LTL$_f$-based Trace Alignment: a Planning-based Approach

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Process Mining

Process Mining: analysis of (business) processes starting from *event logs* [van der Aalst, 2016]

Event Log

Events model process activities:

a =register request, b =examine thoroughly

c =examine casually, d = check ticket

e =decide, f =reinitiate request,

g =pay compensation, h =reject request

Traces: event sequences modeling a process run

1. a, b, d, e, h
2. a, d, c, e, h
3. $a, c, d, e, f, b, d, e, g$
4. a, d, b, e, h

...

Event Log: set of traces

case id	event id	properties		
		timestamp	activity	resource
1	35654423	30-12-2010:11.02	register request	Pete
	35654424	31-12-2010:10.06	examine thoroughly	Sue
	35654425	05-01-2011:15.12	check ticket	Mike
	35654426	06-01-2011:11.18	decide	Sara
	35654427	07-01-2011:14.24	reject request	Pete
2	35654483	30-12-2010:11.32	register request	Mike
	35654485	30-12-2010:12.12	check ticket	Mike
	35654487	30-12-2010:14.16	examine casually	Pete
	35654488	05-01-2011:11.22	decide	Sara
	35654489	08-01-2011:12.05	pay compensation	Ellen
3	35654521	30-12-2010:14.32	register request	Pete
	35654522	30-12-2010:15.06	examine casually	Mike
	35654524	30-12-2010:16.34	check ticket	Ellen
	35654525	06-01-2011:09.18	decide	Sara
	35654526	06-01-2011:12.18	reinitiate request	Sara
	35654527	06-01-2011:13.06	examine thoroughly	Sean
	35654530	08-01-2011:11.43	check ticket	Pete
	35654531	09-01-2011:09.55	decide	Sara
	35654533	15-01-2011:10.45	pay compensation	Ellen
4	35654641	06-01-2011:15.02	register request	Pete
	35654643	07-01-2011:12.06	check ticket	Mike
	35654644	08-01-2011:14.43	examine thoroughly	Sean
	35654645	09-01-2011:12.02	decide	Sara
	35654647	12-01-2011:15.44	reject request	Ellen

Problems in Process Mining

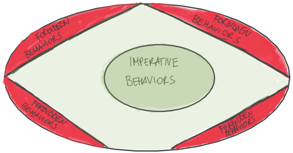
Typical problems in Process Mining:

- Process Discovery: discover the underlying process that produced the log [Cook and Wolf, 1995]
- Conformance Checking: check whether a log conforms to a given process model [Rozinat and van der Aalst, 2008]
- Monitoring: monitor the current trace wrt a given process model [Ly et al., 2013]

Declarative Process Mining

Imperative Process Model

- Prescriptive specification
- Process fully specified
- Common Models:
  - Petri Net
  - Finite-state automaton
  - BPMN
  - ...



Declarative Process Model

- Descriptive specification
- Behaviors subject to constraints
- Behaviors allowed unless violating
- Constraints expressed in:
  - DECLARE [Pesic et al., 2007]
  - $\text{LTL}_f/\text{LDL}_f$ [De Giacomo and Vardi, 2013]

Declarative Process Mining (this talk): Event Log + Declarative Process Model

Trace Alignment

Trace Alignment is a form of Conformance Checking

- Traces often *dirty* (involve human activities)
  - *spurious* or *missing* events
  - in general, *discrepancies* may be present
- Process model not enforced

Trace Alignment

Trace Alignment is the problem of *cleaning* and *repairing* dirty traces to make them compliant with the underlying process model [van der Aalst, 2016]

Solving the problem allows for:

- Identifying trace errors
- Taking corrective actions
- Measuring deviation wrt process model

Trace Alignment (in Declarative Process Mining)

Trace Alignment [Bose and van der Aalst, 2010] (declarative variant)

Given:

- A trace ρ over a finite event alphabet $\Sigma = \{\sigma_1, \ldots, \sigma_n\}$
- A constraint φ (expressed in some formal language, see below)
- A cost function *cost* associating non-negative costs to *additions* and *deletions* of each event

Find trace ρ' over Σ s.t.:

- ρ' satisfies φ, written $\rho \models \varphi$
- Cost $cost(\rho, \rho')$ of turning ρ into ρ' is minimal (wrt the cost of changes made to ρ)

Trace Alignment (in Declarative Process Mining)

Example

- $\rho = a\ a\ c\ b\ a\ c\ a$
- $\varphi =$ "whenever a occurs, b eventually occurs after a"
- all changes cost 1

- ρ does not satisfy φ (last a has no matching b)
  1. Remove all a's: $\rho_1 = a\ a\ c\ b\ a\ c\ a = c\ b\ c$, $cost(\rho, \rho_1) = 4$
  2. Add b after every a: $\rho_2 = a\ b\ a\ b\ c\ b\ a\ b\ c\ a\ b$, $cost(\rho, \rho_1) = 4$
  3. Add b at end only: $\rho_3 = a\ a\ c\ b\ a\ c\ a\ b$, $cost(\rho, \rho_1) = 1$ (solution!)

Observations:

- if φ satisfiable, repaired trace always exists
- we can think of $cost(\rho, \rho')$ as the distance of ρ from φ (if $\rho' \models \varphi$)

Applications

Some uses of trace alignment in BP:

- Check whether expected process is correctly executed and quantify deviation (costs)
- Identify and correct errors in process execution
- Identify common patterns among log traces

But also in AI:

- Use traces to model agent behaviors (e.g., executed actions)
- Use trace alignment to:
  - compare observed behavior with expected/desired one
  - quantify discrepancies and repair
  - identify behavioral patterns
  - ...

This Talk

1. A technique for trace alignment [De Giacomo et al., 2017]:
   - automata-based approach
   - solved with cost-optimal planning
2. Experimental results
3. (Extension to metric temporal constraints)

Standard language in Declarative PM is DECLARE [Pesic et al., 2007]

Defined through *templates*:

- *Existence*(a): activity a is executed at least once
  $b\ a\ c\ a$, $b\ c\ c$
- *Response*(a, b): if a occurs then b eventually occurs after a
  $a\ c\ a$, $a\ c\ a\ b$, $c\ d\ c$
- *Choice*(a, b): a or b (possibly both) eventually occur
  $a\ c\ a$, $a\ c\ b$, $c\ c\ b$, $d\ c\ c$
- *ChainResponse*(a, b): whenever a occurs, b immediately follows
  $a\ c\ c\ b$, $d\ c\ c$, $d\ a\ b$)
- ...

DECLARE is a fragment of LTL$_f$

LTL$_f$ (linear-time temporal logic over finite traces [De Giacomo and Vardi, 2013])

$\varphi := \mathit{true} \mid a \mid \neg\varphi \mid \varphi \wedge \varphi \mid \mathbf{X}\varphi \mid \varphi \mathbf{U} \varphi$

- $\mathbf{X}\varphi$ ("next φ"): next event satisfies φ
- $\varphi_1 \mathbf{U} \varphi_2$ ("φ_1 until φ_2"): an event satisfying φ_2 eventually occurs (possibly now) and all events until then satisfy φ_1

Standard abbreviations (Boolean as usual):

- $\mathbf{F}\varphi \doteq \mathit{true}\mathbf{U}\varphi$ ("eventually φ"): φ eventually holds
- $\mathbf{G}\varphi \doteq \neg\mathbf{F}\neg\varphi$ ("always φ"): φ always holds

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Some examples

DECLARE template	LTL$_f$ translation
Existence(a)	$\mathbf{F}a$
Response(a, b)	$\mathbf{G}(a \rightarrow \mathbf{F}b)$
Choice(a, b)	$\mathbf{F}a \vee \mathbf{F}b$
ChainResponse(a, b)	$\mathbf{G}(a \rightarrow \mathbf{X}b)$

We use full LTL$_f$ (in fact, could go even beyond and use LDL$_f$)

Trace Alignment with LTL_f Constraints

Example

- $\rho = a \; a \; c \; b \; a \; c \; a$
- $\varphi = \mathbf{G}(a \rightarrow \mathbf{F} b)$ ("whenever a occurs, b eventually occurs after a")
- ...

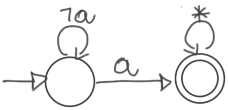
LTL$_f$ Formulas as NFAs

Theorem ([De Giacomo and Vardi, 2013])

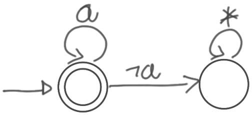
Every LTL$_f$ formula φ has a corresponding (exponential) NFA $\mathcal{A}_\varphi$ s.t.

$$\textit{for every trace } \rho : \ \rho \models \varphi \Leftrightarrow \ \mathcal{A}_\varphi \textit{ accepts } \rho$$

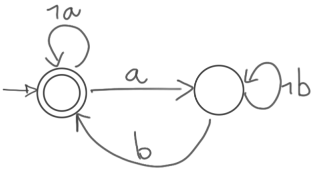
$\varphi = \mathbf{F}a$



$\varphi = \mathbf{G}a$



$\varphi = \mathbf{G}(a \rightarrow \mathbf{F}b)$



Given:

- trace ρ
- constraint φ (one, w.l.o.g.)

Define:

- *Augmented trace automaton* $\mathcal{T}^+$: accepts all modifications of ρ
- *Augmented constraint automaton* $\mathcal{A}^+$:
  accepts all traces that satisfy φ **plus** all modifications of ρ that satisfy φ

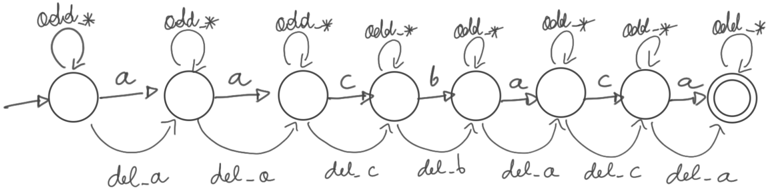
Find miminal-cost ρ' s.t.:

- ρ' is accepted by $\mathcal{T}^+$
- ρ' is accepted by $\mathcal{A}^+$

Augmented trace automaton $\mathcal{T}^+$

Example:

- $\rho = a\ a\ c\ b\ a\ c\ a$



Accepts all modifications of ρ, with changes **marked**, e.g.:

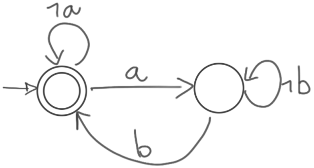
1. Remove all a's: $del\_a\ del\_a\ c\ b\ del\_a\ c\ del\_a$
2. Add b after every a: $a\ add\_b\ a\ add\_b\ c\ b\ a\ add\_b\ c\ a\ add\_b$
3. Add b at end only: $a\ a\ c\ b\ a\ c\ a\ add\_b$

Augmented constraint automaton $\mathcal{A}^+$

Example:

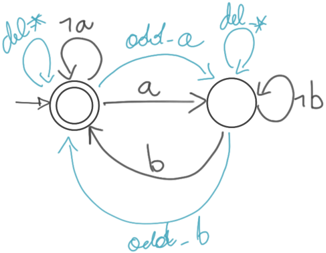
- $\varphi = \mathbf{G}(a \rightarrow \mathbf{F}b)$("whenever a occurs, b eventually occurs after a")

Plain Constraint Automaton



$\Longrightarrow$

Augmented Constraint automaton



Observe: accepts also traces that are not modifications of ρ

Automata-based Solution

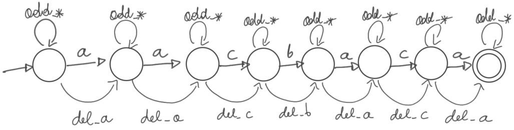
Problem

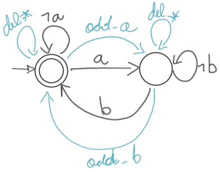
Find **miminal-cost** ρ' s.t.:

- ρ' is accepted by $\mathcal{T}^+$, i.e., changes wrt ρ are marked by adds and dels
- ρ' is accepted by $\mathcal{A}^+$, i.e., ρ' "repairs" ρ

Corresponds to finding minimal-cost accepting path ρ' on product automaton $\mathcal{T}^+ \times \mathcal{A}^+$

- $\rho = a\ a\ c\ b\ a\ c\ a$, $\varphi = \mathbf{G}(a \rightarrow \mathbf{F}b)$
- $\rho' = a\ a\ c\ b\ a\ c\ a\ add\_b$





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Theorem

Trace alignment can be solved in time polynomial wrt $|\rho| \times 2^{|\varphi|}$

- *Searching min-cost path in* $\mathcal{T}^+ \times \mathcal{A}^+$*:* $\mathcal{O}(N \log N)$*, with* $N = |\mathcal{T}^+ \times \mathcal{A}^+| = |\mathcal{T}^+| \times |\mathcal{A}^+|$
- $|\mathcal{T}^+| = \mathcal{O}(|\rho|)$*, time:* $\mathcal{O}(|\rho|)$
- $|\mathcal{A}_\varphi| = \mathcal{O}(2^{|\varphi|})$*, time:* $\mathcal{O}(2^{|\varphi|})$
- $|\mathcal{A}^+|$*:* $\mathcal{O}(|\mathcal{A}_\varphi|)$*, time:* $\mathcal{O}(|\mathcal{A}_\varphi|)$

Trace alignment as minimal-cost planning

Use planning to search for minimal-cost ρ'

- Domain:
  - Models product automaton $\mathcal{T}^+ \times \mathcal{A}^+$
  - *sync* actions with null cost model events
  - *add* and *del* actions with positive costs model changes to input trace
  - Dynamics model *synchronous* execution of all augmented automata (trace+constraints)
- Problem:
  - Initial state: all automata in their starting state
  - Goal: all automata in a final state
- Solution:
  - Minimal-cost goal-reaching sequence of actions

Trace alignment as minimal-cost planning

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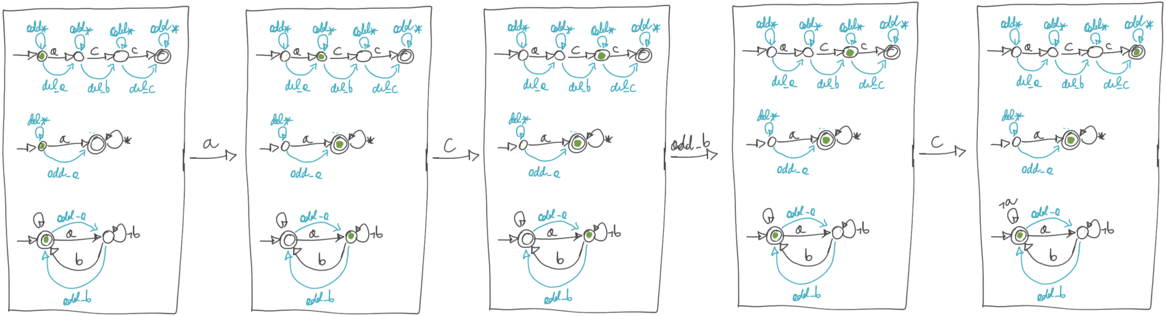
Use planning to search for minimal-cost ρ'

- Actions with costs model events and changes to ρ
- Adds and dels have (possibly different) positive cost
- Augmented automata (trace and constraints) modeled by domain
- Solution: sequence of actions that takes all automata to accepting state

TASK: find minimal-cost plan

- $\rho = a\ c\ c$
- $\varphi_1 = \mathbf{F} a$
- $\varphi_2 = \mathbf{G}(a \rightarrow \mathbf{F} b)$
- $\rho' = a\ c\ add\_b\ c$



Solving trace alignment with planning

The problem can be encoded in PDDL 2.1 [Fox and Long, 2003]

```
(define (domain alignment)
    (:requirements :typing :disjunctive-preconditions :conditional-effects
    :universal-preconditions :action-costs)
    (:types trace_state automaton_state - state activity)
    (:predicates
        (trace ?t1 - trace_state ?e - activity ?t2 - trace_state)
        (cur_state ?s - state)
        (automaton ?s1 - automaton_state ?e - activity ?s2 - automaton_state)
        (final_state ?s - state)
    )
    (:functions total-cost)
```

```
(:action add
    :parameters (?e - activity)
    :effect (and
                (increase (total-cost) 1)
                (forall (?s1 ?s2 - automaton_state)
                    (when (and (cur_state ?s1) (automaton ?s1 ?e ?s2))
                        (and (not (cur_state ?s1))(cur_state ?s2)))
                )
            )
)
```

```
(:action sync
    :parameters (?t1 - trace_state ?e - activity ?t2 - trace_state)
    :precondition (and (cur_state ?t1)(trace ?t1 ?e ?t2))
    :effect(and
                (not (cur_state ?t1))
                (cur_state ?t2)
                (forall (?s1 ?s2 - automaton_state)
                    (when (and (cur_state ?s1) (automaton ?s1 ?e ?s2))
                        (and (not (cur_state ?s1))(cur_state ?s2)))
                )
            )
)
```

```
(:action del
    :parameters (?t1 - trace_state ?e - activity ?t2 - trace_state)
    :precondition (and (cur_state ?t1)(trace ?t1 ?e ?t2))
    :effect(and
                (increase (total-cost) 1)
                (not (cur_state ?t1)) (cur_state ?t2)
            )
)
```

Various encodings are possible, huge impact on performance

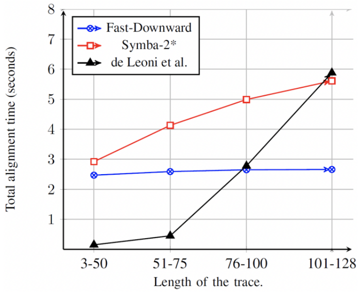
Experiments

- Tested (cost-optimal) planners:
  - Fast-Downward [Helmert, 2006]
  - SymBA* [Torralba et al., 2016]
  - (Assumed unitary costs for adds and dels)
- Compared against
  - Ad-hoc SOA approach implemented in ProM
    [de Leoni and van der Aalst, 2013, de Leoni et al., 2015]
- Dataset
  - Real-life logs (loan application in Dutch financial institute), 16 constraints
  - Synthetic logs with 10, 15 and 20 constraints

Results

planning vs ad-hoc on real-life logs

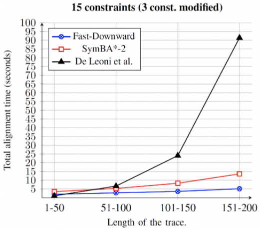
trace length	no. traces	Fast-Downward	SymbA-2*	de Leoni et al.	Alignment Cost
Real-life log		16 constraints			
3-50	607	2.47	2.92	0.15	0.63
51-75	38	2.59	4.13	0.45	1.02
76-100	5	2.65	4.99	2.78	2.4
101-128	4	2.66	5.61	5.88	2.5

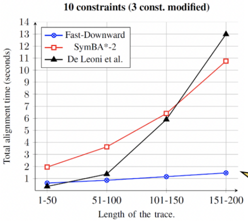


Results

planning vs ad-hoc on synthetic logs

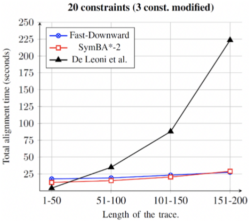
Trace length	Fast-Downward	SymbA-2*	de Leoni et al.	Alignment Cost
3 const. modified	10 constraints			
1-50	0.62	1.95	0.34	1.77
51-100	0.85	3.63	1.37	2.11
101-150	1.15	6.4	5.9	3.03
151-200	1.46	10.75	12.98	3.79
	15 constraints			
1-50	1.97	3.49	1.08	1.71
51-100	2.79	5.3	6.64	2.23
101-150	3.61	8.26	24.05	3.07
151-200	5.12	13.63	91.39	4.2
	20 constraints			
1-50	17.63	12.42	3.99	1.87
51-100	19.05	15.02	34.91	2.61
101-150	23.23	20.45	87.89	3.35
151-200	27.49	28.97	223.47	4.2





Our approach **outperforms** ProM by **several orders of magnitude** when the **model becomes larger** and the **noise increases.**

The ad-hoc approach implemented in ProM is faster only for **short traces** with **little noise.**



Results

1. Automata-based approach implemented with planning technology (available at: `tinyurl.com/glymp9d`)

2. Outperforms ad-hoc solutions
   - More scalable
   - More flexible (other planners can be plugged)

3. PDDL encoding has huge impact, usually little preprocessing required –great benefit

Ongoing Extensions

- Extending the planning-based approach to LDL_f [De Giacomo and Vardi, 2013], i.e., LTL_f with RE
  (as expressive as FSA)

- Testing new encodings

- Decidability of the problem for MTL_f [Koymans, 1990], the time-metric extension of LTL_f (see below)

Timed Trace Alignment

Ongoing

- Timed extension of Trace Alignment
- Conceptually analogous to basic version but:
  - Events have (rational) timestamps
  - Constraints involve metric temporal properties
- Results in a **significantly more challenging** setting

Timed Trace Alignment

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Example

- $\rho = (a, 0)\ (a, 0.7)\ (c, 1.25)\ (a, 2.56)\ (c, 3.04)\ (b, 3.7)$
- $\varphi =$ "whenever a occurs, b eventually occurs within 2 time units (tu)"
- costs as before –no dependence on time
- ρ does not satisfy φ: first two a's have no matching b within 2 tu
  - $(a, 0)\ (a, 0.7)\ (c, 1.25)\ (a, 2.56)\ (c, 3.04)\ (b, 3.7)$

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Metric Temporal Logic (MTL_f)

$\varphi ::= \mathit{true} \mid e \mid \varphi \wedge \varphi \mid \neg\varphi \mid \mathbf{X}_I\varphi \mid \varphi \mathbf{U}_I \varphi$

I: open, closed, or semi-open interval with integer (or ∞) endpoints

- $\mathbf{X}_I\varphi$: next event occurs within interval I and satisfies φ
- $\varphi_1 \mathbf{U}_I \varphi_2$: an event occurs within interval I which satisfies φ_2 and all events until then satisfy φ_1

Standard abbreviations essentially same as LTL_f (but with interval subscripts)

MTL_f captures the timed extension of DECLARE

Timed Constraint Specification

Example

"whenever a occurs, b eventually occurs within 2 time units (tu)":

- $\varphi = \mathbf{G}_{[0,\infty]}(a \rightarrow \mathbf{F}_{[0,2]} b)$

Each MTL_f formula φ admits an automaton accepting the traces that satisfy φ

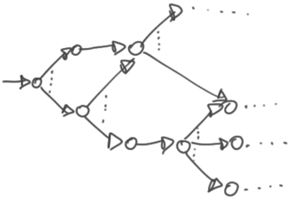
- 1-clock Alternating Timed Automata (1-ATA)
- Unfortunately, 1-ATA induce infinite-state, infinite-branching automata
- Automata-based Approach for NFA not suitable as-is

MTL_f is decidable [Ouaknine and Worrell, 2007]: can check whether trace ρ exists s.t. $\rho \models \varphi$

But: how to search for **optimal** ρ?

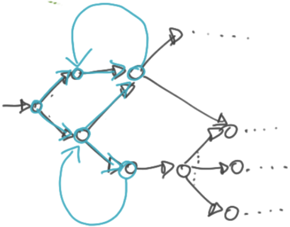
- Main obstacles: state- and branching-infiniteness

From this:



$\Longrightarrow$

To this:



- 1-ATA semantics
- infinite-branching
- infinite-state

- 1-ATA semantics **abstraction**
- finite-branching
- finite-state

Abstraction obtained by combining two results:

- (Computable) Abstraction for MTL_f decidability [Ouaknine and Worrell, 2007]
- Reachability for *well-structured* transition systems [Finkel and Schnoebelen, 2001]

We extended the results to visit the whole (abstract) space of traces

Essentially same approach as for basic version:

- Construct Abstraction of Timed augmented trace 1-ATA
- Construct Abstraction of Timed augmented constraint 1-ATA
- Combine both in a (abstract) Product Automaton
- Search for optimal trace in Product Automaton

Complexity: non-primitive recursive (essentially, non-elementary)

- Formalization as path-search on a 1-ATA
- Problem is solvable
- Complexity: non-primitive recursive ☹

Complexity

Untimed version

Exponential wrt size of constraints

- Constraints typically small
- Behaves well in practice with planning-based approach (worst-case rarely shows up)

Timed version

Non-elementary

- Constraints in practice are small
- Impact in practice? (Future work)
- Examples of tools with non-elem complexity but well-behaving in practice:
  - MONA: non-elementary [Henriksen et al., 1995]
  - Acceptable performance in practice [Zhu et al., 2017]
- (There is hope!)

Conclusions & Future Work

Summing up:

- Problem originated in Declarative Process Mining
- Practical and Speculative Relevance also to AI (Agent Behaviors)
- Two variants considered: untimed and timed
- AI-planning technique provides best results in untimed setting
- Timed setting solvable but practicality to be assessed

Future work:

- Extend untimed version to LDL_f and new PDDL encodings (ongoing)
- Study well-behaved fragments of MTL_f or
  effects of constraints on repairs (e.g., fixed number of adds within two events)
- Implement solution approaches for timed variant (planning-based?)
- Consider data-aware setting (where activities carry a payload) –particularly relevant to KR

Thank you!

Questions?

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