

Recovering Consistency by Forgetting Inconsistency

Sylvie Coste-Marquis Pierre Marquis

October 6, 2008

Abstract

In this paper, we introduce and study a new paraconsistent inference relation \models_c in the setting of 3-valued paraconsistent logics. Using inconsistency forgetting as a key mechanism for recovering consistency, it guarantees that the deductive closure $Cn_{\models_c}(\Sigma)$ of any belief base Σ is classically consistent and classically closed. This strong feature, not shared by previous inference relations in the same setting, allows to interpret an inconsistent belief base as a set of classical worlds (hence to reason classically from them).

1 Introduction

Reasoning in a non-trivial way from inconsistent pieces of information (the paraconsistency issue) is a fundamental problem in artificial intelligence. Its importance is reflected by the number of approaches developed so far to address it: paraconsistent logics, belief revision, belief merging, reasoning from preferred consistent subsets, knowledge integration, argumentative logics, purification, etc. (see [Besnard and Hunter, 1998; Hunter, 1998; Priest, 2002] for a survey).

The variety of existing approaches can be explained by the fact that paraconsistency can be achieved in various ways, depending on the exact nature of the problem at hand (hence, the available information). Each of them has its own pros and cons, and is more or less suited to different inconsistency handling scenarios. For instance, when Σ represents the (conflicting) beliefs of several agents, a merged base giving the beliefs of the group of agents can be designed by logically weakening some local belief bases (associated to the agents) in order to restore global consistency [Grant and Subrahmanian, 1995; Lin, 1996; Revesz, 1997; Konieczny and Pino Pérez, 1998; Konieczny, 2000].

Compared with the other approaches listed above, paraconsistent logics (taken *stricto sensu*) offer a *basic* way to address the trivialization issue in presence of inconsistency. Indeed, belief revision, belief merging, knowledge integration, reasoning from preferred consistent subsets and purification need some extra-logical information in order to be well-defined and avoid trivializing. Such extra-logical information can be rather poor: A splitting between the belief base and

the revision formula in the belief revision setting, a set (or multi-set) organization of the beliefs in a belief merging scenario. They can also be rather sophisticated: Preference relations over beliefs, knowledge gathering actions for purification. In both cases, they are required. In particular, unlike paraconsistent logics, none of those approaches can address in a significant way the case when the available information take the form of a *single* piece (hence encoded as a unique formula in a logical language)¹.

Several (non mutually exclusive) techniques can be used to define an inference relation that avoid trivialization from an inconsistent propositional formula (see [Priest, 2002]). One of them consists in *preventing classically inconsistent belief bases from having no model*, through the consideration of more general notions of interpretations. Several multi-valued logics are related to this line of research (among others, see [D’Ottaviano and da Costa, 1970; Belnap, 1977; Frisch, 1987; Levesque, 1989; Priest, 1989; Priest, 1991; Besnard and Schaub, 1997; Besnard and Schaub, 1998; Arieli and Avron, 1998; Arieli and Avron, 1999; Konieczny and Marquis, 2002; Marquis and Porquet, 2003; Coste-Marquis and Marquis, 2005]).

In the following, the focus is laid on *three-valued paraconsistent logics*. The additional (epistemic) truth value (called middle element) intuitively means “proved both true and false” and allows to still reasoning meaningfully with variables that are not embedded directly in a contradiction. While a number of paraconsistent inference relations have been defined in this setting, none of them ensures that deductive closures are always classically consistent and classically closed. This is a strong drawback of such approaches since it prevents from interpreting inconsistent belief bases as sets of classical worlds (i.e., 2-interpretations), and consequently it questions the possibility to exploit further the information encoded by an inconsistent belief base using standard inference or decision-making techniques (since such techniques typically require classically consistent information).

In this paper, we fill the gap by introducing and studying a new paraconsistent inference relation \models_c in the setting of three-valued paraconsistent logics. This inference relation elaborates on a valuable paraconsistent inference relation \models^{\leq} introduced by Priest [Priest, 1991]. Basically, the preferred 3-models of a belief base Σ w.r.t. \models_c are the 2-interpretations which are as close as possible to the preferred 3-models of a belief base Σ w.r.t. \models^{\leq} . Determining the latter models mainly amounts to forgetting the inconsistent “truth value” in the former interpretations. Interestingly, \models_c guarantees that the deductive closure $Cn_{\models_c}(\Sigma)$ of any belief base Σ is classically consistent and classically closed (what we call the *classical closure property*).

The rest of this paper is organized as follows. In Section 2, we present some background on three-valued paraconsistent logics; especially, we define the logical framework into which our inference relation \models_c takes place. In Section 3,

¹Note that approaches based on consistent subsets take advantage of a specific “comma” connective [Konieczny *et al.*, 2005] which is not equivalent to conjunction in the general case; every singleton consisting of an inconsistent formula like $\{a \wedge (\neg a \vee b) \wedge c \wedge \neg c\}$ has \emptyset as its unique consistent subset.

we present the classical closure property and show that three-valued paraconsistent inference relations from the literature do not satisfy it. On this ground, we introduce our relation \models_c ; we show that it satisfies a number of expected logical properties, including the strong paraconsistency condition (i.e., the deductive closure of a belief base never trivializes), the preservation property (i.e., the deductive closure of a belief base coincides with its classical closure when the belief base is classically consistent), as well as all the properties of system P [Kraus *et al.*, 1990] but reflexivity. We also investigate some computational aspects of \models_c , show that it is not harder than the underlying relation \models^\leq from a complexity point of view and explain how to turn any finite belief base Σ into a consistent propositional formula $cl(\Sigma)$ such that $Cn_{\models_c}(\Sigma)$ is equal to the classical closure of $cl(\Sigma)$ (thus, $cl(\Sigma)$ can be viewed as a compilation of Σ as a propositional formula, classically interpreted). Finally, Section 4 concludes the paper.

2 Three-valued Paraconsistent Logics

When a belief base is classically inconsistent, every formula is a classical consequence of it (“*ex falso quodlibet sequitur*”). In order to avoid such a trivialization, one can take advantage of any logic in which an (epistemic) truth value “both” (\top) denotes that a formula can be proved at the same time “true” (1) and “false” (0). This allows to highlight contradictory pieces of information, but still reasoning “reasonably” about the remaining ones. Thus the third truth value has to be understood as some encoding of the epistemic attitude “proved both true and false”, and not as a standard truth value.

Now, there are a number of many-valued paraconsistent logics where such an (epistemic) truth value “both” is considered. In the following, we consider Kleene’s strong three-valued logic with middle element designated, restricted to the so-called monotone fragment [Arieli and Avron, 1998], i.e., the morphology of the language of the logic is reduced to the connectives \neg, \vee, \wedge , only. When restricted to this fragment, this logic is equivalent to a number of other logics pointed out so far in the literature, including *LP* [Priest, 1989], *J₃* [D’Ottaviano and da Costa, 1970], *THREE* [Arieli and Avron, 1998] and other logics by Levesque [Levesque, 1989] and Frisch [Frisch, 1987].

Definition 1 (language). *PROP_{PS} is the propositional language generated from a finite set PS of propositional symbols, the unary connective \neg (negation) and the binary connectives \vee (disjunction), and \wedge (conjunction).*

Clearly, this language coincides with a standard language for classical propositional logic.

We will write propositional symbols a, b, \dots and formulas from *PROP_{PS}* will be denoted by lower case Greek letters α, β, \dots . Belief bases, that will be denoted by upper case Greek letters Σ, \dots are (conjunctively-interpreted) sets of formulas. In order to alleviate notations, we identify every singleton belief base

$\{\alpha\}$ with the formula α in it. $Var(\Sigma)$ denotes the set of propositional symbols occurring in Σ .

A literal is a symbol $x \in PS$ or a negated one $\neg x$. x and $\neg x$ are said to be complementary literals. A proper subset of $PROP_{PS}$ is composed by the CNF formulas, i.e., the (finite) conjunctions of clauses, where a clause is a (finite) disjunction of literals. Another proper subset of $PROP_{PS}$ is composed by the DNF formulas, i.e., the (finite) disjunctions of terms, where a term is a (finite) conjunction of literals.

In the following, we consider a number of inference relations \vdash over $PROP_{PS}$:

Definition 2 (inference relation). – An inference relation \vdash is a subset of $2^{PROP_{PS}} \times PROP_{PS}$.

- For every Σ in $2^{PROP_{PS}}$, $Cn_{\vdash}(\Sigma)$ denotes the deductive closure of a set of formulas Σ w.r.t. the inference relation \vdash , i.e., $Cn_{\vdash}(\Sigma) = \{\alpha \in PROP_{PS} \mid \Sigma \vdash \alpha\}$.

We will also need the following notions of interpretations:

Definition 3 (interpretations). – A 3-interpretation ω over $PROP_{PS}$ is a total function from PS to $\{0, 1, \top\}$.

- A 2-interpretation ω over $PROP_{PS}$ is a total function from PS to $\{0, 1\}$.

$3 - \Omega$ (resp. $2 - \Omega$) denotes the set of all 3-interpretations (resp. 2-interpretations). 2-interpretations are the classical worlds. Clearly, they are also 3-interpretations. However, the converse does not hold (we have $2 - \Omega \subset 3 - \Omega$).

In the logic under consideration, all the connectives are truth functional ones and the semantics $\omega(\alpha)$ of a formula α from $PROP_{PS}$ in a 3-interpretation ω is defined in the obvious compositional way given the following truth tables.

α	β	$\neg\alpha$	$\alpha \wedge \beta$	$\alpha \vee \beta$
0	0	1	0	0
0	1	1	0	1
0	\top	1	0	\top
1	0	0	0	1
1	1	0	1	1
1	\top	0	\top	1
\top	0	\top	0	\top
\top	1	\top	\top	1
\top	\top	\top	\top	\top

Table 1: Truth tables.

It is easy to check that restricting the entries of the previous table to 0 and 1, one recovers the standard semantics for the connectives \neg , \vee , \wedge . Accordingly, a belief base can be considered classically unless it becomes inconsistent (typically via its expansion by a new, yet conflicting, piece of evidence).

In classical logic, notions of model and consequence are defined as:

Definition 4 (\models_2). *Let ω be a 2-interpretation over $PROP_{PS}$. Let α be a formula from $PROP_{PS}$, and let Σ be a set of formulas of $PROP_{PS}$:*

- ω is a 2-model of α iff $\omega(\alpha) = 1$.
- ω is a 2-model of Σ iff $\omega(\alpha) = 1$ for every $\alpha \in \Sigma$. $2\text{-mod}(\Sigma)$ denotes the set of 2-models of Σ .
- α is a 2-consequence of Σ , noted $\Sigma \models_2 \alpha$, iff every 2-model of Σ is a 2-model of α .

A belief base Σ is *classically consistent* iff it has a 2-model iff $Cn_{\models_2}(\Sigma) \neq PROP_{PS}$. It is well-known that \models_2 is not strongly paraconsistent:

Definition 5 (strong paraconsistency). *An inference relation \vdash satisfies the strong paraconsistency property iff for every Σ in $2^{PROP_{PS}}$, $Cn_{\vdash}(\Sigma) \neq PROP_{PS}$.*

When dealing with more than two truth values, one has to make precise the set of designated values, i.e., the set of values that a formula can take to be considered as satisfied. Since we want to define a paraconsistent logic, we choose $\mathcal{D} = \{1, \top\}$: intuitively, a formula is satisfied if it is “at least true” (but it can also be false!). We are now ready to extend the previous notions of model and consequence to the three-valued case:

Definition 6 (\models_3). *Let ω be a 3-interpretation over $PROP_{PS}$. Let α be a formula from $PROP_{PS}$, and let Σ be a set of formulas of $PROP_{PS}$:*

- ω is a 3-model of α iff $\omega(\alpha) \in \mathcal{D}$.
- ω is a 3-model of Σ iff $\omega(\alpha) \in \mathcal{D}$ for every $\alpha \in \Sigma$. $3\text{-mod}(\Sigma)$ denotes the set of 3-models of Σ .
- α is a 3-consequence of Σ , noted $\Sigma \models_3 \alpha$, iff every 3-model of Σ is a 3-model of α .

Two formulas α and β are said to be *strongly (3-)equivalent* iff for every 3-interpretation ω , we have $\omega(\alpha) = \omega(\beta)$.

Unlike \models_2 , an interesting feature of the inference relation \models_3 is that it is strongly paraconsistent; indeed, every formula from $PROP_{PS}$ has a 3-model (the 3-interpretation ω_{\top} such that $\forall x \in PS, \omega_{\top}(x) = \top$). Thus, while we have $a \wedge \neg a \models_2 b$, we do *not* have $a \wedge \neg a \models_3 b$.

As evoked in the introduction, \models has several other interesting properties. From the computational side, deciding it is “only” coNP-complete in the general case [?], and is even in P in the CNF fragment [Levesque, 1989; ?]. From the logical side, it satisfies all the (three-valued counterparts of) postulates from system P and is even monotonic.

A problem is that \models_3 is a very weak inference relation. Especially, it is well-known that the disjunctive syllogism is not satisfied by \models_3 : $a \wedge (\neg a \vee b) \not\models_3 b$. Thus, \models_3 does not satisfy the expected preservation property:

Definition 7 (preservation). *An inference relation \vdash satisfies the preservation property iff for every Σ in $2^{PROP_{PS}}$, if Σ is classically consistent, then $Cn_{\vdash}(\Sigma) = Cn_{\models_2}(\Sigma)$.*

In order to circumvent this difficulty, other three-valued paraconsistent inference relations have been proposed. Some of them are based on the following principle: focus on some preferred models of Σ in order to keep as much information as possible. Thus, in LP_m [Priest, 1991], Priest suggests to prefer those 3-models of a belief base Σ which are “as classical as possible”. Formally, let us consider the partial preordering \leq over the set of 3-interpretations defined by $\omega \leq \omega'$ if and only if $\{x \in PS \mid \omega(x) = \top\} \subseteq \{x \in PS \mid \omega'(x) = \top\}$; the “most classical” 3-models of a belief base are the 3-models that are minimal w.r.t. \leq :

Definition 8 (\models^{\leq}). *Let Σ be a set of formulas of $PROP_{PS}$. Let α be a formula from $PROP_{PS}$. $\Sigma \models^{\leq} \alpha$ iff $\forall \omega \in \min(3 - \text{mod}(\Sigma), \leq)$, $\omega(\alpha) \in \mathcal{D}$.*

The resulting relation \models^{\leq} is still strongly paraconsistent and it is strictly less cautious than \models_3 , i.e., we have the inclusion $\models_3 \subset \models^{\leq}$. Unlike \models_3 , it is non-monotonic; for instance, we have $a \wedge (\neg a \vee b) \models^{\leq} b$ but $a \wedge (\neg a \vee b) \wedge \neg a \not\models^{\leq} b$. Furthermore, \models^{\leq} satisfies the preservation property: the preferred 3-models w.r.t. \models^{\leq} of any classically consistent belief base Σ are exactly its 2-models.

Other inference relations have been defined so far for refining the inference relation \models^{\leq} (especially in order to discriminate between the 3-consequences of a belief base Σ which are subject to a contradiction – like a if $\Sigma = a \wedge \neg a \wedge b$ – and those which are contradiction-free – like b if $\Sigma = a \wedge \neg a \wedge b$). Here are the main ones [Konieczny and Marquis, 2002]:

Definition 9 (refined inference relations). *Let Σ be a set of formulas of $PROP_{PS}$. Let α be a formula from $PROP_{PS}$.*

- $\Sigma \models_{\text{arg}}^{\leq} \alpha$ iff $\Sigma \models^{\leq} \alpha$ and $\Sigma \not\models^{\leq} \neg \alpha$.
- $\Sigma \models_1^{\leq} \alpha$ iff $\forall \omega \in \min(3 - \text{mod}(\Sigma), \leq)$, $\omega(\alpha) = 1$.
- $\Sigma \models_t^{\leq} \alpha$ iff $\forall \omega \in \min(3 - \text{mod}(\Sigma), \leq)$, $\omega(\Sigma) \leq_t \omega(\alpha)$ where the so-called “truth ordering” \leq_t is such that $0 \leq_t \top \leq_t 1$.

Those three relations correspond respectively to three refinement principles:

- considering only argumentative consequences of the belief base.
- selecting those consequences of the belief base that are “conflict-free” (i.e., true but not false).
- selecting as consequences of the belief base formulas that are informally “more true” than the belief base.

All those relations are non-monotonic, strongly paraconsistent and they satisfy the preservation property. Furthermore they are strictly more cautious than \models^{\leq} (see [Konieczny and Marquis, 2002] for more details).

3 Recovering Consistency by Forgetting Inconsistency

3.1 The inference relation \models_c

Now, a major problem with the inference relations considered in the previous section (except \models_2 which is not paraconsistent) is that they do not satisfy the classical closure property:

Definition 10 (classical closure). *An inference relation \vdash satisfies the classical closure property iff for every Σ in $2^{PROP_{PS}}$, $Cn_{\vdash}(\Sigma)$ is classically consistent and is closed w.r.t. classical deduction, i.e., $Cn_{\models_2}(Cn_{\vdash}(\Sigma)) = Cn_{\vdash}(\Sigma)$.*

This is obvious for \models_3 , \models^{\leq} , and \models_t^{\leq} since those relations are “reflexive” [Konieczny and Marquis, 2002], i.e., for every α in $PROP_{PS}$, we have α is a consequence of α w.r.t. the relation. Thus, take $\Sigma = a \wedge \neg a$; Σ has to belong to its deductive closure w.r.t. any of those three relations, hence it cannot be classically consistent. As to $\models_{\text{arg}}^{\leq}$, consider the classically inconsistent CNF formula $\Sigma = (a \vee b) \wedge (\neg a \vee b) \wedge (a \vee \neg b) \wedge (\neg a \vee \neg b)$. Each of the four clauses in it is a consequence of Σ w.r.t. $\models_{\text{arg}}^{\leq}$: since their conjunction Σ is classically inconsistent, it cannot be the case that $Cn_{\models_{\text{arg}}^{\leq}}(\Sigma)$ is classically consistent and closed w.r.t. classical deduction. Finally, one can prove that $Cn_{\models_t^{\leq}}(\Sigma)$ is always classically consistent but this set is not necessarily closed w.r.t. classical deduction: take $\Sigma = a \wedge \neg a$; we have $\Sigma \not\models_t^{\leq} a \vee \neg a$. Since $a \vee \neg a$ is a classical tautology, the conclusion follows.

Using any of those inference relations thus prevents from interpreting inconsistent belief bases as sets of classical worlds (i.e., 2-interpretations), and consequently it questions the possibility to exploit further the information encoded by an inconsistent belief base using standard inference or decision-making techniques (since such techniques typically require classically consistent information). This motivates the introduction of our inference relation \models_c .

Intuitively, the preferred 3-models of a belief base Σ w.r.t. \models_c are the 2-interpretations which are as close as possible to the preferred 3-models of a belief base Σ w.r.t. \models^{\leq} . Determining the latter models mainly amounts to forgetting the inconsistent “truth value” in the former interpretations. Formally, for any belief base Σ , we define $IncForg(\Sigma)$ as the set of 2-interpretations ω which are as close as possible to a 3-interpretation $\omega' \in \min(3\text{-mod}(\Sigma), \leq)$, in the sense that $\forall x \in PS$, if $\omega'(x) \neq \top$, then $\omega'(x) = \omega(x)$. More formally, $IncForg(\Sigma) = \{\omega \in 2 - \Omega \mid \exists \omega' \in \min(3\text{-mod}(\Sigma), \leq) \forall x \in PS, \text{ if } \omega'(x) \neq \top, \text{ then } \omega'(x) = \omega(x)\}$. Computing $IncForg(\Sigma)$ amounts to projecting each preferred 3-models of Σ on the variables classically interpreted in it (hence, forgetting inconsistency) and interpreting the resulting partial interpretations in a classical way. We are now ready to define \models_c :

Definition 11 (\models_c). *Let Σ be a set of formulas of $PROP_{PS}$. Let α be a formula from $PROP_{PS}$. $\Sigma \models_c \alpha$ iff $\forall \omega \in IncForg(\Sigma), \omega(\alpha) = 1$.*

Example 1. Let $\Sigma = a \wedge (\neg a \vee b) \wedge c \wedge \neg c$. Assuming that $PS = \{a, b, c\}$, $\min(3 - \text{mod}(\Sigma), \leq)$ has only one preferred 3-model ω such that $\omega(a) = \omega(b) = 1$ and $\omega(c) = \top$. Accordingly, $\text{IncForg}(\Sigma)$ contains two elements ω' and ω'' such that $\omega'(a) = \omega'(b) = \omega''(a) = \omega''(b) = 1$ and $\omega'(c) = 0$ and $\omega''(c) = 1$. As a consequence, we have $\Sigma \models_c a \wedge b$, $\Sigma \not\models_c c$, and $\Sigma \not\models_c \neg c$. This contrasts with \models^{\leq} which is such that $\Sigma \models^{\leq} c \wedge \neg c$.

Clearly enough, \models_c is a non-monotonic inference relation. For instance, we have $a \models_c a$ but $a \wedge \neg a \not\models_c a$.

3.2 Logical properties

We now investigate in more depth the logical properties satisfied by \models_c . Interestingly, \models_c compares favourably with the underlying inference relation \models^{\leq} w.r.t. logical properties: first of all, like \models^{\leq} , \models_c also is strongly paraconsistent and satisfies the preservation property. Furthermore, it satisfies the classical closure property:

Proposition 1. \models_c is strongly paraconsistent and satisfies the preservation property and the classical closure property.

Proof.

- *Strong paraconsistency:* Direct from the fact that $\min(3 - \text{mod}(\Sigma), \leq)$ is not empty whatever the belief base Σ , since this is the case for $3 - \text{mod}(\Sigma)$ and \leq is noetherian since PS is finite.
- *Preservation:* If Σ is classically consistent, then $\min(3 - \text{mod}(\Sigma), \leq) = 2 - \text{mod}(\Sigma)$. Consequently, $\text{IncForg}(\Sigma) = 2 - \text{mod}(\Sigma)$, conclusion follows.
- *Classical closure:* Since $\min(3 - \text{mod}(\Sigma), \leq)$ is not empty (see above), this is also the case of $\text{IncForg}(\Sigma)$. Hence $\models_c(\Sigma)$ is classically consistent. Since $\text{IncForg}(\Sigma) \subseteq 2 - \Omega$, we obviously have that $Cn_{\models_c}(\Sigma)$ is closed w.r.t. classical deduction: $Cn_{\models_2}(Cn_{\models_c}(\Sigma)) = Cn_{\models_c}(\Sigma)$.

□

Now, compared with $\models_{\text{arg}}^{\leq}$, \models_1^{\leq} and \models_t^{\leq} , \models^{\leq} exhibits quite a good logical behaviour in the sense that it is a preferential inference relation [Konieczny and Marquis, 2002]:

Definition 12 (system P). An inference relation \vdash is preferential iff it satisfies the following properties (system P):

(Ref) $\alpha \vdash \alpha$	<i>Reflexivity</i>
(LLE) <i>If α and β are strongly 3-equivalent and $\alpha \vdash \gamma$, then $\beta \vdash \gamma$</i>	<i>Left Logical Equivalence</i>
(RW) <i>If $\alpha \vdash \beta$ and $\beta \models_3 \gamma$, then $\alpha \vdash \gamma$</i>	<i>Right Weakening</i>
(Or) <i>If $\alpha \vdash \gamma$ and $\beta \vdash \gamma$, then $\alpha \vee \beta \vdash \gamma$</i>	<i>Or</i>
(Cut) <i>If $\alpha \wedge \beta \vdash \gamma$ and $\alpha \vdash \beta$, then $\alpha \vdash \gamma$</i>	<i>Cut</i>
(CM) <i>If $\alpha \vdash \beta$ and $\alpha \vdash \gamma$, then $\alpha \wedge \beta \vdash \gamma$</i>	<i>Cautious Monotony</i>

Following seminal works in non-monotonic logic [Gabbay, 1985; Makinson, 1994; Kraus *et al.*, 1990; Lehmann and Magidor, 1992], this set of normative properties that a non-monotonic inference relation should satisfy has been given in [Kraus *et al.*, 1990]. These properties have been primarily stated in the framework of classical logic [Kraus *et al.*, 1990], but they can be extended to multi-valued settings in a straightforward way as above (such an extension has also been considered in [Arieli and Avron, 1998]).

Thus, an important question is to determine whether going from \models^{\leq} to \models_c leads to lose such valuable logical properties. Fortunately, most important properties still hold but reflexivity:

Proposition 2. \models_c satisfies all the properties of system P, except reflexivity.

Proof.

- *Reflexivity:* Take $\alpha = a \wedge \neg a$. We have $\alpha \not\models_c \alpha$.
- *Left Logical Equivalence:* Obvious from the fact that (strongly) equivalent formulas have the same 3-models.
- *Right Weakening:* If $\beta \models_3 \gamma$, then $\beta \models_2 \gamma$ due to the inclusion $2 - \text{mod}(\beta) \subseteq 3 - \text{mod}(\beta)$. The fact that \models_c satisfies the classical closure property concludes the proof.
- *Or:* We have that $3 - \text{mod}(\alpha \vee \beta) = 3 - \text{mod}(\alpha) \cup 3 - \text{mod}(\beta)$. As a consequence, $\min(3 - \text{mod}(\alpha \vee \beta), \leq) \subseteq \min(3 - \text{mod}(\alpha), \leq) \cup \min(3 - \text{mod}(\beta), \leq)$. Therefore, $\text{IncForg}(\alpha \vee \beta) \subseteq \text{IncForg}(\alpha) \cup \text{IncForg}(\beta)$. Since every $\omega \in \text{IncForg}(\alpha) \cup \text{IncForg}(\beta)$ is such that $\omega(\gamma) = 1$ when $\alpha \vdash \gamma$ and $\beta \vdash \gamma$, this must be the case for every $\omega \in \text{IncForg}(\alpha \vee \beta)$.
- *Cut:* We first prove the following lemma:

Lemma 1. *Let ω and ω' be two 3-interpretations such that $\forall x \in PS$, if $\omega'(x) \neq \top$, then $\omega'(x) = \omega(x)$. Then for any formula α of PROP_{PS} , we have that if $\omega'(\alpha) = 1$ (resp. $\omega'(\alpha) = 0$), then $\omega(\alpha) = 1$ (resp. $\omega(\alpha) = 0$).*

The proof of this lemma is easy by structural induction on α . Now, by *reductio ad absurdum*, assume that there exists $\omega \in \text{IncForg}(\alpha)$ such

that $\omega(\gamma) = 0$. Then by definition of $IncForg(\alpha)$, there exists $\omega' \in \min(3 - \text{mod}(\alpha), \leq)$ such that $\forall x \in PS$, if $\omega'(x) \neq \top$, then $\omega'(x) = \omega(x)$. Since $\omega' \in 3 - \text{mod}(\alpha)$, we have that $\omega'(\alpha) \neq 0$. Since $\alpha \models_c \beta$, we have that $\omega(\beta) = 1$. As a consequence of the lemma, we get that $\omega'(\beta) \neq 0$. Hence, we have $\omega'(\alpha \wedge \beta) \neq 0$: $\omega' \in 3 - \text{mod}(\alpha \wedge \beta)$. Since $3 - \text{mod}(\alpha \wedge \beta) \subseteq 3 - \text{mod}(\alpha)$ and $\omega' \in \min(3 - \text{mod}(\alpha), \leq)$, we must have $\omega' \in \min(3 - \text{mod}(\alpha \wedge \beta), \leq)$. Hence $\omega \in IncForg(\alpha \wedge \beta)$. Since $\alpha \wedge \beta \models_c \gamma$, we must have $\omega(\gamma) = 1$, contradiction.

- *Cautious Monotony*: We first exploit the previous lemma to show that for any formulas α and β of $PROP_{PS}$, if $\alpha \models_c \beta$, then $\alpha \models^{\leq} \beta$. By *reduction ad absurdum*, assume that there exists $\omega' \in \min(3 - \text{mod}(\alpha), \leq)$ such that $\omega'(\beta) = 0$. From the lemma, for every 2-interpretation ω that $\forall x \in PS$, if $\omega'(x) \neq \top$, then $\omega'(x) = \omega(x)$, we must have $\omega(\beta) = 0$. Since $\omega' \in \min(3 - \text{mod}(\alpha), \leq)$, for at least one 2-interpretation $\omega \in IncForg(\alpha)$, we must have $\omega(\alpha) = 0$. This contradicts the fact that $\alpha \models_c \beta$.

Now, in order to prove the Cautious Monotony property, it is enough to show that whenever $\alpha \models_c \beta$, we have that $\min(3 - \text{mod}(\alpha \wedge \beta), \leq) = \min(3 - \text{mod}(\alpha), \leq)$. Let $\omega \in \min(3 - \text{mod}(\alpha), \leq)$. Since $\alpha \models_c \beta$, we have that $\alpha \models^{\leq} \beta$. Hence, ω is a 3-model of β . Since it is a 3-model of α , it is a 3-model of $\alpha \wedge \beta$. Since $3 - \text{mod}(\alpha \wedge \beta) \subseteq 3 - \text{mod}(\alpha)$, we have that $\omega \in \min(3 - \text{mod}(\alpha \wedge \beta), \leq)$. Hence the inclusion $\min(3 - \text{mod}(\alpha), \leq) \subseteq \min(3 - \text{mod}(\alpha \wedge \beta), \leq)$ holds. Conversely, assume that there exists $\omega' \in \min(3 - \text{mod}(\alpha \wedge \beta), \leq) \setminus \min(3 - \text{mod}(\alpha), \leq)$. Since $3 - \text{mod}(\alpha \wedge \beta) \subseteq 3 - \text{mod}(\alpha)$, there exists $\omega \in \min(3 - \text{mod}(\alpha), \leq)$ such that $\omega < \omega'$ (i.e., $\omega \leq \omega'$ and $\omega' \not\leq \omega$). From the previous inclusion, we must have that $\omega \in \min(3 - \text{mod}(\alpha \wedge \beta), \leq)$. The fact that $\omega < \omega'$ contradicts that $\omega' \in \min(3 - \text{mod}(\alpha \wedge \beta), \leq)$.

□

Observe that there would be no way to keep reflexivity while ensuring the classical closure property. Indeed, we have the following easy proposition:

Proposition 3. *No inference relation \vdash satisfies both reflexivity and the classical closure property.*

Proof. Consider $\Sigma = a \wedge \neg a$. If $\Sigma \not\vdash \Sigma$ then it does not satisfy reflexivity. Contrastingly, if $\Sigma \vdash \Sigma$ then it does not satisfy the classical closure property since Σ is classically inconsistent. □

It is also interesting to note that \models_c satisfies other properties which are not shared by \models^{\leq} [Konieczny and Marquis, 2002], especially “transitivity” (this is a direct consequence of the fact that it satisfies both the classical closure property and the preservation property):

Proposition 4. *\models_c satisfies transitivity, i.e. for any formulas α, β, γ from $PROP_{PS}$, if $\alpha \models_c \beta$ and $\beta \models_c \gamma$, then $\alpha \models_c \gamma$.*

Proof. If $\alpha \models_c \beta$ then, by definition, $IncForg(\alpha) \subseteq 2 - mod(\beta)$. Since $min(3 - mod(\alpha), \leq)$ is never empty, we get that β is classically consistent.

As a consequence, since \models_c satisfies the preservation property, we obtain that $IncForg(\beta) = 2 - mod(\beta)$. Now, when $\beta \models_c \gamma$, we also have that $IncForg(\beta) \subseteq 2 - mod(\gamma)$, and transitivity of \subset concludes the proof. \square

Finally, it is important to determine whether the relaxation of \models^{\leq} we realised to ensure the classical closure property does not lead to a too weak inference relation \models_c . The following inclusions show that this is not the case:

Proposition 5. $\models_1^{\leq} \subset \models_c \subset \models^{\leq}$.

Proof. Lemma 1 in the proof of Prop. 2 shows in particular that if $\omega' \in min(3 - mod(\Sigma), \leq)$ is such that $\omega'(\alpha) = 1$ then every 2-interpretation ω s.t. $\forall x \in PS$, if $\omega'(x) \neq \top$ then $\omega'(x) = \omega(x)$ satisfies also $\omega(\alpha) = 1$. Subsequently, we have that if $\Sigma \models_1^{\leq} \alpha$ then $\Sigma \models_c \alpha$.

The converse does not hold since e.g. $a \wedge \neg a \not\models_1^{\leq} a \vee \neg a$ while $a \wedge \neg a \models_c a \vee \neg a$.

This shows that $\models_1^{\leq} \subset \models_c$.

Let us now show that $\models_1^{\leq} \subset \models_c$. By reduction ad absurdum: assume that there exists $\omega' \in min(3 - mod(\Sigma), \leq)$ such that $\omega'(\alpha) = 0$. From Lemma 1, every interpretation ω s.t. $\forall x \in PS$ if $\omega'(x) \neq \top$ then $\omega'(x) = \omega(x)$ also satisfies $\omega(\alpha) = 0$. This contradicts the assumption $\Sigma \models_c \alpha$. The fact that $a \wedge \neg a \models^{\leq} a \wedge \neg a$ but $a \wedge \neg a \not\models_c a \wedge \neg a$ shows that the inclusion is strict (i.e. $\models_c \subset \models^{\leq}$) and concludes the proof. \square

Thus, all the ‘‘conflict-free’’ consequences α of a belief base Σ w.r.t. \models^{\leq} are preserved by \models_c . Furthermore, \models_c does not add consequences that would not be derivable using \models_1^{\leq} .

3.3 Computational aspects

In this section, we investigate some computational aspects of \models_c . We assume the reader familiar with some basic notions of complexity, especially the complexity classes $coNP$ and Π_2^P of the polynomial hierarchy PH (see [Papadimitriou, 1994] for a survey).

We first consider the complexity of the inference problem for \models_c :

Definition 13 (\models_c -INFERENCE). \models_c -INFERENCE is the following decision problem:

- **Input:** A finite set Σ of formulas from $PROP_{PS}$ and a formula α in $PROP_{PS}$.
- **Question:** Does $\Sigma \models_c \alpha$ hold?

We have obtained the following result:

Proposition 6. \models_c -INFERENCE is Π_2^P -complete.

Proof. Membership is easy; one considers the complementary problem: in order to show that $\Sigma \models_c \alpha$ holds, we guess a 2-interpretation ω and a 3-interpretation ω' over $Var(\Sigma) \cup Var(\alpha)$; then we check that ω' belongs to $min(3-mod(\Sigma), \leq)$ (one call to an NP oracle since this problem is in coNP); finally, we check in polynomial time that for every $x \in Var(\Sigma) \cup Var(\alpha)$, we have that $\omega(x) = \omega'(x)$ whenever $\omega'(x) \neq \top$, and that $\omega(\alpha) = 1$.

Hardness holds even in the restricted case when Σ is a CNF formula and α is a propositional symbol; we consider the problem of determining, given a CNF formula Σ and a symbol a , whether every element ω of $min(3-mod(\Sigma), \leq)$ is such that $\omega(a) \neq \top$. This problem has been shown Π_2^P -hard in [Coste-Marquis and Marquis, 2005]. The fact that every element ω of $min(3-mod(\Sigma), \leq)$ is such that $\omega(a) \neq \top$ if and only if $\Sigma \wedge (a \vee b) \wedge (\neg a \vee b) \models_c b$ where $b \in PS \setminus Var(\Sigma)$, completes the proof. \square

This proposition shows that \models_c is not harder than the underlying relation \models^{\leq} from a computational complexity point of view; indeed, the inference problem for \models^{\leq} also is Π_2^P -complete [Coste-Marquis and Marquis, 2005].

We now show how to turn any finite belief base Σ (viewed as the conjunction of its elements) into a “classical” consistent propositional formula $cl(\Sigma)$ such that $Cn_{\models_c}(\Sigma)$ is equal to the classical closure of $cl(\Sigma)$. The basic idea is to turn first Σ into a DNF formula which is strongly equivalent. As in classical propositional logic, such a DNF formula can be computed by applying iteratively to Σ the following equivalences, considered as rewrite rules (left-to-right oriented):

- $\neg(\neg\alpha)$ is strongly 3-equivalent to α .
- $\neg(\alpha \vee \beta)$ is strongly 3-equivalent to $(\neg\alpha) \wedge (\neg\beta)$.
- $\neg(\alpha \wedge \beta)$ is strongly 3-equivalent to $(\neg\alpha) \vee (\neg\beta)$.
- $\alpha \wedge (\beta \vee \gamma)$ is strongly 3-equivalent to $(\alpha \wedge \beta) \vee (\alpha \wedge \gamma)$ (and similarly for $(\beta \vee \gamma) \wedge \alpha$).

Of course, the obtained DNF formula can be of exponential size in the size of Σ . It now remains to forget inconsistencies in this DNF formula after isolating terms representing the preferred models (the minimization step); formally, for every term α , let $inc(\alpha)$ be the set of “inconsistencies” occurring in α : $inc(\alpha) = \{x \in PS \mid x \text{ and } \neg x \text{ occur in } \alpha\}$. $cl(\Sigma)$ is the DNF formula obtained by successively:

1. removing in the current DNF every term α such that $inc(\alpha)$ is not minimal w.r.t. set-inclusion in the set $\{inc(\alpha) \mid \alpha \text{ a term in the current DNF}\}$.
2. removing in every term of the resulting DNF formula every literal l when the complementary literal also occurs in the term, then removing every empty term (and finally adding $a \vee \neg a$ if the resulting DNF formula contains no term).

We have that:

Proposition 7. $Cn_{\models_c}(\Sigma) = Cn_{\models_2}(cl(\Sigma))$.

Proof. Let $dnf(\Sigma)$ be the DNF formula obtained by applying the given rewrite rules. Since these rules preserve strong 3-equivalence, we get that Σ has the same 3-models as $dnf(\Sigma)$, hence the same minimal 3-models.

Now, let us consider the following obvious lemma.

Lemma 2. *Let α be a term. Then $min(3 - mod(\alpha), \leq) = \{\omega \in \mathfrak{3} - \Omega \mid \forall x \in PS, \text{ if } x \in inc(\alpha) \text{ then } \omega(x) = \top \text{ else if } x \text{ occurs as a positive literal in } \alpha \text{ then } \omega(x) = 1 \text{ else if } \neg x \text{ occurs as a negative literal in } \alpha \text{ then } \omega(x) = 0\}$.*

As a consequence of this lemma, if α, β are two terms such that $inc(\alpha) \subset inc(\beta)$, then for every $\omega_\beta \in min(3 - mod(\beta), \leq)$ there exists $\omega_\alpha \in min(3 - mod(\alpha), \leq)$ such that $\omega_\alpha \leq \omega_\beta$. Since $min(3 - mod(\alpha \vee \beta), \leq) = min(min(3 - mod(\alpha), \leq) \cup min(3 - mod(\beta), \leq), \leq)$ we get that $min(3 - mod(\alpha \vee \beta), \leq) = min(3 - mod(\alpha), \leq)$. Hence, by an obvious induction on the number of terms in $dnf(\Sigma)$, the formula $dnf1(\Sigma)$ obtained at the end of step 1 is such that $min(3 - mod(dnf1(\Sigma)), \leq) = min(3 - mod(dnf(\Sigma), \leq))$.

Finally step 2 amounts to forgetting inconsistency in the minimally inconsistent terms of $dnf(\alpha)$: let ω be any 2-model of the resulting DNF formula $cl(\Sigma)$ (such an ω exists since by construction: if every term of $dnf1(\Sigma)$ is removed during step 2 the the classically consistent (and valid) formula $a \wedge \neg a$ is generated and otherwise the resulting formula contains at least one classically consistent term). Then the construction ensures that there exists $\omega' \in min(3 - mod(dnf1(\Sigma)), \leq)$ s.t. $\forall x \in PS, \text{ if } \omega' \neq \top \text{ then } \omega'(x) = \omega(x)$. Hence the conclusion follows. \square

As a matter of illustration, consider again Example 1: let $\Sigma = a \wedge (\neg a \vee b) \wedge c \wedge \neg c$ and $PS = \{a, b, c\}$. Σ is strongly 3-equivalent to the following DNF formula $(a \wedge \neg a \wedge c \wedge \neg c) \vee (a \wedge b \wedge c \wedge \neg c)$. Now, forgetting inconsistency in Σ leads to the DNF formula $cl(\Sigma) = a \wedge b$ (the first term $(a \wedge \neg a \wedge c \wedge \neg c)$ of the previous DNF is removed during the minimization step). We can easily check that $Cn_{\models_c}(\Sigma) = Cn_{\models_2}(cl(\Sigma))$.

Since the computation of $cl(\Sigma)$ can be achieved in time polynomial in the size of Σ when Σ is a DNF and since $cl(\Sigma)$ is a DNF formula, we easily get that:

Proposition 8.

- Under the restriction where Σ is a DNF formula, \models_c -INFERENCE is coNP-complete.
- Under the restriction where Σ is a DNF formula and α is a CNF formula, \models_c -INFERENCE is in P.

Proof.

- If Σ is already in DNF, then the algorithm given by the two steps 1 and 2 enables to compute $cl(\Sigma)$ in time polynomial in $|\Sigma|$. From Proposition 7, for every $\alpha \in PROP_{PS}$, we have that $\Sigma \models_c \alpha$ iff $cl(\Sigma) \models_2 \alpha$, hence the membership to $coNP$. The hardness comes from the fact that $a \models_2 \alpha$ iff α is valid.
- Tractability when α is a CNF formula comes immediately from the fact that $cl(\Sigma)$ is a DNF formula : $cl(\Sigma) \models_2 \alpha$ iff every non-valid clause of α contains a literal from every term of $cl(\Sigma)$.

□

Thus the formula $cl(\Sigma)$ is a classically consistent formula which can be viewed as a compilation of Σ (in the sense that any finite belief base Σ interpreted w.r.t. \models_c is equivalent to the corresponding formula $cl(\Sigma)$ classically interpreted and that the inference problem from $cl(\Sigma)$ is computationally easier than the inference problem from Σ , unless the polynomial hierarchy collapses at the first level).

4 Conclusion

In this paper, we have introduced and studied a new paraconsistent inference relation \models_c in the setting of 3-valued paraconsistent logics. Using inconsistency forgetting as a key mechanism for recovering consistency, it guarantees that the deductive closure $Cn_{\models_c}(\Sigma)$ of any belief base Σ is classically consistent and classically closed. This strong feature, not shared by previous inference relations in the same setting, allows to interpret an inconsistent belief base as a set of classical worlds (hence to reason classically from them). We have investigated the logical properties and the computational complexity of \models_c . Among other things, we have shown that \models_c satisfies many interesting properties which are shared by the underlying inference relation \models^{\leq} , without any complexity shift compared to it.

We have considered in this paper a basic language for three-valued paraconsistent logic (the monotone fragment). A first perspective for further research is to extend the approach to more complex morphologies. It is also clear that the inconsistency forgetting mechanism at work here could be applied to other many-valued paraconsistent logics, especially four-valued ones. This is another extension of this work that we plan to do.

References

- [Arieli and Avron, 1998] O. Arieli and A. Avron. The value of four values. *Artificial Intelligence*, 102:97–141, 1998.
- [Arieli and Avron, 1999] O. Arieli and A. Avron. A model-theoretic approach for recovering consistent data from inconsistent knowledge bases. *J. of Automated Reasoning*, 22(2):263–309, 1999.

- [Belnap, 1977] N. Belnap. *Modern Uses of Multiple-Valued Logic*, chapter A useful four-valued logic, pages 8–37. Reidel, 1977.
- [Besnard and Hunter, 1998] Ph. Besnard and A. Hunter. *Handbook of Defeasible Reasoning and Uncertainty Management Systems*, volume 2, chapter Introduction to actual and potential contradictions, pages 1–11. Kluwer Academic, 1998.
- [Besnard and Schaub, 1997] Ph. Besnard and T. Schaub. Circumscribing inconsistency. In *Proc. of IJCAI'97*, pages 150–155, Nagoya (Japan), 1997.
- [Besnard and Schaub, 1998] Ph. Besnard and T. Schaub. Signed systems for paraconsistent reasoning. *J. of Automated Reasoning*, 20:191–213, 1998.
- [Coste-Marquis and Marquis, 2005] S. Coste-Marquis and P. Marquis. On the complexity of paraconsistent inference relations. In Torsten Schaub Leopoldo Bertossi, Anthony Hunter, editor, *Inconsistency tolerance*, volume 3300 of *LNCS state-of-the-art subseries*, pages 151–190. Springer-Verlag, 2005.
- [Coste-Marquis and Marquis, 2008] S. Coste-Marquis and P. Marquis. Recovering consistency by forgetting inconsistency. Technical report, CRIL UMR 8188, 2008.
- [D'Ottaviano and da Costa, 1970] I.M.L. D'Ottaviano and N.C.A. da Costa. Sur un problème de Jaśkowski. Technical report, Comptes Rendus de l'Académie des Sciences de Paris, 1970.
- [Frisch, 1987] A.M. Frisch. Inference without chaining. In *Proc. of IJCAI'87*, pages 515–519, Milan (Italy), 1987.
- [Gabbay, 1985] D. M. Gabbay. Theoretical foundations for nonmonotonic reasoning in experts systems. In K. Apt, editor, *Logic and Models of Concurrent Systems*. Springer Verlag, 1985.
- [Grant and Subrahmanian, 1995] J. Grant and V.S. Subrahmanian. Reasoning in inconsistent knowledge bases. *IEEE Trans. on Knowledge and Data Engineering*, 7(1):177–189, 1995.
- [Hunter, 1998] A. Hunter. *Handbook of Defeasible Reasoning and Uncertainty Management Systems*, volume 2, chapter Paraconsistent logics, pages 11–36. Kluwer Academic, 1998.
- [Konieczny and Marquis, 2002] S. Konieczny and P. Marquis. Three-valued logics for inconsistency handling. In *Proc. of JELIA'02*, volume 2424 of *LNAI*, pages 332–344, Cosenza (Italy), 2002. Springer-Verlag.
- [Konieczny and Pino Pérez, 1998] S. Konieczny and R. Pino Pérez. On the logic of merging. In *Proc. of KR'98*, pages 488–498, Trento (Italy), 1998.

- [Konieczny *et al.*, 2005] S. Konieczny, J. Lang, and P. Marquis. Reasoning under inconsistency: The forgotten connective. In *Proc. of IJCAI'05*, pages 484–489, Edinburgh (UK), 2005.
- [Konieczny, 2000] S. Konieczny. On the difference between merging knowledge bases and combining them. In *Proc. of KR'00*, pages 135–144, Breckenridge (CO), 2000.
- [Kraus *et al.*, 1990] S. Kraus, D. Lehmann, and M. Magidor. Nonmonotonic reasoning, preferential models and cumulative logics. *Artificial Intelligence*, 44(1-2):167–207, 1990.
- [Lehmann and Magidor, 1992] D. Lehmann and M. Magidor. What does a conditional knowledge base entail? *Artificial Intelligence*, 55:1–60, 1992.
- [Levesque, 1989] H.J. Levesque. A knowledge-level account of abduction (preliminary version). In *Proc. of IJCAI'89*, pages 1061–1067, Detroit (MI), 1989.
- [Lin, 1996] J. Lin. Integration of weighted knowledge bases. *Artificial Intelligence*, 83(2):363–378, 1996.
- [Makinson, 1994] D. Makinson. *Handbook of Logic in Artificial Intelligence and Logic Programming*, volume III, chapter General Pattern in nonmonotonic reasoning, pages 35–110. Clarendon Press, Oxford, 1994.
- [Marquis and Porquet, 2003] P. Marquis and N. Porquet. Resource-bounded paraconsistent inference. *Ann. of Mathematics and Artificial Intelligence*, 39(4):349–384, 2003.
- [Papadimitriou, 1994] Ch. H. Papadimitriou. *Computational Complexity*. Addison-Wesley, 1994.
- [Priest, 1989] G. Priest. Reasoning about truth. *Artificial Intelligence*, 39:231–244, 1989.
- [Priest, 1991] G. Priest. Minimally inconsistent LP. *Studia Logica*, 50:321–331, 1991.
- [Priest, 2002] G. Priest. *Handbook of Philosophical Logic*, volume 6, chapter Paraconsistent Logic, pages 287–393. Kluwer Academic, 2002.
- [Revesz, 1997] P.Z. Revesz. On the semantics of arbitration. *International Journal of Algebra and Computation*, 7(2):133–160, 1997.