~~An Introduction to Software Product Lines and Modelling and Analysing Variability~~ Quantitative Modelling and Analysis of Variability in Highly Configurable Systems

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Based on joint work with Stefania Gnesi, Franco Mazzanti (ISTI–CNR), Alessandro Fantechi (UNIFI), Erik de Vink, Tim Willemse (TU/e), Axel Legay (UCL/Inria), Alberto Lluch Lafuente, Andrea Vandin (DTU)

~~IPA Fall Days on Models in Software Engineering~~
~~WestCord de Veluwe, Garderen, The Netherlands~~
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July 13, 2021

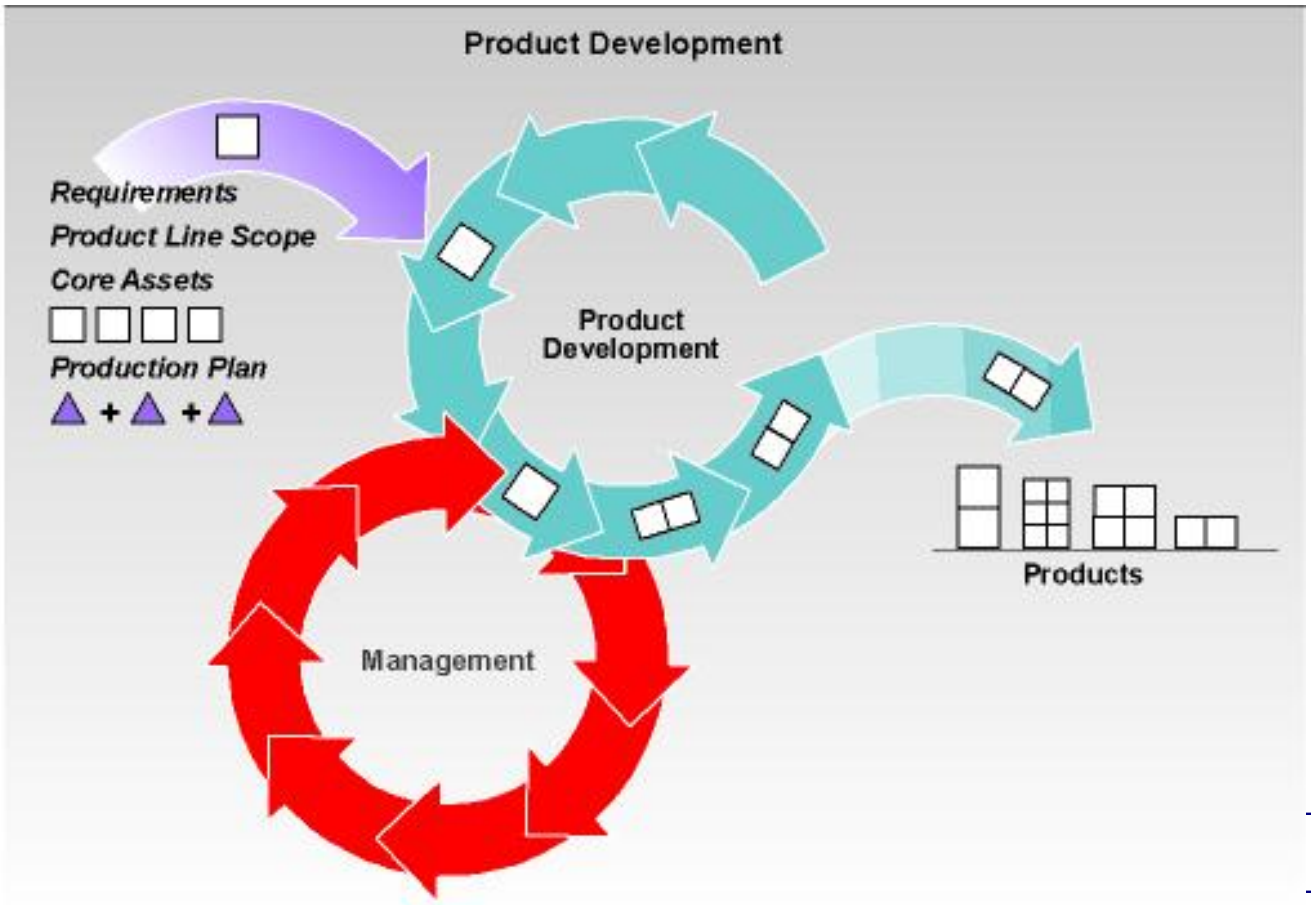
Outline

An introduction to Software Product Lines

- (Software) Product Line Engineering
- Product variability and features
- Variability modelling and analysis

These slides are partly based on slides by Klaus Pohl, Sven Apel and Slinger Jansen

Product line engineering in theory…



…and in practice

Software Product Line Engineering

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  - Application engineering: develop individual products by reusing domain artefacts
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Two main differences with classical software engineering

- Two distinct development processes
  - Domain engineering: develop reusable domain artefacts
  - Application engineering: develop individual products by reusing domain artefacts
- Variability
  - Common features that are part of all products
  - Variable features that can be selected for a product

Variability in requirements

R12: The navigation system must allow the user to make inputs using a control panel or by voice entry

- R12 comprises the following three realisations

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  3. A navigation system that allows the user to make inputs only via the control panel and by voice entry
- Conjunction is a logical “or” or an exclusive “or”?
- Is only one system asked for, or two or three different systems?

Variation points and variants

- A variation point represents an aspect of a product family that varies among the different products

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  R12: “input via control panel”, “input via voice entry”

Variability: prerequisite for success

- Domain engineering: explicit documentation of variability supports the identification of possible variable aspects and fosters explicit decisions about which aspects shall be variable in the product family (variation points) and which options shall exist for each variable aspect (variants);

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- Application engineering: explicit documentation of variability in terms of variation points and variants supports system development by making explicit the necessary decisions and decision options

Features

- What is a feature?

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  - End-user visible behaviour or property of a system…
  - …that may be optional and/or may have alternatives

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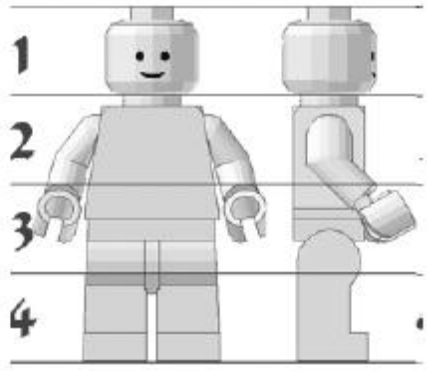
  - End-user visible behaviour or property of a system…
  - …that may be optional and/or may have alternatives
- Features represent commonalities and variabilities of (software) systems



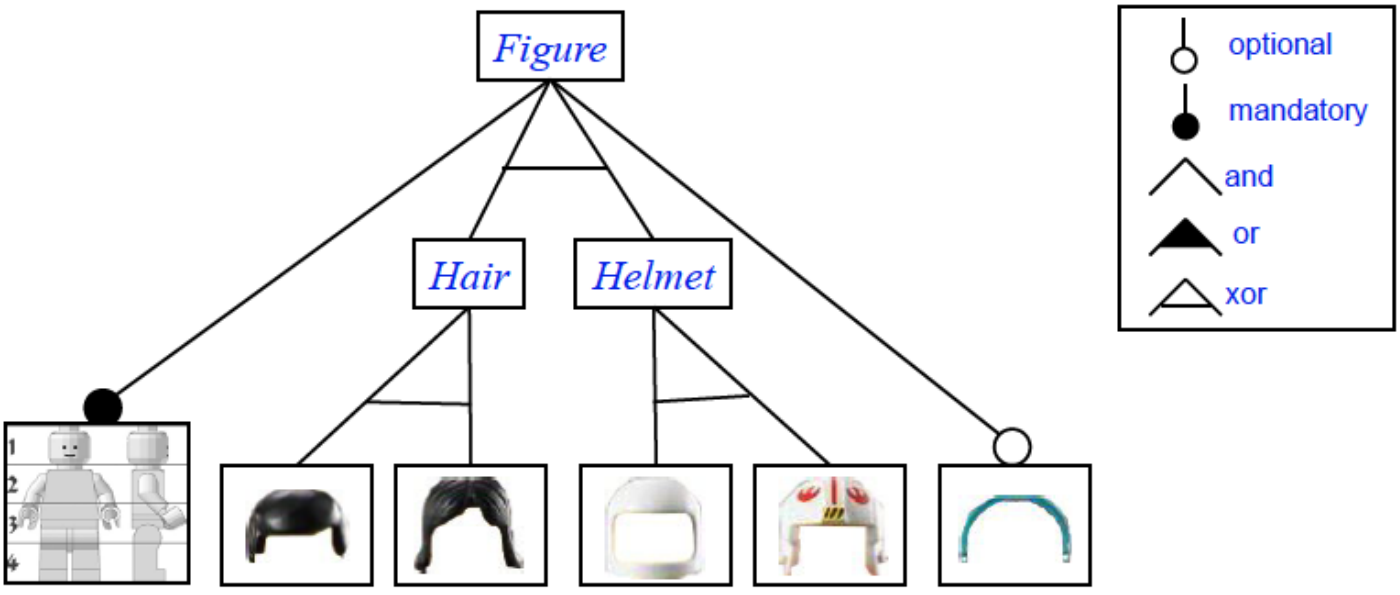
What's in a *feature*?

Reference	Definition
Kang *et al.* [3]	*"a prominent or distinctive user-visible aspect, quality or characteristic of a software system or systems"*
Kang *et al.* [8]	*"distinctively identifiable functional abstractions that must be implemented, tested, delivered, and maintained"*
Eisenecker and Czarnecki [6]	*"anything users or client programs might want to control about a concept"*
Bosch *et al.* [9]	*"A logical unit of behaviour specified by a set of functional and non-functional requirements."*
Chen *et al.* [10]	*"a product characteristic from user or customer views, which essentially consists of a cohesive set of individual requirements"*
Batory [11]	*"an elaboration or augmentation of an entity(s) that introduces a new service, capability or relationship"*
Batory *et al.* [12]	*"an increment in product functionality"*
Apel *et al.* [13]	*"a structure that extends and modifies the structure of a given program in order to satisfy a stakeholder's requirement, to implement and encapsulate a design decision, and to offer a configuration option."*

(Classen *et al.* @ FASE'08)

Feature selection

Typically, only a subset of feature combinations is valid



$Visor \Rightarrow Helmet$

Products and product lines

- Product ⇔ valid feature combination (configuration)





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- Product ⇔ valid feature combination (configuration)

- Product line ⇔ set of valid feature combinations of a domain

...

Features and software

- Main concept in SPLE
  - Easy to use in informal models
  - Easily converts into business: product sales
  - Easily converts into product design: variability
  - Enables reuse of features

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- Main concept in SPLE
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  - Easily converts into product design: variability
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- In telecommunication, features became popular in the 1960s with the advent of computer-controlled telephone switches; telecommunication software has been conceived in terms of features ever since
  - 1992-2009 International Conference on Feature Interactions in Telecommunications and Software Systems

Variability models: explicit decisions

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- Feature diagram/model: hierarchical tree structure, with the family as its root, features as its nodes and possibly further cross-tree constraints (Kang *et al*. ’90)

Variability models: explicit decisions

- Compact representations of all products of a product family in terms of their features
- Feature diagram/model: hierarchical tree structure, with the family as its root, features as its nodes and possibly further cross-tree constraints (Kang *et al*. ’90)
- Common Variability Language (CVL): OMG's effort to standardise variability modelling as a separate and generic language to define variability on base models
- Orthogonal Variability Model (Pohl *et al*. ’05), etc., etc.

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- Improved communication with different stakeholders (e.g. communicate to customers which variants can be selected at which variation points)
- Transparent decisions i.e. the originator of a variation point is forced to state the rationale for introducing variability in a specific domain artefact
- Relationships between requirements and variants become traceable (e.g. stakeholders can document which requirements, design, implementation and test artefacts are influenced by a variant)

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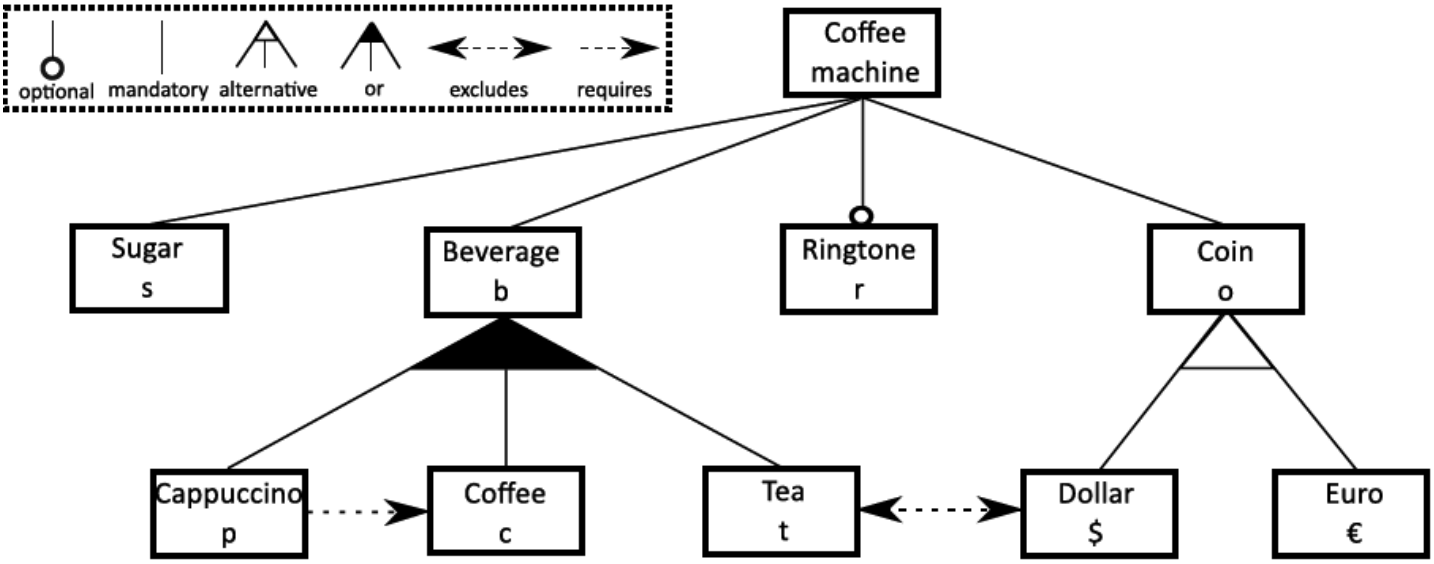
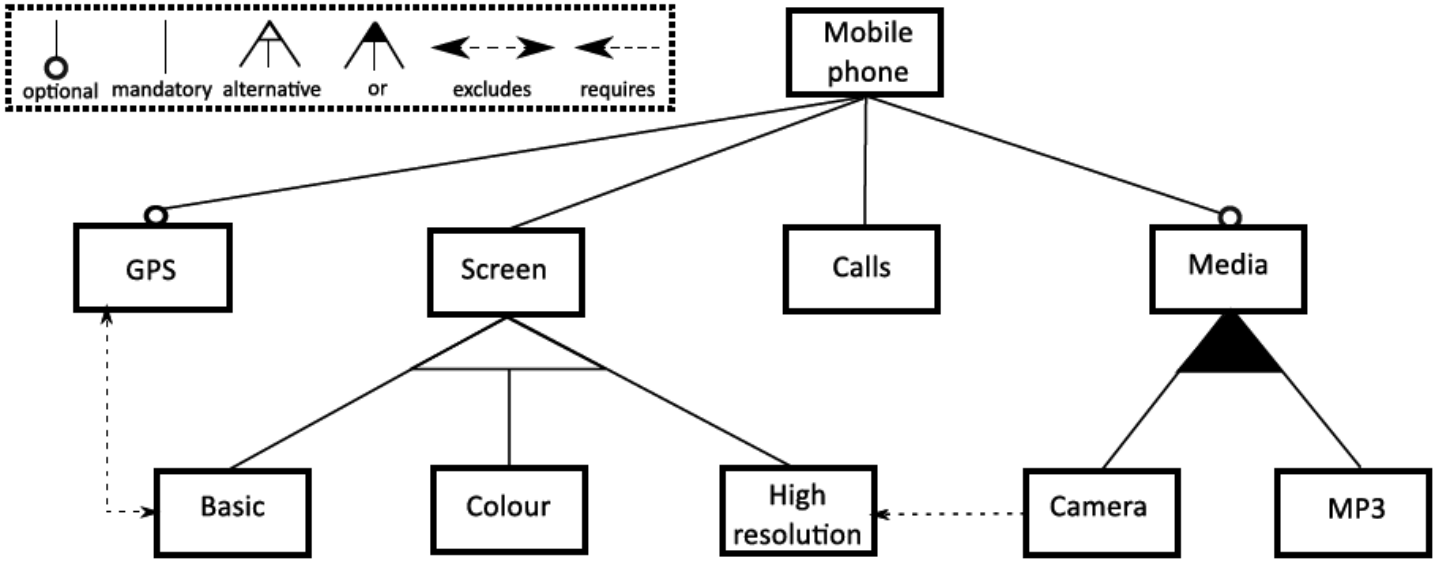
5. As soon as the user has taken her/his beverage, the coffee machine must return in its idle state

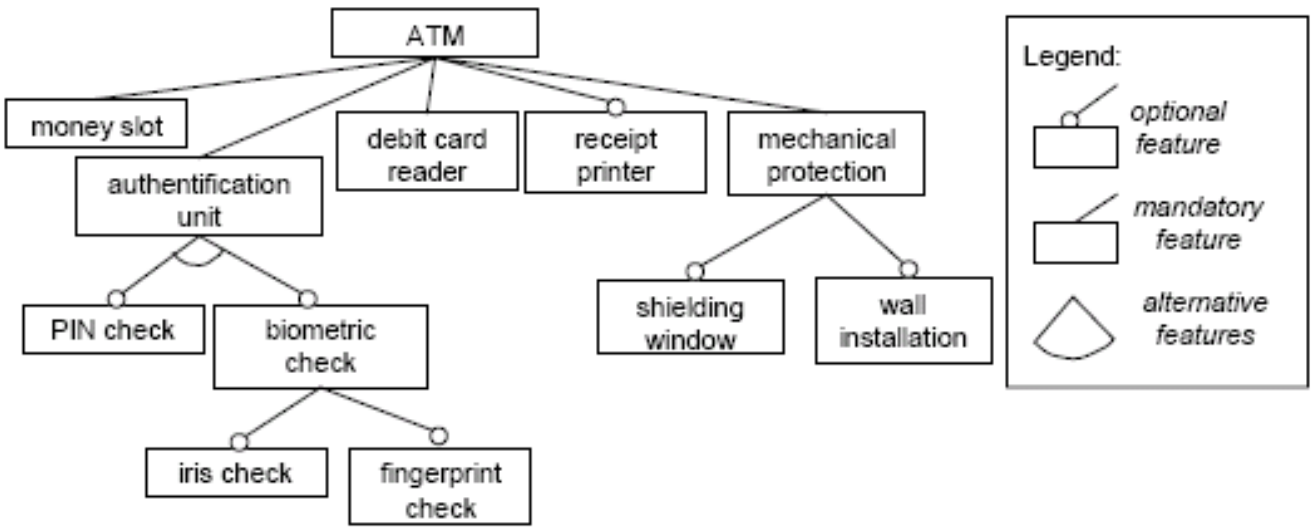
Coffee machine feature diagram



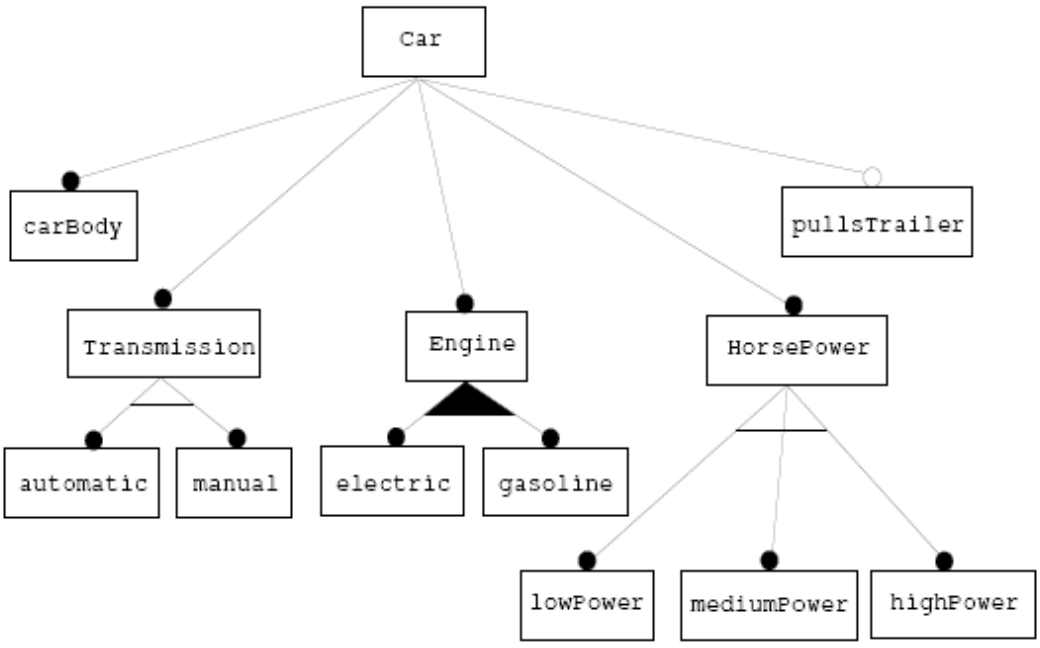
Mobile phone feature diagram



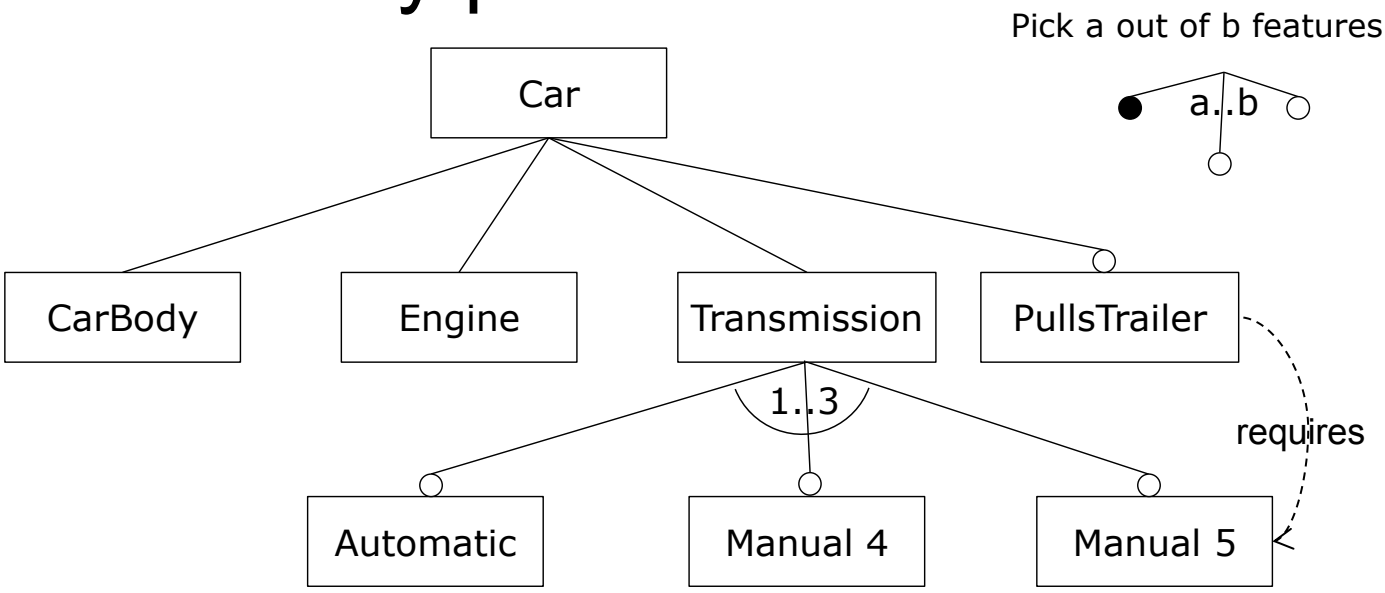
ATM feature diagram



Automotive feature diagram



How many products?



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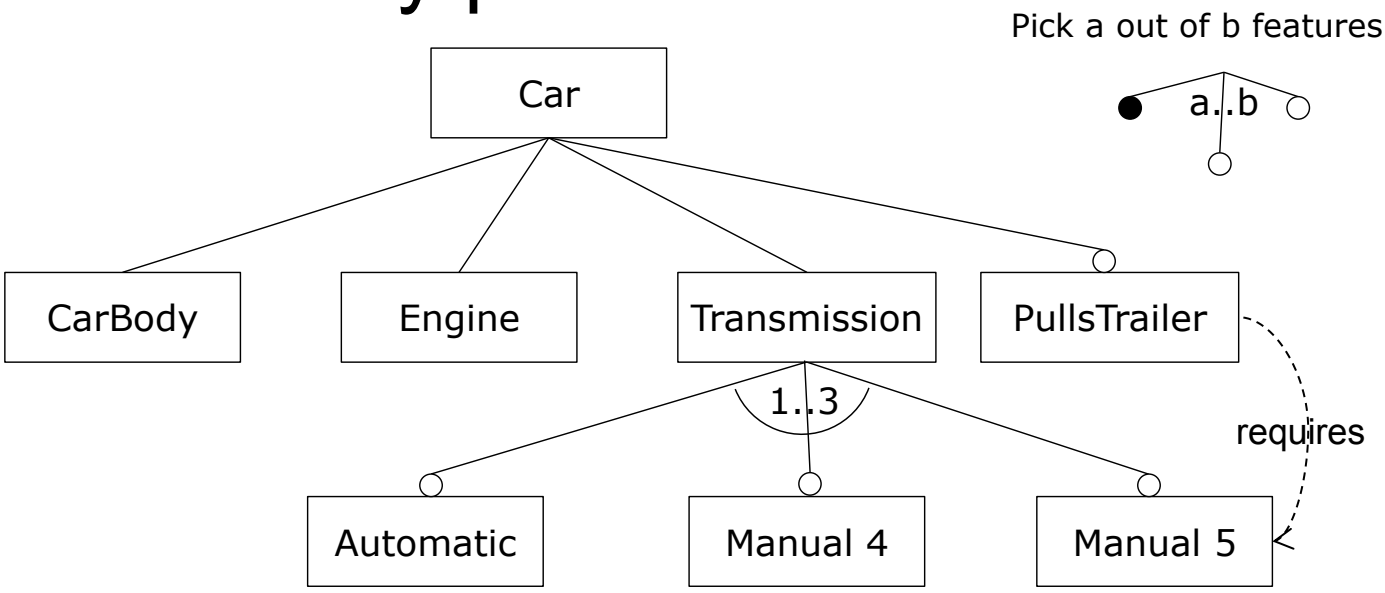

Transmission contributes one of three options, multiplier = 3
Car contributes two options, multiplier = 2, but…

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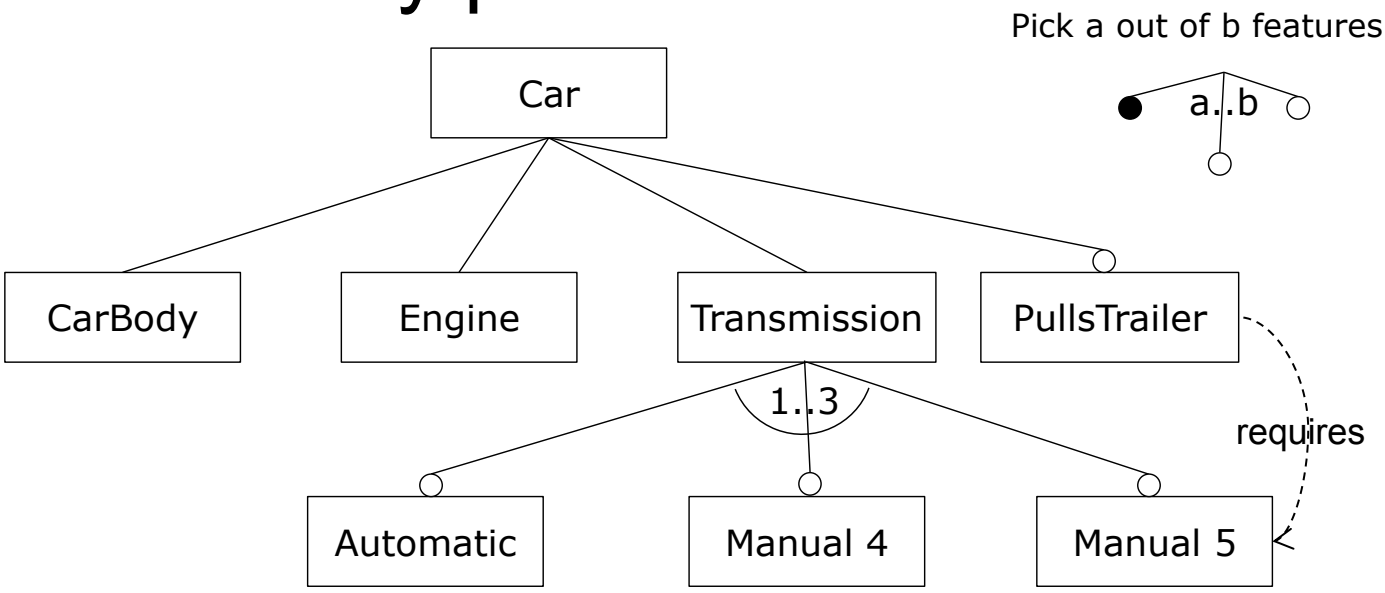
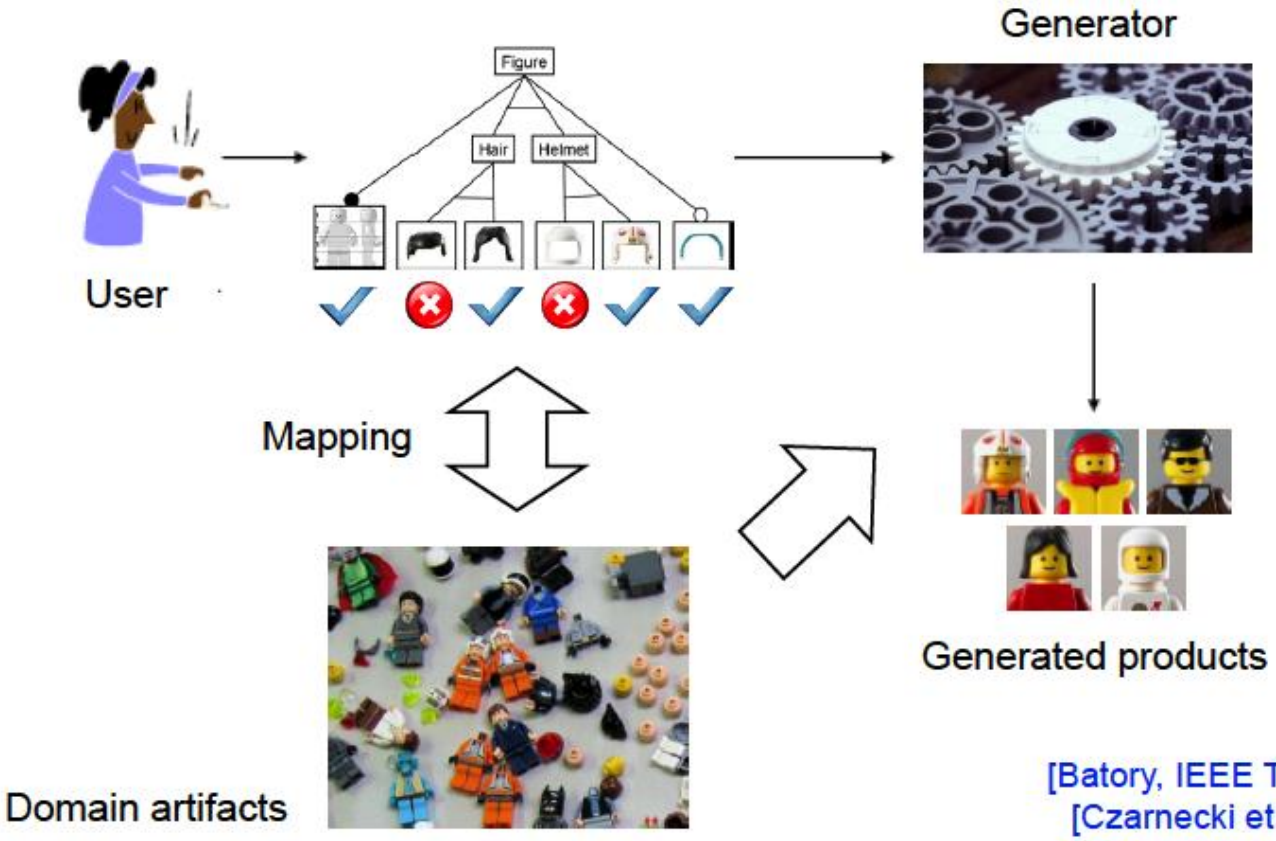


Transmission contributes one of three options, multiplier = 3
Car contributes two options, multiplier = 2, but…
…actually only works in one case; thus: 4 different products

Applications of feature diagrams

- Communicate with stakeholders
- Identify objects for reuse
- Identify objects for sales opportunities
- Identify cross-cutting concerns
- Software composition and deployment
- etc.

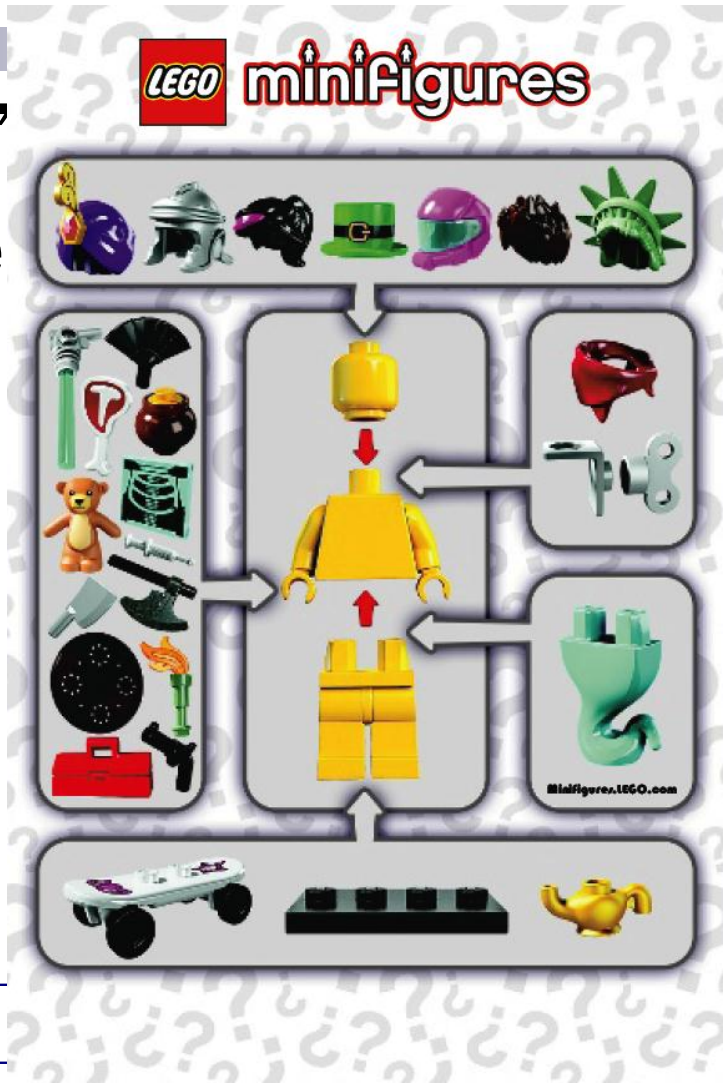
… Automated product derivation



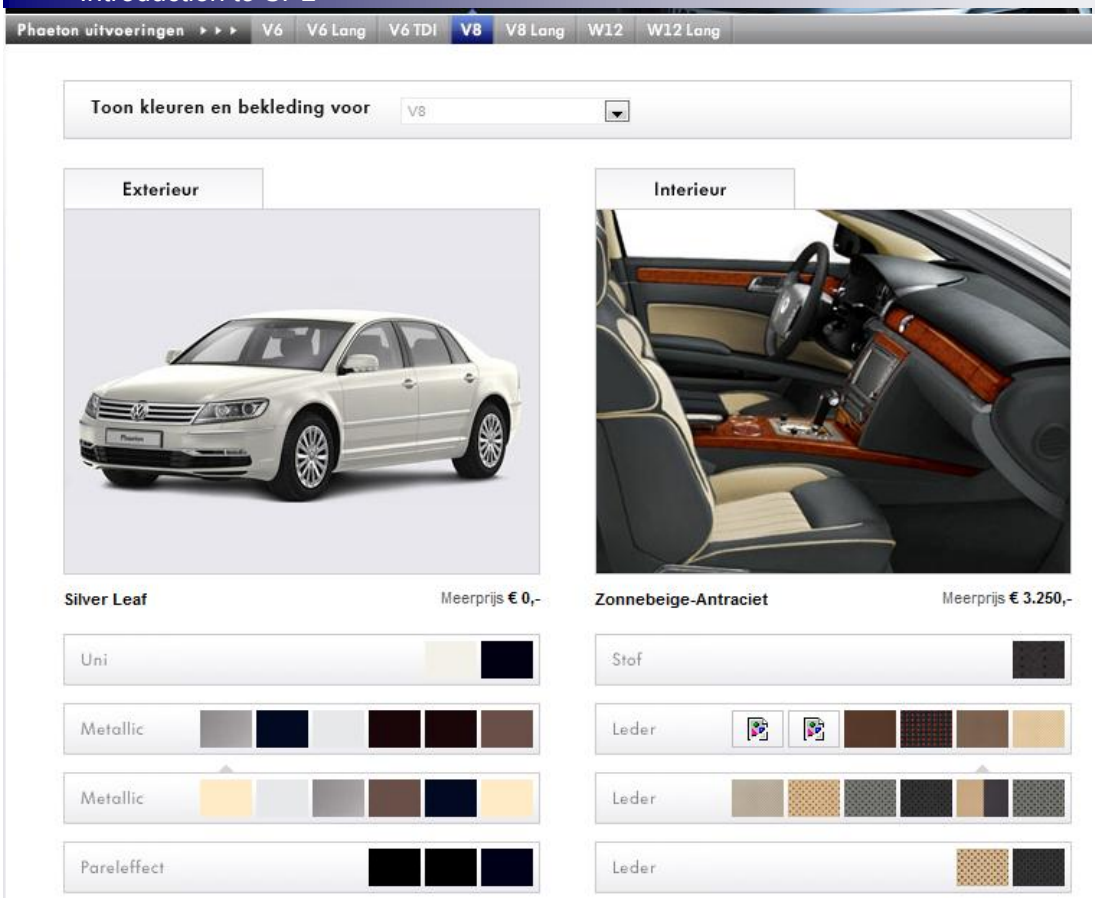
[Batory, IEEE TSE 2004]
[Czarnecki et al., 2000]

A product line of Lego minifigures (16 valid feature combinations)

‘Feature diagram’ for configuring the 16 valid products (allowing more…)



VW features


Phaeton uitvoeringen
V6
V6 Lang
V6 TDI
V8
V8 Lang
W12
W12 Lang
Toon kleuren en bekleding voor
V8
Exterieur
Interieur
Silver Leaf
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Budget

Vehicle type

- All
- Petrol
- Diesel
- Hybrid
- Electric Vehicle

Body type

- Saloon
- Touring
- Convertible
- Coupé
- Gran Turismo
- Sports Hatch
- Roadster
- Sports Activity Coupé
- Sports Activity Vehicle

Number of seats

30 Vehicles (465 Model variants)

1

BMW 1 Series 3-door Sports Hatch (34)
from £ 17,775.00

BMW 1 Series 5-door Sports Hatch (39)
from £ 18,305.00

2

BMW 2 Series Coupé (14)
from £ 24,265.00

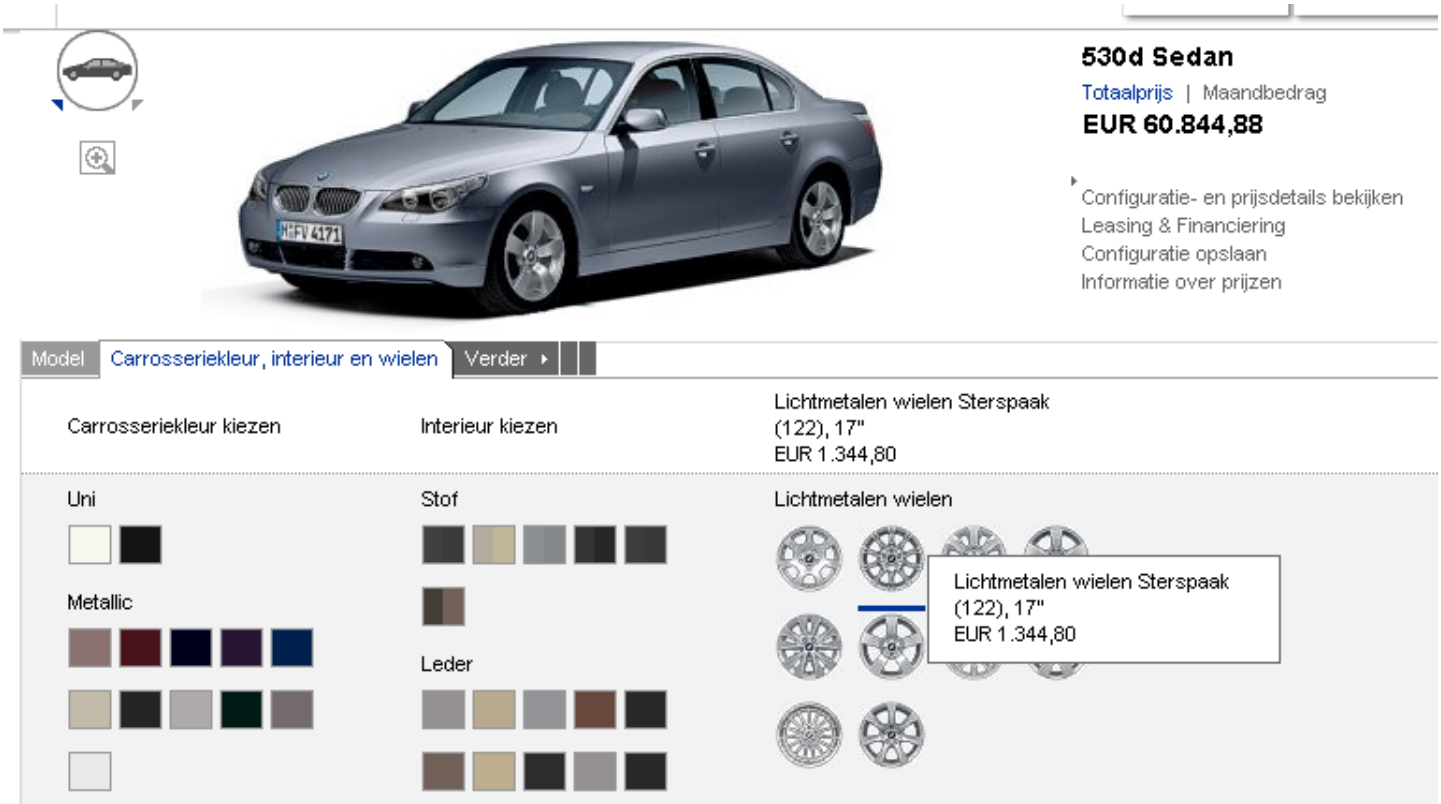
3

BMW 3 Series Saloon (56)
from £ 23,550.00

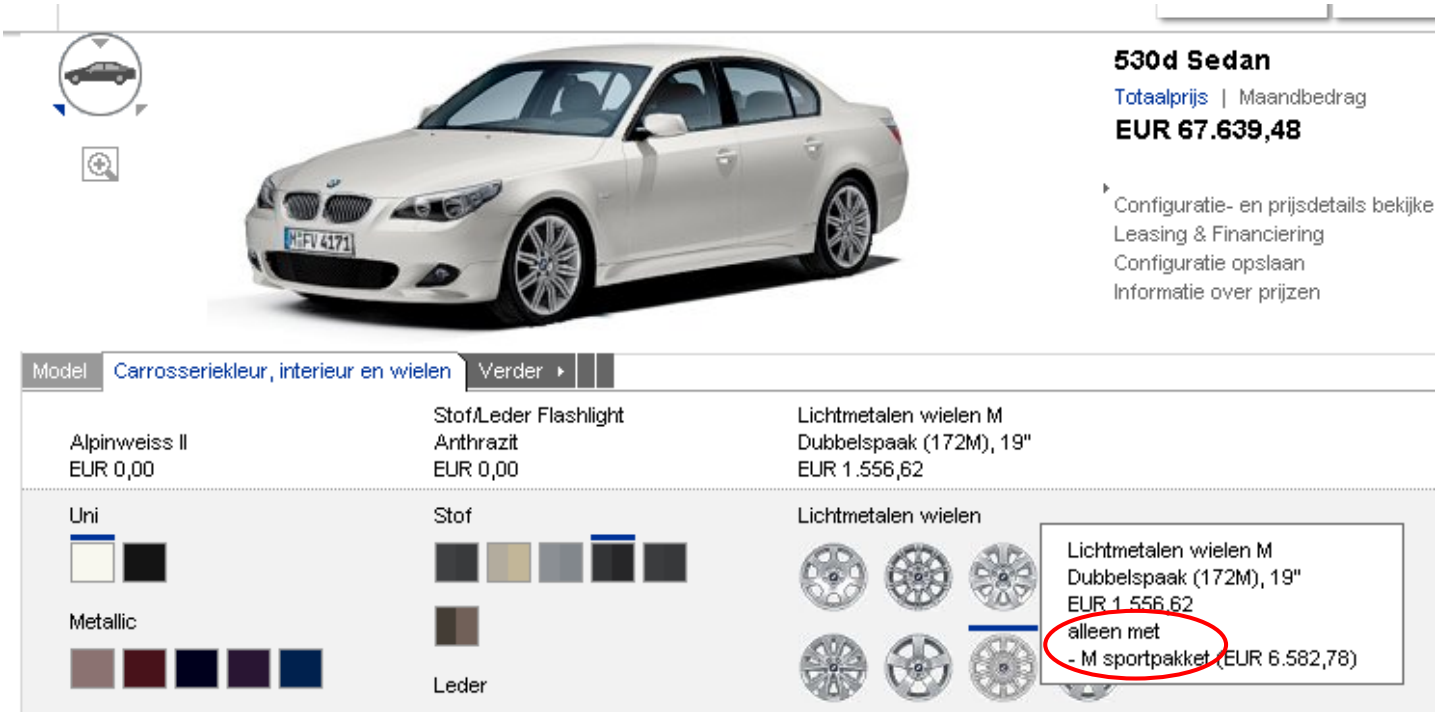
BMW 3 Series Touring (54)
from £ 24,865.00

BMW 3 Series Gran Turismo (39)
from £ 29,200.00

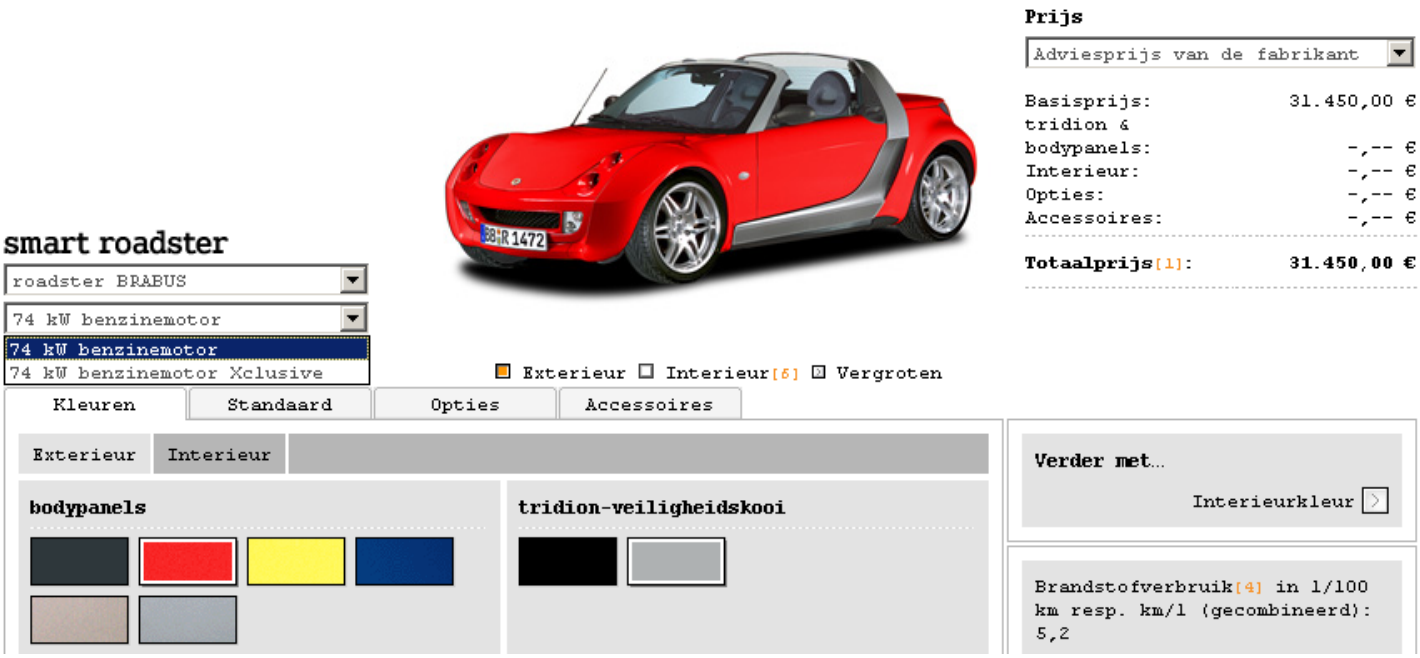
BMW product configurator



BMW feature packages



Smart constraints (1/2)



Smart constraints (2/2)

Feature binding times

- The moment a choice is made for a variable feature

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  - Compile time
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- For lego:
  - Playing time 

Variability dependencies (1/2)

Allowed choices of variants at a specific variation point

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- Mandatory variant: if the variation point is selected, this variant *must* always be selected
- Optional variant: if the variation point is selected, this variant *may* be selected but it does not have to be
- Alternative choice i.e. a collection of at least two optional variants together with a [min…max] notation to indicate the permissible number of variants to be selected: if the variation point is selected, at least "min" variants *must* be selected while at most "max" variants *may* be selected

Variability dependencies (2/2)

Cross-tree constraints

- Requires: indicates that the presence of one feature requires the presence of another feature

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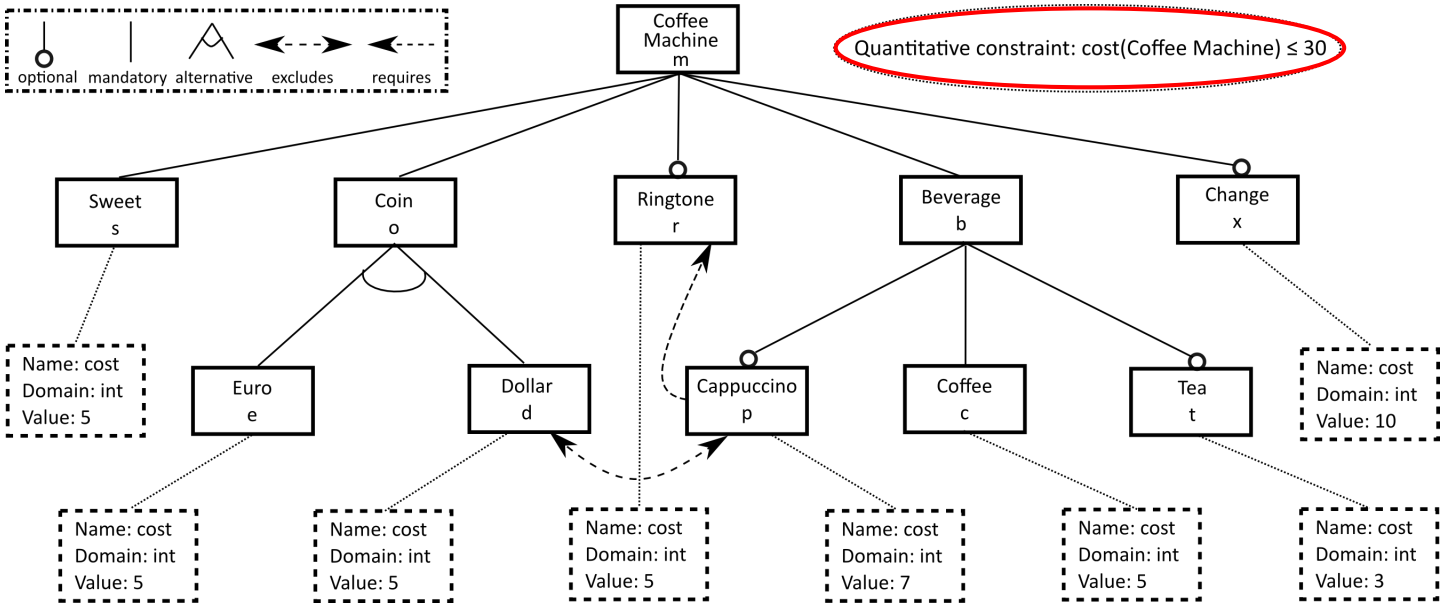
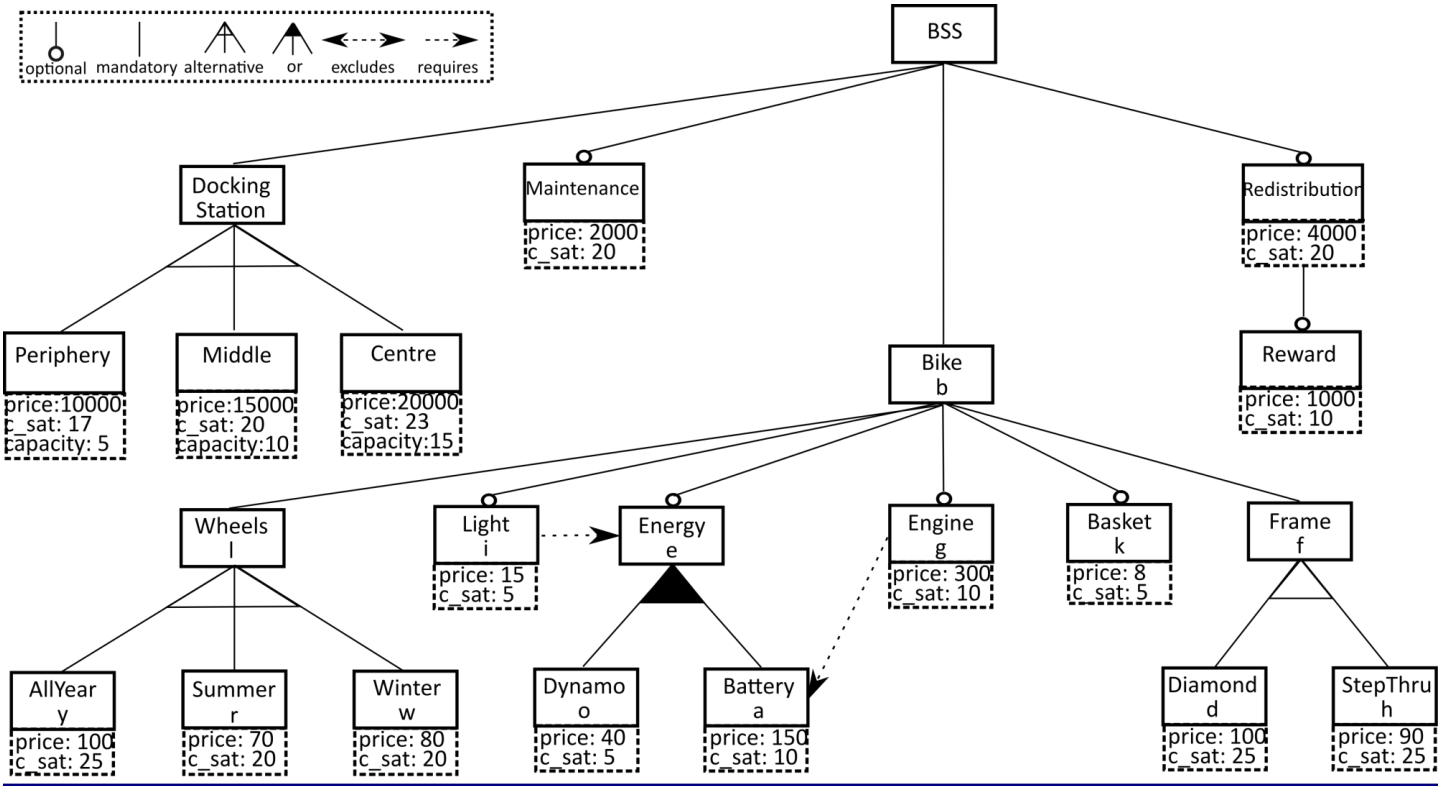
Quantitative constraints

- Feature attributes (non-functional): *cost*(feature) = 7, etc.
- *cost*(product) = ∑{*cost*(feature) | feature ∈ product }

Attributed feature model (1/2)



Attributed feature model (2/2)



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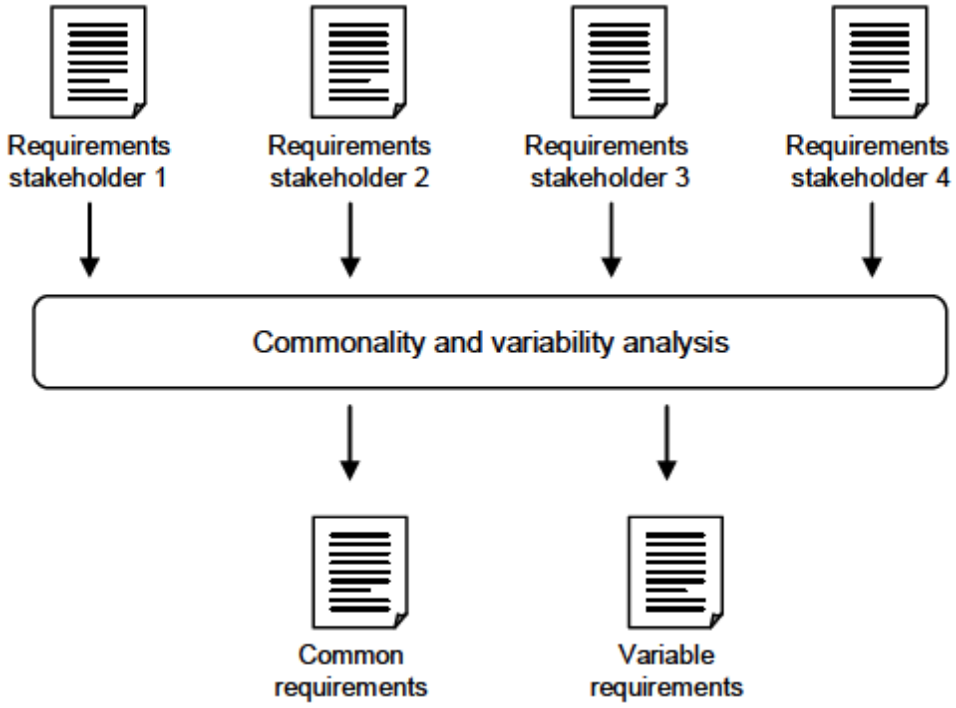
- Basis for: (i) developing the entire SPL family (ii) defining the requirements of each product
- Comprises the same core and cross-sectional RE activities as RE for single systems;

  these activities have the same goals plus, in addition, the goal to define the SPL variability

Elicitation of requirements variability



Application RE

- During application RE, the requirements for a specific application of the SPL are defined by exploiting the domain requirements artefacts (incl. defined variation points and variants)

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  2. Documenting the variability binding

So why have variability?

- Flexibility to deliver
  - Different versions of products based on the same trunk of code (Windows XP professional, Windows XP Home edition, etc.)
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"We always have 126,000,000 different bicycles in store!
(but only the parts for 1,000…)"

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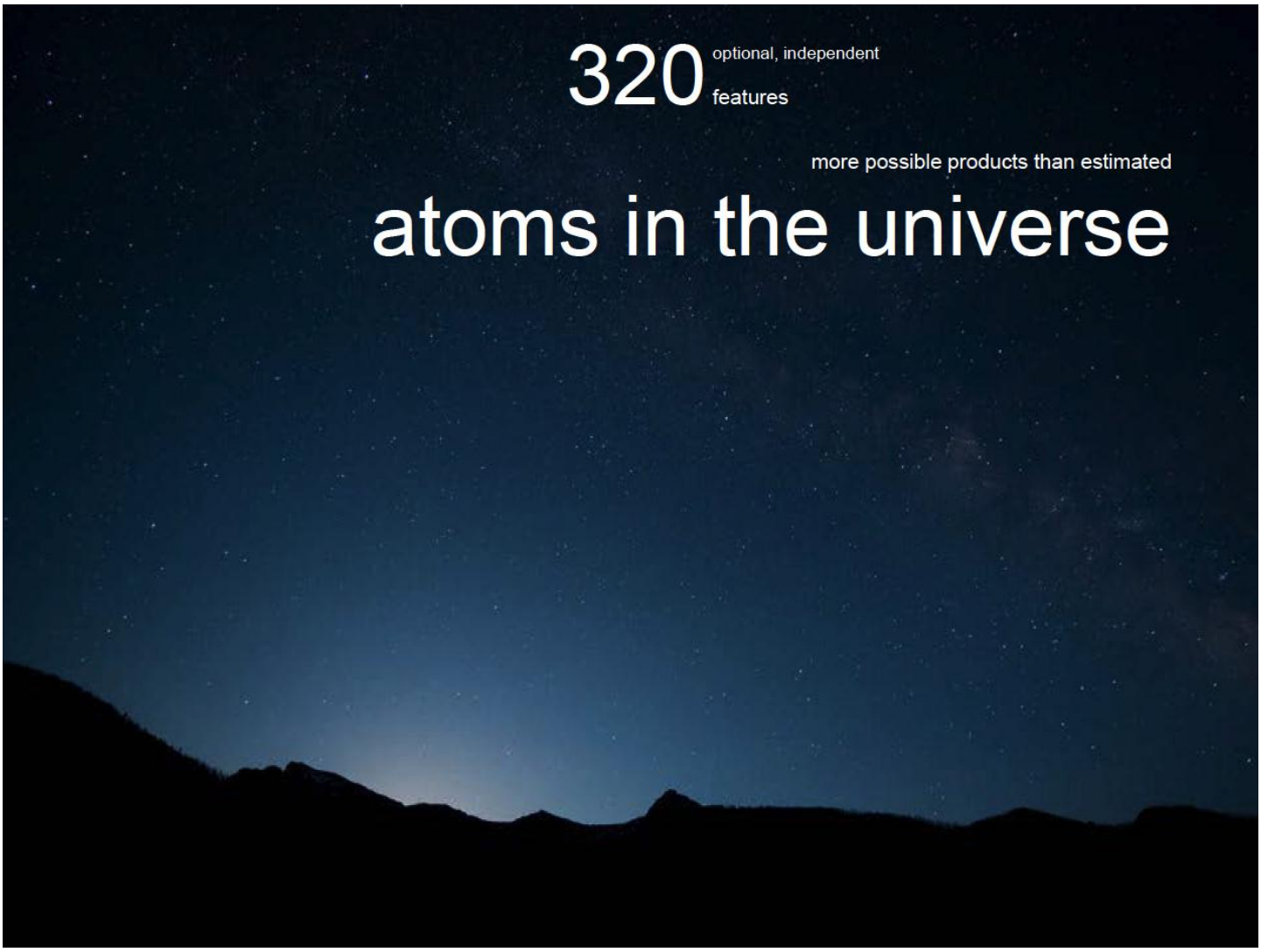
  2. Carolina is accepted into the 3-way call

Weakness: complexity/scalability

with 33 optional, independent features

a unique product for every

person on this planet


320 optional, independent features
more possible products than estimated
atoms in the universe

(Behavioural) variability analysis

Rigorously establish critical system requirements (for quality assurance) with formal models and automated analysis tools

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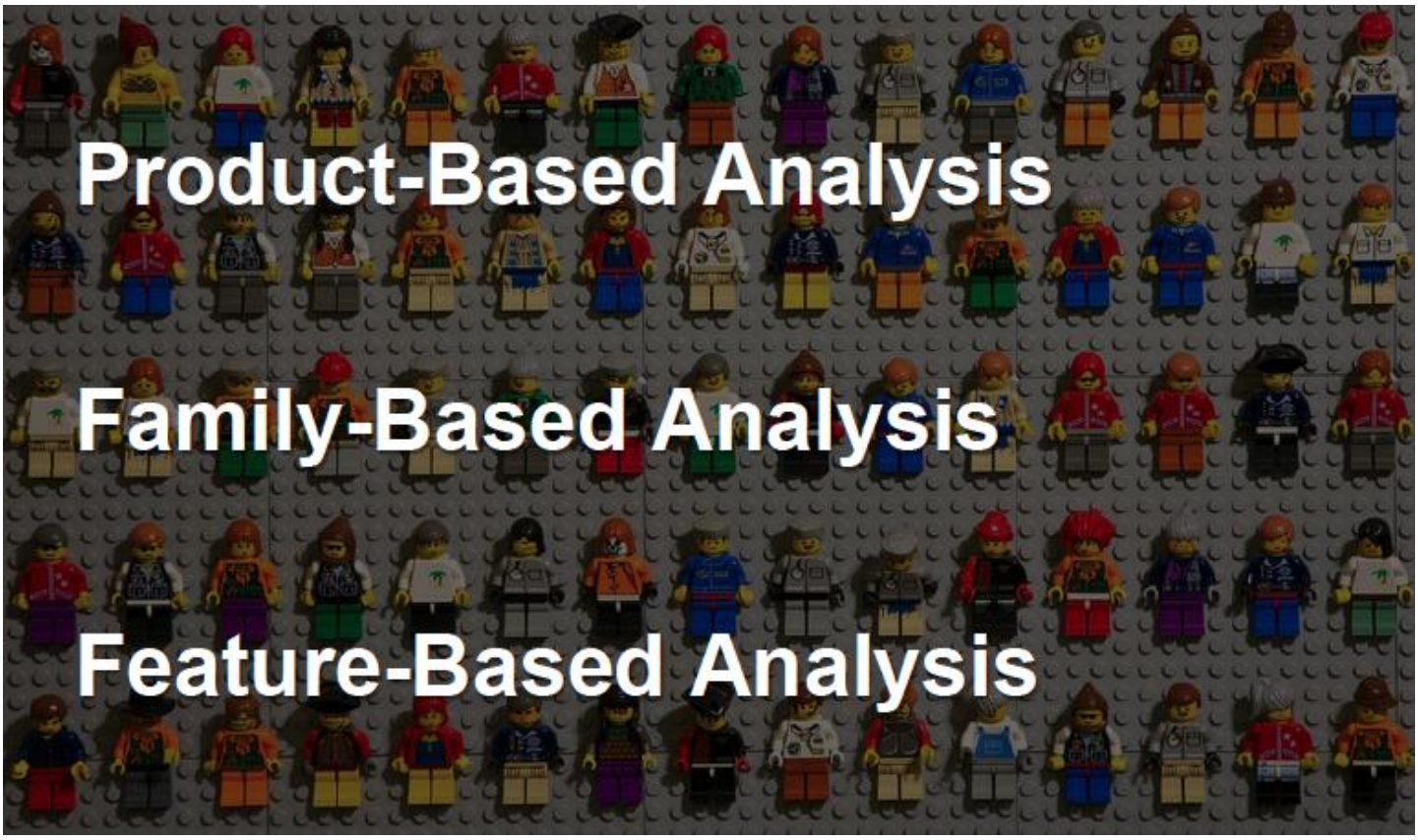
Traditionally

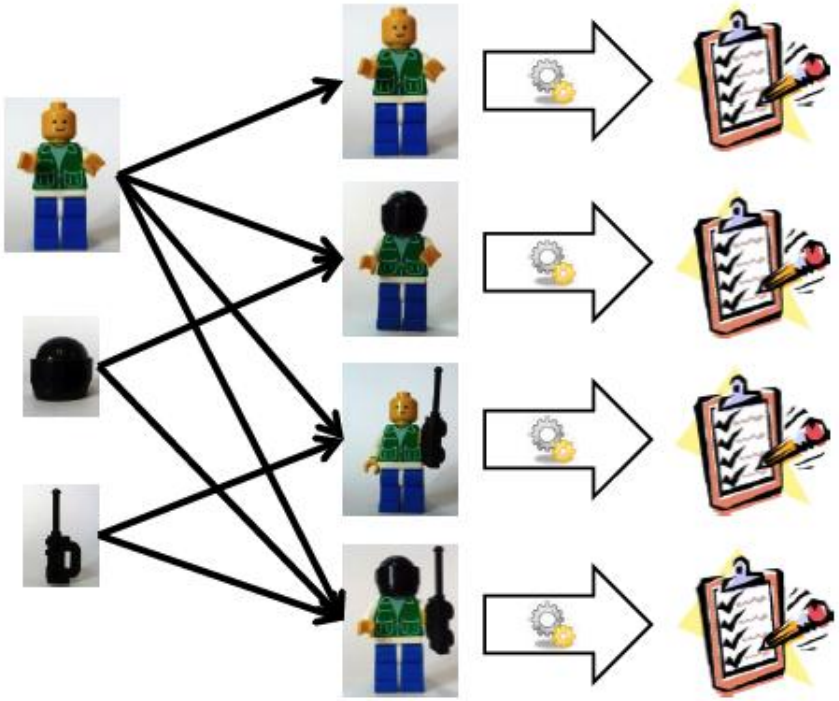
- Mainstream formal methods do *not* consider variability directly
- Formal methods that *have* been applied in SPLE mainly focus on structural rather than behavioural properties (feature model analysis: e.g. dead features, false optional features, etc.)

Variability analysis strategies

(type checking, static analysis, model checking, theorem proving, testing, etc.)

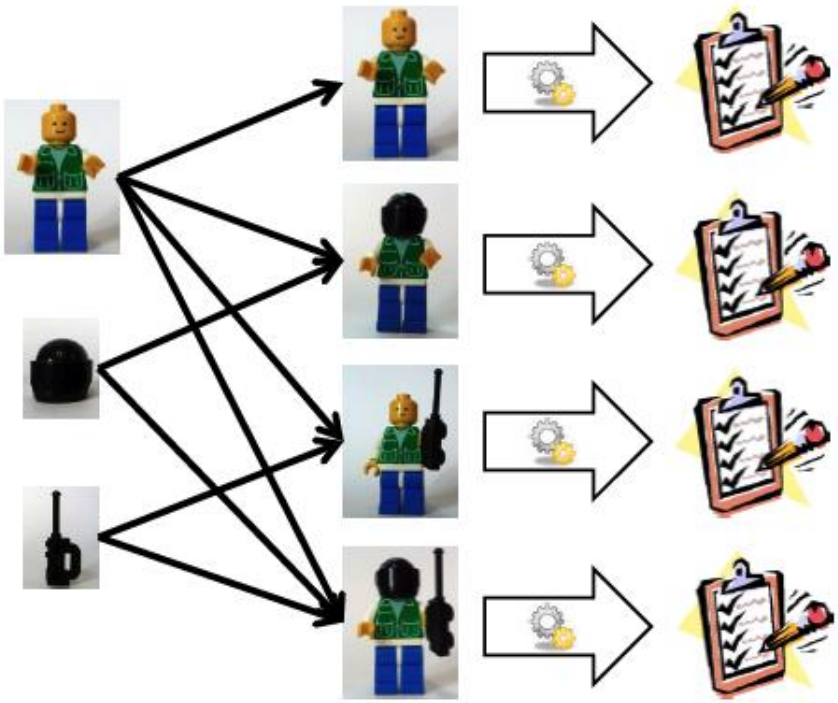


Product-based analysis



$O(2^n)$ for n features

Product-based analysis



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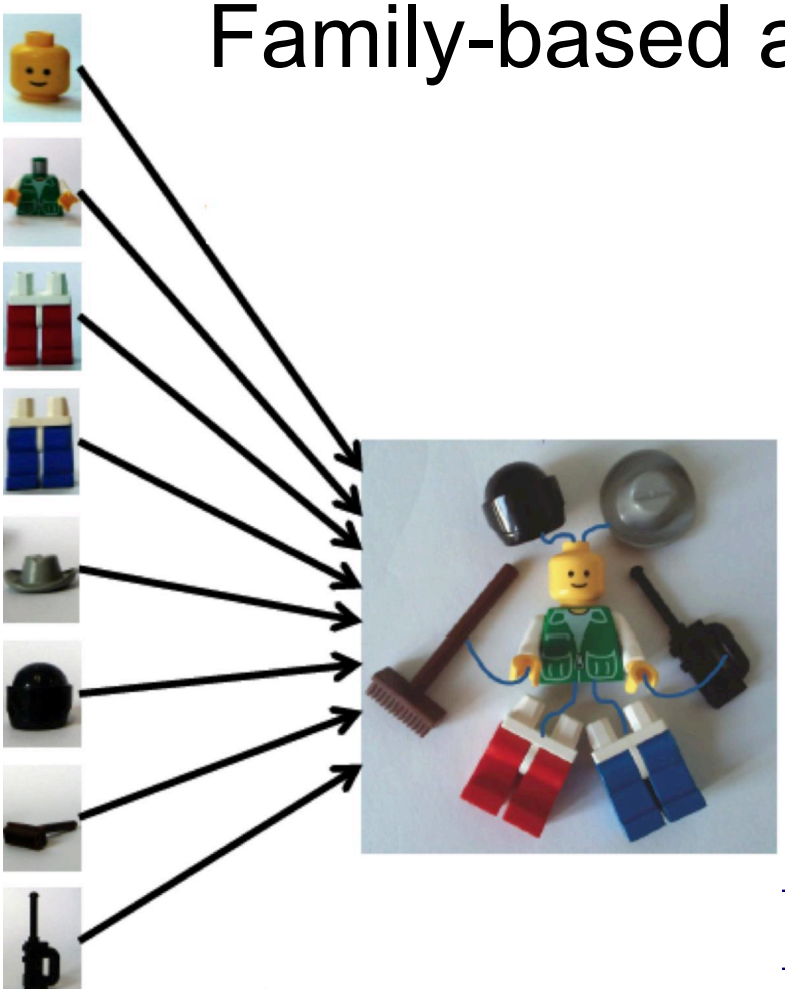
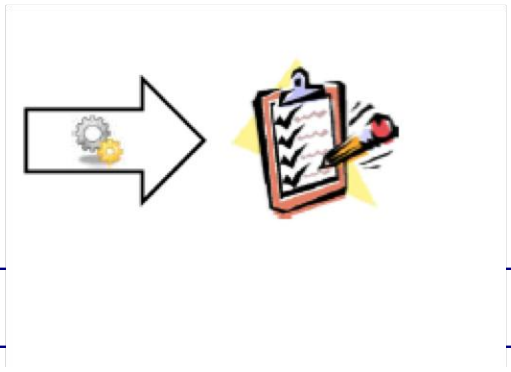
Family-based analysis





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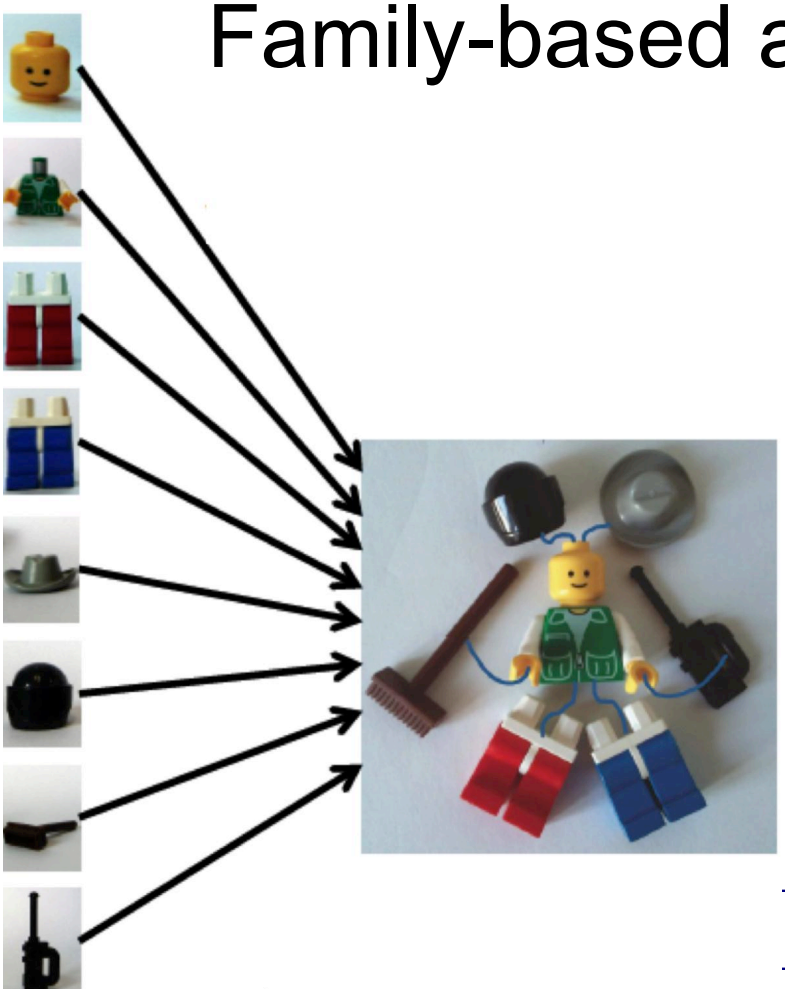
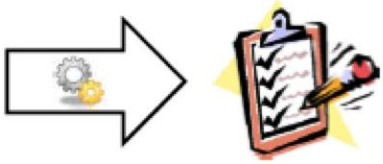


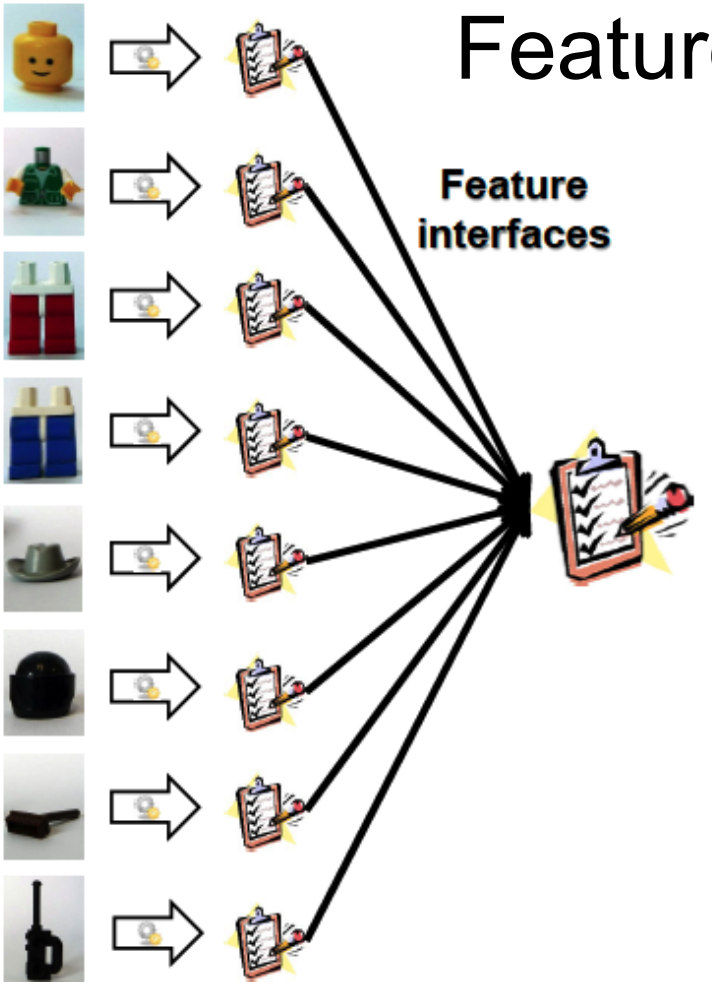
Beneficial for many products with substantial similarities

Generates complex analysis tasks

Requires (compact) family metamodels



Feature-based analysis



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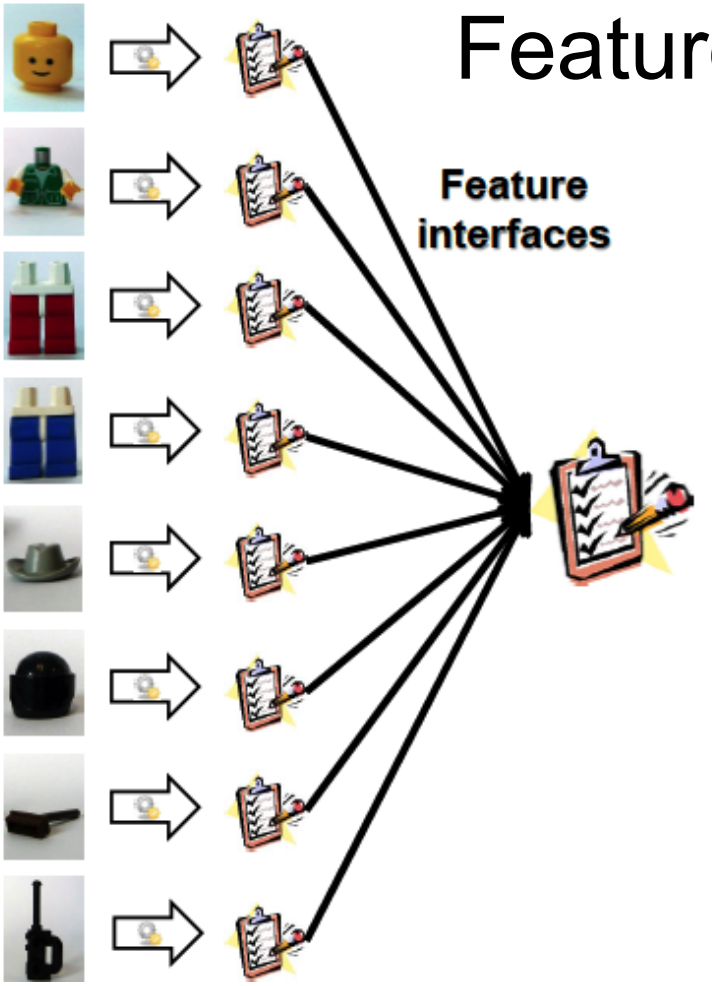

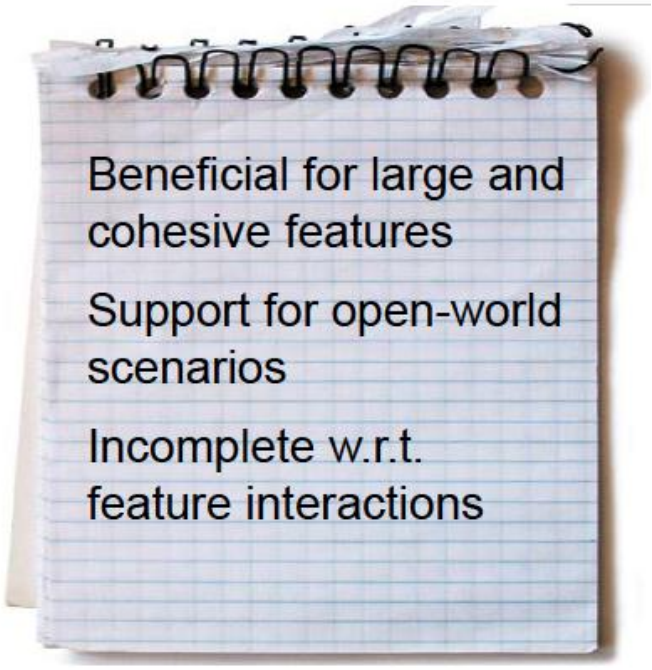

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Modelling and Analysing Variability

Lift success stories known for single systems (products) to sets of products (families) by exploiting variability modelling and analysis

$\Rightarrow$ challenges known models and tools by potentially high number of different products, each giving rise to a large state space in general

- Featured Transition Systems (FTS)

  Classen *et al.* @ ICSE'10, *IEEE TSE*, 2013, *Sci. Comput. Program.*, 2014

  SNIP/fPROMELA/fLTL, fNuSMV/fSMV/fCTL, ProVeLines

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- Modal Transition Systems (MTS) with variability constraints

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  Variability Model Checker VMC/v-ACTL

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- UML SPL profile, PL-CCS, variable I/O automata, feature nets, etc.

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FTS for SPLE

Recall (atomic propositions used for verification purposes):

De Nicola & Vaandrager @ *J. ACM*, 1995

A Doubly-Labelled Transition System (L^2TS) is a sextuple $(Q, A, \overline{q}, \rightarrow, AP, L)$ with states Q, actions A, initial state $\overline{q}$, transitions $\rightarrow \subseteq Q \times A \times Q$, atomic propositions AP, and labeling function $L : S \rightarrow 2^{AP}$

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

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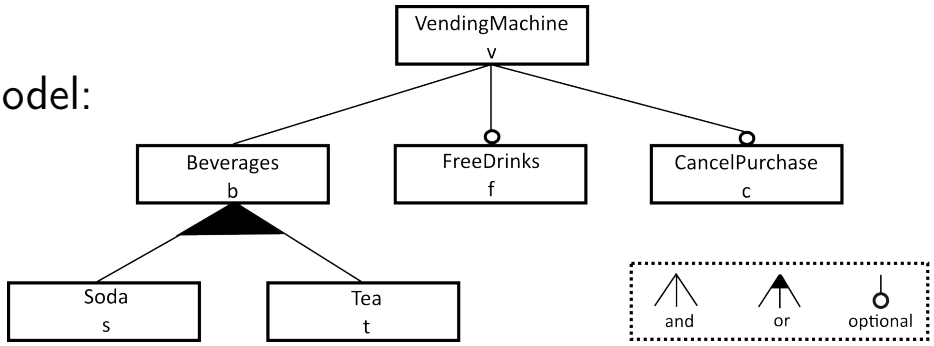
FTS of example SPL: a vending machine

Feature model:



12 valid products

e.g. {v,b,s,t}, {v,b,s,c}

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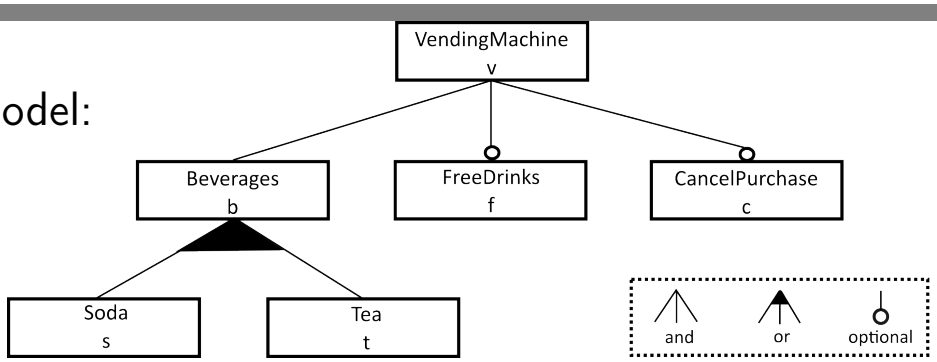

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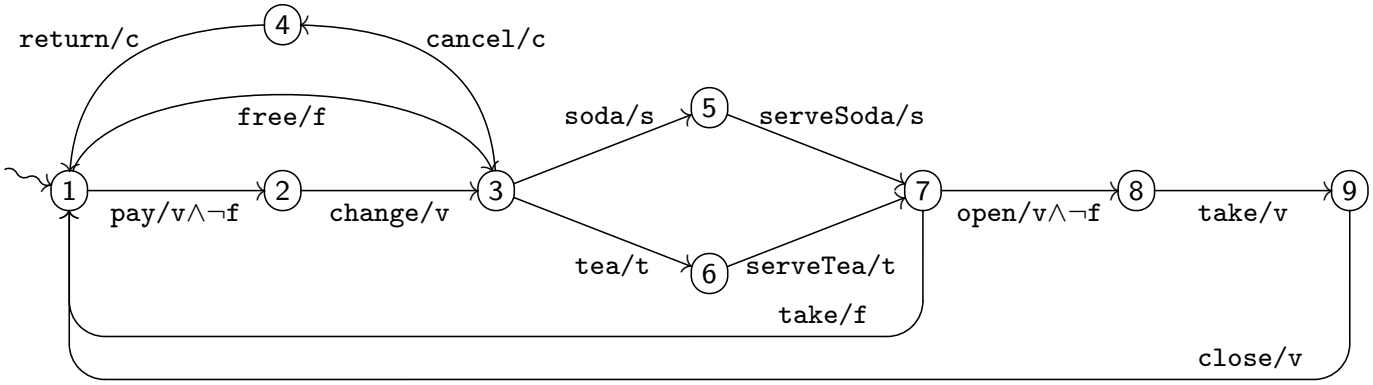

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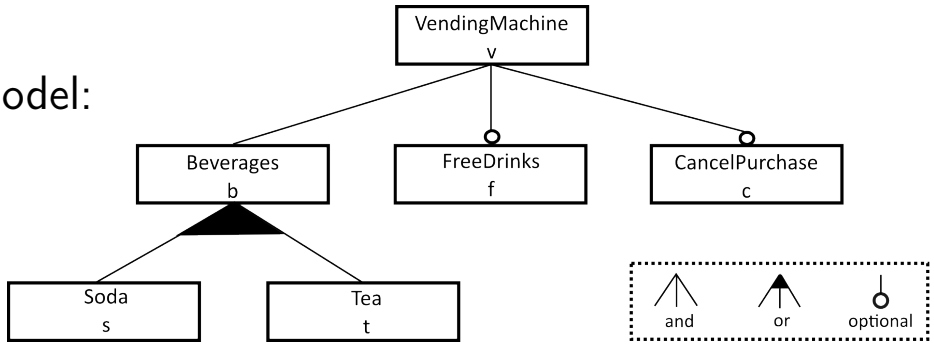

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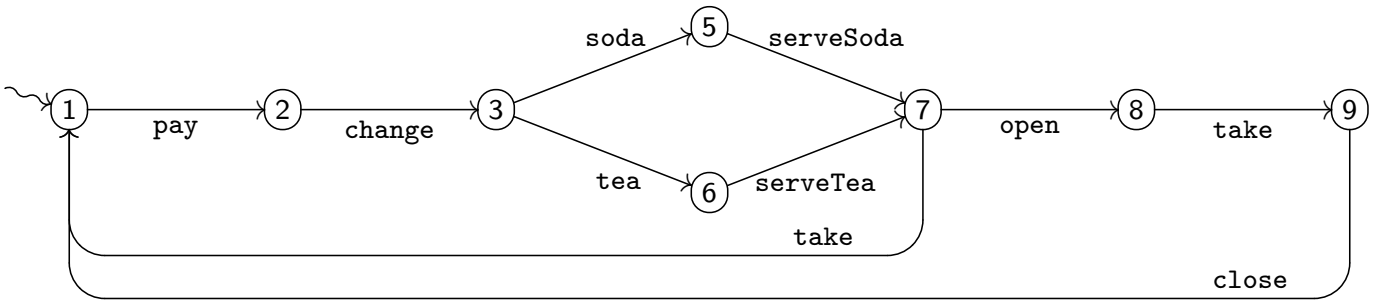

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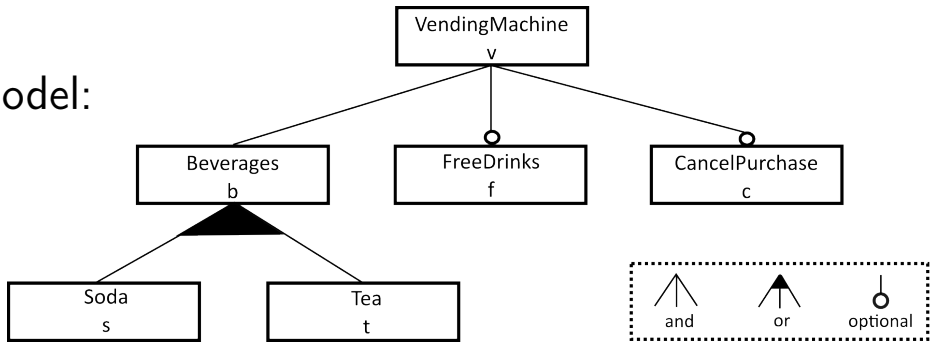

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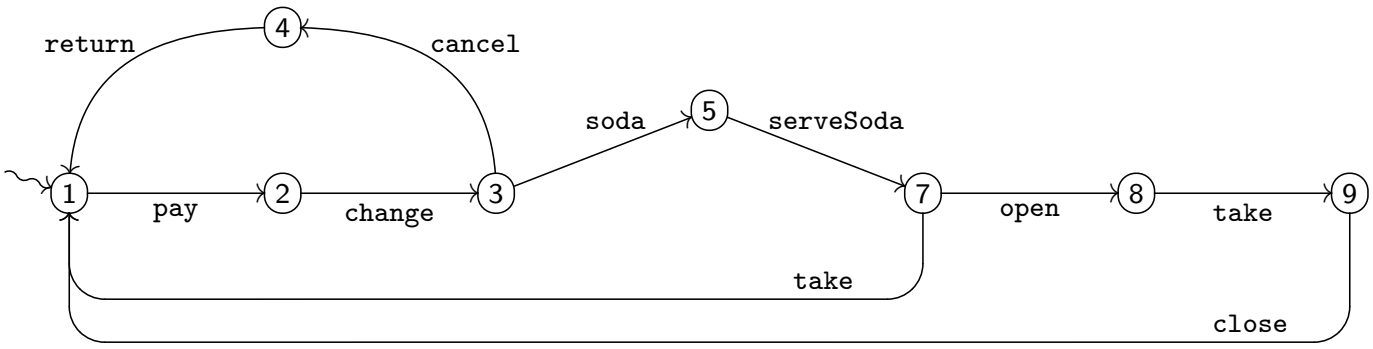
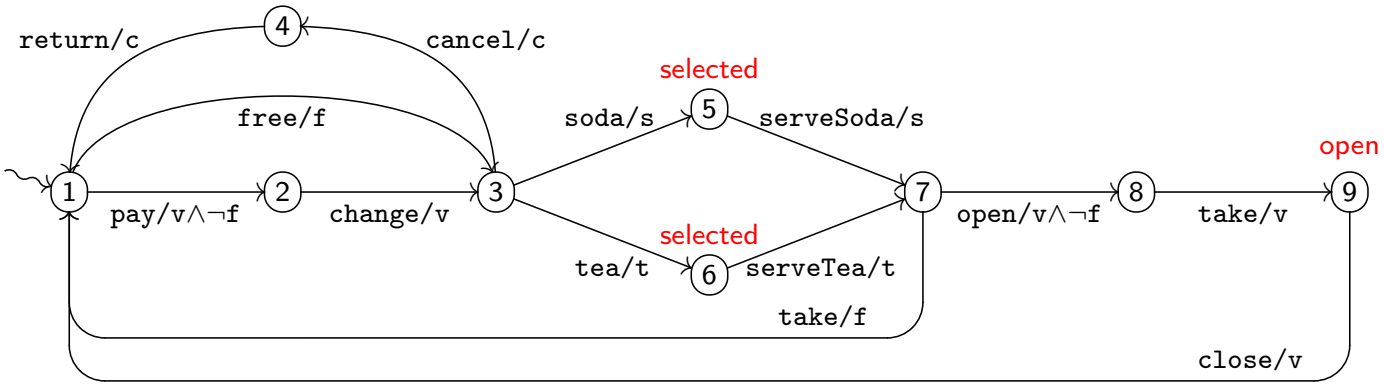


Dedicated FTS model checker SNIP (now ProVeLines)

fPROMELA:

```
typedef features {
    bool v;
    bool f;
    ...
};
features F;
```

```
gd :: F.v && !F.f;
        pay;
   :: F.f;
        free;
   :: else;
        skip;
dg;
```



fLTL: $[\neg\, \mathtt{f}]\ \Box\,(\mathtt{selected} \Rightarrow \Diamond\, \mathtt{open})$

Similarly fNuSMV with fSMV/fCTL

MTSυ for SPLE

Main ingredient: Modal Transition Systems (MTS)

- LTS distinguishing possible (may) and required (must) transitions

  Larsen & Thomsen @ LICS'88

- Recognised as a useful model to describe in a compact way the possible behaviour of all the products (LTS) of a product family

  Fischbein *et al.* @ ROSATEA'06, Fantechi & Gnesi @ ESEC/FSE'07, SPLC'08

MTS cannot model variability constraints regarding alternative features, nor regarding requires/excludes inter-feature relations, resulting in several variants and extensions

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Our solution: add a set of variability constraints to the MTS to be able to decide which derivable products (LTS) are valid ones

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MTS with...

Recall:

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Next we define MTS with variability constraints:

A Modal Transition System (MTS) is a quintuple $(Q, A, \overline{q}, \rightarrow_\Box, \rightarrow_\Diamond)$ such that $(Q, A, \overline{q}, \rightarrow_\Box \cup \rightarrow_\Diamond)$ is an LTS, called its underlying LTS

An MTS has two distinct transition relations

1. may transition relation $\rightarrow_\Diamond \subseteq Q \times A \times Q$: possible transitions
2. must transition relation $\rightarrow_\Box \subseteq Q \times A \times Q$: required transitions

By definition, any required transition is also possible: $\rightarrow_\Box \subseteq \rightarrow_\Diamond$
(denote $\dashrightarrow \equiv \rightarrow_\Diamond \setminus \rightarrow_\Box$: optional transitions)

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. . . variability constraints (accepted by VMC)

Variability constraints of form ALTernative, EXCludes, REQuires, etc.

a_1 ALT $\cdots$ ALT a_n : precisely one among the $n \geq 2$ actions $a_1, ..., a_n$ is reachable in $\mathcal{L}$ (i.e. is the label of a reachable transition)

b_1 OR $\cdots$ OR b_n, where b_i is either a_i or $\neg\, a_i$: at least one among the conditions on $n \geq 2$ actions $b_1, ..., b_n$ holds, i.e. $b_i = a_i$ is reachable in $\mathcal{L}$ or $b_i = \neg\, a_i$ is not reachable in $\mathcal{L}$

a_1 EXC a_2 : at most one of the actions a_1 and a_2 is reachable in $\mathcal{L}$

a_1 REQ a_2 : action a_2 is reachable in $\mathcal{L}$ whenever a_1 is reachable in $\mathcal{L}$

a_1 REQ (a_2 ALT $\cdots$ ALT a_n) : precisely one among the $n \geq 2$ actions $a_2, ..., a_n$ is reachable in $\mathcal{L}$ if a_1 is reachable in $\mathcal{L}$

a_1 REQ (a_2 OR $\cdots$ OR a_n) : at least one among the $n \geq 2$ actions $a_2, ..., a_n$ is reachable in $\mathcal{L}$ if a_1 is reachable in $\mathcal{L}$

Derive products (implemented in VMC)

A product LTS is obtained from a family MTS in the following way:

1. include all (reachable) must transitions and
2. include subset of the (reachable) optional transitions, remove rest
3. satisfy assumptions of coherence and consistency
4. satisfy variability constraints

$\Rightarrow$ Each selection gives rise to a different variant

Let $(Q, A, \overline{q}, \delta^{\Diamond}, \delta^{\Box}, \Upsilon)$ be a coherent MTSυ, i.e. $\exists \xrightarrow{a} \implies \nexists \xrightarrow{a}$

The set $\{ \mathcal{P}_i = (Q_i, A, \overline{q}, \delta_i) \mid i > 0 \}$ of product LTS is obtained by considering each pair of $Q_i \subseteq Q$ and $\delta_i \subseteq \delta^{\Diamond} \cup \delta^{\Box}$ to be defined s.t.

1. every $q \in Q_i$ is reachable in $\mathcal{P}_i$ from $\overline{q}$ via transitions from δ_i
2. there exists no $(q, a, q') \in \delta^{\Box} \setminus \delta_i$ such that $q \in Q_i$
3. LTS is consistent: both $\xrightarrow{a} \rightsquigarrow \xrightarrow{a}$ and $\not\xrightarrow{a}$ not allowed
4. $\mathcal{P}_i$ satisfies all variability constraints in Υ

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$\Rightarrow$ Each selection gives rise to a different variant

Let $(Q, A, \overline{q}, \delta^{\Diamond}, \delta^{\Box}, \Upsilon)$ be a coherent MTSυ, i.e. $\exists \xrightarrow{a} \implies \nexists \xrightarrow{a}$

The set $\{ \mathcal{P}_i = (Q_i, A, \overline{q}, \delta_i) \mid i > 0 \}$ of product LTS is obtained by considering each pair of $Q_i \subseteq Q$ and $\delta_i \subseteq \delta^{\Diamond} \cup \delta^{\Box}$ to be defined s.t.

1. every $q \in Q_i$ is reachable in $\mathcal{P}_i$ from $\overline{q}$ via transitions from δ_i
2. there exists no $(q, a, q') \in \delta^{\Box} \setminus \delta_i$ such that $q \in Q_i$
3. LTS is consistent: both $\xrightarrow{a} \rightsquigarrow \xrightarrow{a}$ and $\not\xrightarrow{a}$ not allowed
4. $\mathcal{P}_i$ satisfies all variability constraints in Υ

MTSυ equally expressive as FTS

ter Beek *et al.* @ SEFM'15, *Sci. Comput. Program.*, 2019

Theorem (FTS2MTSυ transformation is sound and complete)

Let $\mathcal{F}$ be an FTS and let $\mathcal{M}$ be the MTSυ generated from $\mathcal{F}$ according to the FTS2MTSυ model transformation algorithm. Then the sets of derived variants $\mathsf{lts}(\mathcal{F})$ *and* $\mathsf{lts}(\mathcal{M})$ *coincide, up to dummy transitions and action relabelling.*

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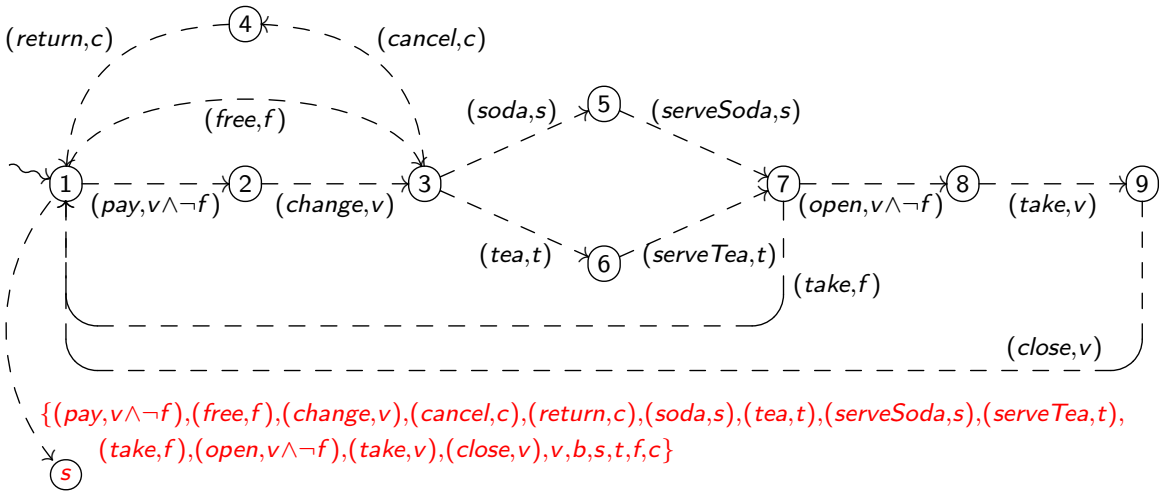

$$\Upsilon = \{(\mathit{pay}, v \wedge \neg f) \Leftrightarrow (v \wedge \neg f), (\mathit{free}, f) \Leftrightarrow f,\ (\mathit{change}, v) \Leftrightarrow v, (\mathit{cancel}, c) \Leftrightarrow c, (\mathit{return}, c) \Leftrightarrow c, (\mathit{soda}, s) \Leftrightarrow s, (\mathit{tea}, t) \Leftrightarrow t,$$
$$(\mathit{serveSoda}, s) \Leftrightarrow s, (\mathit{serveTea}, t) \Leftrightarrow t, (\mathit{take}, f) \Leftrightarrow f, (\mathit{open}, v \wedge \neg f) \Leftrightarrow (v \wedge \neg f), (\mathit{take}, v) \Leftrightarrow v, (\mathit{close}, v) \Leftrightarrow v\}$$

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Dedicated MTSυ Variability Model Checker VMC

VMC builds on optimization of UMC (input: UML state machines)

ter Beek *et al.* @ *Sci. Comput. Program.*, 2011

VMC: bounded, on-the-fly model checking, providing explanations

↘ Biere *et al.* @ TACAS'99

VMC accepts as input a specification in (value-passing) modal process algebra, possibly with additional variability constraints

- interactively explore the model (MTS)
- derive and explore (all) the model's valid products (LTS)
- visualize the model/products graphically as MTS/LTS
- verify v-ACTL properties over MTS/LTS
- interactively explain why a property is (not) satisfied

Model checking of v-ACTL formulae on MTS can be achieved in a complexity that is linear w.r.t. the state space size

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Variability analysis strategies supported by VMC

VMC offers both product-based and family-based variability analyses:

1. The actual set of all valid product behaviour can explicitly be generated and the resulting LTS can all be verified against one and the same logic property (expressed in Action-based CTL)

   De Nicola, Vaandrager @ *J. ACM*, 1995

2. A logic property (expressed in variability-aware ACTL) can directly be verified against the MTS, relying on the fact that under certain syntactic conditions validity over the MTS implies validity of the same property for all its derived products (more later)

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VMC v6.4 is freely usable online:

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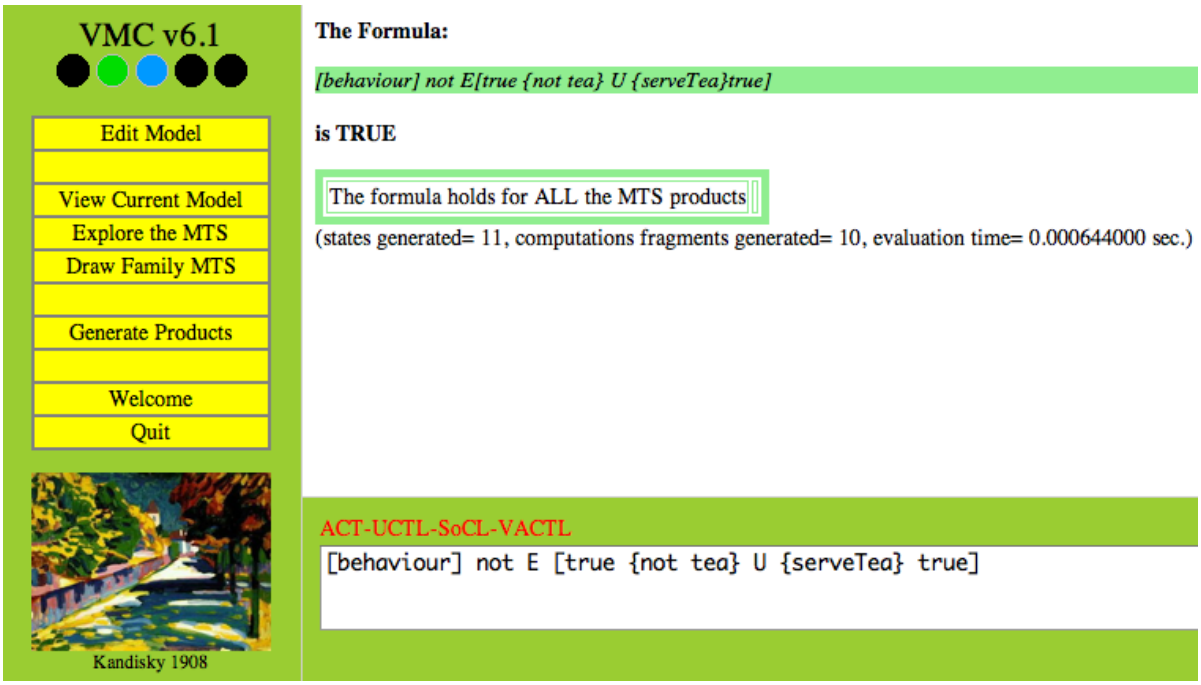
Vending Machine: family-based analysis

VMC notifies whenever preservation of an analysis result is applicable



It is not possible that serveTea occurs without being preceded by tea

Vending Machine: product-based analysis

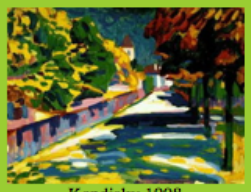
VMC lists for each product the action labels of all may transitions that have been preserved (as must transitions) in that product

VMC v6.1

New Model ...
Edit Current Model
Explore the MTS

View Current Model
Draw Family MTS
Generate Products

Welcome
Quit



Kandisky 1908

Evaluation of the formula "[behaviour] [pay] AF {takePaid} true" on all family products

product_1+Soda+open+pay+soda	Formula evaluates	TRUE
product_10+CancelPurchase+FreeDrinks+Tea+cancel+free+takeFree+tea	Formula evaluates	TRUE
product_11+FreeDrinks+Soda+Tea+free+soda+takeFree+tea	Formula evaluates	TRUE
product_12+CancelPurchase+FreeDrinks+Soda+Tea+cancel+free+soda+takeFree+tea	Formula evaluates	TRUE
product_2+CancelPurchase+Soda+cancel+open+pay+soda	Formula evaluates	FALSE
product_3+Tea+open+pay+tea	Formula evaluates	TRUE
product_4+CancelPurchase+Tea+cancel+open+pay+tea	Formula evaluates	FALSE
product_5+Soda+Tea+open+pay+soda+tea	Formula evaluates	TRUE
product_6+CancelPurchase+Soda+Tea+cancel+open+pay+soda+tea	Formula evaluates	FALSE
product_7+FreeDrinks+Soda+free+soda+takeFree	Formula evaluates	TRUE
product_8+CancelPurchase+FreeDrinks+Soda+cancel+free+soda+takeFree	Formula evaluates	TRUE
product_9+FreeDrinks+Tea+free+takeFree+tea	Formula evaluates	TRUE

Logic Formula for all Products

```
[behaviour] [pay] AF {takePaid} true
```

Whenever pay occurs, eventually takePaid occurs

Recall: Action-based CTL

Action formulae (Boolean compositions of actions, denoted by χ), state formulae (ϕ) and path formulae (π)

$$\begin{aligned}\phi &::= \mathit{true} \mid \neg\phi \mid \phi \wedge \phi \mid [\chi]\,\phi \mid \langle\chi\rangle\,\phi \mid E\,\pi \mid A\,\pi \mid \\ &\quad\ \mu\,Y.\phi(Y) \mid \nu\,Y.\phi(Y) \\ \pi &::= X\,\{\chi\}\,\phi \mid [\phi\ \{\chi\}\ U\ \{\chi'\}\ \phi'] \mid [\phi\ \{\chi\}\ W\ \{\chi'\}\ \phi'] \mid \\ &\quad\ [\phi\ \{\chi\}\ U\ \phi'] \mid [\phi\ \{\chi\}\ W\ \phi'] \mid F\,\phi \mid F\,\{\chi\}\,\phi \mid G\,\phi \mid G\,\{\chi\}\,\phi\end{aligned}$$

(Y is a propositional variable, $\phi(Y)$ is syntactically monotone in Y)

μ and ν: recursion (greatest fixed point and least fixed point)

X, U, W, F, G: action-based versions of neXt, Until, Weak until, Future ("eventually"), Globally ("always")

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v-ACTL: variability-aware, action-based CTL

Additional variability-aware (action-based) versions of Box, Diamond, neXt, Future, Globally

$\langle\chi\rangle^{\Box}\,\phi$ a next state exists, reachable by a must transition, executing an action satisfying χ, in which ϕ holds

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Preservation of formulae in v-ACTL$^{\Box}$/v-ACTLive$^{\Box}$

v-ACTL$^{\Box}$/v-ACTLive$^{\Box}$:

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any formula that is true for MTS, is also true for all products (LTS)

v-ACTL$^{\neg}$:

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Live states use SPL-specific information

$$S \models \phi \;\Rightarrow\; S_p \models \phi \quad \forall \text{ product LTS } S_p \text{ of MTS } S$$

Recall: all (reachable) must transitions are preserved ($\langle\rangle^{\Box}, []^{\Box}, X^{\Box}, F^{\Box}$)

Live action sets define live states (not occur as final in any product)

MTS

Assume a OR b

LTS

In any product in which p occurs,
p has at least one outgoing transition

$\Rightarrow$ p is a live state, since a OR b gives rise to a live action set $\{a, b\}$

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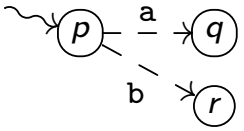
MTS 

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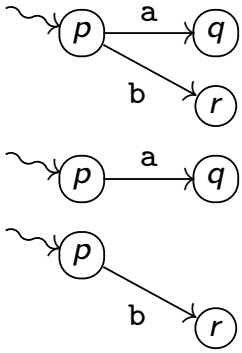

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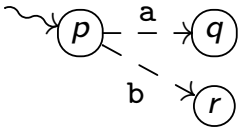
MTS 

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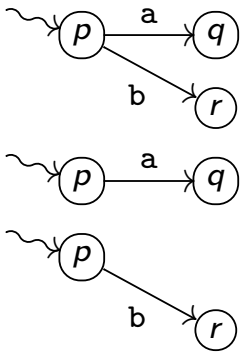

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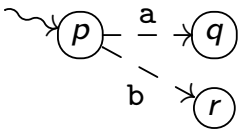
MTS 

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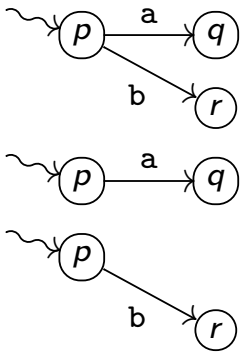

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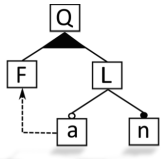
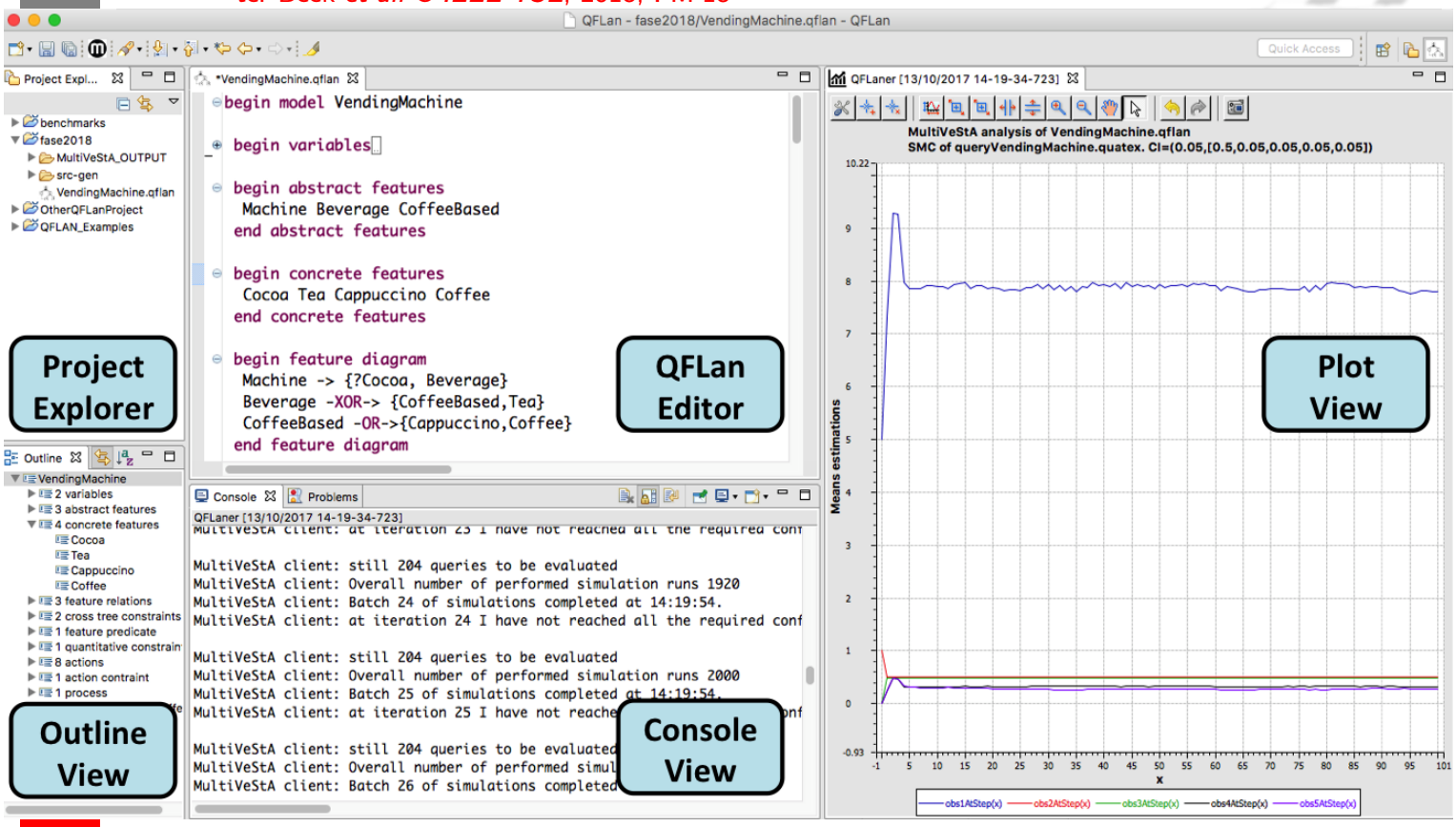
QFLan: a framework for quantitative modelling and analysis of highly (re)configurable systems

ter Beek *et al.* @ *IEEE TSE*, 2018, FM'18



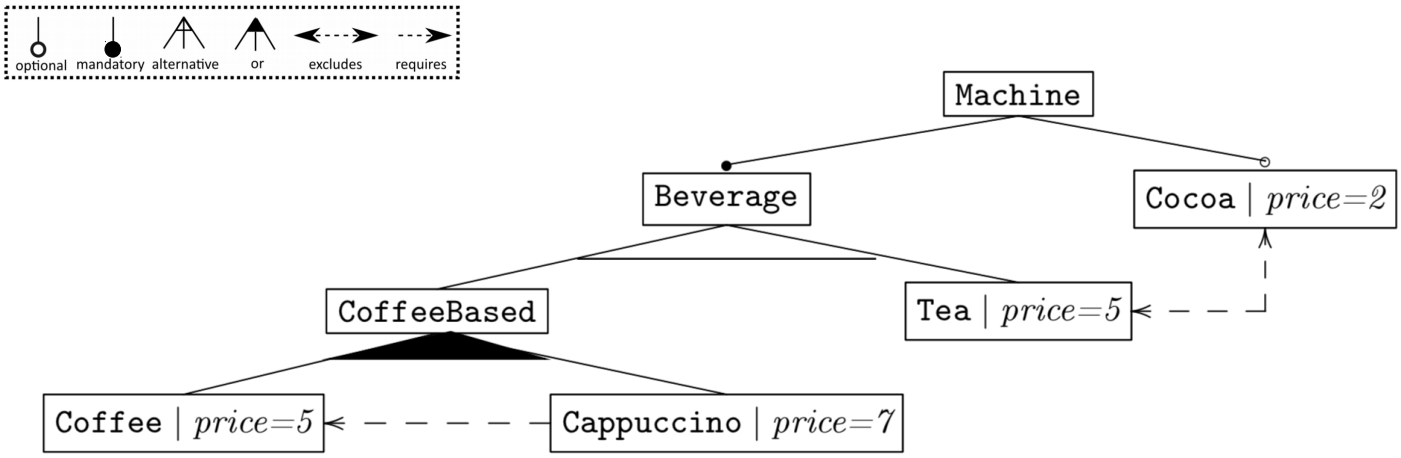


https://github.com/qflanTeam/QFLan/

(more in his lectures!)

These slides on QFLan are largely based on slides by Andrea Vandin

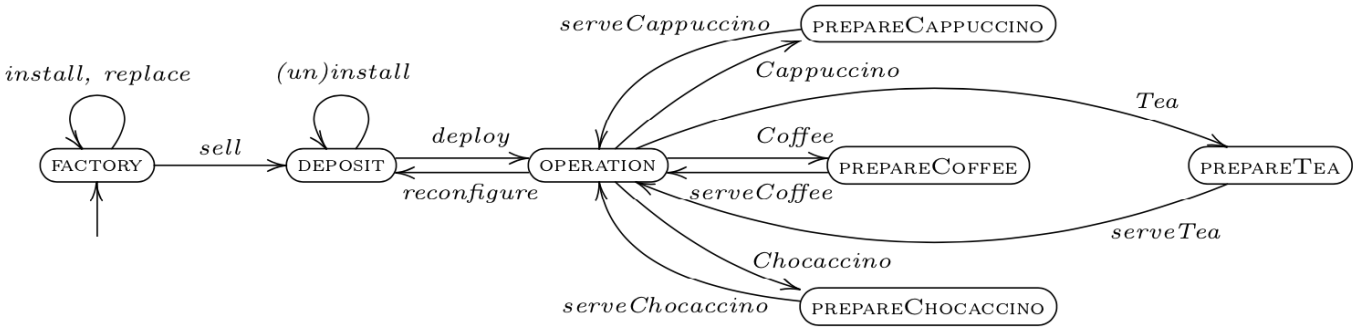
A simple coffee vending machine product line: attributed feature model with quantitative constraints




```
begin abstract features
 Machine Beverage CoffeeBased
end abstract features

begin concrete features
 Cocoa Tea Cappuccino Coffee
end concrete features

begin feature diagram
 Machine -> {?Cocoa, Beverage}
 Beverage -XOR-> {CoffeeBased,Tea}
 CoffeeBased -OR->{Cappuccino,Coffee}
end feature diagram

begin cross-tree constraints
 Cappuccino requires Coffee
 Tea excludes Cocoa
end cross-tree constraints
```

```
begin feature predicates
 price= { Cappuccino = 7, Coffee = 5,
          Cocoa = 2, Tea = 5 }
end feature predicates
begin quantitative constraints
 { price(Machine) <= 10 }
end quantitative constraints
```

A simple coffee vending machine product line: probablistic behaviour with action constraints




```
begin variables
 sold = 0
 deploys = 0
end variables

begin actions
 sell deploy reconfigure
 chocaccino
 serveCoffee serveCappuccino
 serveChocaccino serveTea
end actions

begin action constraints
 do(chocaccino) -> (has(Cappuccino)
                    and has(Cocoa) )
end action constraints

begin init
 installedFeatures = { Coffee }
 initialProcesses = dynamics
end init
```

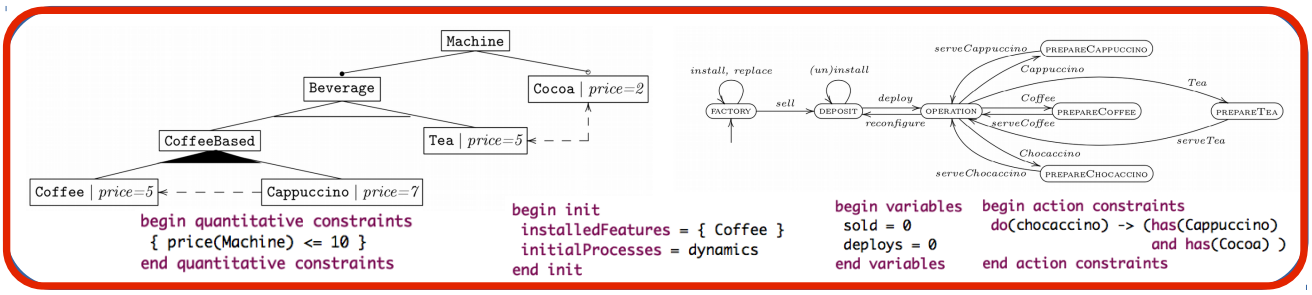
```
begin processes diagram
 begin process dynamics

 states = factory , deposit , operating , prepareCoffee ,
          prepareCappuccino, prepareTea , prepareChocaccino

 transitions =
   //Factory
   factory -(replace(Coffee,Tea),20)->factory,
   factory -(install(Cocoa),10)->factory,
   factory -(install(Cappuccino),10)->factory,
   factory -(sell,1,{sold=1})-> deposit,

   //Deposit
   deposit -(install(Cappuccino),2.0)->deposit,
   deposit -(uninstall(Cappuccino),2.0)->deposit,
   deposit -(install(Cocoa),2.0)->deposit,
   deposit -(uninstall(Cocoa),2.0)->deposit,
   deposit -(deploy,2,{deploys=deploys+1})-> operating

   //Operating
       //Coffee
   operating -(Coffee,3)-> prepareCoffee,
   prepareCoffee -(serveCoffee,1) -> operating,
       //Cappuccino
   operating -(Cappuccino,3)-> prepareCappuccino,
   prepareCappuccino -(serveCappuccino,1) -> operating,
       //Chocaccino
   operating -(chocaccino,2)-> prepareChocaccino,
   prepareChocaccino -(serveChocaccino,1) -> operating,
       //Tea
   operating -(Tea,3)-> prepareTea,
   prepareCappuccino -(serveTea,1) -> operating,

   operating -(reconfigure,1) -> deposit
 end process
end processes diagram
```

A simple coffee vending machine product line: statistical model checking with MultiVeSta

Sebastio & Vandin @ VALUETOOLS'13

(more in his lectures!)

Pinpoint the precise moment in which a coffee machine is sold




```
begin analysis

query = eval when {sold == 1.0 } :
{  price(Machine) [delta=0.5],
   Coffee , Tea , Cappuccino , Cocoa
}

default delta=0.05
alpha = 0.05
parallelism = 1

end analysis
```

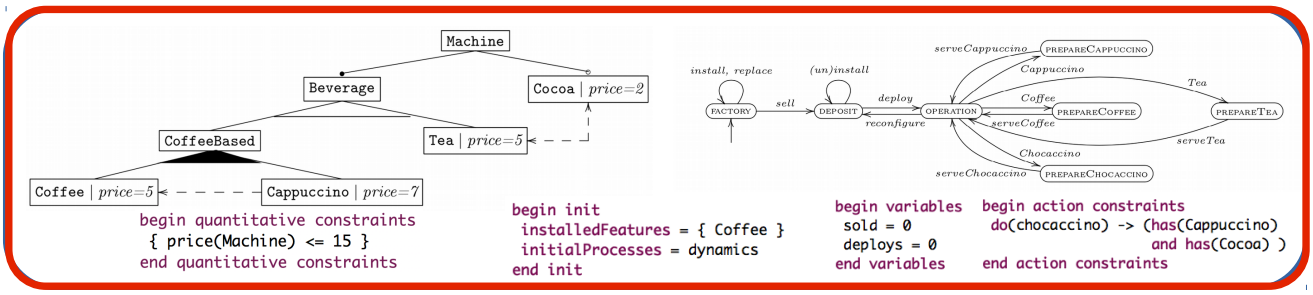
```
begin processes diagram
 begin process dynamics

 states = factory , deposit , operating , prepareCoffee ,
          prepareCappuccino, prepareTea , prepareChocaccino

 transitions =
   //Factory
   factory -(replace(Coffee,Tea),20)->factory,
   factory -(install(Cocoa),10)->factory,
   factory -(install(Cappuccino),10)->factory,
   factory -(sell,1,{sold=1})-> deposit,

   //Deposit
   deposit -(install(Cappuccino),2.0)->deposit,
   deposit -(uninstall(Cappuccino),2.0)->deposit,
   deposit -(install(Cocoa),2.0)->deposit,
   deposit -(uninstall(Cocoa),2.0)->deposit,
   deposit -(deploy,2,{deploys=deploys+1})-> operating ,
```

A simple coffee vending machine product line: statistical model checking with MultiVeSta

Sebastio & Vandin @ VALUETOOLS'13

(more in his lectures!)

Average price and probability of features of sold coffee machines




```
begin analysis

query = eval when {sold == 1.0 } :
{  price(Machine) [delta=0.5],
   Coffee , Tea , Cappuccino , Cocoa
}

default delta=0.05
alpha = 0.05
parallelism = 1

end analysis
```

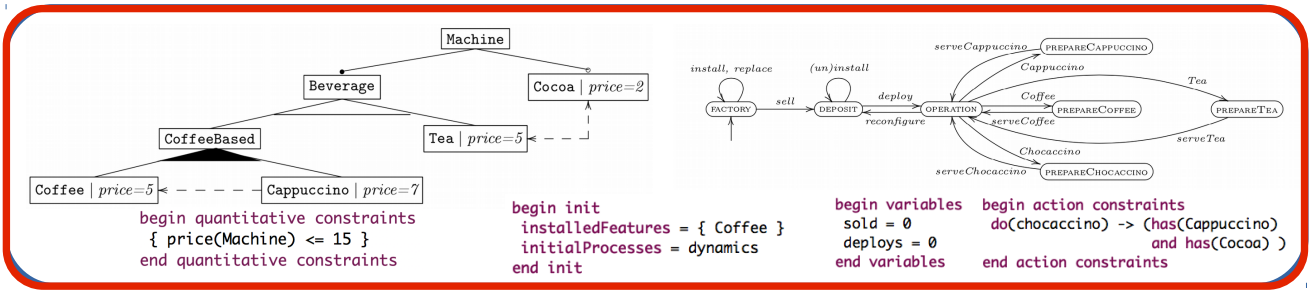
	Price	Coffee	Tea	Cappuccino	Cocoa
price(machine) <= 10	5.68	0.36	0.64	0.00	0.34
price(machine) <= 15	9.07	0.49	0.51	0.45	0.44

A simple coffee vending machine product line: statistical model checking with MultiVeSta

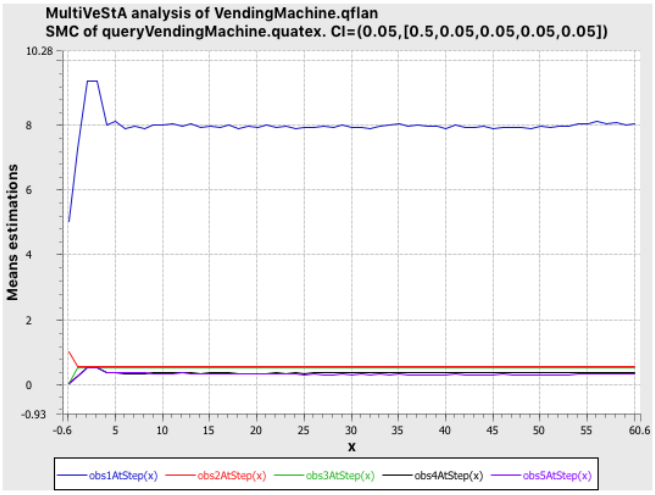
Sebastio & Vandin @ VALUETOOLS'13

Average price and probability of features at varying of time

(more in his lectures!)




```
begin analysis

query = eval from 0 to 60 by 1 :
{  price(Machine) [delta=0.5],
   Coffee , Tea , Cappuccino , Cocoa
}

default delta=0.05
alpha = 0.05
parallelism = 1

end analysis
```



Dedicated vs. off-the-shelf model checkers

Recall: dedicated SPL model checkers like SNIP, VMC, QFLan, etc.

☞ Dedicated model checkers need to be maintained and optimised

Dimovski *et al.*, Family-based model checking without a family-based model checker @ SPIN'15
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Chrszon *et al.*, ProFeat: feature-oriented engineering for family-based probabilistic model checking @ *FAC*, 2018

Our approach towards family-based model checking with mCRL2:

- Product-based model checking of FTSs with mCRL2
  ter Beek & de Vink @ FormaliSE'14, SPLC'14
- Branching feature bisimulation for FTSs
  Belder, ter Beek & de Vink @ FMSPLE'15
- Feature-oriented modal μ-calculi for reasoning on FTSs
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. . .

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  ter Beek, de Vink & Willemse @ FASE'17
  ter Beek, van Loo, de Vink & Willemse @ FASE'20

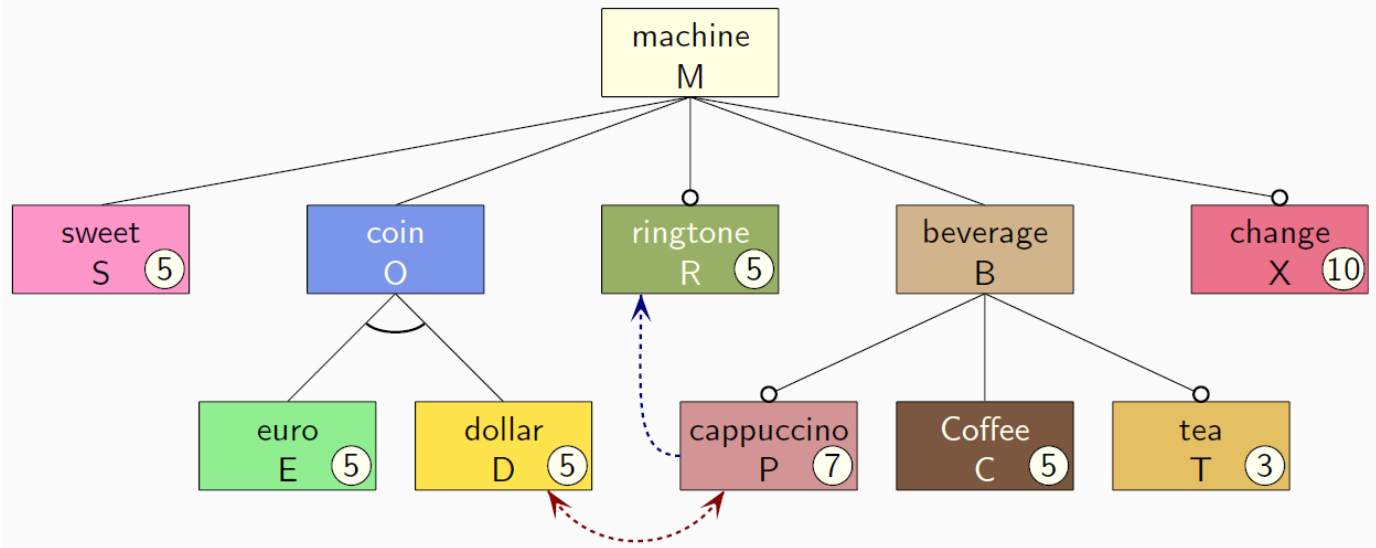
Model checking the coffee machine with mCRL2

Recall: a product line or family of coffee machines

- initially, money must be inserted: either at least one euro's worth in coins, *exclusively* for European products, or at least one dollar's worth in coins, *exclusively* for Canadian products
- input of money can be cancelled via a cancel button; *optionally*, the coffee machine returns change if more than one euro or one dollar was inserted
- once the coffee machine contains at least one euro or one dollar, the user chooses whether (s)he wants sugar, by pressing one out of two buttons, after which (s)he can select a beverage
- the choice of beverage (coffee, tea, cappuccino) varies, but coffee *must* be offered by all products, whereas cappuccino *may* be offered *solely* by European products
- *optionally*, a ringtone *may* be rung after delivering a beverage; a ringtone *must* be rung by *all* products offering cappuccino
- after the beverage is taken, the coffee machine returns idle

These slides on mCRL2 are largely based on slides by Erik de Vink

The coffee machine: attributed feature model

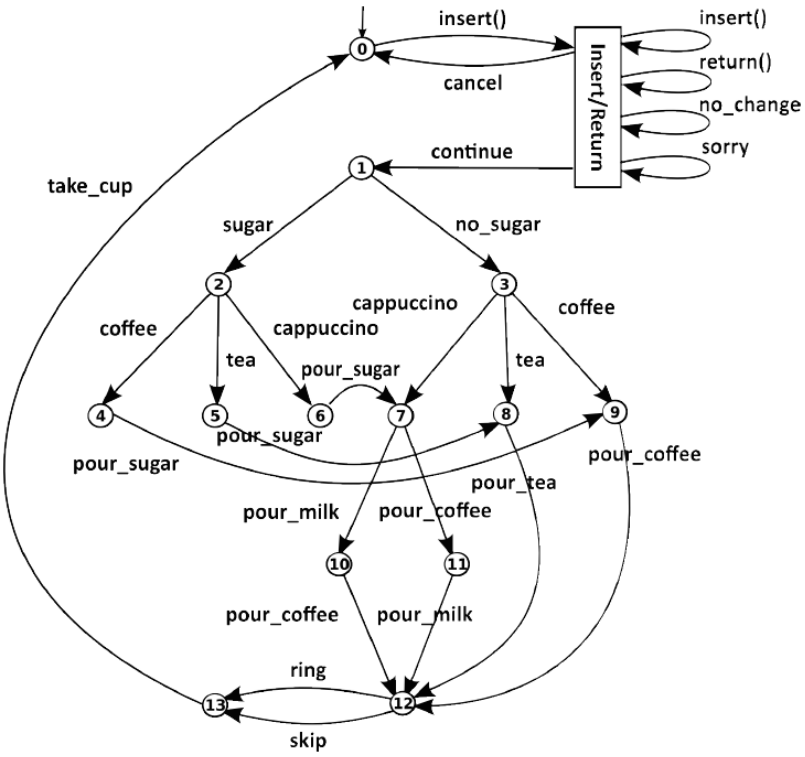


total cost $\leqslant 30$

Recall:
Non-functional attributes: $cost\,(product) = \sum\{\, cost\,(feature) \mid feature \in product \,\}$

From $2^{10} - 1 \xrightarrow{\text{feature diagram}} 2^5 \xrightarrow{\text{cross-tree constraints}} 20 \xrightarrow{\text{attributes}} 16$ valid products

The coffee machine: family behaviour



FTS feature expression labels omitted for readability

mCRL2 code: declarations

```
sort
  Feature = struct M | S | O | R | B | X | D | E | P | T | C ;
  FSet = List( Feature );
  Coin = struct dime | quarter | half | dollar |
    ct10 | ct20 | ct50 | euro ;
  Currency = struct Dollar | Euro ;

act
  insert, return : Coin ;
  continue, cancel, sorry, no_change,
  sugar, no_sugar, coffee, tea, cappuccino,
  pour_sugar, pour_milk, pour_coffee, pour_tea,
  ring, skip, take_cup ;
  setS, setO, setR, setB, setX,
  setD, setE, setP, setT, setTP, setC ;
  set_ko, ctc_ok ;
  set_ok : FSet ;
  cost : Int ;
```

mCRL2 code: auxiliary operations (1/3)

```
map isSorted: FSet -> Bool;
    noDuplicates: FSet -> Bool;
    isSet: FSet -> Bool;
var ft,ft': Feature;
    fset: FSet;
eqn isSorted([]) = true;
    isSorted([ft]) = true;
    isSorted(ft |> (ft' |> fset)) =
      ft <= ft' && isSorted(ft' |> fset);
    noDuplicates([]) = true;
    noDuplicates(ft |> fset) =
      !(ft in fset) && noDuplicates(fset);
    isSet(fset) = isSorted(fset) && noDuplicates(fset);
```

mCRL2 code: auxiliary operations (2/3)

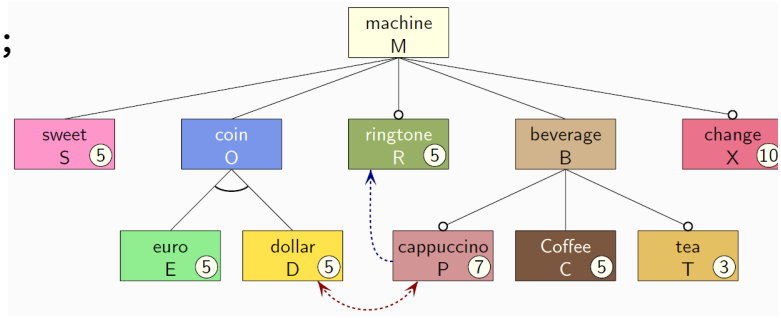
```
map insert: Feature # FSet -> FSet;
var ft, ft': Feature;
    fset: FSet;
eqn insert(ft, []) = [ft];
    (ft < ft')  -> insert(ft, ft' |> fset) = ft |> ft' |> fset;
    (ft == ft') -> insert(ft, ft' |> fset) = ft' |> fset;
    (ft > ft')  -> insert(ft, ft' |> fset) = ft' |> insert(ft, fset);

map union: FSet # FSet -> FSet;
var ft, ft': Feature;
    fset, fset': FSet;
eqn union([], fset) = fset;
    union(fset, []) = fset;
    (ft < ft')  -> union(ft |> fset, ft' |> fset') =
      ft |> union(fset, ft' |> fset');
    (ft == ft') -> union(ft |> fset, ft' |> fset') =
      ft' |> union(fset, fset');
    (ft > ft')  -> union(ft |> fset, ft' |> fset') =
      ft' |> union(ft |> fset, fset');
```

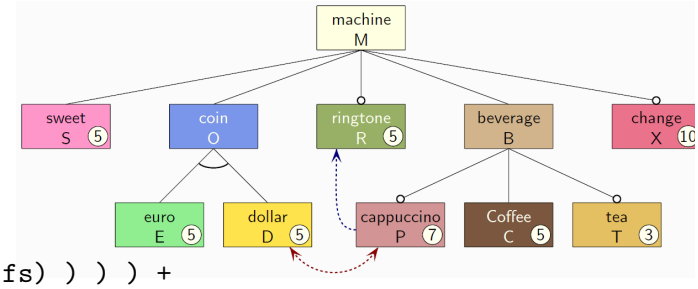
mCRL2 code: auxiliary operations (3/3)

```
map fcost : Feature -> Int ;
eqn fcost(M) =  0 ;
    fcost(S) =  5 ;
    fcost(O) =  0 ;
    fcost(B) =  0 ;
    fcost(R) =  5 ;
    fcost(D) =  5 ;
    fcost(E) =  5 ;
    fcost(X) = 10 ;
    fcost(C) =  5 ;
    fcost(T) =  3 ;
    fcost(P) =  7 ;

map tcost : FSet -> Int ;
var ft : Feature ;
    fset : FSet ;
eqn tcost([]) = 0;
    tcost(ft |> fset) = fcost(ft) + tcost(fset) ;
```



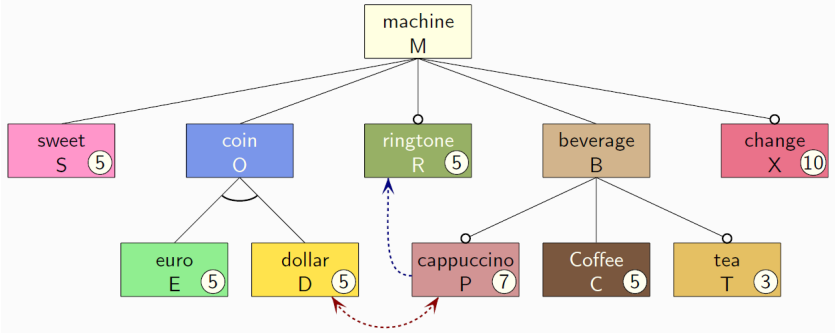
mCRL2 code: selection process Sel (1/2)




```
init
  Sel(0,[M]) ;

proc Sel(st:Int,fs:FSet) =
  %% feature states
  ( st == 0 ) -> (
    ( M in fs ) -> ( setS . Sel(1, insert(S,fs) ) ) ) +
  ( st == 1 ) -> (
    ( M in fs ) -> ( setO . Sel(2, insert(O,fs) ) ) ) +
  ( st == 2 ) -> (
    ( M in fs ) ->
      ( tau . Sel(3, fs ) + setR . Sel(3, insert(R,fs) ) ) ) +
  ( st == 3 ) -> (
    ( M in fs ) -> ( setB . Sel(4, insert(B,fs) ) ) ) +
  ( st == 4 ) -> (
    ( M in fs ) ->
      tau . Sel(5, fs ) + setX . Sel(5, insert(X,fs) ) ) +
  ( st == 5 ) -> (
    ( O in fs ) -> (
      setD . Sel(6, insert(D,fs) ) + setE . Sel(6, insert(E,fs) ) ) ) +
  ( st == 6 ) -> (
    ( B in fs ) -> (
      tau . Sel(7, fs ) +  setT . Sel(7, insert(T,fs) ) +
      setP . Sel(7, insert(P,fs) ) + setTP . Sel(7, union([T,P],fs) ) ) ) +
    ...
```

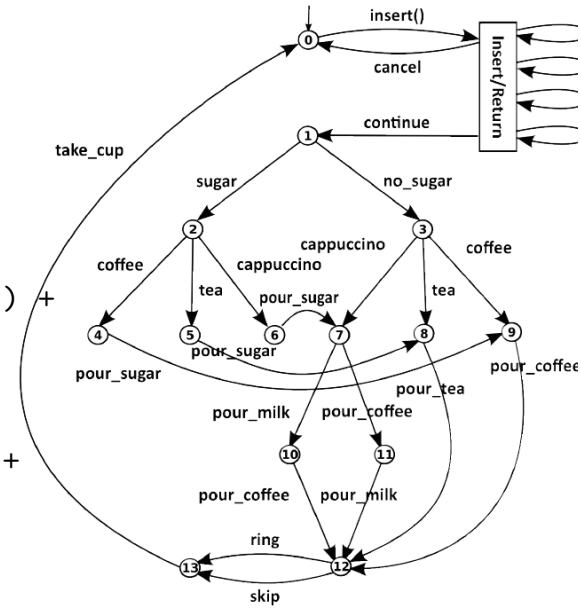
mCRL2 code: selection process Sel (2/2)




```
  ...
( st == 7 ) -> (
  ( B in fs ) -> ( setC . Sel(8, insert(C,fs) ) )
) +
%% cross-tree constraints
( st == 8 ) -> (
  ( ( D in fs ) && ( P in fs ) ) ->
    set_ko( fs ) . deadlock <>
  ( !( R in fs ) && ( P in fs ) ) ->
    set_ko( fs ) . deadlock <> ctc_ok . Sel(9,fs)
) +
%% attribute constraints
( st == 9 ) -> (
  ( tcost(fs) <= 30 ) ->
    set_ok( fs ) . cost( tcost(fs) ) . Prod(0,fs) <> set_ko . deadlock
) ;
```

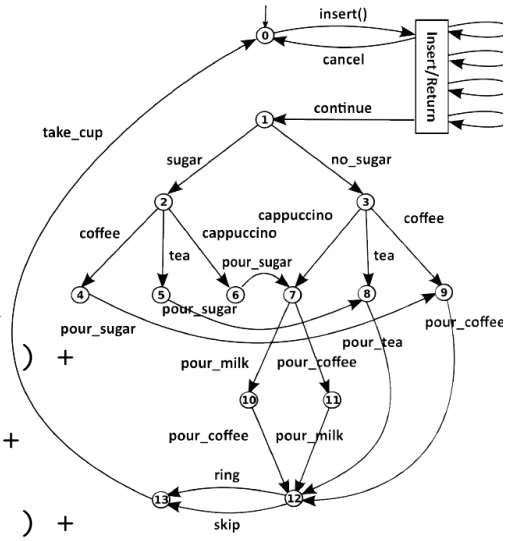
mCRL2 code: product behaviour process Prod (1/2)

```
proc Prod(st:Int,fs:FSet) =
  ( st == 0 ) -> (
    Insert(0,fs) ) +
  ( st == 1 ) -> (
    ( S in fs ) -> ( sugar . Prod(2,fs) ) +
    ( S in fs ) -> ( no_sugar . Prod(3,fs) ) ) +
  ( st == 2 ) -> (
    ( C in fs ) -> coffee . Prod(4,fs) +
    ( T in fs ) -> tea . Prod(5,fs) +
    ( P in fs ) -> cappuccino . Prod(6,fs) ) +
  ( st == 3) -> (
    ( C in fs ) -> coffee . Prod(9,fs) +
    ( T in fs ) -> tea . Prod(8,fs) +
    ( P in fs ) -> cappuccino . Prod(7,fs) ) +
  ( st == 4 ) -> (
    ( M in fs ) -> ( pour_sugar . Prod(9,fs) ) ) +
  ( st == 5 ) -> (
    ( M in fs ) -> ( pour_sugar . Prod(8,fs) ) ) +
  ( st == 6 ) -> (
    ( M in fs ) -> ( pour_sugar . Prod(7,fs) ) ) +
    ...
```



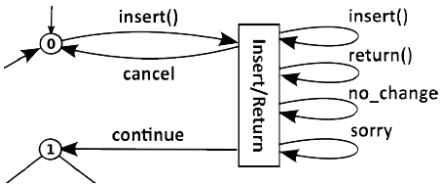
mCRL2 code: product behaviour process Prod (2/2)

```
  ...
( st == 7 ) -> (
  ( M in fs ) -> ( pour_milk . Prod(10,fs) ) +
  ( M in fs ) -> ( pour_coffee . Prod(11,fs) ) ) +
( st == 8 ) -> (
  ( M in fs ) -> ( pour_tea . Prod(12,fs) ) ) +
( st == 9 ) -> (
  ( M in fs ) -> ( pour_coffee . Prod(12,fs) ) ) +
( st == 10 ) -> (
  ( M in fs ) -> ( pour_coffee . Prod(12,fs) ) ) +
( st == 11 ) -> (
  ( M in fs ) -> ( pour_milk . Prod(12,fs) ) ) +
( st == 12 ) -> (
  ( R in fs ) -> ( ring . Prod(13,fs) ) +
  ( !(R in fs) ) -> ( skip . Prod(13,fs) ) ) +
( st == 13 ) -> (
  ( M in fs ) -> ( take_cup . Prod(0,fs) ) ) ;
```

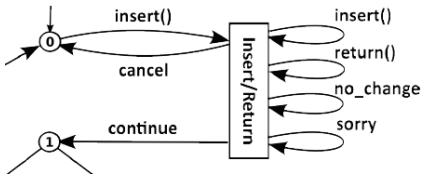


mCRL2 code: money handling process Insert

```
proc Insert(bal:Nat,fs:FSet) =
  ( bal < 100 ) -> (
    ( D in fs ) -> (
      insert(dime) . Insert(bal+10,fs) +
      insert(quarter) . Insert(bal+25,fs) +
      insert(half) . Insert(bal+50,fs) +
      insert(dollar) . Insert(bal+100,fs) ) +
    ( E in fs ) -> (
      insert(ct10) . Insert(bal+10,fs) +
      insert(ct20) . Insert(bal+20,fs) +
      insert(ct50) . Insert(bal+50,fs) +
      insert(euro) . Insert(bal+100,fs) ) ) +
  ( ( bal > 0) && ( bal < 100 ) ) ->
    Return(bal,fs) . cancel . Prod(0,fs) +
  ( bal >= 100 ) -> (
    ( ( !(X in fs) ) ->
      no_change . continue . Prod(1,fs) <>
    Return(Int2Nat(bal-100),fs) .
      continue . Prod(1,fs) )
  ) ;
```

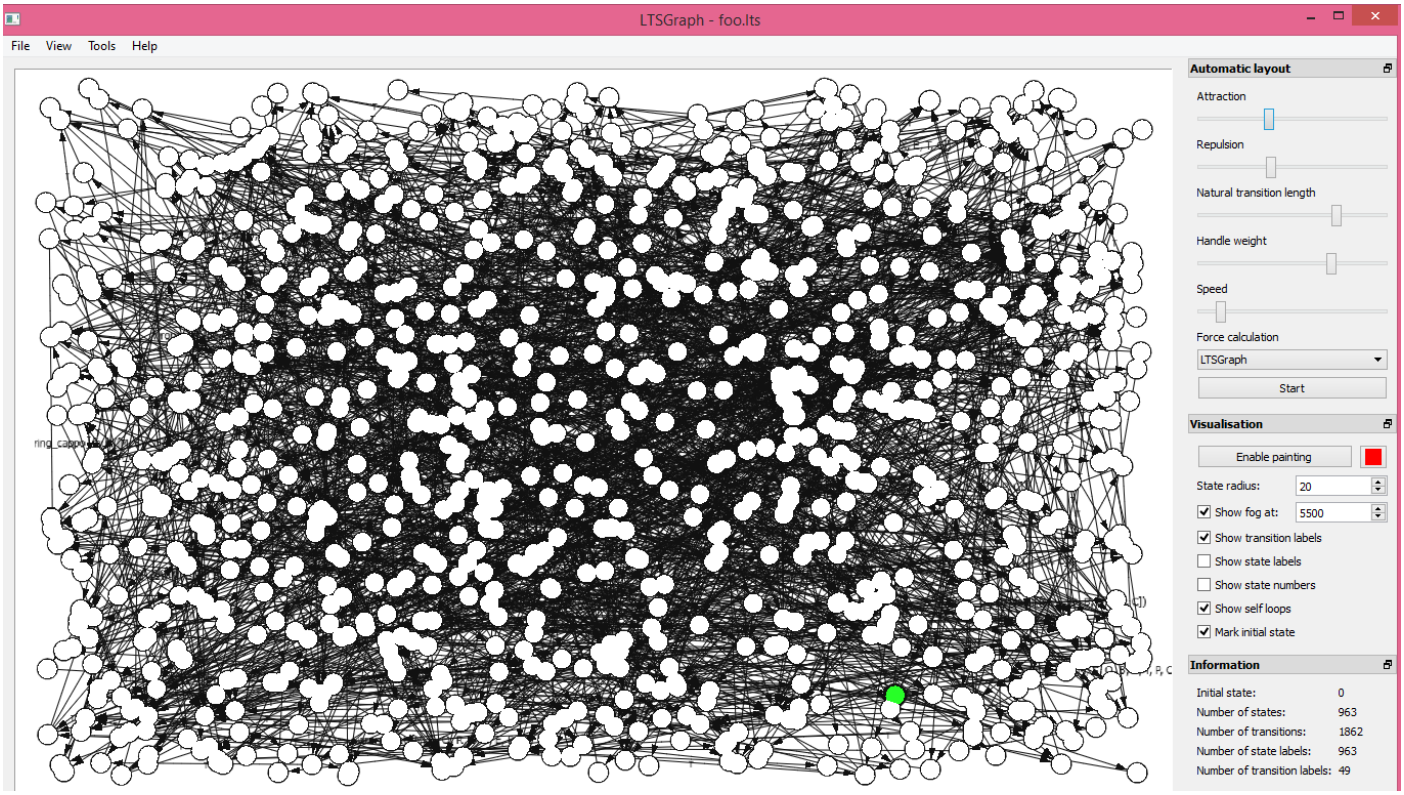


mCRL2 code: money handling process Return

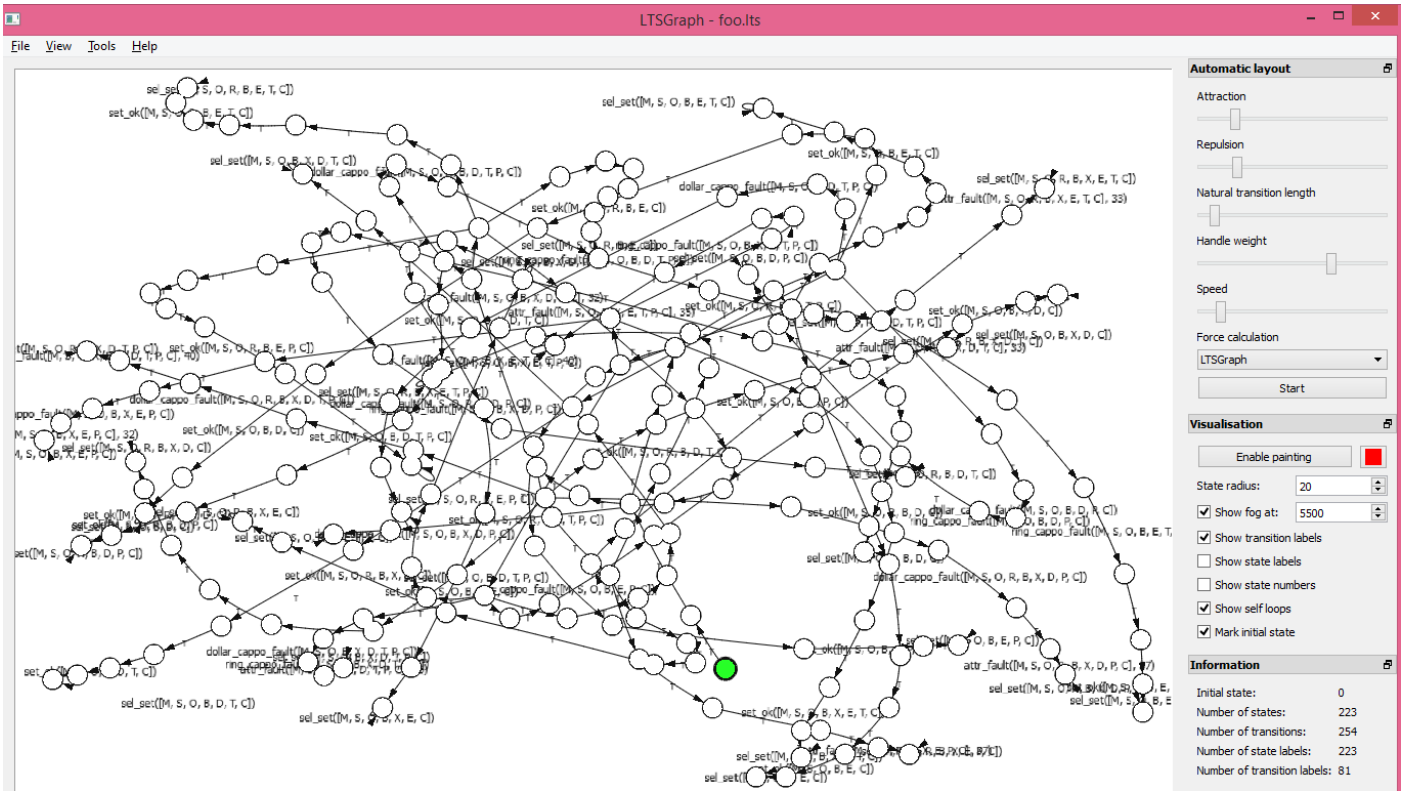



```
proc Return(bal:Nat,fs:FeatSet) =
  ( bal == 0 ) -> tau +
  ( D in fs ) -> (
    ( bal >= 50 ) ->
      return(half) . Return(Int2Nat(bal-50),fs) +
    ( ( bal < 50 ) && ( bal >= 25 ) ) ->
      return(quarter) . Return(Int2Nat(bal-25),fs) +
    ( ( bal < 25 ) && ( bal >= 10 ) ) ->
      return(dime) . Return(Int2Nat(bal-10),fs) +
    ( ( bal < 10 ) && ( bal > 0 ) ) ->
      sorry . Return(0,fs) ) +
  ( E in fs ) -> (
    ( bal >= 50 ) ->
      return(ct50) . Return(Int2Nat(bal-50),fs) +
    ( ( bal < 50 ) && ( bal >= 20 ) ) ->
      return(ct20) . Return(Int2Nat(bal-20),fs) +
    ( ( bal < 20 ) && ( bal > 0 ) ) ->
      return(ct10) . Return(Int2Nat(bal-10),fs) +
    ( ( bal < 10 ) && ( bal > 0 ) ) ->
      sorry . Return(0,fs)
  ) ;
```

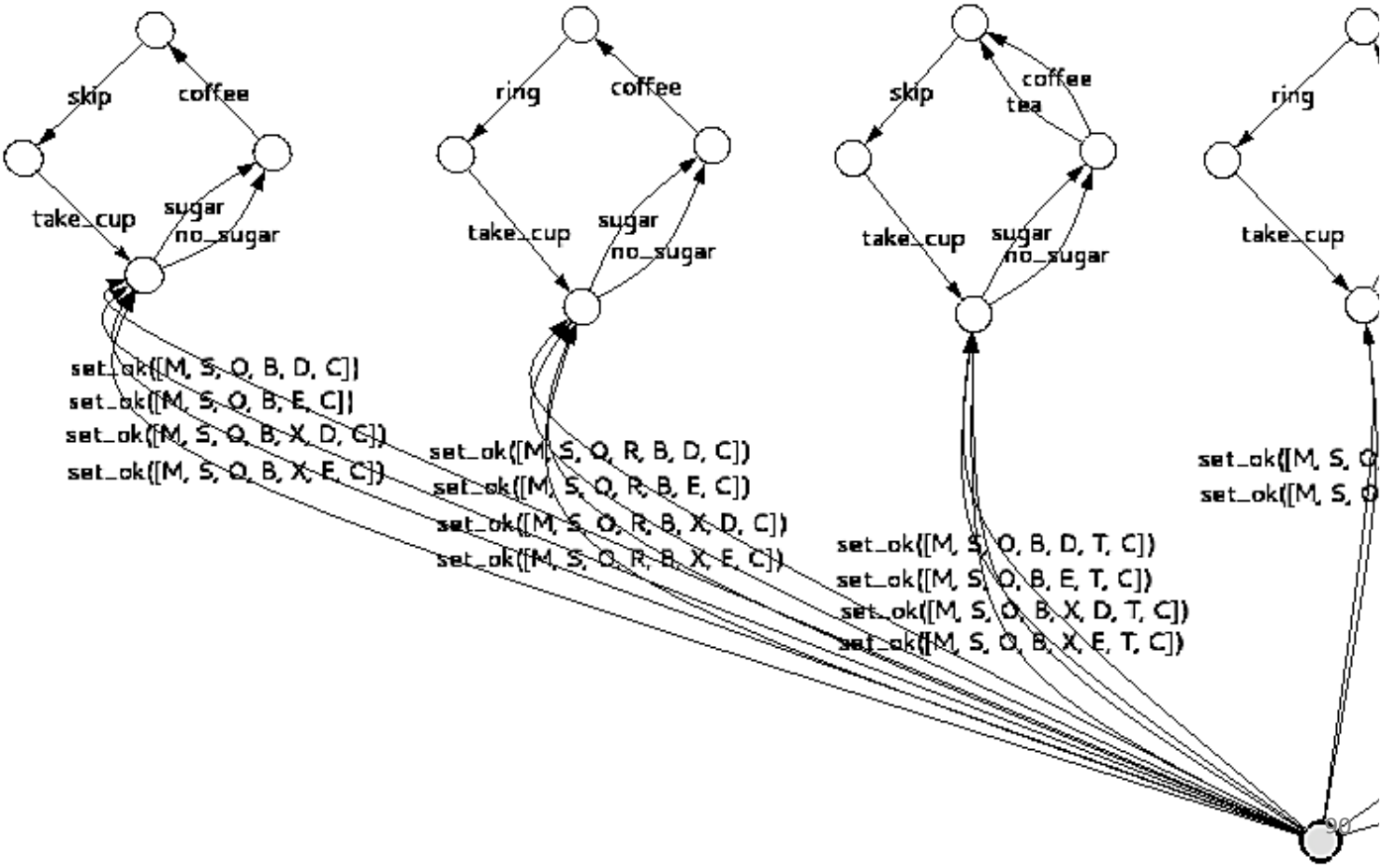
Visual inspection of the state space



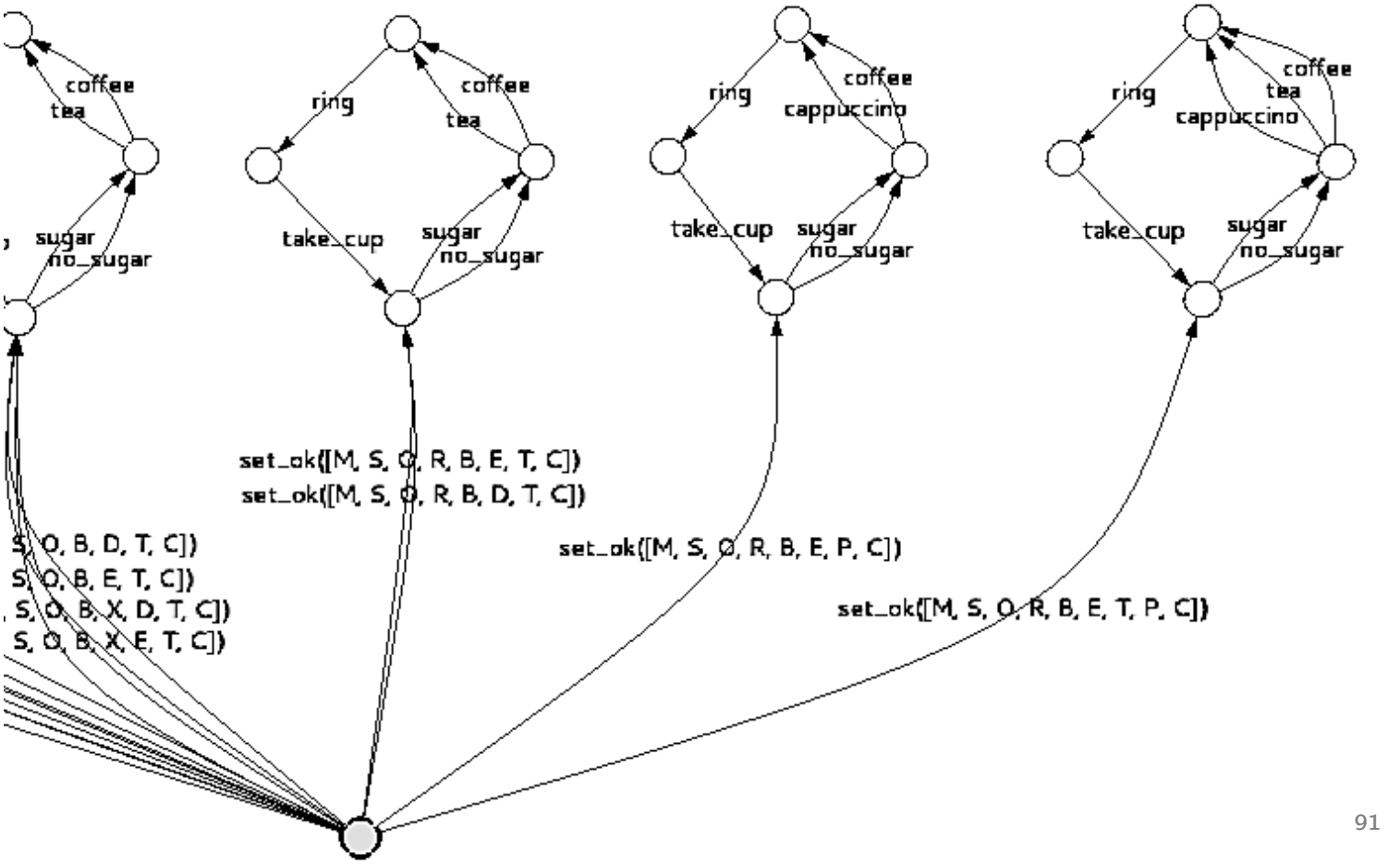
Visual inspection of the state space: behavioural reduction



Product behaviour abstracting from . . .



. . . configuration and payment



Product-based analysis with mCRL2: example properties

- `[(!continue)*.take_cup] false`
  if payment is not settled, no beverage is delivered
- `[true*.setX.true*.no_change] false`
  once feature `X` is selected, `no_change` will not occur
- `[true*] forall fs:FSet.`
  `<set_ok(fs)>(val((D in fs) => !(P in fs)))`
  if a product is configured successfully,
  then it cannot accept dollars and also provide cappuccino
- `mu Y.(<exists fs:FSet.set_ok(fs)>true ||`
  `<exists fs:FSet.set_ko(fs)>true || [true]Y)`
  eventually either `set_ok` or `set_ko` can occur
- `forall c:Coin.[true*.insert(c)]`
  `mu Y.(<cancel||take_cup>true || [true]Y)`
  after money is inserted, eventually a beverage is given
  or money insertion is cancelled
- `[true*]forall n:Nat.[cost(n)](val(n<=30))`
  all valid products have a total cost at most 30

Outlook

~~Next talk: Family-Based Model Checking with mCRL2 (Erik de Vink)~~

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  ter Beek & Legay @ QSPL special section, *LNCS FoMaC*, 2018

- Quantitative specification and verification techniques for systems with variability
- Modelling and analysis of real-time, hybrid or probabilistic systems with variability
- Analysis of safety, security or dependability properties of systems with variability
- Modelling and analysis of dynamic, adaptive and (runtime) reconfigurable systems

  - Variable UML Sequence Diagrams, Performance-Annotated UML Activity Diagrams
  - Featured Timed Automata, Configurable Parametric Timed Automata, Featured Modal Contract Automata, Featured Weighted Automata, Priced Featured Automata,
  - Probablistic/Statistical Model Checking, SMT solving
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