Verification of Deployed Artifact Systems via Data Abstraction

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Overview

1. Motivation: Artifact Systems
2. Verification of infinite-state data-aware systems
3. Key contribution: verification of bounded infinite-state systems is decidable
4. Application of the result to significant cases
5. Conclusion and future directions

Artifact and Artifact Systems

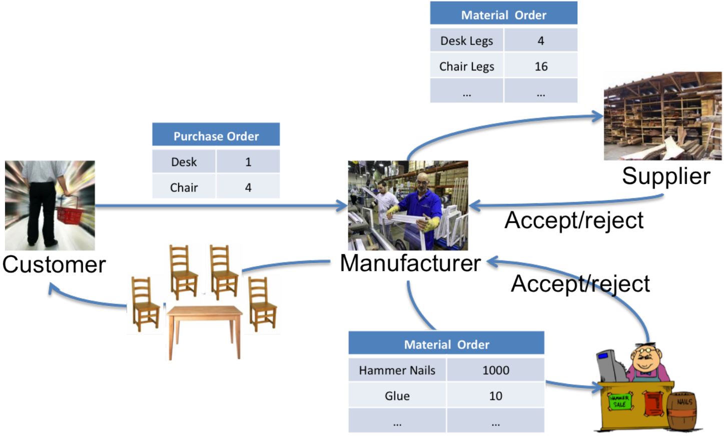
Recent Paradigm for Business Process modeling and development [CH09]

- *Artifact*: information model + lifecycle
  - (Nested) records equipped with actions
  - Actions may affect several artifacts
- *Artifact System*: set of interacting artifacts

Data and processes are given same emphasis
Modularized approach (sort of Object-Orientation for BPs)

Artifact Systems

Motivating Scenario



Artifact Systems

Motivating Scenario (cont.)

CPO			
id	*customer_id*	*product_code*	*status*

- $createPO(id, cid, code)$
- $deletePO(id)$
- $addItemPO(id, itm, qty)$
- ...

WO			
id	*cpo*	*line_itms*	*status*

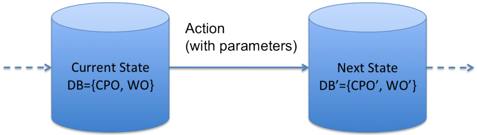
- $createWO(id, cpo)$
- $deleteWO(id)$
- $addLineItemWO(id, mat, qty)$
- ...

Artifact Systems

- As the process goes on, artifact actions are executed
  - e.g., the Customer Purchase Order is sent to the Manufacturer.
- Actions add/remove artifacts or change artifact attributes
  - e.g., the CPO status changes from *created* to *submitted*

The whole system can be seen as a *data-aware* dynamic system

- At every step, an action yields a change in the current state



Framework

Preliminaries

Preliminary (standard) notions and notation

- A *database schema* is a set $\mathcal{D} = \{P_1/a_1, \ldots, P_n/a_n\}$ of relation symbols P_i, each with its *arity* a_i
- A *$\mathcal{D}$-interpretation* (or *instance*) over (possibly infinite) U is a mapping associating each P_i with a finite a_i-ary relation $D(P_i) \subseteq U^{a_i}$
- *Active domain*: $adom(D) \subseteq U$ is the (finite) set of all distinct elements occurring in D
- First-Order formulas/sentences are syntactically defined as usual but evaluated under *active-domain* semantics:
  - *quantified variables range over the active domain*

Framework

Artifact Systems: Syntax

How do we describe an Artifact System?

Definition (Artifact System)

An *Artifact System* is specified as a tuple $\mathcal{S} = \langle \mathcal{D}, U, D_0, \Phi \rangle$, where:

- $\mathcal{D} = \{P_1/a_1, \ldots, P_n/a_n\}$ is a *database schema*
- U is a possibly infinite *interpretation domain*
- D_0 is an *initial* $\mathcal{D}$-instance over U
- Φ is a finite set of *parametric actions* of the form $\alpha(\vec{x}) = \langle \pi(\vec{y}), \psi(\vec{z}) \rangle$, where:
  - $\alpha(\vec{x})$ is the *action signature* and $\vec{x}$ the set of its *formal parameters*
  - $\vec{x} = \vec{y} \cup \vec{z}$
  - $\pi(\vec{y})$ is a FO-formula over $\mathcal{D}$ called the *action precondition*
  - $\psi(\vec{z})$ is a FO-formula over $\mathcal{D} \cup \mathcal{D}'$ called the *action postcondition*, where $\mathcal{D}' \doteq \{P'_1/a_1, \ldots, P'_n/a_n\}$

Framework

Artifact Systems: Semantics

Definition (Model of an Artifact System)

Given an *Artifact System* $\mathcal{S} = \langle \mathcal{D}, U, D_0, \Phi \rangle$, its *model* is the Kripke structure $\mathcal{K} = \langle \Sigma, D_0, \tau \rangle$, where:

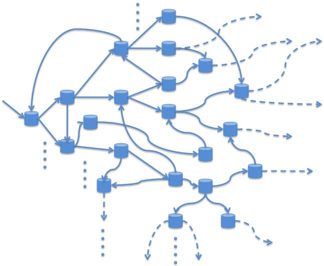
- $\Sigma \subseteq \mathcal{I}_{\mathcal{D}}(U)$ is the set of *states* ($\mathcal{I}_{\mathcal{D}}(U)$: all instances of $\mathcal{D}$ over U)
- $D_0 \in \Sigma$ is the *initial state*
- $\tau : \Sigma \to \Sigma$ is the *transition relation* s.t. $\tau(D, D')$ iff for some α there exists an execution $\alpha(\vec{u}) = \langle \pi(\vec{v}), \psi(\vec{w}) \rangle$ such that:
  - $adom(D') \subseteq adom(D) \cup \{w_1, \ldots, w_\ell\} \cup const(\psi)$
  - $D \models \pi(\vec{v})$, i.e., the action is *enabled*
  - $D \oplus D' \models \psi(\vec{w})$, where $D \oplus D'$ interprets unprimed symbols as in D and primed ones as in D'.

NOTE: First-Order formulas evaluated under *active-domain* semantics.

Framework

Intuition

- Each state is a $\mathcal{D}$-instance
- As actions are executed, new states are reached
- Action parameters can introduce new values
- Infinite U yields potentially infinitely many distinct states
- In general, infinite branching and infinite run-length



The Problem
Intuition

Check whether all possible system evolutions satisfy a desired property

- Does the system satisfy a (branching-time) *temporal* specification? E.g.:
  - It is always the case that every artifact can be deleted
  - There exists a way to create a certain number of artifacts
  - A product can be shipped to the customer only after assemblage
- Flavor of Model Checking, but:
  - *relational* states
  - infinite interpretation domain
  - infinite state space

Verification Formalism: FO-CTL

Syntax

How to specify system properties?

Definition (Syntax of FO-CTL over $\mathcal{S}$)

$$\varphi ::= \phi \mid \varphi \wedge \varphi \mid \neg\varphi \mid AX\varphi \mid A\varphi\mathcal{U}\varphi \mid E\varphi\mathcal{U}\varphi,$$

where ϕ is a FO-sentence over $\mathcal{D}$ and U.

(Other operators derived as usual)
Essentially, CTL with propositional formulas replaced by FO *sentences*
E.g.:

- $\varphi_{ship} = AG\ \forall c\ (shippedCPO(c) \rightarrow \forall m\ (related(c, m) \rightarrow shippedMPO(m)))$
- $\varphi_{t+} = EF\ \exists x_1, \ldots, x_{t+1}\ \bigwedge_{i \neq j} x_i \neq x_j$
- $\varphi_{empty} = AG\ EF\ (emptyCPO \wedge emptyWO \wedge emptyMPO)$

Verification Formalism: FO-CTL

Semantics

(A *run* r is a sequence of successor states. $r(i)$ *selects* the i-th r-state.)

Definition (Semantics of FO-CTL over $\mathcal{S}$)

Let $\mathcal{K}$ be the model of $\mathcal{S}$ and $D \in \Sigma$ a $\mathcal{K}$-state.

$(\mathcal{K}, D) \models \varphi$ iff $D \models \varphi$, if φ is an FO-sentence;

$(\mathcal{K}, D) \models \neg\varphi$ iff $(\mathcal{K}, D) \not\models \varphi$;

$(\mathcal{K}, D) \models \varphi \rightarrow \psi$ iff $(\mathcal{K}, D) \not\models \varphi$ or $(\mathcal{K}, D) \models \psi$;

$(\mathcal{K}, D) \models AX\varphi$ iff for all $\mathcal{K}$-runs r s.t. $r(0) = D$, $(\mathcal{K}, r(1)) \models \varphi$;

$(\mathcal{K}, D) \models A\varphi\mathcal{U}\psi$ iff for all $\mathcal{K}$-runs r s.t. $r(0) = D$, $\exists k \geq 0$ s.t. $(\mathcal{K}, r(k)) \models \psi$ and $\forall j$ s.t. $0 \leq j < k$, $(\mathcal{K}, r(j)) \models \varphi$;

$(\mathcal{K}, D) \models E\varphi\mathcal{U}\psi$ iff for some $\mathcal{K}$-run r, $r(0) = D$, $\exists k \geq 0$ s.t. $(\mathcal{K}, r(k)) \models \psi$, and $\forall j$ s.t. $0 \leq j < k$, $(\mathcal{K}, r(j)) \models \varphi$.

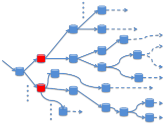
A formula φ is *true* in $\mathcal{K}$, written $\mathcal{K} \models \varphi$, if $(\mathcal{K}, D_0) \models \varphi$.

$\mathcal{S}$ satisfies φ, written $\mathcal{S} \models \varphi$, if $\mathcal{K} \models \varphi$.

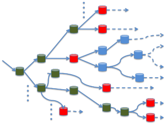
FO-CTL Semantics

Intuition

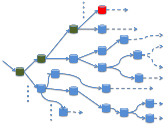
$AX\varphi$:



$A\varphi\mathcal{U}\psi$:



$E\varphi\mathcal{U}\psi$:



Verification of Artifact Systems

General Formulation

- *Model Checking problem for Artifact Systems*:

  Given $\mathcal{S}$ and φ, does $\mathcal{S} \models \varphi$ hold?

  - Similar to Model Checking but technically more challenging
    - Relational states
    - Infinite state-space

Theorem

The MC problem for Artifact Systems is undecidable.

  - BUT decidable over finite interpretation domains:
    - by reduction to standard propositional case (*propositionalise* FO facts).

Verification of Bounded Artifact Systems

- Here we devise a notable case of decidability
- If all the $\mathcal{D}$-instances (states) of the system are **bounded**, then, though **infinite-state**, model-checking the system is decidable.

Bounded Artifact System

Definition (b-Bounded (Artifact) System)

Consider a system $\mathcal{S} = \langle \mathcal{D}, U, D_0, \Phi \rangle$, and a bound $b \in \mathbb{N}$ such that $b \geq |D_0|$. $\mathcal{S}$ is *b-bounded* if its model $\mathcal{K}_b = \langle \Sigma_b, D_0, \tau_b \rangle$ is such that

- for every $D \in \Sigma_b$, $|D| \leq b$

Verification of Bounded Artifact Systems

We consider the following problem:

- *Model Checking of Bounded Artifact Systems*:

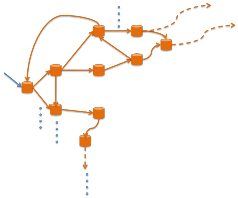
  Given a b-bounded artifact system $\mathcal{S}$ and a property φ, does $\mathcal{K}_b \models \varphi$?

Verification of Bounded Artifact Systems

Cont.

As a result of the infinite interpretation domain, we still have:

- Infinite branching
- Infinite state-space



QUESTIONS:

- Is the problem decidable?
- ☞ How can we model-check a bounded system?

Non-trivial! (we cannot *construct* the (infinite) model)

Abstract System

Definition

Given a b-bounded system $\mathcal{S} = \langle \mathcal{D}, U, D_0, \Phi \rangle$ and a property φ, the (b, φ)-*bounded Abstract System* of $\mathcal{S}$ is the Artifact System $\hat{\mathcal{S}}_{b,\varphi} = \langle \mathcal{D}, \hat{U}, D_0, \Phi \rangle$, s.t. $\hat{U} = C_{\mathcal{S},\varphi} \cup \hat{C}$, with:

- $C_{\mathcal{S},\varphi} = const(\varphi) \cup \bigcup_{\phi \in \Phi} const(\phi)$
- $\hat{C} \cap C_{\mathcal{S},\varphi} = \emptyset$
- $|\hat{C}| = b + v$, with $v = \max_{\phi \in \Phi}\{|vars(\phi)|\}$

Intuition:

- $\hat{\mathcal{S}}_{b,\varphi}$ analogous to $\mathcal{S}$ except for $U \neq \hat{U}$
- $\hat{U}$ contains:
  - all constants mentioned in $\mathcal{S}$ and φ
  - enough distinct abstract symbols to “fill” the bound and have “fresh” actual parameters for action executions
- $\hat{U}$ is finite!

Abstract System Verification

- Obviously, $\hat{\mathcal{S}}_{b,\varphi} \models \varphi$ is decidable, as $\hat{U}$ is finite
- But we want to check whether $\mathcal{K}_b \models \varphi$
- So, what is the relationship between $\mathcal{K}_b$ and $\hat{\mathcal{S}}_{b,\varphi}$?

Theorem

Consider a b-bounded system $\mathcal{S}$ with U infinite, and a FO-CTL specification φ.[a] *If $\hat{\mathcal{S}}_{b,\varphi}$ is the (b,φ)-bounded abstract system of $\mathcal{S}$ then*

$$\mathcal{K}_b \models \varphi \Leftrightarrow \hat{\mathcal{K}}_{b,\varphi} \models \varphi,$$

where:

- $\mathcal{K}_b$ *is the model of* $\mathcal{S}$, *and*
- $\hat{\mathcal{K}}_{b,\varphi}$ *is the model of* $\hat{\mathcal{S}}_{b,\varphi}$.

[a] In fact for the whole FO μ-calc

Complexity

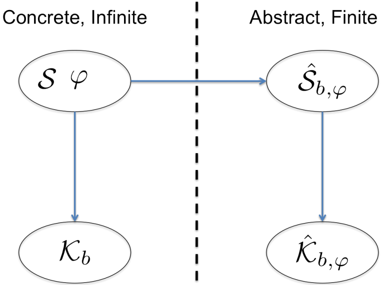
- Upper bound:
$$\mathcal{O}(2^{|\hat{U}|^{a}+|\hat{U}||\varphi|})$$
- Technique based on reduction to propositional CTL MC (viable as abstract interpretation domain finite)
- $\hat{\mathcal{K}}_{b,\varphi}$-states propositionalised (single exponential wrt $|\hat{U}| = b + v + |C_{\mathcal{S},\varphi}|$ but doubly wrt a)
- Quantifiers eliminated from φ (single exponential in $|\varphi|$)

Observations:

- Not far from similar results ([DSV07, DHPV09, BCD^{+}11])
- Some performing well in practice ([DSV07])
- Non-optimal technique

Abstract System Verification

Technique



- $\hat{\mathcal{K}}_{b,\varphi} \models \varphi$ can be reduced to standard MC
- We have an actual technique to model-check $\mathcal{K}_b$!

Data Abstraction

$$\mathcal{K}_{\boldsymbol{b}} \models \varphi \Leftrightarrow \hat{\mathcal{K}}_{\boldsymbol{b},\varphi} \models \varphi$$

- What's behind the scene?
- How did we get rid of an infinite number of elements and transitions?

We applied an *abstraction process* based on two formal notions:

1. *Isomorphism* between DB instances
2. *Bisimulation* between Kripke structures

Data Abstraction

Isomorphic instances

Definition (C-isomorphic $\mathcal{D}$-instances)

Two $\mathcal{D}$-instances D and $\hat{D}$, respectively over U and $\hat{U}$, are said C-isomorphic, for $C \subseteq U, \hat{U}$, written $D \sim_C D$, iff there exists a bijection $i : adom(D) \cup C \mapsto adom(\hat{D}) \cup C$ that is the identity on C, and such that for every $j = 1, \ldots, n$, and for every $\vec{u} \in adom(D)^{a_i}$, $D \models P_j(\vec{u}) \Leftrightarrow \hat{D} \models P_j(i(\vec{u}))$, where $i(\vec{u}) \doteq \langle i(u_1), \ldots, i(u_{a_j}) \rangle$.

In words: Instances obtained by uniformly renaming the elements not in C
E.g., for $C = \{1\}$, $i(1) = 1$, $i(2) = a$, $i(3) = b$, $i(4) = c$.

D

1	2	3
2	4	3

$\hat{D}$

1	a	b
a	c	b

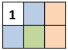
Data Abstraction

Isomorphic instances (cont.)

Isomorphic instances have a notable (well-known) property:

Lemma

If $D \sim_C \hat{D}$ then for every FOL φ s.t. $const(\varphi) \subseteq C$, $D \models \varphi \Leftrightarrow \hat{D} \models \varphi$.

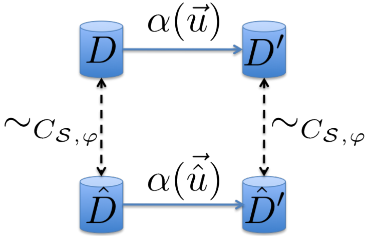


- The "coloured instance" satisfies φ iff all the instances isomorphic to it do
- The "coloured" instance stands for infinitely many isomorphic instances (*isomorphism type*):
  - same values iff same colours
- IDEA: No FO (sub-)formula from $\mathcal{S}$ or φ can distinguish two $C_{\mathcal{S},\varphi}$-isomorphic instances
- Observation: for given b, only finitely many isomorphism types

Crux of the Result

Theorem

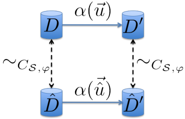
If $D \sim_{C_{\mathcal{S},\varphi}} \hat{D}$, every concrete transition $\langle D, D' \rangle$ has an abstract counterpart $\langle \hat{D}, \hat{D}' \rangle$ s.t. $D' \sim_{C_{\mathcal{S},\varphi}} \hat{D}'$, and viceversa.



- Execution: $\alpha(\vec{u}) = \langle \pi(\vec{v}), \psi(\vec{w}) \rangle$

Crux of the Result

If-Part (Intuition)



Need to prove that there exist $\vec{\hat{v}}, \vec{\hat{w}}, \hat{D}'$ s.t.
(i) $\hat{D} \models \pi(\vec{\hat{v}})$, *(ii)* $\hat{D} \oplus \hat{D}' \models \psi(\vec{\hat{w}})$, and *(iii)* $D' \sim_{C_{\mathcal{S},\varphi}} \hat{D}'$

- See $\vec{u}$ as a (1-tuple) relation
- We can prove that there exists $\hat{D}'$ and $\vec{\hat{u}}$, and a $C_{\mathcal{S},\varphi}$-isomorphism between

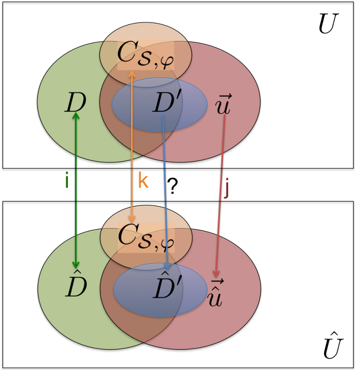
$$\{D, D', \vec{u}\} \text{ and } \{\hat{D}, \hat{D}', \vec{\hat{u}}\}$$

- This is enough, as π and φ are invariant wrt $C_{\mathcal{S},\varphi}$-isomorphic instances

Crux of the Result

If-Part (Intuition) Cont.

$C_{\mathcal{S},\varphi}$-isomorphism between $\{D, D', \vec{u}\}$ and $\{\hat{D}, \hat{D}', \hat{\vec{u}}\}$:



1. obtain $\hat{\vec{u}}$ by renaming the elements in $\vec{u}$ according to i, k, and preserving (in)equalities – $\hat{U}$ contains enough elements
2. obtain $\hat{D}'$ by renaming the elements in D' according to i and j

Data Abstraction

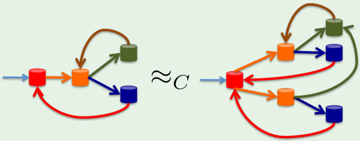
Bisimilar Kripke Structures

Definition (C-bisimilar Kripke structures)

Given $\mathcal{K} = \langle \Sigma, D_0, \tau \rangle$, $\hat{\mathcal{K}} = \langle \hat{\Sigma}, \hat{D}_0, \hat{\tau} \rangle$, and C, $\mathcal{K}$ and $\hat{\mathcal{K}}$ are *C-bisimilar* ($\mathcal{K} \approx_C \hat{\mathcal{K}}$) iff there exists a relation $R \subseteq \Sigma \times \hat{\Sigma}$, called *$C$(-preserving) bisimulation*, s.t. $\langle D_0, \hat{D}_0 \rangle \in R$, and if $\langle D, \hat{D} \rangle \in R$ then:

- $D \sim_C \hat{D}$;
- for all D' s.t. $\tau(D, D')$ there exists $\hat{D}'$ s.t. $\hat{\tau}(\hat{D}, \hat{D}')$ and $\langle D', \hat{D}' \rangle \in R$;
- for all $\hat{D}'$ s.t. $\hat{\tau}(\hat{D}, \hat{D}')$ there exists D' s.t. $\tau(D, D')$ and $\langle D', \hat{D}' \rangle \in R$.

Example



Data Abstraction

Bisimilar Kripke Structures (cont.)

Lemma

If $\mathcal{K} \approx_C \hat{\mathcal{K}}$, for every FO-CTL ($\mu$-calc) sentence φ such that const$(\varphi) \subseteq C$,

$$\mathcal{K} \models \varphi \Leftrightarrow \hat{\mathcal{K}} \models \varphi.$$

That is, C-bisimilar Kripke structures cannot be distinguished by FO-CTL formulas using only constants from C. Thus

- If $\hat{\mathcal{K}}$ is finite-state, we are able to check whether $\mathcal{K} \models \varphi$
- (In this case each $\hat{\mathcal{K}}$ transition abstracts infinitely many $\mathcal{K}$-transitions)

Back to the Abstract System

Lemma

Consider a b-bounded $\mathcal{S} = \langle \mathcal{D}, U, D_0, \Phi \rangle$, *and a FO-CTL formula* φ.
Let:

- $\hat{\mathcal{S}}_{b,\varphi} = \langle \mathcal{D}, \hat{U}, D_0, \Phi \rangle$ *be the* (b, φ)*-bounded abstract system of* $\mathcal{S}$
- $\mathcal{K}_b$ *be the model of* $\mathcal{S}$
- $\hat{\mathcal{K}}_{b,\varphi}$ *be the model of* $\hat{\mathcal{S}}_{b,\varphi}$

Then

$$\mathcal{K}_b \approx_{C_{\mathcal{S},\varphi}} \hat{\mathcal{K}}_{b,\varphi}$$

Proof by induction:

- base case: D_0 is $C_{\mathcal{S},\varphi}$-isomorphic wrt itself
- induction step: crux of the result shown above

Given a b-bounded $\mathcal{S}$ and φ,

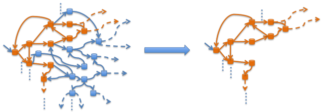
$$\mathcal{K}_b \models \varphi \Leftrightarrow \hat{\mathcal{K}}_{b,\varphi} \models \varphi$$

Application to the General Case

Preservation Theorem

- What if $\mathcal{S}$ is unbounded? (Apart from undecidability)

Observation: for fixed b, the (b,φ)-bounded abstract system $\mathcal{S}_{b,\varphi}$ corresponds to an (infinite) fragment of $\mathcal{S}$



Preservation theorem for the *existential fragment* FO-ECTL.

$$\varphi ::= \phi \mid \varphi \vee \varphi \mid \varphi \wedge \varphi \mid EX\varphi \mid E\varphi\mathcal{U}\varphi$$

Theorem

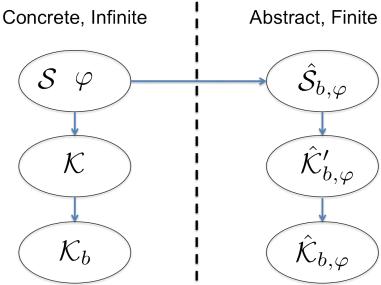
Given $\mathcal{S}$, $b \geq |D_0|$, and a FO-ECTL formula φ, if $\hat{\mathcal{K}}_{b,\varphi} \models \varphi$ then $\mathcal{S} \models \varphi$.

Observe we can iterate on b

Application to Deployed Systems

What if $\mathcal{S}$ is unbounded?

- Actual machines are memory-bounded
- Executed artifact systems cannot exceed the memory bound
- We can verify the artifact system up to a given bound



Technically requires an additional step, but conceptually same approach as for bounded systems

Conclusion

- Problem originating in the context of Business Processes
- Related to verification of database-driven systems (cf. ICDT 09)
- Contribution to scarcely investigated field (verification of processes in presence of data)
- Abstraction-based approach to bounded verification
  - Decidability
  - Actual technique, complete wrt bounded version
  - Practically relevant: any system runs on an actual, memory-bounded machine
- Partial solution to general case:
  - satisfied FO-ECTL properties preserved from abstract bounded to concrete unbounded system
- High complexity, but:
  - comparable to similar work (sometime good practical performance)
  - current technique non-optimal, space for improvements
    - e.g., CEGAR [CGL94] applied to the abstract system?

Future Directions

1. Quantification across modal operators (bounded case)
   - $AG\ EF\ \forall x \exists y.P(x,y)$ ✔
   - $AG\ \forall x\ EF \exists y.P(x,y)$? Ongoing
     - ★ Decidabile? We conjecture so! (FO-CTL with active-domain quantification)
     - ★ Complexity? (at least) double exponential
2. Extension to MAS, in the context of Quantified Interpreted Systems [BL09, BLP11]
   - Agents capture the actors that execute the actions
   - Epistemic operators: K (Ongoing), C, D
   - Requires intensional specification of the accessibility relation ✔
3. Unbounded systems: what for formulas practically relevant?

Questions?

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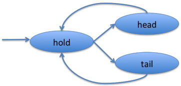
In *Proc. of ICDT*, 2009.

Alin Deutsch, Liying Sui, and Victor Vianu.
Specification and Verification of Data-Driven Web Applications.
J. Comput. Syst. Sci., 73(3):442–474, 2007.

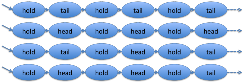
Model Checking

In one slide

Problem: check wether a finite-state *transition-system* satisfies a *temporal* specification[CGP00]

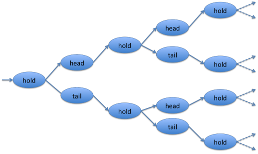


Linear-time: the system defines (infinite-length) runs



E.g., LTL: $\Box\Diamond hold$, $\neg\Box\Diamond tail$

Branching-time: the system defines an (infinite-depth) tree



E.g., CTL: $AG(hold \rightarrow EX(head) \wedge EX(tail))$

Model Checking

(Well... two!)

Model Checking for *finite systems* is very well understood

The main challenge is *efficiency*, not decidability.

- CTL:
  - Check whether the property holds over the generated tree
  - PTIME-complete
- LTL:
  - Check whether the property holds over the generated runs
  - PSPACE-complete
- CTL*:
  - Mixes the above
  - PSPACE-complete