A Survey of Temporal Extensions of DLs

Research school: Foundations and Challenges of Change in Ontologies and Databases 2014
Free University of Bozen-Bolzano, Italy

Group 6:

► Daniele Dell’Aglio
  ▷ DEIB – Politecnico di Milano
  ▷ daniele.dellaglio@polimi.it

► Fariz Darari
  ▷ KRDB – Università di Bolzano
  ▷ fadirra@gmail.com

► Davide Lanti
  ▷ KRDB – Università di Bolzano
  ▷ davide.lanti.sersante@gmail.com

Mentor:

► Michael Zakharyaschev
  ▷ Birkbeck College
What we will see

The paper:


Outline:

- Overview
- Running Example
- A Survey on Existing Solutions
- Current Hot Topics, Future Directions
Outline

► Overview

► Running Example

► A Survey on Existing Solutions
  ▶ State-change based DLs
  ▶ Temporal DLs with internal approach
  ▶ Point-based temporal DLs
  ▶ Interval-based temporal DLs

► Current Hot Topics, Future Directions
Temporal extensions of DLs

➤ How can time be modelled?

▶ Point-based notion of time
▶ Interval-based notion of time

▶ Implicit notion of time: sequences of events through state-change representations
▶ Explicit notion of time: definition of temporal operators and new formulae

➤ Internal point of view: different states of an individual are modelled as different individual components
➤ External point of view: an individual has different states in different moments
Temporal extensions of DLs

- How can time be modelled?
  - Point-based notion of time
  - Interval-based notion of time

Daniele Dell’Aglio, Fariz Darari and Davide Lanti
A Survey of Temporal Extensions of DLs
Temporal extensions of DLs

► How can time be modelled?
  ▶ Point-based notion of time
  ▶ Interval-based notion of time

► How can the temporal dimension be handled?
Temporal extensions of DLs

▶ How can time be modelled?

▷ Point-based notion of time

▷ Interval-based notion of time

▶ How can the temporal dimension be handled?

▷ Implicit notion of time: sequences of events through state-change representations

▷ Explicit notion of time: definition of temporal operators and new formulae
Temporal extensions of DLs

▶ How can time be modelled?

▷ Point-based notion of time

▷ Interval-based notion of time

▶ How can the temporal dimension be handled?

▷ Implicit notion of time: sequences of events through state-change representations

▷ Explicit notion of time: definition of temporal operators and new formulae

► Internal point of view: different states of an individual are modelled as different individual components

► External point of view: an individual has different states in different moments
## Classification of the DL temporal extensions

<table>
<thead>
<tr>
<th></th>
<th>Point-based time</th>
<th>Interval-based time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Implicit time</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Explicit time</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Internal approach</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>External approach</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Classification of the DL temporal extensions

<table>
<thead>
<tr>
<th>Implicit time</th>
<th>Point-based time</th>
<th>Interval-based time</th>
</tr>
</thead>
<tbody>
<tr>
<td>State-change based DLs</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Explicit time Internal approach</th>
<th></th>
<th></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Explicit time External approach</th>
<th></th>
<th></th>
</tr>
</thead>
</table>
## Classification of the DL temporal extensions

<table>
<thead>
<tr>
<th></th>
<th>Point-based time</th>
<th>Interval-based time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Implicit time</strong></td>
<td>State-change based DLs</td>
<td></td>
</tr>
<tr>
<td><strong>Explicit time</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal approach</td>
<td></td>
<td>Temporal DLs with internal approach</td>
</tr>
<tr>
<td><strong>Explicit time</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External approach</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Classification of the DL temporal extensions

<table>
<thead>
<tr>
<th></th>
<th>Point-based time</th>
<th>Interval-based time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implicit time</td>
<td>State-change based DLs</td>
<td></td>
</tr>
<tr>
<td>Explicit time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal approach</td>
<td>Temporal DLs with internal approach</td>
<td></td>
</tr>
<tr>
<td>Explicit time</td>
<td>Point-based temporal DLs</td>
<td></td>
</tr>
<tr>
<td>External approach</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Classification of the DL temporal extensions

<table>
<thead>
<tr>
<th></th>
<th>Point-based time</th>
<th>Interval-based time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Implicit time</strong></td>
<td>State-change based DLs</td>
<td></td>
</tr>
<tr>
<td><strong>Explicit time</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal approach</td>
<td>Temporal DLs with internal approach</td>
<td></td>
</tr>
<tr>
<td>External approach</td>
<td>Point-based temporal DLs</td>
<td>Interval-based temporal DLs</td>
</tr>
</tbody>
</table>
Outline

► Overview

► Running Example

► A Survey on Existing Solutions
  ▶ State-change based DLs
  ▶ Temporal DLs with internal approach
  ▶ Point-based temporal DLs
  ▶ Interval-based temporal DLs

► Current Hot Topics, Future Directions
Running example

- How to become a doctor:
  - Be a PhD student for some years (3-4)
  - Defend a thesis
  - Become a doctor

Let’s try to model it with different temporal logics!
Outline

- Overview
- Running Example
- A Survey on Existing Solutions
  - State-change based DLs
  - Temporal DLs with internal approach
  - Point-based temporal DLs
  - Interval-based temporal DLs
- Current Hot Topics, Future Directions
Defend the thesis

PhD Student

Doctor
A Survey of Temporal Extensions of DLs

Daniele Dell’Aglio, Fariz Darari and Davide Lanti

9 – 39
**C L A S P [DL96]**

- Actor
- Defend the thesis
- Pre-condition
- PhD Student
- Goal
- Doctor
- Action
- States
**CLASP [DL96]**

![Diagram of CLASP with concepts and relationships]

- **Actor**: Person, PhD Student, Doctor
- **Action**: Defend the thesis
- **Goal**: States
- **Pre-condition**: Plan expression, Complete the major research

Daniele Dell’Aglio, Fariz Darari and Davide Lanti
A Survey of Temporal Extensions of DLs
\textbf{CLASP [DL96]}
CLASP [DL96]
CLASP

- A system to reason about plans, proposed by Devambu and Litman (first half of 90s)
A system to reason about plans, proposed by Devambu and Litman (first half of 90s)

Two formalisms

- The CLAsic DL to define states, actions, plans and relation among them
- A set of operators to specify the plan expressions
  - SEQUENCE, LOOP, TEST, OR, ...
  - The plan expression is converted in a finite automata
A system to reason about plans, proposed by Devambu and Litman (first half of 90s)

Two formalisms

- The CLASIC DL to define states, actions, plans and relation among them
- A set of operators to specify the plan expressions
  - SEQUENCE, LOOP, TEST, OR, ...
  - The plan expression is converted in a finite automata

CLASP performs

- Plan subsumption
- Plan recognition: determines if a scenario belong to a given plan
CLASP considerations

- Actions are instantaneous
- The temporal expressivity of Clasp is implicit in the language
- Alternatives can be expressed through disjunctions (\texttt{OR})
**CLASP considerations**

- Actions are instantaneous
- The temporal expressivity of Clasp is implicit in the language
- Alternatives can be expressed through disjunctions (\(\lor\))
- Explicit temporal constraints are not expressible
- The terminological representation of states:
  - is not as expressive as the predicate calculus representation used in STRIPS
  - avoids doing general theorem proving when computing state subsumption
Outline

- Overview
- Running Example
- A Survey on Existing Solutions
  - State-change based DLs
  - Temporal DLs with internal approach
  - Point-based temporal DLs
  - Interval-based temporal DLs
- Current Hot Topics, Future Directions

<table>
<thead>
<tr>
<th>Implicit time</th>
<th>State-change based DLs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explicit time Internal approach</td>
<td>Temporal DLs with internal approach</td>
</tr>
<tr>
<td>Explicit time External approach</td>
<td>Point-based temporal DLs</td>
</tr>
</tbody>
</table>
T-Rex [WL92]

- Defend the thesis
- Make a PhD
- Doctor
T-Rex [WL92]

- Make a PhD
- Defend the thesis
- action
- Doctor

$t$
T-Rex [WL92]

- Make a PhD
- Defend the thesis
- Doctor
- action
- finishes

Diagram showing the timeline of making a PhD and defending the thesis, with actions and relationships between these events.
**T-Rex [WL92]**

Diagram showing relationships between Make a PhD, Defend the thesis, action, and Doctor.

- Make a PhD
- Defend the thesis
- Doctor
- Action

Relationships:
- Make a PhD → Doctor
- Defend the thesis → Doctor
-Action

Temporal representation along the t axis.
T-Rex

A system to represent and reason about plans developed by Weida and Litman (90s)
A system to represent and reason about plans developed by Weida and Litman (90s)

Like CLASP, two different formalisms are used

- The K-Rep or the CLASSIC DLs to describe the actions
- A temporal constraint network to represent the plans
  - Constraints defined through the Allen’s relationships
  - before, meets, after, finishes, …
A system to represent and reason about plans developed by Weida and Litman (90s)

Like CLASP, two different formalisms are used

- The K-Rep or the CLASSIC DLs to describe the actions
- A temporal constraint network to represent the plans
  - Constraints defined through the Allen’s relationships
    - before, meets, after, finishes, ...

T-Rex performs the following reasoning tasks:

- subsumption
- plan recognition: the system determines if a set of observations are compatible with (i.e., could instantiate) the plan set
  - plans are classified in possible, necessary and impossible
T-Rex considerations

- T-Rex conceptual model captures the actions
  - States are not represented
T-Rex considerations

- T-Rex conceptual model captures the actions
  - States are not represented

- T-Rex is an example of external notion of time with an internal approach
  - It uses the Allen’s relationships to specify the constraints (explicit notion of time)
  - Plans capture the time notion (internal approach)
T-Rex considerations

► T-Rex conceptual model captures the actions
  ▶ States are not represented

► T-Rex is an example of external notion of time with an internal approach
  ▶ It uses the Allen’s relationships to specify the constraints (explicit notion of time)
  ▶ Plans capture the time notion (internal approach)

► The plan subsumption is NP-Complete
  ▶ The crux is to determine the mappings between plans
Time as Concrete Domain [BH91]

**Idea:**

- Abstract individuals are related to values in a *concrete domain* via features
- Tuples of concrete values identified by features can be constrained to belong to a predicate over the concrete domain
Example [AF00]

- Poor-Manager $\models$ Manager $\cap \forall$MONTHLY-BALANCE.∃(INCOME, EXPENSES). ≤

- INCOME and EXPENSES are features from $\Delta^T$ to the concrete domain $\mathcal{R}$
- ≤ is a predicate defined over the concrete domain
ALC(\mathcal{D}) [BH91]

- ALC extended with concrete predicates

\((\exists (u_1, \ldots, u_n).P)^\mathcal{I} := \{a \in \Delta^\mathcal{I} | \langle u_1^\mathcal{I}(a), \ldots, u_n^\mathcal{I}(a) \rangle \in P^\mathcal{D} \}\)

- \(u_1, \ldots, u_n\) are compositions of features

- \(\mathcal{D}\) is called concrete domain
Running Example

Postdoc ⊑ PHD-STATE : PhD-Student ⊓ DOC-STATE : (Doctor ⊓ ¬PhD-Student) ⊓

∃(PHD-STATE ◦ HAS-TIME, DOC-STATE ◦ HAS-TIME).meets

► Recall: “different states of an individual are modelled as different individuals”
Considerations

- $\text{ALC}(D),\ \text{ALCF}(D)$
  - concept satisfiability, subsumption, and ABox consistency
    - PSPACE-complete
  - .. under the assumption that satisfiability in the concrete domain is in PSPACE
- $\text{ALCRP}(D)$
  - Undecidable
    - Decidability if avoiding the interaction of complex roles with existential and universal restrictions
Outline

▶ Overview
▶ Running Example
▶ A Survey on Existing Solutions
  ▶ State-change based DLs
  ▶ Temporal DLs with internal approach
  ▶ Point-based temporal DLs
  ▶ Interval-based temporal DLs
▶ Current Hot Topics, Future Directions

<table>
<thead>
<tr>
<th></th>
<th>Point-based time</th>
<th>Interval-based time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implicit time</td>
<td>State-change based DLs</td>
<td></td>
</tr>
<tr>
<td>Explicit time</td>
<td>Temporal DLs with internal approach</td>
<td></td>
</tr>
<tr>
<td>Internal approach</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Explicit time</td>
<td>Point-based temporal DLs</td>
<td></td>
</tr>
<tr>
<td>External approach</td>
<td>Interval-based temporal DLs</td>
<td></td>
</tr>
</tbody>
</table>
Combining Description Logics and Tense Operators: $\mathcal{ALCT}$ [Sch93]

- Combination of $\mathcal{ALC}$ with point-based modal temporal connectives
  - $\Diamond p, \Box p, \circ p, \mathcal{U} p, \mathcal{U} p$

- Time part of the semantic structure
  - $A^\mathcal{I} \subseteq \mathcal{T} \times \Delta^\mathcal{I}$
  - $R^\mathcal{I} \subseteq \mathcal{T} \times \Delta^\mathcal{I} \times \Delta^\mathcal{I}$

- Recall: “an individual has different states at different moments”

- Temporal connectives can be applied only to concepts
  - $\Diamond C_i^\mathcal{I} := \{ a \in \Delta^\mathcal{I} \mid \exists t'. t' \leq t \land a \in C_i^{t'} \}$
Every doctor has been a PhD student in the past

\[
\text{Doctor} \sqsubseteq \Diamond^p \text{PhD-Student}
\]

Every thesis defender is a PhD student that has been a PhD student in the past

\[
\text{Thesis-Defender} \sqsubseteq \text{PhD-Student} \sqcap \Diamond^p \text{PhD-Student}
\]
Running Example

- Every doctor has been a PhD student in the past
  \[ \text{Doctor} \sqsubseteq \diamond_{p} \text{PhD-Student} \]

- Every thesis defender is a PhD student that has been a PhD student in the past
  \[ \text{Thesis-Defender} \sqsubseteq \text{PhD-Student} \sqcap \diamond_{p} \text{PhD-Student} \]
Running Example

- Every doctor has been a PhD student in the past
  \[ \text{Doctor} \subseteq \Diamond_p \text{PhD-Student} \]

- Every thesis defender is a PhD student that has been a PhD student in the past
  \[ \text{Thesis-Defender} \subseteq \text{PhD-Student} \cap \Diamond_p \text{PhD-Student} \]
Considerations

- $\mathcal{ALCT}$
  - Empty Abox
  - Linear, unbounded and discrete time structure
    - PSPACE-complete for satisfiability checking
  - Branching, unbounded and discrete time structure
    - EXPTIME-hard
  - Interval-based time structure
    - Undecidable

- Open questions (still open?)
  - Extending $\mathcal{ALCT}(\mathcal{N})$ with past tense?
  - Real numbers?
Outline

- Overview
- Running Example
- A Survey on Existing Solutions
  - State-change based DLs
  - Temporal DLs with internal approach
  - Point-based temporal DLs
  - Interval-based temporal DLs
- Current Hot Topics, Future Directions
Interval-based Temporal DLs

- Schmiedel’s Formalism
  - Idea
  - Examples

- The Undecidable Realm
  - Idea
  - Examples

- Towards Decidable Logic
  - Idea
  - Examples
Interval-based Temporal DLs: Characteristics

- Interval-based

- Explicit, eg: *alltime*, ◇ *TE*

- Follows the external approach, eg: *C⟨i, a⟩* for temporal concept assertions and *R⟨i, a, b⟩* for temporal role assertions
Schmiedel’s Formalism: Idea

- The first of such an interval-based temporal DL (made in 1990)
- Underlying DL = $\mathcal{FLN}^-\mathcal{R}$ (no $\top$, $\bot$, $\neg$, $\sqcup$ but with cardinality restrictions on roles, and role conjunction)
- Temporal operators = at, alltime, sometime
- Subsumption is argued to be undecidable
Schmiedel’s Formalism: Examples

Concept: PhD students during 1993
(at 1993 PhDStudent)

Terminological Axiom: Doctors were PhD students
Doctor ⊑ (sometime(x)(metBy now x).(at x (PhDStudent)))
The Undecidable Realm: Idea

- Developed by Bettini
- Variable-free extension with existential and universal temporal quantification
  - Arbitrary relationships between more than two intervals can’t be represented
- Satisfiability and subsumption are undecidable
- Starting from the DL $\mathcal{ALC}N$
- Two concept constructors: $\diamond TE.C$ and $\Box TE.C$
The Undecidable Realm: Examples

Concept: Persons who become a doctor sometime
\( \Diamond \text{after.Doctor}, \)
eg: \( \langle 1990, michael \rangle \) belongs to this, if \( \langle 1992, michael \rangle \) belongs to Doctor

Terminological Axiom: Doctors were PhD students
\( \text{Doctor} \sqsubseteq \Diamond (\text{metBy}).\text{PhDStudent} \)
Towards Decidable Logics: Idea

- Developed by Artale and Franconi
- Decidable: Expressivity is reduced, universal quantification on temporal variables has been eliminated
- Underlying DL (most expressive): $\mathcal{TTL-ALCF}$
- Temporal variables are introduced by the temporal existential quantifier $\Diamond$, excluding the predefined temporal var $\#$
Towards Decidable Logics: Examples

Terminological Axiom: Doctors were PhD students

\[ \text{Doctor} \sqsubseteq \Diamond (x)(\# \text{metBy } x).\text{PhDStudent}@x \]

Terminological Axiom: PhD thesis defenders finish their PhDs

\[ \text{PhDThesisDefender} \sqsubseteq \Diamond (x)(\# \text{finishes } x).\text{PhDStudent}@x \]
Outline

► Overview

► Running Example

► A Survey on Existing Solutions
  ▶ State-change based DLs
  ▶ Temporal DLs with internal approach
  ▶ Point-based temporal DLs
  ▶ Interval-based temporal DLs

► Current Hot Topics, Future Directions
Hot Topics: Temporal DLs for OBDA

- OBDA over temporal data with validity time
- Ontologies capable of temporal conceptual modeling
- Developed TQL extending OWL 2 QL, still preserving FO rewritability
- Example:
  - A fact with its validity time: \( \text{givesBirth}(\text{diana, michael}, 1970) \)
  - A temporal axiom: \( \Diamond_p \text{givesBirth} \sqsubseteq \text{motherOf} \)
Hot Topics: Stream Query Processing
Query language for RDF streams

REGISTER STREAM SWhoIsWhereOnFb AS
PREFIX : <http://.../sr4ld2013-onto#>
CONSTRUCT { ?person :isIn ?room }
FROM STREAM <http://.../fb> [RANGE lm STEP 10s]
WHERE {
}

Credit: http://emanueledellavalle.org/
A Survey of Temporal Extensions of DLs

Research school: Foundations and Challenges of Change in Ontologies and Databases 2014
Free University of Bozen-Bolzano, Italy

Group 6:

► Daniele Dell’Aglio
▷ DEIB – Politecnico di Milano
▷ daniele.dellaglio@polimi.it

► Fariz Darari
▷ KRDB – Università di Bolzano
▷ fadirra@gmail.com

► Davide Lanti
▷ KRDB – Università di Bolzano
▷ davide.lanti.sersante@gmail.com

Mentor:

► Michael Zakharyaschev
▷ Birkbeck College
[AF00] Alessandro Artale and Enrico Franconi.  
A survey of temporal extensions of description logics.  

A scheme for integrating concrete domains into concept languages.  

Taxonomic plan reasoning.  

[Sch93] Klaus Schild.  
Combining terminological logics with tense logic.  