Many-valued Logic Programming and Fixpoint Semantics for Higher-order Herbrand Models

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Abstract. In this paper we compare the two versions of knowledge invariant transformations of the original Many-valued logic programs: the strict Annotated logic programs and the 'meta' logic programs obtained by the ontological encapsulation [1]. We show that the first one has the higher-order Herbrand interpretations, while the last can be seen as the flattening of the first one. These two knowledge invariant 2-valued logic transformations of the 4-valued Belnap’s bilattice-based logic, able to handle incompleteness and inconsistency of knowledge-base systems, are mutually inverse in Galois connection based on predicate compression and decompression (flattening). Consequently, we can use this Galois connection between them to establish their fixpoint semantics relationship. This results generalize the truth-knowledge fixpoint semantics for many-valued logic programming [2].

1 Introduction

So far, research in many-valued logic programming has proceeded along different directions: Signed logics [3, 4] and Annotated logic programming [5–7] which can be embedded into the first, Bilattice-based logics, [8, 9], and Quantitative rule-sets, [10, 11]. Earlier studies of these approaches quickly identified various distinctions between these frameworks. For example, one of the key insights behind bilattices was the interplay between the truth values assigned to sentences and the (non classic) notion of implication in the language under considerations. Thus, rules (implications) had weights (or truth values) associated with them as a whole. The problem was to study how truth values should be propagated "across" implications. Annotated logics, on the other hand, appeared to associate truth values with each component of an implication rather than the implication as a whole. Roughly, based on the way in which uncertainty is associated with facts and rules of a program, these frameworks can be classified into implication based (IB) and annotation based (AB).

In the IB approach a rule is of the form $A \leftarrow^{\alpha} B_1, \ldots, B_n$, which says that the certainty associated with the implication is $\alpha$. Computationally, given an assignment $I$ of logical values to the $B_i$s, the logical value of $A$ is computed by taking the “conjunction” of logical values $I(B_i)$ and then somehow “propagating” it to the rule head $A$.

That is the standard case of a many-valued Logic Programming, as for example, the fuzzy or Bilattice-based logic where to each ground atom we can assign some value in the interval $[0, 1]$ or of the particular Bilattice respectively.

In the AB approach a rule is of the form $A : f(\beta_1, \ldots, \beta_n) \leftarrow B_1 : \beta_1, \ldots, B_n : \beta_n$, which asserts "the certainty of the atom $A$ is least (or is in) $f(\beta_1, \ldots, \beta_n)$, whenever the certainty of the atom $B_i$ is at least (or is in) $\beta_i$, $1 \leq i \leq n$", where $f$ is an n-ary computable function and $\beta_i$ is either constant or a variable ranging over many-valued logic values. The comparison in [12] shows:

1- the way implication is treated on the AB approach is closer to the classical logic, the way rules are fired in the IB approach has definite intuitive appeal.
2- the AB approach is strictly more expressive than IB. The down side is that query processing in the AB approach is more complicated, e.g. the fixpoint operator is not continuous in general, while it is in the IB approaches.
3- the Fitting fixpoint semantics for logic programs, based exclusively on a bilattice-algebra operators, suffer two drawbacks: the lack of the notion of tautology (bilattice negation operator is an epistemic negation) leads to difficulties in defining proof procedures and to the need for additional complex truth-related
formed into an annotation), generates the virtually inverse: we can consider annotations as contexts for the original atoms of the logic theory. Such knowledge invariant number of attributes of its relations are hidden (compressed) but not eliminated as in the case of ordinary bilattice-based logic programs are defined in [13] as the simple belief-revision solution for the management of the mutually inconsistent information in Data Integration Systems.

In what follows we will consider only the compression of the logic attribute of the flattened predicates: obtained compressed predicates are identical to predicates from the original many-valued logic program, but the value for their ground atoms is not value of a bilattice \( \mathcal{B} \) but the function (higher-order value type) in \( 2^\mathcal{B} \).

Let \( H_F \) be the Herbrand base of an ontologically encapsulated Logic Program \( P^A \) and \( Pred(H_F) \) be the set of all predicate symbols. The compression of a predicate \( r_F(x, \alpha) \), \( r_F \in Pred(H_F) \), where \( x = \{ x_j \mid 1 \leq j \leq n \} \) is the set of ordinary attributes, and \( \alpha \) is the logic attribute to be parameterized (transformed into an annotation), generates the compressed predicate \( r(x) \) for the annotated logic program. We will denote by \( W = \mathcal{B} \) the domain of the logic attribute \( \alpha \) of the predicate \( r_F(x, \alpha) \).

Notice that the compressed predicate \( r(x) \) is not a simple projection \( \pi_x \alpha \) of the original predicate over attributes in \( x \), that is, \( r(x) \neq \pi_x r_F(x, \alpha) \), because it contains also all hidden parameters, and its interpretations are of higher-type: the logic values of its ground atoms are functions instead of classic logic values in \( 2 = \{ 0, 1 \} \); these functions encapsulate the semantics of the hidden attributes.

Remark: in what follows, for simplicity, we will not make the clear formal distinction between predicate symbol \( r \), its predicate form \( r(t_1, t_2) \), where \( t_1, t_2 \) are terms (variables or functional forms) and a binary relation. We will use shortly ‘predicate’ for a ‘predicate form’.

The plan of this paper is the following: After a brief introduction to Many-valued bilattice-based logic, in
Section 2 we introduce the invariant knowledge transformation of predicates, based on the flattening and compression duality; we introduce the higher-order Herbrand interpretations and its correspondent flattening into the ordinary Herbrand interpretations. This duality holds also for the fixpoint semantics of these logic programs: given a fixpoint semantics for the first one we can derive the fixpoint semantics of the second, and vice versa.

In Section 3 we show how these concepts can be applied to the many-valued bilattice-based logic: we show that the annotated 2-valued transformation of the original logic program has the higher-order Herbrand interpretation, isomorphic to the original many-valued Herbrand interpretation, while the 2-valued ontological encapsulation (corresponds to flattening) of the original many-valued logic program has a standard Herbrand interpretation over a new Herbrand base, obtained by enlarging each original predicate by a new logic attribute.

1.1 Introduction to Many-valued epistemic logic based on a Bilattice

In [14], Belnap introduced a logic intended to deal in a useful way with inconsistent or incomplete information. It is the simplest example of a non-trivial bilattice and it illustrates many of the basic ideas concerning them. We denote the four values as \{t, f, \top, \bot\}, where t is true, f is false, \top is inconsistent (both true and false) or possible, and \bot is unknown. As Belnap observed, these values can be given two natural orders: truth order, \leq_t, and knowledge order, \leq_k, such that f \leq_t t, f \leq_k \bot, and \bot \leq_k f \leq_k t.

Meet and join operators under \leq_t are denoted \land and \lor; they are natural generalizations of the usual conjunction and disjunction notions. Meet and join under \leq_k are denoted \otimes (consensus, because it produces the most information that two truth values can agree on) and \oplus (gullibility, it accepts anything it’s told), such that hold:

\[ f \otimes t = \bot, f \oplus t = \top, \land = f \text{ and } \lor = t. \]

There is a natural notion of truth negation, denoted \sim, (reverses the \leq_t ordering, while preserving the \leq_k ordering): switching f and t, leaving \bot and \top, and corresponding knowledge negation, denoted \bar{\sim} (reverses the \leq_k ordering, while preserving the \leq_t ordering), switching \bot and \top, leaving f and t. These two kind of negation commute: \sim x = \bar{\sim} x for every member x of a bilattice.

It turns out that the operations \land, \lor and \sim, restricted to \{t, f, \bot\} are exactly those of Kleene’s strong 3-valued logic. A more general information about bilattices may be found in [15]: he also defines exact members of a bilattice, when x = \sim x (they are 2-valued consistent), and consistent members, when x = \sim x (they are 3-valued consistent), but a specific 4-valued consistence will be analyzed in the following paragraphs.

The Belnap’s 4-valued bilattice is infinitary distributive. In the rest of this paper we denote by \mathcal{B}_4 a special case of the Belnap’s bilattice.

One of the key insights behind bilattices [8, 9] was the interplay between the truth values assigned to sentences and the (non classic) notion of implication. The problem was to study how truth values should be propagated “across” implications. We proposed [1] the implication based approach, which extends the definition in [16] based on the following intuitionistic many valued implication:

\[ \begin{array}{cccc}
    & t & \bot & f & \top \\
 t & t & \bot & f & \top \\
 \bot & t & t & \top & \top \\
f & t & t & t & t \\
\top & t & \bot & \bot & \top \\
\end{array} \]

The Herbrand base, \mathcal{H}_B, is the set of all ground (i.e., variable free) atoms. A (ordinary) Herbrand interpretation is a many-valued mapping \mathcal{I} : \mathcal{H}_B \rightarrow \mathcal{B}. If \mathcal{P} is a many-valued logic program with the Herbrand base \mathcal{H}_B, then the ordering relations and operations in a bilattice \mathcal{B} are propagated to the function space \mathcal{B}^{\mathcal{H}_B}, that is the set of all Herbrand interpretations (functions), \mathcal{I}_B : \mathcal{H}_B \rightarrow \mathcal{B}. It is straightforward [15] that this makes a function space \mathcal{B}^{\mathcal{H}_B} itself a complete infinitary distributive bilattice.
2 Invariant Knowledge transformation: Flattening and compression duality

The higher-order Herbrand interpretations of logic programs (for example Databases), produce models where the true values for ground atoms are not truth constants but functions. In this section we will give the general definitions for such higher-order Herbrand interpretation types for logic programs and their models. We denote by \( A \Rightarrow B \), or \( B^A \), the set of all functions from \( A \) to \( B \).

**Definition 1.** (Higher-order Herbrand interpretation types)  
Let \( H^\text{com} \) be a Herbrand base, then, the higher-order Herbrand interpretations are defined by \( I_{\text{com}} : H^\text{com} \rightarrow T \), where \( T \) denotes the functional space \( W_1 \Rightarrow \ldots \Rightarrow (W_n \Rightarrow 2) \ldots \), denoted also as \( \ldots \Rightarrow ((2^{W_2})^{W_n})^{W_1} \ldots \), and \( W_i \), \( i \in [1, n] \), \( n \geq 1 \), the sets of parameters. In the case \( n = 1 \), \( T = (W_1 \Rightarrow 2) \), we will denote this interpretation by \( I_{\text{com}} : H^\text{com} \rightarrow 2^{W_1} \).

The interpretations \( I_{\text{com}} : H^\text{com} \rightarrow 2^{W} \) are higher-order types of Herbrand interpretations: the set of truth values for them are functions instead of constants. We pass from a flat truth structure for atoms in a Herbrand interpretations of original database \( DB \), to non flat functional space truth structure for atoms in the compressed Herbrand base \( H^\text{com} \). The hidden parameters make “curve” the truth space for these atoms, as what happens when the real astronomical space curves in a presence of hidden (black) gravitational mass. Notice that in the Def. 3, the interpretation of compressed database \( I_{\text{com}} : H^\text{com} \rightarrow 2^{W} \) is the case when \( n = 1 \) (the simplest higher type \( T = (W \Rightarrow 2) \) for higher Herbrand interpretations).

Now we will introduce the top-down transformation, called flattening, where the context (uncertain or approximated information), defined as the set of possible worlds \( W \), is fused into the Herbrand base by enlarging original predicates of old theory with new attributes taken from the context. In this way the hidden information of the context becomes the visible information and a visible part of the logic language.

**Definition 2.** (Flattening) Each higher-order Herbrand interpretation \( I_{\text{com}} : H^\text{com} \rightarrow T \), where \( T \) denotes the functional space \( W_i \Rightarrow \ldots \Rightarrow (W_n \Rightarrow 2) \ldots \), \( W = W_1 \times \ldots \times W_n \) cartesian product, can be flattened into the Herbrand interpretation \( I_F : H_F \rightarrow 2 \), where \( H_F = \{ r_F(d, w) \mid r(d) \in H^\text{com} \} \) and \( w \in W \), is the Herbrand base of predicates \( r_F \), obtained as extension of original predicates \( r \) by parameters, such that for any \( r_F(d, w) \in H_F \), \( w = (w_1, \ldots, w_n) \), holds that \( I_F(r_F(d, w)) = I_{\text{com}}(r(d))(w_1)\ldots(w_n) \).

We define as parameterizable database \( DB(y) \) any database such that all its relational schemas have the common set of attributes \( y = \{ y_1, y_2, \ldots, y_k \} \). In this, most simple case of compression, we can obtain an compressed database, denoted by \( DB^\text{com}(y) \), in the way that these common attributes become hidden attributes.

**Definition 3.** (Global compression).  
Let \( I_F : H_F \rightarrow 2 \) be the 2-valued Herbrand interpretation for a parameterizable database \( DB \) with the Herbrand base \( H_B \) and the model \( M_H = \{ r_F(d, w) \mid r_F(d, w) \in H_F \) and \( I_F(r_F(d, w)) = 1 \} \). Then the interpretation for its compressed database \( DB^\text{com}(y) \) is defined by \( I_{\text{com}} : H^\text{com} \rightarrow 2^{W} \), such that \( I_{\text{com}} = [I_F \circ is] \), where \( W = Dom_{y_1} \times \ldots \times Dom_{y_k} \) is the set of all parameter tuples, \( H^\text{com} \) is a Herbrand base for the compressed database \( DB^\text{com}(y) \), i.e., \( H^\text{com} = \{ r(d) \mid \exists w \ r_F(d, w) \in H_F \} \), \( is : H^\text{com} \times W \simeq H_F \) is a bijection, \([\_] \) is the currying (\( \lambda \) abstraction) for functions, and \( 2^W \) is the set of functions from \( W \) to \( 2 = \{ 0, 1 \} \).

No one of subsets \( S \subseteq H^\text{com} \) can be model for \( DB^\text{com} \); that is, the models for compressed database are not ordinary Herbrand models but some kind of higher-order type of Herbrand models.

**Definition 4.** In the case of the Global compression, in Definition 3, over variables in \( \{ w_1, \ldots, w_n \} \), \( n \geq 1 \) with a domain \( W \) (\( n \)-tuples in the Herbrand Universe), we are able to define the following two partial orders

1. For any two \( I_F, I'_F \in 2^{H_F} \) we define the partial order \( \leq_F \) as follows
   \[
   I_F \leq_F I'_F \iff \forall A \in H_F : (I_F(A) \leq I'_F(A)).
   \]
2. For any two \( I_{\text{com}}, I'_{\text{com}} \in (2^W)^{H^\text{com}} \) we define the partial order \( \leq_{\text{com}} \) as follows
   \[
   I_{\text{com}} \leq_{\text{com}} I'_{\text{com}} \iff \forall A \in H^\text{com}, w \in W : (I_{\text{com}}(A)(w) \leq I'_{\text{com}}(A)(w)).
   \]
Obviously, the functional spaces $2^{H_F}$ and $(2^W)^{H_{\text{com}}}$ of ordinary and Higher-order Herbrand interpretations are complete lattices w.r.t. the partial orderings $\leq_F$ and $\leq_{\text{com}}$ respectively. We denote by $(2^{H_F}, \leq_F)$ and $((2^W)^{H_{\text{com}}}, \leq_{\text{com}})$ the flattened and compressed domains respectively.

**Proposition 1** Let $\alpha : 2^{H_F} \rightarrow (2^W)^{H_{\text{com}}}$, and $\beta : (2^W)^{H_{\text{com}}} \rightarrow 2^{H_F}$, be the two mappings such that
- for any $I_F \in 2^{H_F}$ the $\alpha(I_F)$ is the mapping, such that for each $r(d) \in H_{\text{com}}$ and $w \in W$, holds that $\alpha(I_F)(r(d))(w) = I_F(r_F(d,w))$;
- for any $I_{\text{com}} \in (2^W)^{H_{\text{com}}}$ the $\beta(I_{\text{com}})$ is the mapping, such that for each $r_F(d,w) \in H_F$, holds that $\beta(I_{\text{com}})(r_F(d,w)) = I_{\text{com}}(r(d))(w)$.

Then the following three conditions define a Galois connection between the flattened and compressed domains:
1. $\alpha = \lfloor \circ i s \rfloor$ and $\beta = \lfloor \circ i s \rfloor^{-1}$ are monoton functions.
2. $\forall I_{\text{com}} \in (2^W)^{H_{\text{com}}} \{\alpha(\beta(I_{\text{com}}))\} \leq_{\text{com}} I_{\text{com}}$.
3. $\forall I_F \in 2^{H_F} (\beta(\alpha(I_F))) \leq I_F$.

**Proof:** $\alpha = \lfloor \circ i s \rfloor$ and $\beta = \lfloor \circ i s \rfloor^{-1}$ come from Definition 3 and 2 respectively. Let us prove that $\alpha$ is monotonic and suppose that $I_F \leq I_F'$, than from point 3 in Definition 4 we have that for any $r_F(d,w) \in H_F$, holds $I_F(r_F(d,w)) \leq I_F'(r_F(d,w))$, that $\alpha(I_F)(r(d))(w) \leq \alpha(I_F')(r(d))(w)$, or, for $r(d) \in H_{\text{com}}$, $w \in W$ holds $\alpha(I_F)(r(d))(w) \leq \alpha(I_F')(r(d))(w)$, thus $\forall A \in H_{\text{com}}, w \in W \alpha(I_F)(A)(w) \leq \alpha(I_F')(A)(w)$, and, consequently, than from point 3 in Definition 4 we have that $\alpha(I_F) \leq_{\text{com}} \alpha(I_F')$. The same holds for $\beta$. Points 2 and 3 hold because $\beta$ is inverse of $\alpha$.

Galois connections give us the formal framework to prove the equivalency (the $\alpha$ and $\beta$ transformations are inverse so that we have the particular case when the property 2 and 3 in the Galois conditions are equations) and mutual-inversion property between the flattened and Higher-order Herbrand interpretations: that is the reason that we informally defined, in Definition 2, the flattening as inverse of data compression.

Informally, the inverse monotonic homomorphisms in Galois connection, $\alpha : (2^{H_F}, \bigcup F) \rightarrow ((2^W)^{H_{\text{com}}}, \bigcup_{\text{com}})$, and $\beta : ((2^W)^{H_{\text{com}}}, \bigcup_{\text{com}}) \rightarrow (2^{H_F}, \bigcup F)$, which represent the mutually-inverse operations of predicate compression and flattening, are information-conservative transformations: by compression we only hide (but do not eliminate) a part of information, by flattening we render such hidden information visible (without addition of new information). Thus, if we have some monotonic “immediate consequence operator” in one of these two join-semilattice algebras, then intuitively, must exist such one operator also in the other algebra. This intuition can be formalized as follows:

**Proposition 2** (Fixpoint adjunction)
Let $T_P : 2^{H_F} \rightarrow 2^{H_F}$ be a monotonic “immediate consequence operator” in the space of Herbrand interpretations, then $\Phi_P = [T_P(\lfloor \circ i s \rfloor)] : (2^W)^{H_{\text{com}}} \rightarrow (2^W)^{H_{\text{com}}}$ is the monoton operator in the higher-order Herbrand space $(2^W)^{H_{\text{com}}}$.

Viceversa, let $\Phi_P : (2^W)^{H_{\text{com}}} \rightarrow (2^W)^{H_{\text{com}}}$ be the monoton operator in the higher-order Herbrand space. Then $T_P = \Phi_P([\lfloor \circ i s \rfloor])^{-1} \circ i s^{-1} : 2^{H_F} \rightarrow 2^{H_F}$ is the monoton operator in the Herbrand space.

**Proof:** Form the Galois connection and Proposition 1 We have that $\Phi_P = \alpha \circ T_P \circ \beta = \lfloor \circ i s \rfloor \circ T_P \circ \lfloor \circ i s \rfloor^{-1} \circ i s^{-1} = [T_P \circ \lfloor \circ i s \rfloor^{-1} \circ i s^{-1} = [T_P(\lfloor \circ i s \rfloor)]$, where $\alpha, \beta$ are monotonic operators. Thus if $T_P$ is monoton then also $\Phi_P$ is monoton. Analogously, we have that $T_P = \beta \circ \Phi_P \circ \alpha = \lfloor \circ i s \rfloor^{-1} \circ i s^{-1} \circ \Phi_P \circ \lfloor \circ i s \rfloor = \Phi_P([\lfloor \circ i s \rfloor])^{-1} \circ i s^{-1}$.

### 3 Predicate Compression and Flattening in Many-valued Logic Programming

It is obvious that the immediate-consequence monoton operator in the Herbrand join-semilattice is w.r.t. the truth ordering $\leq_F$; but its “dual” operator in the higher-order join-semilattice can have different from truth ordering. For instance, in the case of normal logic programs and its 3-valued fixpoint semantics WFS (Well-Founded Semantics for normal programs) based on the strong Kleene 3-valued logic, such semantics can not be formalized in the ordinary Herbrand join-semilattice algebra- that means that, in some way, the WFS must be embedded into the higher-order Herbrand join-semilattice with knowledge ordering $\leq_{\text{com}}$. 


Interesting point, analyzed in less general framework, is that the flattening of such knowledge (higher-order) monotonic operator into ordinary Herbrand space of interpretations must be truth ordered [2]. Such flattening of the original many-valued bilattice based program into the 2-valued logic is denominated by ontological-encapsulation, where encapsulation of original many-valued logic program into the 2-valued "meta" logic program corresponds to the flattening process described here so that also the logic values in the Belnap’s bilattice \( \mathcal{B} \) from hidden become visible values in this "meta" logic program, and is developed in a number of papers [17, 1].

Here we will present a slightly modified version of this ontological encapsulation of a many-valued logic program.

We assume that the Herbrand universe is \( I_{1} = I \cup \Omega \), where \( I \) is ordinary domain of database constants, and \( \Omega \) is an infinite enumerable set of marked null values, \( \Omega = \{ \omega_{0}, \omega_{1}, \ldots \} \), and for a given logic program \( P \) composed by a set of predicate and function symbols, \( P_{S}, P_{F} \) respectively, we define a set of all terms, \( T_{S} \), and its subset of ground terms \( T_{0} \). Then the atoms are defined as:

\[ A_{S} = \{ \psi_{p} \mid p \in P_{S}, n = \text{arity}(p) \text{ and } c_{1} \in T_{S} \}. \]

We introduce [17] the program encapsulation (flattening) transformation \( \mathcal{E} \):

**Definition 5. (Flattening of Many-valued Logic Programs)**

Let \( P \) be a many-valued logic program with the set of predicate symbols \( P_{S} \), Herbrand base \( H_{B} \), and for any predicate \( p \in P_{S} \) we introduce a mapping \( \kappa_{p} : T_{0}^{\text{arity}(p)} \mapsto \mathcal{B} \). The translation \( \mathcal{E} \) in the encapsulated syntax version \( P_{F} \) is as follows:

1. Each positive literal in \( P \), we introduce a new predicate \( p_{F} \) as follows
   \[ \mathcal{E}(p(x_{1}, \ldots, x_{n})) = p_{F}(x_{1}, \ldots, x_{n}, \kappa_{p}(x_{1}, \ldots, x_{n})); \]
2. Each negative literal in \( P \), we introduce a new predicate \( p_{F} \) as follows
   \[ \mathcal{E}(- p(x_{1}, \ldots, x_{n})) = p_{F}(x_{1}, \ldots, x_{n}, \sim \kappa_{p}(x_{1}, \ldots, x_{n})); \]
3. \( \mathcal{E}(\phi \land \varphi) = \mathcal{E}(\phi) \land \mathcal{E}(\varphi); \quad \mathcal{E}(\phi \lor \varphi) = \mathcal{E}(\phi) \lor \mathcal{E}(\varphi); \)
4. \( \mathcal{E}(\phi \leftrightarrow \varphi) = \mathcal{E}(\phi) \leftrightarrow \mathcal{E}(\varphi) \), where \( \leftrightarrow \mathcal{A} \) is a symbol for the implication at the encapsulated 2-valued 'meta' level. Thus, the obtained 'meta' program is equal to \( P_{F} = \{ \mathcal{E}(\phi) \mid \phi \text{ is a clause in } P \} \), with the 2-valued Herbrand base:
   \[ H_{F} = \{ \psi_{F}(c_{1}, \ldots, c_{n}, \alpha) \mid \psi_{F}(c_{1}, \ldots, c_{n}) \in H_{B} \text{ and } \alpha \in \mathcal{B} \}. \]

This embedding of the many-valued logic program \( P \) into a 2-valued 'meta' logic program \( P_{F} \) is an ontological embedding: it views formulae of \( P \) as beliefs and interprets the negation \( \sim p(x_{1}, \ldots, x_{n}) \) in rather restricted sense - as belief in the falsehood of \( p(x_{1}, \ldots, x_{n}) \), rather as not believing that \( p(x_{1}, \ldots, x_{n}) \) is true (like in an ontological embedding for classical negation). Like Moore’s autoepistemic operator, the encapsulation operator \( \mathcal{E} \) (restricted to atoms), \( \mathcal{E}\phi \) intends to capture the notion of, "I know that \( \phi \) has a value \( \nu_{B}(\phi) \"", for a given valuation \( \nu_{B} \) of the many-valued logic program.

Notice, that with the transformation of the original many-valued logic program \( P \) into its encapsulated 'meta' version program \( P_{F} \) we obtain a positive logic program, thus with a unique minimal Herbrand model \( I_{F} : H_{F} \rightarrow 2 \).

Now we will show how many-valued logic can be transformed into 2-valued logic with higher-order Herbrand interpretations.

Let us consider an original many-valued logic clause (bold variables denote a tuple of variables)

\[ A(x) \leftarrow B_{1}(x_{1}), \ldots, B_{k}(x_{k}), \sim B_{k+1}(x_{k+1}), \ldots, \sim B_{k}(x_{k}). \]

Its transformation into an annotated clause will be the following

\[ A(x) : \psi \leftarrow B_{1}(x_{1}) : \beta_{1}, \ldots, B_{k}(x_{k}) : \beta_{k}, B_{k+1}(x_{k+1}) : \beta_{k+1}, \ldots, B_{k}(x_{k}) : \beta_{k}, \]

where \( \psi \) is a bilattice algebra term \( (\beta_{1} \land \ldots \land \beta_{k} \land \sim \beta_{k+1} \land \ldots \land \sim \beta_{n}) \). So that the interpretation (true or false) of each ground annotated atom \( B_{i}(c_{i}) : \beta_{i} \) is a mapping \( I_{A} : H_{B} \times \mathcal{B} \rightarrow 2 \), such that \( I_{A}(B_{i}(c_{i}), \beta_{i}) \) has the true or false value in \( 2 \), or equivalently (by \( \lambda \)-abstraction), \( I_{\text{com}} = \lambda I_{A} : H_{B} \rightarrow 2^{\mathcal{B}} \), with \( I_{\text{com}}(B_{i}(c_{i})) = h : \mathcal{B} \rightarrow 2 \) a function from \( \mathcal{B} \) into the set of truth values \( 2 \).

The image of this mapping is a subset, denoted by \( \mathcal{B}_{\delta} \subseteq 2^{\mathcal{B}}, \) such that its cardinality is equal to the cardinality of \( \mathcal{B} \), that is \( |\mathcal{B}_{\delta}| = |\mathcal{B}| \), defined as follows:

**Definition 6. (Higher-order Belnap’s bilattice)**

We define the functional version of the Belnap’s bilattice \( \mathcal{B}_{\delta} \) as follows,

\[ \mathcal{B}_{\delta} = \{ \delta_{\kappa} : \mathcal{B} \rightarrow 2, \kappa \in \mathcal{B} \text{ such that } \delta_{\kappa}(v) = 1 \text{ if } v = \kappa; \quad 0, \text{ otherwise } \} \subseteq 2^{\mathcal{W}}, \]
with truth order, \( \leq_t \), and knowledge order, \( \leq_k \), such that \( \delta_f \leq_t \delta_\tau \leq_t \delta_t \), \( \delta_f \leq_t \delta_\perp \leq_t \delta_t \), and \( \delta_\perp \leq_k \delta_\tau \).

This functional Belnap’s bilattice \( B_\delta \) is interchangeable with original Belnap’s bilattice \( B \) because of the following isomorphism:

**Proposition 3 (Belnap’s isomorphism)** There exists the isomorphism \( \delta : B \simeq B_\delta \), such that for any \( v \in B \), \( \delta(v) = \delta_\mu \), and \( \delta^{-1}(\delta_\mu) = v \).

Let \( I_B : H_B \rightarrow B \), that is, \( I_B \in B^{H_B} \), be a many-valued interpretation for a normal logic program \( P \) with a Herbrand base \( B \). Such many-valued interpretation can be transformed into the many-valued interpretation \( J : H_B \rightarrow B_\delta \subseteq 2^B \), where the original Belnap’s 4-valued knowledge-ordered lattice \( B \) is replaced by the 4-valued lattice \( B_\delta \) by the \( \delta : B \simeq B_\delta \) bijection, \( \kappa \mapsto \delta_\kappa \), which preserves the knowledge ordering, so that for any ground atom \( A \in H_B \), \( J(A) = \delta_{H_B(A)} \).

We denote by \( \preceq_k \) its extension to the functional space \((2^B)^{H_B}\) such that:

\[
J \preceq_k J' \iff \forall A \in H_B \ (J(A) \preceq_k J'(A)).
\]

The following proposition demonstrates that by such many-valued logic transformation we obtain the logic program with higher-order Herbrand models type.

**Proposition 4** Let \( P \) be a normal logic program with a Herbrand base \( H_B \), over the lattice \( B \) with knowledge ordering \( \preceq_k \) and the Fitting’s monotonic "immediate-consequence operator" \( \Psi_P : B^{H_B} \rightarrow B^{H_B} \). Let denote by \( \Phi_P \) the same monotonic operator obtained by replacing the original lattice \( B \) with equivalent to it lattice \( B_\delta \). Then this operator is monotonic operator over the join-semilattice \(((2^B)^{H_B}, \cup_{com})\), where \( W = B \) and \( H^{com} = H_B \).

**Proof:** From the definitions above we have that \( I_{com} = J \) and that the the extension of the knowledge ordering, \( \preceq_k \), is equal to the partial ordering \( \preceq_{com} \), so, by replacing original lattice \( B \) by the equivalent "functional" lattice \( B_\delta \), we obtain the logic program with higher-order Herbrand models.

- Notice that the initial interpretation \( I_{B_H} : H_B \rightarrow B \) for many-valued fixpoint operator \( \Psi_P : B^{H_B} \rightarrow B^{H_B} \) is a bottom knowledge element in the lattice of the many-valued interpretations \( B^{H_B} \) (such that for any ground atom \( A \in H_B \), \( I_{B_H}(A) = \bot \)), corresponds to the initial higher-order interpretation \( I_{com_0} : H_B \rightarrow 2^B \), which is a bottom element in the join-semilattice \(((2^B)^{H_B}, \preceq_k) = ((2^B)^{H_B}, \preceq_{com}), \) such that \( I_{com_0}(A) = \delta_\bot \). So, the reducibility of the knowledge fixpoint semantics to the truth fixpoint semantics, described in [2] where is defined also the transformation of the original many-valued logic programs into 2-valued "meta" logic programs (at the level of Herbrand bases it equals to the flattening), is the direct consequence of the propositions 2 and 4.

- In fact, let \( I_B : H_B \rightarrow B \) be the least fixpoint many-valued Herbrand model of a many-valued logic program \( P \), and \( I_{com} : H^{com} \rightarrow 2^B \) be the least fixpoint in the joint-semilattice \(((2^B)^{H^{com}}, \cup_{com})\) obtained from the many-valued Herbrand model \( I_B \) by replacing the logic values in \( B \) with their correspondent values in \( B_\delta \).

Then, for the Herbrand interpretation \( I_F = \beta(I_{com}) : H_F \rightarrow 2 \), the consistent 2-valued flattened model is equal to:

\[
M_F = \{ r_F(d, v) \mid I_{com}(r_F(d)) = \delta_\bot \} = \{ r_F(d, v) \mid I_F(r_F(d, v)) = 1 \}.
\]

The consistency of the flattened model \( M_F \) means that cannot exist two ground atoms \( r_F(d, v) \) and \( r_F(d, v_1) \) in \( M_F \) such that \( v \neq v_1 \). Such consistency correspond to the fact that each ground atom \( r(d) \in H_B \) in the original many-valued program \( P \) can have only one value in the Belnap’s bilattice \( B \).

Vice versa, given a consistent 2-valued ‘meta’ model \( M_F \), we can define the compressed Herbrand interpretation \( I_{com} : H^{com} \rightarrow 2^B \), by:

\[
I_{com}(r(d)) = \delta_\bot \quad \text{iff} \quad r_F(d, v) \in M_F,
\]

so that a many-valued Herbrand model \( I_B : H_B \rightarrow B \) can be obtained from \( I_{com} \) by replacing the logic values in \( B_\delta \) by correspondent values in \( B \).

This correspondence between the many-valued Herbrand model \( I_B : H_B \rightarrow B \) of the original many-valued logic program, with the two 2-valued knowledge invariant transformations, annotated program with a higher-order Herbrand model \( I_{com} : H_B \rightarrow 2^B \) and flattened (ontologically encapsulated) ‘meta’ logic
program with a Herbrand model $I_F : H_F \rightarrow 2$ (over an enlarged Herbrand base $H_F$), can be briefly represented by the following table:

<table>
<thead>
<tr>
<th>PROGRAM</th>
<th>Original program P</th>
<th>Annotated program $P_A$</th>
<th>'meta' program $P_F$ (ontological encapsulation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOGIC</td>
<td>Many-valued logic</td>
<td>2-valued logic</td>
<td>2-valued logic</td>
</tr>
<tr>
<td>HERBRAND MODEL</td>
<td>$I_B : H_B \rightarrow \mathcal{B}$</td>
<td>Higher-order $I_{com} : H_B \rightarrow \mathcal{B}_A \subset 2^{\mathcal{B}_A}$</td>
<td>Standard</td>
</tr>
<tr>
<td>GALOIS</td>
<td>compression</td>
<td>flattening</td>
<td></td>
</tr>
</tbody>
</table>

so that for any ground atom $p(c) \in H_B$ hold

\[
I_{com}(p(c))(I_B(p(c))) = I_F(p(c,I_B(p(c)))) = 1, \quad \text{and} \\
I_{com}(p(c))(\alpha) = I_F(p(c,\alpha)) = 0, \quad \text{if} \quad \alpha \neq I_B(p(c)),
\]

which express the knowledge invariancy between program transformations.

4 Conclusion

In this paper we have shown how the implication-based Many-valued logic programs can be equivalently transformed into the Annotated logic programs with higher-order Herbrand interpretations. We have shown that the flattening of such higher-order Herbrand interpretations leads to the two-valued logic programs, identical to 'meta' logic programs obtained by an ontological encapsulation of the original Many-valued logic programs [17, 1]. Consequently, the Galois connection of the fixpoint semantics between higher-order Herbrand interpretations and their flattening into ordinary two-valued Herbrand interpretations, is the more general version of the knowledge-truth correspondence [2] between the fixpoint semantics of the original Many-valued logic programs and their ontologically encapsulated two-valued logic programs.

References

2. Z.Majkić, “Truth and knowledge fixpoint semantics for many-valued logic programming,” 19th Workshop on (Constraint) Logic Programming (W(C)LP 2005), February 21-23, Ulm, Germany, 2005.