

# Formalization of AMR Inference via Hybrid Logic Tableaux

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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 Hansen's (2007) tableau method for first-order hybrid logic with varying domain semantics (*FHL*) and Blackburn and Jørgensen's (2012) tableau method for basic hybrid tense logic (*BHTL*). We motivate the merging of these AMR variants, present their interpretation and inference in the combination of *FHL* and *BHTL*, which we will call *FHTL* (first-order hybrid tense logic), and demonstrate *FHTL*'s soundness, completeness, and decidability.

## 1 Introduction

## 2 Related Work

### 2.1 Semantic Features in AMR and Possibility 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). This uses a neo-davidsonian representation for the target first-order logic semantics.

## 3 Merging Quantified Hybrid Logic and Indexical Hybrid Tense Logic

### 3.1 Background

Hybrid logic is an extension of the propositional modal logic  $K$  ( $K$  has no conditions on the modal frame of its underlying models) allowing for explicit reference to modal states/worlds through a prefix notation. Where ordinary modal logic writes  $\Diamond p$  to indicate that there is some world where  $p$  holds at some world accessible from that world, hybrid logic by default writes one of  $a\Diamond p$ ,  $a:\Diamond p$ , or  $@_a\Diamond p$  (we use the latter notation from here on), to indicate  $p$  holds at some world accessible from  $a$  specifically.  $a$  in this notation is a *nominal*, which uniquely names a world in the underlying model. A *world* in a modal or hybrid model for us is essentially just a maximal set of sentences in the language, that is for any proposition  $p$  and nominal  $a$  we have either  $@_ap$  or  $@_a\neg p$ . Worlds are used to model any notion consistent with it, usually possible states of affairs, in particular we will use them to describe states of affairs at different points in time.

### 3.2 First-order Hybrid Logic

First-order modal logic (or quantified modal logic / QML) extends first-order predicate logic in a way analogous to how propositional modal logic extends first order propositional logic. An introduction to both QML and propositional modal logic can be found in Fitting and Mendelsohn (1998). Hansen (2007)

from  
 Blackburn and Marx (2002)

### 3.3 Basic Hybrid Tense Logic

Blackburn and Jørgensen (2012)

## 4 First-order Hybrid Tense Logic - Syntax and Semantics

The syntax of *FHTL* is identical to *FHL* as given in Hansen (2007) except uses of  $\downarrow$  as in  $\downarrow w.\varphi$  are omitted along with  $\Box$  and  $\Diamond$  as in  $\Box\varphi$  and  $\Diamond\varphi$ .  $\Box$  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 *FHL*, 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:

$$\neg\varphi \mid \varphi \wedge \psi \mid \varphi \vee \psi \mid \varphi \rightarrow \psi \mid \exists x\varphi \mid \forall x\varphi \mid F\varphi \mid G\varphi \mid P\varphi \mid H\varphi \mid @_n\varphi$$

Since we want the domain of quantification to be indexed over the collection of nominals/times, we look to Fitting and Mendelsohn's (1998) treatment of first-order modal logic with varying domain semantics and use it to alter the *FHL* model definition to the following:

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

Thus with varying domain semantics a *FHTL* model is identical to the definition for a *FHL* 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. Namely, where  $D = \cup_{t \in T} D_t$ ,  $(D, I_t)$  is a first-order model where:

- $I_t(q) \in D$  where  $q$  is a unary function symbol.
- $I_t(P) \in D^k$  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. This permits us to distinguish between the domain of a frame and the domain of a time/world, in a way that prevents a variable  $x$  from failing to refer at a given time/world, even if it has no interpretation at that time. Intuitively this permits *FHTL* to handle interpretation of entities in natural language utterances, which while reasonable to refer to do not exist at a current time, e.g. previous and future presidents.

Free variables are handled similarly as in *FHL*. Where again  $D = \cup_{t \in T} D_t$ , a *FHTL* assignment is a function:

$$g: \text{SVAR} \cup \text{FVAR} \rightarrow T \cup D$$

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

- $\bar{x} = g(x)$  for  $x$  a variable.
- $\bar{c} = I_t(c)$  for  $c$  a constant and some  $t \in T$ .
- For  $q$  a unary function symbol:
  - For  $n$  a nominal:  

$$\overline{@_n q} = I_{I_{nom}(n)}(q)$$
  - For  $n$  a state variable:  

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

Finally we say an assignment  $g'$  is an  $x$ -variant of  $g$  if  $g'$  and  $g$  on all variables except possibly  $x$ . In particular, we say  $g'$  is an  $x$ -variant of  $g$  at  $t$ , a time, if  $g'$  and  $g$  on all variables except possibly  $x$  and  $g'(x) \in D_t$ . We omit definitions for  $\wedge$ ,  $\rightarrow$ ,  $H$ ,  $G$ , and  $\forall$ , since they can be defined in terms of the other rules. Given a model  $\mathfrak{M}$ , a variable assignment  $g$ , and a state  $s$ , the inductive definition of  $\mathfrak{M}, s \models_g \varphi$  is:

$$\begin{aligned}
\mathfrak{M}, s \models_g P(t_1, \dots, t_n) &\iff \langle \bar{t}_1, \dots, \bar{t}_n \rangle \in I_s(P) \\
\mathfrak{M}, s \models_g t_i = t_j &\iff \bar{t}_i = \bar{t}_j \\
\mathfrak{M}, s \models_g n &\iff I_{nom}(n) = s, \text{ for } n \text{ a nominal} \\
\mathfrak{M}, s \models_g w &\iff g(w) = s, \text{ for } w \text{ a state variable} \\
\mathfrak{M}, s \models_g \neg\varphi &\iff \mathfrak{M}, s \not\models_g \varphi \\
\mathfrak{M}, s \models_g \varphi \vee \psi &\iff \mathfrak{M}, s \models_g \varphi \text{ or } \mathfrak{M}, s \models_g \psi \\
\mathfrak{M}, s \models_g \exists x\varphi &\iff \mathfrak{M}, s \models_{g'} \varphi \text{ for some } x\text{-variant } g' \text{ of } g \text{ at } s \\
\mathfrak{M}, s \models_g F\varphi &\iff \mathfrak{M}, t \models_g \varphi \text{ for some } t \in T \text{ such that } Rst \\
\mathfrak{M}, s \models_g P\varphi &\iff \mathfrak{M}, t \models_g \varphi \text{ for some } t \in T \text{ such that } Rts \\
\mathfrak{M}, s \models_g @_n\varphi &\iff \mathfrak{M}, I_{nom}(n) \models_g \varphi \text{ for } n \text{ a nominal} \\
\mathfrak{M}, s \models_g @_w\varphi &\iff \mathfrak{M}, g(w) \models_g \varphi \text{ for } w \text{ a state variable}
\end{aligned}$$

## 4.1 The Tableau Calculus

Following Fitting and Mendelsohn (1998) we assume for each nominal or state variable  $s$ , there is an infinite list of parameters, where parameters are free variables which are never quantified over, arranged in such a way that different nominals/state variables never share the same parameter. Informally we write  $p_s$  to indicate a parameter is associated with a nominal/state variable  $s$ .

## 4.2 Soundness and completeness

**Definition 4.1 (Quasi-subformula).** A formula  $\varphi$  is a *quasi-subformula* of a formula  $\psi$  if one of the the following is the case:

1.  $\varphi$  is a subformula of  $\psi$  modulo renaming of free variables and substitution of free variables in  $\varphi$  for grounded terms.
2.  $\varphi$  is of the form  $\neg\chi$  where  $\chi$  is a subformula of  $\psi$  modulo renaming of free variables in  $\chi$  for grounded terms.

Altering the definition to allow grounded terms being substituted for free variables ensures compatibility of the following proofs with the quantifier and term rules. We say a formula  $@_s\varphi$  on a *FHTL* tableau branch  $\Theta$  is a *root subformula* if  $\varphi$  is a quasi subformula of the root formula of the tableau.

**Lemma 4.1 (Subformula Property).** *Where  $\Theta$  is a tableau branch in the FHTL calculus, and a formula  $@_s\varphi$  occurs on  $\Theta$  where  $\varphi$  is not of the form  $a$ ,  $Fa$ , or  $Pa$  for  $a$  a nominal, or  $u = t$  for optionally prefixed closed terms  $t$  and  $u$ , then  $\varphi$  is a root subformula.*

*Proof.* This is verified by checking the tableau rules. □

**Definition 4.2 ( $\prec_\Theta$ ).** Where  $\Theta$  is a tableau branch in the *FHTL* calculus, if a nominal  $a$  is introduced to the branch by application of of  $F$  or  $P$  to a premise  $@_s\varphi$ , we say  $a$  is *generated* by  $s$  on  $\Theta$  and write  $s \prec_\Theta a$ . We write  $\prec_\Theta^*$  to denote the reflexive and transitive closure of  $\prec_\Theta$ .

**Definition 4.3 ( $N_\Theta$ ).** The set of nominals and state variables which occur on  $\Theta$  is written  $N_\Theta$

**Lemma 4.2.** *Where  $\Theta$  is a tableau branch in the FHTL calculus, the graph  $G = (N_\Theta, \prec_\Theta)$  is a wellfounded finitely branching tree.*

*Proof.* Each aspect is proved below:

- *Wellfoundedness of trees in  $G$*

We have that if  $a \prec_\Theta b$  then the first occurrence of  $a$  on  $\Theta$  is before the first occurrence of  $b$ , thus by induction any subset of  $N_\Theta$  under the relation  $\prec_\Theta$  has a least element and each tree in  $G$  is wellfounded.

**Propositional rules:**

$$\frac{\begin{array}{c} @_s(\varphi \vee \psi) \\ @_s\varphi \mid @_s\psi \end{array}}{ @_s\varphi } (\vee)$$

$$\frac{\begin{array}{c} @_s\neg(\varphi \vee \psi) \\ @_s\neg\varphi \end{array}}{ @_s\neg\psi } (\neg\vee)$$

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

**Modal rules:**

$$\frac{\begin{array}{c} @_sF\varphi \\ @_sFa \end{array}}{ @_a\varphi } (F)^{ab}$$

$$\frac{\begin{array}{c} @_sP\varphi \\ @_sPa \end{array}}{ @_a\varphi } (P)^{ab}$$

$$\frac{\begin{array}{c} @_s\neg P\varphi \\ @_t\neg\varphi \end{array}}{ @_a\varphi } (\neg P) \quad \frac{\begin{array}{c} @_sPt \\ @_t\neg\varphi \end{array}}{ @_a\varphi } (\neg P) \quad \frac{\begin{array}{c} @_s\neg F\varphi \\ @_t\neg\varphi \end{array}}{ @_a\varphi } (\neg F) \quad \frac{\begin{array}{c} @_s\neg Ft \\ @_t\neg\varphi \end{array}}{ @_a\varphi } (\neg F)$$

**Quantifier rules:**

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

$$\frac{\begin{array}{c} @_s\neg\exists x\varphi \\ @_s\neg\varphi[t/x] \end{array}}{ @_s\varphi } (\neg\exists)^d$$

**Equality rules:**

$$\frac{}{@_ij:t = j:t} (\text{ref})^e$$

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

**@ rules:**

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

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

$$\frac{\begin{array}{c} @_st \\ @_t\varphi \end{array}}{ @_t\varphi } (\text{nom})$$

$$\frac{[i \text{ on the branch}]}{@_ii} (\text{nom ref})$$

$$\frac{\begin{array}{c} @_sPt \\ @_tFs \end{array}}{ @_tFs } (P\text{-trans})$$

$$\frac{\begin{array}{c} @_sFt \\ @_tPs \end{array}}{ @_tPs } (F\text{-trans})$$

$$\frac{\begin{array}{c} @_sPt \\ @_sPu \end{array}}{ @_s\varphi } (P\text{-bridge})$$

$$\frac{\begin{array}{c} @_sFt \\ @_sFu \end{array}}{ @_s\varphi } (F\text{-bridge})$$

**FHTL term rules:**

$$\frac{\begin{array}{c} @_ik_1:t = k_2:s \\ @_ik_1:t = k_2:s \end{array}}{ @_ik_1:t = k_2:s } (\text{:1})$$

$$\frac{\begin{array}{c} @_ij \\ @_ki:t = j:t \end{array}}{ @_kj:t = j:t } (\text{:2})^a$$

$$\frac{}{@_ik:j:t = j:t} (\text{:3})^a$$

$$\frac{\begin{array}{c} @_iR(t_1, \dots, t_n) \\ @_iR(i:t_1, \dots, i:t_n) \end{array}}{ @_iR(i:t_1, \dots, i:t_n) } (\text{:fix 1}) \quad \frac{\begin{array}{c} @_i\neg R(t_1, \dots, t_n) \\ @_i\neg R(i:t_1, \dots, i:t_n) \end{array}}{ @_i\neg R(i:t_1, \dots, i:t_n) } (\text{:fix 2}) \quad \frac{\begin{array}{c} @_it = s \\ @_it = i:s \end{array}}{ @_it = i:s } (\text{:fix 3}) \quad \frac{\begin{array}{c} @_i\neg t = s \\ @_i\neg t = i:s \end{array}}{ @_i\neg t = i:s } (\text{:fix 4})$$

$$\frac{}{@_if(t_1, \dots, t_n) = f(i:t_1, \dots, i:t_n)} (\text{:func})^g$$

<sup>a</sup>The nominal  $a$  is new to the branch.

<sup>b</sup>The formula  $\varphi$  is not a nominal.

<sup>c</sup> $s:p$  is new to the branch.

<sup>d</sup> $p$  is any ground term or parameter which exists at  $s$ .

<sup>e</sup>Where  $t$  is a closed term.

<sup>f</sup> $\varphi[j:t//k:s]$  is  $\varphi$  where some occurrences of  $j:t$  have been replaced by  $k:s$ .

<sup>g</sup> $f$  is an  $n$ -ary function symbol and  $t_1, \dots, t_n$  are closed terms.

- $G$  is a tree

Every nominal in  $N_\Theta$  can be generated by at most one other nominal, and every nominal in  $N_\Theta$  must have one of the finitely many nominals in the root formula as an ancestor.

- $G$  is finitely branching

We show  $G$  is finitely branching by showing that given a nominal  $a$ , there can only be finitely many distinct nominals  $b$  such that  $a \prec_\Theta b$ . Each nominal  $b$  such that  $a \prec_\Theta b$  is generated by applying one of  $F, P$  to a premise of the form  $\text{@}_i F \varphi$  or  $\text{@}_i P \varphi$  respectively, where by our restrictions, either  $\varphi$  is not a nominal, or the entire premise is a root subformula. Since there can only be finitely many root subformulae of the form of one of the the possible premises, where  $i$  is the prefix nominal in each case, only finitely many new nominals have been generated from  $i$ . Thus  $G$  is finitely branching.

□

**Lemma 4.3.** Where  $\Theta$  is a tableau branch in the FHTL calculus,  $\Theta$  is infinite if and only if there exists an infinite chain of nominals and state variables  $a_1 \prec_\Theta a_2 \prec_\Theta \dots \prec_\Theta a_n \prec_\Theta \dots$

*Proof.* Since the structure of the formulae and tableau rules are not involved in the proof from Bolander and Blackburn (2009) holds here as well.

□

**Definition 4.4** ( $\subseteq_\Theta$ ). Where  $a$  and  $b$  are nominals occurring on an FHTL tableau branch  $\Theta$ ,  $a$  is included in  $b$  with respect to  $\Theta$  if for any root subformula  $\varphi$ , if  $\text{@}_a \varphi$  occurs on  $\Theta$  then  $\text{@}_b \varphi$  also occurs on  $\Theta$ , similarly for their negations. If  $a$  is included in  $b$  with respect to  $\Theta$ , and the first occurrence of  $b$  on  $\Theta$  is before the first occurrence of  $a$  on  $\Theta$ , then we write  $a \subseteq_\Theta b$ .

**Definition 4.5** ( $\sim_\Theta$ ). Where  $\Theta$  is a FHTL tableau branch, define a binary relation  $\sim_\Theta$  on  $N_\Theta$  by  $a \sim_\Theta b$  if and only if  $\text{@}_a b$  occurs on  $\Theta$ . Let  $\sim_\Theta^*$  be reflexive, transitive, and symmetric closure of  $\sim_\Theta$ .

**Definition 4.6** ( $W, \approx$ ). Let  $W$  be the subset of  $N_\Theta$  containing any nominal  $a$  with the property that there is no nominal  $b$  such that  $a \subseteq_\Theta b$ . Let  $\approx$  be the restriction of  $\sim_\Theta$  to  $W$ .

**Definition 4.7.** Let  $R$  be the binary relation defined on  $W$  defined by  $a R c$  if and only if there are nominals  $a' \approx a$  and  $c' \approx c$  satisfying one of the following conditions:

1. The formula  $\text{@}_{a'} F c'$  or  $\text{@}_{a'} P c'$  occurs at  $\Theta$  and was introduced to the branch by  $F$  or  $P$  respectively.
2. There is a nominal  $d \in N_\Theta$  such that the formula  $\text{@}_{a'} F d$  or  $\text{@}_{a'} P d$  was introduced to the branch by  $F$  or  $P$  respectively and  $d \subseteq_\Theta c'$
3. The formula  $\text{@}_{a'} F c'$  or  $\text{@}_{a'} P c'$  occurs at  $\Theta$  and  $a'$  or  $c'$  occurs in the root formula.

### 4.3 Tableau Construction

**Definition 4.8 (Closed and open).** If a tableau branch contains a formula  $\text{@}_s \varphi$  and its negation  $\text{@}_s \neg \varphi$  we say the branch is *closed*. If every branch of the tableau is closed we say the tableau itself is closed. If a tableau or branch is not closed we say it is *open*.

A closed tableau is a proof of the unsatisfiability of the tableau's root formula, i.e. there is no model or assignment of variables in which it holds. The question of when a tableau indicates satisfiability of the root formula leads us to our next definition.

**Definition 4.9 (Saturation).** A tableau branch is *saturated* if no more rules can be applied to the branch in a way that satisfies their constraints. If every branch of the tableau is saturated we say the tableau is saturated.

## 5 Model Checking via Tableaux

For our task of AMR inference, we are not concerned with the determining the general satisfiability or validity of an AMR formula translated into *FHTL*, but rather whether it holds in the smallest model consistent with an established set of *FTHL* translations of AMR sentences. This model will necessarily be finite, since across any finite number of AMR sentences only a finite number of times and entities can be referenced. In particular, we have a case of a local model-checking problem where given formula  $\varphi$ , a finite *FHTL* model structure  $\mathfrak{M}$ , a time  $t$  in  $\mathfrak{M}$ , and a variable assignment  $g$ , we need to determine whether  $\mathfrak{M}, t \models_g \varphi$  (Müller-Olm et al., 1999).

Consequently our use of tableaux for *FHTL* formulae will provide a decision procedure for their satisfiability within a finite model generated by some set of AMR sentences, rather than their general validity or invalidity, as is usually the case with tableaux methods. We develop an approach to using tableaux as a means of model checking for *FHTL* based on the approach in Bohn et al. (1998).

<u>Equality rules:</u>		
$\frac{[i \text{ and } j \text{ on the branch.}]}{\text{@}_i j:t = j:t} \text{ (ref)}^a$	$\frac{\text{@}_i j:t = k:s \quad \text{@}_i \varphi}{\text{@}_i \varphi[j:t//k:s]} \text{ (sub)}^b$	
<u><i>FHTL</i> term rules:</u>		
$\frac{\text{@}_i j_1:t = j_2:s}{\text{@}_k j_1:t = j_2:s} \text{ (:1)}^c$	$\frac{\text{@}_i j}{\text{@}_k i:t = j:t} \text{ (:2)}^{cd}$	$\frac{}{\text{@}_k j:i:t = i:t} \text{ (:3)}^{cd}$
$\frac{\text{@}_i R(t_1, \dots, t_n)}{\text{@}_i R(i:t_1, \dots, i:t_n)} \text{ (:fix 1)}^e$	$\frac{\text{@}_i \neg R(t_1, \dots, t_n)}{\text{@}_i \neg R(i:t_1, \dots, i:t_n)} \text{ (:fix 2)}^e$	
$\frac{\text{@}_i t = s}{\text{@}_i i:t = i:s} \text{ (:fix 3)}^e$	$\frac{\text{@}_i \neg t = s}{\text{@}_i \neg i:t = i:s} \text{ (:fix 4)}^e$	
$\frac{[i \text{ and one of the two function terms on the branch}]}{\text{@}_i f(t_1, \dots, t_n) = f(i:t_1, \dots, i:t_n)} \text{ (:func)}^f$		

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<sup>a</sup> $t$  is a closed term on the branch,  $j$  not among its prefixes.  
<sup>b</sup> $\varphi[j:t//k:s]$  is  $\varphi$  where some occurrences of  $j:t$  have been replaced by  $k:s$ .  
<sup>c</sup> $k$  on the branch.  
<sup>d</sup> $t$  is a closed term on the branch, and  $i, j$  are distinct nominals on the branch, not among the prefixes of  $t$ .  
<sup>e</sup> $i$  is not among the prefixes of the terms in the consequent.  
<sup>f</sup> $f$  is an  $n$ -ary function symbol and  $t_1, \dots, t_n$  are closed terms with  $i$  not among their prefixes.

## 5.1 Systematic tableau construction

**Definition 5.1** (*Tableau construction algorithm*). Where  $\text{@}_a \varphi$  is the formula whose validity we are deciding. We inductively define a sequence of finite tableaux  $\mathcal{T}_0, \mathcal{T}_1, \mathcal{T}_2, \dots$  each where each element of the sequence is embedded in all of its successors. We let  $\mathcal{T}_0$  be the finite tableau consisting of the formula  $\neg \text{@}_a \varphi$ . Assuming the finite tableau  $\mathcal{T}_n$  is defined. If possible, apply an arbitrary *FHTL* tableau rule with the following restriction.

- (**Loop check**) The rule  $F$  is not applied to a formula occurrence  $\text{@}_a F \varphi$  at a branch  $\Theta$  if there is a nominal  $b$  such that  $a \subseteq_\Theta b$ , and similarly for the rule  $P$ .

Let  $\mathcal{T}_{n+1}$  be the resulting tableau.

**Theorem 5.1.** *The systematic tableau construction algorithm terminates.*

*Proof.* Suppose by contradiction the ned □

## 5.2 Node Annotation

The approach involves annotating each node of an open branch with the variable assignments in the model which witness the formula at the node, building inductively from the terminal nodes. If the root formula of the tableau with at least one open branch can be annotated with non-empty set of variable assignments, then it is satisfiable in the model. If a tableau is closed then the root formula  $\text{@}_s \varphi$  is unsatisfiable. As a result if the root formula is of the form  $\text{@}_s \neg \psi$  then this constitutes a proof of the validity of  $\text{@}_s \psi$  by contradiction. We now view each node in the

tableau graph as a pair  $(@_s\varphi, \mathcal{V})$ , of the formula at the node and the set  $\mathcal{V}$  of variable assignments in our model  $\mathfrak{M}$  which witness the formula. We define an annotation function  $ann(@_s\varphi) = \mathcal{V}$  beginning with terminal nodes:

$$ann(@_s\varphi) = \{g \mid \mathfrak{M}, I_{nom}(s) \models_g \varphi\}$$

## 6 AMR Interpretation in FHTL

### 6.1 Examples

- (1) a. Carl filled out the forms and everyone will submit them 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 f2
    :ARG1 p2))
c. Technically correct:
@now ∃x[form(x) ∧ Pfill-out-03(Carl, x)] ∧ @now ∃x[form(x) ∧ ∀y[person(y) → Fsubmit-01(y, x)]]
d. Correct wrt plurality:
@now ∀x[form(x) ∧ Pfill-out-03(Carl, x)] ∧ @now ∀x[form(x) ∧ ∀y[person(y) → Fsubmit-01(y, x)]]
e. Correct wrt reentrance (but not plurality) (maybe requires the passive for singular case?):
@now ∃x[form(x) ∧ Pfill-out-03(Carl, x) ∧ ∀y[person(y) → Fsubmit-01(y, x)]]
```

- (2) a. It was impossible not to notice the car.

b.

```
(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))
c. Incorrect:
@now ¬F ∃x[car(x) ∧ ¬Pnotice-01(x)]
d. Technically correct:
@now ¬F ∃x[car(x) ∧ ¬∀y[person(y) → Pnotice-01(x, y)]]
e. Correct wrt particularity of the car:
@now ¬F ¬∀x[person(y) → Pnotice-01(car, y)]]
```

NB: Will complete these translations in full.

### 6.2 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.

### 6.3 General Extraction Algorithm

---

**Algorithm 1:** Basic transformation into *FHTL* clauses and connectives.

---

**Input:** AMR sentence  
**Output:** *FHTL* formula

```

Def InterpretEntry (AMR) :
    root = Root(AMR)
    now = current date/time
    if root ∈ {and, or, cond} then
        connective = filter(root, { $\wedge$ ,  $\vee$ ,  $\rightarrow$ })
        clauses = []
        for op ∈ Children(root) do
            | append(clauses, InterpretClause (op))
        end
        return @now join(connective, clauses)
    end
    return @now InterpretClause (root)

Def InterpretClause (AMR) :
    time = Time (AMR)
    nominal = Reference (time)
    tense = Tense (time)
    pred = Pred (AMR)(tense)
    Arg0, Arg1 = GetArgs (AMR)
    return @nominal Apply (Arg0, Apply (Arg0, pred))

```

---

**Algorithm 2:** Supporting definitions.

---

**Input:** AMR sentence  
**Output:** *FHTL* formula

```

Def Apply (pred1,pred2) :
    | return  $\lambda\varphi.\text{pred}_1(\lambda\psi.\text{pred}_2(\lambda\gamma.\varphi(\psi(\gamma))))$ 

Def InterpretPred (UnaryPred) :
    | if hasMods(UnaryPred) then
        | | mods = [name(UnaryPred)]
        | | for mod ∈ Children(UnaryPred) do
        | | | | append(mods, name(mod)(x))
        | | end
        | | FinalPred =  $\lambda x.$  join(mods,  $\wedge$ )
    | end
    | else
    | | FinalPred =  $\lambda x.$  name(UnaryPred)(x)
    | end
    | if Quant(UnaryPred) == :all then
    | | return  $\lambda k.\forall x[\text{FinalPred}(x) \rightarrow k(x)]$ 
    | end
    | else
    | | return  $\lambda k.\exists x[\text{FinalPred}(x) \wedge k(x)]$ 
    | end

```

---

## 7 Future Work

### 7.1 $\downarrow$ 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.

### 7.2 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.

### 7.3 Automated Inference and HTab

HTab (Hoffmann and Areces, 2009) provides an implementation of  $\mathcal{H}(@, A)$ , 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.

### 7.4 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 logically has the best outlook?

## 8 Conclusion

We have demonstrated how the core aspects of AMR along with annotations for scope, quantification, and tense, can be accommodated in first-order hybrid tense logic, and that *FHTL* better affords reasoning and inference than AMR, given its general tableau method which acts as a proof procedure for *FHTL* sentences and its terminating tableau method which acts as a model checker.

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