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Intuitionistic three-valued logic and logic programming


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INTUITIONISTIC THREE-VALUED LOGIC
AND LOGIC PROGRAMMING (*)

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Abstract. - In this paper, we study the semantics of logic programs with the help of trivalued logic, introduced by Girard in 1973.
Trivalued sequent calculus enables to extend easily the results of classical SLD-resolution to trivalued logic. Moreover, if one allows negation in the head and in the body of Horn clauses, one obtains a natural semantics for such programs regarding these clauses as axioms of a theory written in the intuitionistic fragment of that logic.
Finally, we define in the same calculus an intuitionistic trivalued version of Clark's completion, which gives us a declarative semantics for programs with negation in the body of the clauses, the evaluation method being SLDNF-resolution.

I. INTRODUCTION

In this paper we investigate the links between three-valued logic and logic programming; instead of the more usual model-theoretical approach ([4, 10]) we adopt a proof-theoretical viewpoint, like Gallier's [5] for classical logic. For this, we use the three-valued sequent calculus introduced by Girard [7],

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that is a three-valued version of Gentzen’s sequent calculus [6], and particularly its intuitionistic subsystem.

In section II, we recall some results on SLD-resolution and in appendix A, we give the proofs of these results using Gentzen’s sequent calculus to show how we can extend them to three-valued logic.

In section III.1 and appendix B, we define the notions of three-valued models and Girard’s three-valued logic.

In sections III.2 and III.3 we show that we can easily extend the resolution method and SLD-resolution to three-valued logic; the results of these sections are very close to those of Schmitt [12].

In section III.4 we show the completeness and the soundness of the extension of SLD-resolution to clauses containing negative literals (also in the head of the clauses) with respect to intuitionistic three valued logic; many expert systems use such resolution and so, it is useful to work out an exact semantics for these systems. Delahaye announced close results, without proofs, and using Fitting’s approach in [3].

In section IV, we study negation as failure: we define for each program P, Comp* (P), which is a three-valued version in Girard’s logic of the Clark’s completion. Though Fitting [4] and Kunen [10] use three-valued logic to define semantics for negation as failure, our approach is different.

We show the soundness of SLDNF-resolution with respect to Comp* (P) in intuitionistic three valued logic as suggested by Shepherdson [15] (for programs with variables) and the completeness in the propositional case.

For another axiomatization of negation as failure, using Girard’s linear logic, see [1].

II. SLD-RESOLUTION

In this section, we recall some results on SLD-resolution. We suppose that the reader is familiar with these notions. If not, he can consult [5] or [11]. The results that we want to extend to three-valued logic are proved in appendix A: we adopt a proof-theoretical viewpoint and so, we use Gentzen’s sequent calculus and we show what results are intuitionistically valid.

If a formula A is classically (resp. intuitionistically) provable in a classical (resp. intuitionistic) theory T, we write T |- A (resp. T |- A).

II.1. Definition: (i) A clause is a formal expression $\Gamma \vdash \Delta$, $\Gamma$ and $\Delta$ being sequences (possibly empty) of atomic formulae; the meaning of a clause,
A_1, \ldots, A_n \vdash B_1, \ldots, B_p \text{ is, as usual, } A_1 \& \ldots \& A_n \rightarrow B_1 \lor \ldots \lor B_p \text{ (see A.1.3).}

(ii) A horn clause is a clause \( \Gamma \vdash \Delta \) such that \( \Delta \) contains at most one atom.

(iii) A definite clause is a Horn clause \( \Gamma \vdash \Delta \) where \( \Delta \) contains (exactly) one formula. A definite clause where \( \Gamma \) is empty is said to be a positive clause.

(iv) A negative clause is a Horn clause \( \Gamma \vdash \Delta \) such that \( \Delta \) is empty.

(v) An anti-Horn clause is a formula \( A \) where \( A \) is a conjunction \( B_1 \& \ldots \& B_n \), each \( B_i \) being a literal, and at most one \( B_i \) being negative. The associated-clause of \( A \) is the Horn clause \( B_1, \ldots, B_i, \ldots, B_n \rightarrow C_i \) if \( B_i = \neg C_i \) is the negative literal, otherwise it is \( B_1, \ldots, B_n \vdash \) (if there is no negative literal).

II.2. Definition: A logic program is a pair \( (P, Q) \) where \( P \) is a set of Horn clauses, and \( Q \) a formula of the form \( A_1 \lor \ldots \lor A_q \), each \( A_i \) being an anti-Horn clause. We say that \( Q \) is the query and we consider for SLD-refutations the set of clauses obtained by adding to clauses of \( P \) the associated-clause of \( A_i \) for each \( A_i \). We denote the existential closure of \( Q \) by \( \exists Q \).

Remark that if \( Q = \neg H_1 \lor \ldots \lor \neg H_q \), where each \( H_i \) (\( \neg A_i \)) is a Horn-clause and if \( P \vdash Q \), then the inconsistency of \( P \cup \{H_1, \ldots, H_q\} \) may be checked by SLD-resolution, because all clauses in this set are indeed Horn clauses.

We are interested in this form of programs because, in our generalization to clauses containing negation in their head (part IV), naturally negative \( N \)-clauses appear.

II.3. Theorem (completeness): let \( (P, Q) \) be a logic program; then,

1) either \( P \) is inconsistent, and there exists at least one SLD-refutation of \( P \) with goal a negative clause of \( P \); no other negative clause is used in the refutation;

2) or \( P \) is consistent and then,

(i) if \( Q \) is a disjunction \( A_1 \lor \ldots \lor A_q \), each \( A_i \) being a conjunction of atoms, and if \( P \vdash \exists Q \), then \( P \vdash Q \theta \) (for some substitution \( \theta \)) and \( Q \) succeeds with answer including \( \theta \) under all computation rules (using SLD-resolution);

(ii) if \( Q \) is a disjunction of anti-Horn clauses, and if \( P \vdash \exists Q \), then there exists a sequence of substitutions \( \theta_1, \ldots, \theta_n \) such that \( P \vdash Q \theta_1 \lor \ldots \lor Q \theta_n \) and \( Q \) succeeds (under SLD-resolution) with indefinite answers including \( \theta_1, \ldots, \theta_n \).

Proof: See appendix A: theorem A.4.1; (ii) is first proved in [5]. Remark that if \( P \) is a set of definite clauses, it is always consistent.
II.4. Theorem (soundness): (i) Let \((P, Q)\) be a logic program with 
\[Q = A_1 \lor \ldots \lor A_q\]
(each \(A_i\) being an anti-Horn clause). Let \(\pi\) be a SLD-resolution and 
\[(C_1 \sigma_1), \ldots, (C_n \sigma_n)\] the substitutions of associated-clauses of 
formulae \(A_1, \ldots, A_q\) used in \(\pi\), then \(P \vdash Q \theta_1 \lor \ldots \lor Q \theta_n\).

(ii) Moreover, if \(P\) is a set of definite clauses, if each \(A_i\) is a conjunction of 
atoms, and if \(\theta\) is the result substitution, then \(P \vdash \exists Q\) and \(P \vdash \forall Q\) are
intuitionistically derivable from \(P\).

Proof: See [5] for (i); (ii) only one negative clause is used in the refutation, 
and this clause is the associated-clause of \(A_i\) for some \(i (1 \leq i \leq q)\); then, by 
(i) \(A_1 \theta \lor \ldots \lor A_q \theta\) is a logical consequence of \(P\) and by lemma A.3.4 of 
appendix A, it is intuitionistically derivable from \(P\); then \(Q \theta\) and \(\exists Q\) are
intuitionistically derivable from \(P\).

III. THREE-VALUED LOGIC

III.1. Kleene’s three-valued structures and Girard’s three-valued logic

In this section we recall some definitions and results on three-valued models 
and three-valued logic. The reader can find more details, references and 
proofs, in [7] and in [9].

III.1.1. Definition: Let \(L\) be a fixed first-order language. A three-valued 
structure \(M\) for \(L\) consists of the following data:
(i) a non-empty set \(|M|\), the domain of \(M\);
(ii) for each \(n\)-ary function letter \(f\) of \(L\), a function \(M(f): |M|^n \rightarrow |M|\);
(iii) for each \(n\)-ary predicate \(p\) of \(L\), a function \(M(p): |M|^n \rightarrow \{t, u, f\}\) (i.e. 
true, undetermined, false).

- A three-valued structure is binary if it does not take the value \(u\) (hence, 
it is a binary structure in the familiar sense).

We shall denote by \(L[M]\) the language obtained by adding to \(L\) new 
constants \(c\), for each \(c \in |M|\).

III.1.2. Definition: (i) If \(t\) is a closed term of \(L[M]\) one defines its value 
\(M(t)\) by: 
\(M(c) = c; M(ft_1 \ldots t_n) = M(f)(M(t_1) \ldots M(t_n))\).

(ii) If \(A\) is a closed formula of \(L[M]\), one defines its value \(M(A)\) by:
(1) \(M(pt_1 \ldots t_n) = M(p)(M(t_1) \ldots M(t_n))\);
(2) the values of formulae beginning with a propositional connective are defined according to the following truth tables:

<table>
<thead>
<tr>
<th>$A$</th>
<th>$B$</th>
<th>$A &amp; B$</th>
<th>$A \lor B$</th>
<th>$A \rightarrow B$</th>
<th>$\neg A$</th>
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<tr>
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</table>

(3) if $M(A(c))$ is true (resp. false) for some $c \in |M|$, then $M(\exists x, A(x)) = t$ [resp. $M(\forall x, A(x)) = f$];
- if $M(A(c))$ is true (resp. false) for all $c \in |M|$, then $M(\forall x, A(x)) = t$ [resp. $M(\exists x, A(x)) = f$];
- in the other cases $M(\exists x, A(x))$ and $M(\forall x, A(x))$ take the value $u$.

III. 1.3. Definition: (i) The language 3L is defined as follows:

- **terms**: the terms of L.
- **formulae**: the normal expressions $\neg A$ and $A$, where $A$ is a formula of L. We shall represent an arbitrary formula of 3L by $\xi A$, $\eta A$, where $\xi$, $\eta$ vary through the set {?, !}. We use the symbol $*$ as follows: $\xi^* = !$ if $\xi = ?$, and $\xi^* = ?$ if $\xi = !$.

(ii) A sequent in 3L is a formal expression $\Gamma \vdash \Delta$, where $\Gamma$ and $\Delta$ are finite sequences (possibly empty) of formulae in 3L.

III. 1.4. Definition: (i) The closed formula $\xi A$ of 3L[M] is valid in the three-valued structure M iff

- $\xi = !$ and $M(A) = t$ (we say that $A$ is necessary in M);
- $\xi = ?$ and $M(A) = f$ (we say that $A$ is possible in M).

We shall denote this fact by $M \vDash \xi A$ (and $M \not\vDash \xi A$ otherwise).

(ii) The closed sequent $A_1, \ldots, A_n \vdash B_1, \ldots, B_m$ of 3L[M] is valid in the three-valued structure M iff:

- if $n \neq 0$ and $m \neq 0$: if $M \vDash A_1$ and ... and $M \vDash A_n$ then $M \vDash B_1$ or ... or $M \vDash B_m$;
- if $n \neq 0$ and $m = 0$ then $M \not\vDash A_1$ or ... or $M \not\vDash A_n$;
- if $n = 0$ and $m \neq 0$ then $M \vDash B_1$ or ... or $M \vDash B_m$;
- if $n = 0$ and $m = 0$ the sequent $\vdash$ means absurdity.
III.1.5. **Definition:** Let S be a set of sequents of 3L. A **three-valued model** M of S is a three-valued structure where any closed instance of a sequent of S is valid in M. S is **3-consistent** if it has at least one three-valued model.

If not, we say that S is **3-inconsistent**.

If all closed instances of a formula A of 3L are valid in any three-valued model of a set S of sequents of 3L, we say that A is a (three-valued) logical consequence of S.

Girard has defined the sequent calculus 3LK (resp. 3LI) in the spirit of Gentzen’s calculus LK (resp. LI); these systems enjoy completeness and soundness with respect to classical (resp. intuitionistic) three-valued models and can be extended to second order logic (see [7] and [9]). We present these systems in appendix B. For the definition of intuitionistic three-valued models (topological or Kripke three-valued models) see [7].

If a formula A or a sequent Γ ⊢ Δ is provable in the theory S in 3LK (resp. 3LI), we write S ⊢_3 K A or S ⊢_3 I Γ ⊢ Δ (resp. S ⊢_3 I A or S ⊢_3 I Γ ⊢ Δ).

III.2. **3-resolution**

III.2.1. **Definition:** A **3-clause** is a sequent of 3L, containing only formulae of the form !A, ?A, A being an atom (we say that the formula x A is a 3-atom).

III.2.2. **Definition:**

- We define the language L2 as follows: variables, constants, functions symbols are those of L. For each predicate letter of L, we introduce two predicate letters p! and p? with the arity of p.
  - For each formula A of 3L, we define a formula (A)_2 of L2 (and we say that (A)_2 is the 2-translated of A), as follows:
    \[
    (\xi p (t_1, \ldots, t_n))_2 = (p \xi) (t_1, \ldots, t_n)
    \]
    \[
    (\xi v A)_2 = \neg (\xi P A)_2, \quad (\xi A \land B)_2 = (\xi A)_2 \land (\xi B)_2
    \]
    \[
    (\xi A \lor B)_2 = (\xi A)_2 \lor (\xi B)_2
    \]
    \[
    (\xi A \rightarrow B)_2 = (\xi P A)_2 \rightarrow (\xi B)_2
    \]
    \[
    (\xi \exists x, A (x))_2 = \exists x (\xi A (x))_2
    \]
    \[
    (\xi \forall x, A (x))_2 = \forall x (\xi A (x))_2
    \]

- For each sequent Γ ⊢ Δ of 3L, we define its 2-translated (Γ ⊢ Δ)_2: it is the sequent obtained by replacing any formula occurring in the sequent by its 2-translated.

- If M is a three-valued structure, we define a binary structure M2 for L2 as follows: the interpretation of the constants and of the function symbols
does not change. As for the predicate symbols, we define

\[ M_2 \models (p \xi)(t_1 \ldots t_n) \iff M \models \xi p(t_1 \ldots t_n) \]

III. 2.3. LEMMA: Let \( R \) be the set of all 3-clauses

\[ !p(x_1, \ldots, x_n) \vdash ?p(x_1, \ldots, x_n) \quad (\text{for each predicate } p) \]

Let \( S \) be a set of sequents of \( 3L \), \( S_2 \) the set of the 2-translated of the sequents of \( S \).

(i) if \( M \) is a three-valued model of \( S \), \( M_2 \) is a binary model of \( S_2 \cup R_2 \).

(ii) if \( N \) is a binary model of \( S_2 \cup R_2 \), then there exists a three-valued model \( M \) of \( S \) with \( N = M_2 \).

Proof: Immediate.

III. 2.4. LEMMA: Let \( A \) be a formula of \( 3L \) and \( S \) be a set of sequents of \( 3L \), then there exists a set \( T \) of 3-clauses which satisfies the following proposition:

\( A \) is a logical consequence of \( S \) iff \( T \) is 3-inconsistent.

Proof: We replace the set \( S \) and the formula \( A \) by their 2-translated \( S_2 \) and \( (A)_2 \); \( A \) is a three-valued consequence of \( S \) iff \( (A)_2 \) is a logical consequence of \( S_2 \cup R_2 \); we construct (as usual) a set \( T' \) of 2-clauses so that: \( T' \) is inconsistent iff \( (A)_2 \) is a logical consequence of \( S_2 \cup R_2 \). Let \( T \) be the set of 3-clauses so that \( T_2 = T' - R_2 \); using lemma III.2.3, we obtain the result.

III. 2.5. DEFINITION: We define 3-resolution just like ordinary resolution (which we designate by 2-resolution), but the clauses involved are 3-clauses instead of ordinary clauses; remark that a 3-atom \( !A \) (resp. \( ?A \)) can be unified with a 3-atom \( !B \) (resp. \( ?B \)) iff \( A \) and \( B \) can be unified. A 3-atom \( !A \) cannot be unified with a 3-atom \( ?B \).

III. 2.6. THEOREM (soundness and completeness): Let \( S \) be a set of 3-clauses and \( S^* \) the set obtained by adding to \( S \) the following 3-clauses \( !p \vdash ?p \) (for each predicate \( p \) occurring in \( S \)).

Then \( S \) is 3-inconsistent iff the sequent \( \vdash \) is provable with 3-resolution from clauses of \( S^* \).

(In fact it is enough to add to \( S \) only clauses \( !p \vdash ?p \) for each predicate \( p \) such that \( !p \) appears in the right part of a clause, and \( ?p \) appears in the left part of a clause.)

Proof: It is an immediate consequence of soundness and completeness for resolution in the binary case and of lemma III.2.3: by lemma III.2.3, \( S \) is
3-inconsistent iff $\mathbf{S^*2}$ is (classically) inconsistent; but, $\mathbf{S^*2}$ is inconsistent iff $\vdash h$ is provable by 2-resolution using the clauses of $\mathbf{S^*2}$; then a proof of the sequent $\vdash h$ using 2-resolution from $\mathbf{S^*2}$ can easily be transformed in a proof of the sequent $\vdash h$ using 3-resolution from $\mathbf{S^e}$ and vice-versa [replacing each predicate $(p\xi)$ by $\xi p$].

III. 3. Horn 3-clauses

2-resolution is a very expensive process, and therefore, often, we only consider the subclass of Horn clauses. Similarly, for three-valued resolution, we will restrict our study to the class of Horn 3-clauses (defined below).

III. 3.1. Definition: (i) A Horn 3-clause is a 3-clause such that the right part contains at most one 3-atom.

As examples,

(i) $\neg A(x, y), \neg B(x, y) \vdash \neg C(x, z)$  

(ii) $\neg A(x, y), \neg A(x, y) \vdash$  

(iii) A definite 3-clause is a Horn 3-clause where the right part contains (exactly) one formula (example 1).

(iv) A negative 3-clause is a Horn 3-clause where the right part is empty (example 2).

(v) An anti-Horn clause is a formula $\xi A$ where $A$ is a conjunction $B_1 \& \ldots \& B_n$, each $B_i$ being a literal, and at most one $B_i$ being negative. The associated-clause to $\xi A$ is the Horn clause $\xi B_1, \ldots, \xi B_{i-1}, \neg \xi B_{i+1}, \ldots, B_n \vdash \xi C_i$ if $B_i = \neg C_i$ is the negative literal, otherwise it is $\xi B_1, \ldots, \xi B_n \vdash$ (if there is no negative literal).

III. 3.2. Definition: We define 3 SLD-resolution (resp. 3 SLD-refutation) just like SLD-resolution (resp. SLD-refutation) replacing clauses by 3-clauses.

III. 3.3. Definition: A 3-logic program is a pair $(P, Q)$ where $P$ is a set of 3-Horn clauses, and $Q$ is a disjunction $\xi A_1 \lor \ldots \lor A_n$, each $A_i$ being an anti-Horn 3-clause. We say that $Q$ is the query and we consider for 3SLD-refutations the set of clauses obtained by adding to clauses of $P$ the associated-clause of $\xi A_i$ (for each $i$), and clauses $!p \vdash ?p$ for each atom $p$.

(In fact it is enough to add to $S$ only clauses $!p \vdash ?p$ for each predicate $p$ such that $!p$ appears in the right part of a clause, and $?p$ appears in the left part of a clause.)
III.3.4. **Theorem** (soundness and completeness): *Theorems II.3 and II.4 carry over to 3-logic programs provided we apply 3SLD-resolution to the set above defined.*

*Proof:* For soundness: as in III.2.2, we replace each predicate $\xi p$ by $(p \xi)$ and use the result of II.3. For completeness: if we replace each formula by its 2-translated, we can use the results of appendix A, and then we easily draw the conclusions of the theorem; remark that, since we work in extensions of classical (or intuitionistic) sequent calculus to three-valued logic, all results remain true.

III.3.5. **Comparison with related work**

In [12], Schmitt investigates a three-valued logic; he considers two negations symbols ($\sim$ and $\neg$) and four kinds of literals: $A$, $\neg A$, $\sim A$ and $\sim \neg A$ which mean respectively "$A$ is true", "$A$ is false", "$A$ is not true", "$A$ is not false". Hence they respectively correspond, in our language, to $\mathcal{A}$, $\neg \mathcal{A}$, $\mathcal{A} \neg \mathcal{A}$.

He considers $A$ and $\sim \neg A$ as positive literals (i.e. our positive literals), and $\sim A$ and $\neg A$ as negative literals (i.e. our negative literals); he defines the implication $A \Rightarrow B$ as an abbreviation of $\sim A \lor B$; a clause is a disjunction of literals and a Horn clause is a clause containing at most one positive literal.

He shows that the usual soundness and completeness results for SLD-resolution (a query being an existential conjunction of positive literals) carry over provided we apply SLD-resolution to the program augmented by all clauses $A \Rightarrow \sim \neg A$ for all atoms $A$.

A structure $\mathcal{M}$ is a model of a Schmitt Horn clause $A_1 & \ldots & A_n \Rightarrow B$ iff $\mathcal{M}$ is a model of the 3-clause $A_1^*, \ldots, A_n^* \vdash B^*$ obtained by replacing each positive literal $A$ by the corresponding positive literal $A^*$ in our language. Remark that, in this translation, the translated of $A \Rightarrow \sim \neg A$ is $!A \vdash ?A$.

But our result differs from the Schmitt's one in the form of the queries.

III.4. **Horn N-clauses. Semantics for programs with negation**

In this section, we study classical logic programs with negation. We allow the negation to appear also in the head of the clauses. We show that the natural semantics for these programs is three-valued semantics.

III.4.1. **Definition:** We define the notions of N-clause, Horn N-clause, definite N-clause, negative N-clause, just as we have defined the similar notions
for clauses: for this, we replace in definition II.1 the term “atom” by “literal”.

As examples,

$$A(x, y), \quad \neg B(x, y) \vdash \neg C(x, z)$$

is a definite \(N\)-clause;

$$A(x, y), \quad \neg A(x, y) \vdash$$

is a negative \(N\)-clause.

III. 4.2. Definition: We define the language \(LN\) as follows: the variables, constant, function symbols are those of \(L\). For each predicate letter of \(L\), we introduce the predicate letter \(p^*\) with the arity of \(p\).

- If \(\Gamma \vdash \Delta\) is a \(N\)-clause, and if we replace in this clause any negative literal \(\neg p(t_1, \ldots, t_n)\) by \(p^*(t_1, \ldots, t_n)\), we obtain a clause (in the familiar sense) of \(LN\); we say that the clause obtained is the \(N\)-translated of \(\Gamma \vdash \Delta\).

If in \(\Gamma \vdash \Delta\), we replace any literal \(A\) by \(\neg A\), we obtain a sequent of \(3L\), and we say that this sequent is the \(3\)-translated of \(\Gamma \vdash \Delta\).

- If \(M\) is a three-valued structure, we define a binary structure \(MN\) for \(LN\), as follows:

$$MN \models p(t_1, \ldots, t_n) \quad \text{iff} \quad M \models p(t_1, \ldots, t_n)$$

$$MN \models p^*(t_1, \ldots, t_n) \quad \text{iff} \quad M \models \neg p(t_1, \ldots, t_n)$$

the interpretation of the constant and of the functions symbols being unchanged.

III. 4.3. Definition: Let \(M\) be a three-valued structure; we say that \(M\) is a three-valued model for a set \(S\) of \(N\)-clauses iff any \(3\)-translated of a \(N\)-clause of \(S\) is valid in \(M\). If \(S\) has a three-valued model, we say that \(S\) is \(3\)-consistent; otherwise we say that \(S\) is \(3\)-inconsistent.

III. 4.4. Lemma: Let \(R\) be the set of all \(N\)-clauses of \(L\) \(p(x_1, \ldots, x_n), \neg p(x_1, \ldots, x_n) \vdash\) (for each predicate \(p\) of \(L\)).

Let \(S\) be a set of \(N\)-clauses, \(SN\) (resp. \(RN\)) the set of the \(N\)-translated of clauses of \(S\) (resp. \(R\)), \(S^*\) the set of the \(3\)-translated of clauses of \(S\).

(i) If \(M\) is a three-valued model of \(S^*\), \(MN\) is a binary model of \(SN \cup RN\).

(ii) If \(T\) is a binary model of \(SN \cup RN\), then there exists a three-valued model \(M\) of \(S^*\) such that \(T = MN\).

Proof: Immediate.
III. 4.5. **Définition**: Un programme logique N est un couple \((P, Q)\) où \(P\) est un ensemble de clauses Horn N, et \(Q\) une formule de la forme \(A_1 \lor \ldots \lor A_n\), chaque \(A_i\) étant une conjonction de littéraux: \(A_i = B_{i1} \& \ldots \& B_{iq_i}\). Ensuite, pour construire des refutations NSLD, nous ajoutons à \(P\) les clauses Horn N \(B_{i1}, \ldots, B_{iq_i}\) (pour chaque \(i\)) et les clauses \(p, \neg p\) (pour chaque prédicat \(p\)).

III. 4.6. **Définition**: Nous définissons la résolution NSLD comme la résolution pour les clauses Horn N; donc, nous pouvons étendre l'unification ordinaire aux littéraux (positive et negative).

III. 4.7. **Théorème** (complétude): Soit \((P, Q)\) un programme logique N; alors,

1. soit \(P\) est 3-inconsistant, et il existe au moins une refutation NSLD de \(P\) avec but une clause N-négative de \(P\) ou \(R\) (avec les notations du lemme III. 4.4); aucun autre clause N-négative n'est utilisée dans la refutation;
2. soit \(P\) est 3-consistant et alors, si \(P \vdash 3K \exists Q\), alors \(P \vdash 3I \exists Q\) et \(P \vdash 3I Q \theta\) (pour une substitution \(\theta\)) et \(Q\) réussit avec une réponse incluant \(\theta\). Di de plus, aucune clause de la forme \(p, \neg p\) est utilisée dans la démonstration.

*Preuve*: (1) si \(P\) est 3-inconsistant, alors \(P_N \cup R_N\) est (classiquement) inconsistente (lemme III. 4.4); il existe une refutation SLD; puis nous avons transformé cette refutation SLD en une refutation NSLD, remplaçant toute clause \(p^*\) par \(\neg p\);

(2) si \(P\) est 3-consistant alors \(P_N \cup R_N\) est (classiquement) conséquent; puis nous avons appliqué les résultats de la section II pour obtenir une refutation SLD que nous avons facilement transformée en une refutation NSLD. La question \(\exists Q\) et \(Q \theta\) sont intuitionniste dérivable de \(P\), vient de la fait que les preuves de l'appendice A peut être porté Girard's trois-valoré logique (voir l'appendice B).

III. 4.8. **Théorème** (sensibilité): Soit \((P, Q)\) un programme logique N avec \(Q = A_1 \lor \ldots \lor A_n\) (chaque \(A_i\) étant une conjonction de littéraux). Soit \(\pi\) une refutation NSLD et \(\theta\) la substitution de résultat, alors, si \(P\) est 3-inconsistant et seulement une clause \(p, \neg p\) est utilisée dans \(\pi\), ou \(P\) est 3-consistant et alors, aucune clause \(p, \neg p\) est utilisée dans la refutation NSLD et \(P \vdash 3I \exists Q\) et \(P \vdash 3I Q \theta\).

*Preuve*: Remplace toute clause de la refutation NSLD par son N-translated; nous obtenir une refutation SLD. Par résultats de la section II, seulement une clause negative est utilisée; si la clause negative utilisée est \(p, p^*\) pour un prédicat \(p\) alors \(P_N \cup R_N\) est 2-inconsistant (avec les notations de LDL III. 3.4) et donc, \(P\) est 3-inconsistant (lemme III. 4.4); si la clause negative est le N-translated d'une clause \(B_1, \ldots, B_q\) nous avons facilement obtenu le résultat. Pour prouver l'intuitionniste dérivable, nous procédons comme en théorème II. 4.
III. 4.9. Remark

If we consider a 3-consistent set of Horn N-clauses $P$ and if we add a positive $N$-clause $\top A$, $A$ being a literal, a NSLD refutation of the above set of $N$-clauses corresponds to the query $? \exists B$ with $B = \neg A$ if $A$ is a positive literal, and $A = \neg \neg B$ otherwise; many substituted-clauses of $\top A$ can occur in the NSLD-refutation and then we obtain an indefinite answer (that is, substitutions $\theta_1, \ldots, \theta_q$ where $? B \theta_1 \lor \ldots \lor B \theta_q$ is a logical consequence of $P$).

III. 4.10. Comparison with related work

In [3], Delahaye studies the semantics of programs with negation possibly in the body and in the head of clauses. He considers Kleene's three-valued connectives for $\neg$, $\&$, $\lor$ and defines, as Kunen in [10], a new connective $\Rightarrow$, for implication: $A \Rightarrow B$ is false if $A$ is true and $B$ is false or undetermined, and $A \Rightarrow B$ is true otherwise. Using Fitting's methods [4], he announces correction and completeness results. Remark that $M$ is a three-valued model of a Delahaye's clause $A_1 \& \ldots \& A_n \Rightarrow B$ ($A_1, \ldots, A_n, B$ being literals) iff $M$ is a three-valued model of our 3-translated $!A_1, \ldots, !A_n \vdash !B$ of the $N$-clause $A_1, \ldots, A_n \vdash B$.

IV. NEGATION AS FAILURE

In this section we define the completion $\text{Comp}^*(P)$ of a general program $P$ with respect to intuitionistic 3-valued logic, in the spirit of Clark's completion $\text{Comp}(P)$; we show the soundness of SLDNF-resolution with respect to $\text{Comp}^*(P)$ in intuitionistic 3-valued logic.

If $P$ is propositional, then we also obtain the completeness of SLDNF-resolution with respect to $\text{Comp}^*(P)$.

We define as usual the notion of SLDNF-resolution: see, for example [11] or [15]; we use their terminology, particularly concerning computation rules.

We suppose that we have in $L$ a predicate "="", whose intended interpretation is the identity relation.

IV. 1. Definition: Let $P$ be a normal program, that is a set of clauses

$$L_1, \ldots, L_q \vdash p(t_1, \ldots, t_n)$$
The **3-valued translation** of this clause is defined to be:

\[ \L \cdots \L q \p(t_1, \ldots, t_n) \]

and the **normal form** of this clause is defined to be:

\[ \exists y_1 \ldots \exists y_k (x_1 = t_1 \land \ldots \land x_n = t_n \land \L_1 \land \ldots \land \L_q) \vdash p(x_1, \ldots, x_n) \]

if \( y_1, \ldots, y_k \) are the variables of the original clause.

If the \( n \)-place predicate \( p \) occurs \( m \) times (\( m > 0 \)) in the head of a clause in \( P \), and if the normal form of these clauses are: \( E_i \vdash p(x_1, \ldots, x_n) \) (for \( 1 \leq i \leq m \)) then the completed definition of \( p \) is the set of the \( m \) 3-valued translations of the clauses, and of the "completed-sequent" of \( p \):

\[ ?p(x_1, \ldots, x_n) \vdash ?E_1 \lor \ldots \lor E_m \]

If the \( n \)-place predicate \( p \) does not occur in the head of any program clause, then the completed definition of \( p \) is the set containing only the 3-clause: \( ?p(x_1, \ldots, x_n) \vdash . \)

**IV.2. Definition:** We define **CET** (Clark’s equational theory) to be the set of 3-clauses:

1. \( \vdash !x = x \) for each variable \( x \);
2. \( !t(x) = x \vdash \) for each term \( t(x) \) different from \( x \) in which \( x \) occurs;
3. \( !x_1 = y_1, \ldots, !x_n = y_n \vdash !f(x_1, \ldots, x_n) = f(y_1, \ldots, y_n) \) for each function \( f \);
4. \( !x_1 = y_1, \ldots, !x_n = y_n \vdash \xi p(x_1, \ldots, x_n) = \xi p(y_1, \ldots, y_n) \) for each predicate \( p \);
5. \( !f(x_1, \ldots, x_n) = f(y_1, \ldots, y_n) \vdash !x_i = y_i \) for each \( n \)-place function \( f \) and for each \( i (1 \leq i \leq n) \);
6. \( !f(x_1, \ldots, x_n) = g(y_1, \ldots, y_m) \vdash \) for all pairs of distinct functions;
7. \( ?x = y \vdash !x = y \) for all pairs of variables.

Axioms (1)-(6) are the usual ones; axioms (7) say that the equality relation "=" is 2-valued.

**IV.3. Definition:** Let \( P \) be a normal program. The **intuitionistic 3-valued completion** of \( P \), denoted \( \text{Comp}^*(P) \) is the union of the completed definitions for each predicate \( p \) and of CET.

**IV.4. Proposition:** Let \( P \) be a normal program, then \( \text{Comp}^*(P) \) is consistent.
Proof: This is an easy consequence of [15] (theorem 36) because Comp*(P) is a three-valued consequence of the three-valued Clark’s completion Comp(P) used by Kunen (see IV .10).

IV .5. Definition (Shepherdson [14]): The notions of success tree and failure tree of a query Q (Q being a conjunction of literals) are defined recursively as follows:

Basis:
- if Q is “success” (“fail”) then the tree consisting of the single node Q is a success (failure) tree for Q.

Inductive step:
- if Lt is the chosen literal of Q, and if Lt is a positive literal which does not match any clause of P, then the tree with a single “fail” node hanging from the root is a failure tree for Q;
- if Lt is a positive literal which matches one or more clauses of P, and if Q1, . . ., Qp are the resulting derived queries, then a success tree for Q is a tree consisting of a success tree for some Qk hanging from the root Q; a failure tree for Q is a tree consisting of failure trees for each of Q1, . . ., Qp hanging form the root Q;
- if Lt is a negative ground literal ¬i A, a success tree for Q is a tree consisting of a failure tree for A and a success tree for Q’ hanging from the root Q, a failure tree for Q is a tree consisting of a failure tree for A and a failure tree for Q’ hanging from the root Q, or a success tree for A hanging from the root Q.

IV .6. Lemma: (a) If p (s1, . . ., sn) and p (t1, . . ., tn) are not unifiable then

\[ \text{CET} \vdash_{31} s_1 = t_1, \ldots, s_n = t_n \]

(b) If p (s1, . . ., sn) and p (t1, . . ., tn) are unifiable with mgu

\[ \theta = (x_1/r_1, \ldots, x_k/r_k) \]

then

\[ \text{CET} \vdash_{31} !s_1 = t_1, \ldots, !s_n = t_n \vdash !x_i = r_i \quad (\text{for } 1 \leq i \leq k) \]

and

\[ \text{CET} \vdash_{31} !x_1 = r_1, \ldots, !x_k = r_k \vdash !s_i = t_i \quad (\text{for } 1 \leq i \leq n) \]

IV.7. Theorem: SLDNF-resolution is sound with respect to Comp*(P) in intuitionistic three-valued logic, i.e. suppose that Q is a conjunction of literals:

- if Q succeeds with answer 0 then Comp*(P) ⊢ 3_1 ⊢ ! Q 0;
- if Q fails then Comp*(P) ⊢ 3_1 ⊢ ! ⊥ ∋ Q.

Proof: This theorem and its proof are suggested in [15] (theorem 39) but Shepherdson says that he is “not sure exactly how to formulate that”. We use an induction on success and failure trees:

Basis:

(i) Q is the positive literal M, and M matches with a clause ⊢ A, i.e. there exists a mgu 0 of A and M, then since ⊢ A is a sequent of Comp*(P), then Comp*(P) ⊢ 3_1 ⊢ ! M 0;

(ii) if M = p(s_1, . . . , s_n) is the chosen positive literal of Q:

- if p does not appear in the head of any clause of program P: then the complete definition of p is ?p(x_1, . . . , x_n) ⊢ ; thus obviously Comp*(P) ⊢ 3_1 ? M ⊢ and Comp*(P) ⊢ 3_1 ⊢ ! ⊥ ∋ Q;

- if M does not unify with the head of any clause of P, then suppose that the 3-valued translations of the clauses with head p are: ! L_{i_1}, . . . , ! L_{i_q} ⊢ ! p(t_{i_1}, . . . , t_{i_n}); if the completed-sequent of p is: ?p(x_1, . . . , x_n) ⊢ ? E_1 ∨ . . . ∨ E_m then, by lemma IV.6. CET ⊢ 3_1 ? (s_1 = t_{i_1} & . . . & s_n = t_{i_n}) ⊢ for each i (1 ≤ i ≤ m); hence, CET ⊢ 3_1 ? s_1 = t_{i_1} & . . . & s_n = t_{i_n} & L_{i_1} & . . . & L_{i_q} ⊢ for each i (1 ≤ i ≤ m); and hence, using the completed-sequent of p: Comp*(P) ⊢ 3_1 ? p(s_1, . . . , s_n) ⊢ and then Comp*(P) ⊢ 3_1 ⊢ ! ⊥ ∋ Q.

Inductive step:

- if M_j is the chosen positive literal of Q which matches one or more clause of P: M_j = p(s_1, . . . , s_n);

(i) let Q_1, . . . , Q_p be the resulting derived queries and suppose that we have a success tree for one Q_i; then if Q = M_1 & . . . & M_r, if p is a mgu of p(s_1, . . . , s_n) and of p(t_{i_1}, . . . , t_{i_n}) and if

Q_i = M_1 & . . . & M_{j-1} & L_{i_1} & . . . & L_{i_q} & M_{j+1} & . . . & M_r,

by induction hypothesis, Comp*(P) ⊢ 3_1 ⊢ ! Q_i σ (if Q_i succeeds with answer σ); then, using the clause ! L_{i_1}, . . . , ! L_{i_q} ⊢ ! p(t_{i_1}, . . . , t_{i_n}), we see that Comp*(P) ⊢ 3_1 ⊢ ! Q 0 (with 0 = p ° σ);
(ii) let $Q = M_1 \& \ldots \& M_r$ and $Q_1, \ldots, Q_p$ be the resulting derived queries and suppose that we have failure trees for all $Q_i$; then, by induction hypothesis,

$$\text{Comp}^*(P) \vdash s_1 \vdash ! \neg \exists Q_i$$  \hspace{1cm} \text{[for each } i (1 \leq i \leq p)],

and

$$Q_i = (M_1 \& \ldots \& M_{i-1} \& L_{i-1} \& \ldots \& L_{i_k} \& M_{i+1} \& \ldots \& M_r) \rho.$$  

[if $\rho$ is a mgu of $p(s_1, \ldots, s_n)$ and of $p(t_1, \ldots, t_m)$; then using lemma IV. 6 and axioms 7 of CET,

$$\text{CET} \vdash s_1 ? s_1 = t_1 \& \ldots \& s_n = t_n \vdash \exists x_1 = r_1 \& \ldots \& x_k = r_k;$$

then, we prove that:

$$\text{Comp}^*(P) \vdash s_1 \vdash \exists M_1 \& \ldots \& M_{j-1} \& L_{i-1} \& \ldots \& L_{i_k} \& M_{j+1} \& \ldots \& M_r$$

$$\vdash \exists (M_1 \& \ldots \& M_{j-1} \& L_{i-1} \& \ldots \& L_{i_k} \& M_{j+1} \& \ldots \& M_r) \rho;$$

therefore, $\text{Comp}^*(P) \vdash s_1 \vdash ! \neg \exists Q$;

- if $M_j$ is the chosen ground negative literal $\neg A$, and if $A$ has a failure tree and $Q'$ a success tree, $Q'$ being the query obtained from $Q$ by deleting $\neg A$, then by induction hypothesis, $\text{Comp}^*(P) \vdash s_1 \vdash Q' \theta$ and $\text{Comp}^*(P) \vdash s_1 \vdash ! Q \theta$;

- if $M_j$ is the chosen ground literal $\neg A$, and if $A$ has a failure tree and $Q'$ (defined as above) has a failure tree, then by induction hypothesis, $\text{Comp}^*(P) \vdash s_1 \vdash ! \neg \exists Q'$, then $\text{Comp}^*(P) \vdash s_1 \vdash ! \neg \exists Q$;

- if $M_j$ is the chosen ground negative literal $\neg A$, and if $A$ has a success tree, then by induction hypothesis, $\text{Comp}^*(P) \vdash s_1 \vdash ! A$ and therefore, $\text{Comp}^*(P) \vdash s_1 \vdash ! \neg \exists Q$.

IV. 8. **Lemma:** Let $P$ be a propositional normal program and $Q$ be an atom: if $\text{Comp}^*(P) \vdash s_1 \vdash ! Q$ then $Q$ succeeds under SLNDF-resolution; if $\text{Comp}^*(P) \vdash s_1 \vdash ! \neg Q$ then $Q$ fails under SLNDF-resolution.

**Proof:** If all clauses of $P$ are propositional, then the completed-sequent of a proposition $p$ is $? p \vdash ? E_1 \lor \ldots \lor E_m$ with $E_i = L_{i_1} \& \ldots \& L_{i_k}$; we define the **classic-completed** definition of $p$ as the union of the set of the $m$ 3-valued translations of the clauses with head $p$ and of the set of the 3-translated of
N-clauses (see section III) obtained from the completed sequent (N-clausal form of the sequent \( \neg E_1 \land \ldots \land \neg E_m \vdash \neg p \)).

Example: Let \( r, \neg s \vdash p \) and \( t, \neg u \vdash p \) the clauses with head \( p \). Then the classic-completed definition of \( p \) is the set of six N-clauses: \( !r, \neg s \vdash !p \) and \( !t, \neg u \vdash !p \) (the two 3-valued translations) and \( \neg r, \neg t \vdash \neg p \); \( \neg r, \neg u \vdash \neg p \); \( \neg s, \neg t \vdash \neg p \); \( s, \neg u \vdash \neg p \).

If \( p \) does not appear in the head of any program clause, the classic-completed definition of \( p \) is \( \vdash \neg p \).

We define \( \text{Comp}_c(P) \) as the union of the classic-completed definitions of all propositions \( p \) occurring in \( P \) together with CET.

Remark that \( \text{Comp}_c(P) \) is a set of 3-translated clauses of N-clauses. Then: if \( \text{Comp}^*(P) \vdash_{31} ! Q \), then \( \text{Comp}_c(P) \vdash_{3K} ! Q \) and by results of section III, \( \text{Comp}_c(P) \vdash_{31} ! Q \); moreover, the deduction only uses the cut and exchange rules (see lemma B.1.3); also, if \( \text{Comp}^*(P) \vdash_{31} \neg Q \), \( \text{Comp}_c(P) \vdash_{31} \neg Q \); we transform this proof to obtain a proof by "hyperresolution": i.e. we extend the usual notion of hyperresolution (see for example [16]) to formulae \( !A \) where \( A \) is a literal; then by induction on the proof of \( \vdash ! Q \) (or of \( \vdash \neg Q \)), we construct a success (or a failure) tree for \( Q \).

IV.9. Theorem: If \( P \) is a propositional normal program, then SLNDF-resolution is complete with respect to \( \text{Comp}^*(P) \) in three-valued intuitionistic logic i.e. if \( Q \) is a conjunction of literals: if \( \text{Comp}^*(P) \vdash_{31} ! Q \) then \( Q \) succeeds under SLNDF-resolution; if \( \text{Comp}^*(P) \vdash_{31} \neg Q \) then \( Q \) fails under SLNDF-resolution.

Proof: Let \( Q = Q_1 \land \ldots \land Q_p \) (each \( Q_i \) being a literal):

- if \( \text{Comp}^*(P) \vdash_{31} ! Q \), then, for each \( i \) (\( 1 \leq i \leq p \)) \( \text{Comp}^*(P) \vdash_{31} ! Q_i \); then, by lemma IV.8, if \( Q_i \) is an atom, \( Q_i \) succeeds under SLNDF-resolution, and if \( Q_i = \neg A_i \), \( A_i \) fails under SLNDF-resolution. Then, \( Q \) succeeds under SLNDF-resolution;

- if \( \text{Comp}^*(P) \vdash_{31} \neg Q \), then \( \text{Comp}_c(P) \vdash_{3K} ! A_1 \lor \ldots \lor A_p \), with \( A_i = \neg Q_i \) if \( Q_i \) is an atom, or else (if \( Q_i \) is a negative literal) \( Q_i = \neg A_i \); by the results of appendix B (lemma B.1.3), \( \text{Comp}_c(P) \vdash_{31} ! A_k \) for one \( k \) (\( 1 \leq k \leq p \)); hence, \( \text{Comp}^*(P) \vdash_{31} ! A_k \); then, by lemma IV.8, if \( Q_k \) is an atom, then \( Q_k \) fails and hence, \( Q \) fails; if \( Q_k = \neg A_k \), \( A_k \) succeeds, and then \( Q_k \) and \( Q \) fail.
IV. 10. Comparison with related work

It is well known that if negation as failure (SLNDF-resolution) is sound with respect to Clark's completed $\text{Comp}(P)$ in classical logic, it is not complete (see for example [11] or [15]).

For example, if we consider the program $P$ with the unique clause $\neg A \leftarrow A$ (in Prolog: $A: \neg \neg A$), then the formula $A \leftrightarrow \neg A$ is an axiom of $\text{Comp}(P)$ and, since $\text{Comp}(P)$ is inconsistent, $A$ is a consequence of $\text{Comp}(P)$ but the query $A$ does not succeed.

Shepherdson ([13] and [14]) shows the soundness of SLDNF with respect to Clark's completed $\text{Comp}(P)$ in intuitionistic logic, but, as the above example shows, we have not the completeness, even for the propositional case and in intuitionistic logic.

Kunen [10] considers a three-valued version of $\text{Comp}(P)$: in the completed definition of a predicate $p(x_1, \ldots, x_n) \leftrightarrow E_1 \lor \ldots \lor E_m$, the equivalence takes the value true if the two members take the same value, and takes the value false otherwise. Kunen proves the soundness of SLDNF with respect to this classical three-valued logic and the completeness for the propositional case.

Kunen does not define a proof-system for the specific version of three-valued logic that he uses; but we can translate $\text{Comp}(P)$ into our system, replacing each axiom $p(x_1, \ldots, x_n) \leftrightarrow E_1 \lor \ldots \lor E_m$ by the four sequents:

\[
! E_1 \lor \ldots \lor E_m \vdash ! p(x_1, \ldots, x_n) \\
? E_1 \lor \ldots \lor E_m \vdash ? p(x_1, \ldots, x_n) \\
! p(x_1, \ldots, x_n) \vdash ! E_1 \lor \ldots \lor E_m \\
? p(x_1, \ldots, x_n) \vdash ? E_1 \lor \ldots \lor E_m
\]

We obtain a system $\text{Comp}_K(P)$ and, since each three-valued structure is a (classical) model of $\text{Comp}(P)$ iff it is a (classical) three-valued model of $\text{Comp}_K(P)$, and each (classical) three-valued model of $\text{Comp}_K(P)$ is an intuitionistic model of $\text{Comp}^*(P)$, $\text{Comp}^*(P)$ is consistent; moreover, our completeness result is entailed by Kunen's completeness result while our soundness result entails Kunen's soundness result.
A. GENTZEN'S SEQUENT CALCULUS AND HORN CLAUSES

In this paragraph we define Gentzen's sequent calculus, and we show some properties of logic programs consisting of Horn clauses, using proof-theoretical methods. Most of these results have been previously proved, by similar or other methods, in [5].

A.1. Gentzen's sequent calculus

In this paper L stands for a fixed first-order language; we assume the language L has some fixed set of constant, function and relation symbols, and formulae of L are defined in the usual way, using \(\neg, \&, \lor, \rightarrow, \forall, \exists\).

We define, as usual, the notions of substitution, closed instance of formula, interpretation, and model of a set of formulae.

A.1.1. DEFINITION: We define the formal system LK:

(i) A sequent in LK is a formal expression \(\Gamma \vdash \Delta\), where \(\Gamma\) and \(\Delta\) are finite sequences (possibly empty) of formulae in L.

(ii) The sequent calculus LK is defined as follows:

(1) axioms: \(A \vdash A\) for each atomic formula \(A\);

(2) logical rules:

- conjunction

\[
\frac{\Gamma \vdash \Delta, A \quad \Lambda \vdash \Pi, B}{\Gamma, \Lambda \vdash \Delta, \Pi, A \& B} \quad r&
\]

\[
\frac{A, \Gamma \vdash \Delta}{A \& B, \Gamma \vdash \Delta} \quad l1 &
\]

\[
\frac{B, \Gamma \vdash \Delta}{A \& B, \Gamma \vdash \Delta} \quad l2 &
\]

- disjunction

\[
\frac{\Gamma \vdash \Delta, A}{\Gamma \vdash \Delta, A \lor B} \quad r1 \lor
\]

\[
\frac{\Gamma \vdash \Delta, B}{\Gamma \vdash \Delta, A \lor B} \quad r2 \lor
\]

\[
\frac{A, \Gamma \vdash \Delta}{A \lor B, \Gamma \vdash \Delta} \quad l \lor
\]

\[
\frac{B, \Lambda \vdash \Pi}{A \lor B, \Gamma, \Lambda \vdash \Delta, \Pi} \quad l \lor
\]
— negation

\[
\frac{\Gamma \vdash \Delta, A}{\neg A, \Gamma \vdash \Delta} \quad \frac{A, \Gamma \vdash \Delta}{\neg \Gamma, \neg A}
\]

— implication

\[
\frac{\Gamma \vdash \Delta, A \quad \Lambda \vdash \Pi}{A \rightarrow B, \Gamma, \Lambda \vdash \Delta, \Pi} \quad \frac{A, \Gamma \vdash \Delta, B}{\Gamma \vdash \Delta, A \rightarrow B}
\]

— for all

\[
\frac{A(t), \Gamma \vdash \Delta}{\forall x, A(x), \Gamma \vdash \Delta} \quad \frac{\Gamma \vdash \Delta, A(x)}{\Gamma \vdash \forall x, A(x)}
\]

— there is

\[
\frac{A(x), \Gamma \vdash \Delta}{\exists x, A(x), \Gamma \vdash \Delta} \quad \frac{\Gamma \vdash \Delta, A(t)}{\Gamma \vdash \exists x, A(x)}
\]

(*) we have the following restriction on variables: x not free in \(\Gamma, \Delta\).

(**) \(t\) is an arbitrary term of \(L\).

(3) structural rules:

— weakening

\[
\frac{\Gamma \vdash \Delta}{A, \Gamma \vdash \Delta} \quad \frac{\Gamma \vdash \Delta}{\Gamma \vdash \Delta}
\]

— contraction

\[
\frac{A, A, \Gamma \vdash \Delta}{\Gamma \vdash \Delta} \quad \frac{\Gamma \vdash \Delta, A, A}{\Gamma \vdash \Delta, A}
\]

— exchange

\[
\frac{\Pi, A, B, \Gamma \vdash \Delta}{\Pi, B, A, \Gamma \vdash \Delta} \quad \frac{\Gamma \vdash \Delta, A, B, \Pi}{\Gamma \vdash \Delta, B, A, \Pi}
\]

(4) cut

\[
\frac{\Gamma \vdash \Delta, A}{\Gamma, \Lambda \vdash \Delta, \Pi, A, \Lambda \vdash \Pi} \quad \frac{\Gamma \vdash \Delta, A}{\Gamma, \Lambda \vdash \Delta, \Pi}
\]

(we say that \(A\) is the cut-formula).

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A. 1.2. Terminology and notations

(i) We define, as usual the notion of proof in a formal system.

(ii) The rules (1), (2) and (3) are the cut-free rules; a cut-free proof is a proof using only the cut-free rules.

(iii) The logical rules are divided into right rules and left rules according to the fact that the main formula (for example in \( \& \) the main formula is \( A \& B \)) appears in the right part or in the left part of the sequent.

(iv) If we want to indicate the use of exchange rules, we shall often write \( \equiv \) instead of \( : \)

\[
\frac{\Gamma \vdash \Delta}{\Gamma' \vdash \Delta'}
\]

means that \( \Gamma' \vdash \Delta' \) has been obtained from \( \Gamma \vdash \Delta \) by a finite number (possibly zero) of exchange rules; for example,

\[
\frac{\Gamma \vdash \Delta, A \quad A, \Lambda \vdash \Pi}{\Gamma, \Lambda \vdash \Delta, \Pi}
\]

Cut means that finitely many exchange rules, together with one application of cut have been used.

A. 1.3. Définitions:

(i) If \( M \) is a structure (or interpretation) for \( L \), we define the language \( L[M] \) by adding to \( L \) new constants \( \varsigma \) for all \( c \in |M| \), and we associate, a value \( M(t) \) [resp. \( M(A) \)] to each term \( t \) (resp. formula \( A \)) of \( L[M] \). We use the notation \( M \vdash A \) for \( M(A) = t \) (i.e. true) and \( M \nvdash A \) for \( M(A) = f \) (i.e. false).

(ii) The closed sequent \( A_1, \ldots, A_n \vdash B_1, \ldots, B_m \) of \( L[M] \) is valid in the structure iff:

- if \( n \neq 0 \) and \( m \neq 0 \): if \( M \vdash A_i \) and \( \ldots \) and \( M \vdash A_n \) then \( M \vdash B_1 \) or \( \ldots \) or \( M \nvdash B_m \);
- if \( n \neq 0 \) and \( m = 0 \) then \( M \nvdash A_1 \) or \( \ldots \) or \( M \nvdash A_n \);
- if \( n = 0 \) and \( m \neq 0 \) then \( M \nvdash B_1 \) or \( \ldots \) or \( M \vdash B_m \);
- if \( n = 0 \) and \( m = 0 \), the sequent \( \vdash \) means absurdity.

A. 1.4. Définition: Let \( S \) be a set of sequents of \( LK \). A model \( M \) of \( S \) is a structure such that any closed instance of a sequent of \( S \) is valid in \( M \). \( S \) is consistent iff it has at least one model.

We denote by \( SLK \) the extension of the calculus \( LK \) obtained by adding the sequents of \( S \) to the axioms of \( LK \). We say that \( SLK \) is a theory and that the sequents of \( S \) are the proper axioms of the theory. If a sequent \( \Gamma \vdash \Delta \) is provable in \( SLK \), we write \( S \vdash_k \Gamma \vdash \Delta \).
A.1.5. **Theorem** (soundness): The rules of LK preserve validity of the sequents: i.e. if all closed instances of the premises are valid, all closed instances of the conclusion are valid.

Thus, if S is a set of sequents, and if the sequent \( \Gamma \vdash \Delta \) is provable in SLK, \( \Gamma \vdash \Delta \) is valid in any model of S.

A.1.6. **Theorem** (completeness): If all closed instances of a sequent \( \Gamma \vdash \Delta \) of LK are valid in all structures for L, then \( \Gamma \vdash \Delta \) is provable in LK.

A.1.7. **Theorem**: \( \Gamma \vdash \Delta \) enjoys cut-elimination (i.e. the cut rule is redundant: if a sequent of LK is provable, it is cut-free provable).

A.1.8. **Remark**: The above theorem is Gentzen’s famous Hauptsatz. Consequently, we have a subformula property: for any cut-free proof of a sequent \( A_1, \ldots, A_n \vdash B_1, \ldots, B_m \), each formula occurring in the proof is a subformula of one \( A_i \) or of one \( B_i \).

A.1.9. **Theorem**: Let S be a set of sequents of LK closed under substitution (i.e. if \( \Gamma(x) \vdash \Delta(x) \in S \) then, for each term \( t \), \( \Gamma(t) \vdash \Delta(t) \in S \)).

If a sequent is provable in SLK, then any closed instance of this sequent is valid in any model of S (soundness).

If a sequent \( \Gamma \vdash \Delta \) of LK is valid in any model M of S, then it is provable in SLK (completeness). Moreover there is a proof in which all cut-formulae occur in some sequent of S; hence, any formula occurring in this proof is a subformula of a formula occurring in S, or in \( \Gamma \vdash \Delta \).

A.2. The intuitionistic case

A.2.1. **Definitions**: (i) A sequent of LI is a formal expression \( \Gamma \vdash \Delta \) such that \( \Gamma \) is a finite sequence (possibly empty) of formulae of L, and \( \Delta \) is empty, or consists in one formula of L. We say that \( \Gamma \vdash \Delta \) is an intuitionistic sequent.

(ii) The sequent calculus LI is the subsystem of LK obtained from LK by using the following restrictions:

- all sequents considered are intuitionistic sequents;
- we consider as rules of LI only the rules of LK which, applied to intuitionistic sequents, yield intuitionistic sequents [with an exception for the rule (lv)]:

  \[
  \frac{A, \Gamma \vdash \Delta}{A \lor B, \Gamma, \Lambda \vdash \Delta}^{\text{lv}}
  \]

  (a) for logical rules: the rule (lv) is replaced by \( A, \Gamma \vdash \Delta \)

  (b) the only right structural rules are \((r W)\) [because \((r E)\) and \((r C)\) necessitate more than one formula on the right].
(ii) We define SLI from LI, as we have defined SLK from LK. If a sequent \( \Gamma \vdash \Delta \) is provable in SLI, we write \( S \vdash_1 \Gamma \vdash \Delta \).

### A.2. Horn clauses

In the following part of this section let \( S \) be a set of Horn clauses, closed under substitution.

**Lemma (Girard [8]):** If the clause \( \Gamma \vdash \Delta \) is provable in SLK, then there exists a Horn clause \( \Gamma' \vdash \Delta' \) provable in SLI, and any formula \( A \) occurring in \( \Gamma' \) is a formula of \( \Gamma \) and if \( \Delta' \) is not empty, it consists of one formula \( A \) of \( \Delta \); moreover, no weakening nor contraction rule is used in the proof.

**Proof:** By theorem A.1.9, there exists a proof of \( \Gamma \vdash \Delta \) where all the cuts are on formulae occurring in a sequent of \( S \); first, remark that, by subformula property, no logical rule is used in the proof; we construct, by induction on the proof \( D \), a proof \( t(D) \) and we verify that the conditions of the theorem are fulfilled:

- if \( D \) is an axiom we set \( t(D) = D \);
- if the last rule of \( D \) is a structural rule:

\[
P
D: \begin{array}{c} \Gamma_1 \vdash \Delta_1 \\ \Gamma \vdash \Delta 
\end{array}
\]

we set \( t(D) = t(P) \);
- if the last rule of \( D \) is a cut:

\[
P \quad Q
D: \begin{array}{c} \Gamma \vdash \Delta, A \\ A, \Lambda \vdash \Pi 
\end{array} \quad \text{Cut}
\]

by induction hypothesis, we have proofs \( t(P) \) and \( t(Q) \) of sequents \( \Gamma_1 \vdash \Delta_1 \) and \( \Lambda \vdash \Pi_1 \); if \( \Delta_1 \neq A \), we set \( t(D) = t(P) \); if \( \Delta_1 = A \) and \( A \) does not occur in \( \Lambda \), we set \( t(D) = t(Q) \); if \( \Delta_1 = A \) and \( A \) occurs \( n \) times in \( \Lambda \), then we set:

\[
\begin{array}{c} t(P) \\ t(Q) 
\end{array} \quad \begin{array}{c} \Gamma_1 \vdash A \\ A, \Lambda_2 \vdash \Pi_1 
\end{array} \quad \text{Cut}
\]

and we apply cuts: using \( t(P) \) and \( t(D) \), we define \( t_{i+1}(D) \); finally, \( t(D) = t_n(D) \).
Remark that if a negative clause of $S$ has been used, then $\Delta'$ is empty, and only a negative clause is used in the proof $t(D)$.

A.3.2. COROLLARY: We denote by $SLI^*$ the subsystem of $SLI$, having as only rules the exchange and cut rules. Let $S$ be a consistent set of Horn clauses:

(i) if the closure of a positive clause $\vdash A$ is valid in any model of $S$, then $\vdash A$ is provable in $SLI^*$;

(ii) if the closure of a negative clause $A \vdash$ is valid in any model of $S$, then $\Gamma \vdash$, $\Gamma$ being a sequence containing only occurrences of $A$, is provable in $SLI^*$.

Proof: (i) By theorem A.1.9 and lemma A.3.1 the sequent $\vdash$ or the sequent $\vdash A$ are provable in $SLI$. Since $S$ is consistent, $\vdash$ is not provable (soundness of $SLK$ and thus, of $SLI$); hence, we obtain the result, since if an axiom $A \vdash A$ is used, the only rule that we can apply is a cut, therefore we can suppress it;

(ii) it is an immediate consequence of A.1.9 and A.3.1.

A.3.3. LEMMA: The lemma A.3.1 remains true if $\Delta$ is a sequence of formulae built with $\&$, $\lor$, $\exists$.

Proof: By the subformula property, the only logical rules possibly used are: $(r1\lor)$, $(r2\lor)$, $(r\&)$, $(r\exists)$; so, the proof of A.1.2 has to be completed:

- if the last rule is $(r1\lor)$:

$$\begin{equation}
D: \begin{array}{c}
\Gamma \vdash \Delta_1, A \\
\Gamma \vdash \Delta_1, A \lor B
\end{array}
\end{equation}
$$

by induction hypothesis, we have a deduction $t(P)$ of a sequent $\Gamma'' \vdash \Delta'_1$; if $\Delta'_1$ is not $A$, we set $t(D) = t(P)$; otherwise, we set:

$$t(D): \begin{array}{c}
\Gamma'' \vdash A \\
\Gamma'' \vdash A \lor B
\end{array}
$$

- if the last rule is $(r2\lor)$, the proof is similar;

- if the last rule is $(r\&)$

$$\begin{equation}
D: \begin{array}{c}
\Gamma_1 \vdash \Delta_1, A \\
\Lambda_1 \vdash \Pi_1, B
\end{array}
\end{equation}
$$

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by induction hypothesis, we have proofs \( t(P) \) and \( t(Q) \) of sequents \( \Gamma'_1 \vdash \Delta'_1 \) and \( \Lambda'_1 \vdash \Pi'_1 \); if \( \Delta'_1 \) is not \( A \), we set \( t(D) = t(P) \); if \( \Delta'_1 \) is not \( B \), we set \( t(D) = t(Q) \); otherwise we set:

\[
\frac{t(P) \quad t(Q)}{t(D)} \frac{\Gamma'_1 \vdash A \quad \Lambda'_1 \vdash B}{\Gamma'_1, \Lambda'_1 \vdash A \land B \quad r \&}
\]

- if the last rule is \( (r \exists) \)

\[
P \quad D: \frac{\Gamma'_1 \vdash \Delta'_1, A(t)}{\Gamma'_1 \vdash \Delta'_1, \exists x, A(x) \quad r \exists}
\]

by induction hypothesis, we have a proof \( t(P) \) of a sequent \( \Gamma'_1 \vdash \Delta'_1 \); if \( \Delta'_1 \) is not \( A(t) \), we set \( t(D) = t(P) \); otherwise we set:

\[
\frac{t(P)}{t(D)} \frac{\Gamma'_1 \vdash A(t)}{\Gamma'_1 \vdash \exists x, A(x) \quad r \exists}
\]

A.3.4. Corollary: Let \( S \) be a consistent set of Horn clauses. If any closed instance of a formula \( \exists x_1 \ldots \exists x_q, A_1 \lor \ldots \lor A_n \) each \( A_i \) being a conjunction of atoms, \( (A_i = B_{i1} \& \ldots \& B_{i(r)}) \) is valid in any model of \( S \), then there exists an index \( i (1 \leq i \leq n) \) and terms \( t_1, \ldots, t_q \) such that \( B_{ik}(t_1, \ldots, t_q) \) (for each \( k, 1 \leq k \leq l \)) is provable in \( SLK^* \).

Proof: It is a consequence of properties of intuitionistic calculus: by theorem A.1.9 and lemma A.1.4 the sequent \( \vdash \exists x_1 \ldots \exists x_q, A_1 \lor \ldots \lor A_n \) is provable in \( SLI \) (without using contractions nor weakenings), then by induction on the proof, we construct the required proofs: remark first that, by the subformula property, all rules \( (r \&), (r 1 \lor), (r 2 \lor) \) are applied before \( (r 1 \lor) \) or \( (r 2 \lor) \), and that these ones are applied before \( (r \exists) \) rules; then, by induction on the proof we may delete all \( (r \&), (r 1 \lor), (r 2 \lor), (r \exists) \) rules; and we obtain the proofs.

A.3.5. Remark: The above corollary is not true if one of the \( B_{ik} \)'s is a negative literal; take, for example for \( S \), the Horn clause: \( p(a), p(b) \vdash \); then \( \vdash \exists x \neg p(x) \) is valid in any model of \( S \), and thus, is provable in \( SLK \), but not in \( SLI \); so, there does not exist a term \( t \) such that \( p(t) \) is provable in \( SLI \).
(neither in SLK). A proof in SLK of \( \vdash \exists x \neg p(x) \) is the following:

\[
\begin{align*}
& p(a), p(b) \vdash r \neg \\
& p(b) \vdash \neg p(a) \\
& p(b) \vdash r \neg \\
& \vdash \neg p(a), \neg p(b) \\
& \vdash r \exists \\
& \vdash \exists x \neg p(x) \\
& \vdash r \exists \\
& \vdash \exists x \neg p(x)
\end{align*}
\]

A.3.6. Lemma: Let \( S \) be a consistent set of Horn clauses. If any closed instance of a formula \( \exists x_1 \ldots \exists x_q \ Q \) (with \( Q = A_1 \lor \ldots \lor A_n \) each \( A_i \) being an anti-Horn clause: see definition II.1) is valid in any model of \( S \), then there exists tuples of terms \( (t_{11}, \ldots, t_{1q}), \ldots, (t_{k1}, \ldots, t_{kq}) \) satisfying the following property:

\[
\vdash Q(t_{11}/x_1, \ldots, t_{1q}/x_q), \ldots, Q(t_{k1}/x_1, \ldots, t_{kq}/x_q)
\]

is provable in SLK.

Proof: By theorem A.1.9, the sequent \( \vdash \exists x_1 \ldots \exists x_q \ Q \) is provable in SLK and we can choose the proof such that any cut-formula occurs in a sequent of \( S \). Observe that, by the subformula property, only \((r \neg)\), \((r \&), (r 1 \lor)\), \((r 2 \lor)\), \((r \exists)\), are used as logical rules in the proof and that \((r \neg)\) rules are used, for any right occurrence of a formula, before \((r \&), (r \&)\) are used before \((r 1 \lor), (r 2 \lor)\) rules and the latter before \((r \exists)\)-rules; then delete in the proof all applications of a \((r \exists)\)-rule and weakenings or contractions so that the main formula is existential; we obtain a proof of a sequent

\[
\vdash Q(t_{11}/x_1, \ldots, t_{1q}/x_q), \ldots, Q(t_{k1}/x_1, \ldots, t_{kq}/x_q).
\]

Then, by soundness of SLK, the closure of the formula

\[
Q(t_{11}/x_1, \ldots, t_{1q}/x_q) \lor \ldots \lor Q(t_{k1}/x_1, \ldots, t_{kq}/x_q)
\]

is valid in any model of \( S \).
A.4. SLD-resolution

In this section, we use SLD-resolution. We suppose that the reader is familiar with this notion. If not, he can consult [11] or [5]. We define in the same way as Gallier the notion of logic program (see II.2).

A.4.1. Theorem (completeness): Let \((P, Q)\) be a logic program; then,

1. if \(P\) is inconsistent, and there exists at least one SLD-refutation of \(P\) with goal a negative clause of \(P\); no other negative clause is used in the refutation;

2. or \(P\) is consistent and then,

   (i) if \(Q = A_1 \lor \ldots \lor A_n\), each \(A_i\) being a conjunction of atoms \(B_i\); if the query \(\exists Q\) is a logical consequence of \(P\), then it is an intuitionistic consequence of \(P\) and there exists at least one n-uple \((t_1, \ldots, t_q)\) of terms of \(L\) satisfying the property that \(Q(t_1/x_1, \ldots, t_q/x_q)\) is a (intuitionistic) logical consequence of \(P\); for any such n-uple there exists one SLD-refutation with answer substitution \(\theta\) and a ground substitution \(\rho\) with the restriction of \(\theta \circ \rho\) to \((x_1, \ldots, x_q)\) being \((t_1/x_1, \ldots, t_q/x_q)\)

   (ii) if \(Q = A_1 \lor \ldots \lor A_n\) is a disjunction of anti-Horn clauses, then if the query \(\exists Q\) is a logical consequence of \(P\), there exists a sequence, \((t_{11}, \ldots, t_{1q}), \ldots, (t_{k1}, \ldots, t_{kq})\) of n-tuples of terms of \(L\) satisfying:

\[
Q(t_{11}/x_1, \ldots, t_{1q}/x_q) \lor \ldots \lor Q(t_{11}/x_1, \ldots, t_{kq}/x_q)
\]

is a (classical) consequence of \(P\); moreover, there exists a SLD-refutation and substitutions \(\theta_1, \ldots, \theta_k\) and a ground substitution \(\rho\) with the restrictions of \(\theta_1 \circ \rho, \ldots, \theta_k \circ \rho\) to \((x_1, \ldots, x_q)\) being respectively

\[
(t_{11}/x_1, \ldots, t_{1q}/x_q), \ldots, (t_{k1}/x_1, \ldots, t_{kq}/x_q).
\]

Proof: If \((P, Q)\) is a logic program, let \(S\) be the set (in general infinite) of all clauses obtained by substitution from clauses of \(P\). If we consider a proof in \(SLF\) (or in \(SFI\)), only a finite number of clauses of \(S\) occur in the proof and these clauses are in the form \(C\theta\), \(C\) being a clause of \(P\), and \(\theta\) a substitution. Remark that a proof of the sequent \(\vdash\) in \(SLF\) can be transformed into a SLD-refutation with goal, the only negative clause used in the proof: we prove this fact for propositional calculus, then we extend it to first-order logic using lifting techniques (this tool is well-known and we don’t develop it here); thus,

1. if \(P\) is inconsistent we get the result by lemma A.3.1 and the above remark;

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(2) if \( P \) is consistent;

(i) by corollary A.3.4, there is an index \( i \) so that for each \( j (1 \leq j \leq l) \) \( B_{ij}(t_1/x_1, \ldots, t_q/x_q) \) is provable in \( \text{SL}_T^* \) (if we suppose that

\[
A_i = B_{i1} \& \ldots \& B_{il}
\]

and only definite clauses are used in the proofs; then, if we add to \( S \) the closure under substitution of the negative clause \( B_{i1}, \ldots, B_{il} \), we obtain a set \( S' \) and we easily construct a proof in \( S'L_I^* \) of the sequent \( \vdash \); this proof can be transformed into a \( \text{SLD-refutation} \) satisfying the conditions of the theorem;

(ii) by lemma A.3.6, there exists a proof in \( \text{SLK} \) of the sequent

\[
\vdash Q(t_{11}/x_1, \ldots, t_{1q}/x_q), \ldots, Q(t_{k1}/x_1, \ldots, t_{kq}/x_q).
\]

If we suppose that we add to \( S \) all substitutions of clauses obtained from negations of formulae \( A_i (1 \leq i \leq n) \), we obtain a set \( S' \) of Horn clauses and we construct easily a proof in \( S'L_K \) of the sequent \( \vdash \). But, since all clauses in \( S' \) are Horn clauses, we have a proof in \( S'L_I^* \) of the sequent \( \vdash \) (by lemma A.3.1), and therefore a \( \text{SLD-refutation} \).

**APPENDIX B**

**B. THREE-VALUED SEQUENT CALCULUS**

**B. 1. Classical and intuitionistic three valued sequent calculus**

**B.1.1. Definitions:** We suppose that the language \( 3L \) is defined as in III.1.3. We define the formal system \( 3L_K \) (we use notations of section III and \( \xi, \eta \) vary through \( !, ? \)):

(1) **axioms:** \( \xi A \vdash \xi A \) and \( ! A \vdash ? A \) for each atomic formula \( A \);

(2) **logical rules:**

- **conjunction**

\[
\frac{\Gamma \vdash \Delta, \xi A \quad \Lambda \vdash \Pi, \xi B}{\Gamma, \Lambda \vdash \Delta, \Pi, \xi A \& B} \quad \text{r\&} \\
\frac{\xi A, \Gamma \vdash \Delta}{\xi A \& B, \Gamma \vdash \Delta} \quad 11 \& \\
\frac{\xi B, \Gamma \vdash \Delta}{\xi A \& B, \Gamma \vdash \Delta} \quad 12 \&
\]

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- **disjunction**

\[
\frac{\Gamma \vdash A, \xi A}{\Gamma \vdash A \lor B} \quad r_1 \lor \quad \frac{\Gamma \vdash A, \xi B}{\Gamma \vdash A \lor B} \quad r_2 \lor
\]

\[
\frac{\xi A, \Gamma \vdash A}{\xi A \lor B, \Gamma, \Lambda \vdash \Lambda, \Pi} \quad l \lor
\]

- **negation**

\[
\frac{\Gamma \vdash A, \xi A}{\xi \neg A, \Gamma \vdash \neg A} \quad l \neg \quad \frac{\Gamma \vdash \Lambda, \xi A}{\xi \neg A, \Gamma \vdash \neg A} \quad r \neg
\]

- **implication**

\[
\frac{\Gamma \vdash A, \xi \neg A, \Lambda \vdash \Pi}{\xi A \rightarrow B, \Gamma, \Lambda \vdash \Pi} \quad l \rightarrow \quad \frac{\gamma \neg A, \Lambda \vdash \Pi}{\Gamma \vdash A, \xi A \rightarrow B} \quad r \rightarrow
\]

- **for all**

\[
\frac{\xi A(t), \Gamma \vdash \Lambda}{\xi \forall x, A(x), \Gamma \vdash \Lambda} \quad l \forall (**) \quad \frac{\Gamma \vdash \Lambda, \xi A(x)}{\Gamma \vdash \forall x, A(x)} \quad r \forall (*)
\]

- **there is**

\[
\frac{\xi A(x), \Gamma \vdash \Lambda}{\xi \exists x, A(x), \Gamma \vdash \Lambda} \quad l \exists (*) \quad \frac{\Gamma \vdash \Lambda, \xi \exists x, A(x)}{\Gamma \vdash \exists x, A(x)} \quad r \exists (**)
\]

(*) we have the following restriction on variables: \(x\) not free in \(\Gamma, \Delta\).

(**) \(t\) is an arbitrary term of \(L\).

(3) **structural rules**

- **weakening**

\[
\frac{\Gamma \vdash \Lambda}{\xi A, \Gamma \vdash \Lambda} \quad lW \quad \frac{\Gamma \vdash \Lambda}{\Gamma \vdash \Lambda, \xi A} \quad rW
\]

- **contraction**

\[
\frac{\xi A, \xi A, \Gamma \vdash \Lambda}{\xi A, \Gamma \vdash \Lambda} \quad lC \quad \frac{\Gamma \vdash \Lambda, \xi A, \xi A}{\Gamma \vdash \Lambda, \xi A} \quad rC
\]

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$$\frac{\Pi, \xi A, \xi B, \Gamma \vdash \Delta}{\Pi, \xi B, \xi A, \Gamma \vdash \Delta} \quad 1E$$

$$\frac{\Gamma \vdash \Delta, \xi A, \xi B, \Pi}{\Gamma \vdash \Delta, \xi B, \xi A, \Pi} \quad rE$$

(4) cut

$$\frac{\Gamma \vdash \Delta, \xi A}{\xi A, \Lambda \vdash \Pi} \quad \text{Cut}$$

We define the intuitionistic three-valued sequent calculus \(3LI\) from \(3LK\), just as we have defined the sequent calculus \(LI\) from \(LK\).

B. 1.2. Definitions and theorems: We define classical three-valued structures and models (see III.1.4). For intuitionistic three-valued models, see [7].

Theorems A.1.5, A.1.6, A.1.9 (soundness, completeness, cut-elimination) can be extended to \(3LK\) (and \(3LI\)).

B. 1.3. Lemma: Let \(S^*\) be a consistent set of 3-translated of Horn N-clauses of a set \(S\) (see definition III.4.2); if \(S^* \vdash_{3K} ! A_1 \lor \ldots \lor A_p\) each \(A_i\) being a literal, then \(S^* \vdash_{3I} ! A_k\) for one \(k\) \((1 \leq k \leq p)\).

Proof: It is a consequence of lemma A.3.4: replace (as in III.4.2) in the proof (in \(S^*3LK\)) of \(\vdash ! A_1 \lor \ldots \lor A_p\) each literal \(\neg p(t_1, \ldots, t_n)\) by \(p^*(t_1, \ldots, t_n)\) and remove all symbols "!!": we obtain a proof in \(SLK\); apply corollary A.3.4 to obtain a proof in \(SLI\) of \(! A_k\) or of \(! B_k^*\) (with \(A_k = \neg B_k\)) (for one \(k\) such that \(1 \leq k \leq p\)); then replace in the proof each atom \(p^*(t_1, \ldots, t_n)\) by \(\neg ! \neg p(t_1, \ldots, t_n)\) and each atom \(p(t_1, \ldots, t_n)\) by \(\neg ! p(t_1, \ldots, t_n)\): we obtain the required proof.

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THREE-VALUED LOGIC AND LOGIC PROGRAMMING