Data-aware Processes: Modeling, Mining, and Verification

Part 3: Verification

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Outline

1. Formal verification
2. Verification for Data-Centric Dynamic Systems
3. Conclusions

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Outline

Why formal verification?

Errors in computerized systems can be costly.

Pentium chip (1994)

Bug found in FPU. Intel offers to replace faulty chips.

Estimated loss: 475m $

Ariane 5 (1996)

Esploded 37secs after launch. Cause: uncaught overflow exception.

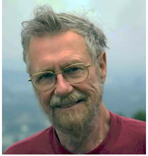
Toyota Prius (2010)

Software “glitch” found in anti-lock braking system.

185,000 cars recalled.

Why verify?

“Testing can only show the presence of errors, not their absence.” [Edgar Dijkstra]



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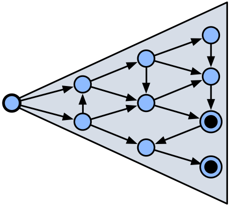
Verification via model checking

Verification via model checking

Process control-flow

Finite-state transition system



$\models \Phi$

Propositional temporal formula

(Un)desired property

[2007 Turing Award: Clarke, Emerson, Sifakis]

Model checking technology requires the transition system to be finite.

Business process analysis

In BPM, **process model analysis** is considered the second most influential topic in the last decade (after process modeling languages) [Aalst 2012].

However:

- Data has been abstracted away.
- Emphasis has been on the control-flow dimension:
  $\leadsto$ sophisticated techniques for absence of deadlocks, boundedness, soundness, or domain-dependent properties expressed in LTL or CTL.

Basic assumption: control-flow is captured by a (possibly infinite-state) propositional labeled transition system,

- labels represent the process tasks/activities
- concurrency is represented by interleaving
- transition system usually not represented explicitly, but is implicitly "folded" into a Petri net

Verification of Petri nets

Verification of Petri nets:

- Undecidable in general [Esparza 1997, 1998].
- Decidable for safe/bounded nets (transition graph is finite-state).

No satisfactory solution for specification and analysis of data-aware processes:

- Colored Petri nets not suited to represent a DB:
  - Data are variables associated to tokens.
  - Data are manipulated by procedural attachments to the transition in the net $\rightsquigarrow$ Cannot be analyzed!
- BPMN (OMG standard) and BPEL (OASIS standard) suffer from similar problems:
  - They leave connection between data and process unspecified (e.g., do not capture atomic task behaviour).
  - Hence, require to attach a program to every BPMN atomic task or BPEL service.

Impact of data on verification

The presence of data complicates verification significantly:

- **States** must be **modeled relationally** rather than propositionally.
- The resulting transition system is typically **infinite state**.
- Query languages for analysis need to combine two dimensions:
  - a temporal dimension to query the process execution flow, and
  - a first-order dimension to query the data present in the relational structures.

  $\leadsto$ We need **first-order variants of temporal logics**.

Model checking data-aware processes becomes immediately undecidable!

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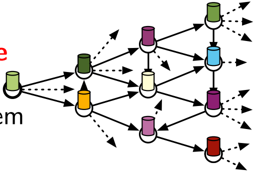
Formal verification of data-aware processes

Process + Data

↓

Infinite-state relational transition system



$\models \Phi$

First-order temporal formula

?

↑

(Un)desired property

Standard model checking technology fails!

Why first-order temporal logics

- To inspect data: **FO queries**
- To capture system dynamics: **temporal modalities**
- To track the evolution of objects: FO **quantification across** states

Example:

It is always the case that every order is eventually either cancelled or paid.

$$\mathbf{G}(\forall x.Order(x) \rightarrow \mathbf{F}(State(x, \texttt{cancelled}) \vee State(x, \texttt{paid})))$$

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Finding the right balance

How can we mediate between:

- the form of data-aware processes, and
- the expressiveness of the temporal property language

such that

1. we are able to capture notable, real-world scenarios, but
2. verification stays decidable, and possibly efficient.

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Dimensions of the verification problem space

We can consider variations of the verification problem that differ along various dimensions:

1. Static information model
2. Dynamic component
3. Interaction between static and dynamic component
4. Interaction with environment
5. Verification task / language

The richness of the problem space has brought about a great variety of approaches and results, and it is **difficult to** compare them and **get a comprehensive picture**.

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Dim. 1: Static information model

- Propositional symbols $\rightsquigarrow$ Finite state system
- Fixed number of values from an unbounded domain
- Full-fledged database:
  - relational database
  - tree-structured data, XML
  - graph-structured data

Moreover:

- Presence or absence of constraints, and how they are considered
- Data under incomplete information
  - ontology (with intensional part usually assumed to be fixed)
  - full-fledged ontology-based data access system

Dim. 2: Dynamic component

- Implicit representation of time vs. implicit progression mechanism vs. explicit process
- When an explicit process is present:
  - how is the process dynamics represented?
  - procedural vs. declarative approaches (e.g., finite state machines vs. rule-based)
- Deterministic vs. non-deterministic behaviour
- Linear time vs. branching time model
- Finite vs. infinite traces

Dim. 3: Interaction between structure and dynamics

- Data is only accessed, but not modified
- No new values are inserted
- Full-fledged combination of the temporal and structural dimensions
- Restrictions play an important role:
    - restricted forms of querying the data
    - restricted quantification across time

Dim. 4: Interaction with environment

- Bounded vs. unbounded input
- Synchronous vs. asynchronous communication
  - message passing, possibly with queues
  - one-way or two-way service calls
- Which components are assumed fixed, and which may vary over time:
  - fixed database vs. varying database vs. varying portion of data
- Multiple devices/agents interacting with each other

Dim. 5: Verification task / language

Type of verification:

- Verification of specific temporal properties, e.g., reachability, absence of deadlock, boundedness, (weak) soundness, ...
- Verification of arbitrary formulas specified in some temporal logic
- Checking of properties with queries across the temporal dimension (in the style of temporal DBs)
- Different forms of verification / analysis:
  - dominance, simulation, containment, equivalence
  - synthesis from a given specification
  - composition of available components

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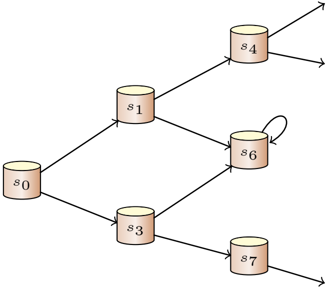
Semantics of DCDSs via transition systems

Semantics of a DCDS $\mathcal{S}$ is given in terms of a **transition system** $\Upsilon_{\mathcal{S}}$:

- each state of $\Upsilon_{\mathcal{S}}$ has an associated DB over a common schema;
- the initial state is associated to the initial DB of the DCDS.



Note: $\Upsilon_{\mathcal{S}}$ is in general **infinite state**:

- infinite branching, due to the results of service calls,
- infinite runs, since infinitely many DBs may occur along a run;
- the DBs associated to the states are of unbounded size.

Verification for DCDSs

We are interested in the **verification** of temporal properties over $\Upsilon_{\mathcal{S}}$.

Idea to overcome infiniteness:

1. Devise a **finite-state** transition system $\Theta_{\mathcal{S}}$ that is a **faithful abstraction** of $\Upsilon_{\mathcal{S}}$ **independent of the formula** to verify.
2. Reduce the verification problem $\Upsilon_{\mathcal{S}} \models \Phi$ to the verification of $\Theta_{\mathcal{S}} \models \Phi$.

Problem: Verification of DCDSs is undecidable even for propositional reachability properties.
$\leadsto$ We need to pose restrictions on DCDSs.

We could draw inspiration from chase termination for tuple-generating dependencies in data exchange, and specifically from weak-acyclicity.

Restrictions on DCDSs

Run-bounded DCDS

Runs cannot accumulate more than a fixed number of different values.

- Transition system is still infinite-state due to infinite branching.
- This is a semantic condition, whose checking is undecidable.
  $\leadsto$ Sufficient syntactic condition: Weak-acyclicity.
- Run-boundedness is very restrictive for DCDSs with nondeterministic services.

State-bounded DCDS

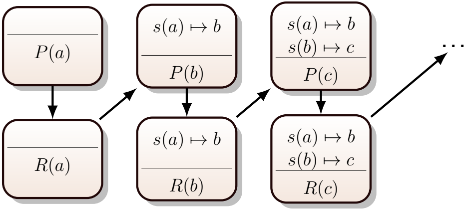
States cannot contain more than a fixed number of different values.

- Relaxation of run-boundedness.
- Infinite runs are possible.
- This is a semantic condition, whose checking is undecidable.
  $\leadsto$ Sufficient syntactic condition: e.g., GR-acyclicity.

Weak-acyclicity [Fagin et al. 2005]

$\mathcal{I}_0 = \{P(a)\}$

$$\alpha : \begin{cases} P(x) \rightsquigarrow R(x), \\ R(x) \rightsquigarrow P(s(x)) \end{cases}$$



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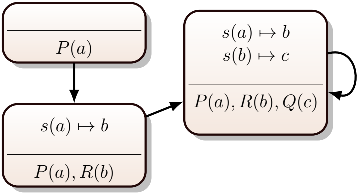
$$\alpha : \begin{cases} P(x) \rightsquigarrow P(x), \\ P(x) \rightsquigarrow R(s(x)) \\ R(x) \rightsquigarrow Q(s(x)) \end{cases}$$



(We consider s to be a deterministic service.)

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Weak-acyclicity [Fagin et al. 2005]

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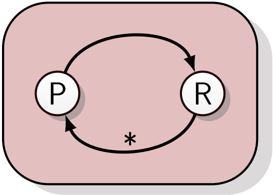

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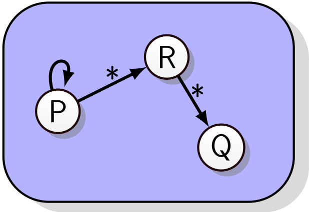

(We consider s to be a deterministic service.)

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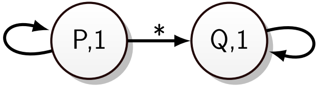
GR-acyclicity [Bagheri Hariri et al. 2013]

Example

Consider a DCDS with process $\{\text{true} \mapsto \alpha()\}$, a non-deterministic service s, and

$$\alpha() : \left\{ \begin{array}{l} P(x) \rightsquigarrow P(x) \\ P(x) \rightsquigarrow Q(s(x)) \\ Q(x) \rightsquigarrow Q(x) \end{array} \right\}$$

We approximate the DCDS data-flow through a **dependency graph**.



The system is **not** state-bounded, due to:

- a generate cycle that continuously feeds a path issuing service calls;
- a recall cycle that accumulates the obtained results;
- (+ the fact that both cycles are simultaneously active).

GR-acycliclity detects exactly these undesired situations.

Verification formalisms for DCDSs

Boundedness is not sufficient for decidability.
We introduce two extensions of the modal μ-calculus $\mu\mathcal{L}$ / LTL with **restricted** forms of first order quantification.

History-Preserving quantification: $\mu\mathcal{L}_A$ / LTL-FO$_A$

FO quantification ranges over current active domain only.

Examples:

LTL-FO$_A$: $\forall x.\textsc{live}(x) \wedge \mathsf{Customer}(x) \rightarrow \mathbf{F}\ \mathsf{Gold}(x)$

$\mu\mathcal{L}_A$: $\forall x.\textsc{live}(x) \wedge \mathsf{Customer}(x) \rightarrow \mu Z.\mathsf{Gold}(x) \vee [-]Z$

Persistence-Preserving quantification: $\mu\mathcal{L}_P$ / LTL-FO$_P$

FO quantification ranges over persisting individuals only.

Examples:

LTL-FO$_P$: $\forall x.\textsc{live}(x) \wedge \mathsf{Gold}(x) \rightarrow \mathbf{G}\ \mathsf{Gold}(x)$

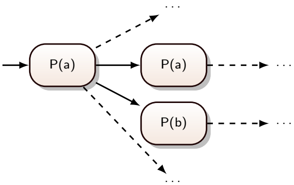
$\mu\mathcal{L}_P$: $\forall x.\textsc{live}(x) \wedge \mathsf{Gold}(x) \rightarrow \nu Z.\mathsf{Gold}(x) \wedge \textsc{live}(x) \wedge [-]Z$

$\mu\mathcal{L}_{FO}$/LTL-FO
↑
$\mu\mathcal{L}_A$/LTL-FO$_A$
↑
$\mu\mathcal{L}_P$/LTL-FO$_P$
↑
$\mu\mathcal{L}$
↑
LTL

Towards decidability

We need to tame the two sources of infinity in DCDSs:

- infinite branching, due to external input;
- infinite runs, i.e., runs visiting infinitely many DBs.



To prove decidability of model checking for a specific restriction and a specific verification formalism:

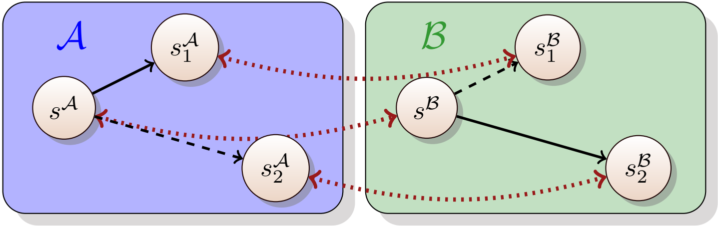
- We use bisimulation as a tool.
- We show that restricted DCDSs have a finite-state bisimilar transition system.

Bisimulation between transition systems

States $s^{\mathcal{A}}$ and $s^{\mathcal{B}}$ of transition systems $\mathcal{A}$ and $\mathcal{B}$ are bisimilar if:

1. $s^{\mathcal{A}}$ and $s^{\mathcal{B}}$ are isomorphic;
2. If there exists a state $s_1^{\mathcal{A}}$ of $\mathcal{A}$ such that $s^{\mathcal{A}} \Rightarrow_{\mathcal{A}} s_1^{\mathcal{A}}$, then there exists a state $s_1^{\mathcal{B}}$ of $\mathcal{B}$ such that $s^{\mathcal{B}} \Rightarrow_{\mathcal{B}} s_1^{\mathcal{B}}$, and $s_1^{\mathcal{A}}$ and $s_1^{\mathcal{B}}$ are bisimilar;
3. The other direction!

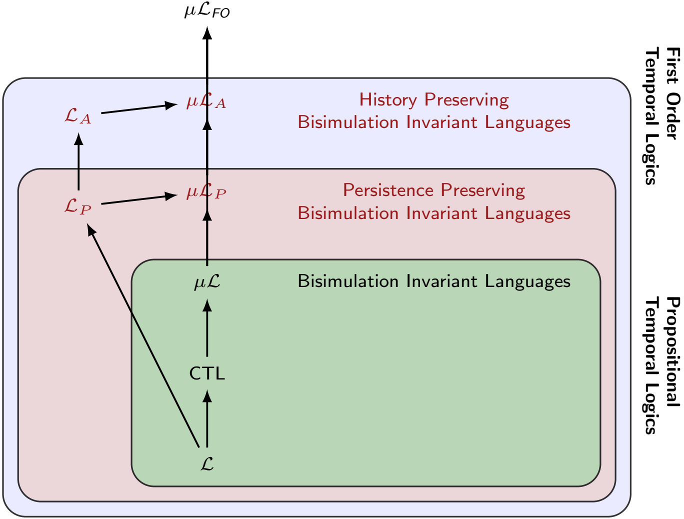
$\mathcal{A}$ and $\mathcal{B}$ are bisimilar, if their initial states are bisimilar.



$\mu\mathcal{L}$ invariance property of bisimulation:

Bisimilar transition systems satisfy the same set of $\mu\mathcal{L}$ properties.

Adapting the notion of bisimulation



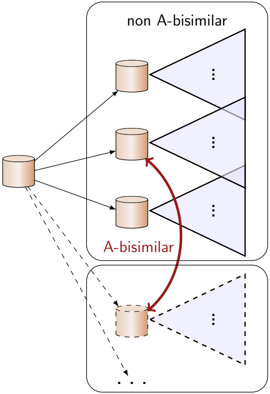
Decidability of $\mu\mathcal{L}$ extensions for run-bounded systems

Theorem

Verification of $\mu\mathcal{L}_A$ over run-bounded DCDSs is decidable and can be reduced to model checking of propositional μ-calculus over a finite transition system.

Idea: use **isomorphic types** instead of actual values.

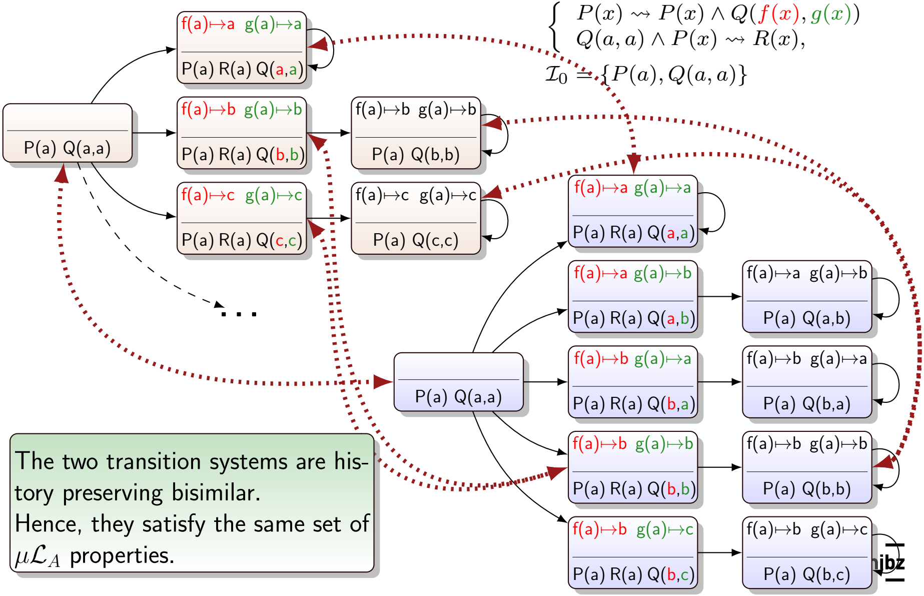
Remember: runs are bounded!



History preserving bisimulation

$$\begin{cases} P(x) \rightsquigarrow P(x) \land Q(f(x), g(x)) \\ Q(a,a) \land P(x) \rightsquigarrow R(x), \end{cases}$$

$$\mathcal{I}_0 = \{P(a), Q(a,a)\}$$



The two transition systems are history preserving bisimilar.
Hence, they satisfy the same set of $\mu\mathcal{L}_A$ properties.

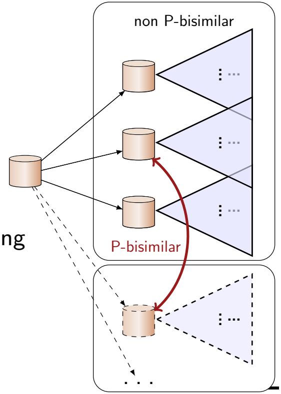
Decidability of $\mu\mathcal{L}$ extensions for state-bounded systems

Theorem

Verification of $\mu\mathcal{L}_P$ over state-bounded DCDSs is decidable and can be reduced to model checking of propositional μ-calculus over a finite transition system.

Steps:

1. **Prune** infinite branching (isomorphic types).
2. Finite abstraction along the runs:
   - $\mu\mathcal{L}_P$ looses track of previous values that do not exist anymore.
   - New values can be replaced with old, non-persisting ones.
   - This eventually leads to **recycle** the old values without generating new ones.



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What about LTL-FO?

For verification of LTL-FO over DCDSs, analogous decidability results hold:

Theorem

Verification of LTL-FO$_A$ over run-bounded DCDSs, and
LTL-FO$_P$ over state-bounded DCDSs
are decidable and can be reduced to model checking of propositional LTL over a finite transition system.

Moreover:

Theorem

Verification of LTL-FO$_A$ over state-bounded DCDSs is undecidable.

Intuition: LTL-FO$_A$ can arbitrarily quantify over the infinitely many values encountered during a single run, and start comparing them.

Proof is based on a reduction from satisfiability of LTL with freeze quantifiers over infinite data words.

And verification of $\mu\mathcal{L}_A$ over state-bounded DCDSs?

Well-known

Propositional LTL can be expressed in $\mu\mathcal{L}$, i.e., the propositional μ-calculus.

Folklore "theorem" (see, e.g., [Okamoto 2010])

This correspondence carries over to the FO-variants, i.e., LTL-FO can be expressed in $\mu\mathcal{L}_{FO}$.

Note: This, together with the undecidability of LTL-FO_A verification over state-bounded DCDSs, would imply that also:

Verification of $\mu\mathcal{L}_A$ over state-bounded DCDSs is undecidable.

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Verification of $\mu\mathcal{L}_{FO}$ over state-bounded DCDSs

Instead, the following positive result holds:

Theorem

Verification of $\mu\mathcal{L}_{FO}$ (and hence $\mu\mathcal{L}_{A}$) over state-bounded DCDSs is decidable.

Relies on the fact that DCDSs generate transition systems that are **generic**:

- Intuitively, if a state s has a successor state s' with fresh values $\vec{v}$, then it has also all successor states that are obtained from s' by varying in all possible ways the fresh values $\vec{v}$.
- This is a consequence of the fact that the progression mechanism is defined by means of a logical specification.

Lemma

- For generic TSs (with infinite domain), persistence-preserving bisimilarity and bisimilarity (and hence history-preserving bisimilarity) coincide.
- For TSs of state-bounded DCDSs, we can devise finite state abstractions that are faithful for $\mu\mathcal{L}_{FO}$ formulas (although such abstractions may depend on the formula).

Genericity

We consider isomorphisms $\sim_h$ between interpretations, where h is a bijection between the interpretation domains that preserves relations and constants.

Generic transition system

A TS Υ with domain Δ is **generic** if for all states s_1, s_2 and every bijection $h : \Delta \mapsto \Delta$, if $\mathcal{I}(s_1) \sim_h \mathcal{I}(s_2)$ and there exists s'_1 s.t. $s_1 \to s'_1$, then there exists s'_2 s.t. $s_2 \to s'_2$ and $\mathcal{I}(s'_1) \sim_h \mathcal{I}(s'_2)$.

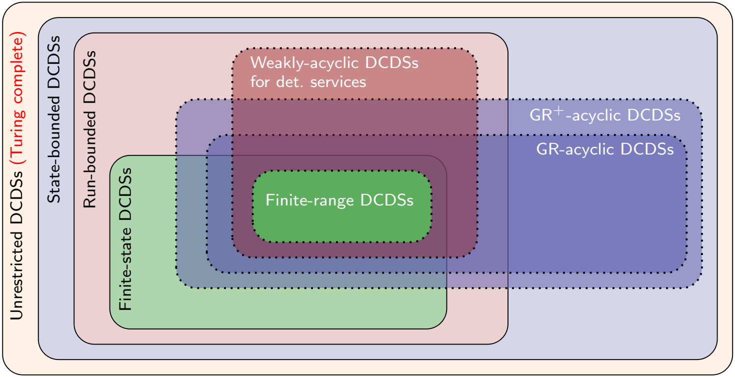
Note: s_1 and s_2 can be the same state, hence the existence of a successor state induces the existence of all successor states isomorphic to it.

DCDS enjoy genericity since:

- The progression mechanism is defined by means of a logical specification.
- In particular, the semantics of service calls induces the existence of a successor state for each combination of values returned by the service calls.

It follows that **successor states are "indistinguishable"** from each other, modulo isomorphisms on the results of service calls.

Results on decidability of verification for DCDSs



	Unrestricted	State-bounded	Run-bounded	Finite-state
LTL-FO / $\mu\mathcal{L}_{FO}$	**U**	**U** / **N**	? / **N**	**D**
LTL-FO$_A$ / $\mu\mathcal{L}_A$	**U**	**U** / **N**	**D**	**D**
LTL-FO$_P$ / $\mu\mathcal{L}_P$	**U**	**D**	**D**	**D**
LTL / $\mu\mathcal{L}$	**U**	**D**	**D**	**D**

D: decidable **U**: undecidable **N**: decidable, but no finite abstraction

Outline

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Conclusions

- There is a huge amount of work carried out in database theory that is relevant to data-aware process analysis, using a plethora of techniques.
- The problem space has several dimensions that partly interact.
  $\leadsto$ Thorough systematization of the area is still missing.
- Many of the works are based on specific restrictions and assumptions that make them difficult to compare.
- Moreover, the positive results appear rather fragile.
- Analysis techniques are typically exponential in those data that "change"
  $\leadsto$ Circumscribing what can be changed is a key point.
- The assumptions would need validation also from the practical and business perspective.
  $\leadsto$ Requires making frameworks more robust.
- Some of the techniques are borrowed from different fields, although underlying assumptions and objectives might be different.
  $\leadsto$ Basic assumptions need to be reassessed.

Acknowledgements

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Thank you for your attention!

References I

[1] Wil M. P. van der Aalst. "A Decade of Business Process Management Conferences: Personal Reflections on a Developing Discipline". In: *Proc. of the 10th Int. Conf. on Business Process Management (BPM)*. Vol. 7481. Lecture Notes in Computer Science. Springer, 2012, pp. 1–16.

[2] Javier Esparza. "Decidability of Model Checking for Infinite-State Concurrent Systems". In: *Acta Informatica* 34.2 (1997), pp. 85–107.

[3] Javier Esparza. "Decidability and Complexity of Petri Net Problems – An Introduction". In: *Lectures on Petri Nets I*. Lecture Notes in Computer Science. Springer, 1998, pp. 374–428.

[4] Ronald Fagin et al. "Data Exchange: Semantics and Query Answering". In: *Theoretical Computer Science* 336.1 (2005), pp. 89–124.

[5] Babak Bagheri Hariri et al. "Verification of Relational Data-Centric Dynamic Systems with External Services". In: *Proc. of the 32nd ACM SIGACT SIGMOD SIGAI Symp. on Principles of Database Systems (PODS)*. 2013.

References II

[6] Keishi Okamoto. "Comparing Expressiveness of First-Order Modal μ-calculus and First-Order CTL*". In: *RIMS Kokyuroku* 1708 (2010), pp. 1–14.