Modular Verification of Temporal Safety Properties of Procedural Programs

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  Grumberg & Long 1994: finite–state systems, ACTL
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  "built–in" for Hoare–logic based approaches

- Model checking procedural programs:
  Das, Lerner & Seigl 2002: property simulation (ESP)
  Esparza et al 2002: model checking pushdown systems

This work

- started in 2001
- original goal: verify Javacard programs in the presence of post–issuance loading of applets on smart cards
- joint work with Marieke Huisman, Christoph Sprenger, Irem Aktug, Siavash Soleimanifard, Afshin Amighi, Pedro Gomez

Compositionality and Modularity

Compositionality and Modularity

Compositionality as a *mathematical principle*:

- express the meaning of the whole through the meaning of the parts
- example: denotational semantics
- example: definitions and proofs by structural induction

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Modularity as a *systems design principle*:

- control the complexity of the system
  by braking it down into manageable pieces that are
  designed, implemented, tested and maintained *independently*

Verification

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  i.e., *relativize* global properties on local ones

This relativization allows verification in the presence of *variability*

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- static code evolution
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Spacial variablility:

- multiple variants, as arising from software product lines

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How shall one plan for the verification of a global property ψ?

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- as early as possible
- with minimal effort: reuse results

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$$\mathit{impl}(A) + \mathit{spec}(B) + \mathit{spec}(C) + \mathit{spec}(D) \models \psi$$

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But... how, and is there an algorithmic solution?

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2. model check models against local specifications:

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perform the following steps:

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2. from module specifications: construct (so-called maximal) models
3. compose extracted with constructed models
4. model check composed model against global property ψ:
   $mod(impl(A)) + max(spec(B)) + max(spec(C)) + max(spec(D)) \models \psi$

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The third task:

$$mod(impl(A)) + max(spec(B)) + max(spec(C)) + max(spec(D)) \models \psi$$

thus entails:

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Most details in:
Compositional Verification of Sequential Programs with Procedures
Dilian Gurov, Marieke Huisman and Christoph Sprenger
Journal of Information and Computation
vol. 206, no. 7, pp. 840–868, 2008

Tutorial Outline

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1. Preliminaries: Models, Simulation, Logic
2. Flow Graphs, Behaviour and Extraction
3. Property Specification and Verification
4. Maximal Flow Graphs
5. Tool Support
6. Application: Software Product Lines
7. Conclusion

1. Models, Simulation, Logic

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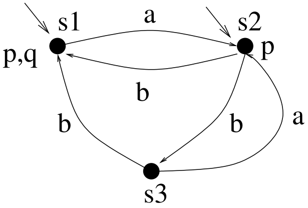
A model $\mathcal{M}$



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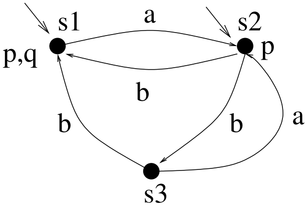

Definition (Model)

A structure $\mathcal{M} = (S, L, \rightarrow, A, \lambda)$ where:

(i) S a set of states

(ii) L a set of transition labels

(iii) $\rightarrow \subseteq S \times L \times S$ a transition relation

(iv) A a set of atomic propositions

(v) $\lambda : S \rightarrow \mathcal{P}(A)$ a valuation

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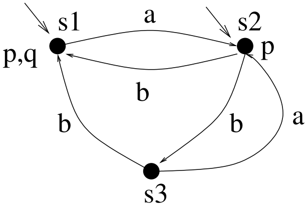

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An intialised model $(\mathcal{M}, E)$ is a model $\mathcal{M}$ with a designated set of entry states $E \subseteq S$

Simulation

Let $\mathcal{M}_1 = (S_1, L, \rightarrow_1, A, \lambda_1)$ and $\mathcal{M}_2 = (S_2, L, \rightarrow_2, A, \lambda_2)$ be models over the same sets of labels and atomic propositions.

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  - (i) $\lambda_1(s_1) = \lambda_2(s_2)$
  - (ii) for any $a \in L$ and $s_1' \in S_1$
    $s_1 \xrightarrow{a}_1 s_1'$ entails $s_2 \xrightarrow{a}_2 s_2'$ for some $s_2' \in S_2$ such that $(s_1', s_2') \in R$

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- $(\mathcal{M}_2, E_2)$ simulates $(\mathcal{M}_1, E_1)$ if
  every $s_1 \in E_1$ is simulated by some $s_2 \in E_2$

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The formulas of the logic are inductively defined through the BNF:

$$\phi ::= p \mid \neg p \mid X \mid \phi_1 \wedge \phi_2 \mid \phi_1 \vee \phi_2 \mid [a]\,\phi \mid \nu X.\phi$$

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- $\nu X.\ p \wedge [a]\,\mathrm{ff} \wedge [b]\,X$

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Corollary

Maximal models are unique up to simulation equivalence

Constructing Maximal Models

Labels $\{a, b\}$, atoms $\{p\}$, formula $[b]\,\mathrm{ff} \wedge p$

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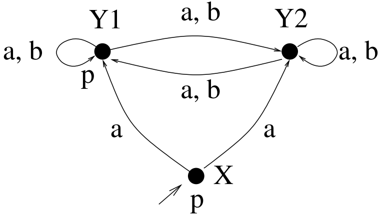

$(\mathcal{M}, E)$

2. Flow Graphs, Interfaces and Behaviour

Flow Graphs: The structure of program control flow (as a model)

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class Number {

   public static boolean even(int n){
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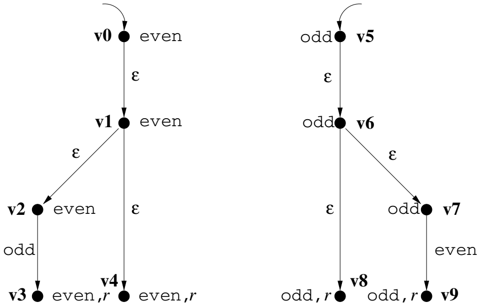

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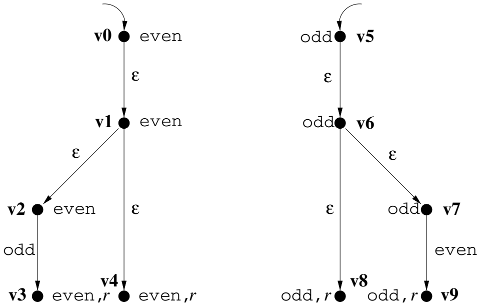

Interfaces: provided and required methods

Flow Graph Behaviour

A flow graph induces a *pushdown automaton* (PDA):

- configurations (v, σ) are pairs of control point and call stack
- productions induced by:
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The behaviour of a flow graph is the behaviour of the induced PDA (again a model)

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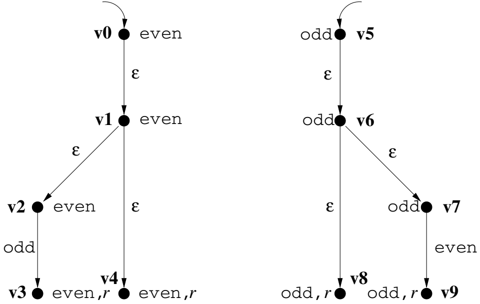

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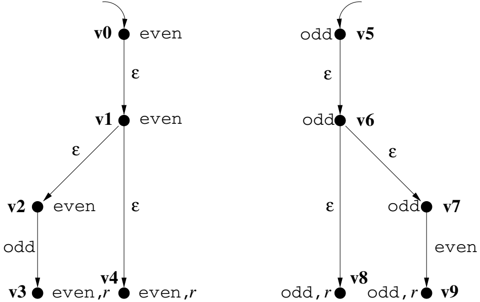

Example run through the behaviour, from an initial configuration:

(v_0, ε)

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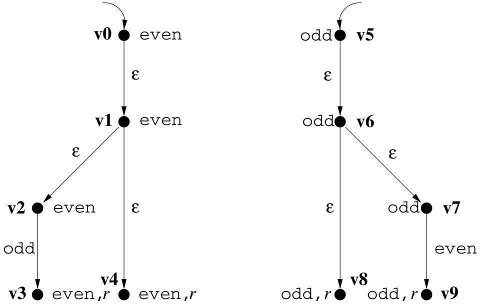

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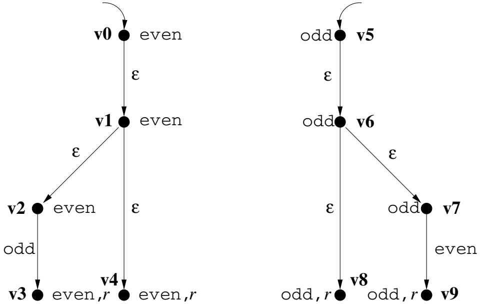

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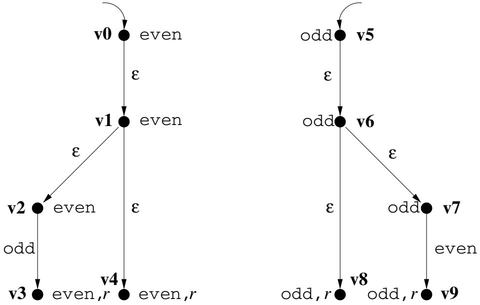

Example run through the behaviour, from an initial configuration:

$(v_0, \varepsilon) \xrightarrow{\tau} (v_1, \varepsilon) \xrightarrow{\tau} (v_2, \varepsilon) \xrightarrow{\text{even call odd}}$

(v_5, v_3)

Flow Graph Behaviour

Flow Graph:

```
class Number {

   public static boolean even(int n){
      if (n == 0)
         return true;
      else
         return odd(n-1);
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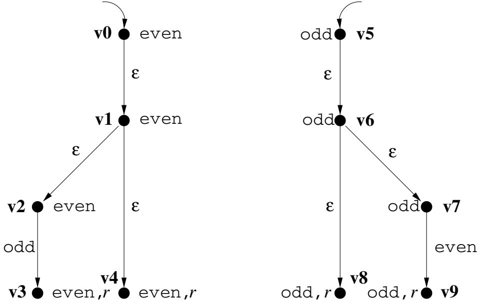

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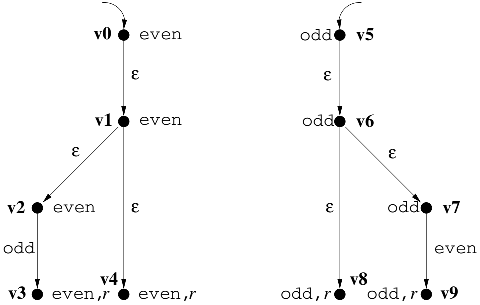

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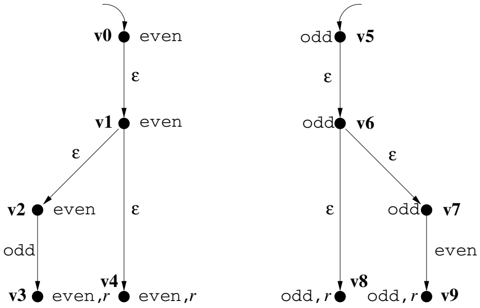

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Open Flow Graph Behaviour

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Example run of method `even` as an open flow graph:

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- instructions define outgoing edges

Complications: sound, precise, modular

- virtual method call resolution
- exceptional flow

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Java program:

```
public static void Meth(boolean flag, ExtA myobj) {
   try {
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Code:
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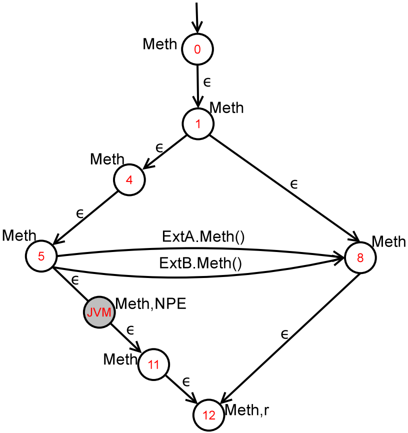

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Details in:
Provably Correct Flow Graphs from Java Programs with Exceptions
Afshin Amighi, Pedro de Carvalho Gomez and Marieke Huisman
In Proceedings of FoVeOOS'11, pp. 31–48

Public Interface Abstraction

We can abstract from private methods through inlining:

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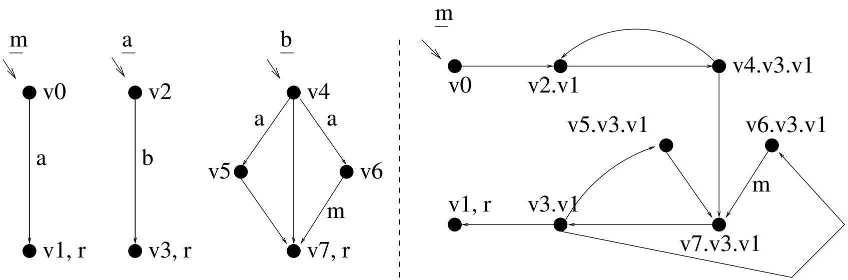

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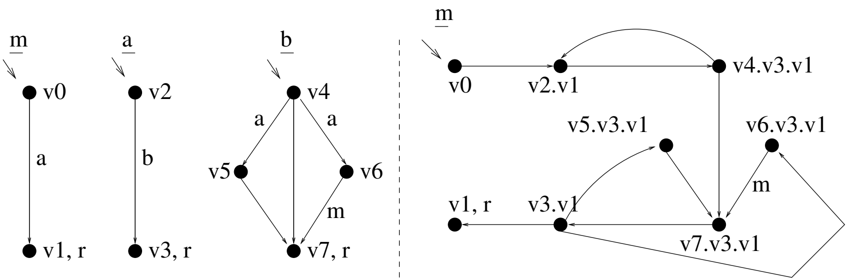

Details in:
Interface Abstraction for Compositional Verification
Dilian Gurov and Marieke Huisman
In Proceedings of SEFM'05, pp. 414–423

3. Property Specification and Verification

We instantiate both simulation and simulation logic to flow graphs and flow graph behaviour

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- first call of `even` is not to itself:

$$\mathtt{even} \Rightarrow \nu X.\ [\mathtt{even}\,\mathsf{call}\,\mathtt{even}]\, \mathsf{ff} \wedge [\tau]\, X$$

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- "a vote only is submitted after validation"
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- "no non–atomic operations within transactions"

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Then, the maximal flow graph for a structural formula ϕ and interface I is simply the maximal model for $\phi \wedge \theta_I$

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Hence, we can even verify global behavioural properties with local structural specifications!

For instance, specify `even` and `odd` structurally, and verify the global behavioural specification:

$$\mathtt{even} \Rightarrow \nu X.\ [\mathtt{even}\ \mathsf{call}\ \mathtt{even}]\,\mathsf{ff} \wedge [\tau]\,X$$

Modular Verification: Example

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Structural specification for even:

Interface: prov. even, req. odd

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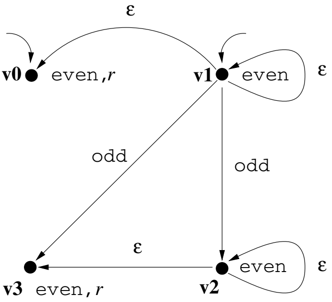

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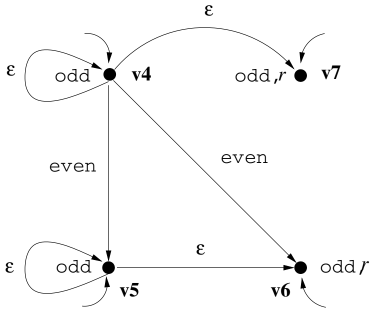

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- translate behavioural properties to structural ones: expensive
- restrict behavioural logic: atomic calls only: caret

Property Translation

Property Translation

Behavioural property "no send after read":

$$\begin{array}{rcl}\phi & = & \nu X.\ [\tau]\, X \wedge [\mathsf{a\ caret}\ \mathtt{send}]\, X \wedge [\mathsf{a\ call\ a}]\, X \wedge [\mathsf{a\ ret\ a}]\, X \wedge [\mathsf{a\ caret}\ \mathtt{read}]\, \phi' \\ \phi' & = & \nu Y.\ [\tau]\, Y \wedge [\mathsf{a\ caret}\ \mathtt{read}]\, Y \wedge [\mathsf{a\ call\ a}]\, Y \wedge [\mathsf{a\ ret\ a}]\, Y \wedge [\mathsf{a\ caret}\ \mathtt{send}]\, \mathsf{ff}\end{array}$$

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gives rise to several structural properties, most notably:

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Details in:

Reducing Behavioural to Structural Properties

Dilian Gurov and Marieke Huisman

In Proceedings of VMCAI'09, pp. 136–150

Restricted Behavioural Logic: Atomic Calls

Behavioural specification of `even`:

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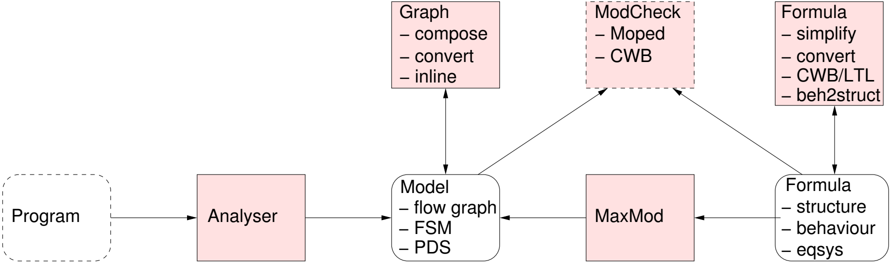
obtained through a *direct* translation!

5. Tool Support

The CVPP Tool Set



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```
/** @global_LTL_prop:
 *    even -> X ((even && !entry) W odd)
 */
public class EvenOdd {
   /** @local_interface: requires {odd}
    *
    *  @local_SL_prop:
    *   nu X1. (([even call even]ff) /\ ([tau]X1) /\
    *     [even caret odd] nu X2.
    *       (([even call even]ff) /\
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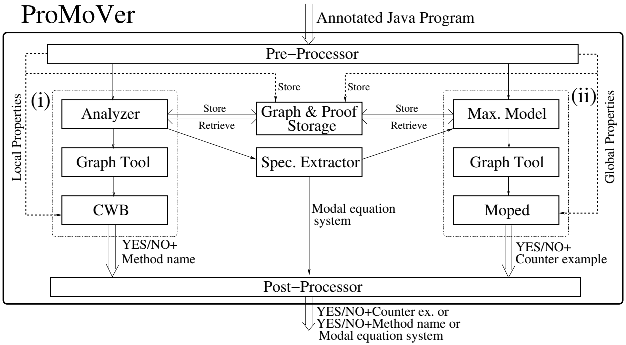
ProMoVer: A wrapper around CVPP



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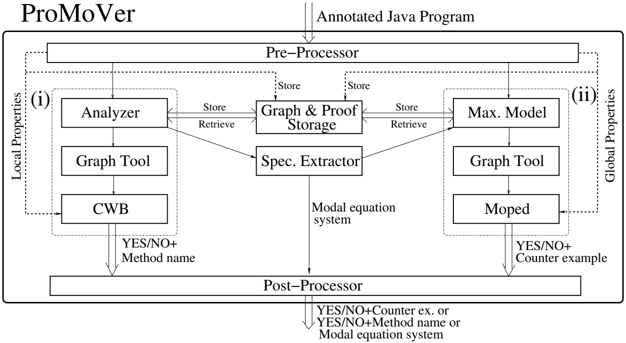
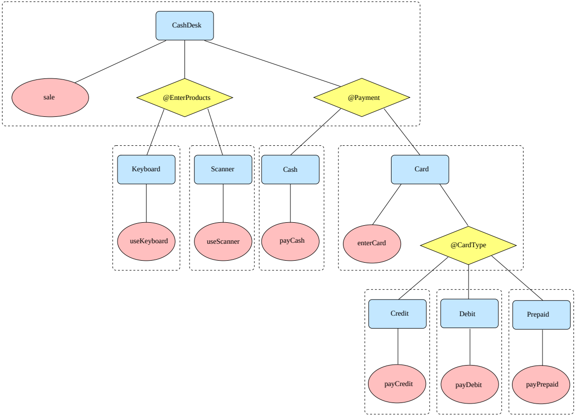


Details in:
ProMoVer: Modular Verification of Temporal Safety Properties
Siavash Soleimanifard, Dilian Gurov and Marieke Huisman
In Proceedings of SEFM'11, pp. 366–381

6. Application: Software Product Lines

A hierarchical variability model for software product lines:



Software Product Lines Verification

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Details in:
Compositional Algorithmic Verification of Software Product Lines
Ina Schaefer, Dilian Gurov and Siavash Soleimanifard
In Post–proceedings of: FMCO'10, pp. 184–203

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