

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

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

- ▶ 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/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

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

$$\frac{\begin{array}{c} @_s @_t \varphi \\ @_t \varphi \end{array}}{(@)}$$

$$\frac{\begin{array}{c} @_s (\exists x) \varphi \\ @_s \varphi[s:p/x] \end{array}}{(\exists)^3}$$

$$\frac{\begin{array}{c} @_i j:t = k:s \quad @_i \varphi \\ @_i \varphi[j:t//k:s] \end{array}}{(\text{sub})^4}$$

¹The nominal a is new to the branch.

²The formula φ is not a nominal.

³ $s:p$ is new to the branch.

⁴ $\varphi[j:t//k:s]$ is φ where some occurrences of $j:t$ have been replaced by $k:s$.

FHTL Tableau Example

$$\begin{array}{lcl}
 (1) & & \\
 (2) & @_s(\exists x)[P((\exists y)[f(x, y) = f(y, x)]) \vee \neg(\exists z)[x = z]] & \\
 (3) & @_sP((\exists y)[f(s_1, y) = f(y, s_1)]) \vee \neg(\exists z)[s_1 = z] & \\
 & \swarrow \quad \searrow & \\
 (4) & @_sP((\exists y)[f(s_1, y) = f(y, s_1)]) & @_s\neg(\exists z)[s_1 = z] \\
 (5) & @_sPt & @_s\neg[s_1 = s_1] \\
 (6) & @_t(\exists y)[f(s_1, y) = f(y, s_1)] & @_s[s_1 = s_1] \\
 (7) & \dots & \otimes
 \end{array}$$

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:

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

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

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

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

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

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

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

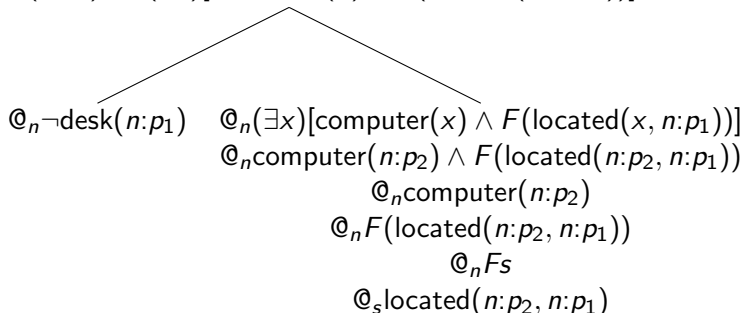
$$D_{now} = \{computer_1, computer_2, desk_1, desk_2, desk_3\}$$

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

Model Checking Example

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

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



Where we assign $s = t = \text{tomorrow}$, $n:p_2 = \text{computer}_1$ and $n:p_1 = \text{desk}_2$, or $n:p_2 = \text{computer}_2$ and $n:p_1 = \text{desk}_1$ 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. $@_tP\psi$
- ▶ 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 (...))
```

$$\llbracket \text{op1} \rrbracket \vee \llbracket \text{op2} \rrbracket \vee \llbracket \text{op3} \rrbracket$$

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

$$\llbracket \text{<primary-scope>} \rrbracket (\llbracket \text{<secondary-scope>} \rrbracket (\llbracket \text{pred} \rrbracket))$$

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)
```

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

$$\llbracket \text{now} \rrbracket \triangleright \text{now}$$

$$\llbracket \text{after} \rrbracket \triangleright F$$

(c / computer)

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

(d / desk

:quant (e/ every))

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

Interpretation Example

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

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

Interpretation Example

First application:

$\llbracket \textit{computer will be located at it} \rrbracket =$

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

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

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

Interpretation Example

Second application:

$$\begin{aligned}
 & \lambda\varphi. \llbracket \text{every desk} \rrbracket (\lambda\psi \llbracket \text{computer will be located at it} \rrbracket (\lambda\gamma. \varphi(\psi(\psi)))) \triangleright_{\beta} \\
 & \lambda\varphi. (\lambda\varphi'. \forall x [\text{Desk}(x) \rightarrow \varphi'(x)]) (\lambda\psi \llbracket \text{computer located at it} \rrbracket (\lambda\gamma. \varphi(\gamma(\psi)))) \\
 & \lambda\varphi. (\forall x) [\text{Desk}(x) \rightarrow (\llbracket \text{computer located at it} \rrbracket (\lambda\gamma. \varphi(\gamma(x))))] = \\
 & \lambda\varphi. (\forall x) [\text{Desk}(x) \rightarrow ((\lambda\varphi'. (\exists y) (\text{computer}(c) \wedge (\varphi(\lambda x. F(\text{loc}(y, x))))) (\lambda\gamma. \varphi(\gamma(x)))))] \\
 & \lambda\varphi. (\forall x) [\text{Desk}(x) \rightarrow (\exists y) [\text{Computer}(y) \wedge \varphi(F(\text{loc}(x, y)))]
 \end{aligned}$$

Interpretation Example

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

$$(\lambda\varphi.(\forall x)[Desk(x) \rightarrow (\exists y)[Computer(y) \wedge \varphi(F(loc(x, y)))]])(\lambda k.k) \triangleright_{\beta} \\ (\forall x)[Desk(x) \rightarrow (\exists y)[Computer(y) \wedge F(loc(x, y))]]$$

Finally attaching the nominal:

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

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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