A Lightweight Integration of Theorem Proving and Model Checking for System Verification

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Outline of the talk

- Background and motivation
  - Comparison between theorem proving and model checking.
  - Target point in theorem proving that we focus on
  - Verification flow of the lightweight integration.
- The translator – Cafe2Maude
  - Data type module translation
  - OTS module translation
  - Invariant property defining module translation
  - Initial state generation
- Conclusion and Future work

Part I: Background and motivation

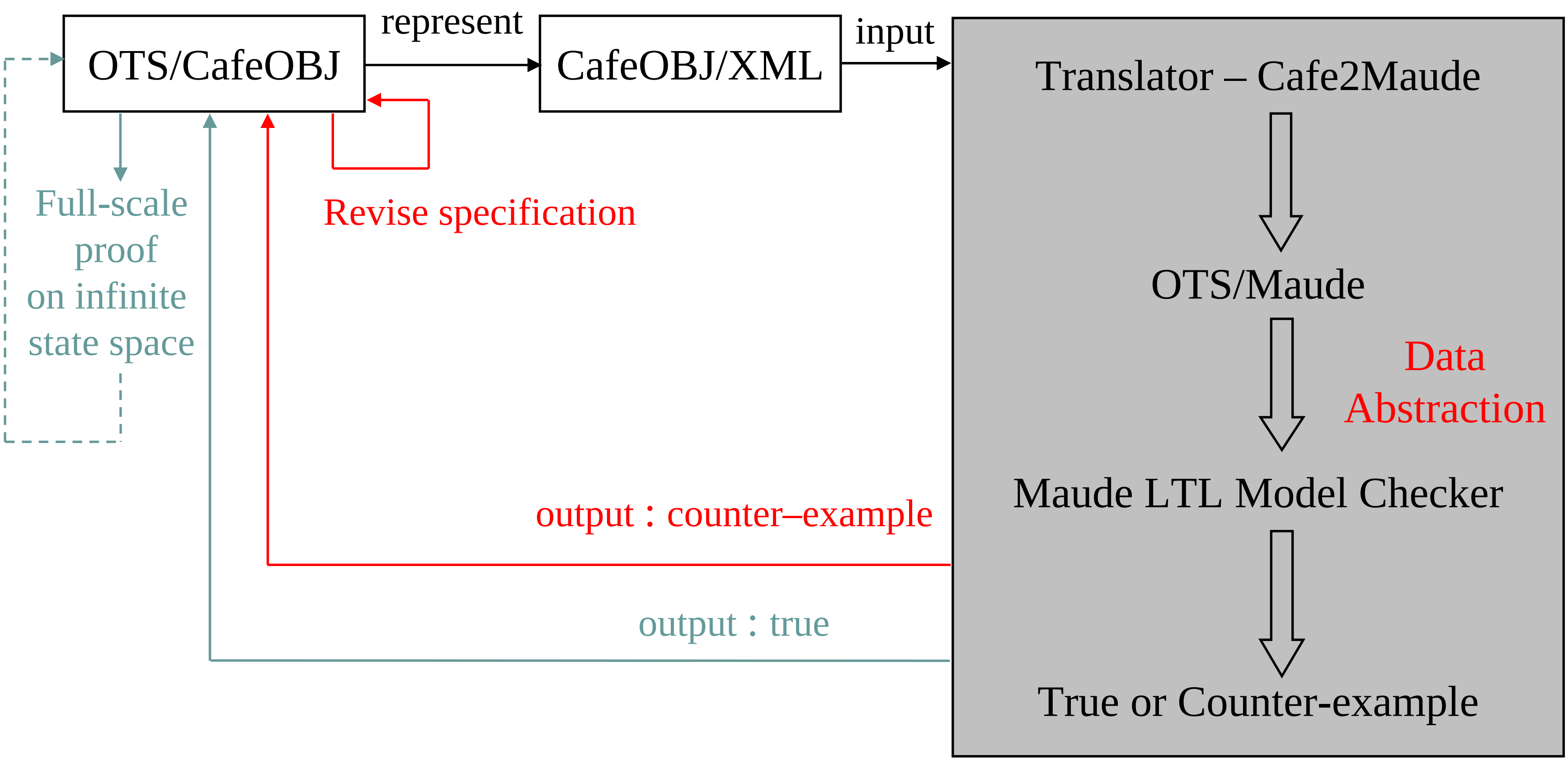
A general comparison of typical theorem proving and model checking:

	Theorem proving	Model Checking
State space	Infinite	Finite
Verification procedure	Limited automatic	Fully automatic
Counter-example	No automatic	Automatic
Obtaining insight of the system	Tell how the system is correct	Tell how the system is incorrect

Our target point in theorem proving

- In case that a property fails to hold
  - Difficult to extract enough information from the verification result
    - Errors exist in specifications? If so, where?
    - Need more guidance to complete the proof?
  - Considerable time is used to discover and prove auxiliary invariants.
- If counter-example can be generated automatically
  - Easier to find out the reason for the failure
  - Benefit from firstly model checking the newly founded invariant:
    - If counter-example, then revise specifications or discard the invariant
    - If true, then there might exist a proof for the invariant
- To able to find "bugs" in the early stage of verification (before we write proofs manually) and ease the hard-work of theorem proving.

Verification flow when using Cafe2Maude

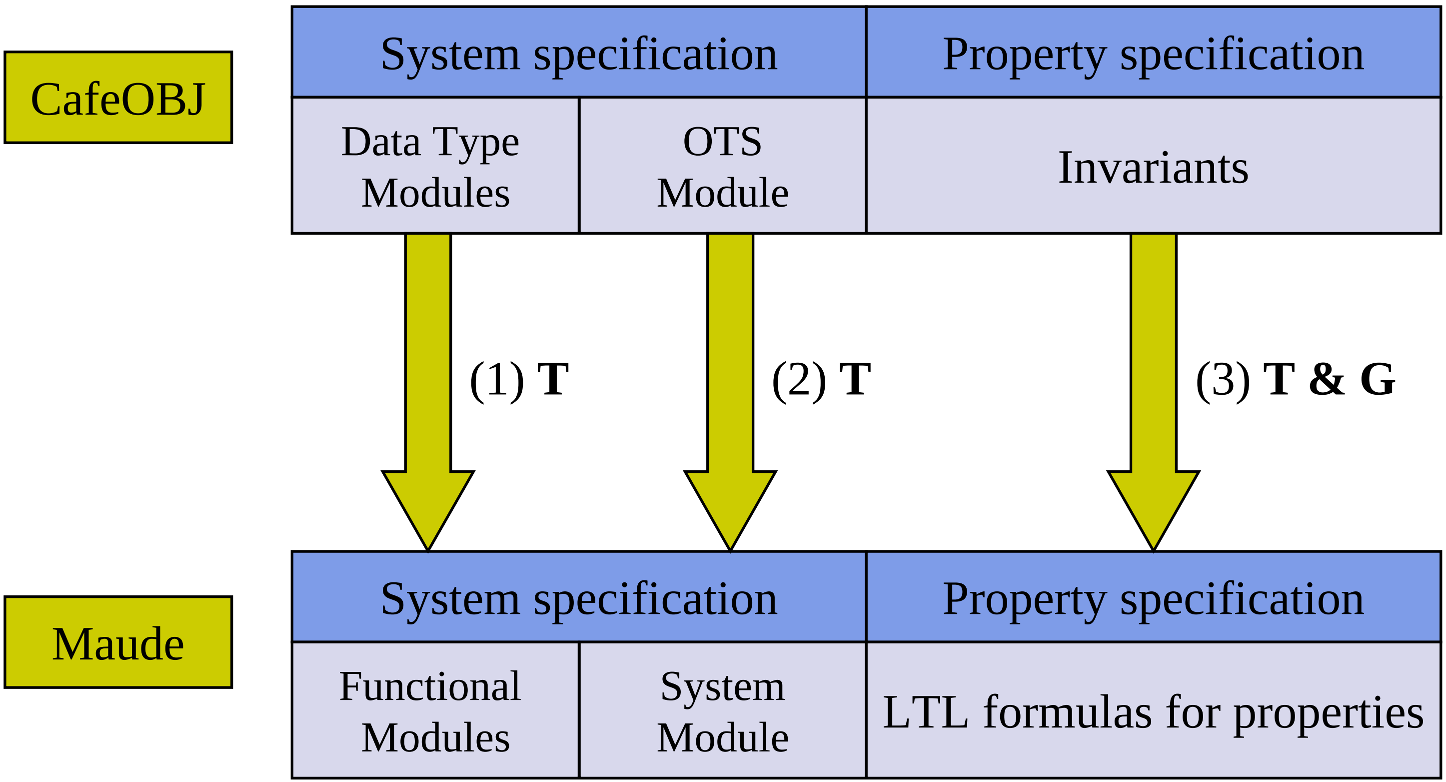


Why called “lightweight”

- Good aspects: the formalisms of OTS/CafeOBJ and OTS/Maude are quite similar (both based on equations).
  - Equations are easy to understand and use.
  - Similar formalisms can alleviate the burden for the users to learn two different formalisms.

- Bad aspects: the data abstraction method we used may not preserve soundness.
  - The abstracted model may has some property that does not hold in the original model.
    - But, this simple abstraction method is effective when aim to exposing bugs

Part II: Cafe2Maude introduction



Given a user's input of data abstraction:
T : Translation   G : (Initial State) Generation

A Mutual Exclusion Algorithm

Pseudo-code of the mutual exclusion algorithm:

l1 : *put(queue, i)*
l2 : repeat until *top(queue) = i*
Critical Section
cs : *get(queue)*

Initially, each process *i* is at label *l1* and *queue* is empty.

- The algorithm is modeled as an OTS <*O*, *I*, *T* >:
  - Observers: *queue* and *pc*
  - Transition rules: *wait*, *try* and *exit*

Data type module translation

CafeOBJ Data Type Module	Maude Functional Module

mod! LABEL {
[Label]
ops l1 l2 cs : -> Label
op _=_ : Label Label -> Bool {comm}
var L : Label
eq (L = L) = true .
eq (l1 = l2) = false .
eq (l1 = cs) = false .
eq (l2 = cs) = false .
}
	fmod LABEL is
	sort Label .
	ops l1 l2 cs : -> Label .
	endfm

- Other two data type module PID and QUEUE are translated similarly.

OTS module translation (1)

CafeOBJ OTS module – signature	Maude system module
-- hidden sort declaration *[Sys]*	subsort OValue TRule < Sys . op none : -> Sys . op _ _ : Sys Sys -> Sys [assoc comm id : none]
-- observer declaration bop o : Sys V_{i_1} … V_{i_m} -> V -- (m >= 1) bop o : Sys -> V -- otherwise	op (o[_,…,_] : _) : V_{i_1} … V_{i_m} V -> OValue . op (o : _) : V -> OValue .
-- transition rule declaration bop t : Sys V_{i_1} … V_{i_m} -> Sys	op t : V_{i_1} … V_{i_m} -> TRule .

OTS module translation (Example 1)

CafeOBJ operator declarations	Maude operator declarations
-- observers bop pc : Sys Pid -> Label bop queue : Sys -> Queue -- transition rules bop want : Sys Pid -> Sys bop try : Sys Pid -> Sys bop exit : Sys Pid -> Sys	*** Observers op pc[_] : _ : Pid Label -> OValue . op queue : _ : Queue -> OValue . *** transition rules op want : Pid -> TRule . op try : Pid -> TRule . op exit : Pid -> TRule .

OTS module translation (2)

CafeOBJ OTS module – equations	Maude system module – transition rule
-- equations defining state transition Given a transition rule $t_{j_1,\ldots,j_n}$ denoted by t, and the observers needed and affected (return value is changed) by this transition rule are $o_1,\ldots,o_l$, the equations are translated to one (conditional) rewrite law as follows:	*** Maude rewrite law crl [relaw] : $t(X_{j_1},\ldots,X_{j_n})$ $(o^1[X_{i_1}{}^1,\ldots,X_{i_{m_1}}{}^1] : X_1)\ \ldots\ (o^l\,[X_{i_1}{}^l,\ldots,X_{i_{m_1}}{}^l] : X_l\,)$ => $t(X_{j_1},\ldots,X_{j_n})$ $(o^1[X_{i_1}{}^1,\ldots,X_{i_{m_1}}{}^1] : X_1{}')\ \ldots\ (o^l\,[X_{i_1}{}^l,\ldots,X_{i_{m_1}}{}^l] : X_l{}')$ if $c\text{-}t(X_{j_1},\ldots,X_{j_n}, X_{i_1}{}^1,\ldots,X_{i_{m_1}}{}^1, X_1, X_{i_1}{}^l,\ldots,X_{i_{m_1}}{}^l, X_l)$.

OTS module translation (Example 2)

CafeOBJ equations defining action	Maude rewrite law defining action

op c-want : Sys Pid -> Bool
eq c-want(S,I) = (pc(S,I) = l1) .
ceq pc(want(S,I),J) =
        (if I = J then l2 else pc(S,J) fi)
        if c-want(S,I) .
ceq queue(want(S,I)) = put(queue(S),I)
        if c-want(S,I) .
ceq want(S,I) = S if not c-want(S,I) .
	crl [want] :
	want(I) (pc[I] : LABEL) (queue : QUEUE)
	  =>
	want(I) (pc[I] : l2) (queue : put(QUEUE,I))
	if LABEL == l1 .

- Equations defining transition rules *try* and *exit* are translated similarly.

Property translation (1)

Procedure of model checking OTS using Maude.

- Given a Maude system module, say M
  - Defining a new module, say M-PREDS that defines state predicates.
  - Defining a new module, say M-CHECK that defines LTL formulas for properties.
  - Given an initial state init, model check defined properties

```
Maude>  red modelCheck(init, property)
```

Property translation (2)

Properties to be proved for the mutual exclusion algorithm

predicates

```
mod INV {
Pr (QLOCK)
… -- constant, operator and variable declarations
eq inv1(S,I,J) = (pc(S,I) = cs and pc(S,J) = cs implies I = J) .
eq inv2(S,I) = (pc(S,I) = cs implies top(queue(S)) = I) .
eq inv3(S,I) = (pc(S,I) = l2 or pc(S,I) = cs implies not empty?(queue(S))) .
eq inv4(S,I) = (pc(S,I) = l2 implies I /in queue(S)) .
```

- An invariant consists of a set of predicates and logical connectives.
- What we need to do is to firstly extract these predicates and then define state predicates in the module M-PREDS

Property translation (3)

- Assumption: Each predicate has at most one observation operator. Predicates with two (or more) observation operators should be written separately. Such as pc(S,I) = pc(S,J), should be written as pc(S,I) = VAR and pc(S,J) = VAR.

- Predicates *without observation operator* (such as I = J):

$bool(V_1,\ldots,V_m) \Rightarrow S \models prop(V_1,\ldots V_m) = true \text{ if } bool(V_1,\ldots V_m)$.

  - Example
    - T => S |= prop(T) = true if T .
    - I = J => S |= prop(I,J) = true if I = J .

Property translation (4)

- Predicates *with observation operator*
  - In the form of normal observation equation

$o(S,V_1,\ldots,V_m) = term$

$=>$

$(o[V_1,\ldots,V_m] : term)\ S \mid= prop(V_1,\ldots,V_m , X_1,\ldots X_n) = true$.

* *term* contains no observation operator due to the assumption.

- Example:
  - pc(S,I) = cs => (pc[I] : cs) S |= prop(I) = true .

Property translation (5)

- Predicates *with observation operator*
  - Other non-normal ones

    $pred(\ldots, o(S, V_1, \ldots, V_m), \ldots)$
    =>
    $(o[V_1, \ldots, V_m] : VAR)\ S \models prop(V_1, \ldots, V_m, X_1, \ldots, X_n) = true$
    if $pred(\ldots, VAR, \ldots)$.

    - Example:
      - top(queue(S)) = I => (queue : VAR) S |= prop(I) = true
        if top(VAR) = I .
      - I /in queue(S) => (queue : VAR) S |= prop(I) = true
        if I /in VAR .

Property translation (Example)

- Translate the properties based on the declared *props*.

```
eq inv1(S,I,J) = (pc(S,I) = cs and pc(S,J) = cs implies I = J) .
```

```
eq (pc[I] : cs) S |= prop1(I) = true .
eq (pc[J] : cs) S |= prop2(J) = true .
eq S |= prop3(I,J) = true if I = J .
```

```
"and"      ---->   "/\"
"implies"  ---->   "->"
"[]"       ---->   "Always"
```

```
eq property1(I,J) = [] (prop1(I) /\ prop2(J) -> prop3(I,J)) .
```

Data abstraction for translated properties

- Simple data abstraction (reduction or valuation): reducing the infinite domain of each sort to some concrete values, where variables belonging to this sort occur in the formula for property.

```
[] (prop1(I) /\ prop2(J) -> prop3(I, J)) .
```

sort Pid ⇔ p1, p2

```
[] (((prop1(p1) /\ prop2(p1)) -> prop3(p1, p1))
  /\ ((prop1(p1) /\ prop2(p2)) -> prop3(p1, p2))
  /\ ((prop1(p2) /\ prop2(p2)) -> prop3(p2, p2))
  /\ ((prop1(p2) /\ prop2(p1)) -> prop3(p2, p1))) .
```

Initial state generation

CafeOBJ equations defining initial state, say init	Maude equations defining initial state

• eq pc(init,I) = l1 .
eq queue(init) = empty .
 	
• Information about
  • transition rules
  • data abstraction
	eq init = want(p1) try(p1) exit(p1)
	want(p2) try(p2) exit(p2)
	(pc[p1] : l1) (pc[p2] : l1)
	(queue : empty) .

Part III: Conclusion and future work

- Conclusion
  - Designed and implemented a translator from OTS/CafeOBJ to OTS/Maude. (using Java, currently about 4000 line codes)
  - Proposed a simple method to make theorem proving task easier by taking advantage of model checking.
- Future work
  - Doing more non-trivial case studies to convince people that our integration is useful
    - Secure workflow
    - Authentication and ecommerce protocols
  - Formally prove the correctness of the translation.

Thanks!