Formalizing AMR Inference via Hybrid Logic Tableaux

CL Masters Thesis Defense

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Introduction

Semantic representation:

- Capture meaning of natural language content.
- Designed for software to manipulate and interpret.

Abstract Meaning Representation (AMR):

- Graph-based (DAG), nodes are *concepts*, edges are *relations*.
- Built on predicative core of a sentence.
- Ignores syntactic and fine grained semantic differences between sentences.

Introduction

(Core) AMR is reductionistic. Optimal for:

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

Not optimal for:

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

Introduction

- AMR designers made a choice that works well in data-driven NLP.
- Modular AMR extensions.
- Some extensions afford richer logical interpretation:

Motivation

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

- Statistically driven techniques are unnecessarily 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.

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.
  - Speech 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 $p \land (q \lor \neg r)$.
- Modal propositional logic extends propositional logic with an operator $\Diamond$
- It is not possible that p and $\neg p$ are the case:

$$\neg \Diamond (p \land \neg p)$$

- Meaning of $\Diamond$: There is a *possible world* where p is true, and this possible world is *accessible* from the current one.
- The problem: the "current world" is implicit and dependent on context.
- How to make it explicit?

Hybrid Logic

- Extend propositional modal logic, with the operator @, which specifies the 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: F and P
- 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 for whom it is possible to own a car:

$$@_n(\exists x)(Person(x) \wedge (\exists y)(Car(y) \wedge \Diamond Afford(x, y)))$$

Hybrid Logic Variants

A problem

$$@_n(\exists x)(Person(x) \wedge (\exists y)(Car(y) \wedge \Diamond Afford(x, y)))$$

What's the domain of quantification?

- Option 1: The domain is the same at every world: *There is someone (out of all people all people at all worlds) who can afford some car (out of all cars at all worlds).*
- Option 2: Each world has a different domain: *There is someone (out of everyone in this world) who can afford some car (out of all cars in this world).*

Hybrid Logic Variants

- We tend to mean there is some person (and more loosely some car) here/now.
- Option 2 is closer to how quantification works in natural language.
- We use this approach (presentist quantification).

First-Order Hybrid Tense Logic

First-order Hybrid Tense Logic ($FHTL$) is:

- Quantified hybrid logic, with tense modalities F and P instead of $\Diamond$.
- Presentist quantification:
  - Each world has its own domain.
  - Quantification is domain sensitive.

First-Order Hybrid Tense Logic

In logic models are interpretations of symbols and constants in the language. An *FHTL* model $\mathfrak{M}$ is a tuple

$$(T, \mathcal{R}, (D_t)_{t \in T}, I_{nom}, (I_t)_{t \in T})$$

Where:

- T is a set of times/worlds.
- $\mathcal{R}$ is the binary accessibility relation over times.
- D_t is the domain of a time t
- I_{nom} assigns nominals to worlds.
- I_t interprets the value of terms at a time t.

First-Order Hybrid Tense Logic

- The satisfiability of a formula with free variables depends on a *variable assignment function*.
- A formula with no free variables is called a *sentence*.

Two main tasks for a sentence $@_s\varphi$:

- Theorem proving – is $@_s\varphi$ true regardless of the model?
- Model checking – is $@_s\varphi$ true in a given model $\mathfrak{M}$?

For both we use versions of the tableau method.

Tableau Method

- Tableau for a formula is a tree structure.
- A tableau calculus for a logic breaks down and transforms formulae
- Rules of the calculus use semantics of connectives/quantifiers/modifiers.
- *FHTL* tableau based on *QHL* tableau modified for tense rules.

Tableau Method

- A tableau branch is a subtree of the main tableau tree.
- A tableau *branches* for rules involving disjunctions.
- A branch is *closed* if it contains both a formula $@_s\varphi$ and its negation $@_s\neg\varphi$. Otherwise it is open.
- A branch is *saturated* if no rules of the calculus can be applied without adding a redundant formula on the branch.

Tableau Example Rules

$$\frac{@_s F\varphi}{\begin{array}{c}@_s Fa\\ @_a\varphi\end{array}}\,\mathbf{(}F\mathbf{)}^{12}$$

$$\frac{@_s(\exists x)\varphi}{@_s\varphi[s{:}p/x]}\,\mathbf{(\exists)}^{3}$$

$$\frac{@_s @_t\varphi}{@_t\varphi}\,\mathbf{(@)}$$

$$\frac{@_i j{:}t = k{:}s \qquad @_i\varphi}{@_i\varphi[j{:}t//k{:}s]}\,\mathbf{(sub)}^{4}$$

[1] The nominal a is new to the branch.

[2] The formula φ is not a nominal.

[3] $s{:}p$ is new to the branch.

[4] $\varphi[j{:}t//k{:}s]$ is φ where some occurences of $j{:}t$ have been replaced by $k{:}s$.

FHTL Tableau Example

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

Tableau Proofs

- The *root formula* of a tableau is unsatisfiable if every branch of the tableau closes.
- If we want to prove $@_s\varphi$ then we begin the tableau with $@_s\neg\varphi$ (proof by contradiction).
- Need to show for tableau method (or any proof system) that it is:
  - Sound – if a tableau is closed then the root formula is unsatisfiable.
  - Complete – if a formula is unsatisfiable it has a closed tableau proof.

Tableau Proofs

- Soundness is demonstrated by checking the rules.
- Completeness is demonstrated by contrapositive.
- Open tableau branch $\rightarrow$ there is a model which satisfies the root.
- Construct the model out of equivalence classes of everything that shows up on the branch.

Tableaux for Model Checking

- So far the tableau method has been about general theorem proving.
- Problem: no tableau construction method guaranteed to terminate (if there was we'd have decidability of first-order logic).
- Most of the time however we are reasoning about an AMR/*FHTL* sentence in some local context.
- Revise tableau rules, trade completeness for termination.

Tableaux for Model Checking

NB: Terms in *FHTL* have nominal prefixes since their value can depend on the world they are evaluated in, i.e. $i{:}t$, $i{:}j{:}t$. There are three things that prevent tableau construction from terminating:

- Universal tableau rules ($\neg\exists$, $\forall$) – can generate an arbitrary number of conclusions.
- Term rules – can keep adding prefixes to terms.
- Nominal rules – generating redundant nominals (our complete rules take care of this).

- Idea: give tableau a reasonable chance to close, but make sure it terminates.
- Fix some $q \in \mathbb{N}^+$ and let universal rules generate at most q conclusions. (Fitting (1988) says $q = 1$ works surprisingly often.)
- Restrict term rules to depend on nominals and terms already on the branch. Prevent redundant prefixes (no $i{:}j{:}i{:}t$ etc.).

Model checking procedure

- Build tableau using restricted rules.
- Check tableau tree from leaves up, skipping closed branches.
- Every formula on the branch has a set of variable and parameter assignments which satisfy it in the model.
- Solve for a formula's set based on the sets of its conclusions.
- If the root formula is satisfied in the model by every variable assignment then it holds.

Model Checking Example

- *Every desk will have a computer located there.*
- 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:

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

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

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

$$I_{yesterday}(\texttt{be-located-at-91}) = \dots$$

$$I_{now}(\texttt{be-located-at-91}) = \dots$$

$$I_{tomorrow}(\texttt{be-located-at-91}) = \{\langle computer_2, desk_2 \rangle, \langle computer_1, desk_1 \rangle\}$$

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

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

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

Model Checking Example

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

Left branch:

$$@_n\neg\text{desk}(n{:}p_1)$$

Right branch:

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

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

In this new annotation time information is of the form:

`:<aspect> <polarity> :time (<reference> :op1 (<speech>))`

- `<speech>` is some $t \in T$, so formula has the prefix $@_t\varphi$
- `<reference>` (if present) is the tense, e.g. $@_t P\psi$
- We don't make use of aspect (right now).

Interpretation

Every AMR in this annotation is either of the form (for a connective `or`, `and`, or `cond`):

```
(<connective>
   :op1 (...)
   :op2 (...)
   :op3 (...))
```

Or

```
(s / scope
      :pred (...
         :ARG0 (...)
         :ARG1 (...))
      :ARG0 <primary-scope>
      :ARG1 <secondary-scope>)
```

Interpretation Examples

```
(o / or
   :op1 (...)
   :op2 (...)
   :op3 (...))
```

$$[\![\mathrm{op1}]\!] \vee [\![\mathrm{op2}]\!] \vee [\![\mathrm{op3}]\!]$$

```
(s / scope
      :pred (...
         :ARG0 (...)
         :ARG1 (...))
      :ARG0 <primary-scope>
      :ARG1 <secondary-scope>)
```

$$[\![\texttt{<primary-scope>}]\!]([\![\texttt{<secondary-scope>}]\!]([\![\mathrm{pred}]\!]))$$

Interpretation Examples

```
(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)
```

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

$$[\![\texttt{now}]\!] \rhd \mathit{now}$$

$$[\![\texttt{after}]\!] \rhd F$$

```
(c / computer)
```

$$\lambda\varphi.(\exists x)[\mathit{Computer}(x) \wedge \varphi(x)]$$

```
(d / desk
     :quant (e/ every))
```

$$\lambda\varphi.(\forall x)[\mathit{Desk}(x) \rightarrow \varphi(x)]$$

Interpretation Example

```
(:pred (b / be-located-at-91 :ongoing -
                             :complete +
                             :time (a / after
                                      :op1 (n / now))
```

$$\lambda\varphi.\lambda x.\lambda y.\varphi(\texttt{be-located-at-91}(x, y))$$

Interpretation Example

First application:

$$[\![\textit{computer will be located at it}]\!] =$$

$$\lambda\varphi.(\lambda\varphi'.(\exists c)[Computer(c) \wedge \varphi'(c)])(\lambda\psi.(\lambda\psi'.\psi'(\lambda x.\lambda y.F(loc(x,y))))(\lambda\gamma.\varphi(\gamma(\psi))))\rhd_\beta$$

$$\lambda\varphi.(\exists c)[Computer(c) \wedge ((\lambda\psi'.\psi'(\lambda x.\lambda y.F(loc(x,y))))(\lambda\gamma.\varphi(\gamma(c))))]\rhd_\beta$$

$$\lambda\varphi.(\exists c)[Computer(c) \wedge \varphi(\lambda y.F(loc(c,y)))]$$

Interpretation Example

Second application:

$$\lambda\varphi.[\![\textit{every desk}]\!](\lambda\psi[\![\textit{computer will be located at it}]\!](\lambda\gamma.\varphi(\psi(\psi))))\rhd_\beta$$

$$\lambda\varphi.(\lambda\varphi'.\forall x[\textit{Desk}(x) \to \varphi'(x)])(\lambda\psi[\![\textit{computer located at it}]\!](\lambda\gamma.\varphi(\gamma(\psi))))$$

$$\lambda\varphi.(\forall x)[\textit{Desk}(x) \to ([\![\textit{computer located at it}]\!](\lambda\gamma.\varphi(\gamma(x))))] =$$

$$\lambda\varphi.(\forall x)[\textit{Desk}(x) \to ((\lambda\varphi'.(\exists y)(\textit{computer}(c) \wedge (\varphi(\lambda x.F(\textit{loc}(y,x)))))(\lambda\gamma.\varphi(\gamma(x))))]$$

$$\lambda\varphi.(\forall x)[\textit{Desk}(x) \to (\exists y)[\textit{Computer}(y) \wedge \varphi(F(\textit{loc}(x,y)))]]$$

Interpretation Example

Use the trivial continuation $\lambda k.k$:

$$(\lambda\varphi.(\forall x)[Desk(x) \to (\exists y)[Computer(y) \land \varphi(F(loc(x,y)))]])(\lambda k.k) \rhd_\beta$$

$$(\forall x)[Desk(x) \to (\exists y)[Computer(y) \land F(loc(x,y))]]$$

Finally attaching the nominal:

$$@_{now}(\forall x)[Desk(x) \to (\exists y)[Computer(y) \land F(loc(x,y))]]$$

Conclusion

- We explored how AMR can benefit from formal inference.
- Described a combination of AMR extensions.
- Sketched a first-order hybrid logic variant with general proof procedure and model checking methods.
- Demonstrated how sentences are handled by these methods.
- Showed how AMR sentences can be translated into *FHTL*

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