Using mCRL2 for the Analysis of Software Product Lines

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FormaliSE’14
Hyderabad, India
June 3rd 2014
Outline

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EU FP7-ICT FET-Proactive STREP: 1 April 2013 – 31 March 2017

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Collective Adaptive Systems (CAS)

Many examples of decentralized collective adaptive behavior in nature

QUANTICOL: focus on applications arising in context of smart cities

Highly distributed systems with adaptive behavior relying on continuous feedback of vast numbers of consumers and producers
Characteristics of CAS and the project

- Coordination based on (local) decentralized interaction
- Large scale, heterogeneous agents, competing goals, open
- Capacity to smoothly adapt to changing circumstances
- Spatially inhomogeneous distribution influences global patterns
- Multiple scales in time and space, systems of systems
- Decentralized and centralized control

Vision: develop an innovative formal design framework consisting of
- mathematical (quantified) representations of the dynamic behavior of spatially inhomogeneous CAS
- a formal specification language and quantified logic for CAS
- tool-supported, scalable analysis and verification techniques
- design patterns for emergent behavior and control over spatially distributed CAS
Scalable verification approaches (model checkers)
Quantitative business models and product families

Concrete case study on bike-sharing systems (BSS)

- Popular sustainable means of transportation in urban environment
- Challenging case study offering interesting runtime optimization problems and exhibiting variability in the kind of features and in their quantitative characteristics

T3.3 Relating local and global system views with variability analysis

- Study relations between (representations of) small populations and compact (family) representation of large population ‘built’ from them by indicating the commonalities and variabilities of single entities in their overall environment
(Software) Product Line Engineering

To develop a family of products (product line) using a shared platform or architecture (commonalities) and mass customization (variabilities)

Aim: maximize commonalities whilst minimizing cost of variations (i.e., of individual products), thus specifically facilitating (software) reuse in a predictive manner

Variability in terms of features:

- End-user visible pieces of functionality that represent both commonalities (e.g., mandatory, required) and variabilities (e.g., optional, alternative)
- Only specific combinations of features concern valid products

Complex: “We always have 126,000,000 different bicycles in store! But only the parts for 1,000...”
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Example (2/2)

Configure your BMW vehicle

Are you interested in configuring your ideal BMW? Please select a country to visit the configurator in the Virtual Center or contact your local BMW dealer who will be happy to answer all your questions about the BMW model you are interested in.

FIND YOUR BMW.

Filter
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- Vehicle type
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  - 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

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

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

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

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

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

www.quanticol.eu
Attributed feature model: A compact representation of all the family’s products

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

From \( 2^{10} - 1 \) feature diagram \( \rightarrow 2^5 \) cross-tree constraints \( \rightarrow 20 \) attributes \( \rightarrow 16 \) valid products!
Family of 16 valid products (i.e., feature combinations)

‘feature model’ (allowing >16)
Computer-aided analysis of variability models

- Traditionally: focus on modeling/analyzing structural constraints
- But: software systems often embedded/distributed/safety-critical
- Important: model/analyze also behavior (e.g., quality assurance)

Goal: rigorously establish critical requirements of (software) systems
⇒ lift success stories from single product/system engineering to SPLE

Recent approaches to formally model behavioral variability:

- Variants of UML diagrams (Haugen et al., Jézéquel et al.)
- Extensions of Petri nets (Clarke et al.)
- Models with LTS-like semantics: MTS (Fischbein et al., Fantechi et al.), I/O automata (Larsen et al., Lauenroth et al.), CCS/CSP (Gruler et al., Gnesi et al., ter Beek et al.), FTS (Classen et al.), FSM (Millo et al.)
Scalability is a major issue!
(slide by C. Kästner, CMU)

with 33 optional, independent features

a unique product for every person on this planet
Using mCRL2 for behavioral analysis

“adopt and extend state-of-the-art analysis tools”
“examine[s] only valid product variants”
“visualize and (manually or automatically) analyze feature combinations corresponding to products of the product line”
“support (feature) modularity”

Recommendations for Improving the Usability of Formal Methods for Product Lines
(J.M. Atlee, S. Beidu, N.A. Day, F. Faghih & P. Shaker @ FormaliSE’13)

Modularization (in a feature-oriented fashion) are made concrete in ter Beek & de Vink @ ISoLA’14

(Fisler & Krishnamurthi @ ESEC/FSE’01 first recognized that most properties of interest naturally decompose around features)
mCRL2: www.mcrl2.org (open source)

Formal, process-algebraic specification language for distributed and concurrent systems + associated industrial-strength toolset (> 60)
Built on $\mu$CRL (1990), mCRL2 since 2003, now actively maintained
Up to $10^5$ states per second, state spaces of size $10^9$ are the norm
Symbolic exploration of $10^6$ states per second, state spaces of $10^{12}$
Built-in datatypes (Bool, Int, Real, Sets, Functions) + user-defined abstract datatypes to parametrize actions
Formal methods used incl. linear processes, (parametrized) Boolean equation systems, LTS, modal $\mu$-calculus with data (incl. LTL, CTL)
Simulation, visualization, behavioral reduction, model checking, etc.
Highly optimized, up-to-date (i.e. best-known algorithms implemented)
A 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 canceled via a cancel button. *Optionally*, the machine returns change **after** more than one euro or one dollar was inserted.

- Once the machine contains at least one euro or one dollar, the user has to choose whether (s)he wants sugar, by pressing one 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** however be rung by *all* products offering cappuccino.

- **After** the beverage is taken, the machine returns idle.
Recall: attributed feature model

Quantitative constraint: cost(Coffee Machine) ≤ 30
Selection process: specification induced by feature diagram, CTCs, cost

proc Sel(st: Int, fs: FSet) =
  ...
(st == 1) -> ((M in fs) -> ( set0 . Sel(2, insert(0, fs)) ) )
+ 
(st == 2) -> ((M in fs) -> ( tau . Sel(3, fs) +
  setR . Sel(3, insert(R, fs)) ) )
+ 
...

(st == 8) -> ((D in fs) && (P in fs)) -> wrong_set . delta <>
  (!!(R in fs) && (P in fs)) -> wrong_set . delta <>
  ctc_ok . Sel(9, fs)
+

(st == 9) -> (tcost(fs) <= 30) ->
  set_ok(fs) . cost(tcost(fs)) . Prod(0, fs) <>
  wrong_set . delta )
;

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LTS modeling family behavior
proc Prod(st: Int, fs: FSet) =
(st == 0) -> (Insert(0, fs)) +
...
(st == 2) -> ((C in fs) -> coffee. Prod(4, fs) +
(T in fs) -> tea. Prod(5, fs) +
(P in fs) -> cappuccino. Prod(6, fs)) +
...

proc Insert(bal: Nat, fs: FSet) =
(bal < 100) -> (
(D in 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)) )
;
Product behavior abstracting from ...
configuration and payment
If payment is not settled by action continue, no beverage is delivered:
\[ \lnot (\text{continue})^* . \text{take} \text{cup} \] false

Once the $X$-feature is selected, action no\(_\text{change}\) will not occur:
\[ \text{true}^* . \text{set}X. \text{true}^* . \text{no}\_\text{change} \] false

If a product is configured successfully as indicated by the set\(_\text{ok}\) action, then it cannot be a product that accepts dollars and provides cappuccino:
\[
\forall fs: \text{FSet}. \text{val}(\text{is}Set(fs)) \land \lnot \text{true}^*. \text{set}ok(fs) \rightarrow \forall D \in fs \rightarrow \lnot P \in fs
\]

From the initial state, after a finite number of steps, either action set\(_\text{ok}\) (with some parameter $fs$) or action wrong\(_\text{set}\) occurs:
\[
\mu Y. (\exists fs: \text{FSet}. \text{set}ok(fs) \lor \text{wrong}set \lor \text{true} \) Y
\]

After money has been inserted, in a finite number of steps, a beverage can be taken unless the transaction was canceled:
\[
\forall c: \text{Coin}. \text{true}^* . \text{insert}(c) \\
\mu Y. (\lnot \text{cancel} \lor \text{true} \) Y
\]
Position in the PLA cube (Apel et al.)

Sampling based on coverage criteria such as pairwise or \( t \)-wise coverage (or other heuristics)

Possible trade-off?

- **Brute-force product-based analysis** with model checkers highly optimized for single system engineering (e.g., SPIN, mCRL2)
- **Highly innovative family-based analysis** with model checkers developed specifically for SPL (e.g., SNIP by Classen et al.)

\[
\Rightarrow \text{An evaluation of mCRL2 might lead to the desire to implement some SPL-specific features into its model-checking algorithms}
\]
JOURNAL OF
LOGICAL AND ALGEBRAIC METHODS IN PROGRAMMING

Special Issue on
Formal Methods in Software Product Line Engineering

Submission of papers: July 15, 2014
First review decision: December 15, 2014
Revision due: February 15, 2015
Acceptance notification: April 15, 2015
Final manuscript due: June 15, 2015
Expected publication: Summer 2015

Guest editors:
- Maurice ter Beek (ISTI-CNR, Pisa, Italy)
- Dave Clarke (U Uppsala, Sweden & KU Leuven, Belgium)
- Ina Schaefer (TU Braunschweig, Germany)
Publicity (2/3): SPLC’14 in Florence

http://www.splc2014.net/

SPLC 2014
18th International Software Product Line Conference
Florence - Italy, September 15-19, 2014

Research track
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Panels
...

Organised by our Formal Methods and Tools lab of ISTI-CNR, Pisa
Publicity (3/3): deadlines in June!

http://www.splc2014.net/workshops.html

- **REVE** 2nd Int. Workshop on REverse Variability Engineering
  http://www.isse.jku.at/reve2014

- **SUSPL** 1st Int. Workshop on Sustainability in Software Product Lines
  https://sites.google.com/site/susplworkshop/

- **DSPL** 8th Int. Workshop on Dynamic Software Product Lines
  http://www.lero.ie/dspl2014

- **SPLTea** 1st Int. Workshop on Software Product Line Teaching
  http://spltea.irisa.fr/

- **SPLat** A Workshop on Software Product Line Analysis Tools
  http://www.splat2014.org

- **MultiPLE** 2nd Int. Workshop on Multi Product Line Engineering
  https://sites.google.com/site/wmultiple2014/

- **SWORDS** SPES Workshop on Challenges And Deployable Solutions for Seamless Variant Management
  http://swords.in.tum.de