Formalizing AMR Inference via Hybrid Logic Tableaux

CL Masters Thesis Defense

Eli Goldner

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Introduction

- Semantic representation:
  - Capture meaning of natural language content.
  - Designed for manipulation via software.
- Abstract Meaning Representation (AMR):
  - Graph-based (DAG), nodes are *concepts*, edges are *relations*.
  - Built on predicative core of a sentence.
  - Ignores syntactic differences between equivalent sentences.
  - PropBank framesets are used for concepts (entities, events, properties, states).

Introduction

(Basic) AMR is reductionistic. This is awesome for:

- Annotation (esp. by non-experts).
- Semantic parsing (smaller target space).

This is not awesome for:

- Representing and recovering fine-grained meaning.
- Automating reasoning/inference.

Introduction

- The trade-off between ease of generation/use and rich expressivity/inferentiability is at least as old as computing.
- AMR has made a choice that works well in data-driven NLP.
- However AMR can bridge this gap:
- AMR already does this in a modular way with extensions.
- Some of these extensions give afford interpretation in first-order logic:
    - Automated inference for logics is a rich area with lots of tools.
    - This is where we come in.

Motivation

"Why do we need formal methods? Can't state-of-the-art language models do this already?"

Short answer: Not really, and even if they could:

- Statistically driven techniques are unecessarily expensive for formal inference.
- Increasing need for ability to guarantee/verify properties of software:
  - Does the software give us the right *type* of result for an input?
  - Bias in NLP.
- Machine learning (by itself) does not lend itself well to this.

Approach

- Combine two AMR extensions for richer interpretation:
  - Scope and quantification (Pustejovsky et al., 2019)
  - Tense and aspect (Donatelli et al., 2018)
- Interpret these extended AMR into a logic that handles quantification and tense.
- Develop tableau methods for this logic:
  - General method for proving/disproving sentences in the logic.
  - Restricted method for checking if sentence holds in some model.

AMR with Scope and Quantification

- Disambiguates scope.
- Annotates central predicate and its arguments.
- Clearest path for AMR $\rightarrow$ standard first-order predicate logic.

AMR with Tense and Aspect

- Standard AMR structure.
- Central predicate annotated for:
  - Aspect.
  - Event time.
  - Reference time.

Combined Extensions

- Assume each AMR has information from both extensions.
- Attach tense and aspect information to central predicate node.
- Extract a tense-sensitive FOPL representation (details later).

Modal Logic

- Propositional logic lets us form statements like $p \wedge (q \vee \neg r)$.
- Modal propositional logic extends propositional logic with an operator $\Diamond$, read as "possible". i.e. it is not possible that p and $\neg p$ are the case would be:

$$\neg\Diamond(p \wedge \neg p)$$

- (More) formal meaning of $\Diamond$: There is a *possible world* where p is true, and this possible world is *accesible* from the current one.
- The problem: the "current world" is an implicit notion dependent on context. Is there something more expressive?

Hybrid Logic

- Idea: take propositional modal logic, and add an operator @, that lets us know which world we're referring to.
- p or r is possible at world i: $@_i\Diamond(p \vee r)$
- In the above proposition i is called a nominal since it *names* some/is true at exactly one world.
- Everything true at the nominal j is true at the nominal i (they name the same world): $@_i j$

Hybrid Logic Variants

- Hybrid tense logic:
  - Two tense modalities: $\langle F \rangle$ and $\langle P \rangle$
  - World j is in the past of world i: $@_i Pj$
- Quantified hybrid logic:
  - Hybrid logic with first-order quantifiers, relation, and function symbols.
  - At n (now) there is a person who will be president:

$$@_n(\exists x)(Person(x) \wedge F(President(x)))$$

Hybrid Logic Variants

A problem!

- Domain of quantification in

$$@_n(\exists x)(Person(x) \land F(President(x)))$$

First-Order Hybrid Tense Logic

FHTL Tableau Example

$$
\begin{array}{lcc}
(1) & & \\
(2) & \multicolumn{2}{c}{@_s(\exists x)[P((\exists y)[f(x,y) = f(y,x)]) \vee \neg(\exists z)[x = z]]} \\
(3) & \multicolumn{2}{c}{@_s P((\exists y)[f(s_1,y) = f(y,s_1)]) \vee \neg(\exists z)[s_1 = z]} \\
(4) & @_s P((\exists y)[f(s_1,y) = f(y,s_1)]) & @_s\neg(\exists z)[s_1 = y] \\
(5) & @_s Pt & @_s\neg[s_1 = s_1] \\
(6) & @_t(\exists y)[f(s_1,y) = f(y,s_1)] & @_s[s_1 = s_1] \\
(7) & \ldots & \otimes
\end{array}
$$

Model Checking Example

- *Every computer will be located at a desk.*
- AMR with quantification and tense:

```
(s / scope
      :pred (b / be-located-at-91 :ongoing -
                                  :complete +
                                  :time (a / after
                                           :op1 (n / now))
         :ARG0 (c / computer)
         :ARG1 (d / desk
            :quant (e / every)))
      :ARG0 d
      :ARG1 c)
```

- *FHTL* translation:
  $@_{now}(\forall y)[\text{desk}(y) \rightarrow (\exists x)[\text{computer}(x) \wedge F(\text{be-located-at-91}(x, y))]]$

Model Checking Example

Define a small *FHTL* model $\mathfrak{M} = (T, \mathcal{R}, (D_t)_{t \in T}, I_{nom}, (I_t)_{t \in T})$ where:

$$T = \{yesterday, now, tomorrow\}$$

$$\mathcal{R} = \{(yesterday, now), (now, tomorrow), (yesterday, tomorrow)\}$$

$$I_{nom} = \{(y, yesterday), (n, now), (t, tomorrow)\}$$

$$D_{yesterday} = \{computer_1, desk_1\}$$

$$D_{now} = \{computer_1, computer_2, desk_1, desk_2, desk_3\}$$

$$D_{tomorrow} = \{computer_1, computer_2, desk_1, desk_2\}$$

Model Checking Example

$$@_n(\forall y)[\text{desk}(y) \rightarrow (\exists x)[\text{computer}(x) \land F(\text{located}(x, y))]]$$
$$@_n\text{desk}(n{:}p_1) \rightarrow (\exists x)[\text{computer}(x) \land F(\text{located}(x, n{:}p_1))]$$

$$@_n\neg\text{desk}(n{:}p_1) \qquad @_n(\exists x)[\text{computer}(x) \land F(\text{located}(x, n{:}p_1))]$$
$$@_n\text{computer}(n{:}p_2) \land F(\text{located}(n{:}p_2, n{:}p_1))$$
$$@_n\text{computer}(n{:}p_2)$$
$$@_nF(\text{located}(n{:}p_2, n{:}p_1))$$
$$@_nFs$$
$$@_s\text{located}(n{:}p_2, n{:}p_1)$$

Where we assign $s = t = \textit{tomorrow}$, $n{:}p_2 = \textit{computer}_1$ and $n{:}p_1 = \textit{desk}_2$, or $n{:}p_2 = \textit{computer}_2$ and $n{:}p_1 = \textit{desk}_1$ we see that $\mathfrak{M}$ satisfies the *FHTL* sentence.

Extraction

Interpretation

References I

Lucia Donatelli, Michael Regan, William Croft, and Nathan Schneider. 2018. Annotation of tense and aspect semantics for sentential AMR. In *Proceedings of the Joint Workshop on Linguistic Annotation, Multiword Expressions and Constructions (LAW-MWE-CxG-2018)*, pages 96–108, Santa Fe, New Mexico, USA. Association for Computational Linguistics.

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