Techniques for Debugging Model-Transformation Failures

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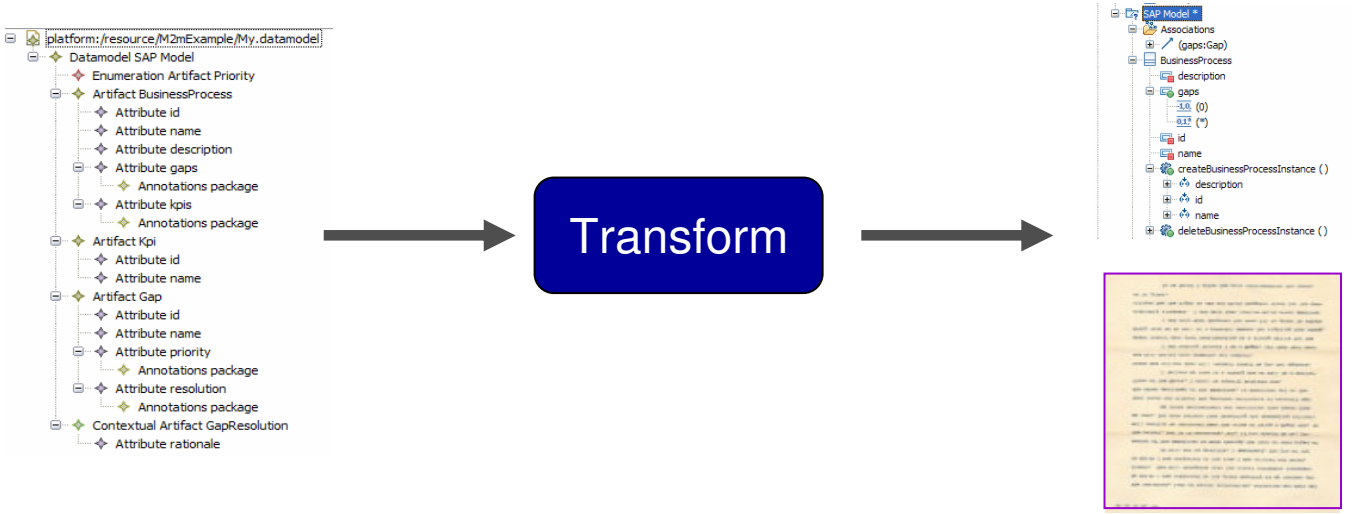
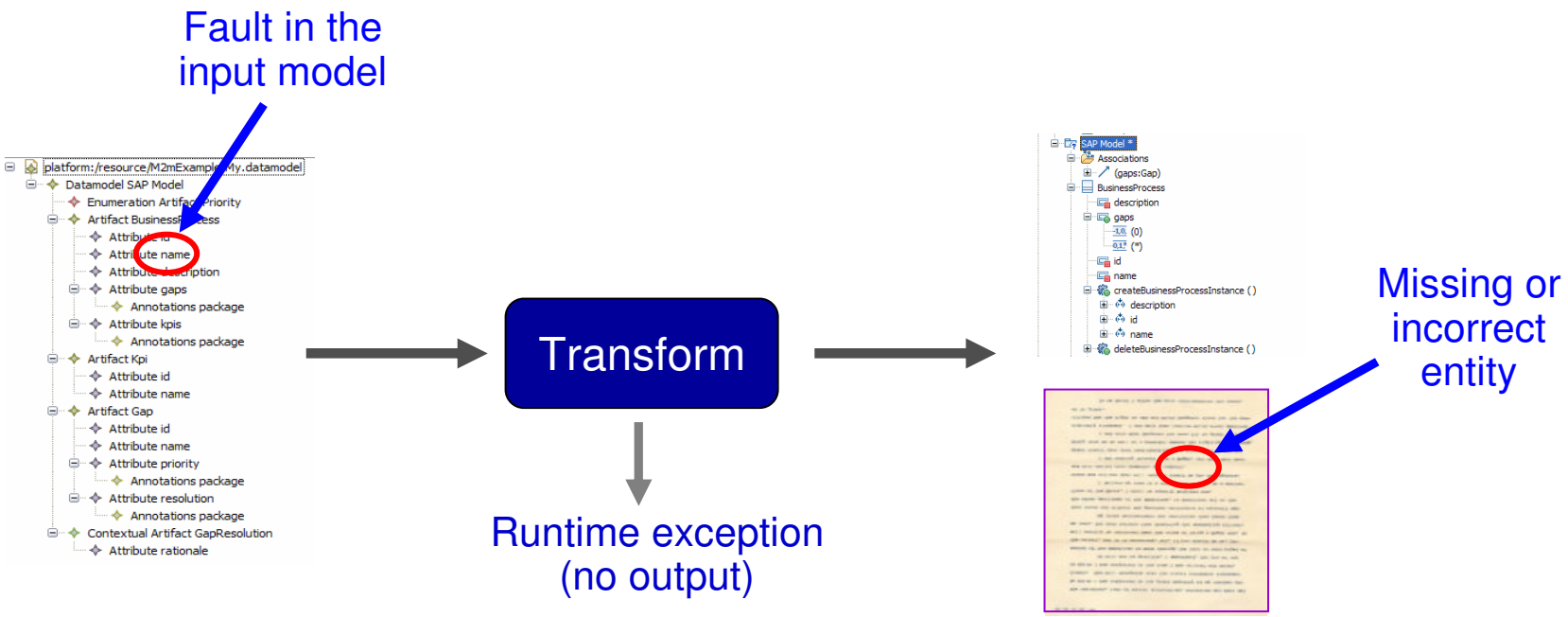
Model Transformation

- A *transform* is an application that converts a model to another model or to text
  - A model is a set of structured data captured in a well defined notation
  - Text output could be configuration files, code, XML, etc.



Model Transformation: Failing Executions



- What is wrong in the input model that caused the failure? (Fault localization)
- How can the faulty model be fixed? (Fault repair)
- Is an input model valid for a transform? (Model validation)

Investigating Model-Transformation Failures

- Transform-user perspective: Goal is to locate input-model faults
  - Some faults can be detected automatically (e.g., faults that violate metamodel constraints)
  - Other faults cannot be detected using model validators
- Limitations of conventional fault-localization techniques
  - Most techniques focus on program faults
  - Some techniques identify failure-relevant inputs (delta debugging, Penumbra)
- Model traceability techniques not applicable to a large class of input-model faults
  - Faults that cause an incorrect path to be traversed in the failing execution
  - Faults that result in missing output entities
  - “Missing input-model entity” faults

Techniques for Investigating Model-Transformation Failures

- Combination of static analysis and dynamic analysis
- Static analysis for model validation
  - Infers code-level constraints from the transform code
  - Maps constraints to metamodel-level rules
  - Rules can be used to construct model validators

  Demystifying model transformations: An approach based on automated rule inference. *OOPSLA 2009*
- Dynamic analysis for fault localization
  - Performs dynamic taint analysis to track flow of information from input model to output
  - Enables iterative fault localization on the input model

  Debugging model-transformation failures using dynamic tainting. *ECOOP 2010*
- Dynamic analysis for fault repair
  - Collects metadata about accesses to model entities, conditionals, and loops
  - Performs pattern analysis over output taint log

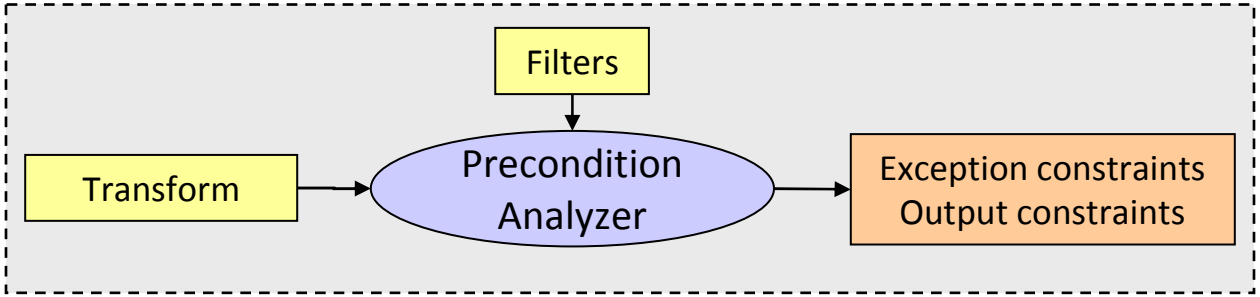
  Automated support for repairing input-model faults. *ASE 2010* (*under review*)

Outline of the Talk

- Static analysis for model validation
- Dynamic-tainting-based fault localization
  - Failure scenarios, example
  - Description of technique
  - Empirical evaluation
- Dynamic analysis for fault repair
- Summary and future work

Static Analysis for Model Validation: Overview of Approach

Step 1: Constraint Inference



Example Model-to-Model Transform

```
<model
 <artifacts name="BusinessProcess">
  <attributes name="id" />
  <attributes name="name" type="integer"/>
 </artifacts>
</model>
```

Input Model

```
public void execute( EObject source, EObject target )
{
 1. Attribute attr = (Attribute)source;
 2. Property prop = (Property)target;
 3. PrimitiveType ptype = null;
 4. if ( attr.getName() != null ) {
 5.     String type_src = attr.getType();
 6.     if ( type_src.equals("String") )
 7.         ptype = UMLUtilities.findType(...);
 8.     if ( ptype != null )
 9.         prop.setType(ptype);
 ...
```

Example Model-to-Model Transform

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Failing Execution

```
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 <artifacts name="BusinessProcess">
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  <attributes name="name" type="integer"/>
 </artifacts>
</model>
```

Input Model

Missing entry for "type"

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Null Pointer Exception

Precondition Analysis: Exception Constraints

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6 type_src = null

Precondition Analysis: Exception Constraints

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5 attr != null
attr.getType() = null

6 type_src = null

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4 attr.getName() != null
attr != null
attr.getType() = null

5 attr != null
attr.getType() = null

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Precondition Analysis: Exception Constraints

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```

1: source.getName() != null
source != null
source.getType() = null

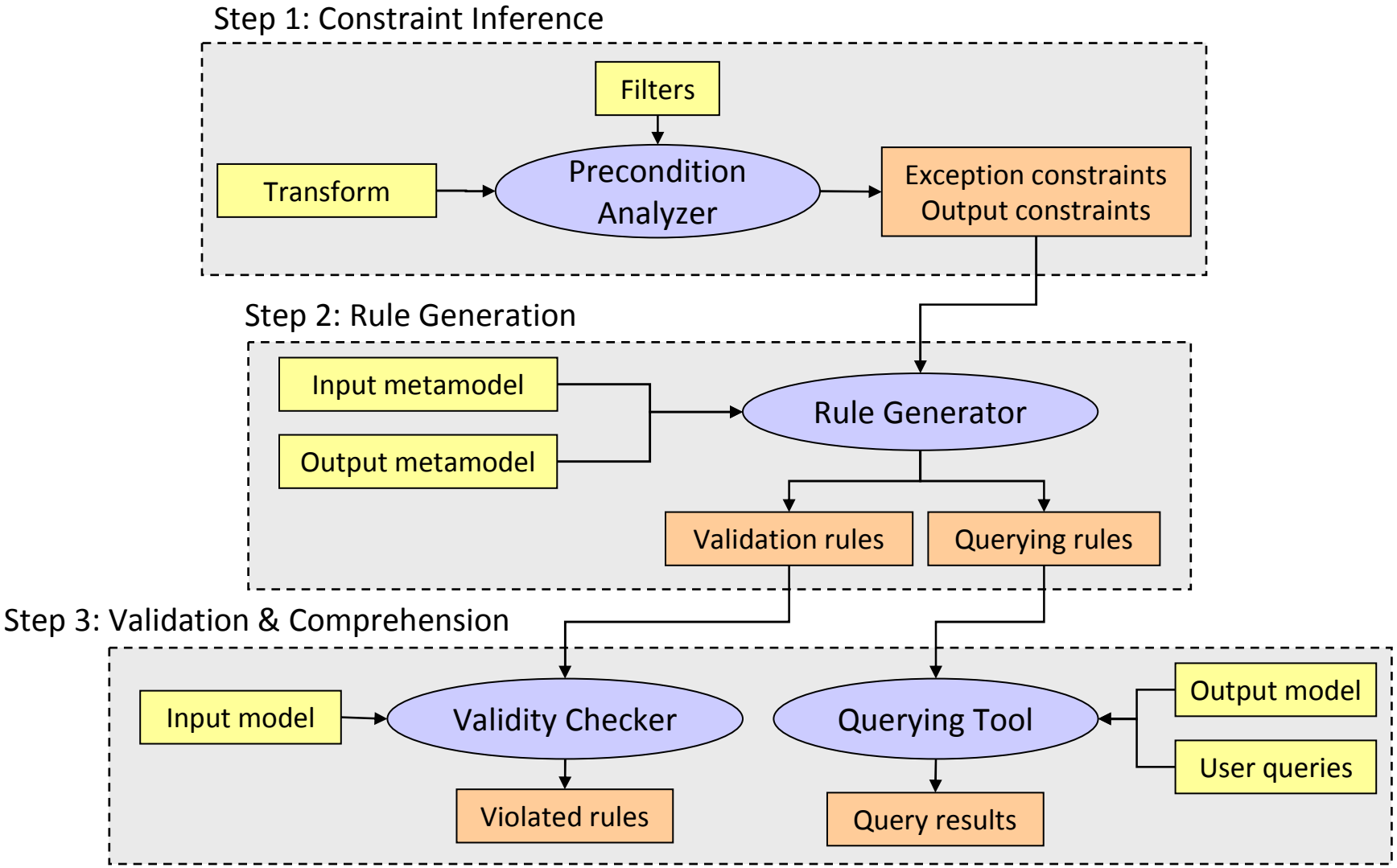
4: attr.getName() != null
attr != null
attr.getType() = null

5: attr != null
attr.getType() = null

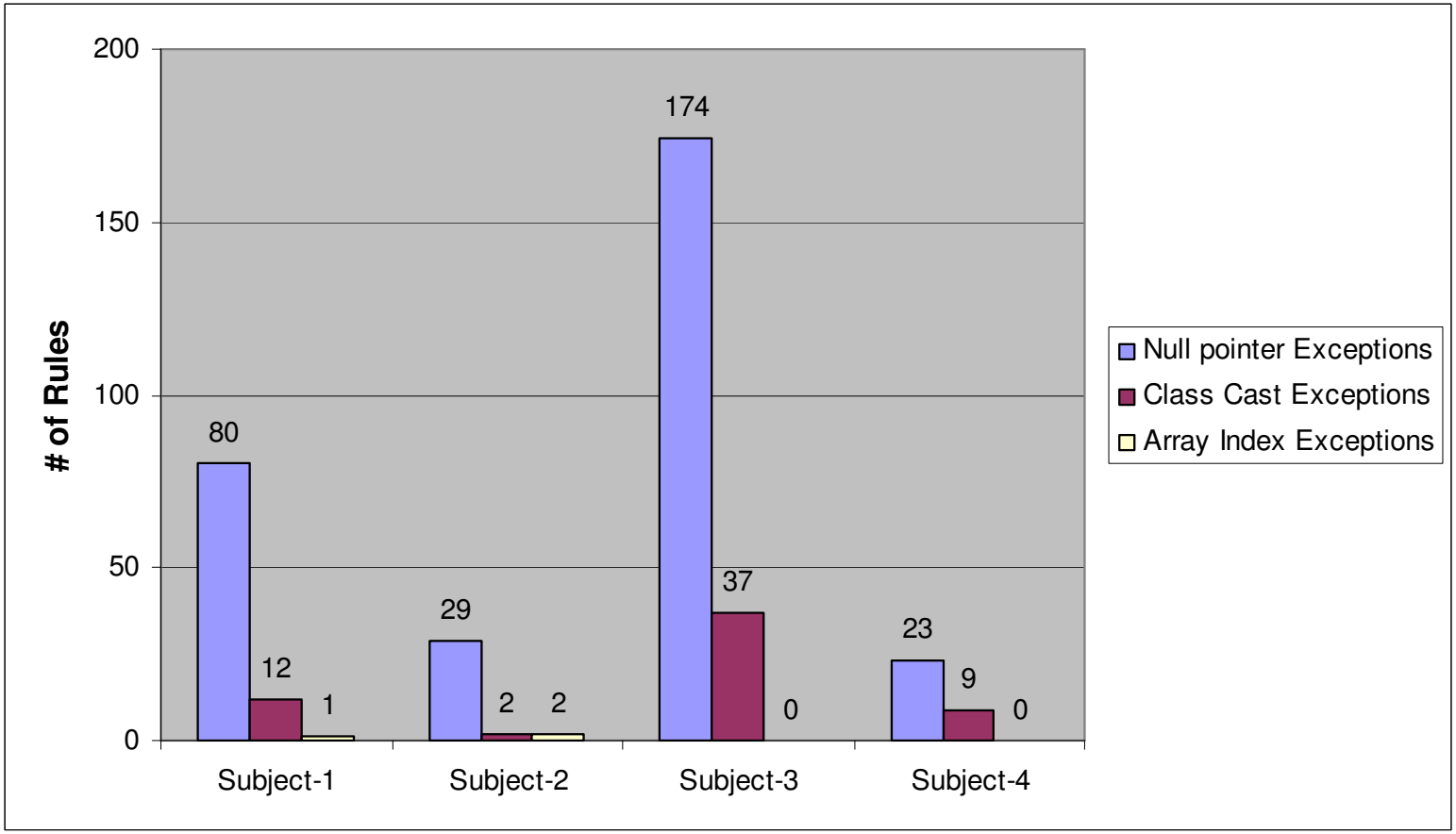
6: type_src = null

source.getName() != null
source != null
source.getType() = null
$\Longrightarrow$ Null pointer Exception at Line 6

Static Analysis for Model Validation: Overview of Approach

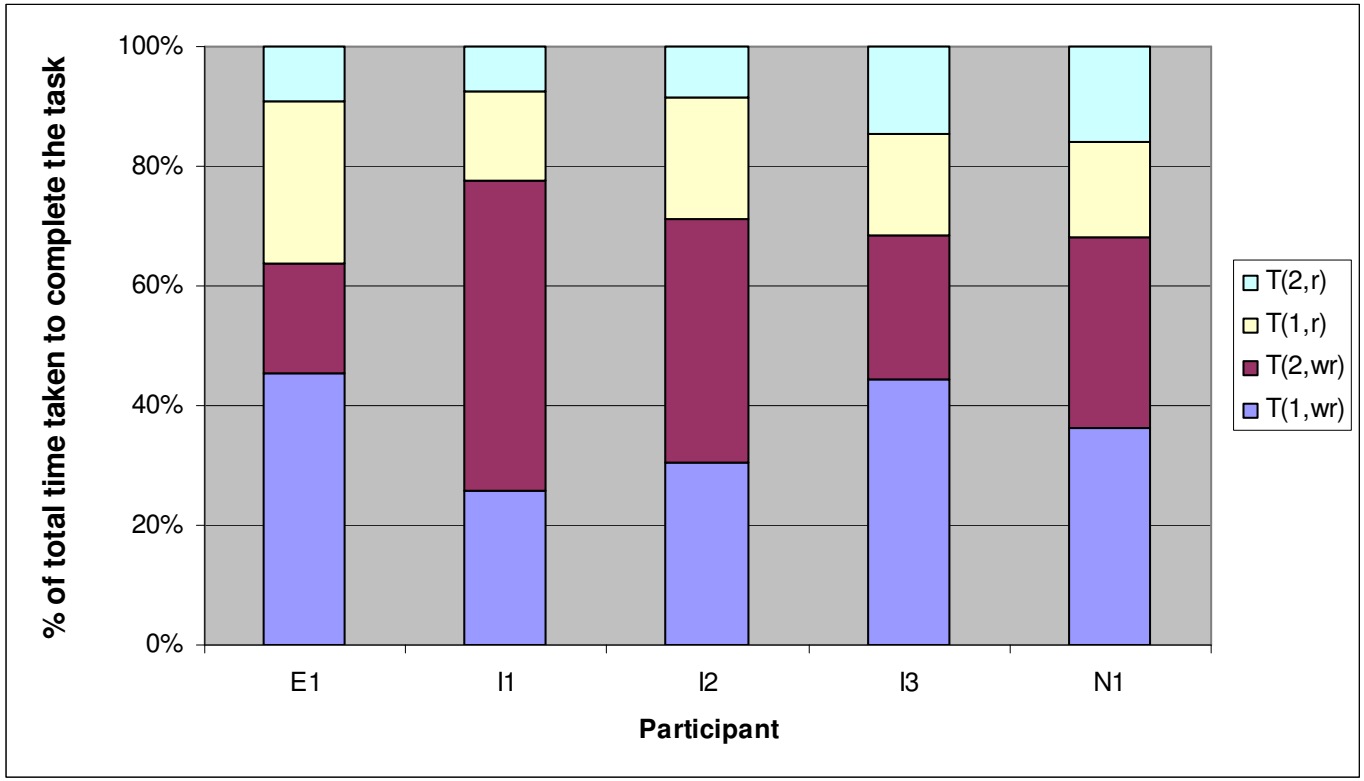


Inference of Validation Rules



- Total of 369 validation rules
  - 306 rules for null-pointer exceptions, 60 rules for class-cast exceptions, 3 rules for array-index exceptions

Debugging Efficiency with and without Rules

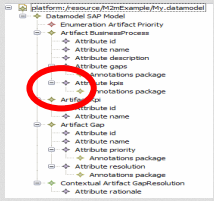


- On average, the participants spent
  - 62 – 78% of the time in fixing the input model without the rules
  - 38 – 22% of the time when using the rules

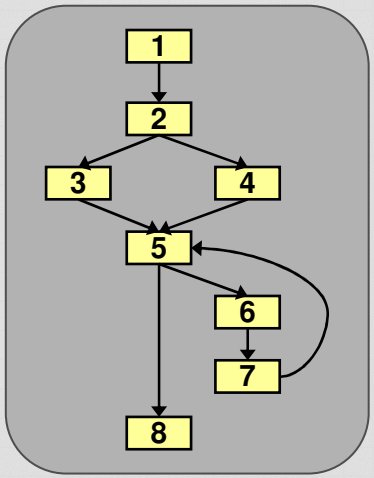
Transformation-Failure Scenarios

Fault

Incorrect value

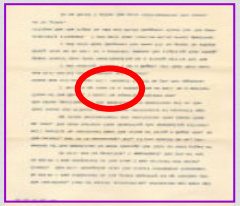


Fault propagation



Failure

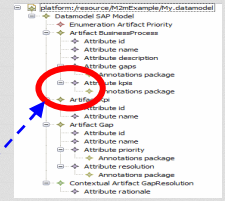
Incorrect string



Transformation-Failure Scenarios

Fault

Incorrect value



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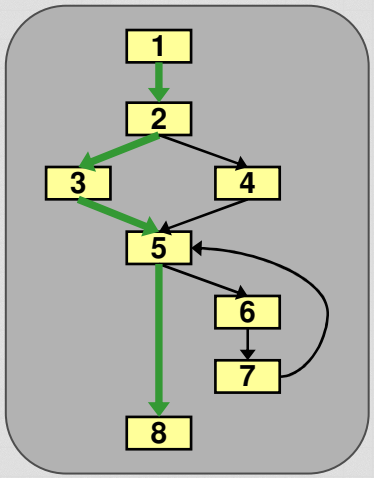

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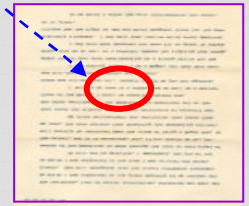
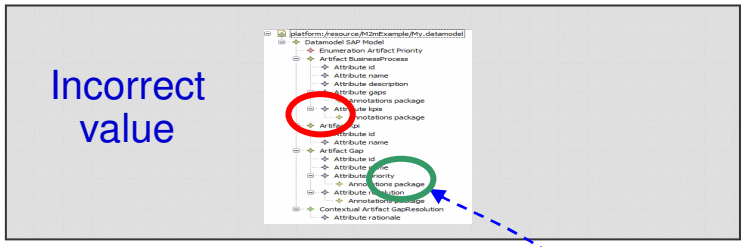


Transformation-Failure Scenarios

Fault



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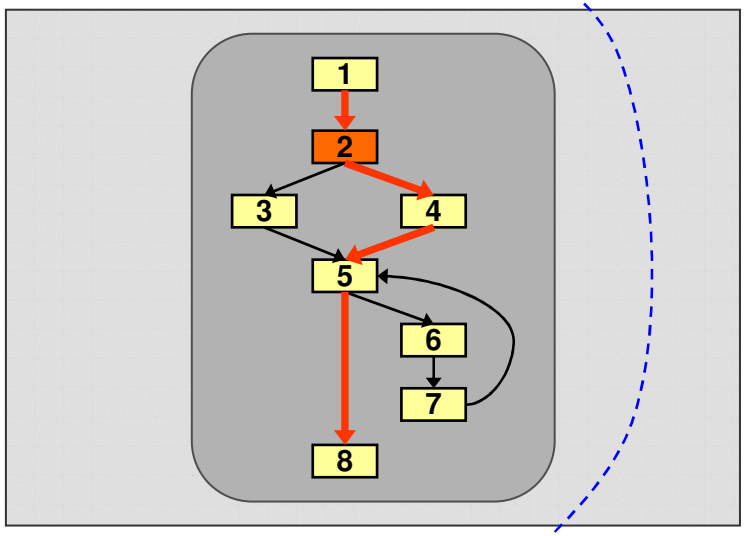

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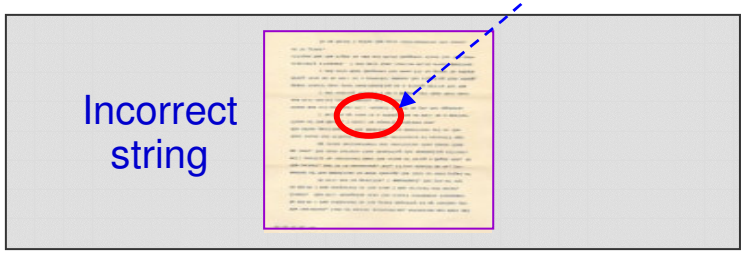

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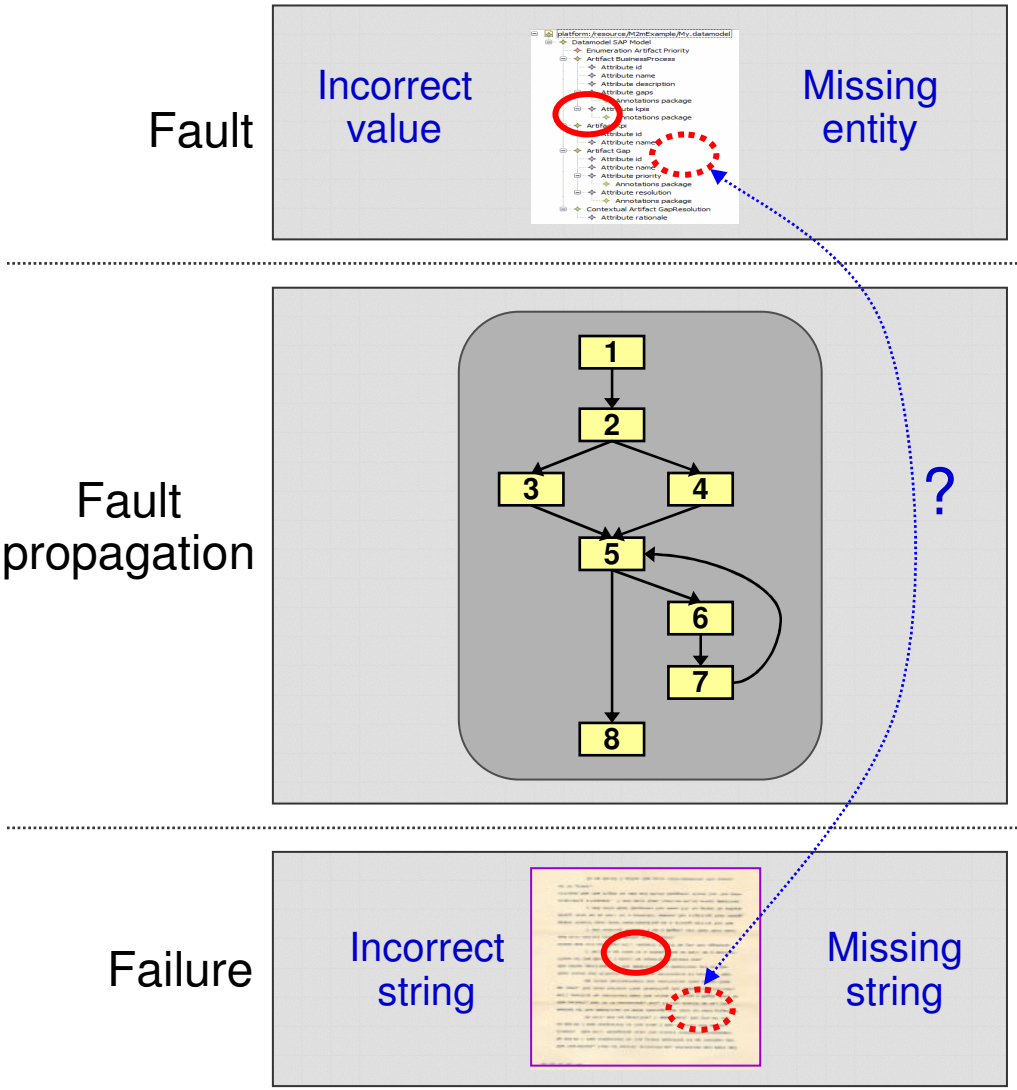

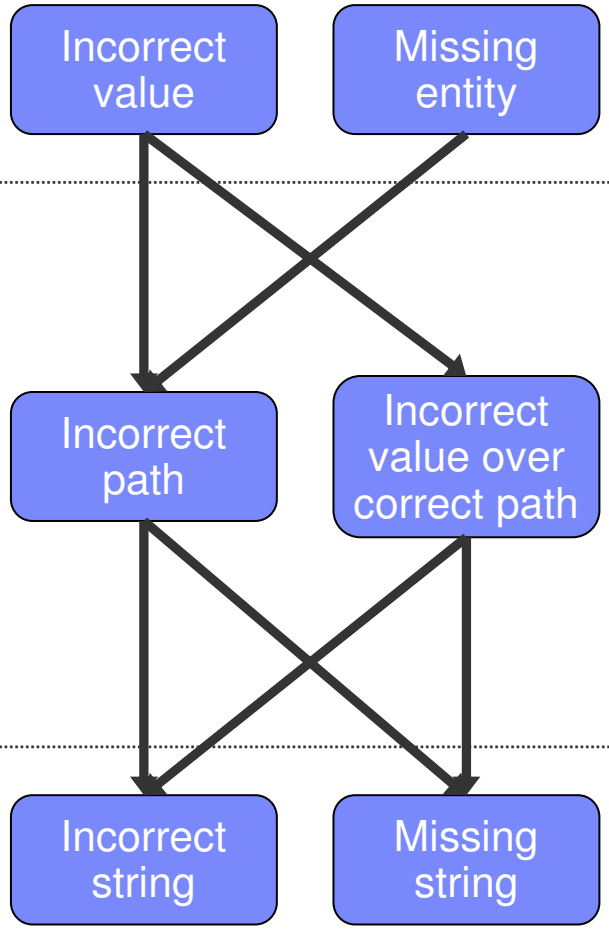

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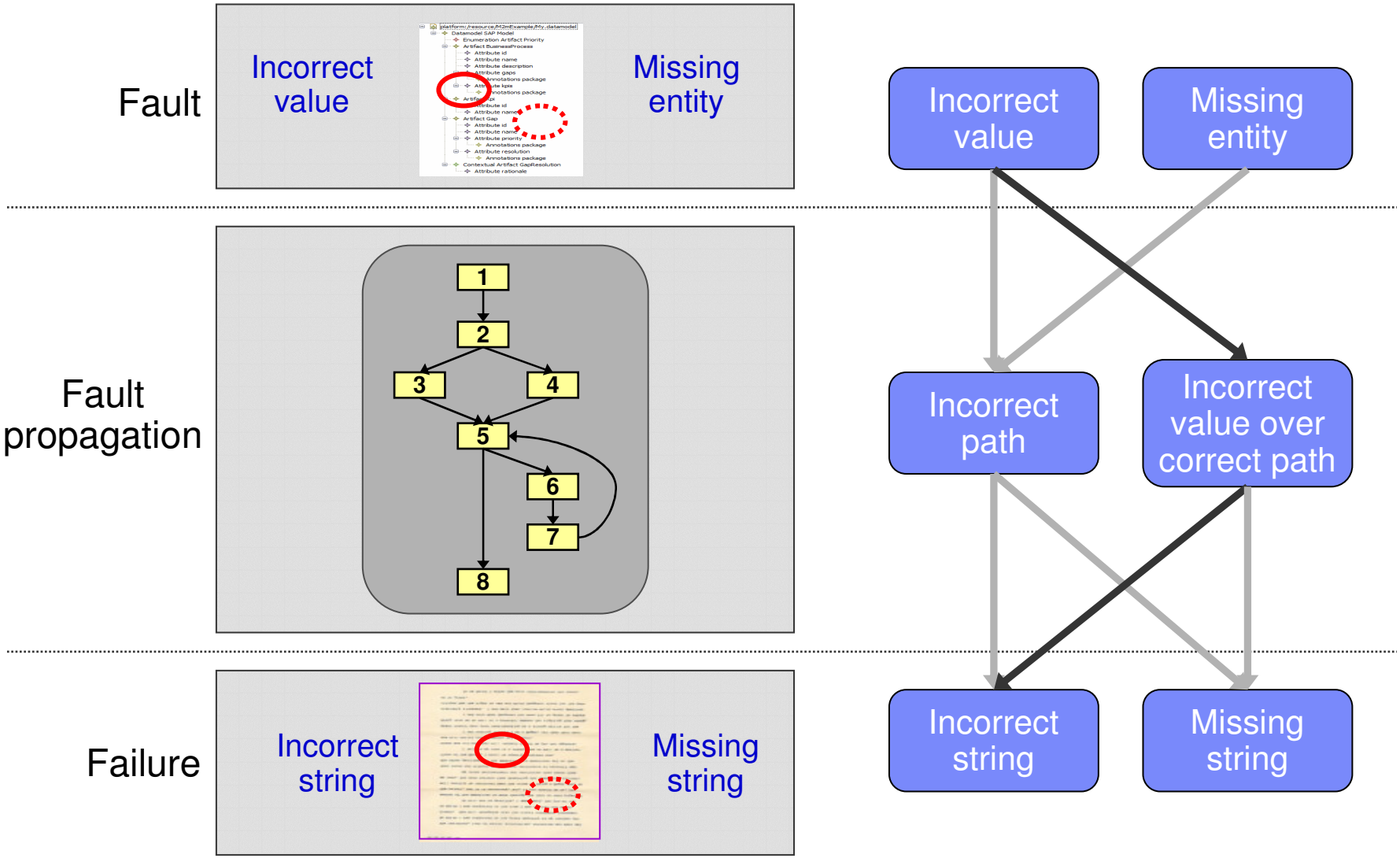
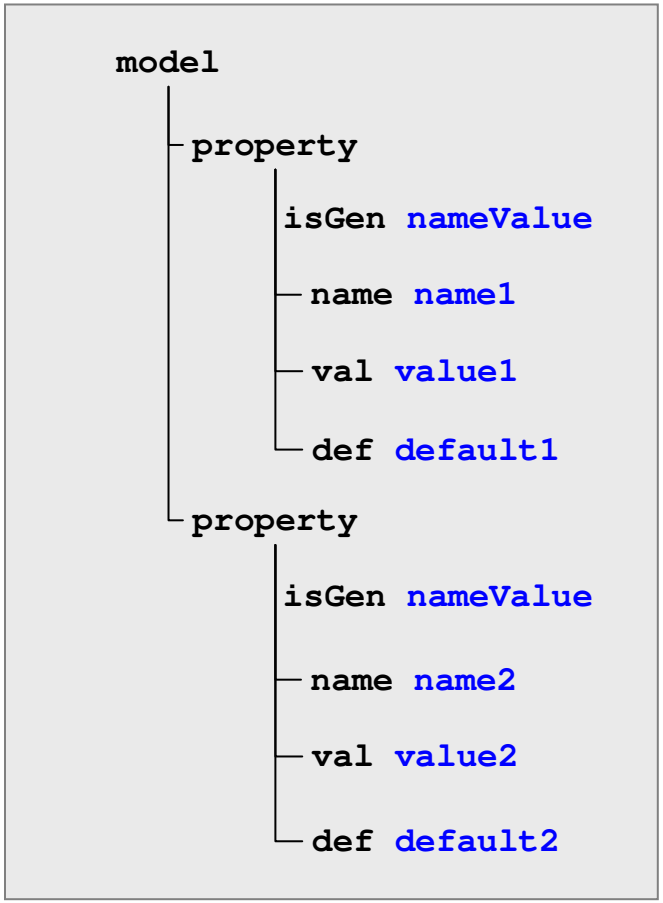


Example Model-to-Text Transform

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Function ApplyModel(Element model)
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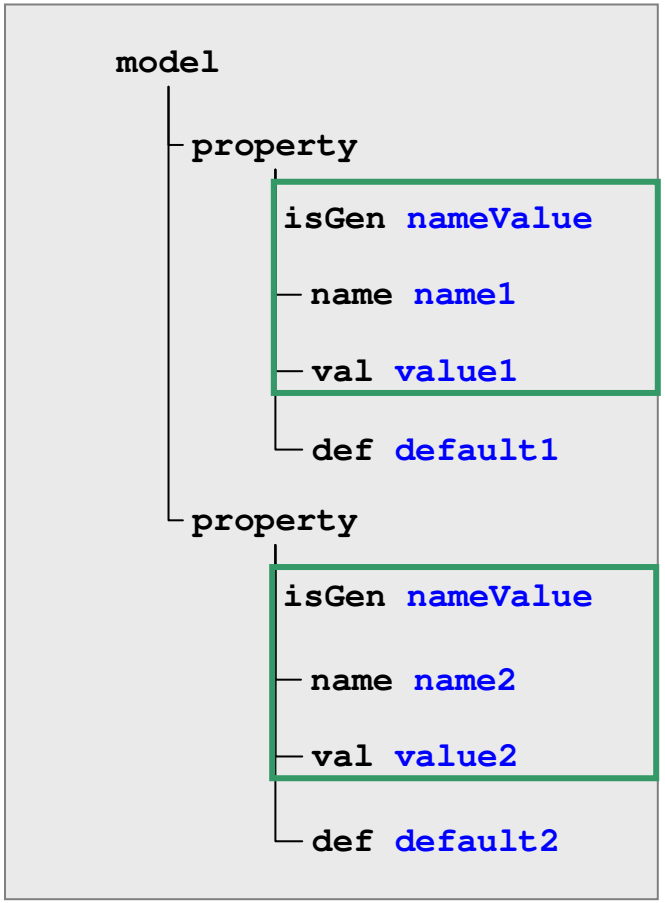


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```
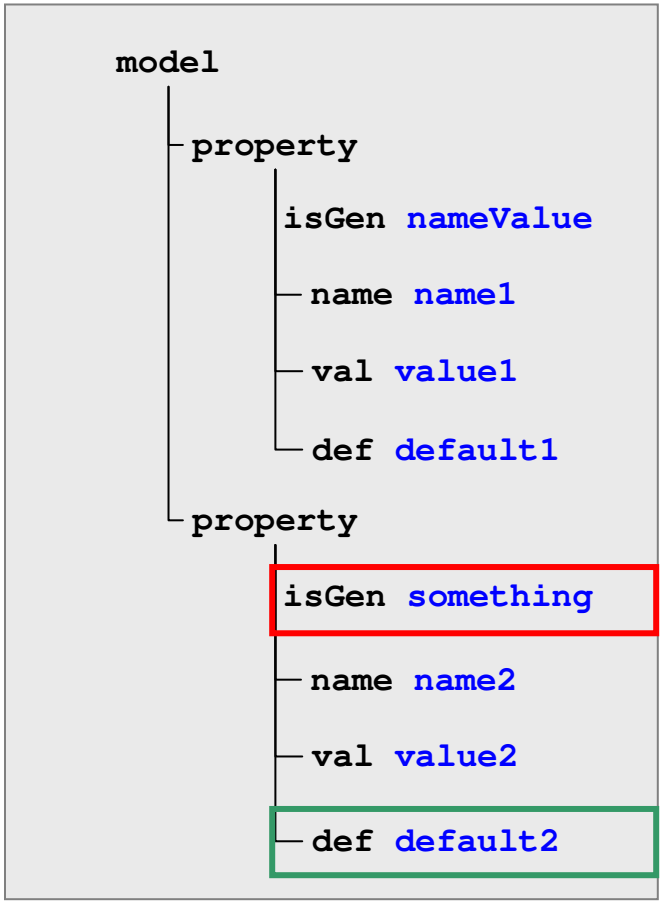

```
name1=value1
value2=value2
```

Failure-inducing Input

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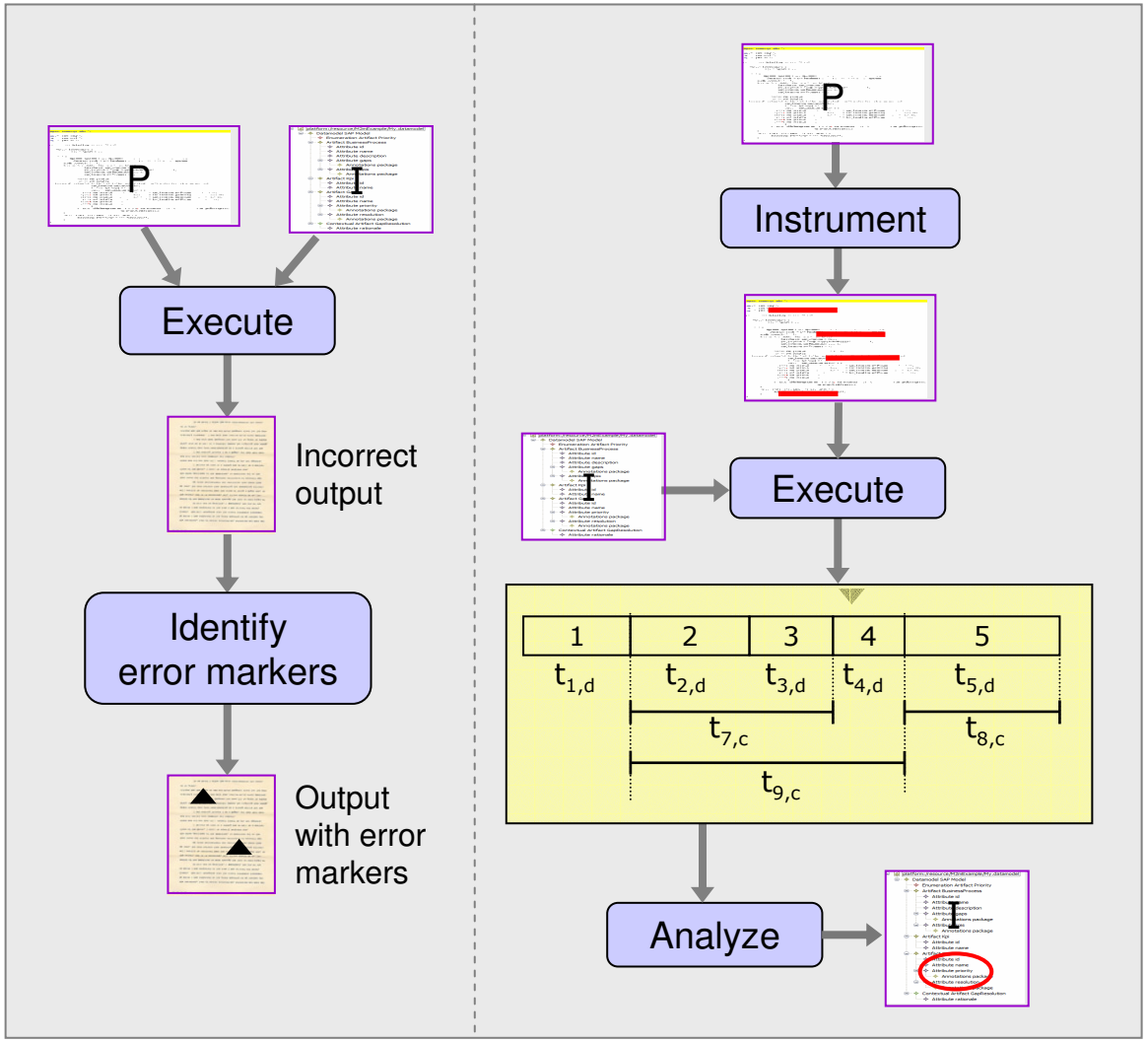
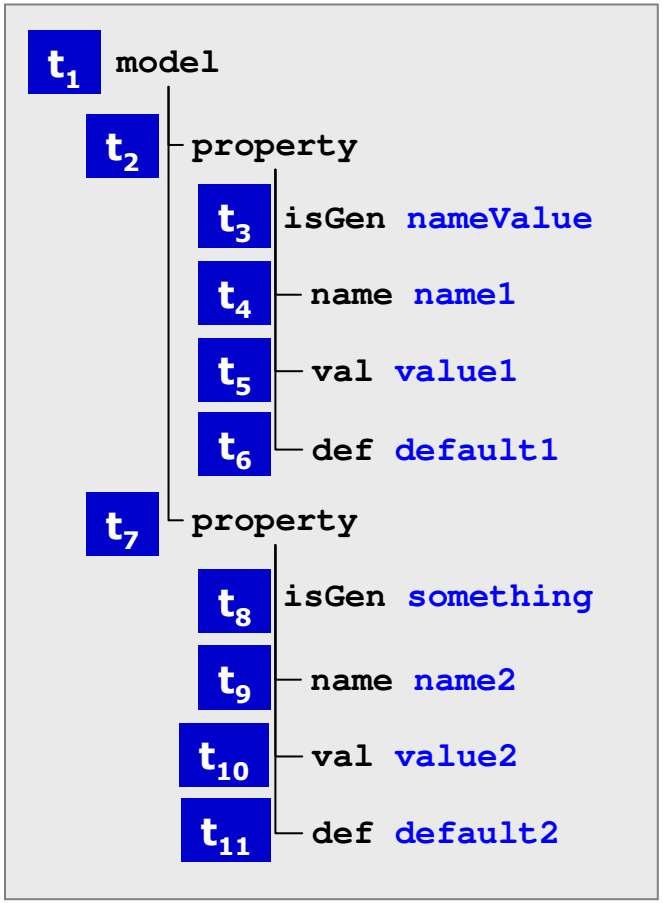
```
name1=value1
default2
```

Dynamic Analysis for Fault Localization: Overview of Approach

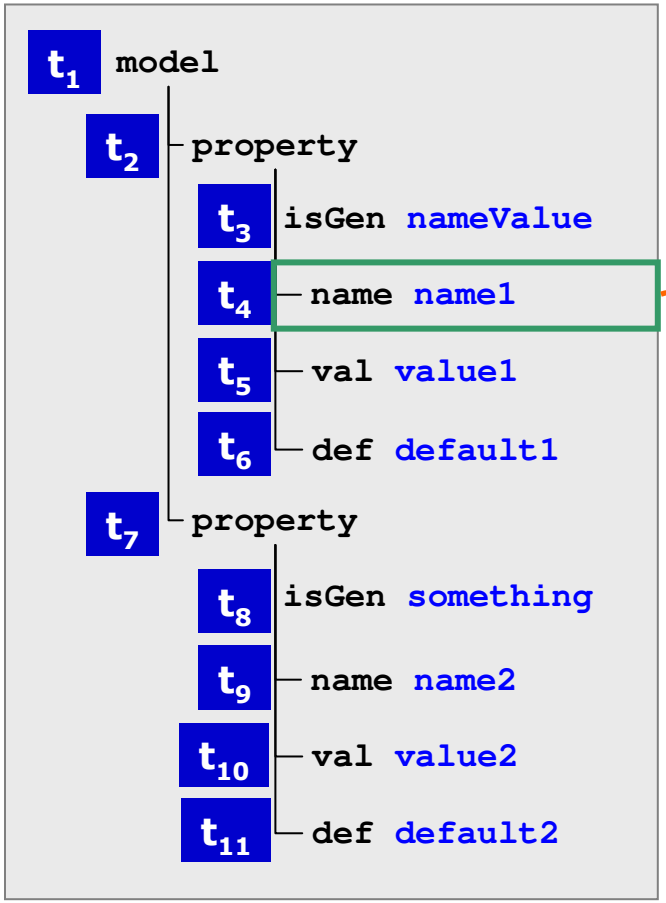


- Taint Initialization
  - Associate taint marks with input-model entities
- Taint Propagation
  - Propagate taint marks to the output string
  - Classify taint marks (data, control, loop)
- Taint-log Analysis
  - Compute the fault space incrementally

Taint Initialization



Taint Propagation (Data Taints)

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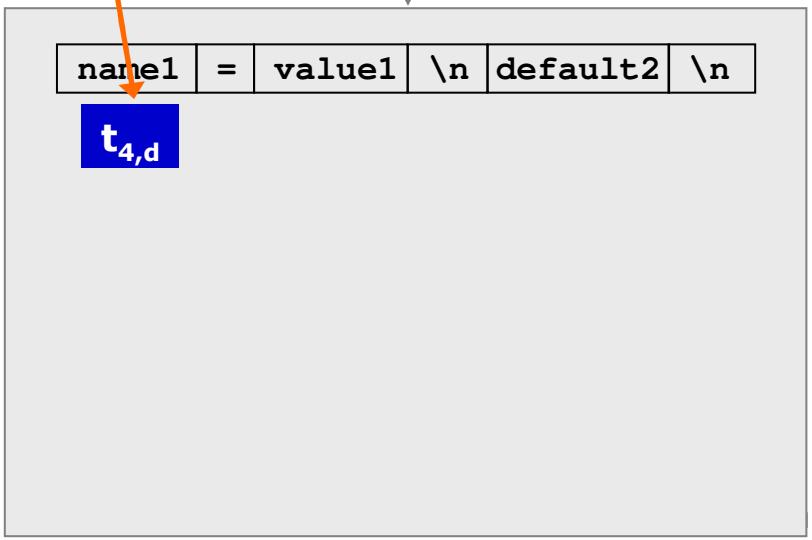

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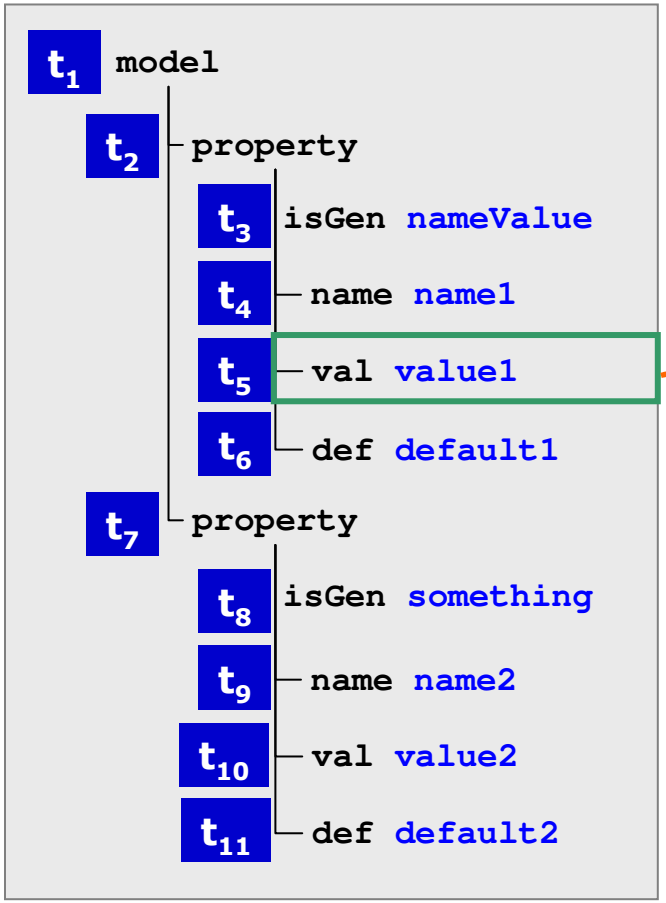


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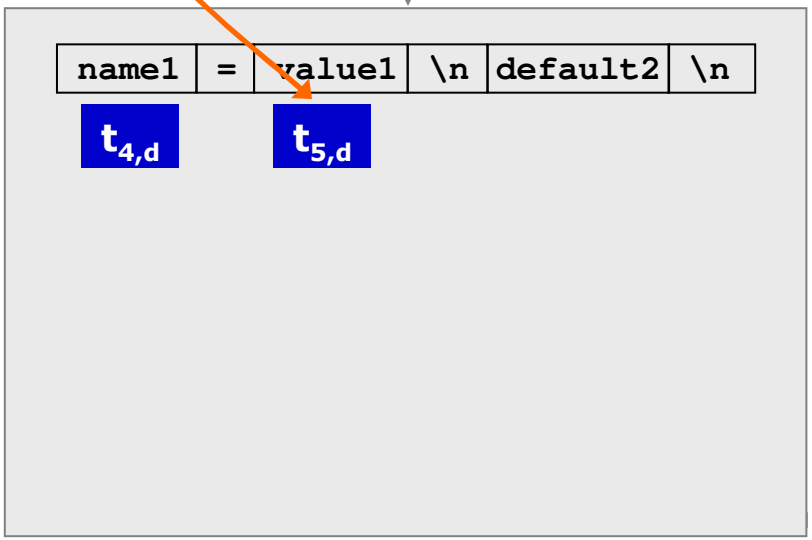

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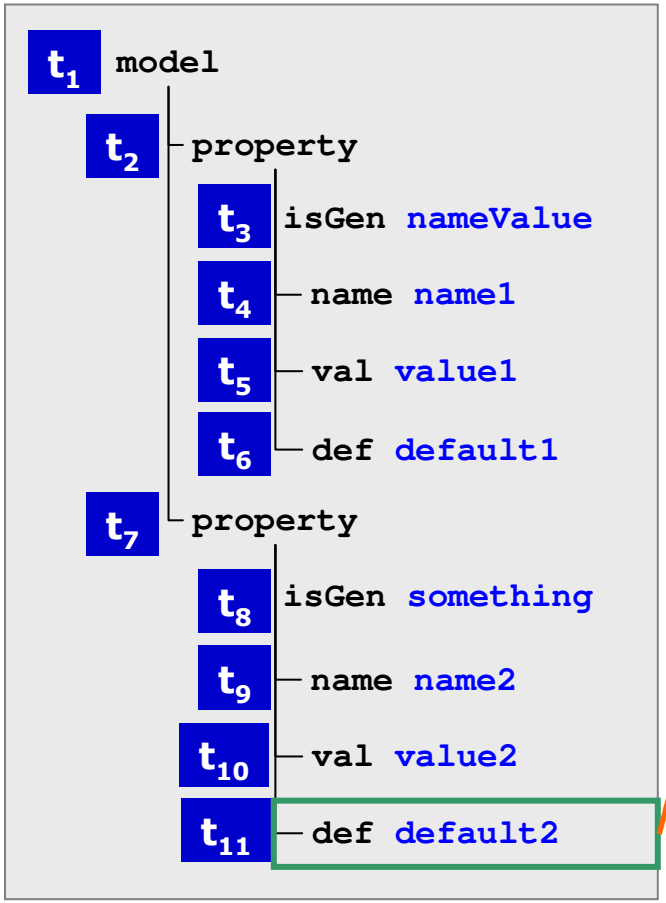


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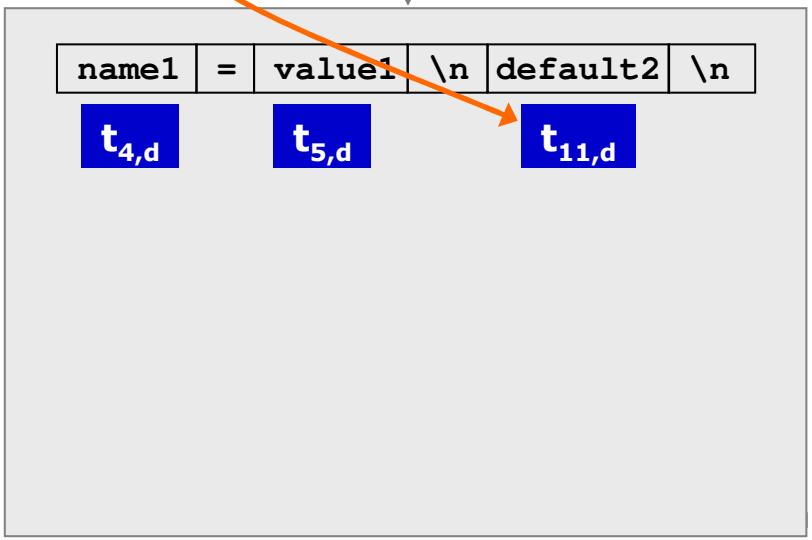
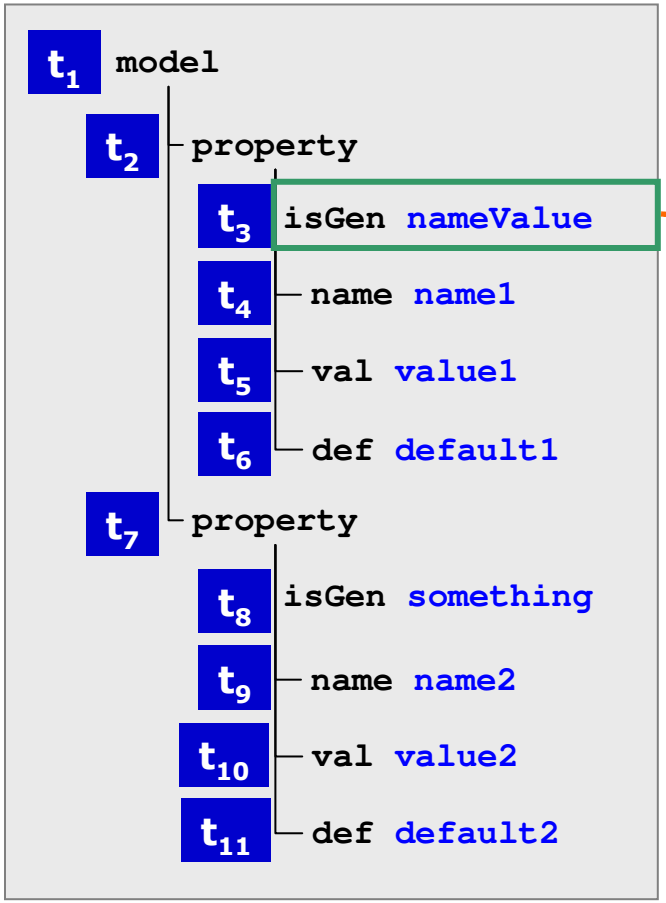


Taint Propagation

- Data taint marks
  - Create traceability for value propagation from input model to output model
  - Propagated at each assignment statement and statement that constructs the output string
- Control taint marks
  - Create traceability for input model entities that influence the outcome of predicates
  - Propagated at conditional statements

Taint Propagation (Control Taints)

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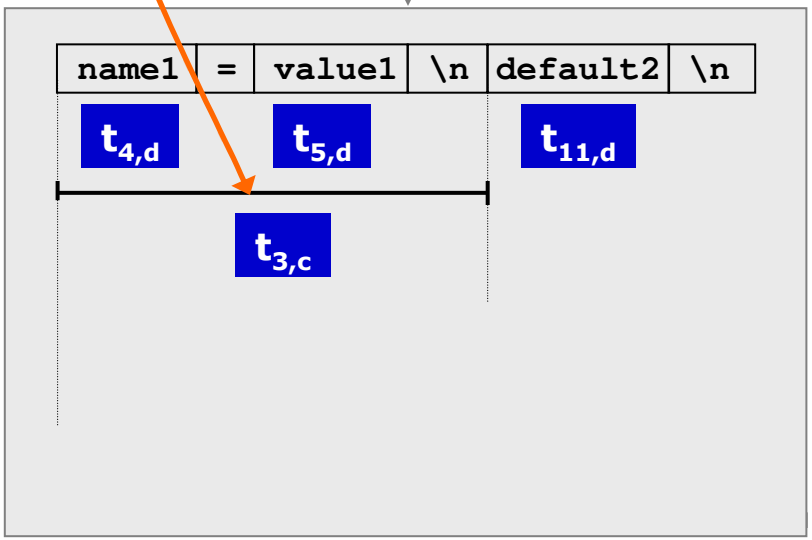

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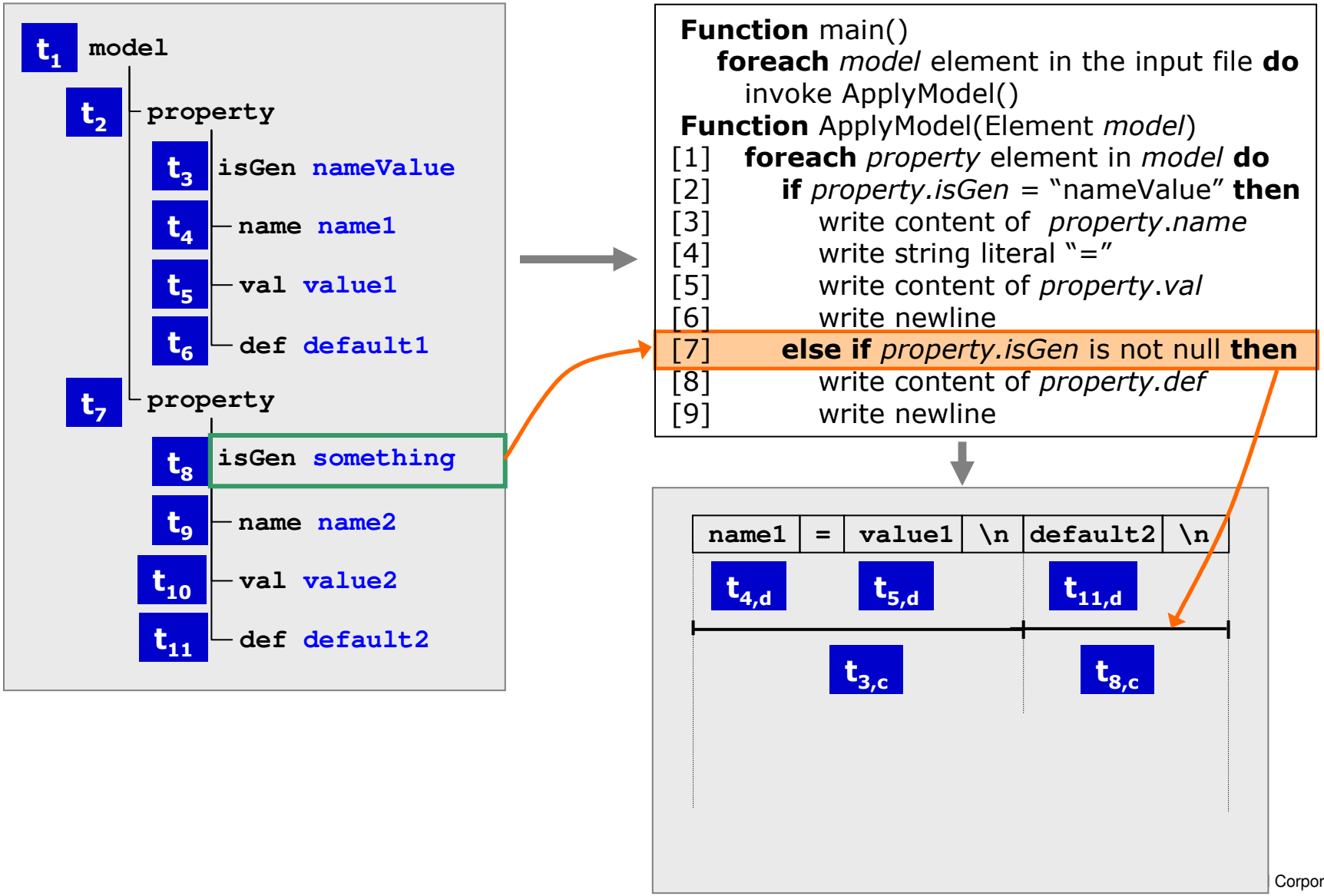

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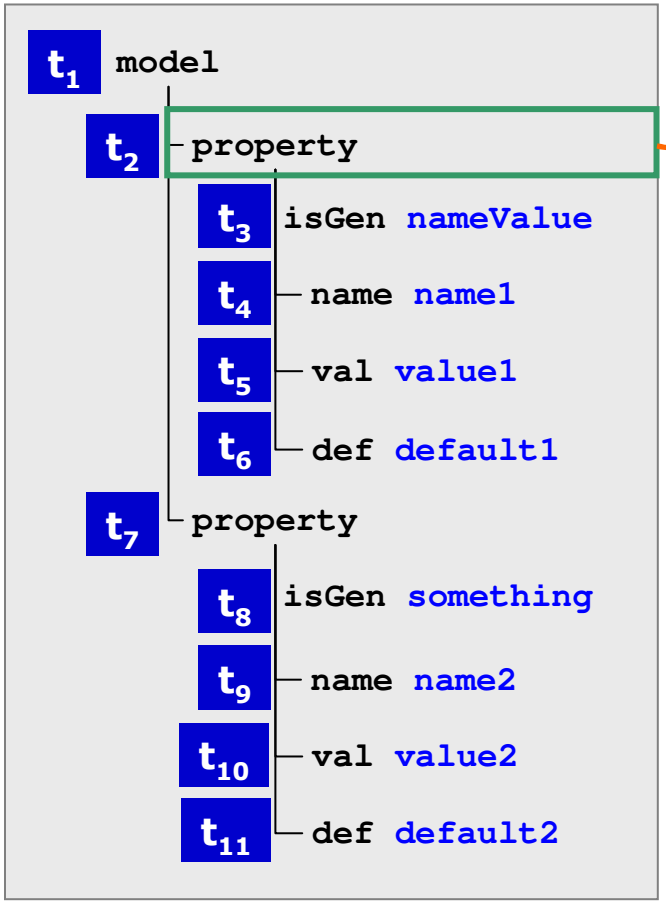


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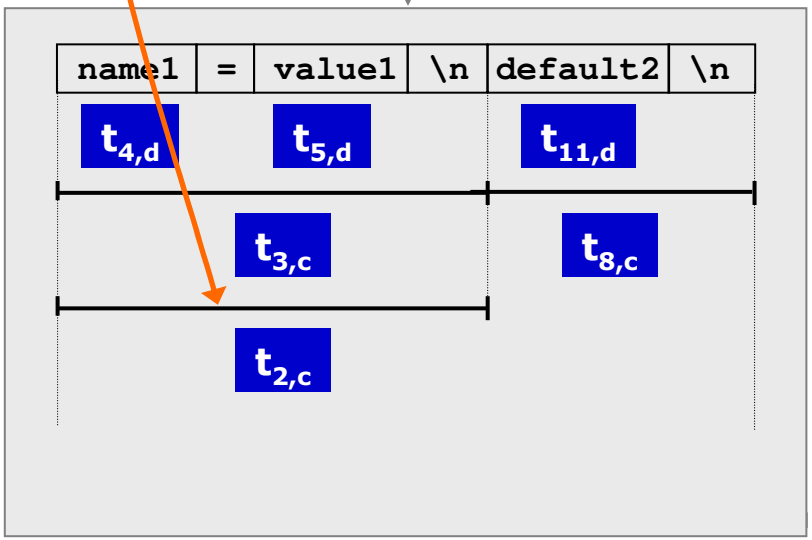
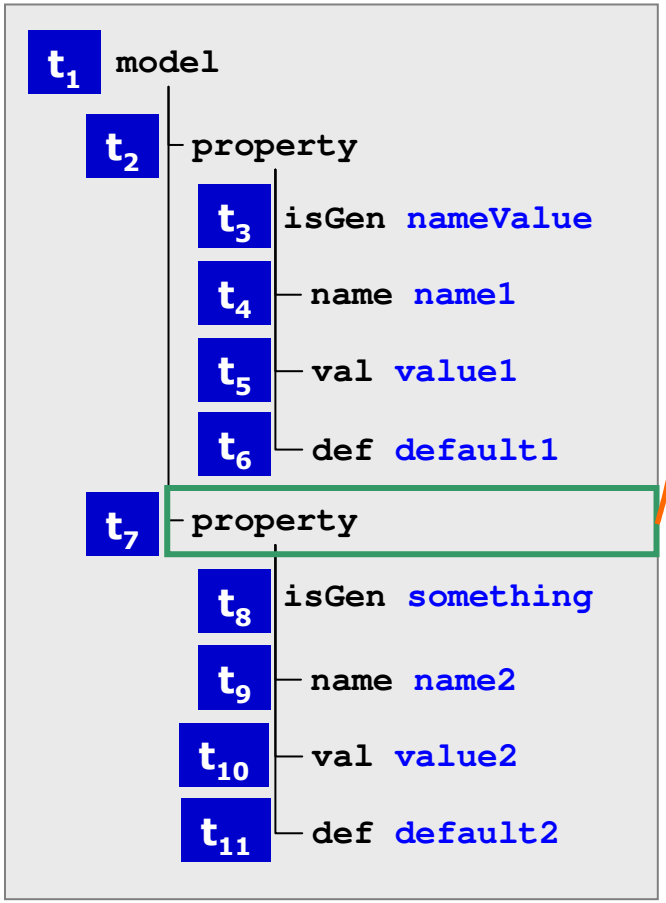


Taint Propagation (Control Taints)

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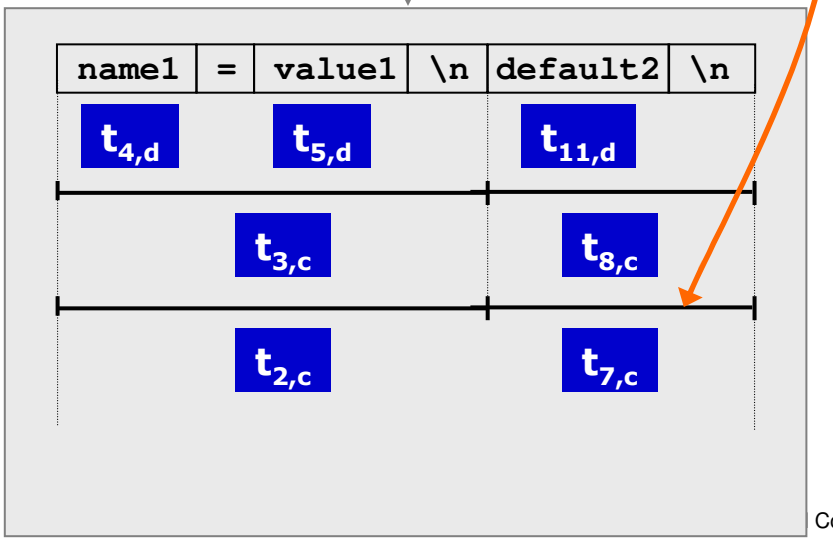
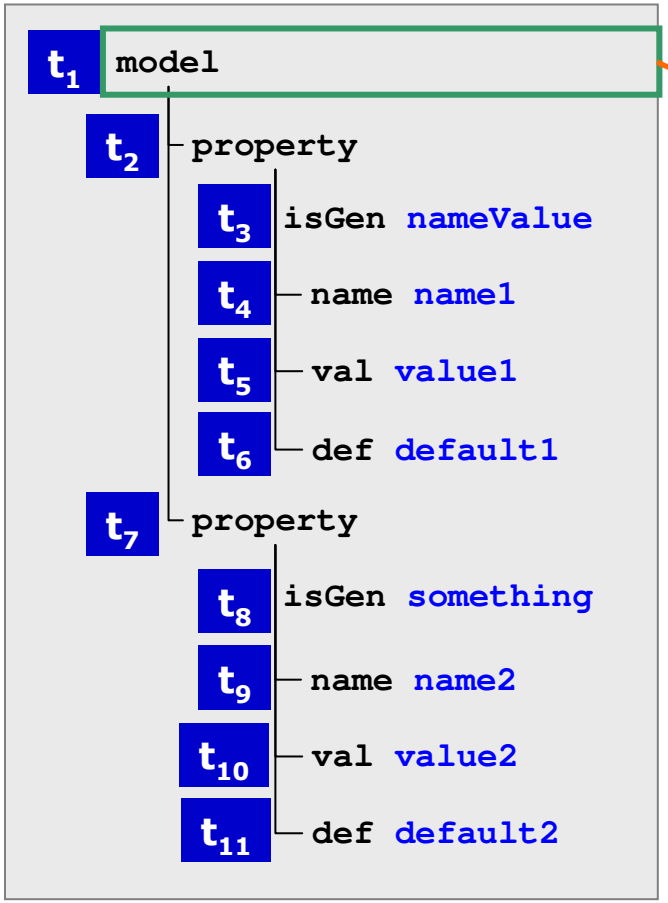


Taint Propagation

- Data taint marks
  - Create traceability for value propagation from input model to output model
  - Propagated at each assignment statement and statement that constructs the output string
- Control taint marks
  - Create traceability for input model entities that influence the outcome of predicates
  - Propagated at conditional statements: based on hammock decomposition of the control-flow graph
- Loop taint marks
  - Create traceability for input model entities that represent “collections”
  - Propagated at looping constructs

Taint Propagation (Loop Taints)

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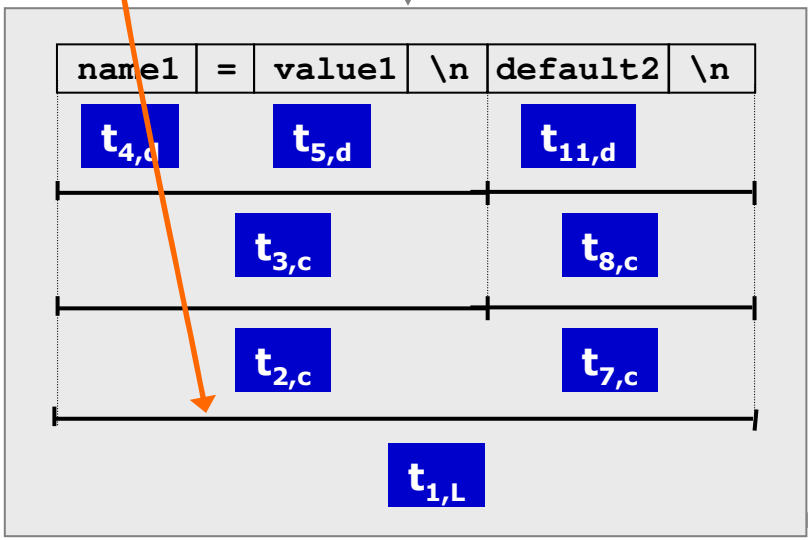
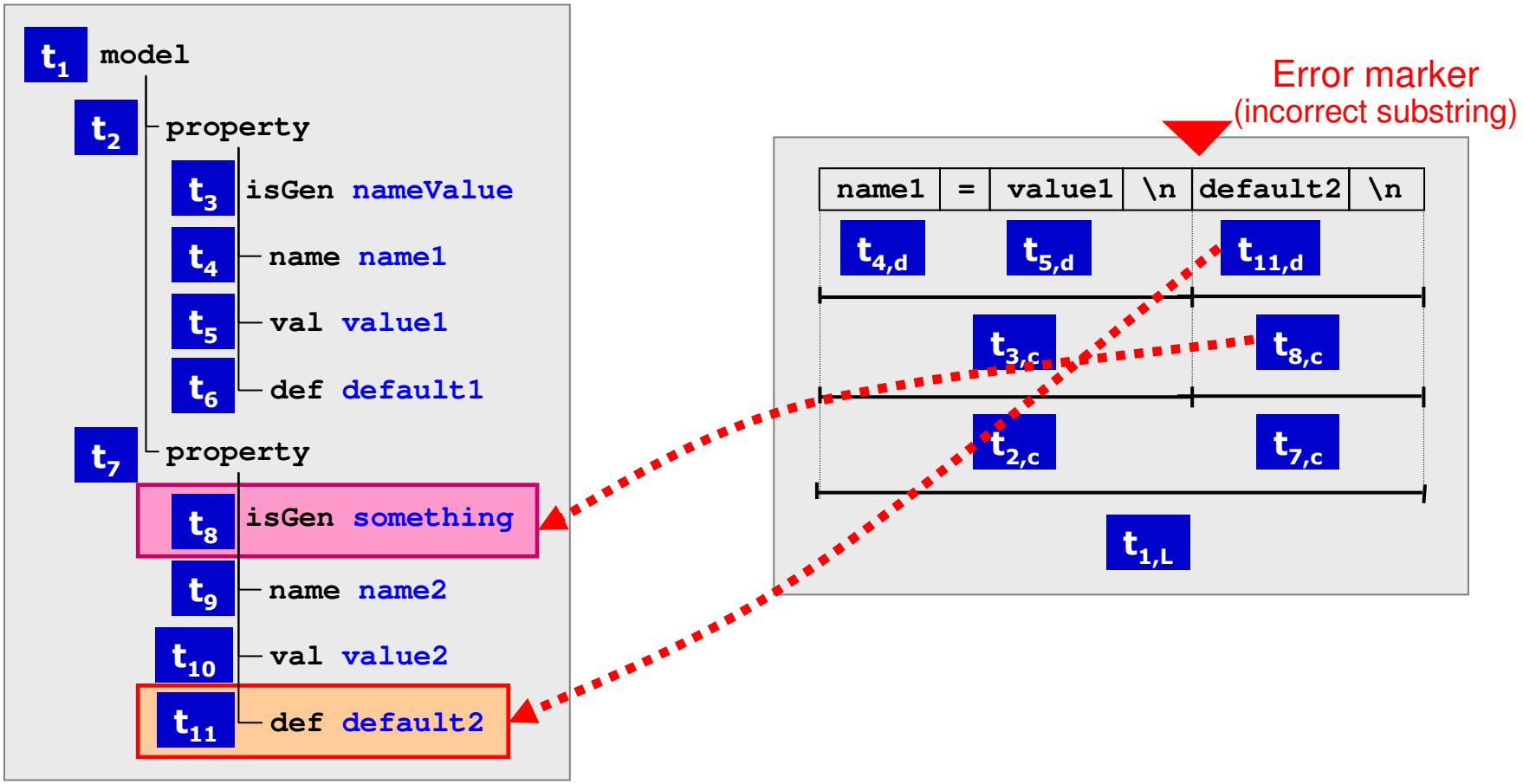


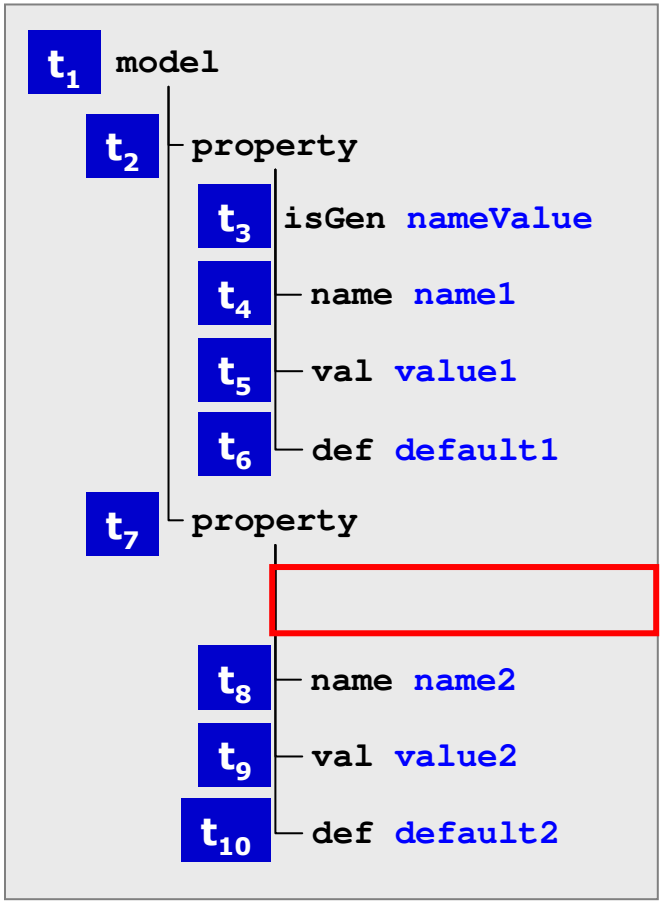
Taint-Log Analysis for Incremental Fault Localization



Incremental Expansion of the Fault Space

- Incorrect substring
  - Initial fault space: Start at a non-empty data taint
  - Fault-space expansion: Iteratively identify enclosing control taints (in reverse order of scope nesting)
- Missing substring
  - Initial fault space: Start at an empty data taint or an empty control taint
  - Fault-space expansion: Iteratively identify enclosing control taints (in reverse order of scope nesting)

Fault Localization for Missing Substrings

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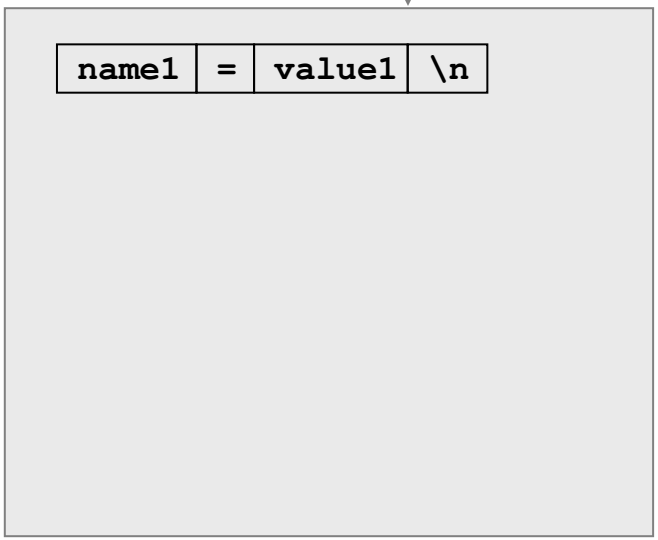
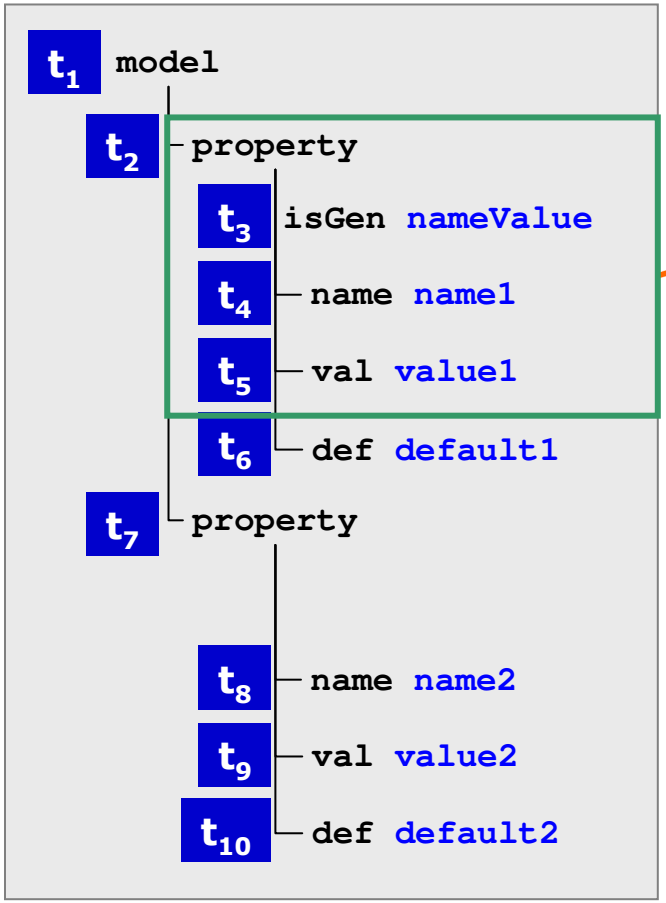


Fault Localization for Missing Substrings

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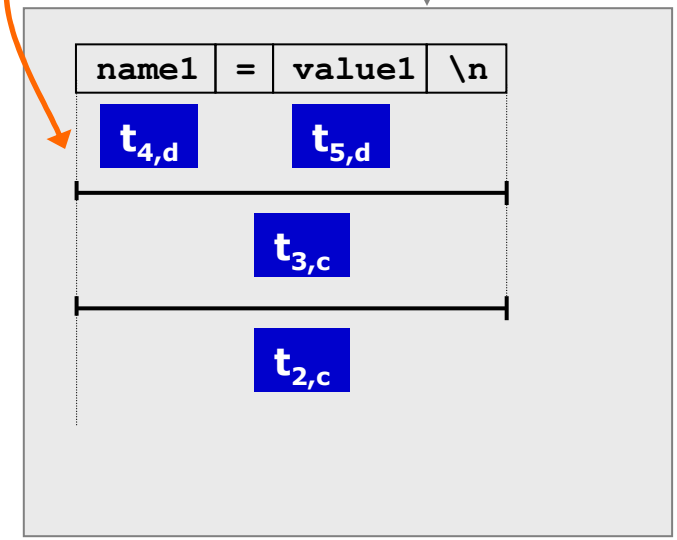

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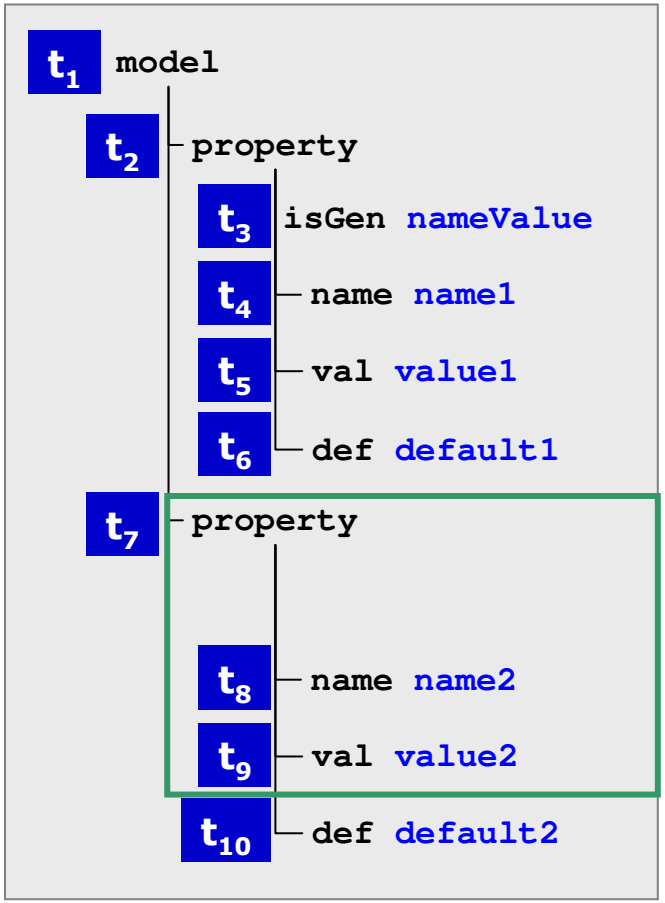


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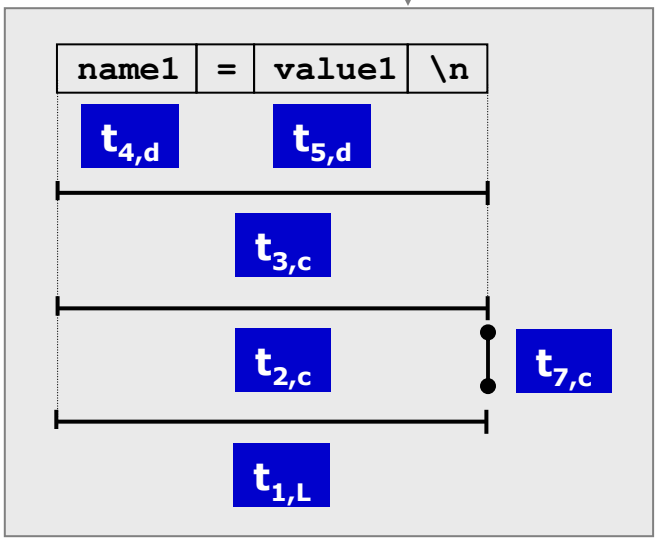
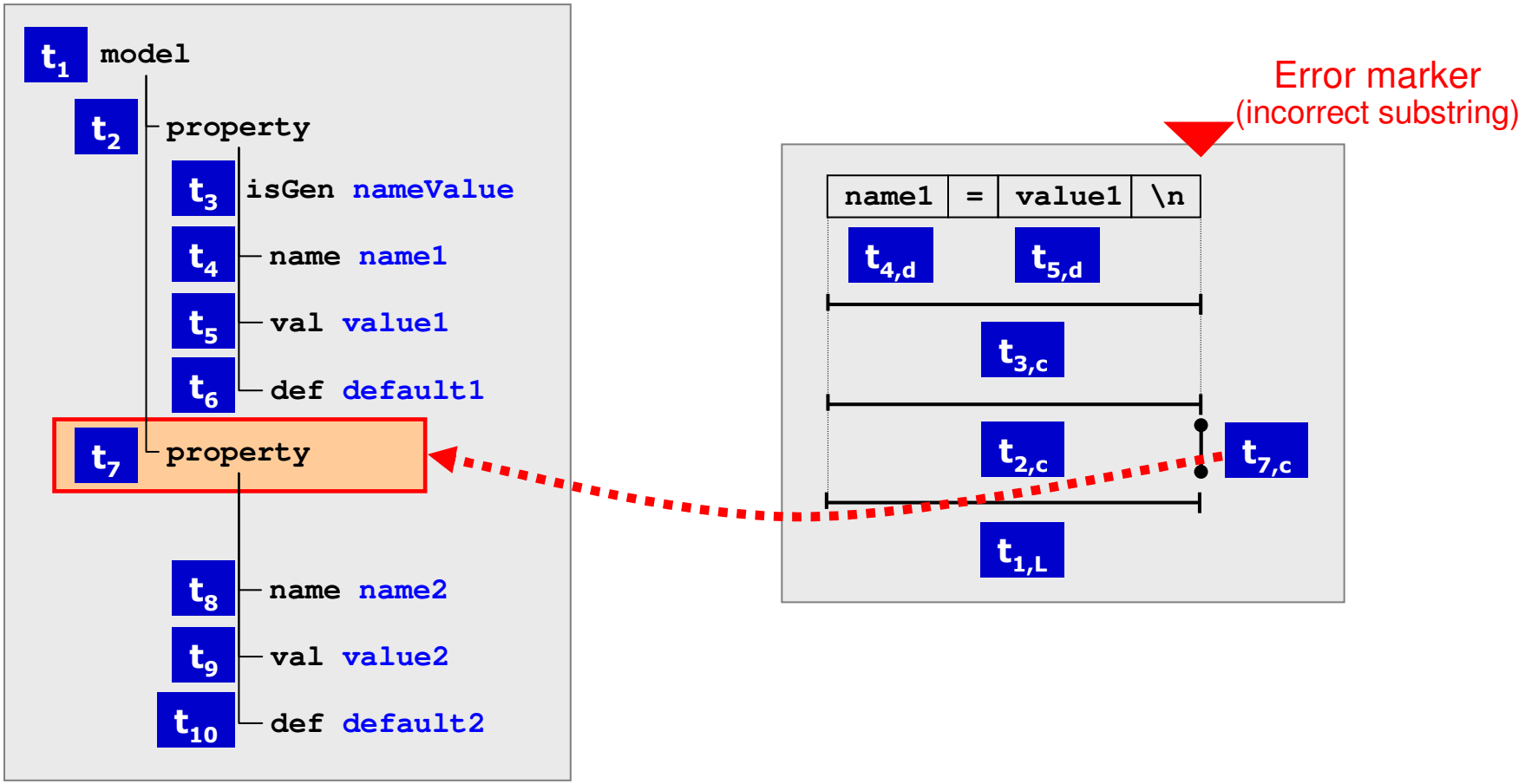
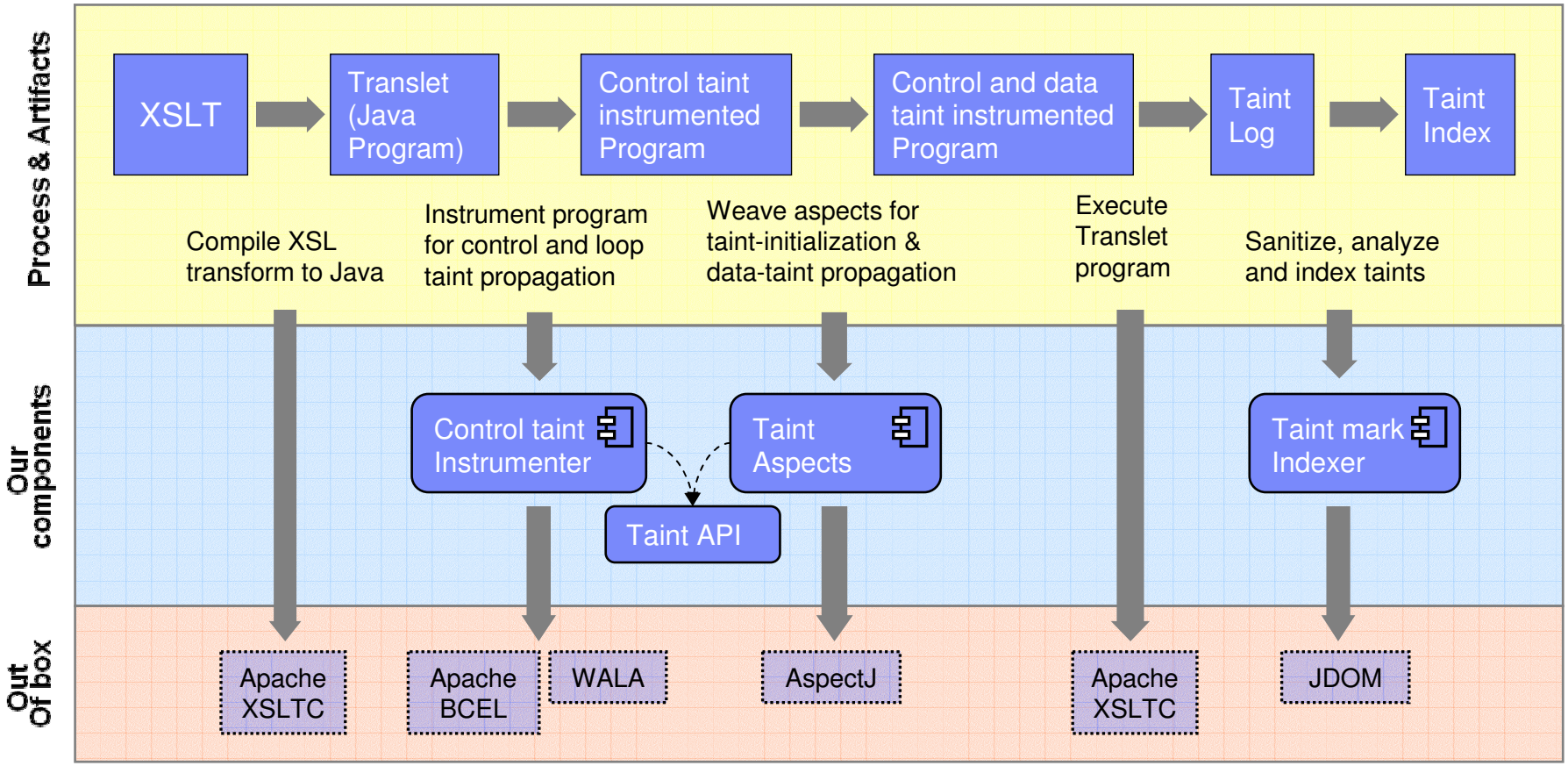


Fault Localization for Missing Substrings



Implementation for XSL-based Transforms

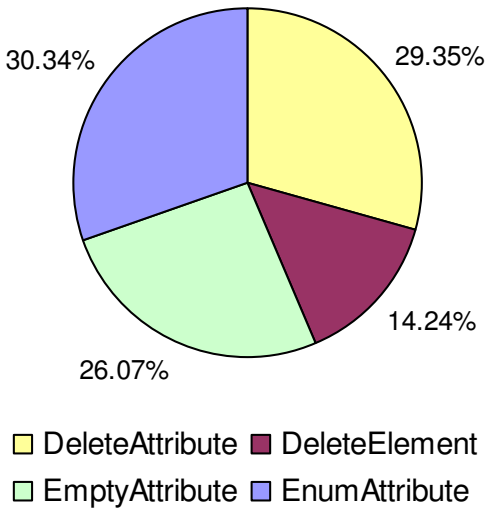


Empirical Evaluation

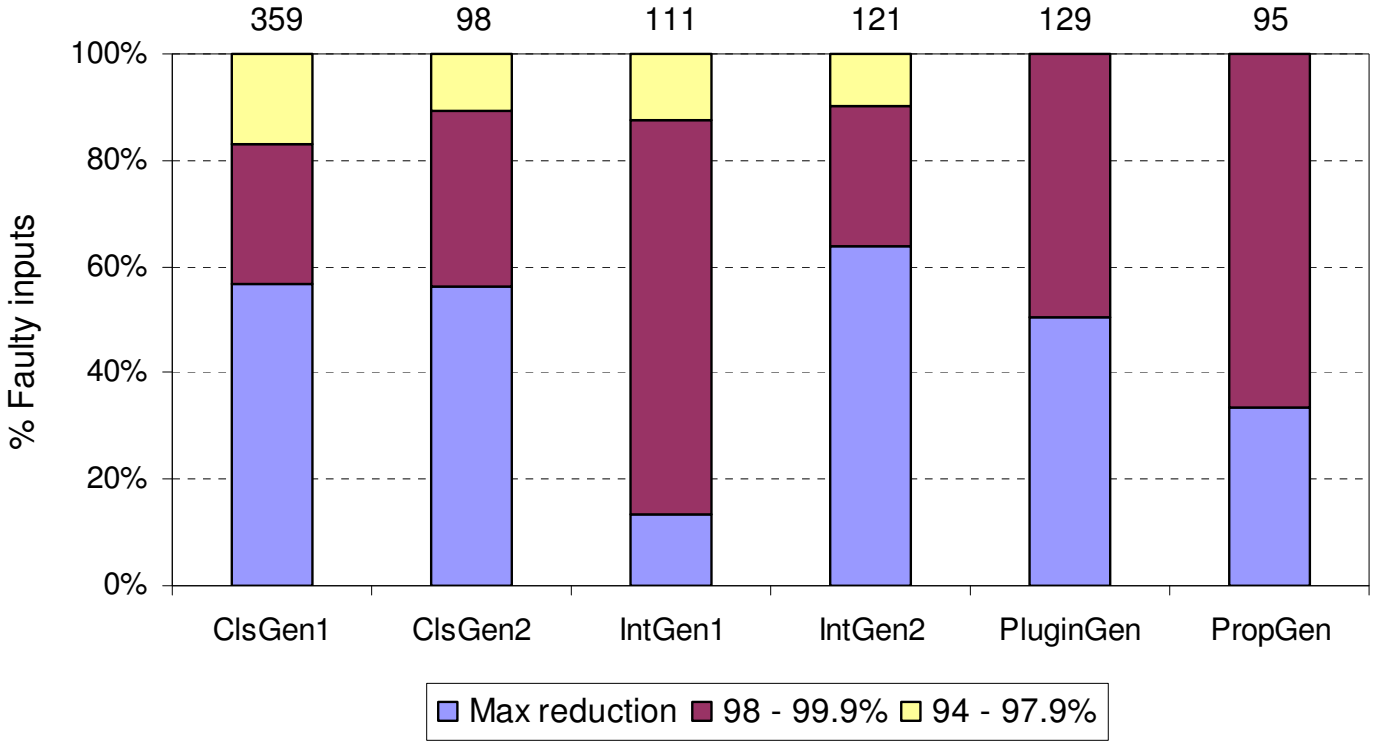
- Two studies
  - Fault-space reduction
  - Significance of control taints

- Experimental subjects
  - Six XSL transforms: Java classes, Java interfaces, configuration file, property file
  - 376–13270 Java bytecode instructions
  - Input model size: 38000–40000 entities

- Faulty input generation
  - Data mutation on valid inputs: four mutation operators
  - 913 faulty inputs

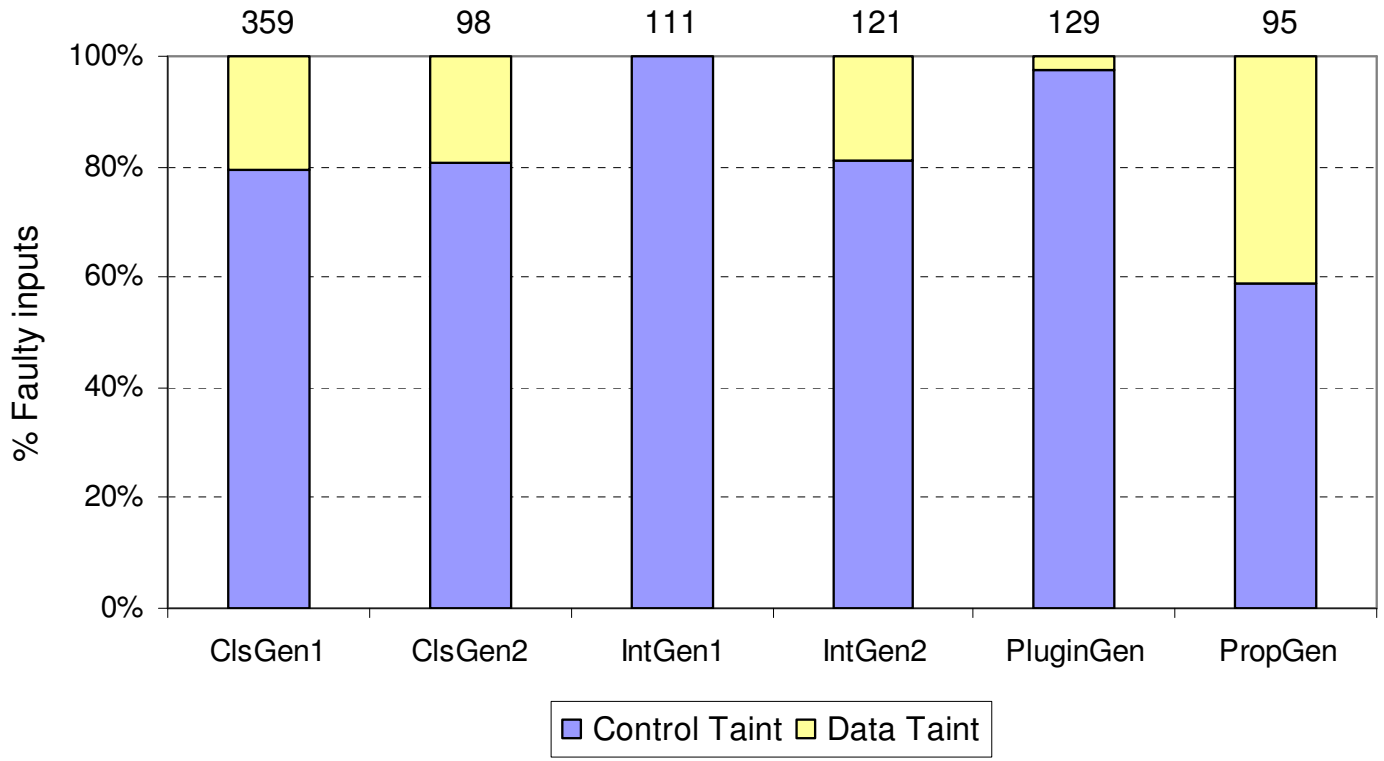


Study 1: Fault-Space Reduction



- Maximum reduction achieved for
  - 468 (51%) of the 913 faulty inputs
  - At least 50% of the faulty inputs for four of the subjects
- Better than 94% reduction for all subjects and faulty inputs

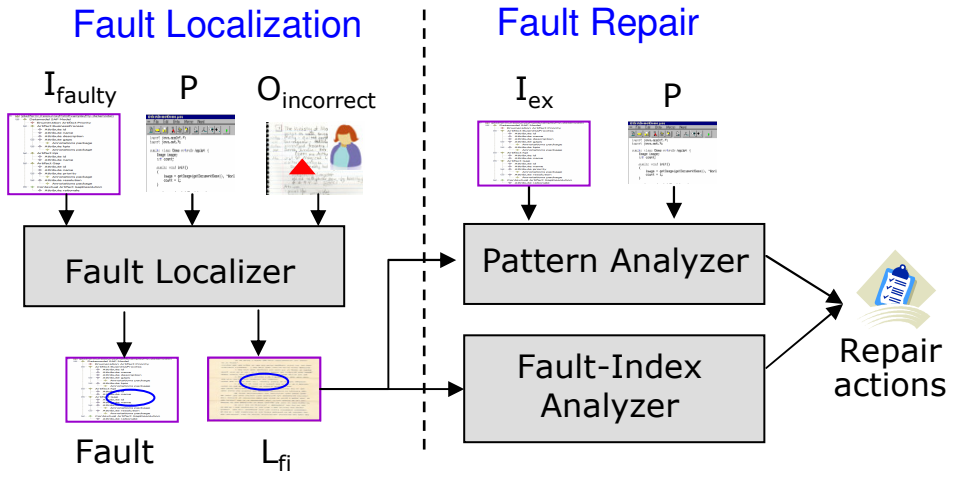
Study 2: Significance of Control Taints



- Overall subjects, 83% of the faulty inputs required control-taint propagation
- For one subject, all faults required control-taint propagation

Automated Support for Fault Repair

- Metadata collection
  - Entity accesses
  - Conditional statements
  - Selections in loops
- Fault-index analysis
  - Analyzes metadata associated with the fault index
  - Computes repair actions
- Pattern analysis
  - Identifies output fragments that are similar to the incorrect output fragment
  - Computes repair actions (based on the metadata) that will lead to a different output at the error marker



Summary and Future Work

- Techniques for debugging model-transformation failures
  - Static analysis for inferring model-validation rules (model validation)
  - Dynamic-taint analysis for localizing input-model faults (fault localization)
  - Dynamic analysis for repairing input-model faults (fault repair)
- Experimentation: additional types of transforms, more subjects
- Another technique for fault repair: predicate switching
- Interactive visual interfaces
- Chained transformations
- Support for identifying error markers

Questions