Partial Models: Towards Modeling and Reasoning with Uncertainty

Michalis Famelis, Rick Salay, and Marsha Chechik

University of Toronto

June 7, 2012

ICSE’12, Zurich, Switzerland
Intuition: Sudoku

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Conclusion

Intuition: Sudoku

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Intuition: Sudoku

- explicate points of uncertainty

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Intuition: Sudoku

- explicate points of uncertainty
- check properties

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Intuition: Sudoku

- Explicate points of uncertainty
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### Intuition: Sudoku

![Sudoku puzzle](https://via.placeholder.com/150)

- **Modeling**
  - Explicate points of uncertainty
  - Dependencies between points of uncertainty

- **Reasoning**
  - Check properties

---

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Intuition: Sudoku

- explicate points of uncertainty
- dependencies between points of uncertainty

Modeling
Reasoning
- check properties
- give feedback for diagnosis

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**Intuition: Sudoku**

<p>| | | | | |</p>
<table>
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**Modeling**
- explicate points of uncertainty
- dependencies between points of uncertainty

**Reasoning**
- check properties
- give feedback for diagnosis

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Source: Wikimedia, 3 / 29
Goal: Uncertainty in Software

Modeling
Explicate points of uncertainty
Correlate points of uncertainty

Reasoning
Check properties
Give feedback to facilitate diagnosis
Designing a P2P Application

Trying to design a P2P client application.

What do I know?

![State diagram showing states: Idle, Leeching, Seeding, and transitions with labels: start(), cancel()](image-url)
Designing a P2P Application

Trying to design a P2P client application.

What do I not know?

- Idle
- Leeching
- Seeding

Can users initiate Seeding?

start()
cancel()
cancel()
Designing a P2P Application

Trying to design a P2P client application.

What do I not know?

- What happens when a download is completed?
- Can you restart downloads?
- Can users initiate Seeding?

Idle -> Leeching
Idle -> Seeding
Leeching -> Seeding
Seeding -> Leeching
Leeching -> Idle
Seeding -> Idle
Designing a P2P Application

Trying to design a P2P client application.

How can I explicate my uncertainty and reason in its presence?

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Contribution

Modeling Uncertainty

- Encode uncertainty in *Partial Models*.
- Semantics: sets of conventional models.

Reasoning in the Presence of Uncertainty

- Check properties.
- Give feedback to facilitate diagnosis.

Evaluation of Reasoning

- Reasoning with Partial models vs. reasoning with a set of conventional models
Presentation of these would take too much time:

- Encoding conventional models in logic and back
- Construction algorithm of Partial Models
- Propositional Normal Form (PNF)
- Graphical Normal Form (GNF)
- Diagnostic cores
- “Property-driven” refinement.
- Translation from PNF to GNF and vice versa
- Evaluation of diagnostic cores and property-driven refinement
- Random generation of experimental inputs
Contribution

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Partial Models

Towards Modeling and Reasoning with Uncertainty

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- Explicate uncertainty
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- Explicate uncertainty
- May elements
- Syntactic annotations [FASE'12]
Partial Models

- Explicate uncertainty
- May elements
- Syntactic annotations [FASE'12]
- Explicate uncertainty
- May elements
- Syntactic annotations [FASE'12]

- May formula
- Correlate points of uncertainty
Partial Models

- Explicate uncertainty
- May elements
- Syntactic annotations [FASE'12]

- May formula
- Correlate points of uncertainty
Semantics of Partial Models

Uncertainty: set of possibilities

\[(\neg A \land B \land \neg D \land \neg E \land \neg F \land G) \lor (A \land \neg B \land D \land \neg E \land F \land G)]
Semantics of Partial Models

Semantics: set of concretizations

\[(\neg A \land B \land \neg D \land \neg E \land \neg F \land G) \lor (A \land B \land D \land E \land F \land G)\]
Semantics of Partial Models

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compact and exact representation of the set

(¬A∧B∧¬D∧¬E∧¬F∧¬G) ∨
(A→B∧D→E→F→G) ∨ (A→B∧D∧E∧F∧G)

encoding
Related Ideas

Behavioral modeling:
- Modal Transition Systems (MTSs) [Larsen’88].
- Disjunctive MTSs [Larsen’91].

Software Product Lines:
- Variability in the metamodel [Morin’09].
- Featured Transition Systems [Classen’10].

Partial Models:
- Language-independent not just behavioral models!
- May formula: exact encoding thorough reasoning
- Focus on systematic management of uncertainty uncertainty-reducing refinement [VOLT’12] transformations [MiSE’12]
Contribution

Modeling Uncertainty

- Encode uncertainty in Partial Models.
- Semantics: sets of conventional models.

Reasoning in the Presence of Uncertainty

- Check properties.
- Give feedback to facilitate diagnosis.

Evaluation of Reasoning

- Reasoning with Partial models vs. reasoning with a set of conventional models
1) Property Checking

Property can be:

- **True**: holds for all concretizations
- **False**: holds for none
- **Maybe**: true for some, false for others

To check a property:
- Encode model and property in propositional logic.
- Use SAT solver.

<table>
<thead>
<tr>
<th>$\Phi_M \land \Phi_p$</th>
<th>$\Phi_M \land \neg \Phi_p$</th>
<th>Property $p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAT</td>
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<td>Maybe</td>
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<tr>
<td>SAT</td>
<td>UNSAT</td>
<td>True</td>
</tr>
<tr>
<td>UNSAT</td>
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<td>False</td>
</tr>
<tr>
<td>UNSAT</td>
<td>UNSAT</td>
<td>(model inconsistent)</td>
</tr>
</tbody>
</table>
Property Checking: Example

\[(\neg A \land B \land \neg D \land \neg E \land \neg F \land \neg G) \lor (A \land \neg B \land D \land \neg E \land \neg F \land G) \lor (A \land \neg B \land \neg D \land E \land \neg F \land G)\]
Property Checking: Example

“No two transitions have the same source and target.”

```
¬A ∧ ¬B ∧ ¬D ∧ ¬E ∧ ¬F ∧ ¬G ∨ 
(A ∧ ¬B ∧ D ∧ ¬E ∧ ¬F ∧ ¬G) ∨ (A ∧ ¬B ∧ ¬D ∧ E ∧ F ∧ G)
```
Property Checking: Example

"No two transitions have the same source and target."

(¬A ∧ B ∧ ¬D ∧ ¬E ∧ ¬F ∧ ¬G) ∨ (A ∧ ¬B ∧ D ∧ ¬E ∧ F ∧ ¬G) ∨ (A ∧ ¬B ∧ ¬D ∧ E ∧ F ∧ G)
Property Checking: Example

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Property Checking: Example

“No two transitions have the same source and target.”

Idle_State ∧ Leeching_State ∧ ...
∧ start_Idle_Leeching_Transition ∧
cancel_Leeching_Idle_Transition ∧ ...

¬A∧¬B∧¬D∧¬E∧¬F∧¬G) ∨
(A∧¬B∧D∧¬E∧¬F∧¬G) ∨ (A∧¬B∧¬D∧E∧F∧G))
"No two transitions have the same source and target."

\[ \Phi_{\text{model}} \]

\[
\text{Idle\_State} \land \text{Leeching\_State} \land \\
\ldots \land \\
\text{start\_Idle\_Leeching\_Transition} \land \\
\text{cancel\_Leeching\_Idle\_Transition} \land \\
\ldots
\]

\[
(\neg A \land B \land \neg D \land \neg E \land \neg F \land \neg G) \lor \\
(A \land \neg B \land D \land \neg E \land \neg F \land \neg G) \lor (A \land \neg B \land \neg D \land E \land F \land G)
\]
Property Checking: Example

"No two transitions have the same target."

\[ \Phi_{\text{property}} \]

\[ \Phi_{\text{model}} \]

\[ \text{Idle\_State} \land \text{Leeching\_State} \land 
\ldots \land 
\text{start\_Idle\_Leeching\_Transition} \land 
\text{cancel\_Leeching\_Idle\_Transition} \land 
\ldots \land 
(\neg A \land B \land \neg D \land \neg E \land \neg F \land \neg G) \lor 
(A \land \neg B \land D \land \neg E \land \neg F \land \neg G) \lor 
(A \land \neg B \land \neg D \land E \land F \land G) \]
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Property Checking: Example

\( \Phi_{\text{model}} \land \neg \Phi_{\text{property}} \)

\( (\neg A \land B \land \neg D \land \neg E \land \neg F \land \neg G) \lor (A \land \neg B \land D \land \neg E \land F \land G) \lor (A \land \neg B \land \neg D \land E \land F \land G) \)
Property Checking: Example

\[ \Phi_{\text{model}} \land \neg \Phi_{\text{property}} \]

\[ (\neg A \land B \land \neg D \land \neg E \land \neg F \land \neg G) \lor (A \land \neg B \land D \land \neg E \land \neg F \land G) \lor (A \land B \land \neg D \land E \land F \land G) \]
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Property Checking: Example

\[ \Phi_{\text{model}} \land \neg \Phi_{\text{property}} \]

\( \Phi_{\text{model}} \land \Phi_{\text{property}} \)

SAT solver

\[ \Phi_{\text{model}} \land \neg \Phi_{\text{property}} \]
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Property Checking: Example
Property Checking: Example

\[ \Phi_{\text{model}} \land \Phi_{\text{property}} \]

\[ \Phi_{\text{model}} \land \rightarrow \Phi_{\text{property}} \]

\[ \text{SAT solver} \]

\[ \text{Property Checking: Example} \]

\[ \text{Partial Models: Towards Modeling and Reasoning with Uncertainty} \]

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Property Checking: Example

“No two transitions have the same source and target.”

```
¬A ∧ B ∧ ¬D ∧ ¬E ∧ ¬F ∧ ¬G ∨
(A ∧ ¬B ∧ D ∧ ¬E ∧ ¬F ∧ ¬G) ∨
(A ∧ ¬B ∧ ¬D ∧ E ∧ F ∧ G)
```
Property Checking: Example

“"No two transitions have the same target.""

```
¬A ∧ ¬B ∧ ¬D ∧ ¬E ∧ ¬F ∧ ¬G

(A ∧ ¬B ∧ D ∧ ¬E ∧ ¬F ∧ ¬G) ∨ (A ∧ ¬B ∧ ¬D ∧ E ∧ F ∧ G)
```

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**Modeling Uncertainty**

- Partial Models
- Semantics

**Reasoning With Uncertainty**

- Property Checking
- Diagnosis

**Evaluation**

- Experiments
- Case Study

**Conclusion**
2) Diagnosis

Feedback:

A concretization of the Partial Model for which the property does not hold.

Reuse the results of property checking:

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</table>
Diagnosis: Example

\[ \Phi_{\text{model}} \land \neg \Phi_{\text{property}} \]

SAT solver

\[ \Phi_{\text{model}} \land \Phi_{\text{property}} \]
Diagnosis: Example

\[ \Phi_{\text{model}} \land \rightarrow \Phi_{\text{property}} \]
Contribution

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Reasoning in the Presence of Uncertainty

- Check properties.
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Evaluation of Reasoning

- Reasoning with Partial models vs. reasoning with a set of conventional models
Questions

Reasoning with Partial models
vs
Reasoning with a set of conventional models

Is there a speedup?

How is speedup affected by changing:
  • model size
  • levels of uncertainty?
Questions

Reasoning with Partial models
vs
Reasoning with a set of conventional models

Is there a speedup?

How is speedup affected by changing:
  • model size
  • levels of uncertainty?

To get answers:
1) Experiments with random inputs.
2) Real-world case study.
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Experiments

Random models as inputs
- increasing model size
Random models as inputs
- increasing model size
- increasing uncertainty level $\rightarrow$ size of set of concretizations
Experiments

Speedup factor = \frac{\text{time for set of conventional models}}{\text{time for partial model}}
Experiments

- S Set of Concretizations
- M Set of Concretizations
- L Set of Concretizations
- XL Set of Concretizations

Speedup Factor

Model Size

S	M	L	XL
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Experiments

Model Size

Speedup Factor

S Set of Concretizations
M Set of Concretizations
L Set of Concretizations
XL Set of Concretizations
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Conclusion
- Consistently faster than reasoning with set.
- Consistently faster than reasoning with set.
- Speedup decreases with model size.
- Speedup increases with uncertainty.
Case Study

Why Case Study?

Triangulate experimental results (randomly inputs) with observations from a real-world scenario.

Case Study details:

• Real-world software project: UMLet.
• Real-world bug from UMLet bugzilla.
• Realistic bug fixes.
• Two properties from literature [V.D.Straeten’03].
• 27,261 elements (XL model size)
• 220 concretizations (XL uncertainty size)
Case study speedups consistent with experiments.
Results of Evaluation

Reasoning with Partial models

vs

Reasoning with a set of conventional models

Is there a speedup?
- Yes, it is consistently faster than reasoning with the set.

How is speedup affected by changing model size and levels of uncertainty?
- Speedup decreases with model size.
- Speedup increases with uncertainty.
- No slowdowns!
Summary

Modeling Uncertainty

- Encode uncertainty in Partial Models.
- Semantics: sets of conventional models.

Reasoning in the Presence of Uncertainty

- Check properties.
- Give feedback to facilitate diagnosis.

Evaluation of Reasoning

- Reasoning with Partial models vs. reasoning with a set of conventional models
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Next Steps

Reasoning [ICSE'12]
Transformation [MiSE'12]
Requirements [RE'12]
Position [MoDeWa'11]
Partially Types [FASE'12]
Refinement [VOLT'12]
Questions?
Language Independent!

Class Diagram example from [MiSE’12].
Bibliography I


B. Morin, G. Perrouin, P. Lahire, O. Barais, G. Vanwormhoudt, and J. M. Jézéquel.
“Weaving Variability into Domain Metamodels”.
*J. Model Driven Engineering Languages and Systems*, pages 690–705, 2009.

R. Salay, M. Chechik, and J. Horkoff.
“Managing Requirements Uncertainty with Partial Models”.

R. Salay, M. Chechik, and J. Gorzny.
“Towards a Methodology for Verifying Partial Model Refinements”.

R. Salay, M. Famelis, and M. Chechik.
“Language Independent Refinement using Partial Modeling”.

R. V. D. Straeten, T. Mens, J. Simmonds, and V. Jonckers.
“Using Description Logic to Maintain Consistency between UML Models”.