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Static Analysis of Featured Transition Systems

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Outline

1. Key idea and aim
2. Featured Transition Systems (FTSs)
   - definition and examples
   - ambiguous FTSs and transformation into unambiguous FTSs
3. Static analysis of FTSs
   - algorithm and experiments
4. Towards family-based model checking
5. Conclusion and Outlook

Key idea and aim

Mimick anomaly detection known from feature model analysis in behavioral SPL models (FTSs) by automated static analysis:

1. dead transitions
2. false optional transitions
3. hidden deadlock states

Catch and offer means to remove possible ambiguities in FTSs:

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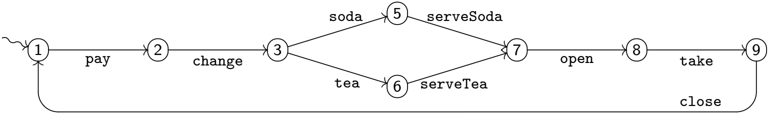

An FTS adds to this a feature model and feature expressions:

Classen *et al.* @ ICSE'10, *IEEE TSE*, 2013

A Featured Transition System (FTS) is a sextuple $(S, \Sigma, s_0, \delta, F, \Lambda)$ with states S, actions Σ, initial state s_0, (featured) transitions $\delta \subseteq S \times \Sigma \times \mathbb{B}(F) \times S$, with Boolean (feature) expressions $\mathbb{B}(F)$ over features F, and (product) configurations $\Lambda \subseteq \{\, \lambda : F \to \mathbb{B} \,\}$

LTS $\mathcal{F}|_\lambda$ specified by configuration $\lambda \in \Lambda$ is called a product of $\mathcal{F}$ (remove: 1) all featured transitions whose feature expressions are not satisfied by λ; 2) all unreachable states and their outgoing transitions)

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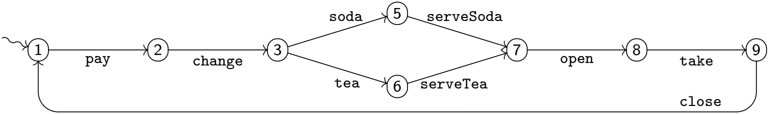

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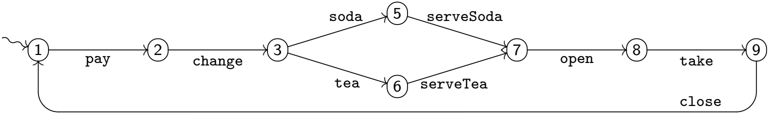

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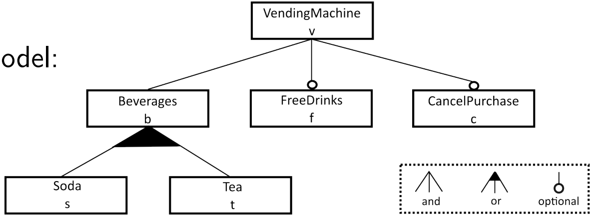
FTS of example SPL: a vending machine

Feature model:



12 valid products

e.g., $\{\mathtt{v,b,s,t}\}$, $\{\mathtt{v,b,s,c}\}$

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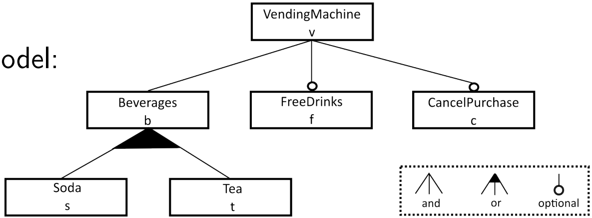

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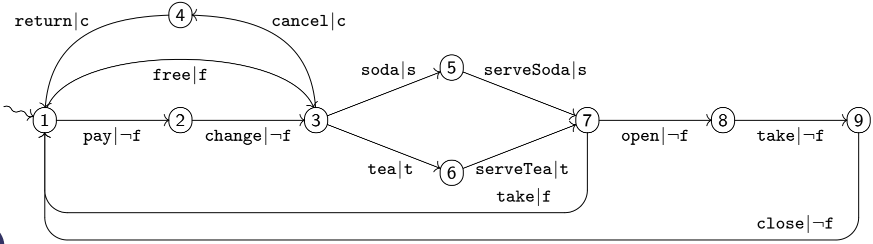

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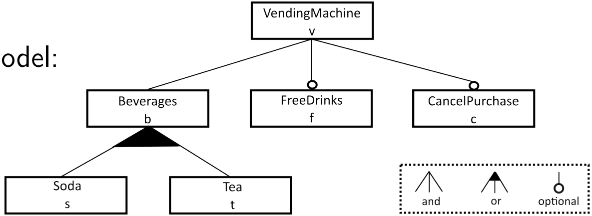

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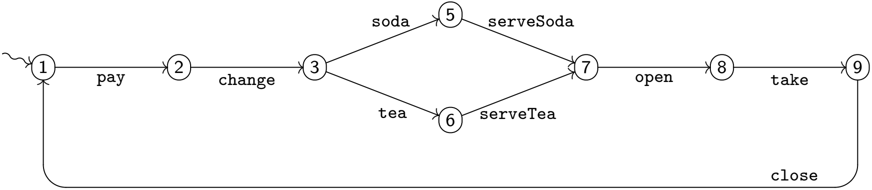

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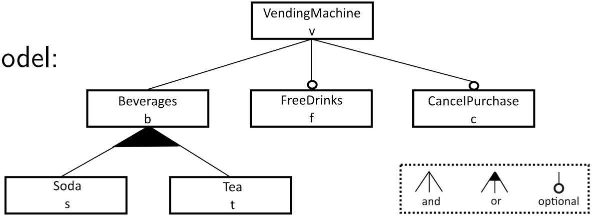

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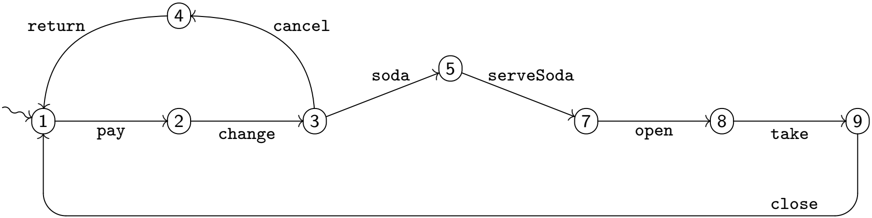

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2. present in every FTS product in which its source state is reachable

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Important safety property: *deadlock freedom*, i.e., system should not reach a state in which no further action is possible, thus guaranteeing *progress* or *liveness*; for configurable systems, this notion is extended to guaranteeing liveness for each system variant (product)

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3. make hidden deadlock states s explicit:
   3.1 add a deadlock state $s_\dagger \notin Q$
   3.2 $\forall s$: add a *deadlock transition* from s to $s_\dagger$ labeled by $\dagger \notin \Sigma$ and by a feature expression that negates the disjunction of the feature expressions of all outgoing transitions of s

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Ambiguous FTS $\longrightarrow$ unambiguous FTS

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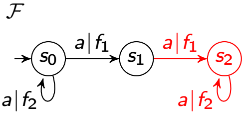
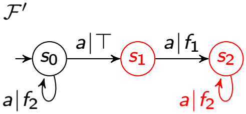
Example transformations

Feature Model: $f_1 \oplus f_2$





products $\lambda_1 = \{f_1\}$ and $\lambda_2 = \{f_2\}$

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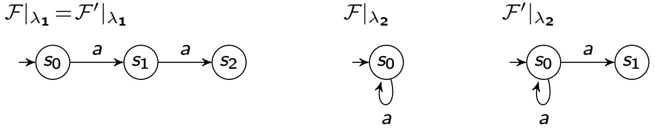

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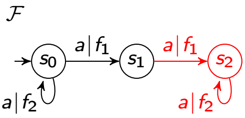

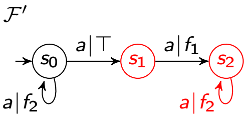

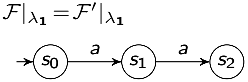

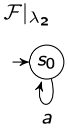

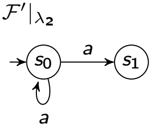

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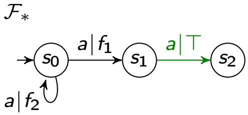

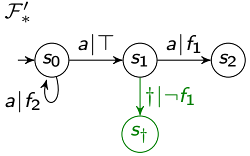

Static analysis algorithm

- Algorithm visits all cycle-free paths (starting in initial state) of FTS in depth-first order and in one unique FTS traversal identifies all ambiguities
- Based on formalization of criteria for ambiguities
- Criteria for ambiguities defined as deciding for a given Boolean formula if it is a tautology or not satisfiable, i.e., checking the criteria are variations of SAT solving
- We use Z3
- We prove its correctness in the paper

Python code publicly available, declared as reusable artifact

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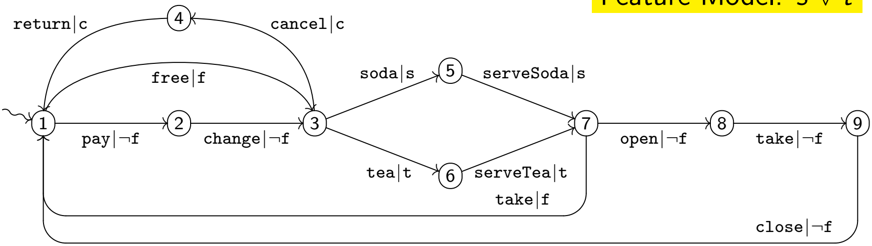
Example static analysis: vending machine

Feature Model: $s \vee t$

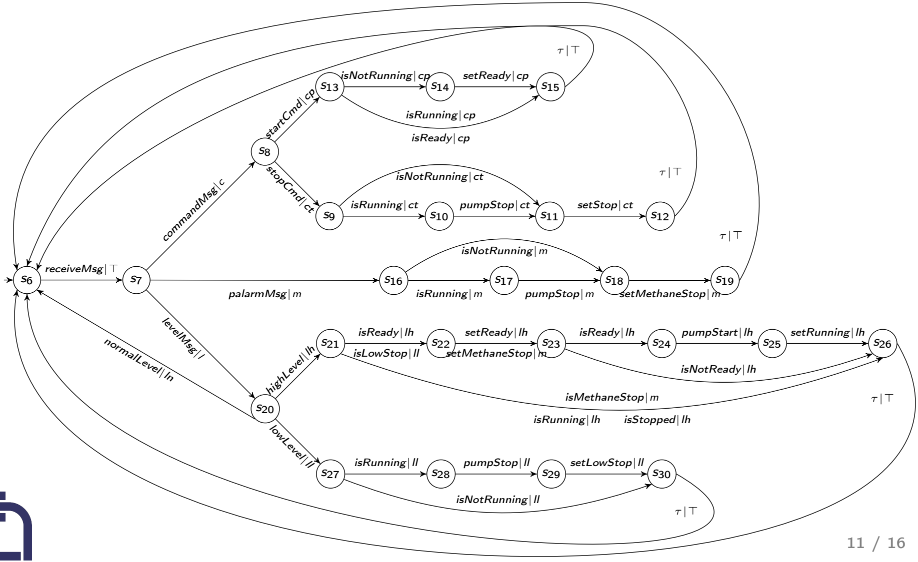


Result of static analysis on FTS

```
Vending Machine: live
 LIVE STATES = [1,2,3,4,5,6,7,8,9]
 DEAD TRANSITIONS = []
 FALSE OPTIONAL TRANSITIONS = [(2,3),(4,1),(5,7),(6,7),(8,9),(9,1)]
 HIDDEN DEADLOCK STATES = []
```

Example static analysis: mine pump (1/2)

Feature Model: $(c \leftrightarrow (ct \vee cp)) \wedge l$



Example static analysis: mine pump (2/2)

Result of static analysis on FTS

```
Mine Pump: not live
 LIVE STATES = [S6,S7,S8,S9,S10,S11,S12,S13,S14,S15,S16,S17,S18,
                S19,S21,S22,S23,S24,S25,S26,S27,S28,S29,S30]
 DEAD TRANSITIONS = []
 FALSE OPTIONAL TRANSITIONS = [(S10,S11),(S11,S12),(S13,S14),
     (S13,S15,isReady),(S13,S15,isRunning),(S14,S15),(S16,S17),
     (S16,S18),(S17,S18),(S18,S19),(S21,S22,isReady),
     (S21,S26,isRunning),(S21,S26,isStopped),(S22,S23,setReady),
     (S23,S24),(S23,S26),(S24,S25),(S25,S26),(S27,S28),(S27,S30),
     (S28,S29),(S29,S30),(S7,S20),(S9,S10),(S9,S11)]
 HIDDEN DEADLOCK STATES = [S20]
```

Experiments

FTS	characteristics			results of static analysis				computational effort	
Model	# states	# transitions	# actions	liveness	# dead transitions	# false optional transitions	# hidden deadlock states	runtime (s)	memory use (Mb)
Vending machine	9	13	12	yes	0	6	0	0.68	41
Coffee machine	14	22	14	yes	0	4	0	1.35	42
Mine pump (system)	25	41	22	no	0	25	1	1.41	44
Mine pump (controller)	77	104	22	no	0	59	4	5.37	48
Mine pump (complete)	417	1255	26	yes	?	?	?	timeout	–

The experiments were performed on a virtual machine Gentoo 201905, CLI Version VirtualBox (VDI) 64 bit, with 2048 Mb of allocated memory on a Windows 10 Pro 64 bit with 16 Gb of RAM and CPU AMD Ryzen 7 1700X (8 core, 16 threads, 3.4 Ghz)

Note

1. any FTS $\mathcal{F}$ can trivially be transformed into an MTS
2. if the FTS is unambiguous, then the corresponding MTS is live

This allows us to carry over a result for MTSs to unambiguous FTSs:

ter Beek *et al.* *JLAMP*, 2015

Any formula ϕ of v-ACTLive$^{\Box}$ is preserved by unambiguous FTSs: given an unambiguous FTS $\mathcal{F}$, whenever $\mathcal{F} \models \phi$, then $\mathcal{F}|_{\lambda} \models \phi$ for all products $\mathcal{F}|_{\lambda}$ of $\mathcal{F}$

Family-based model checking

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Example v-ACTLive$^{\Box}$ formulas that could now be verified with VMC:

ter Beek *et al.* @ FM'12, SPLC'14

1. $AG\ AF_{pay \vee free}\ \top$: *infinitely often, either action pay or action free is executed*
2. $AG\ [open]\ AF_{close}\ \top$: *it is always the case that the execution of action open is eventually followed by that of action close*
3. $AG\ AF_{cancel \vee serveSoda \vee serveTea}\ \top$: *infinitely often, either action cancel or action serveSoda or action serveTea is executed*
4. $\neg E\ [\top_{\neg tea}\ U_{serveTea}\ \top]$: *it is not possible that action serveTea is executed without being preceded by an execution of action tea*
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VMC v6.4 is freely usable online: http://fmt.isti.cnr.it/vmc/

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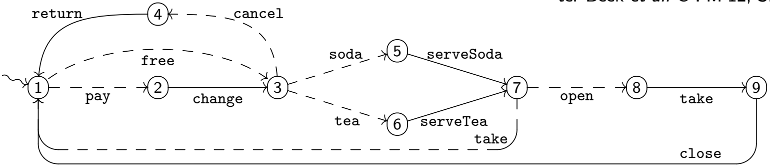

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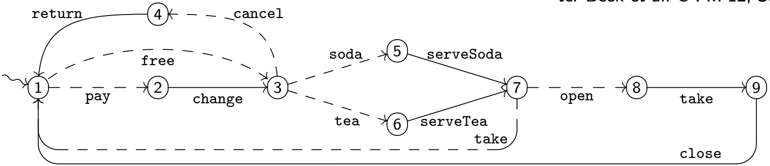

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Conclusion and Outlook

Static analysis of FTSs:

1. effective algorithm
2. proof of correctness
3. example applications
4. python code available

Future work:

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