

Combining Declarative and Procedural Views in the Feature-Oriented Specification and Analysis of Product Families

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joint work with

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(Software) Product Line Engineering

Paradigm

To develop a family of products (product line) using a common platform (architecture) and mass customization

Aim

To lower production costs of the individual products by

- letting them share an overall reference model of the product family
- allowing them to differ w.r.t. particular characteristics to serve, e.g., different markets

Product variants can be derived from a product family, thus allowing for reuse and differentiation

Production process

Maximize commonalities of product whilst minimizing cost of variations

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Feature modeling

Provide compact representations of all the products of a product family in terms of their *features* (pieces of functionality)

Variability modelling

How to explicitly define **optional**, **alternative**, **mandatory**, **required**, or **excluded** features of a product family as variation points

Managing variability with formal methods

Show that a certain product belongs to a product family or—instead—derive a product from a family by properly selecting features
Formally prove characteristics of products and families alike

Variability management/modeling

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Formal methods in SPLE

Aim

- Traditionally: focus on modelling/analysing structural constraints
- But: software systems often embedded/distributed/safety critical
- Important: model/analyse also behaviour (e.g. quality assurance)

Or, in the words of Dave Clarke (Uppsala University, Sweden)

“Behaviour is what we need. Without behaviour, it’s just sticks and balls. With behaviour, you get cricket.”

Since 2006 several approaches

- variants of UML diagrams (Jézéquel et al.)
- extensions of Petri nets (Clarke et al.)
- models with LTS-like semantics: variants of MTS (Fischbein et al., Fantechi et al.), I/O automata (Larsen et al., Lauenroth et al.), CCS (Gruler et al., Gnesi et al.), FTS (Classen et al.), FSM (Millo et al.)

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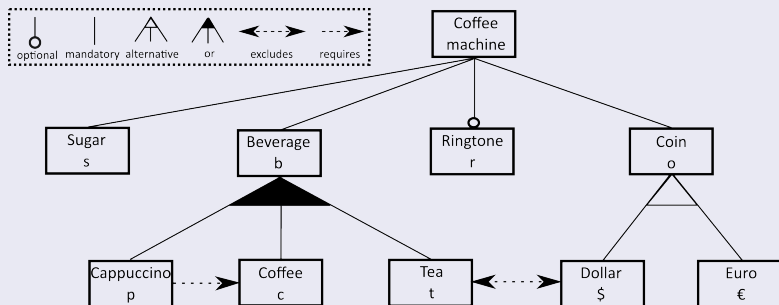
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Running example: Family of coffee machines

Structural constraints: Feature Model

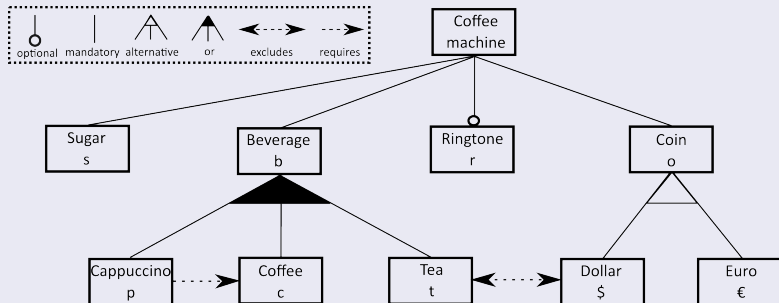


Behavioural constraints

- **Initially** a coin must be inserted, **after** which the user must choose whether s/he wants sugar, **after** which s/he may select a beverage
- A ringtone must be rung **after** serving cappuccino, otherwise it may
- The coffee machine returns idle **after** the beverage has been taken

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FLAN: Feature-oriented Language

Considers both structural and behavioural constraints

- *Concurrent constraint programming paradigm* as applied in calculi
- Implemented in Maude

Combines declarative and procedural specification

- A store of constraints allows specifying all common structural constraints from feature models (incl. cross-tree) in a *declarative* way
- A rich set of process-algebraic operators allows specifying both the configuration and behaviour of products in a *procedural* way
- Semantics neatly unifies static and dynamic feature selection

Declarative and procedural views closely related

- 1 process execution is constrained by store to avoid inconsistencies
- 2 process can query store to resolve configuration/behavioural option
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FLAN: Syntax

With actions $a \in \mathcal{A}$, propositions $p \in \mathcal{P}$ and features $f, g \in \mathcal{F}$

(fragments)	F	::=	$[S \parallel P]$
(constraints)	S, T	::=	$K \mid f \triangleright g \mid f \otimes g \mid S T \mid \top \mid \perp$
(processes)	P, Q	::=	$0 \mid X \mid A.P \mid P + Q \mid P; Q \mid P \mid Q$
(actions)	A	::=	$\text{install}(f) \mid \text{ask}(K) \mid a$
(propositions)	K	::=	$p \mid \neg K \mid K \vee K$

Constraints

- Store: *consistent*(S), inconsistent (\perp) or no constraint at all (\top)
- Universe \mathcal{P} of propositions: predicates *has*(f) and *in*(*context*)
- Action constraints $do(a) \rightarrow p$: guard to allow/forbid executing a

Processes

- 0 : empty process that can do nothing
- X : process identifier
- $A.P$: process willing to perform action A and then to behave as P
- $P+Q$: process that can non-deterministically choose to behave as P or as Q
- $P; Q$: process that must progress first as P and then as Q
- $P \mid Q$: process formed by parallel composition of P and Q , evolving independently

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FLAN: Semantics in SOS style

$\rightarrow \subseteq \mathbb{F} \times \mathbb{F}$, with \mathbb{F} set of all terms generated by F

$$\text{(INST)} \frac{\text{consistent}(S \text{ has}(f))}{[S \parallel \text{install}(f).P] \rightarrow [S \text{ has}(f) \parallel P]}$$

$$\text{(ASK)} \frac{S \vdash K}{[S \parallel \text{ask}(K).P] \rightarrow [S \parallel P]}$$

$$\text{(ACT)} \frac{S \vdash (\text{do}(a) \rightarrow K) \quad S \vdash K}{[S \parallel a.P] \rightarrow [S \parallel P]}$$

$$\text{(OR)} \frac{[S \parallel P] \rightarrow [S' \parallel P']}{[S \parallel P + Q] \rightarrow [S' \parallel P']}$$

$$\text{(SEQ)} \frac{[S \parallel P] \rightarrow [S' \parallel P']}{[S \parallel P; Q] \rightarrow [S' \parallel P'; Q]}$$

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Modulo structural congruence relation $\equiv \subseteq \mathbb{F} \times \mathbb{F}$

$$\begin{array}{llll} P + (Q + R) \equiv (P + Q) + R & P + 0 \equiv P & P + Q \equiv Q + P & \\ P | (Q | R) \equiv (P | Q) | R & 0; P \equiv P & P | Q \equiv Q | P & \\ P; (Q; R) \equiv (P; Q); R & P; 0 \equiv P & & \\ & P | 0 \equiv P & & P \equiv P[0/x] \text{ if } X \doteq Q \end{array}$$

Axioms naturally and efficiently treated by Maude

- 1 semantics is (efficiently) executable
- 2 correspond 1-1 to conditional rewrite rules in Maude implementation
- 3 few rules: semantics and implementation compact and easy to read

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Running example: A specification

$$\begin{aligned} F &\doteq [S \parallel D; R] \\ S &\doteq S_1 S_2 \\ S_1 &\doteq \text{has}(\text{euro}) \vee \text{has}(\text{dollar}) \\ &\quad \text{in}(\text{Europe}) \rightarrow \text{has}(\text{euro}) \quad \text{in}(\text{Canada}) \rightarrow \text{has}(\text{dollar}) \\ &\quad \text{has}(\text{coffee}) \vee \text{has}(\text{cappuccino}) \vee \text{has}(\text{tea}) \quad \text{has}(\text{tea}) \rightarrow \text{in}(\text{Europe}) \\ &\quad \text{dollar} \otimes \text{euro} \quad \text{cappuccino} \triangleright \text{coffee} \\ &\quad \text{do}(\text{euro}) \rightarrow \text{has}(\text{euro}) \quad \text{do}(\text{dollar}) \rightarrow \text{has}(\text{dollar}) \quad \text{do}(\text{tea}) \rightarrow \text{has}(\text{tea}) \\ &\quad \text{do}(\text{coffee}) \rightarrow \text{has}(\text{coffee}) \quad \text{do}(\text{cappuccino}) \rightarrow \text{has}(\text{cappuccino}) \\ &\quad \text{do}(\text{sugar}) \rightarrow \text{has}(\text{sugar}) \quad \text{do}(\text{ringtone}) \rightarrow \text{has}(\text{ringtone}) \\ S_2 &\doteq \text{in}(\text{Europe}) \\ &\quad \text{has}(\text{euro}) \quad \text{has}(\text{dollar}) \\ D &\doteq \text{install}(\text{sugar}).0 \mid \text{install}(\text{coffee}).0 \mid \text{install}(\text{tea}).0 \mid \text{install}(\text{cappuccino}).0 \\ R &\doteq (\text{ask}(\text{in}(\text{Europe})).\text{euro}.0 + \text{ask}(\text{in}(\text{Canada})).\text{dollar}.0); (P_2 + P_3) \\ P_2 &\doteq \text{sugar}.P_3 \\ P_3 &\doteq \text{coffee}.P_4 + \text{tea}.P_4 + \text{cappuccino}.P_5 \\ P_4 &\doteq P_5 + R \\ P_5 &\doteq \text{install}(\text{ringtone}).\text{ringtone}.R \end{aligned}$$

Declarative and procedural feature configuration

Select feature f in an *explicit* and *declarative* way

- Include the proposition $has(f)$ in the initial store
- For features that are surely mandatory for all the family's products

Select feature f in an *implicit* and *declarative* way

- Derive f as a consequence of other constraints
- For features that apparently seem not to be mandatory, but that are indeed enforced by the constraints (e.g. in a store with both constraints $g \triangleright f$ and $has(g)$, the presence of f can be inferred)

Install feature f dynamically in a *procedural* way

- Install f during the execution of a process
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Checking the (in)consistency of the initial constraints

Returns \emptyset if consistent, else subset of inconsistent constraints

```
reduce in ANALYSIS-KRIPKE : inconsistency(S) .  
...  
result neConstraints: has(dollar) has(euro)  
                    dollar * euro
```

Specification needs to be corrected

Delegate installation of *euro* and *dollar* to configuration process *D* by invoking **install(euro).0** and **install(dollar).0**

Returns true if consistent, else false

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reduce in ANALYSIS-KRIPKE : consistent(S) .  
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result Bool: true
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Running example: Revised specification

$F \doteq [S \parallel D; R]$
 $S \doteq S_1 S_2$
 $S_1 \doteq has(euro) \vee has(dollar)$
 $in(Europe) \rightarrow has(euro) \quad in(Canada) \rightarrow has(dollar)$
 $has(coffee) \vee has(cappuccino) \vee has(tea) \quad has(tea) \rightarrow in(Europe)$
 $dollar \otimes euro \quad cappuccino \triangleright coffee$
 $do(euro) \rightarrow has(euro) \quad do(dollar) \rightarrow has(dollar) \quad do(tea) \rightarrow has(tea)$
 $do(coffee) \rightarrow has(coffee) \quad do(cappuccino) \rightarrow has(cappuccino)$
 $do(sugar) \rightarrow has(sugar) \quad do(ringtone) \rightarrow has(ringtone)$
 $S_2 \doteq in(Europe)$
 $\quad \underline{has(euro)} \quad \underline{has(dollar)}$
 $D \doteq install(sugar).0 \mid install(coffee).0 \mid install(tea).0 \mid install(cappuccino).0$
 $\quad \mid install(euro).0 \mid install(dollar).0$
 $R \doteq (ask(in(Europe)).euro.0 + ask(in(Canada)).dollar.0); (P_2 + P_3)$
 $P_2 \doteq sugar.P_3$
 $P_3 \doteq coffee.P_4 + tea.P_4 + cappuccino.P_5$
 $P_4 \doteq P_5 + R$
 $P_5 \doteq install(ringtone).ringtone.R$

Applies rewrite rules until a fix point is reached

```
rewrite in ANALYSIS-KRIPKE : ! [S | D] .
```

```
...
```

```
result KFragment: ! [has(dollar) has(coffee)  
has(tea) has(cappuccino) has(sugar) ... | 0]
```

Checking the consistency of all configurations

FLAN's semantics preserves consistency

Still we can use Maude's model checker to check consistency of all reachable configurations by specifying the property \square *isConsistent* (i.e. consistency is an invariant)

State predicate returns the result of **consistent(S)**

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Checking behavioural properties

Check that runtime behaviour does not introduce inconsistencies

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Check “a ringtone must be rung after serving a cappuccino” ...

```
reduce in ANALYSIS-LTS : modelCheck( ( ! (do('machine)  
[S' | D' ; R]) ) , [] (cappuccino -> <> ringtone) ) .  
...  
result Bool: true
```

... is preserved if we replace procedural by declarative information

The conditional statement used to accept dollar or euro is redundant:
A simpler run-time process replaces it with a non-deterministic choice
that will be consistently solved at runtime since the store contains the
action constraints $do(euro) \rightarrow has(euro)$ and $do(dollar) \rightarrow has(dollar)$
which will forbid the use of actions *euro* or *dollar* if the corresponding
feature has not been installed

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... is preserved if we replace procedural by declarative information

The conditional statement used to accept dollar or euro is redundant:
A simpler run-time process replaces it with a non-deterministic choice
that will be consistently solved at runtime since the store contains the
action constraints $do(euro) \rightarrow has(euro)$ and $do(dollar) \rightarrow has(dollar)$
which will forbid the use of actions *euro* or *dollar* if the corresponding
feature has not been installed

Checking behavioural properties

Check that runtime behaviour does not introduce inconsistencies

```
reduce in ANALYSIS-KRIPKE : modelCheck( ( ! [ S | D ; R ] ) ,  
[ ] isConsistent ) .  
...  
result Bool: true
```

Check “a ringtone must be rung after serving a cappuccino” ...

```
reduce in ANALYSIS-LTS : modelCheck( ( ! (do('machine)  
[S' | D' ; R]) ) , [ ] (cappuccino -> <> ringtone) ) .  
...  
result Bool: true
```

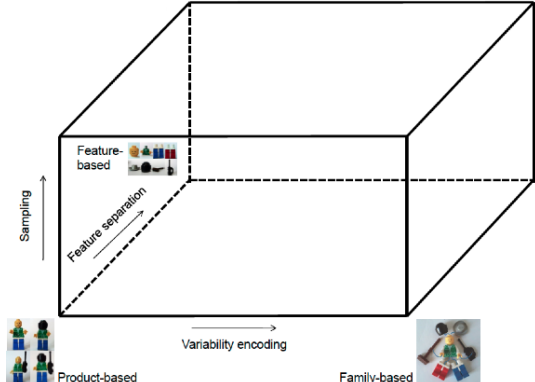
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Final specification

$$\begin{aligned} F &\doteq [S \parallel D; R] \\ S &\doteq S_1 S_2 \\ S_1 &\doteq \text{has}(\text{euro}) \vee \text{has}(\text{dollar}) \\ &\quad \text{in}(\text{Europe}) \rightarrow \text{has}(\text{euro}) \quad \text{in}(\text{Canada}) \rightarrow \text{has}(\text{dollar}) \\ &\quad \text{has}(\text{coffee}) \vee \text{has}(\text{cappuccino}) \vee \text{has}(\text{tea}) \quad \text{has}(\text{tea}) \rightarrow \text{in}(\text{Europe}) \\ &\quad \text{dollar} \otimes \text{euro} \quad \text{cappuccino} \triangleright \text{coffee} \\ &\quad \text{do}(\text{euro}) \rightarrow \text{has}(\text{euro}) \quad \text{do}(\text{dollar}) \rightarrow \text{has}(\text{dollar}) \quad \text{do}(\text{tea}) \rightarrow \text{has}(\text{tea}) \\ &\quad \text{do}(\text{coffee}) \rightarrow \text{has}(\text{coffee}) \quad \text{do}(\text{cappuccino}) \rightarrow \text{has}(\text{cappuccino}) \\ &\quad \text{do}(\text{sugar}) \rightarrow \text{has}(\text{sugar}) \quad \text{do}(\text{ringtone}) \rightarrow \text{has}(\text{ringtone}) \\ S_2 &\doteq \text{in}(\text{Europe}) \\ D &\doteq \text{install}(\text{sugar}).0 \mid \text{install}(\text{coffee}).0 \mid \text{install}(\text{tea}).0 \mid \text{install}(\text{cappuccino}).0 \\ &\quad \mid \text{install}(\text{euro}).0 \mid \text{install}(\text{dollar}).0 \\ R &\doteq (\text{ask}(\text{in}(\text{Europe})).\text{euro}.0 + \text{ask}(\text{in}(\text{Canada})).\text{dollar}.0); (P_2 + P_3) \\ P_2 &\doteq \text{sugar}.P_3 \\ P_3 &\doteq \text{coffee}.P_4 + \text{tea}.P_4 + \text{cappuccino}.P_5 \\ P_4 &\doteq P_5 + R \\ P_5 &\doteq \text{install}(\text{ringtone}).\text{ringtone}.R \end{aligned}$$

FLAN's position in the PLA cube (Apel et al.)



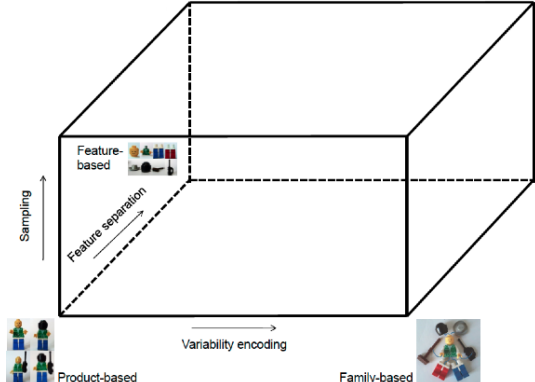
Family-based analysis: check properties of entire product family

In general checks like $[S \parallel P] \models \phi$: does $[S \parallel P]$ satisfy LTL property ϕ ?
A positive result means the whole family specified by $[S \parallel P]$ satisfies ϕ
A negative result—instead—witnesses that *at least one* of its products has at least one behaviour that does not satisfy ϕ

Ongoing work on further interesting analyses

Aim: identify subclasses of configurations satisfying specific properties

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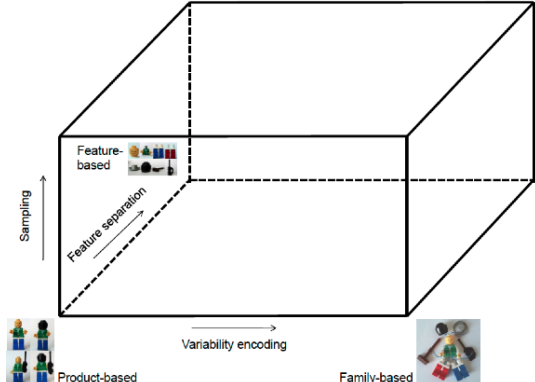
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Conclusions

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- Proof of concept for specifying and analysing both declarative and procedural aspects of product families
- Its semantics neatly unifies static and dynamic feature selection

Not *the* language, but useful features to adopt in other languages

- Concurrent constraint programming: flexible mechanism for both declarative *and* procedural aspects (e.g. delay design decisions until runtime, free runtime specifications from feature constraints, thus resulting in light-weight and understandable specifications)

Implementation in Maude: exploit Maude's rich analysis toolset

- For now SAT solver, reachability analyser and LTL model checker
- e.g. statistical model checker PVESTA to evaluate the performance of product families in *stochastic* and *quantitative* variants of FLAN

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We envisage several potentially interesting extensions of FLAN:

- 1 Adopt further primitives and mechanisms from the concurrent constraint programming tradition
 - e.g. the concurrent constraint π -calculus of Buscemi & Montanari provides synchronisation mechanisms typical of mobile calculi (i.e. name passing), a **check** operation to prevent inconsistencies, a **retract** operation to remove constraints from the store and a general framework for *soft* constraints (i.e. not only boolean)
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 - 1 FLAN becomes a high-level language for those semantic models
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