Probabilistic Event Calculus based on Markov Logic Networks

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Outline

Introduction

Event Calculus in Markov Logic Networks

- Representing Event Calculus Axioms in MLN
- Behaviour of Event Calculus in MLN

Experiments: Activity Recognition

Event Recognition

- Variety of application domains, e.g. health care monitoring, public transport management, activity recognition etc
- Input:
  - *Low-level events* (LLE) — time-stamped symbols
  - LLE come from different sources/sensors
  - e.g. happens(walking(id1), 10), happens(active(id2), 10), ...
- Output:
  - Recognised *high-level events* (HLE)
  - e.g. holdsAt(meeting(id1,id2), 11), holdsAt(meeting(id1,id2), 12), ...
- HLE: Relational structure over other sub-events (HLE or LLE)

Methods:

- Logic-based — very expressive
- Probabilistic-based — handle uncertainty

Event Recognition

Requirements:

- Formal representation language
- Handle uncertainty

The method combines:

- Event Calculus — representation
- Markov Logic Networks — probabilistic inference

Markov Logic Networks (MLN) — in a nutshell

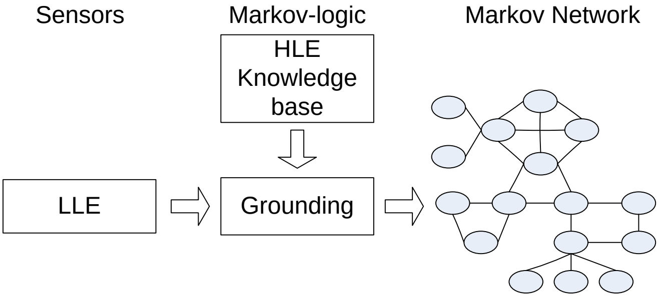
- First-order logic $\rightarrow$ set of hard constraints
- Syntactically: weighted first-order logic formulas (F_i, w_i)
- Semantically: (F_i, w_i) represents a probability distribution over possible worlds (or Herbrand interpretations)

$$P(X = x) = \frac{1}{Z} exp\left(\sum_i w_i\, n_i(x)\right)$$

- possible world ($X = x$)
- partition function (Z)
- number of satisfied ground formulas ($n_i(x)$)

A world violating formulas becomes less probable, but not impossible!

Markov Logic Networks (MLN) — in a nutshell



- Formula $\rightarrow$ clausal form
- Clauses are grounded according to the domain of their distinct variables
- Existentially quantified variables are replaced by the disjunction of their groundings: $\forall X\ \exists Y\ p(Y) \wedge q(X) \equiv (p(1) \wedge q(X)) \vee (p(2) \wedge q(X)) \vee \ldots$
- Open-world assumption for non-evidence predicates

Event Calculus

- Reasoning about events and their effects
- A variety of different dialects
- Ontology
  - Timepoints
  - Events $\rightarrow$ low-level events
  - Fluents $\rightarrow$ high-level events
- Core domain-independent axioms
  - Define whether a fluent holds or not at a specific timepoint
  - **Inertia:** fluents persist over time, unless affected by some event
- Domain-dependent definitions $\rightarrow$ HLE definitions
  - Initiation of a fluent
  - Termination of a fluent

Representing Event Calculus in MLN

Some axioms from Shanahan's Full Event Calculus:

$$\left.\begin{aligned} holdsAt(F,\ T) \leftarrow\ & happens(E,\ T_0) \wedge \\ & initiates(E,\ F,\ T_0) \wedge \\ & T_0 < T \wedge \\ & \neg clipped(F,\ T_0,\ T) \end{aligned}\right\} \quad F \times E \times\ T \times T_0$$

$$\left.\begin{aligned} clipped(F,\ T_0,\ T_1) \leftrightarrow\ & \exists\ E, T \\ & happens(E,\ T) \wedge \\ & T_0 \leq T < T_1 \wedge \\ & terminates(E,\ F,\ T) \end{aligned}\right\} \quad F \times E \times\ T \times T_0 \times T_1$$

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- Huge number of groundings → ($T \times T_0$), ($T \times T_0 \times T_1$)

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- Huge number of groundings
- Combinatorial explosion

Discrete Event Calculus

- Logically equivalent with EC, when the domain of timepoints is limited to integers
- Axioms are defined over successive timepoints

$$\left.\begin{array}{l} \mathit{holdsAt}(F, T+1) \leftarrow \\ \qquad\qquad \mathit{happens}(E, T) \wedge \\ \qquad\qquad \mathit{initiates}(E, F, T) \end{array}\right\} \quad F \times E \times T$$

$$\left.\begin{array}{l} \mathit{holdsAt}(F, T+1) \leftarrow \\ \qquad\qquad \mathit{holdsAt}(F, T) \wedge \\ \qquad\qquad \neg\exists\, E \;\; \mathit{happens}(E, T) \wedge \\ \qquad\qquad \mathit{teminates}(E, F, T) \end{array}\right\} \quad F \times E \times T$$

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\end{array}\right\} \quad F \times E \times T
$$

Creates $2^{|E|}$ clauses

Simplifying Discrete Event Calculus

General form of domain-dependent HLE definition:

$$
\begin{aligned}
&\mathit{initiatedAt}(\mathit{fluent}_k, T) \leftarrow \\
&\qquad \mathit{happens}(\mathit{event}_n, T) \ \wedge \ \ldots \wedge \\
&\qquad \mathit{Conditions}[T]
\end{aligned}
$$

$$
\begin{aligned}
&\mathit{terminatedAt}(\mathit{fluent}_k, T) \leftarrow \\
&\qquad \mathit{happens}(\mathit{event}_n, T) \ \wedge \ \ldots \wedge \\
&\qquad \mathit{Conditions}[T]
\end{aligned}
$$

Simplifying Discrete Event Calculus

$$holdsAt(F, T+1) \leftarrow happens(E, T) \land initiates(E, F, T)$$

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Simplifying Discrete Event Calculus

$$holdsAt(F, T+1) \leftarrow happens(E, T) \wedge initiates(E, F, T)$$

$$holdsAt(F, T+1) \leftarrow initiatedAt(F, T)$$

$$holdsAt(F, T+1) \leftarrow holdsAt(F, T) \wedge \neg\exists\, E\ happens(E, T) \wedge teminates(E, F, T)$$

$$holdsAt(F, T+1) \leftarrow holdsAt(F, T) \wedge \neg teminatedAt(F, T)$$

Simplified Discrete Event Calculus

When a fluent holds:

$$\left.\begin{array}{l} holdsAt(F, T+1) \leftarrow \\ \qquad initiatedAt(F, T) \end{array}\right\} \quad F \times T$$

$$\left.\begin{array}{l} holdsAt(F, T+1) \leftarrow \\ \qquad holdsAt(F, T) \wedge \\ \qquad \neg teminatedAt(F, T) \end{array}\right\} \quad F \times T$$

When a fluent does not hold:

$$\left.\begin{array}{l} \neg holdsAt(F, T+1) \leftarrow \\ \qquad terminatedAt(F, T) \end{array}\right\} \quad F \times T$$

$$\left.\begin{array}{l} \neg holdsAt(F, T+1) \leftarrow \\ \qquad \neg holdsAt(F, T) \wedge \\ \qquad \neg initiatedAt(F, T) \end{array}\right\} \quad F \times T$$

Example: HLE definition

When the fluent 'meeting' is initiated:

$$\begin{aligned}\textbf{initiatedAt}(\textbf{meeting}, \textbf{T}) \leftarrow \\ & happens(event_1, T) \wedge \\ & \neg happens(event_2, T) \wedge \\ & distance(close, T)\end{aligned}$$

$$\begin{aligned}\textbf{initiatedAt}(\textbf{meeting}, \textbf{T}) \leftarrow \\ & happens(event_3, T) \wedge \\ & \neg happens(event_1, T) \wedge \\ & \neg happens(event_2, T) \wedge \\ & distance(close, T)\end{aligned}$$

When the fluent 'meeting' is terminated:

$$\begin{aligned}\textbf{terminatedAt}(\textbf{meeting}, \textbf{T}) \leftarrow \\ & happens(event_4, T)\end{aligned}$$

...

Open-world semantics in MLN

Domain-dependent definitions:

- Conditions under which HLE are initiated or terminated
- Open-world assumption for non-evidence predicates: initiatedAt, terminatedAt and holdsAt

When something is happening that it is not defined in the domain-dependent definitions:

- Cannot determine whether a fluent holds or not
- Loss of the inertia
- This is also known as the *frame problem*
- Solution: predicate completion

Predicate completion

$$
\text{HLE definitions} = \begin{cases}
\mathbf{initiatedAt}(\mathbf{meeting}, \mathbf{T}) \leftarrow \\
\quad \textcolor{blue}{happens(event_1, T) \wedge} \\
\quad \textcolor{blue}{\neg happens(event_2, T) \wedge} \\
\quad \textcolor{blue}{distance(close, T)} \\
\mathbf{initiatedAt}(\mathbf{meeting}, \mathbf{T}) \leftarrow \\
\quad \textcolor{orange}{happens(event_3, T) \wedge} \\
\quad \textcolor{orange}{\neg happens(event_1, T) \wedge} \\
\quad \textcolor{orange}{\neg happens(event_2, T) \wedge} \\
\quad \textcolor{orange}{distance(close, T)} \\
\ldots
\end{cases}
$$

Predicate completion

HLE definitions =

$$\begin{cases} \mathbf{initiatedAt}(\mathbf{meeting}, \mathbf{T}) \leftarrow \\ \quad happens(event_1, T) \wedge \\ \quad \neg happens(event_2, T) \wedge \\ \quad distance(close, T) \\ \mathbf{initiatedAt}(\mathbf{meeting}, \mathbf{T}) \leftarrow \\ \quad happens(event_3, T) \wedge \\ \quad \neg happens(event_1, T) \wedge \\ \quad \neg happens(event_2, T) \wedge \\ \quad distance(close, T) \\ \ldots \end{cases}$$

Completion constraints =
(automatically generated)

$$\begin{cases} \mathbf{initiatedAt}(\mathbf{meeting}, \mathbf{T}) \rightarrow \\ \quad [happens(event_1, T) \wedge \\ \quad \neg happens(event_2, T) \wedge \\ \quad distance(close, T)\ ] \ \bigvee \\ \quad [happens(event_3, T) \wedge \\ \quad \neg happens(event_1, T) \wedge \\ \quad \neg happens(event_2, T) \wedge \\ \quad distance(close, T)\ ] \\ \ldots \end{cases}$$

Predicate completion

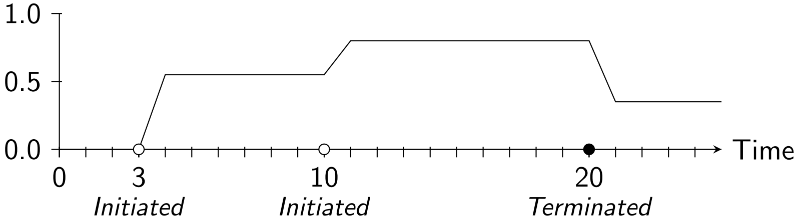
$$\text{HLE definitions} = \begin{cases} \mathbf{1.5} \quad \mathbf{initiatedAt}(\mathbf{meeting}, \mathbf{T}) \leftarrow \\ \qquad happens(event_1, T) \wedge \\ \qquad \neg happens(event_2, T) \wedge \\ \qquad distance(close, T) \\ \mathbf{0.25} \quad \mathbf{initiatedAt}(\mathbf{meeting}, \mathbf{T}) \leftarrow \\ \qquad happens(event_3, T) \wedge \\ \qquad \neg happens(event_1, T) \wedge \\ \qquad \neg happens(event_2, T) \wedge \\ \qquad distance(close, T) \\ \ldots \end{cases}$$

$$\begin{array}{r}\text{Completion constraints} = \\ \text{(automatically generated)}\end{array} \begin{cases} \mathbf{4.0} \quad \mathbf{initiatedAt}(\mathbf{meeting}, \mathbf{T}) \rightarrow \\ \qquad [happens(event_1, T) \wedge \\ \qquad \neg happens(event_2, T) \wedge \\ \qquad distance(close, T)\ ] \ \bigvee \\ \qquad [happens(event_3, T) \wedge \\ \qquad \neg happens(event_1, T) \wedge \\ \qquad \neg happens(event_2, T) \wedge \\ \qquad distance(close, T)\ ] \\ \ldots \end{cases}$$

Inertia in MLN

EC domain-independent axioms are hard-constrained and:

1. Only HLE definitions are soft-constrained

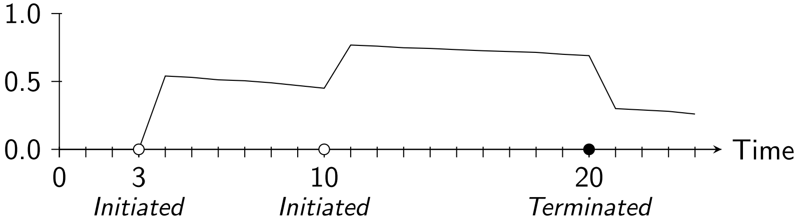


$$P(\mathit{world}) \propto \mathit{exp}\left(\sum(\mathit{weights\ of\ formulas\ it\ satisfies})\right)$$

Inertia in MLN

EC domain-independent axioms are hard-constrained and:

2. Only HLE definitions are soft-constrained and the termination rules in the completion constraints



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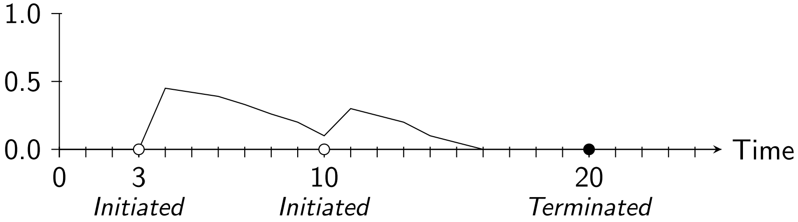
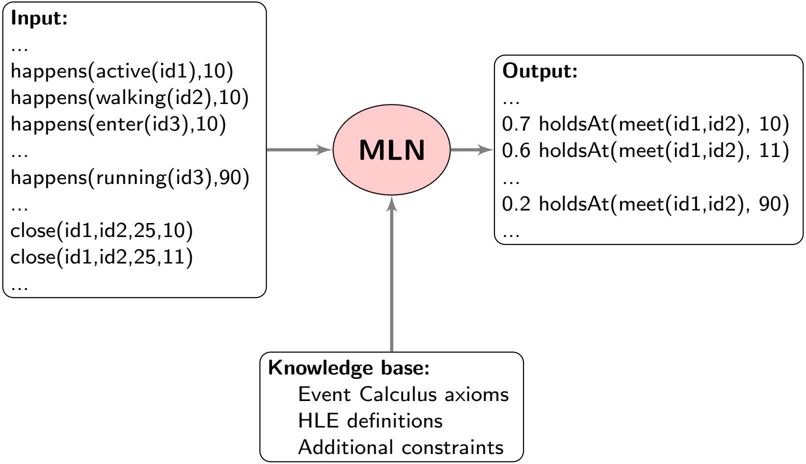


$$P(\mathit{world}) \propto \mathit{exp}\left(\sum(\mathit{weights\ of\ formulas\ it\ satisfies})\right)$$

Experiments — CAVIAR dataset

- 28 surveillance videos
- LLE: active, inactive, walking, running, enter and exit
- HLE: *meeting, moving, fighting* and *leaving an object*



Experiments — results

- **EC-LP:**
  - Logic-programming based EC
  - Knowledge base of HLE for CAVIAR dataset
- **DEC-MLN:**
  - Markov Logic Networks based EC
  - Manualy adjusted weight values for the HLE *meeting*:
    - weak values — low confidence
    - strong values — high confidence
  - DEC-MLN_a: soft-constrained HLE definitions
  - DEC-MLN_b: soft-constrained HLE definitions and termination rules in the completion constraints

Method	TP	FP	FN	Precision	Recall
EC-LP	3099	2258	525	0.578	**0.855**
DEC-MLN_a	3048	1762	576	0.633	0.841
DEC-MLN_b	3048	1154	576	**0.725**	0.841

Source KB and dataset files can be found in http://www.iit.demokritos.gr/∼anskarl

Conclusions

- Probabilistic extension of Event Calculus
- Formal and declarative semantics
- Probabilistic inference
- Emphasis on simplifying the axioms of the EC — reduce the size and the complexity of the network
- Deterministic or probabilistic control of the inertia

Future directions:

- Machine learning — estimate weight values
- Experiments in other real-world data sets

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Thank you for your attention!

Any questions?