

Analytic Proof Systems for Humberstone Logic

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Abstract

We give sequent calculus, analytic tableaux, natural deduction, and clause translation systems for resolution for Humberstone logic.

1 Introduction

In this paper we present calculi for Humberstone logic [8]. Humberstone logic has four truth values $1, 2, 3, 4$ (with $1, 2$ designated), and connectives $\wedge, \vee, \neg, \text{P}$. Its syntax and semantics is detailed in section 2.

We first present a 4-sided sequent calculus in section 3. The fundamental idea for many-sided sequent calculi for finite-valued logics goes back to Schröter [13], Rousseau [10], Takahashi [15]. We follow the method given by Baaz, Fermüller, and Zach [4] and Zach [16] for constructing inference rules. This guarantees that our system automatically has cut-elimination and Maehara lemma.

Signed tableau systems for finite-valued logics were proposed by Surma [14] and Carnielli [6], and generalized by Hähnle [7]. In section 4, we present a signed tableau system for Humberstone logic.

Many-valued natural deduction systems for finite-valued logics have been investigated by Baaz, Fermüller, and Zach [3] and Zach [16]. We give the introduction and elimination rules for the natural deduction system for Humberstone logic in section 5.

In addition to Hähnle's work on tableaux-based theorem proving for finite-valued logic, O'Hearn and Stachniak [9] and Baaz and Fermüller [1] have studied resolution calculi. In order for these calculi to be used to prove that formulas of Humberstone are valid or follow from some others, it is necessary to produce sets of signed clauses. In section 6, we present a translation calculus that yields a set of clauses from a set of formulas.

The rules we provide are optimal in each case, and use the algorithms developed by Salzer [11, 12].

2 Syntax and semantics

Definition 1. The *propositional language* \mathcal{L} for Humberstone logic consists of

*Generated from the truth tables of Humberstone logic by MULTLOG, v. 1.13.

1. propositional variables: x_0, x_1, x_2, \dots
2. propositional connectives, arity given in parenthesis: $\wedge (2), \vee (2), \neg (1)$, and $\mathbf{P} (1)$
3. auxiliary symbols: “(”, “)” and “,”

Formulas are defined inductively:

1. Every propositional variable is a formula.
2. If A and B are formulas, so is $(A \wedge B)$.
3. If A and B are formulas, so is $(A \vee B)$.
4. If A is a formula, so is $\neg A$.
5. If A is a formula, so is $\mathbf{P}A$.

As a notational convention, lowercase letters will be used to denote variables, possibly indexed. Uppercase letters A, B, C, \dots will stand for formulas, greek letters $\Gamma, \Delta, \Lambda, \dots$ for sequences and sets of formulas. The symbol \square stands for general propositional connectives.

Definition 2. The *matrix* for Humberstone logic is given by:

1. the set of *truth values* $V = \{1, 2, 3, 4\}$,
2. the set $V^+ = \{1, 2\} \subseteq V$ of *designated truth values*,
3. the truth functions for connectives \wedge, \vee, \neg and \mathbf{P} , as given below;

The set of *undesignated values* is $V^- = V \setminus V^+ = \{3, 4\}$.

The truth functions for connectives \wedge, \vee, \neg and \mathbf{P} are defined by

$\tilde{\wedge}$	1	2	3	4	$\tilde{\vee}$	1	2	3	4	$\tilde{\neg}$		$\tilde{\mathbf{P}}$	
1	1	1	3	3	1	1	2	1	2	1	4	1	1
2	1	2	3	4	2	2	2	2	2	2	3	2	1
3	3	3	3	3	3	1	2	3	4	3	2	3	1
4	3	4	3	4	4	2	2	4	4	4	1	4	4

Definition 3. Let A be a formula and x_0, x_1, \dots, x_k the variables occurring in A . Then an *interpretation* \mathbf{I} of A is an assignment of truth values to the variables.

Definition 4. Given an interpretation \mathbf{I} , we define the *valuation* $\text{val}_{\mathbf{I}}$ for formulas A to truth values as follows:

1. If A is atomic, then $\text{val}_{\mathbf{I}}(A)$ simply is the interpretation of A .
2. If $A = \square(A_1, \dots, A_n)$, where A_1, \dots, A_n are formulas, and $\tilde{\square}$ is the associated truth function to \square , then $\text{val}_{\mathbf{I}}(A) = \tilde{\square}(\text{val}_{\mathbf{I}}(A_1), \dots, \text{val}_{\mathbf{I}}(A_n))$.

Definition 5. An interpretation \mathbf{I} *satisfies* a formula A , in symbols: $\mathbf{I} \models A$, iff $\text{val}_{\mathbf{I}}(A) \in V^+$.

Definition 6. Δ *entails* A iff $\mathbf{I} \models A$ for every interpretation \mathbf{I} such that $\mathbf{I} \models B$ for all $B \in \Delta$. A is a *tautology* iff it is satisfied by every interpretation \mathbf{I} .

3 Sequent calculus for Humberstone Logic

Definition 7 (Syntax of Sequents). A *sequent* Γ is a quadruple $\Gamma_1 \mid \Gamma_2 \mid \Gamma_3 \mid \Gamma_4$, of finite sequences Γ_v of formulas, where $v \in V$. The Γ_v are called the *components* of Γ .

For a sequence of formulas Δ , and $W \subseteq V$, let $[W:\Delta]$ denote the sequent whose component Γ_v is Δ if $v \in W$ and empty otherwise. For $\{w_1, \dots, w_k\}:\Delta$ we also write $[w_1, \dots, w_k:\Delta]$. If Γ and Γ' are sequents, then Γ, Γ' denotes the sequent $\Gamma_1, \Gamma'_1 \mid \dots \mid \Gamma_4, \Gamma'_4$.

Definition 8. Let \mathbf{I} be an interpretation. \mathbf{I} *satisfies* a sequent Γ iff there is a $v \in V$ so that for some formula $A \in \Gamma_v$, $\text{val}_{\mathbf{I}}(A) = v$. \mathbf{I} is called a *model* of Γ , in symbols $\mathbf{I} \models \Gamma$.

Γ is called *satisfiable* iff there is an interpretation \mathbf{I} so that $\mathbf{I} \models \Gamma$ and *valid* iff for every interpretation \mathbf{I} , $\mathbf{I} \models \Gamma$.

Proposition 9. $\Delta \models A$ iff the sequent $[3, 4:\Delta], [1, 2:A]$ is valid.

Definition 10. The *sequent calculus* for Humberstone logic is given by:

1. axiom schemas of the form $[V:A]$,
2. weakening rules for every truth value v :

$$\frac{\Gamma}{\Gamma, [v:A]} \text{W}:v$$

3. exchange rules for every truth value v :

$$\frac{\Gamma, [v:A, B], \Delta}{\Gamma, [v:B, A], \Delta} \text{X}:v$$

4. contraction rules for every truth value v :

$$\frac{\Gamma, [v:A, A]}{\Gamma, [v:A]} \text{C}:v$$

5. cut rules for every two truth values $v \neq w$:

$$\frac{\Gamma, [v:A] \quad \Delta, [w:A]}{\Gamma, \Delta} \text{CUT}:vw$$

6. an introduction rule $\Box:v$ for every connective \Box and every truth value v , as specified below.

(2)–(5) are called *structural rules*. (6) are called *logical rules*.

The introduction rules for connective \wedge are given by

$$\begin{array}{c}
\frac{\Gamma, [1, 2: B] \quad \Gamma, [1: A, B] \quad \Gamma, [1, 2: A]}{\Gamma, [1: A \wedge B]} \wedge:1 \quad \frac{\Gamma, [2: B] \quad \Gamma, [2: A]}{\Gamma, [2: A \wedge B]} \wedge:2 \\
\frac{\Gamma, [1, 3: A, B] \quad \Gamma, [3, 4: A, B]}{\Gamma, [3: A \wedge B]} \wedge:3 \\
\frac{\Gamma, [2, 4: B] \quad \Gamma, [4: A, B] \quad \Gamma, [2, 4: A]}{\Gamma, [4: A \wedge B]} \wedge:4
\end{array}$$

The introduction rules for connective \vee are given by

$$\begin{array}{c}
\frac{\Gamma, [1, 3: B] \quad \Gamma, [1: A, B] \quad \Gamma, [1, 3: A]}{\Gamma, [1: A \vee B]} \vee:1 \\
\frac{\Gamma, [1, 2: A, B] \quad \Gamma, [2, 4: A, B]}{\Gamma, [2: A \vee B]} \vee:2 \quad \frac{\Gamma, [3: B] \quad \Gamma, [3: A]}{\Gamma, [3: A \vee B]} \vee:3 \\
\frac{\Gamma, [3, 4: B] \quad \Gamma, [4: A, B] \quad \Gamma, [3, 4: A]}{\Gamma, [4: A \vee B]} \vee:4
\end{array}$$

The introduction rules for connective \neg are given by

$$\frac{\Gamma, [4: A]}{\Gamma, [1: \neg A]} \neg:1 \quad \frac{\Gamma, [3: A]}{\Gamma, [2: \neg A]} \neg:2 \quad \frac{\Gamma, [2: A]}{\Gamma, [3: \neg A]} \neg:3 \quad \frac{\Gamma, [1: A]}{\Gamma, [4: \neg A]} \neg:4$$

The introduction rules for connective P are given by

$$\frac{\Gamma, [1, 2, 3: A]}{\Gamma, [1: \mathsf{P}A]} \mathsf{P}:1 \quad \frac{\Gamma}{\Gamma, [2: \mathsf{P}A]} \mathsf{P}:2 \quad \frac{\Gamma}{\Gamma, [3: \mathsf{P}A]} \mathsf{P}:3 \quad \frac{\Gamma, [4: A]}{\Gamma, [4: \mathsf{P}A]} \mathsf{P}:4$$

Definition 11. An upward tree of sequents is called a *proof* in the sequent calculus iff every leaf is an axiom, and all other sequents in it are obtained from the ones standing immediately above it by applying one of the rules. The sequent at the root of P is called its *end-sequent*. A sequent Γ is called *provable* iff it is the end-sequent of some proof.

Theorem 12. *A sequent is provable if and only if it is valid.*

Proof. See Theorems 3.1 and 3.2 of Baaz et al. [4] or Theorems 3.3.8 and 3.3.10 of Zach [16]. \square

Corollary 13. *In Humberstone logic, $\models A$ iff $[1, 2: A]$ has a sequent proof, and $\Delta \models A$ iff $[3, 4: \Delta], [1, 2: A]$ has a proof.*

Theorem 14. *The cut rule is eliminable in the sequent calculus for Humberstone logic.*

Proof. See Theorem 4.1 of Baaz et al. [4] or Theorem 3.5.3 of Zach [16]. \square

4 Tableaux for Humberstone logic

Although the method of Surma [14] and Carnielli [6] for obtaining signed analytic tableaux systems applies to Humberstone logic, it has a drawback. As

Hähnle [7] pointed out, to show that a formula is valid, it is required to provide as many closed tableaux as there are non-designated values. This is usually not desirable; the generalized approach by Hähnle [7] solves this problem. Below we give a tableau system for Humberstone logic using the sets of signs $V \setminus \{v\}$, i.e., the tableau system exactly dual to that of Carnielli (in the sense of [2]).

Definition 15. A *signed formula* is an expression of the form $v: A$ where $v \in V$ and A is a formula.

Definition 16. A *tableau* for a set of signed formulas Δ is a downward rooted tree of signed formulas where each one is either an element of Δ or results from a signed formula in the branch above it by a branch extension rule. A tableau is *closed* if every branch contains, for some formula A , the signed formulas $v: A$ for all $v \in V$, or a signed formula $v: A$ with a branch extension rule that explicitly closes the branch (\otimes).

The branch expansion rules for connective \wedge are given by

$$\frac{1: A \wedge B}{1: B \quad 1: A \quad 1: \bar{A}} \quad \frac{2: A \wedge B}{2: B \quad 2: A} \quad \frac{3: A \wedge B}{1: A \quad 3: A \quad 1: B \quad 3: B \quad 4: A \quad 4: B}$$

$$\frac{4: A \wedge B}{2: B \quad 4: A \quad 2: A \quad 4: B \quad 4: B \quad 4: A}$$

The branch expansion rules for connective \vee are given by

$$\frac{1: A \vee B}{1: B \quad 1: A \quad 1: \bar{A}} \quad \frac{2: A \vee B}{1: A \quad 2: A \quad 2: A \quad 4: A \quad 1: B \quad 2: B \quad 2: B \quad 4: B}$$

$$\frac{4: A \vee B}{3: B \quad 4: A \quad 3: A \quad 4: B \quad 4: B \quad 4: A}$$

The branch expansion rules for connective \neg are given by

$$\frac{1: \neg A}{4: A} \quad \frac{2: \neg A}{3: A} \quad \frac{3: \neg A}{2: A} \quad \frac{4: \neg A}{1: A}$$

The branch expansion rules for connective P are given by

$$\frac{1: \mathsf{P}A}{1: A} \quad \frac{4: \mathsf{P}A}{4: A}$$

$$2: A$$

$$3: A$$

Definition 17. An interpretation \mathbf{I} *satisfies* a signed formula $v: A$ iff $\text{val}_{\mathbf{I}}(A) \neq v$. A set of signed formulas is *satisfiable* if some interpretation \mathbf{I} satisfies all signed formulas in it.

Theorem 18. *A set of signed formulas is unsatisfiable iff it has a closed tableau.*

Proof. Apply Theorems 4.14 and 4.21 of Hähnle [7]; interpreting $v: A$ as $\mathbf{S} A$ where $\mathbf{S} = V \setminus \{v\}$. \square

Corollary 19. *In Humberstone logic, $\models A$ iff $\{v: A \mid v \in V^+\}$ has a closed tableau. $\Delta \models A$ iff $\{v: B \mid v \in V^-, B \in \Delta\} \cup \{v: A \mid v \in V^+\}$ has a closed tableau.*

5 Natural deduction for Humberstone logic

Let Γ be a (set) sequent, $V^+ \subseteq V$ the set of *designated truth values*. The set of non-designated truth values is then $V^- = V \setminus V^+$. We divide the sequent Γ into its designated part Γ^+ and its non-designated part Γ^- in the obvious way:

$$\begin{aligned}\Gamma^+ &:= \langle \Gamma_v \mid v \in V^+ \rangle \\ \Gamma^- &:= \langle \Gamma_v \mid v \in V^- \rangle\end{aligned}$$

Definition 20. The *natural deduction rules* for Humberstone logic are given by:

1. A weakening rule for all $v \in V^+$:

$$\frac{\Gamma^+}{\Gamma^+, [v: A]} \text{w}:v$$

2. For every connective \square and every truth value v an introduction rule $\square\text{I}:v$ (if $v \in V^+$) or an elimination rule $\square\text{E}:v$ (if $v \in V^-$).

The introduction and elimination rules for connective \wedge are given by

$$\begin{array}{c} \frac{\frac{\frac{\Gamma_1^-}{\Gamma_1^+, [1, \mathcal{L}: B]} \quad \frac{\Gamma_2^-}{\Gamma_2^+, [1: A, B]} \quad \frac{\Gamma_3^-}{\Gamma_3^+, [1, \mathcal{L}: A]}}{\Gamma_1^+, \Gamma_2^+, \Gamma_3^+, [1: A \wedge B]} \wedge\text{I}: 1}{\frac{\frac{\Gamma_1^-}{\Gamma_1^+, [\mathcal{L}: B]} \quad \frac{\Gamma_2^-}{\Gamma_2^+, [\mathcal{L}: A]}}{\Gamma_1^+, \Gamma_2^+, [\mathcal{L}: A \wedge B]} \wedge\text{I}: 2}}{\frac{\frac{\Gamma_0^-, [[4: A \wedge B]] \quad \Gamma_1^-, [[\mathcal{L}: A, B]] \quad \Gamma_2^-, [[\mathcal{L}, 4: A, B]]}{\Gamma_0^+, [1, \mathcal{L}: A \wedge B]} \quad \Gamma_1^+, [1: A, B] \quad \Gamma_2^+}{\Gamma_0^+, \Gamma_1^+, \Gamma_2^+} \wedge\text{E}: 3}}{\frac{\Gamma_0^-, [[\mathcal{L}: A \wedge B]] \quad \Gamma_1^-, [[4: B]] \quad \Gamma_2^-, [[4: A, B]] \quad \Gamma_3^-, [[4: A]]}{\Gamma_0^+, [1, \mathcal{L}: A \wedge B]} \quad \Gamma_1^+, [\mathcal{L}: B] \quad \Gamma_2^+ \quad \Gamma_3^+, [\mathcal{L}: A]} \wedge\text{E}: 4}}{\Gamma_0^+, \dots, \Gamma_3^+}\end{array}$$

The introduction and elimination rules for connective \vee are given by

$$\begin{array}{c}
\frac{\Gamma_1^-, [[\mathcal{B}: B]] \quad \Gamma_2^- \quad \Gamma_3^-, [[\mathcal{B}: A]]}{\Gamma_1^+, [1: B] \quad \Gamma_2^+, [1: A, B] \quad \Gamma_3^+, [1: A]} \vee\text{I: } 1 \\
\frac{\Gamma_1^+, \Gamma_2^+, \Gamma_3^+, [1: A \vee B]}{\Gamma_1^-, [[\mathcal{B}: A, B]]} \vee\text{I: } 2 \\
\frac{\Gamma_1^+, [1, \mathcal{B}: A, B] \quad \Gamma_2^+, [\mathcal{B}: A, B]}{\Gamma_1^+, \Gamma_2^+, [\mathcal{B}: A \vee B]} \vee\text{I: } 3 \\
\frac{\Gamma_0^-, [[\mathcal{B}: A \vee B]] \quad \Gamma_1^-, [[\mathcal{B}: B]] \quad \Gamma_2^-, [[\mathcal{B}: A]]}{\Gamma_0^+, [1, \mathcal{B}: A \vee B] \quad \Gamma_1^+ \quad \Gamma_2^+} \vee\text{E: } 3 \\
\frac{\Gamma_0^-, [[\mathcal{B}: A \vee B]] \quad \Gamma_1^-, [[\mathcal{B}, \mathcal{C}: B]] \quad \Gamma_2^-, [[\mathcal{C}: A, B]] \quad \Gamma_3^-, [[\mathcal{B}, \mathcal{C}: A]]}{\Gamma_0^+, [1, \mathcal{B}: A \vee B] \quad \Gamma_1^+ \quad \Gamma_2^+ \quad \Gamma_3^+} \vee\text{E: } 4 \\
\Gamma_0^+, \dots, \Gamma_3^+
\end{array}$$

The introduction and elimination rules for connective \neg are given by

$$\begin{array}{c}
\frac{\Gamma_1^-, [[\mathcal{C}: A]]}{\Gamma_1^+, [1: \neg A]} \neg\text{I: } 1 \quad \frac{\Gamma_1^-, [[\mathcal{B}: A]]}{\Gamma_1^+, [\mathcal{B}: \neg A]} \neg\text{I: } 2 \\
\frac{\Gamma_0^-, [[\mathcal{C}: \neg A]] \quad \Gamma_1^-, [[\mathcal{B}: A]]}{\Gamma_0^+, [1, \mathcal{B}: \neg A] \quad \Gamma_1^+, [\mathcal{B}: A]} \neg\text{E: } 3 \quad \frac{\Gamma_0^-, [[\mathcal{B}: \neg A]] \quad \Gamma_1^-, [[\mathcal{C}: A]]}{\Gamma_0^+, [1, \mathcal{B}: \neg A] \quad \Gamma_1^+, [1: A]} \neg\text{E: } 4 \\
\Gamma_0^+, \Gamma_1^+
\end{array}$$

The introduction and elimination rules for connective P are given by

$$\begin{array}{c}
\frac{\Gamma_1^-, [[\mathcal{B}: A]]}{\Gamma_1^+, [1: \text{P}A]} \text{PI: } 1 \quad \frac{\Gamma_1^-}{\Gamma_1^+, [\mathcal{B}: \text{P}A]} \text{PI: } 2 \quad \frac{\Gamma_0^-, [[\mathcal{C}: \text{P}A]] \quad \Gamma_1^-}{\Gamma_0^+, [1, \mathcal{B}: \text{P}A] \quad \Gamma_1^+} \text{PE: } 3 \\
\frac{\Gamma_0^-, [[\mathcal{B}: \text{P}A]] \quad \Gamma_1^-, [[\mathcal{C}: A]]}{\Gamma_0^+, [1, \mathcal{B}: \text{P}A] \quad \Gamma_1^+} \text{PE: } 4 \\
\Gamma_0^+, \Gamma_1^+
\end{array}$$

Definition 21. A *natural deduction derivation* is defined inductively as follows:

1. Let A be any formula. Then

$$\frac{[V^-: A]}{[V^+: A]}$$

is a derivation of A from the assumption $[V^-: A]$ (an *initial derivation*).

2. If D_k are derivations of Γ_k^+, Δ_k^+ from the assumptions $\Gamma_k^-, \hat{\Delta}_k^-$, and

$$\frac{\left\langle \frac{\Gamma_k^-, [\Delta_k^-]}{\Gamma_k^+, \Delta_k^+} \right\rangle_{k \in K}}{\Pi^+}$$

is an instance of a deduction rule with $\hat{\Delta}_k^-$ a subsequence of Δ_k^- , and all eigenvariable conditions are satisfied, then

$$\frac{\langle D_k \rangle_{k \in K}}{\Pi^+}$$

is a derivation of Π^+ from the assumptions $\bigcup_{k \in K} \Gamma_k^-$. The formulas in $\hat{\Delta}_k^-$ which do not occur in $\bigcup_{k \in K} \Gamma_k^-$ are said to be *discharged* at this inference.

Theorem 22. *A partial sequent Γ^+ can be derived from the assumptions Γ^- in the natural deduction system for Humberstone iff, for every interpretation \mathbf{I} , either some formula in Γ_v^- ($v \in V^-$) evaluates to the truth value v , or there is a $w \in V^+$ and a formula in Γ_w^+ that evaluates to w .*

Proof. See Theorems 4.7 and 5.4 of Baaz et al. [3] or Theorems 4.2.8 and 4.3.4 of Zach [16]. \square

Corollary 23. $\Gamma \models A$ iff there is a natural deduction derivation of $[V^+: A]$ from $[V^-: \Gamma]$.

6 Resolution and clause formation rules for Humberstone logic

The many-valued resolution calculus of Baaz and Fermüller [1] applies to Humberstone logic. We present the framework here, as well as a language preserving clause translation system for Humberstone logic.

Definition 24 (Signed formula). A *signed formula* is an expression of the form A^v , where A is a formula and $v \in V$. If A is a propositional variable, A^v is a *signed atom*.

Definition 25 (Signed clause). A (signed) *clause* $C = \{A_1^{v_1}, \dots, A_n^{v_n}\}$ is a finite set of signed atoms (proper clause). The empty clause is denoted by \square .

An *extended clause* is a finite set of signed formulas.

Definition 26 (Semantics of clause sets). Let \mathbf{I} be an interpretation. \mathbf{I} *satisfies* a clause C iff there is some signed formula $A^v \in C$, so that $\text{val}_{\mathbf{I}}(A) = v$. \mathbf{I} satisfies a clause set \mathcal{C} iff it satisfies every clause in \mathcal{C} . \mathcal{C} is called *satisfiable* iff some structure satisfies it, and *unsatisfiable* otherwise.

The clause formation rules for connective \wedge are given by

$$\frac{\mathcal{C} \cup \{C \cup \{(A \wedge B)^1\}\}}{\mathcal{C} \cup \{C \cup \{B^1, B^2\}, C \cup \{A^1, B^1\}, C \cup \{A^1, A^2\}\}} \wedge:1$$

$$\frac{\mathcal{C} \cup \{C \cup \{(A \wedge B)^2\}\}}{\mathcal{C} \cup \{C \cup \{B^2\}, C \cup \{A^2\}\}} \wedge:2$$

$$\frac{\mathcal{C} \cup \{C \cup \{(A \wedge B)^3\}\}}{\mathcal{C} \cup \{C \cup \{A^1, A^3, B^1, B^3\}, C \cup \{A^3, A^4, B^3, B^4\}\}} \wedge:3$$

$$\frac{\mathcal{C} \cup \{C \cup \{(A \wedge B)^4\}\}}{\mathcal{C} \cup \{C \cup \{B^2, B^4\}, C \cup \{A^4, B^4\}, C \cup \{A^2, A^4\}\}} \wedge:4$$

The clause formation rules for connective \vee are given by

$$\frac{\mathcal{C} \cup \{C \cup \{(A \vee B)^1\}\}}{\mathcal{C} \cup \{C \cup \{B^1, B^3\}, C \cup \{A^1, B^1\}, C \cup \{A^1, A^3\}\}} \vee:1$$

$$\frac{\mathcal{C} \cup \{C \cup \{(A \vee B)^2\}\}}{\mathcal{C} \cup \{C \cup \{A^1, A^2, B^1, B^2\}, C \cup \{A^2, A^4, B^2, B^4\}\}} \vee:2$$

$$\frac{\mathcal{C} \cup \{C \cup \{(A \vee B)^3\}\}}{\mathcal{C} \cup \{C \cup \{B^3\}, C \cup \{A^3\}\}} \vee:3$$

$$\frac{\mathcal{C} \cup \{C \cup \{(A \vee B)^4\}\}}{\mathcal{C} \cup \{C \cup \{B^3, B^4\}, C \cup \{A^4, B^4\}, C \cup \{A^3, A^4\}\}} \vee:4$$

The clause formation rules for connective \neg are given by

$$\frac{\mathcal{C} \cup \{C \cup \{(\neg A)^1\}\}}{\mathcal{C} \cup \{C \cup \{A^4\}\}} \neg:1 \quad \frac{\mathcal{C} \cup \{C \cup \{(\neg A)^2\}\}}{\mathcal{C} \cup \{C \cup \{A^3\}\}} \neg:2$$

$$\frac{\mathcal{C} \cup \{C \cup \{(\neg A)^3\}\}}{\mathcal{C} \cup \{C \cup \{A^2\}\}} \neg:3 \quad \frac{\mathcal{C} \cup \{C \cup \{(\neg A)^4\}\}}{\mathcal{C} \cup \{C \cup \{A^1\}\}} \neg:4$$

The clause formation rules for connective P are given by

$$\frac{\mathcal{C} \cup \{C \cup \{(PA)^1\}\}}{\mathcal{C} \cup \{C \cup \{A^1, A^2, A^3\}\}} P:1 \quad \frac{\mathcal{C} \cup \{C \cup \{(PA)^2\}\}}{\mathcal{C} \cup \{C\}} P:2$$

$$\frac{\mathcal{C} \cup \{C \cup \{(PA)^3\}\}}{\mathcal{C} \cup \{C\}} P:3 \quad \frac{\mathcal{C} \cup \{C \cup \{(PA)^4\}\}}{\mathcal{C} \cup \{C \cup \{A^4\}\}} P:4$$

Theorem 27. Let $T(\mathcal{C})$ be the result of exhaustively applying the translation rules to a clause set \mathcal{C} . Then $T(\mathcal{C})$ is a set of proper clauses, i.e., $T(\mathcal{C})$ contains only signed atoms (all connectives are eliminated). Furthermore, $T(\mathcal{C})$ is satisfiable iff \mathcal{C} is.

Proposition 28. Let A be a sentence and Δ be a set of sentences. Then

1. $\models A$ iff $\{\{A^v \mid v \in V^-\}\}$ is unsatisfiable.
2. $\Delta \models A$ iff

$$\{\{B^w \mid w \in V^+\} \mid B \in \Delta\} \cup \{\{A^v \mid v \in V^-\}\}$$

is unsatisfiable.

Definition 29. A clause R is a *resolvent* of clauses C_1, C_2 if $R = (C_1 \setminus \{A^{v_1}\}) \cup (C_2 \setminus \{A^{v_2}\})$ where $v_1 \neq v_2$

Definition 30. A *resolution refutation* of a clause set \mathcal{C} is a sequence of clauses C_1, \dots, C_n so that for every i , $C_i \in \mathcal{C}$ or C_i is a resolvent of C_j, C_k with $j, k < i$, and $C_n = \emptyset$.

Theorem 31. A clause set \mathcal{C} is unsatisfiable iff it has a resolution refutation.

Proof. See Theorems 3.14 and 3.19 of Baaz and Fermüller [1] or Theorems 2.5.5 and 2.5.8 of Zach [16]. \square

Corollary 32. $\Delta \models A$ iff

$$T(\{\{B^w \mid w \in V^+\} \mid B \in \Delta\} \cup \{\{A^v \mid v \in V^-\}\})$$

has a resolution refutation.

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