Formalization of AMR Inference via Hybrid Logic Tableaux

Eli Goldner

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Abstract

AMR and its extensions have become popular in semantic representation due to their ease of annotation by non-experts, attention to the predicative core of sentences, and abstraction away from various syntactic matter. An area where AMR and its extensions warrant improvement is formalization and suitability for inference, where it is lacking compared to other semantic representations, such as description logics, episodic logic, and discourse representation theory. This thesis presents a formalization of inference over a merging of Donatelli et al.'s (2018) AMR extension for tense and aspect and with Pustejovsky et al.'s (2019) AMR extension for quantification and scope. Inference is modeled with a merging of Blackburn and Marx's tableaux method for quantified hybrid logic (*QHL*) and Blackburn and Jørgensen's tableux method for basic hybrid tense logic (*BHTL*). We motivate the merging of these AMR variants, present their interpretation and inference in the combination of *QHL* and *BHTL*, which we will call *QHTL* (quantified hybrid tense logic), and demonstrate *QHTL*'s the soundess, completeness, and decidability.

1 Introduction

2 Related Work

We draw from a number of areas which motivate this approach, namely designing semantic representations for inferentiability, the history and goals of AMR and its different annotations, and hybrid logic with its variants and their accompanying tableaux methods for proof.

2.1 Inference in Semantic Representation

Semantic representation is the task of representing meaning at the sentential and potentially the discourse levels of language in a formally specifiable way.

2.2 Discourse Representation Theory

Discourse representation theory was developed in 1981 by Hans Kamp (Kamp and Reyle, 1993) and a simlar theory independently in 1982 by Irene Heim under the name of *File Change Semantics* (FCS) (Heim, 1982).

Discourse representation theory (DRT) uses discourse representation structures (DRS) to represent a listeners understanding of the discourse content as it develops over time.

A DRS has two main components:

- A set of *referents*, representing entities which are in the discourse.
- A set of *conditions*, representing information about the discourse referents.

For instance, the single sentence *The farmer saw the rancher.* admits the DRS:

(1) [x, y : farmer(x), rancher(y), saw(x,y)]

The conditions in 1 are *simple*, that is they do not take the form of DRSs or constructions of DRSs, an example of a DRS with complex conditionals, would be for the sentence *If a farmer owns a dog, they feed it.*

(2) $[_1 x$: farmer(x),
$[_2 y$: dog(y), owns(x, y) $\rightarrow [_3 v, w$: feeds(v, w) $]]]$

2.2.1 Segmented Discourse Representation Theory

2.3 Description Logics

More expressive than propositional logic, less expressive than first-order logic. Examples: OWL-DL (Sirin et al., 2007), (Cimiano et al., 2014).

A DL models *concepts*, *roles*, and *individuals*, and relationships among them .

DL relates roles and concepts via *axioms*, the key modeling concept of DL, in contrast to frame spacifications in AI which declare and completely define classes (Grau et al., 2008).

First DL-based knowledge representation system was KL-ONE (Brachman and Schmolze, 1985).

Other 1980s DL systems – *substructural subsumption algorithms*, lower expressivity but polynomial time reasoning (Van Harmelen et al., 2008, Chapter 3).

Introduction of tableaux based algorithms in 90s allowed greater efficiency on problems in more expressive DL.

Modern DL (Sirin et al., 2007) (Tsarkov and Horrocks, 2006) and RacerPro (Haarslev et al., 2012) (from Racer (Haarslev and Möller, 2001))

Advantages: Comparatively expressive but still decidable, good for domain specific knowledge.

Disadvantages: Not expressive enough for semantic representation of language, designed to be a knowledge representation (Schubert, 2015a).

2.4 Situation Semantics and Related

2.4.1 Situation Semantics

2.4.2 Type Theory with Records

2.4.3 PTT

2.4.4 KoS

2.5 Episodic Logic

Episodic Logic is a Montague-style logical form based semantic representation and knowledge representation, with relative strength in semantic expressivity and inferetiability in comparison to other semantic representation, making it better comparatively better suited for deep NLU (Schubert, 2015b). Episodic Logic allows for generalized quantifiers, lambda abstraction, reification and modification of sentences and predicates, intensional predicates, unreliable generalizations, and explicit situational variables (Schubert and Hwang, 2000). Episodic Logic with its inference engine EPILOG provide a way to capture a relatively comprehensive range of semantic phenomena compared to other SR/KRs, in a way which affords inference about semantic data at a comparable efficiency with automated inference engines for first order logic (Schubert, 2015b). It also has an associated knowledge base KNEXT which is capable of parsing sentences into factoids, generalizing them (through a process called quantificational sharpening), and making certain judgements about whether a generalized factoid is redudant or inconsistent with anything established in the knowledge base.

2.6 Semantic Features in AMR and Possbility of Inference

Separating argument structure in AMR from logical structure, enables translation from AMR to DRT (Bos, 2020)

AMR expressivity without recurrent variables (and with no more than one universal quantifier per sentence) are in the decidable two-variable fragment of first-order logic (Bos, 2016)

Extension of sentential AMR to incorporate a coarse grained treatment of tense and aspect (Donatelli et al., 2018)

Continuation based semantics for translating AMR into first-order logic in a way that preserves projection phenomena such as quantification, negation, bound variables, and donkey anaphora, which better affords inference than other first-order logic semantics for AMR (Lai et al., 2020).

2.7 Hybrid Logic and Our Chosen Semantic Features

3 Merging AMR Annotations

3.1 AMR Annotated for Tense and Aspect

3.2 AMR Annotated for Scope and Quantification

4 Merging Quantified Hybrid Logic and Indexical Hybrid Tense Logic

4.1 Background

4.1.1 Quantified Hybrid Logic

4.1.2 Basic Hybrid Tense Logic

4.2 Quantified Hybrid Tense Logic

The syntax of $QHTL$ is identical to QHL except uses of $\downarrow$ as in $\downarrow w.\phi$ are omitted along with $\Box$ and $\Diamond$ as in $\Box\phi$ and $\Diamond\phi$. $\Box$ and $\Diamond$ are replaced by their semantic equivalents F and G and their temporal duals P and H are added.

Atomic formulae are the same as in QHL, symbols in NOM and SVAR together with first-order atomic formulae generated from the predicate symbols and equality over the terms. Thus complex formulae are generated from the atomic formulae according to the following rules:

$$\neg\phi|\phi \wedge \psi|\phi \vee \psi|\phi \to \psi|\exists x\phi|\forall x\phi|F\phi|G\phi|P\phi|H\phi|@_n\phi$$

Since we want the domain of quantification to be indexed over the collection of nominals/times, we alter the QHL model definition to a structure:

$$(T, R, D_w, I_{nom}, I_w)_{w\in W}$$

Identical to the definition for a QHL model in that:

- (T, R) is a modal frame.
- I_{nom} is a function assigning members of T to nominals.

The differences manifest on the level of the model and interpretation. That is, for every $t \in T$, (D_t, I_t) is a first-order model where:

- $I_t(q) \in D_t$ where q is a unary function symbol.
- $I_t(P) \subseteq^k D_t$ where P is a k-ary predicate symbol.

Notice we've relaxed the requirement that $I_t(c) = I_{t'}(c)$ for c a constant and $t, t' \in T$, since the interpretation of the constant need not exist at both times.

Free variables are handled similarly as in QHL. A $QHTL$ assignment is a function:

$$g : \mathsf{SVAR} \cup \mathsf{FVAR} \to T \cup D$$

Where state variables are sent to times/worlds and first-order variables are sent to D_t where t is the time assigned to the state variable by g. Thus given a model and an assignment g, the interpretation of terms t denoted by $\bar{t}$ is defined as:

- $\overline{x} = g_t(x)$ for x a variable and the relevant $t \in T$.
- $\overline{c} = I_t(c)$ for c a constant and some $t \in T$.
  - For q a unary function symbol:

    For n a nominal:

$$\overline{@_n q} = I_{I_{nom}}(n)$$

$$
\begin{array}{ll}
AT_x(p) & := Px \\
AT_x(n) & := x = n \\
AT_x(\neg\phi) & := \langle \lambda x.\neg AT_x(\phi)\rangle(x) \\
AT_x(\phi \wedge \psi) & := \langle \lambda x.AT_x(\phi) \wedge AT_x(\psi)\rangle(x) \\
AT_x(G\phi) & := \langle \lambda x.\forall y(Rxy \rightarrow AT_y(\phi))\rangle(x) \\
AT_x(H\phi) & := \langle \lambda x.\forall y(Ryx \rightarrow AT_y(\phi))\rangle(x) \\
AT_x(@_n\phi) & := \langle \lambda x.\forall x(x = n \rightarrow AT_x(\phi))\rangle(x) \\
AT_x(P(t_1, \ldots, t_k)) & := P'(x, t_1, \ldots, t_k) \\
AT_x(t_i = t_j) & := \langle \lambda x.t_i = t_j\rangle(x) \\
AT_x(\forall v\phi) & := \langle \lambda x.\forall v AT_x(\phi)\rangle(x)
\end{array}
$$

Figure 1: TEST

- For n a state variable:

$$\overline{@_n q} = I_{g(n)}(q)$$

With the final adjustment of having $g^x_{d,s}$ denoting the assignment which is just like g_s except $g_s(x) = d$ for $d \in g(s)$, we can proceed with the inductive definition for satisfaction of a formula give a model $\mathfrak{M}$, a variable assignment g, and a state s. The inductive definition is:

$$
\begin{array}{lll}
\mathfrak{M}, g, s \Vdash P(t_1, \ldots, t_n) & \iff & \langle \overline{t_1}, \ldots, \overline{t_n}\rangle \in I_s(P) \\
\mathfrak{M}, g, s \Vdash t_i = t_j & \iff & \overline{t_i} = \overline{t_j} \\
\mathfrak{M}, g, s \Vdash n & \iff & I_{nom}(n) = s, \text{for } n \text{ a nominal} \\
\mathfrak{M}, g, s \Vdash w & \iff & g(w) = s, \text{for } s \text{ a state variable} \\
\mathfrak{M}, g, s \Vdash \neg\phi & \iff & \mathfrak{M}, g, s \not\Vdash \phi \\
\mathfrak{M}, g, s \Vdash \phi \wedge \psi & \iff & \mathfrak{M}, g, s \Vdash \phi \text{ and } \mathfrak{M}, g, s \Vdash \psi \\
\mathfrak{M}, g, s \Vdash \phi \vee \psi & \iff & \mathfrak{M}, g, s \Vdash \phi \text{ or } \mathfrak{M}, g, s \Vdash \psi \\
\mathfrak{M}, g, s \Vdash \phi \rightarrow \psi & \iff & \mathfrak{M}, g, s \Vdash \phi \text{ implies } \mathfrak{M}, g, s \Vdash \psi \\
\mathfrak{M}, g, s \Vdash \exists x\phi & \iff & \mathfrak{M}, g^x_{d,s}, s \Vdash \phi \text{ for some } d \in D_s \\
\mathfrak{M}, g, s \Vdash \forall x\phi & \iff & \mathfrak{M}, g^x_{d,s}, s \Vdash \phi \text{ for all } d \in D_s \\
\mathfrak{M}, g, s \Vdash F\phi & \iff & \mathfrak{M}, g, t \Vdash \phi \text{ for some } t \in T \text{ such that } Rst \\
\mathfrak{M}, g, s \Vdash G\phi & \iff & \mathfrak{M}, g, t \Vdash \phi \text{ for all } t \in T \text{ such that } Rst \\
\mathfrak{M}, g, s \Vdash P\phi & \iff & \mathfrak{M}, g, t \Vdash \phi \text{ for some } t \in T \text{ such that } Rts \\
\mathfrak{M}, g, s \Vdash H\phi & \iff & \mathfrak{M}, g, t \Vdash \phi \text{ for all } t \in T \text{ such that } Rts \\
\mathfrak{M}, g, s \Vdash @_n\phi & \iff & \mathfrak{M}, g, I_{nom}(n) \Vdash \phi \text{ for } n \text{ a nominal} \\
\mathfrak{M}, g, s \Vdash @_w\phi & \iff & \mathfrak{M}, g, g(w) \Vdash \phi \text{ for } w \text{ a state variable}
\end{array}
$$

4.3 The Tableaux Calculus

Non-branching rules:

$$\frac{@_s\neg\phi}{\neg @_s\phi}\,[\neg] \qquad \frac{\neg @_s\neg\phi}{@_s\phi}\,[\neg\neg]$$

$$\frac{@_s @_t\phi}{@_t\phi}\,[@] \qquad \frac{\neg @_s @_t\phi}{\neg @_t\phi}\,[\neg @]$$

$$\frac{@_s F\phi}{\begin{array}{c} @_s Fa \\ @_a\phi \end{array}}\,[F] \qquad \frac{@_s P\phi}{\begin{array}{c} @_s Pa \\ @_a\phi \end{array}}\,[P]$$

$$\frac{\neg @_s G\phi}{\begin{array}{c} @_s Fa \\ \neg @_a\phi \end{array}}\,[\neg G] \qquad \frac{@_s H\phi}{\begin{array}{c} @_s Pa \\ \neg @_a\phi \end{array}}\,[\neg H]$$

$$\frac{@_s Pt}{@_t Fs}\,P\text{-trans} \qquad \frac{@_s Ft}{@_t Ps}\,F\text{-trans}$$

$$\frac{@_s\exists x\phi(x)}{@_c\phi(c)}\,[\exists] \qquad \frac{@_s\neg\forall x\phi(x)}{\neg @_c\phi(c)}\,[\neg\forall]$$

$$\frac{@_s\forall x\phi(x)}{@_c\phi(c)}\,[\forall] \qquad \frac{\neg @_s\exists x\phi(x)}{\neg @_c\phi(c)}\,[\neg\exists]$$

$$\frac{[s \text{ on the branch}]}{@_s s}\,[\text{ Ref }] \qquad \frac{@_t s}{@_s t}\,[\text{ Sym }]$$

$$\frac{}{t = t}\,[\text{ Ref }] \qquad \frac{@_n m}{@_n q = @_m q}\,[\text{ DD }]$$

$$\frac{@_n(t_i = t_j)}{t_i = t_j}\,@= \qquad \frac{\neg @_n(t_i = t_j)}{\neg(t_i = t_j)}\,\neg @=$$

Figure 2: Non-Branching Rules.

$$\frac{@_s(\phi \vee \psi)}{@_s\phi \mid @_s\psi} \vee \qquad \frac{\neg @_s(\phi \wedge \psi)}{\neg @_s\phi \mid \neg @_s\psi} \neg\wedge$$

$$\frac{@_s(\phi \to \psi)}{\neg @_s\phi \mid @_s\psi} \to$$

$$\frac{@_sH\phi \qquad @_sPt}{@_t\phi} H \qquad \frac{@_sG\phi \qquad @_sFt}{@_t\phi} G$$

$$\frac{@_sPt \qquad @_tu}{@_tPu} P\text{-bridge} \qquad \frac{@_sFt \qquad @_tu}{@_tFu} F\text{-bridge}$$

$$\frac{@_st \qquad @_s\phi}{@_t\phi} \text{Nom} \qquad \frac{@_st \qquad @_t\phi}{@_s\phi} \text{Nom}^{-1}$$

$$\frac{@_st \qquad @_tr}{@_sr} \text{Trans}$$

Branching rules:
Binary rules:
(Sketch)
The main issue with the tableaux of the merged logics is treatment of the quantification rules, for the existential rule, the quantifer is removed and a parameter new on the branch is substituted for the formerly bound variable, and in the universal case, the bound variable in the formula is substituted for a term already grounded on the branch (a first-order consant, parameter, or grounded definite description). What is now at issue is unlike QHL we are not using a fixed domain semantics, thus we must find a way to integrate the constraint that for universal quantification, the grounded term needs to have a known interpretation at the current world/state/time. NB: Other than the issue of encoding this constraint I see no reason why the same approach of merging would not work here as well.

4.4 Soundness and Completeness

(Sketch)

4.5 Decidability

4.5.1 Decidabililty of the Merged Logic

(Proof Sketch)
While $\mathcal{H}(\downarrow @)$ is not decidable, $\mathcal{H}(@)$ is (Areces et al., 1999). Quantified hybrid logic makes use of $\downarrow$ (Blackburn and Marx, 2002), but modulo $\downarrow$ and quantification over first-order variables does not differ from $\mathcal{H}(@)$. Basic hybrid tense logic does not make use of $\downarrow$ (Blackburn and Jørgensen, 2012), and differs only from $\mathcal{H}(@)$ in replacing the $\Box$ and $\Diamond$ with F and P, which respectively have the same sematics and similar semantics (the direction of the accesibility relation is changed) to $\Diamond$. Similarly for G and H respectively in relation to $\Box$. Thus given the absence of $\downarrow$ in the merged logic, replacing $\Box$ and $\Diamond$ with F and P (and by extension G and H) will not have negatively affect the decidability given the analogous complexity of F and P to $\Diamond$. This is especially the case for us because nominals are document creation times, of which there will necessarily be a finite number, all totally ordered, which in turn will make checking accessibility more efficient. Keeping quantification over first-order variables will not affect decidability since we take the domain of quantification to be objects that exist at a particular world, that is at the time indicated by the nominal which picks out that world. That is we use presentist quantification as opposed to eternalist quantification.

4.5.2 Termination of the Tableaux/Decision Procedure

Bolander and Braüner (2006) seems like the clearest place to start from for termination of the tableaux. Norgėla and Šalaviejienė (2007) and Norgėla (2012) seem potentially useful but they discuss things in terms of sequents rather than tableaux.

5 AMR Interpretation in Hybrid Logic

5.1 Examples

(3) a. Carl submitted the forms and everyone will sign up again tomorrow.
b.

```
(a / and
   :op1 (s / scope
      :pred (f / fill-out-03 :ongoing - :complete + :time (b / before :op1 (n / now))
         :ARG0 (p / person
            :name (n2 / name
               :op "Carl"))
         :ARG1 (f2 / form))
      :ARG0 p
      :ARG1 f2)
   :op2 (s2 / scope
      :pred (m / submit-01 :ongoing - :complete + :time (a2 / after :op1 n)
         :ARG0 (p2 / person
            :mod (a3 / all))
         :ARG1 f2)
      :ARG0 p2
      :ARG1 f2))
```

c. It was impossible not to notice the license plate.

d.

```
(s / scope
      :pred (p / possible-01
         :ARG0 (n / notice-01 :ongoing - :complete + :time (b / before :op1 (n2 / now))
            :polarity (n3 / not)
            :ARG1 (c /car)
         :polarity (n4 / not))
      :ARG0 n4
      :ARG1 p))
```

NB: Will complete these translations in full.

5.2 Extraction Steps

With the chosen annotation, the root node can consist of either a logical connective (`and`, `or`, or `cond`) linking two AMR graphs, or a `scope` node with its following predicate and arguments.

5.3 General Extraction Algorithm

6 Future Work

6.1 $\downarrow$ and Quantification over Nominals

Main points, at the cost of undecidability with adding $\downarrow$ some additional things can be done, and at the cost of the integration of generalized quantifiers you can ostensibly handle even things like habitual aspect.

6.2 AMR Reentrancy and Non-Temoral Nominals

There are some difficulties with maintaining the usual notion of possible worlds being maximal with this idea, but there seems to be a direct sympathy between the predicative core of an AMR sentence and in general reentrancy of the nodes with the idea of a nominal as a "point of view" rather than the "name" of a world. Maybe things like epistemic logic could be helpful here.

6.3 Automated Inference and HTab

HTab (Hoffmann and Areces, 2009) provides an implementation of $\mathcal{H}(@, \mathsf{A})$, which does not natively provide a way to reason with P, H, or first-order quantification. The effort required in making the needed changes to handle these remains to be determined.

6.4 The Future of AMR and Parsing for Semantic Features

To what extent can current AMR parsers extract the needed semantic features to make full use of automated inference? Of UMR, Dialogue-AMR, and the AMR annotation variants we've used, which logistically has the best outlook?

7 Conclusion

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