected aspect of models, such a type system consists only of a (potentially very small) subset of the source and target metamodels and some built-in types.

In order to calculate the used subset of the metamodels, we collect every type directly referenced from the transformation program, then for each type we add all their supertypes, and in case of relations type of their endpoint and inverse classes as well. This metamodel pruning method was described in [SMBJ09], and was proven to calculate a superset of the metamodel elements used in the transformation, providing a reduced metamodel with all needed elements for analysis.

After the type system is collected, to each remaining type a unique integer set was assigned in a way, that the set-subset relation between the integer sets represent the inheritance hierarchy in the type system. Informally, we define a mapping function $m : type \mapsto S, S \subset \mathbb{N}$, guaranteeing $\forall T_1, T_2 \in TS : supertypeOf(T_1, T_2) \Leftrightarrow m(T_1) \subset m(T_2)$. An algorithm for creating such a mapping from multiple inheritance hierarchies is proposed in [Cas93].

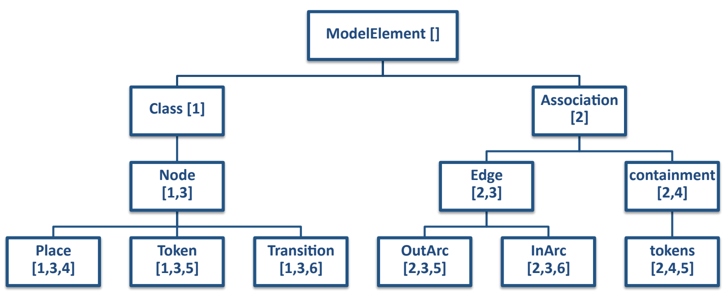


Figure 7: The Type System of the Petri net Simulator (without built-in types)

Example 4 *Figure 7 displays the type system of the Petri net simulator transformation program (with the omission of the built-in types for the sake of readability). The hierarchy also includes three types from the meta-metamodel to be able to refer to every* model element, class *or* association *- this is useful for expressing certain type constraints.*

For every type the associated integer set is also displayed on the figure. For types that are in supertype relation (such as the Node *and* Transition*) the sets are in subset relation (*$m(Node) = \{1,3\} \subset \{1,3,6\} = m(Transition)$*), while for those that are not (such as* Edge *and* Transition*) they are not (*$m(Edge) = \{2,3\} \not\subseteq \{1,3,6\} = m(Transition)$*).*

3.3 Constraint Generation

The type safety of transformation programs can be described as finite domain CSP as follows. For each use of every transformation program variable a CSP variable is created with the domain of the integer sets defined in the type system (TS). These CSP variables represent *the type of a variable* of the transformation program, that will be matched with constraints representing the various uses of the variable. These constraints are created from the *statements of the transformation program*, expressing type information available from the *language specification*, such information is that conditions have the (built-in) boolean type.

In this paper we show how to create type constraints from graph patterns, type constraints from other language elements can be calculated similarly. All other type constraints derived from the transformation language of VIATRA2 are described in detail in [UHV09].

The body of graph patterns consists of a set of pattern variables with a type taken from the metamodel. These can be translated to constraints as follows: as the type of the pattern variable has to be the same as (or a subtype of) the type defined in the pattern, a constraint representing the correct set-subset relation has to be created.

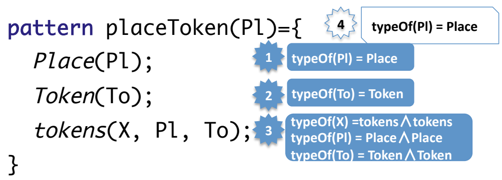
Pattern Graph Element	Type Information	Constraint
`Place(Pl)`	$typeOf(Pl) = Place$	$m(typeOf(Pl)) \subset \{1,3,4\}$
`Token(To)`	$typeOf(To) = Token$	$m(typeOf(To)) \subset \{1,3,5\}$
`tokens(X,Pl,To)`	$typeOf(Pl) = Place$	$m(typeOf(Pl)) \subset \{1,3,4\} \wedge$
	$typeOf(To) = Token$	$m(typeOf(To)) \subset \{1,3,5\} \wedge$
	$typeOf(X) = tokens$	$m(typeOf(X)) \subset \{2,3,5\}$

Figure 8: Constraint Generation from the *PlaceToken* Graph Pattern

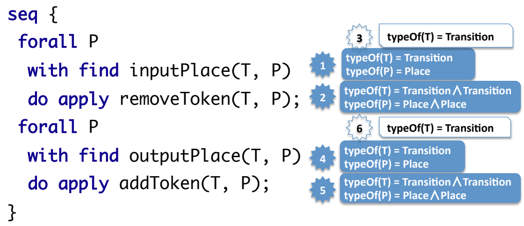
Example 5 *Figure 8 displays the constraint generated from the* PlaceToken *NAC pattern (see in Figure 3b). The first column of the table contains the different pattern graph elements, while the second one displays the derived type information. Finally, the third column display the constraint that can be filled into CSP solvers.*

3.4 Contract Handling

For performance considerations, the transformation program is traversed in a modular way: the transformation programs are split into smaller segments, that are traversed and analyzed separately.



(a) Call Contracts



(b) Block Contracts

Figure 9: The Use of Contracts

The partial analysis results of the segments are described and stored as pre- and postconditions. After assigned to a segment the contract is used to generate the relevant constraints instead of re-traversing the referenced segment.

Such a contract is basically a constraint that stores the externally visible properties of the contracted code segment. In case of type contracts, the type information of the externally visible variables are stored before (precondition) and after (postcondition) the execution of the code segment. This dual storage is only needed if the contract has to represent variable updates, otherwise it is enough to store a single unit of type information.

It is possible to assign a set of contracts to every code segment allowing to represent different behaviour in different execution paths. This construct allows reducing the number of execution paths to consider by filtering out execution paths providing the same type information, but retaining the different results. When reaching a segment with a set of contracts assigned, the segment has to be considered as a statement with multiple possible executions, thus maintaining the exhaustive nature of the traversal.

Call Contracts Callable elements, such as graph patterns, GT and ASM rules give a natural modularization of the transformation program: they are independent blocks running with their own set of variables. The type contracts of patterns and rules (*call contract*) have to store type information for its parameters, other variables used inside it are not visible externally. After that, every call to that pattern or rule can be replaced by the application of the generated call contract.

As the analysis of a callable element depends on other call contracts, it is important to calculate the contracts in inverse call order: first the contract of the called element, then the callers. In case of recursive calls, no such order can be created.

To overcome this challenge, we propose to use a queue of callable elements, initially sorted by inverse call order (circular dependencies are broken). The queue is used to determine the order of contract calculation. After its contract is created or updated, we ensure that every caller of the rule is present in the queue by adding the missing elements, maintaining the inverse call order.

Example 6 *Figure 9a shows the generation of call contract of the* placeToken *graph pattern. Next to each line in the pattern body the associated type information is presented (*1–3*), in the order they are collected. After the constraints are evaluated, (*4*) the contract of the pattern is created. The pattern has a single parameter* Pl*, that is not changed, so the call contract contains a single*

Statement	Type Information	Constraints
`with` `find inputPlace(T,P)`	$typeOf(T) = Transition$ $typeOf(P) = Place$	$m(typeOf(T)) \subset \{1,3,6\}$ $m(typeOf(P)) \subset \{1,3,4\}$
`do` `apply removeToken(P,T)`	$typeOf(P) = Transition$ $typeOf(T) = Token$	$m(typeOf(P)) \subset \{1,3,4\} \wedge$ $m(typeOf(P)) \subset \{1,3,6\}$ $m(typeOf(T)) \subset \{1,3,6\} \wedge$ $m(typeOf(T)) \subset \{1,3,4\}$

Figure 10: Error Detection

type information: $typeOf(Pl) = Place$. *This contract is displayed next to the pattern header.*

Block Contracts The analysis of control structures can also be modularized: blocks defining local variables (such as `let`, `choose` or `forall` rules in ASM) may also offer a compact contract. These *block contracts* store type information for the variables defined outside the block.

Blocks may be embedded into each other, but no circular embedding is possible, thus the ordering of block contract calculation is much simpler: first the contract of the innermost block has to be calculated, then the outer ones. This way, no recalculation of contracts is needed.

Example 7 Figure 9b *shows an example for generating block contracts in the* fireTransition *ASM rule. The rule contains two* `forall` *blocks to create contracts from. To calculate the type of the first rule,* (1) *we read the contracts from the* `inputPlace` *pattern and* (2) *the* `removeToken` *GT rule - both state, that* $typeOf(P) = Place \wedge typeOf(T) = Transition$. (3) *The contract of the block does not contain locally defined variables, so the only variable present in the contract is* T. *The contract of the other* `forall` *rule can be calculated similarly* $(4-6)$.

The performance gains of both call and block contracts over the naive, non-modular traversal approach are detailed in Section 4.3.

3.5 Error Reporting

Most CSP solvers do not give detailed output in case of an unsatisfiable constraint set, only the unsatisfiable variables are reported. In order to obtain context information, we evaluate the constraints in parallel with the traversal. This way, in case of an error is found, both the variable and the last processed statement is known, allowing to associate the error to this segment.

Additionally, every CSP variable and constraint is linked with its source variable or program statement, so it is possible to find the related elements.

If the CSP solver reports an unsatisfiable set of constraints, it means that the various uses of a variable (e.g. its definition and its use) expect *incompatible types*, indicating a type error, that can be presented to the transformation developer as an error. The most common way such errors manifest are parameter mismatching in calls.

Example 8 *The first column of* Figure 10 *shows two modified lines from the previously introduced* fireTransition *ASM rule: the parameters of the* removeToken *call are switched, which is a* *common error committed by transformation developers. In this case the analysis first uses the contract of the* inputPlace *pattern to determine that* $typeOf(T) = Transition$ *and* $typeOf(P) = Place$*. After that, it applies the contract of the* removeToken *GT rule. At this point, the solver has the following constraints for the variable P:* $m(typeOf(P)) \subset \{1,3,4\} \wedge m(typeOf(P)) \subset \{1,3,6\} \Leftrightarrow m(typeOf(P) \subset \{1,3,4,6\}$*, that is not a subset of any allowed set from the type system. Finally, a failure is reported, that no type can satisfy the constraints for variable P.*

As values (and possibly types) of the transformation program variables can change during execution, multiple CSP variables might be needed to represent them. After the constraints are evaluated, the CSP variables need to be also checked whether they return a single, consistent type from the transformation program variable. Inconsistency indicates that the *type of a transformation program variable changes* during execution. Such changes are almost always unintended, but as dynamic languages allow it, only a warning is displayed to the developer.

4 Implementation and Evaluation

4.1 Implementation

The proposed static type checker framework was implemented and evaluated in the VIATRA2 model transformation framework and integrated into its Eclipse-based user interface.

We evaluated various available CSP solvers for Java, most notably the Gecode/J[1] and the `clpfd` module of SICStus Prolog[2]. A preliminary performance comparison between the different solvers are described in [Ujh09]. In our experience neither of them supported our needs well: Gecode/J did become slow with larger sets (about 50 metamodel elements), while SICStus Prolog did not support incremental CSP building required for error reporting.

Thus, we created a simple CSP solver tailored to our requirements. Incremental evaluation was supported by maintaining a constraint graph with variables as nodes and constraints as arc. Type information is propagated through constraints and integer sets are supported using specialized propagation rules.

4.2 Case Studies

To demonstrate the analysis capabilities next to the Petri net firing example larger transformation programs with more complex metamodels are also evaluated.As examples we tried to select different kind of transformation programs: (1) the Petri net simulator and generator are very simple basic transformation programs (see Section 4.2), (2) the AntWorld case study present a larger simulation (see Section 4.2) case study, (3) while the BPEL2SAL (see Section 4.2) case study represents and industrial-sized model transformation.

The Petri net generator program In addition to the Petri net firing transformation program a generator transformation is also defined in [BHRV08]. This transformation is used to generate

[1] http://www.gecode.org/gecodej/

[2] http://www.sics.se/isl/sicstuswww/site/index.html

"balanced" Petri net (here: the number of *places* and *transitions* are approximately equal) test cases for the firing program.

The nets are created using the inverse of six reduction operators that preserve safety and liveness properties of the net. The operators are selected using a weighted random function.

The generator program consists of 9 GT patterns, 5 GT rules and 9 ASM rules instead of the 12 patterns, 2 GT rules and 3 ASM rules of the simulator program. The control structure of the generator program also uses more elaborate ASM rules.

The AntWorld Case Study The AntWorld case study [Zü08] is a model transformation benchmark featured at GraBaTs 2008. AntWorld is inspired by the ant colony optimizationproblem and simulates the life of a simple ant colony searching and collecting food to spawn more ants on a dynamically growing rectangular world. The ant collective forms a swarm intelligence, as ants discovering food sources leave a pheromone trail on their way back so that the food will be found again by other ants.

The case study uses a turn-based simulation, with each turn divided into seven different phases for ant simulation (e.g. grad, search) and world management (e.g. create ants, boundary breached).

The metamodel of the case study is somewhat larger than the Petri net metamodel: it consists of 7 different classes with complex associations between them. The transformation program consists of 17 graph patterns and 13 relatively simple ASM rules as control structure.

The BPEL2SAL Transformation Business processes implemented in BPEL (Business Process Execution Language) are often used to create business-to-business collaborations and complex web services. Their quality is critical to the organization and any malfunction may have a significant negative impact on financial aspects. To minimize the possibility of failures, designers and analysts need powerful tools to guarantee the correctness of business workflows. The BPEL2SAL transformation program [GHV10] is used inside a tool for such analysis.

Both the BPEL and SAL metamodels used in the transformation are much more complex than the AntWorld case study, together consisting of 150 classes and associations between them. To express this transformation, 177 different graph patterns have been defined together with 102 ASM rules, some of them are really complex (over 100 lines of code).

4.3 Performance Assessment

In order to evaluate the performance we measured the execution time of the analysis on the various case studies. We compared the execution time of a *naive traversal* (without contracts) to the modular traversals, using either *call contracts* or both *call and block contracts*. During the measurements we used error-free programs as erroneous execution paths are only analyzed until the first unsatisfiability found, thus shortening analysis time. For measurements we used a developer notebook with a 2.4 GHz Core2Duo processor and 4 GB RAM with a 64 bit Java SE runtime. Measurements were repeated several times, and the average of the analysis time is used.

We tested memory consumption by limiting the available heap size to 500 MB - the analysis could handle every tested transformation. A more detailed evaluation is planned for the future.

Figure 11a summarizes the size of the different transformation programs with the analysis time using the naive traversal approach (without modularization). The first column displays

	LOC	Calls (P/G/A)	Time (naive)
Petri net simulator	120	12/2/3	0,1s
Petri net generator	94	9/5/9	2s
Antworld	300	17/0/13	24min
BPEL2SAL	8339	177/0/102	--

(a) Execution Time with the Naive Traversal Algorithm

		# of contracts	# of execution paths	Avg # of paths in a contract	Max # of paths in a contract	Analysis time
Petri net simulator	Call contract	17	26	1,53	4	0,1s
	Block contract	40	49	1,23	3	0,1s
Petri net generator	Call contract	23	62	2,70	33	1,2s
	Block contract	57	97	1,70	33	0,9s
Antworld	Call contract	30	47	1,57	4	0,2s
	Block contract	56	79	1,41	4	0,3s
BPEL2SAL	Call contract	279	1291	4,63	576	--
	Block contract	1248	1568	1,26	12	69s

(b) Execution Times with the Modular Traversal Approaches

Figure 11: Runtime results

size of the program (number of code lines), while the second the number of graph patterns, GT rules and ASM rules respectively. The third column shows the analysis time. The BPEL2SAL transformation did not terminate in an hour, so its result was omitted.

Figure 11b consists of our measurement results related to the modular traversal approaches: (1) when using only *call contracts* and (2) using both *call and block contracts*. The first column displays the number of contracts created, in case of block contracts holding both call and block contracts. The second column then describes the total number of partial execution paths the analysis must traverse: the total number of different execution paths inside contracted elements.

The third column shows the average number of execution paths per contract. We believe, the performance of the analysis correlates with this number, as it shows how many times a call or block has to be evaluated before its contract can be created. Even worse, a large number of execution paths usually suggests a complex call or block resulting in large CSPs to solve.

The fourth column displays the maximum number of execution paths per contract. In most cases it is similar to the average value, with the notable exception of the BPEL2SAL program. When only call contracts are used, there exists a complex ASM rule responsible for 576 paths, almost half of the total number. We believe, that the use of block contracts reduce this maximum to 12 causes that the analysis becomes possible. Similarly, if the code would be refactored in a way that every call contains only a single block, the performance would increase similarly.

The last column displays the execution time of the analysis. These results show, that even the use of call contracts can reduce the execution time significantly: the AntWorld transformation can be analyzed in 0.2 seconds instead of 24 minutes. Similarly, the use of block contracts allowed to analyze the BPEL2SAL transformation program in about 1 minute.

It is important to note, that the use of block contracts can also increase the analysis time: in case of the AntWorld case study the increased administrative overhead of maintaining contracts outweighed the benefits of the contract generation. As Figure 11b shows, the average number of execution paths is only slightly smaller using block contracts, however, the total number of paths to evaluate grows significantly.

5 Related work

In this section we give a brief introduction to various approaches to the verification of model transformations, and also compare our system with existing type checking solutions.

Verification of Model Transformations Various analysis methods are being researched for the verification and validation of model transformations. Testing methods are very common in the field of traditional software engineering, and its applications to model transformation programs are actively researched [LZG05, KGZ09], but early results show that testing or comparing the output of transformation programs (usually models) can be very time consuming.

Formal methods, such as theorem proving based approaches [Pen08] show the possibility to prove statement validity over graph-based models. For the verification of dynamic properties model checking seems promising [LBA10, Ren04], but the challenge of infinite state spaces needs to be overcome, e.g. by creating an abstraction [RD06] or by statically computing a Petri graph model [KK06]. However, these techniques usually do not scale well and cumbersome to apply to industrial size problems.

In addition to model checking, static analysis techniques have been used in the verification of static properties. They provide efficiently calculable approximations of error-free behaviour, such as unfolding graph transformation systems into Petri nets [BCH+09], creating and validating OCL constraints derived from GT rules [CCGL08], or using a two-layered abstract interpretation introduced in [BW07]. Our approach works similarly: we transform the model transformation program into constraint satisfaction problems, and verify it statically.

Type Checking Approaches As the number of type checking frameworks and algorithms is extremely large, we focus only on the approaches for dynamically typed functional and logical programming languages solve because of their similarities with model transformations.

The well-known Hindley-Milner algorithm [Mil78] for lambda calculus reduces the typing problem to a unification problem of equations, and is widely used in the functional programming community. [JVWS07] shows an extension to this algorithm, providing support for higher-order transformations.

Our approach was influenced by the work started in [Pot05] which translates the typing problem to a set of constraints. As lambda calculus do not conform to the VIATRA2 transformation language, we designed a different mapping and evaluation approach that fitted better with the graph based data structures and multi-level metamodeling.

Type checking of Prolog programs works differently: the basic task of type checking is to infer the concrete type, represented as a hierarchical tree structure from its basic uses. A typical approach is to calculate with different kinds of widening [VB02, Lin96] steps.

Other approaches exists as well for the type checking of logical programming languages: [HCC95] creates type graphs to represent the various Prolog structures, and uses abstract interpretation techniques to validate the program, while [HM04] traces back type safety of Datalog languages to the consistency of ontologies.

6 Conclusion and Future Work

We have presented a static type checker approach for model transformation programs. It was implemented for the VIATRA2 transformation framework, and evaluated using transformation programs of various size. In our initial evaluation the type checker seemed useful for early error detection as it identified typing errors related to swapped variables or erroneous pattern calls.

As for the future, we plan to evaluate the possible usage of static program slicing methods for model transformation programs. This would allow to generate meaningful traces for reaching possibly erroneous parts of the transformation programs, thus helping more precise error identification. The generated slices are also usable to extend the system with additional validation options such as *dead code analysis* to detect unreachable code segments or *use-definition analysis* to detect the use of uninitialized or deleted variables.

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