Feature-based modular verification of software product lines

Maurice ter Beek

ISTI–CNR, Pisa

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joint work with Erik de Vink and Tessa Belder
(TU Eindhoven & CWI Amsterdam, The Netherlands)

SPLE: Software Product Line Engineering

(Software) Product Line Engineering

develop a product line (a.k.a. a family) using a shared architecture or platform (commonalities) and mass customization (variabilities) to serve, e.g., different markets, thus allowing for (software) reuse

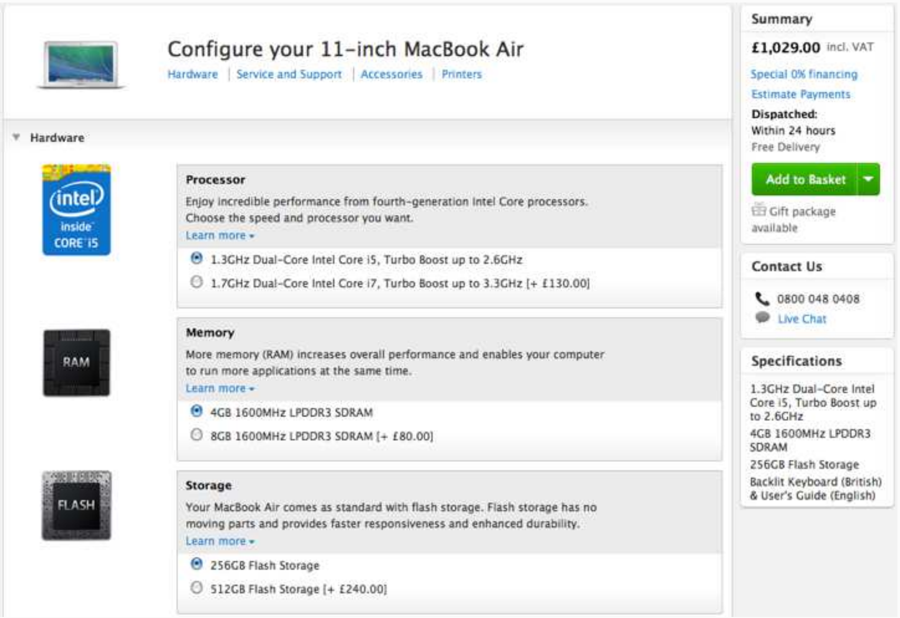
aim: maximize commonalities whilst minimizing cost of variations (i.e. of individual products)

variability in terms of features:

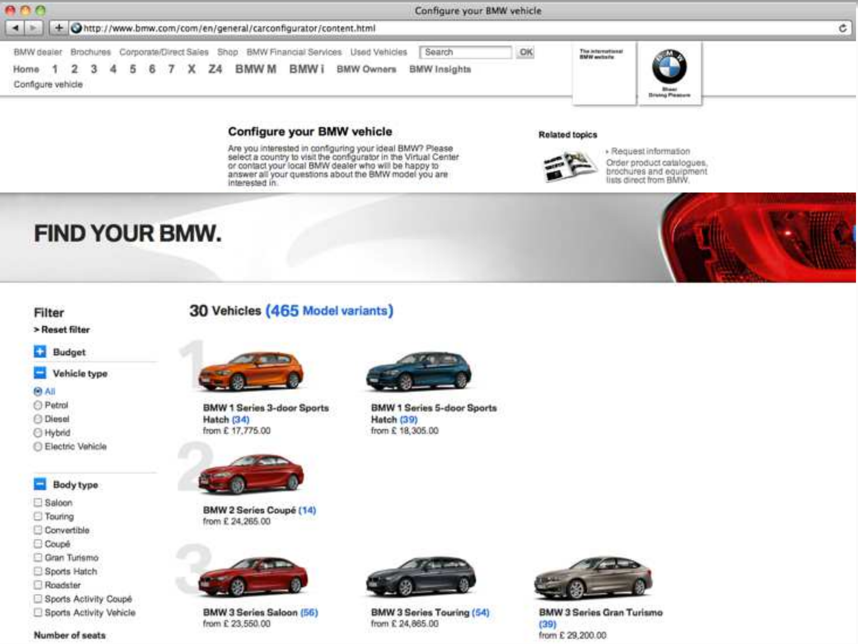
- end-user visible pieces of functionality that represent both commonalities (e.g. mandatory, required) and variabilities (e.g. optional, alternative)
- only specific feature combinations concern valid products

"We always have 126,000,000 different bicycles in store! But only the parts for 1,000..."

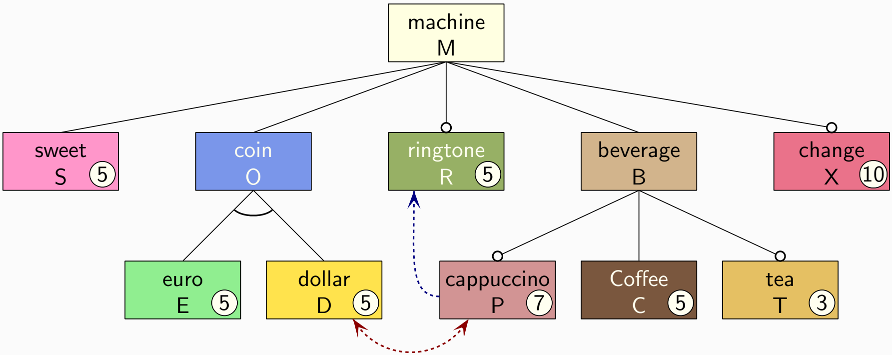
SPL Example (1/2)



SPL Example (2/2)



Attributed feature model: representation of all products

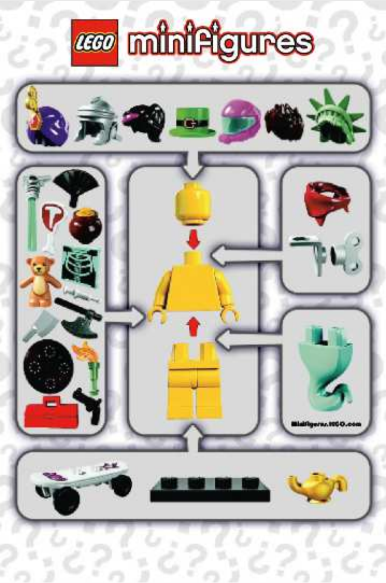


total cost ≤ 30 $\qquad$ $\mathit{cost}\,(\mathit{product}) = \sum\{\, \mathit{cost}\,(\mathit{feature}) \mid \mathit{feature} \in \mathit{product}\,\}$

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

family of 16 valid products
(i.e. feature combinations)

'feature model'
(allowing >16)



Formal modelling and verification in SPLE

computer-aided analysis of variability models

- traditionally focus on modeling/analyzing structural constraints
- but software systems often embedded/distributed/safety-critical
- important to model/verify 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.)
- variety of models with LTS-like semantics: MTS (Fischbein et al., Fantechi et al.), I/O automata (Larsen et al., Lauenroth et al.), CCS/CSP/CCP/SCCP (Gruler et al., Gnesi et al., ter Beek et al., Tribastone), FTS (Classen et al.), FSM (Millo et al.), etc...

Scalability is a major issue! (slide by C. Kästner, CMU)

with 33 optional, independent features

a unique product for every

person on this planet

Tooling for behavioral analysis of SPLs

Recommendations for the Usability of
Formal Methods for Product Lines (Atlee et alii, FormaliSE'13)

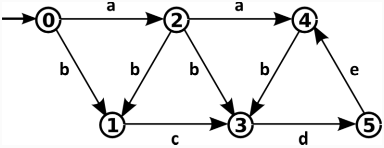
- *adopt and extend state-of-the-art analysis tools*
- *examine[s] only valid product variants*
- *visualize and (manually or automatically) analyze feature combinations corresponding to products of the product line*
- *support (feature) modularity*

Fisler & Krishnamurthi (ESEC/FSE'01) first recognized that most properties of interest naturally decompose around features

mCRL2: language and toolset

- formal, process-algebraic specification of distributed and concurrent systems, associated industrial-strength toolset
- exploration of 10^6 states/s, state spaces up to 10^{12} states
- built-in datatypes, user-defined abstract datatypes, parametrized actions
- modal μ-calculus with data
- visualization, behavioral reduction, model checking
- highly optimized, actively maintained
- intermediate artifacts user-accessable

`www.mcrl2.org`

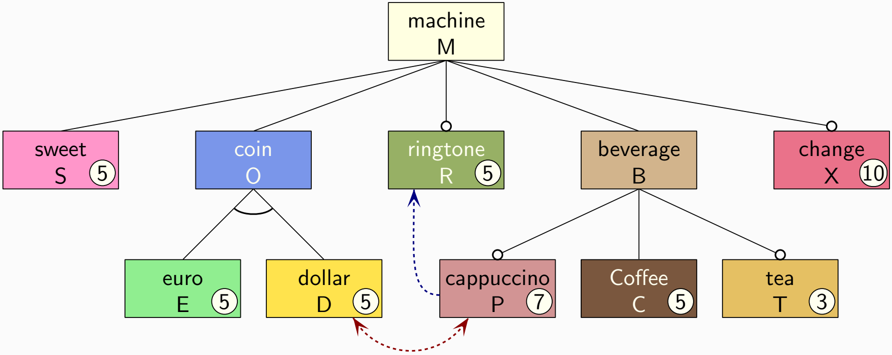



```
proc Foo(st:Int) =
  ( st==0 ) -> ( b.Foo(1) + a.Foo(2) ) +
  ( st==1 ) -> ( c.Foo(3) ) +
  ( st==2 ) -> ( b.Foo(1) + b.Foo(3) + a.Foo(4) ) +
      ...
```

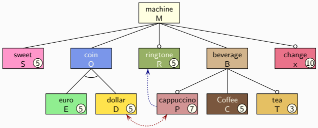
- `[true*]<true>true`: absence of deadlock
- `[true*.b.true*.a] false`: no a after a b
- `mu Y.(<true>true && [!c] Y)`:
  eventually c can be done (or deadlock occurs earlier)
- `mu Y.((nu Z.(<b.d.e> Z)) || [true] Y)`:
  eventually, an infinite sequence of bde is possible

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 canceled via a cancel button; *optionally*, the machine returns change if more than one euro or one dollar was inserted
- once the machine contains at least one euro or one dollar, the user chooses 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* be rung by *all* products offering cappuccino
- after the beverage is taken, the machine returns idle



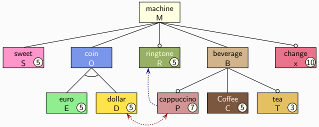
total cost ≤ 30



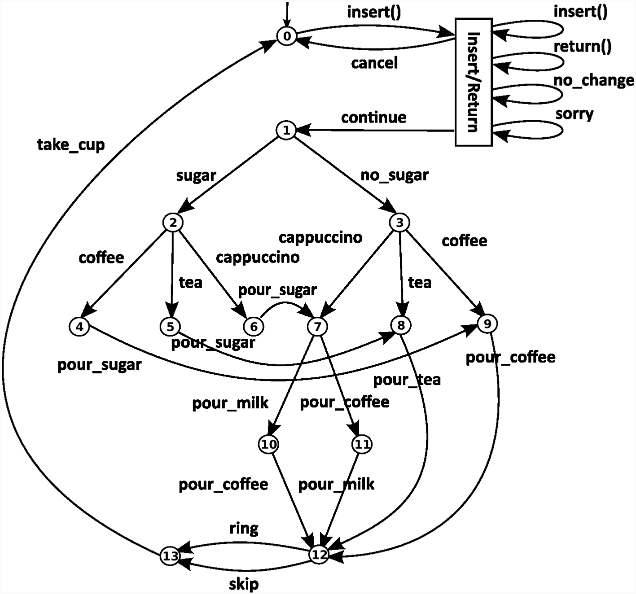
initial call `Sel(0,[M])`

```
proc Sel(st:Int,fs:FSet) =
   ...
( 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) )
) ) + ...
```

mCRL2 process Sel (continued)

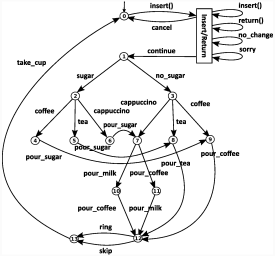



```
    ...
  ( st == 8 ) -> (
  ( ( D in fs ) && ( P in fs ) ) ->
    wrong_set . delta <>
  ( !( R in fs ) && ( P in fs ) ) ->
    wrong_set . delta <>
  ctc_ok . Sel(9,fs)
) +
( st == 9 ) -> (
  ( tcost(fs) <= 30 ) ->
    set_ok(fs) . cost( tcost(fs) ) . Prod(0,fs) <>
  wrong_set . delta );
```



FTS feature labels omitted for readability

mCRL2 process Prod




```
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)
  ) + ...
```

mCRL2 process Insert

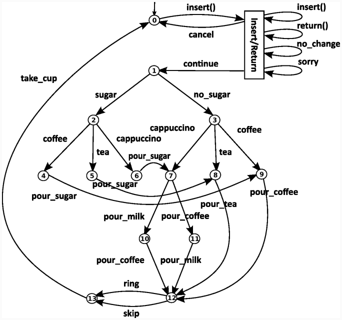
```
proc Insert(bal:Nat,fs:FSet) =
( bal < 100 ) -> (
  ( D in fs ) -> (
    insert(dime) . Insert(bal+10,fs) +
    insert(quarter) . Insert(bal+25,fs) +
    insert(half) . Insert(bal+50,fs) +
    insert(dollar) . Insert(bal+100,fs) ) +
  ( E in fs ) -> (
    insert(ct10) . Insert(bal+10,fs) +
    insert(ct20) . 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) ) );
```

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
      || <wrong_set> true || [true] Y)
  ```
  eventually either set_ok or wrong_set 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 canceled
  ```

A component-based approach

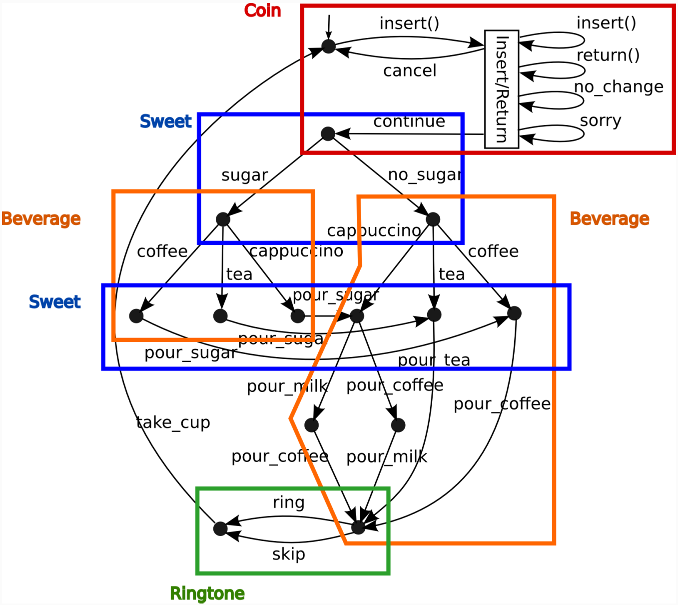
Decomposition of product behaviour



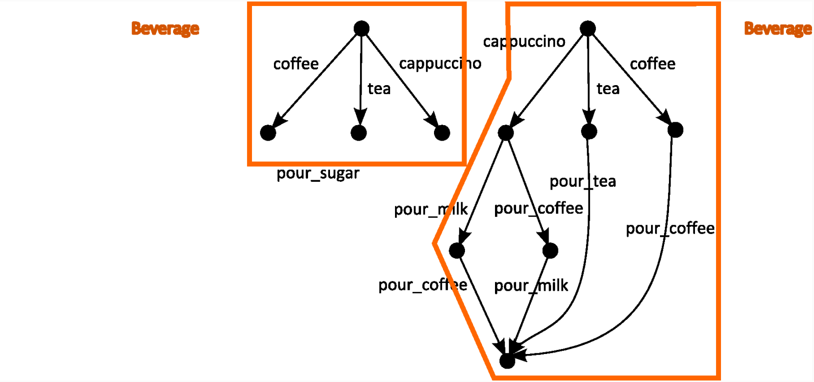
five main components

- Machine (m): take_cup
- Sweet (s): sugar, no_sugar, pour_sugar
- Coin/Change (o,d,e,x): insert, cancel, no_change, sorry, continue
- Ringtone (r): ring, skip
- Beverage (b,c,t,p): coffee, tea, cappuccino, pour_coffee, pour_tea, pour_milk

Decomposition of product behaviour (continued)



Isolated Beverage component



Driver and component processes

```
proc Driver(st:Int) =
  drv_start(st) . sum st':Int . catch(st') . Driver(st');

proc Beverage(fs:FSet) =
  cmp_start(2) . (
    ( C in fs ) -> coffee . raise(4) . Beverage() +
    ( T in fs ) -> tea . raise(5) . Beverage() +
    ( P in fs ) -> cappuccino . raise(6) . Beverage() ) +
    ...
  cmp_start(10) .
    pour_coffee . raise(12) . Beverage() +
  cmp_start(11) .
    pour_milk . raise(12) . Beverage();
```

Driver, component(s) and stub process

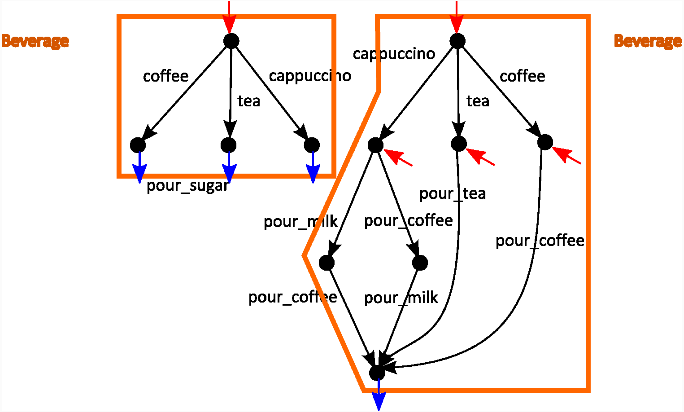
transforming

```
    Driver(0) || Sweet(fs) || Coin(fs) ||
        Ringtone(fs) || Beverage(fs) || Machine
```

into

```
    Driver(0) || Beverage(fs) || Stub
```

```
proc Stub =
  cmp_start(0)  . other . ( raise(2) + raise(3) ) . Stub +
  cmp_start(4)  . other . raise(9) . Stub +
  cmp_start(5)  . other . raise(8) . Stub +
  cmp_start(6)  . other . raise(7) . Stub +
  cmp_start(12) . other . ( raise(2) + raise(3) ) . Stub;
```



(re)entry and exit points

Model checking with stubs

- example property (modal μ-formula in CTL* – next operator)

  `[ true*.coffee ]( mu X. [ !pour_coffee ] X )`

  after a `coffee` action, a `pour_coffee` action happens within a finite number of steps

- model check property against reduced model

  `Driver(0) || Beverage(fs) || Stub`

- verify branching bisimilarity of reduced model

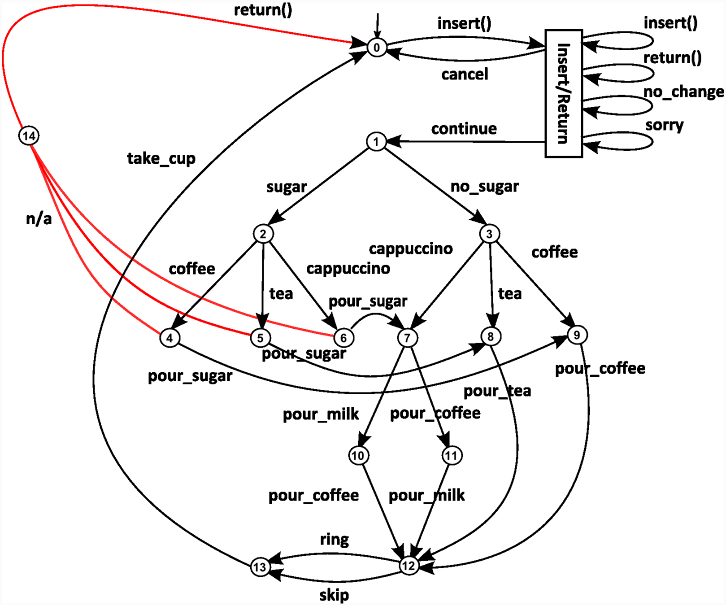
  `Driver(0) || Beverage(fs) || Stub`

  and full model (with `ltscompare` tool in the mCRL2 toolset)

  ```
  Driver(0) || Sweet(fs) || Coin(fs) ||
      Ringtone(fs) || Beverage(fs) || Machine )
  ```

De Nicola & Vaandrager, J. ACM 42 (1995) 458–487

A variation


return()
insert()
insert()
return()
no_change
sorry
Insert/Return
cancel
continue
take_cup
sugar
no_sugar
n/a
cappuccino
coffee
cappuccino
coffee
tea
tea
pour_sugar
pour_sugar
pour_sugar
pour_coffee
pour_tea
pour_milk
pour_coffee
pour_coffee
pour_milk
ring
skip
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

Relevant components

previous example property

```
[ true*.coffee ]( mu X. [ !pour_coffee ] X )
```

new example property

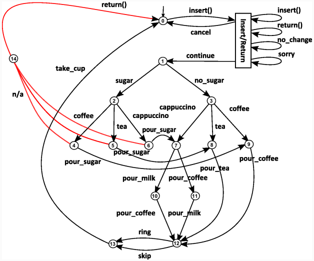
```
[true*.coffee]( mu X.[ !(pour_coffee||return) ]X )
```

action `return` does not belong to component `Beverage`

will check adapted property

```
[true*.coffee]( mu X.[ !(pour_coffee||escape) ]X )
```

action `escape` represents pre-emption of component




```
proc Stub2 =
  cmp_start(0) . other . (raise(2) + raise(3) ) . Stub2 +
  cmp_start(4) . (
    escape . ( raise(2) + raise(3) ) . Stub2 +
    other . raise(9) . Stub2 ) +
  cmp_start(5) . ( ... ) +
  cmp_start(6) . ( ... ) +
  cmp_start(12) . other . ( raise(2) + raise(3) ) . Stub2 ;
```

Model checking with stubs (revisited)

verification of adapted property `adapted_prop`

`[true*.coffee]( mu X.[ !(pour_coffee || escape) ] X )`

against new reduced model `RedSys`

`Driver(0) || Beverage(fs) || Stub2`

conditional to equivalence of satisfaction

`FullSys` $\models$ `new_prop` vs. `RedSys` $\models$ `adapted_prop`

Extend LTS branching bisimulation to FTS

Featured Transition System (Classen et alii, ICSE'10)

$\mathcal{F}$: finite non-empty set of features, $\mathcal{P} \subseteq \mathbf{2}^{\mathcal{F}}$ subset of products

$\mathbb{B}(\mathcal{F})$: set of boolean expressions over $\mathcal{F}$ (feature expressions)

(S, θ, s_0): featured transition system with set S of states, transition constraint function $\theta \colon S \times \mathcal{A} \cup \{\tau\} \times S \to \mathbb{B}(\mathcal{F})$, initial state $s_0 \in S$

we write $s \xrightarrow{\alpha|\psi} s'$ if $\theta(s, \alpha, s') = \psi$

product $P \in \mathcal{P}$ satisfies feature expression $\varphi \in \mathbb{B}(\mathcal{F})$, denoted $P \models \varphi$, if φ is valid when the Boolean variables corresponding to the features of P are assigned value *true* and those not in P value *false*

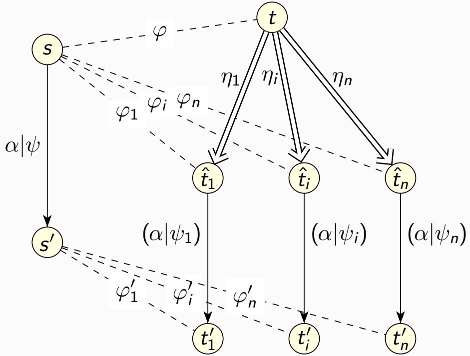
equivalence relation $\sim_{\mathcal{P}}$ on $\mathbb{B}(\mathcal{F})$ given by $\varphi \sim_{\mathcal{P}} \psi$ iff $\forall P \in \mathcal{P}$: $P \models \varphi \Leftrightarrow P \models \psi$; we denote $\widehat{\mathbb{B}}(\mathcal{F}) = \mathbb{B}(\mathcal{F})/{\sim_{\mathcal{P}}}$

Branching feature bisimulation $R \subseteq S \times \widehat{\mathbb{B}}(\mathcal{F}) \times S$

for $s, s' \in S$ and satisfiable $\eta \in \mathbb{B}(\mathcal{F})$ we write $s \stackrel{\eta}{\Rightarrow} s'$ if

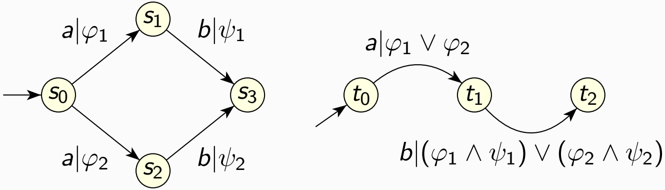
$$\exists n \, \exists s_0, \ldots, s_n \, \exists \eta_1, \ldots, \eta_n :$$
$$s = s_0 \wedge \forall i, 1 \leqslant i \leqslant n \colon s_{i-1} \xrightarrow{\tau|\eta_i} s_i \wedge s' = s_n \wedge \eta = \textstyle\bigwedge_{1 \leqslant i \leqslant n} \eta_i$$

we write $s \xrightarrow{(\alpha|\psi)} s'$ in case $s \xrightarrow{\alpha|\psi} s'$ or $\alpha = \tau \wedge s = s' \wedge \psi = true$

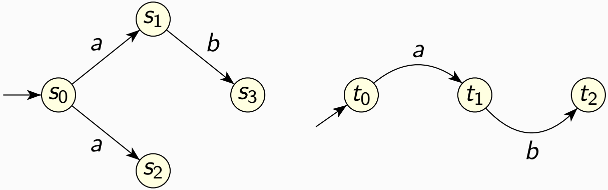


FTS vs. LTS bisimulation

bisimilar FTS assuming $\varphi_1 \wedge \varphi_2 \;\Rightarrow\; (\psi_1 \Leftrightarrow \psi_2)$



non-bisimilar LTS assuming $\varphi_1 \wedge \varphi_2 \wedge \psi_1 \wedge \neg\psi_2$

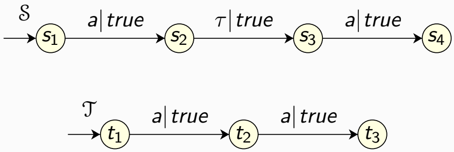


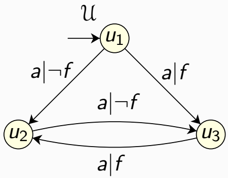
Theorem

Let s, t be states of FTS $\mathcal{S}$. Then $s \simeq_{bf} t$ iff $s \simeq_P t$ for all $P \in \mathcal{P}$.

Minimization modulo branching feature bisimulation

$\mathcal{T}$ and $\mathcal{U}$ are both branching feature bisimilar to $\mathcal{S}$ and both have the minimal number of states, but $\mathcal{U}$ has twice as many transitions as $\mathcal{T}$





Theorem

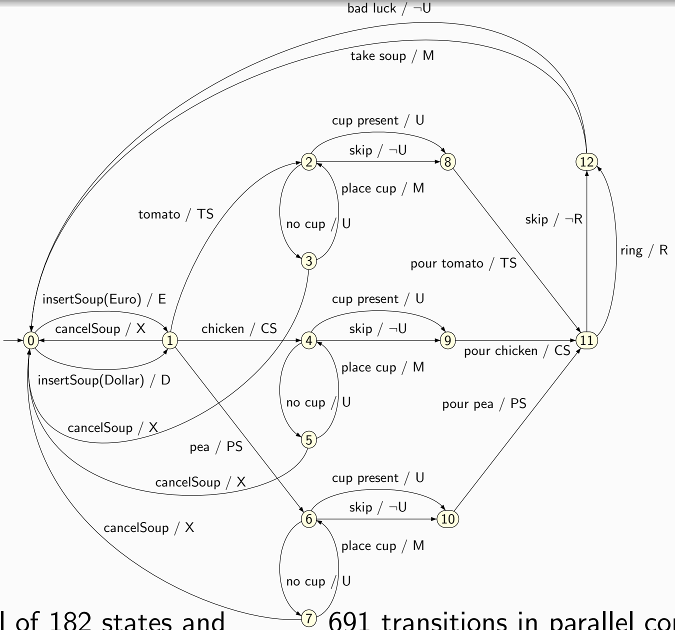
Constructing a minimal branching feature bisimilar FTS is NP-complete.

Theorem

Our polynomial-time sub-optimal algorithm reduces an FTS $\mathcal{S}$ to the smallest FTS $\mathcal{S}_{min}$ for which there exists a coherent branching feature bisimulation relation for $\mathcal{S}$ and $\mathcal{S}_{min}$.

Adaptation of efficient Groote & Vaandrager algorithm (ICALP'90)

Experimental evaluation (beverage + soup component)



(for a total of 182 states and 691 transitions in parallel composition)

mCRL2 results of experimental evaluation (time in seconds)

PROPER-TIES	PRODUCT-BY-PRODUCT				FTS-BASED FAMILY APPROACH			
	WITHOUT BISIMULATION		WITH BISIMULATION		WITHOUT BISIMULATION		WITH BISIMULATION	
	TIME (S)	RESULT	TIME (S)	RESULT	TIME (S)	RESULT	TIME (S)	RESULT
1	42.04	*false*	38.18	*true*	52.96	*false*	13.60	*true*
2	41.78	*true*	41.65	*true*	53.86	*true*	53.69	*true*
3a	42.32	*true*	37.76	*true*	70.57	*true*	7.70	*true*
3b	42.01	*true*	37.78	*true*	59.96	*true*	7.98	*true*
4a	40.62	*true*	38.00	*true*	24.18	*true*	8.65	*true*
4b	40.20	*true*	37.88	*true*	20.78	*true*	10.68	*true*
5a	42.38	*false*	38.51	*true*	66.08	*false*	18.59	*true*
5b	42.34	*false*	38.09	*true*	69.95	*false*	14.92	*true*
6	43.63	*true*	39.17	*true*	105.35	*true*	29.72	*true*
7a	42.45	*true*	38.19	*true*	71.07	*true*	13.84	*true*
7b	42.35	*true*	38.04	*true*	79.05	*true*	9.48	*true*
8	42.82	*true*	39.09	*true*	80.69	*true*	20.47	*true*
TOT	504.94		462.34		754.50		209.32	

1. if a coffee is ordered, then eventually coffee is poured:
   `[ true*.coffee ]( mu X. [ !pour_coffee ] X )`
2. the SPL is deadlock-free: `[true*]<true>true`

etc.

Conclusions and future work

- mCRL2 for software product line analysis
- model reduction before model checking

- automate property and stub adaptation?

- establish subset of modal μ-calculus preserved by branching feature bisimulation
- reduce complexity of minimization algorithm

- does modular verification approach scale to realistic SPL?

`www.mcrl2.org`