A Symbolic Execution-Based Approach to Model Transformation Verification using Structural Contracts

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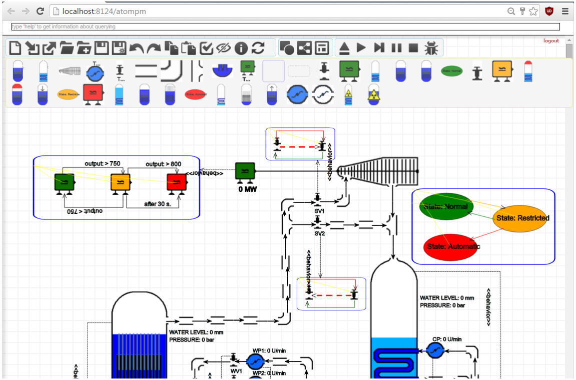
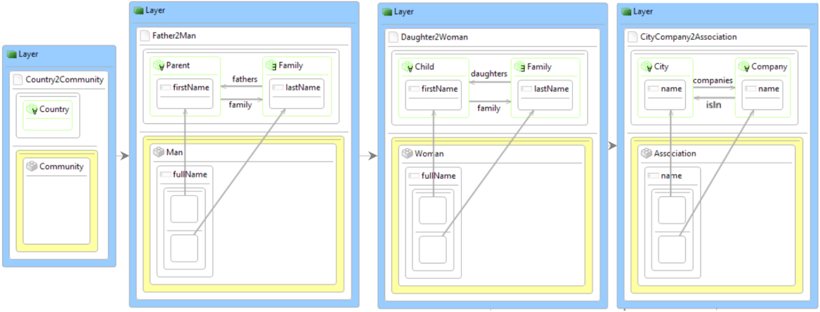
- Model-driven engineering is crucial for creating and understanding complex systems
- Goal: Build a model of a system in the most appropriate language(s) for multiple stakeholders



- Example: A model for simulation/code synthesis/safety analysis of a nuclear reactor (Van Mierlo 2017)
    - Concepts include tanks, pipes, water level, pressure
    - Human-readable, activities possible through model transformation

Model Transformations

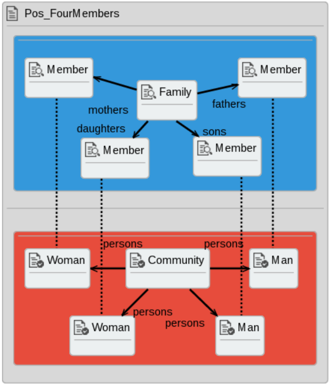
- Problem: Want to have a structured and understandable way to modify/translate/simulate models
- Solution: Use *model transformations*, which are composed of *rules* to manipulate model elements



- Rules are executed in a particular schedule, and *match* elements in the input model to *produce* elements in the output model

Issue: Difficult to understand interactions of rules from examining a transformation

- Problem: Want to understand how an input model to the transformation relates to the corresponding output model
- Solution: Verify pre-/post-condition patterns (*structural contracts*) which guarantee relations and traceability between elements if the contract is *satisfied*



"A *Family* with a *father*, *mother*, *son* and *daughter* should always produce two *Man* and two *Woman* elements connected to a *Community*."

- Result: Combinations of rules where the contract is *satisfied*, and combinations where the contract is *not satisfied*
- Allows the user to better understand the behaviour of the transformation

Research Questions

Five research questions answered by the thesis and this presentation:

Formalization of DSLTrans transformation language

- RQ1) How can the DSLTrans language be precisely formalized?

Transformation verification using contracts

- RQ2) How can the infinite execution possibilities of a DSLTrans transformation be represented in an explicit finite set?
- RQ3)
  - a) How can contracts be proved to be satisfied or non-satisfied on these representations?
  - b) When not satisfied, how do the counter-examples relate to the transformation?

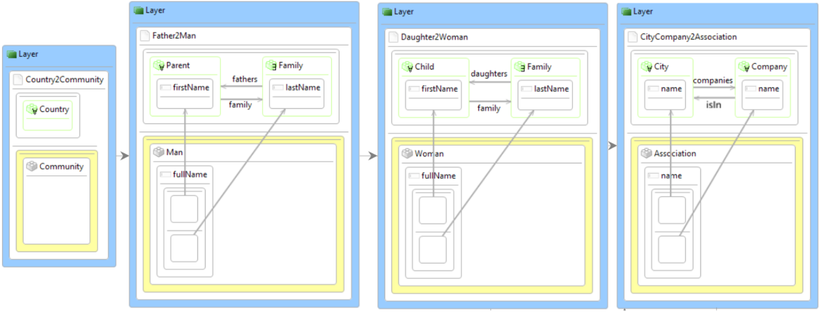
Development of the SyVOLT proving tool

- RQ4) What is the design and work-flow of a contract verification tool?
- RQ5) What are techniques for improving the scalability of the verification tool?

Outline

DSLTrans Overview

- DSLTrans transformation language was conceived by Barroca *et al.* (2011), so not a contribution of the thesis
- Intent was to create a language of limited expressiveness, so that by construction each transformation *terminates* and is *confluent* (rules cannot conflict)

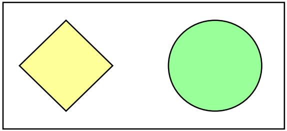


- Rules in DSLTrans are scheduled in *layers*. Rules are fully applied in one layer before moving on
    - Layered nature crucial for understandability and analysability
- Rules provide *traceability links*, to record how elements were built

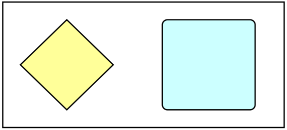
- Problem: Not all constructs of DSLTrans were formally specified
  - Behaviour defined by implementation
- Solution: Describe semantics of DSLTrans in a widely-used model transformation formalization
- Double-pushout approach answers RQ1) *How can the DSLTrans language be precisely formalized?*
- Reasons for selecting the double-pushout approach:
  - Provides elegant (and most appropriate) explanation
  - Aligns semantics with other transformation languages
  - Provides rigour for DSLTrans usability and analysability

- The double-pushout approach divides the application of a rule into the *matching* and *rewriting* stages
- Consider a rule which:
  - Matches on a model with a diamond and a circle
  - Replaces the circle with a rounded square

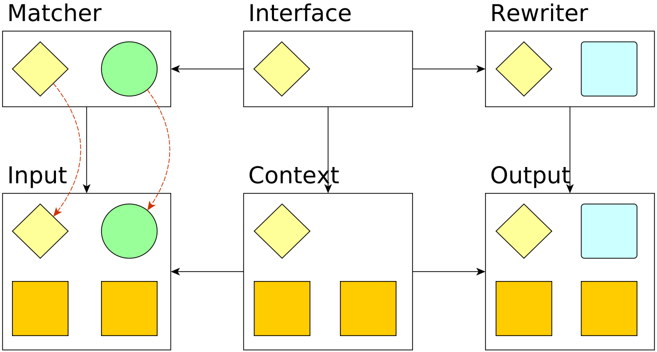
Pre-condition/Matcher / LHS



Post-condition/Rewriter / RHS

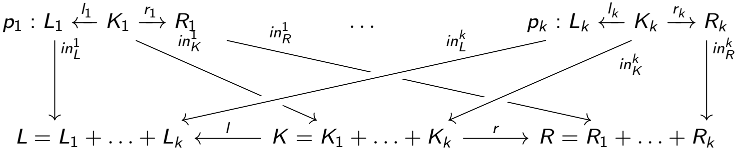


Double-Pushout Approach



- Arrows are *morphisms* between components, providing mappings of nodes and edges
- Element creation is performed through matching and the union operator, termed *push-outs*

- Double-pushout approach allows the creation of elegant *mass productions*
- Technique: Combine the matchers and rewriters of multiple rules



- Allows for all rules in a layer to be applied at once, ensuring they cannot interfere with each other

Formalization Contributions

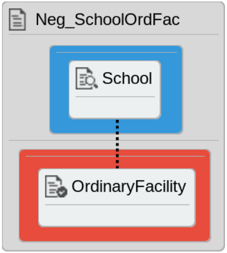
- Precise semantics provided for all DSLTrans constructs in the double-pushout approach
- Examination of termination and confluence properties

Outline

Contract Proving Results

- Verification results indicate which combinations of rules (*path conditions*) *satisfy* or *do not satisfy* each contract
- Allows the user to better understand transformation behaviour

Contract:



"A *School* will always produce an *OrdinaryFacility*"

- Reality: Contract should fail, as a rule exists in the transformation such that *SpecialFacilities* can also be produced

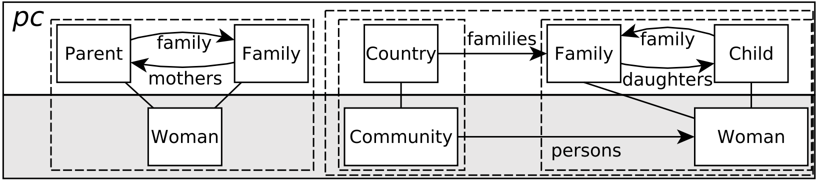
Verification results:

```
a) Name: Neg_SchoolOrdFac
    Num Succeeded Path Conditions: 6
    Num Failed Path Conditions: 3

b) Explaining contract result:
    Good rules: (Rules in success set and not failure set)
        dfacilities...OrdinaryFacilityPerson
    Bad rules: (Rules common to all in failure set)
        dfacilities...SpecialFacilityPerson
```

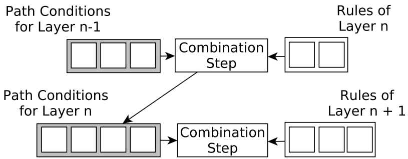
- Answers RQ3 b) When not satisfied, how do the counter-examples relate to the transformation?

- Contract proof is performed on *path conditions*, which represent valid combinations of rule applications
  - Record element presence when rules apply
- First step is to build the path conditions, then the second step is to match the contract onto the path conditions

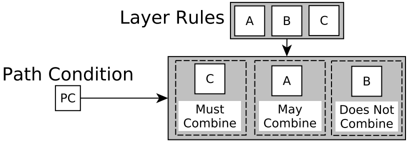


- Example: This path condition represents the application of four rules, where each rule has applied at least once
- Through a formalized *abstraction relation*, this path condition represents an infinite set of transformation executions
  - Abstracts over rule application multiplicity and element overlap
- A set of path conditions answers RQ2: *How can the infinite execution possibilities of a DSLTrans transformation be represented in an explicit finite set?*

- Path conditions are produced through a *symbolic execution* of the transformation's rules, layer-by-layer

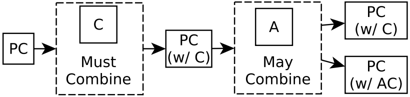


Rules are classified depending on combination with the path condition



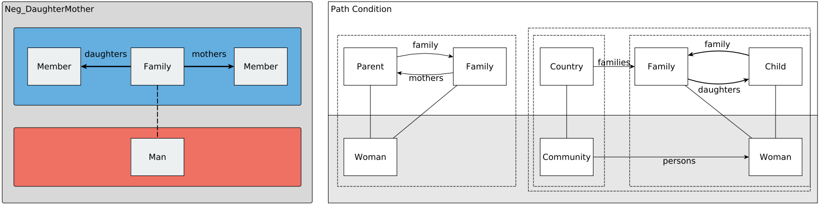
Rule Classification

Combining the rules and path condition creates new path conditions



- Final set of path conditions represents all valid transformation executions

- After path condition generation, the elements in the contracts are matched against the path conditions to determine contract satisfaction
- Answers RQ3: a) How can contracts be proven to be sat
- Issue: In path conditions, unknown whether rule elements overlap or not

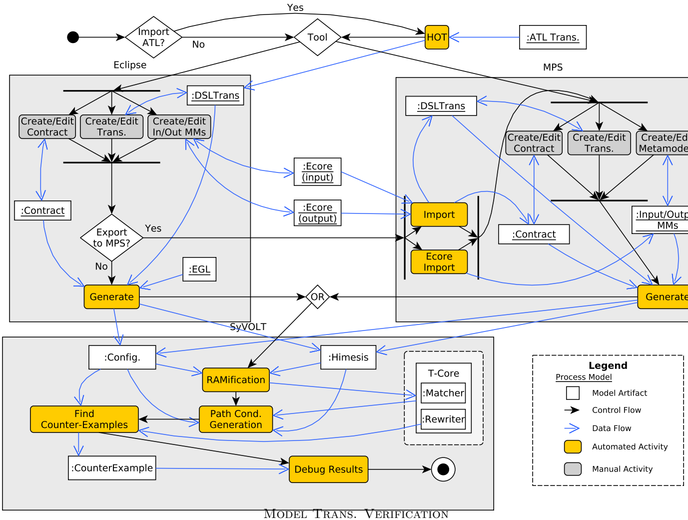


- Major contribution is the "split" morphism for matching contracts and path conditions
  - Allows one contract element to match over multiple path condition elements

Contract Proving Contributions

- Detailed procedure for building the set of path conditions
- Technique for matching contracts onto path conditions to determine counter-examples
- Precise definition for validity of proof result
  - Results of proof on path conditions is related to proof on abstracted transformation executions

- SyVOLT is a tool for contract verification of DSLTrans transformations
- Major contribution of thesis is on efficiency and applicability to industrial-sized transformations
- FTG-PM presented answers RQ4) What is the design and work-flow of a contract verification tool?



Efficiency Techniques

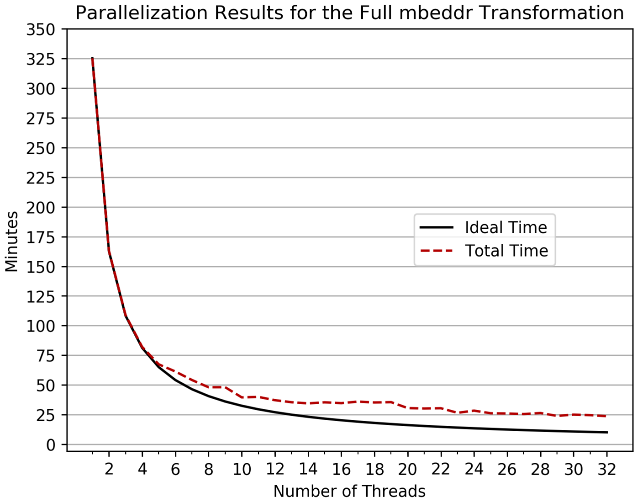
- Thesis presents five case studies ranging from 7 rules to 46 rules
- To improve the scalability of the tool, three efficiency techniques are presented:

- Parallelization
- Slicing
- Pruning

Answers RQ5) What are techniques for improving the scalability of the verification tool?

Parallelization

- Idea: Employ multiple threads to speed up tool
- Technique: Divide path condition generation and contract proving amongst multiple threads
- Results on the 32-core supercomputer for the largest case study of 46 rules:

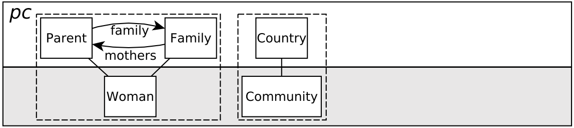


- Idea: Instead of symbolically executing all rules, select the rules relevant to a contract
- Technique: Match elements from contract onto rules to find dependencies
- Speed-up: 3.8x - 72.6x
- Trade-off between generating all path conditions, and smaller set for one contract

Contract Name	**Rules**	**Path Conds.**	**Total Time (s)**
Full	19	4916	59.18
CityCompany	8	43	0.30
CountryCity	6	10	0.13
SchoolOrdFac	5	17	0.17
DaughterMother	9	64	0.43
AssocCity	9	64	0.35
ChildSchool	5	17	0.17
FourMembers	9	64	0.43
MotherFather	9	64	0.45
ParentCompany	5	18	0.16
TownHallComm	11	184	0.86

Pruning

- Idea: Remove invalid path conditions to decrease state space
- Technique: Check if path conditions violate meta-model containment restrictions
  - Example: A meta-model requires that all *Woman* elements are contained in a *Community* through a *persons* link
  - If a *Woman* element exists, but is not connected by a *persons* link, then that path condition is invalid as it doesn't represent a valid output model



- Speed-up: 0.9x - 14.2x
- Warning: Pruning can change contract satisfaction results
  - Counter-examples to a contract can be pruned away

SyVOLT Contributions

- Development of an efficient and scalable contract verification tool
- Detailed presentation of core algorithms and efficiency techniques, their complexity, and advantages/disadvantages
- Examination of multiple case studies (toy to industrial) with results of contract proof

Outline

Conclusion

Thesis provides end-to-end approach to contract verification

- Semantics provided for DSLTrans enables precise usage and verification for all structures
- Contract verification approach efficiently determines counter-examples to contracts, offering insight into transformation behaviour
- Algorithmic design and implementation of a contract prover, which is scalable to industrial-sized transformations

Future Work

- Investigate how symbolic execution and contract proving approach can be transferred to other transformation languages
- Explore assisting the user in systematically creating contracts to verify transformations
  - Promote "contract-based design" of model transformations, with continuous verification

Thank you for your time and attention

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B. Oakes, L. Lúcio, C. Gomes, and H. Vangheluwe. Expressive Symbolic-Execution Contract Proving for the DSLTrans Transformation Language. Technical Report SOCS-TR-2017.1, McGill University, 2017.

B. Oakes, J. Troya, L. Lúcio, and M. Wimmer. Full Contract Verification for ATL using Symbolic Execution. *Software and Systems Modeling*, pages 1–35, 2016.

B. Oakes, J. Troya, L. Lúcio, and M. Wimmer. Fully Verifying Transformation Contracts for Declarative ATL. In *International Conference on Model Driven Engineering Languages and Systems*, pages 256–265, 2015.

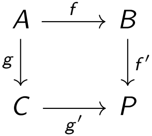
L. Lúcio, **B. Oakes**, C. Gomes, G. Selim, J. Dingel, J. Cordy, and H. Vangheluwe. *SyVOLT: Full Model Transformation Verification using Contracts*. In *International Conference on Model Driven Engineering Languages and Systems*, pages 24–27, 2015.

G. Selim, J. Cordy, J. Dingel, L. Lúcio, and **B. Oakes**. *Finding and Fixing Bugs in Model Transformations with Formal Verification: An Experience Report*. In *Proceedings of Analysis of Model Transformations workshop at Model Driven Engineering Languages and Systems*, pages 26–35, 2015.

L. Lúcio, **B. Oakes**, and H. Vangheluwe. *A Technique for Symbolically Verifying Properties of Graph-based Model Transformations*. Technical Report SOCS-TR-2014.1, McGill University, 2014.

G. Selim, J. Cordy, J. Dingel, L. Lúcio, and **B. Oakes**. *Specification and Verification of Graph-Based Model Transformation Properties*. In *Proceedings of International Conference on Graph Transformation*, pages 113–129, 2014.

Pushout Explanation

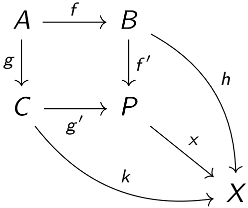


P is a pushout over the morphisms $f : A \to B$ and $g : A \to C$ defined by:

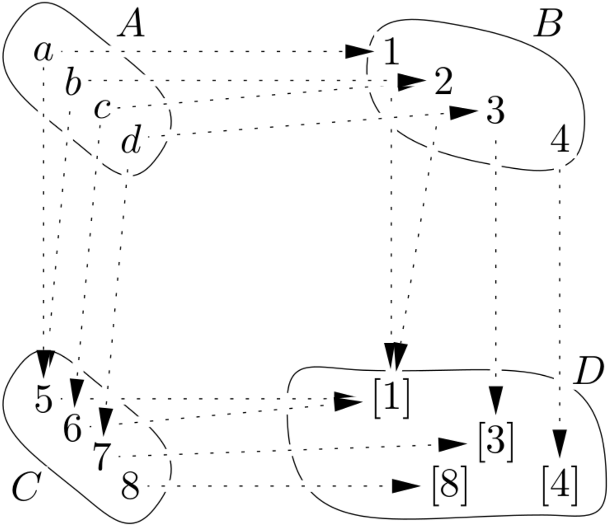
- a pushout object P
- the morphisms $f' : B \to P$ and $g' : C \to P$ with $f' \circ g = g' \circ f$

Definition

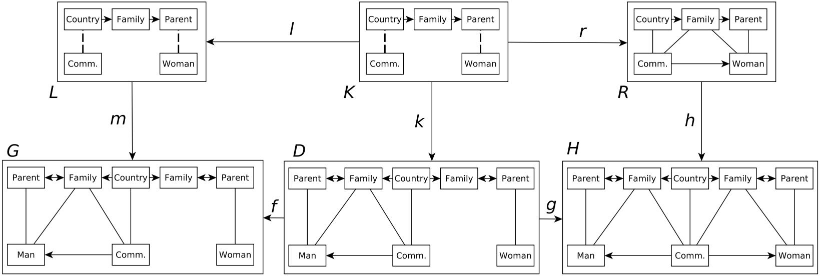
Universal Property
For all objects X, morphisms $h : B \to X$, $k : C \to X$ with $k \circ g = h \circ f$:
there is a unique morphism $x : P \to X$ with $x \circ g' = h$ and $x \circ f' = k$.

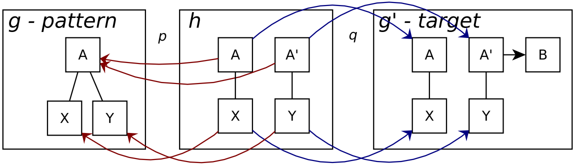


Pushout Example



Double-Pushout Approach Example

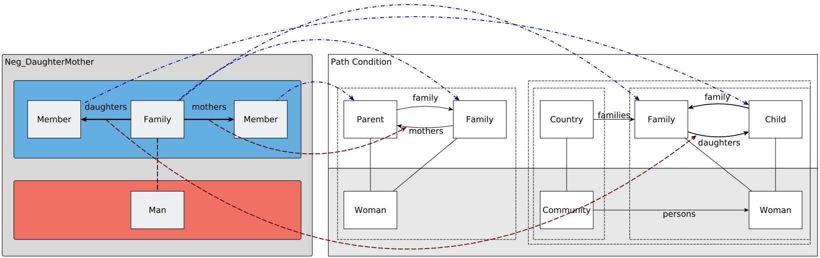




Issue: Need one pattern node to be matched to two target nodes

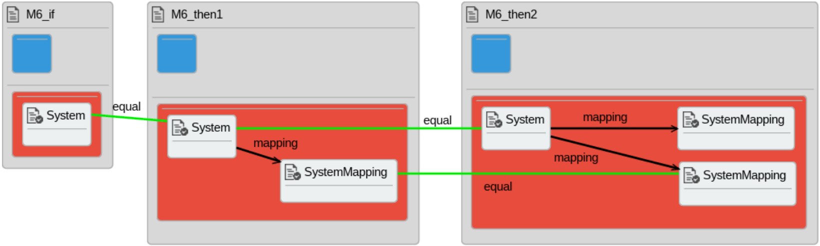
Requirements:

- Pattern nodes are totally matched
- One pattern node to multiple target nodes
  - Attributes must be matched
- Edges must be one-to-one



- The issue is that we are representing rule application, but not all possible ways rules can match over the same elements
- This is prohibitively expensive to calculate explicitly
- This structural information is discarded in the split morphism, allowing the contract to "split" over the path condition, and consider the *Family* elements to be unified

- Contracts can only express very basic structural information
  - Constructs available: *And*, *Or*, *If-Then*, *Not*, *pivots*
  - Can't represent universal operators ("for all element A's, B's must be attached"), or temporal properties
- Multiplicity is unintuitive



If a *System* element exists in the output model, then that *System* element should be connected to a *SystemMapping* element, and not (always) connected to two *SystemMapping* elements

- Language not placed in formal logic (first-order, second-order) framework
- Future work: Replace contract language with another, rather than improve