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To cite this version:

Jorge Fandinno, Luis Fariñas del Cerro. Constructive Logic Covers Argumentation and Logic Programming. 16th International Conference on Principles of Knowledge Representation and Reasoning (KR 2018), Oct 2018, Tempe, United States. pp.128-137. hal-03622665

HAL Id: hal-03622665

https://hal.science/hal-03622665v1

Submitted on 29 Mar 2022

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To cite this version: Fandinno, Jorge and Fariñas del Cerro, Luis *Constructive Logic Covers Argumentation and Logic Programming.* (2018) In: 16th International Conference on Principles of Knowledge Representation and Reasoning (KR 2018), 27 October 2018 - 2 November 2018 (Tempe, United States).

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Constructive Logic Covers Argumentation and Logic Programming

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Abstract

In this work, we show that both logic programming and abstract argumentation frameworks can be interpreted in terms of Nelson's constructive logic N4. We do so by formalising, in this logic, two principles that we call non-contradictory inference and strengthened closed world assumption: the first states that no belief can be held based on contradictory evidence while the later forces both unknown and contradictory evidence to be regarded as false. Using these principles, both logic programming and abstract argumentation frameworks are translated into constructive logic in a modular way and using the object language. Logic programming implication and abstract argumentation supports become, in the translation, a new implication connective following the non-contradictory inference principle. Attacks are then represented by combining this new implication with strong negation.

Introduction

Logic programming (LP) and Abstract Argumentation Frameworks (AFs) are two well-established formalisms for Knowledge Representation and Reasoning (KRR) whose close relation is well-known since the introduction of latter: besides introducing AFs, Dung (1995) studied how logic programs under the *stable models* (Gelfond and Lifschitz 1988) and the *well-founded semantics* (Van Gelder, Ross, and Schlipf 1991) can be translated into abstract argumentation frameworks. Since then, this initial connection has been further studied and extended, providing relations between other semantics and ways to translate argumentation frameworks into logic programs (See Caminada et al. 2015 for an overview and further references).

On the other hand, Nelson's *constructive logic* (Nelson 1949) is a conservative extension of *intuitionistic logic* which introduces the notion of *strong negation* as a means to deal with constructive falsity, in an analogous way as intuitionism deals with constructive truth. Pearce (1996) showed that a particular selection of models of constructive logic, called *equilibrium logic*, precisely characterise the stable models of a logic program. This characterisation was later extended to the *partial stable model* (Przymusinski 1991) and the well-founded semantics in (Cabalar et al. 2007). Versions of constructive logic without the "explosive" axiom $\varphi \rightarrow (\sim\varphi \rightarrow \psi)$ has been extensively studied (See Odintsov and Rybakov (2015) for an overview) and can be considered a kind of *paraconsistent* logics, in the sense, that some formulas may be constructively true and false at the same time. The notion of equilibrium has been extended to one of these logics by Odintsov and Pearce (2005), who also showed that this precise characterise the *paraconsistent stable semantics* (Sakama and Inoue 1995).

In this paper, we formalise in Nelson's constructive logic a reasoning principle, to be called *non-contradictory inference* (denoted **NC**), which states that

NC "*no belief can be held based on contradictory evidence.*"

Interestingly, though different from the logic studied by Odintsov and Pearce (2005), the logic presented here is also a conservative extension of equilibrium logic (and, thus, also of LP under the stable models semantics) which allows us to deal with inconsistent information; and, at the same time, to capture AFs, under the stable semantics, in the *object language level*. Recall that by object language level, we mean that AFs and its logical translation *share the same language* (each arguments in the AF becomes an atom in its corresponding logical theory) and the relation between arguments in the AF (attacks or supports) are expressed by means of logical connectives. This contrast with *meta level approaches*, which talk about the AFs from "above," using another language and relegating logic to talk about this new language. It is important to note that, as highlighted by Gabbay and Gabbay (2015), the object language oriented approaches have the remarkable property of providing alternative intuitive meaning to the translated concepts through their interpretation in logic. In this sense, from the view-point of constructive logic, AFs can be understood as a *strengthened closed world assumption* (Reiter 1980), denoted as **CW**:

CW "*everything for which we do not have evidence of being true or for which we have contradictory evidence, should be regarded as false*"

The relation between AFs and logic has been extensively

*This work is partially supported by the Centre International de Mathématiques et d'Informatique de Toulouse (CIMI). The first author is funded by contract ANR-11-LABEX-0040-CIMI within the program ANR-11-IDEX-0002-02.

studied in the literature (See Gabbay and Gabbay 2015 for an overview and further references). In particular, the approach taken in this paper shares with (Gabbay and Gabbay 2015) the interpretation of the attack as strong negation, but differs in the underlying logic: constructive logic in our case and classical logic in the case of (Gabbay and Gabbay 2015). On the intuitive level, under the constructive logic point of view, *attacks* can be understood as

AT "*means to construct a proof of the falsity of the attacked argument based on the acceptability of the attacker*"

On the practical level, the use of constructive logic allows for a more *compact* and *modular translation*: each attack becomes a (rule-like) formula with the attacker – or a conjunction of attackers in the case of set attacking arguments (Nielsen and Parsons 2007) – as the antecedent and the attacked argument as the consequent. Moreover, when attacks are combined with LP implication, we show that the latter captures the notion of *support* in Evidential-Based Argumentation Frameworks (EBAFs) (Oren and Norman 2008): for accepting an argument, these frameworks require, not only its *acceptability* in Dung's sense, but also that it is supported by some chain of supports rooted in a kind of special arguments called *prima-facie*.

Background

In this section we recall the needed background regarding Nelson's constructive logic, logic programming and argumentation frameworks.

Nelson's Constructive Logic

The concept of constructive falsity was introduced into logic by Nelson (1949) and it is often denoted as **N3**. Versions of constructive logic without the "explosive" axiom are usually denoted as **N4** and they are based on a four valued assignment for each world corresponding to the values *unknown*, *(constructively) true*, *(constructively) false* and *inconsistent* (or *overdetermined*). We describe next a Kripke semantics for a version of **N4** with the falsity constant $\bot$, which is denoted as $\mathbf{N4}^{\bot}$ in (Odintsov and Rybakov 2015). We follow here an approach with two forcing relations in the style of (Akama 1987).

Syntactically, we assume a logical language with a *strong negation* connective "$\sim$". That is, given some (possibly infinite) set of atoms At, a *formula* φ is defined using the grammar:

$$\varphi ::= \bot \mid a \mid \sim\varphi \mid \varphi \wedge \varphi \mid \varphi \vee \varphi \mid \varphi \rightarrow \varphi$$

with $a \in At$. We use Greek letters φ and ψ and their variants to stand for propositional formulas. *Intuitionistic negation* is defined as $\neg\varphi \stackrel{\text{def}}{=} (\varphi \rightarrow \bot)$ and we also define the derived operators $\varphi \leftrightarrow \psi \stackrel{\text{def}}{=} (\varphi \rightarrow \psi) \wedge (\psi \rightarrow \varphi)$ and $\top \stackrel{\text{def}}{=} \sim\bot$.

A Kripke frame $\mathcal{F} = \langle W, \leq \rangle$ is a pair where W is a non-empty set of worlds and $\leq$ is a partial order on W. A valuation $V : W \longrightarrow 2^{At}$ is a function mapping each world to a subset of atoms. A Nelson's interpretation (N-interpretation) is a 3-tuple $\mathcal{I} = \langle \mathcal{F}, V^+, V^- \rangle$ where $\mathcal{F} = \langle W, \leq \rangle$ is a Kripke frame and where both V^+ and V^- are valuations satisfying, for every pair of worlds $w, w' \in W$ with $w \leq w'$ and every atom $a \in At$, the following preservation properties:

i) $V^+(w) \subseteq V^+(w')$, and

ii) $V^-(w) \subseteq V^-(w')$.

Intuitively, V^+ represents our knowledge about constructive truth while V^- represents our knowledge about constructive falsity. We say that $\mathcal{I}$ is *consistent* if, in addition, it satisfies:

iii) $V^+(w) \cap V^-(w) = \varnothing$ for every world $w \in W$.

Two forcing relations $\models^+$ and $\models^-$ are defined with respect to any N-interpretation $\mathcal{I} = \langle \mathcal{F}, V^+, V^- \rangle$, world $w \in W$ and atom $a \in At$ as follows:

$$\begin{array}{lll} \mathcal{I}, w \models^+ a & \text{iff} & a \in V^+(w) \\ \mathcal{I}, w \models^- a & \text{iff} & a \in V^-(w) \end{array}$$

These two relations are extended to compounded formulas as follows:

$$\begin{array}{ll}
\mathcal{I}, w \not\models^+ \bot & \\
\mathcal{I}, w \models^+ \varphi_1 \wedge \varphi_2 & \text{iff } \mathcal{I}, w \models^+ \varphi_1 \text{ and } \mathcal{I}, w \models^+ \varphi_2 \\
\mathcal{I}, w \models^+ \varphi_1 \vee \varphi_2 & \text{iff } \mathcal{I}, w \models^+ \varphi_1 \text{ or } \mathcal{I}, w \models^+ \varphi_2 \\
\mathcal{I}, w \models^+ \varphi_1 \rightarrow \varphi_2 & \text{iff } \forall w' \geq w\ \mathcal{I}, w' \not\models^+ \varphi_1 \text{ or } \mathcal{I}, w' \models^+ \varphi_2 \\
\mathcal{I}, w \models^+ \sim\varphi & \text{iff } \mathcal{I}, w \models^- \varphi \\
\mathcal{I}, w \models^- \bot & \\
\mathcal{I}, w \models^- \varphi_1 \wedge \varphi_2 & \text{iff } \mathcal{I}, w \models^- \varphi_1 \text{ or } \mathcal{I}, w \models^- \varphi_2 \\
\mathcal{I}, w \models^- \varphi_1 \vee \varphi_2 & \text{iff } \mathcal{I}, w \models^- \varphi_1 \text{ and } I, w \models^- \varphi_2 \\
\mathcal{I}, w \models^- \varphi_1 \rightarrow \varphi_2 & \text{iff } \mathcal{I}, w \models^+ \varphi_1 \text{ and } \mathcal{I}, w \models^- \varphi_2 \\
\mathcal{I}, w \models^- \sim\varphi & \text{iff } I, w \models^+ \varphi
\end{array}$$

An N-interpretation is said to be an *N-model* of a formula φ, in symbols $\mathcal{I} \models^+ \varphi$, iff $\mathcal{I}, w \models^+ \varphi$ for every $w \in W$. It is said to be *N-model* of a theory Γ, in symbols also $\mathcal{I} \models^+ \Gamma$, iff it is an N-model of all its formulas $\mathcal{I} \models^+ \varphi$. A formula φ is said to be a *consequence* of a theory Γ iff every model of Γ is also a model of φ, that is $\mathcal{I} \models^+ \varphi$ for every $\mathcal{I} \models^+ \Gamma$. This formalisation characterises **N4** while a restriction to consistent N-interpretations would characterise **N3**. As mentioned above, **N4** is "somehow" paraconsistent in the sense that a formula φ and its strongly negated counterpart $\sim\varphi$ may simultaneously be consequences of some theory: for instance, we have that $\{a, \sim a\} \models^+ a$ and $\{a, \sim a\} \models^+ \sim a$. Intuitively, these two forcing relations determine the four values above mentioned: a formula φ satisfying $\mathcal{I} \not\models^+ \varphi$ and $\mathcal{I} \not\models^- \varphi$ is understood as *unknown*. If it satisfies $\mathcal{I} \models^+ \varphi$ and $\mathcal{I} \not\models^- \varphi$, is understood as *true*. *False* if $\mathcal{I} \models^+ \varphi$ and $\mathcal{I} \not\models^- \varphi$, and *inconsistent* if $\mathcal{I} \models^+ \varphi$ and $\mathcal{I} \models^- \varphi$.

Logic Programming, Equilibrium Logic and Here-and-There Nelson's Models

In order to accommodate the logic programming conventions, we will indistinctly write $\varphi \leftarrow \psi$ instead of $\psi \rightarrow \varphi$ when describing logic programs. An *explicit literal* is either an atom $a \in At$ or an atom preceded by strong negation $\sim a$. A *literal* is either an explicit literal l or an explicit literal preceded by intuitionistic negation $\neg l$. A rule is a formula of the

form $H \leftarrow B$ where H is a disjunction of atoms and B is a conjunction of literals. A logic program Π is a set of rules.

Given a set of literals $\mathbf{T}$ and a formula φ, we write $\mathbf{T} \models^+ \varphi$ if $\langle \mathcal{F}, V^+, V^- \rangle \models^+ \varphi$ holds with $\mathcal{F}$ the Kripke frame with a unique world w and valuations: $V^+(w) = \mathbf{T} \cap At$ and $V^-(w) = \{ a \mid \sim a \in \mathbf{T} \}$. A set of literals $\mathbf{T}$ is said to be *closed* under Π if $\mathbf{T} \models^+ H \leftarrow B$ for every rule $H \leftarrow B$ in Π.

Next, we recall the notions of reduct and answer set (Gelfond and Lifschitz 1991):

Definition 1 (Reduct and Answer Set)**.** *The* reduct *of program* Π *w.r.t. some set of explicit literals* $\mathbf{T}$ *is defined as follows*

i) Remove all rules with $not\ l$ *in the body s.t.* $l \in \mathbf{T}$*,*

ii) Remove all negative literals for the remaining rules.

Set $\mathbf{T}$ *is said to be an* stable model *of* Π *if* $\mathbf{T}$ *is a* $\subseteq$*-minimal closed set under* Π*.* □

In particular, for characterising logic programs in constructive logic, we are only interested in a particular kind of N-interpretations over *Here-and-There* (HT) frames of the form $\mathcal{F}_{HT} = \langle \{h, t\}, \leq \rangle$ where $\leq$ is a partial order satisfying $h \leq t$. An *HT-interpretation* is a N-interpretation with an HT-frame. A *HT-model* is an N-model which is also a HT-interpretation. We use the generic terms *interpretation* (resp. *model*) for both HT and N-interpretations (resp. models) when it is clear by the context. At first sight, it may look that restricting ourselves to HT frames is an oversimplification, however, once the closed world assumption is added to intuitionistic logic, this can be replaced without loss of generality by any proper intermediate logic (Osorio, Pérez, and Arrazola 2005; Cabalar et al. 2017).

Given any HT-interpretation, $\mathcal{I} = \langle \mathcal{F}_{HT}, V^+, V^- \rangle$ we define four sets of atoms respectively verified at each corresponding world and valuation as follows:

$$H^+_{\mathcal{I}} \stackrel{\text{def}}{=} V^+(h) \qquad T^+_{\mathcal{I}} \stackrel{\text{def}}{=} V^+(t)$$
$$H^-_{\mathcal{I}} \stackrel{\text{def}}{=} V^-(h) \qquad T^-_{\mathcal{I}} \stackrel{\text{def}}{=} V^-(t)$$

Note that every HT-interpretation $\mathcal{I}$ is fully determined by these four sets. We will omit the subscript and write, for instance, H^+ instead of $H^+_{\mathcal{I}}$ when $\mathcal{I}$ is clear from the context. Furthermore, any HT-interpretations can be succinctly rewritten as a pair $\mathcal{I} = \langle \mathbf{H}, \mathbf{T} \rangle$ where $\mathbf{H} = H^+ \cup \sim H^-$ and $\mathbf{T} = T^+ \cup \sim T^-$ are sets of literals.[1] Note that, by the preservation properties of N-interpretations, we have that $\mathbf{H} \subseteq \mathbf{T}$. We say that an HT-interpretation $\mathcal{I} = \langle \mathbf{H}, \mathbf{T} \rangle$ is *total* iff $\mathbf{H} = \mathbf{T}$. Given HT-interpretations $\mathcal{I} = \langle \mathbf{H}, \mathbf{T} \rangle$ and $\mathcal{I}' = \langle \mathbf{H}', \mathbf{T}' \rangle$, we write $\mathcal{I} \leq \mathcal{I}'$ iff $\mathbf{H} \subseteq \mathbf{H}'$ and $\mathbf{T} = \mathbf{T}'$. As usual, we write $\mathcal{I} < \mathcal{I}'$ iff $\mathcal{I} \leq \mathcal{I}'$ and $\mathcal{I} \neq \mathcal{I}'$.

Next, we introduce the definition of equilibrium model.

Definition 2 (Equilibrium model)**.** *A HT-model* $\mathcal{I}$ *of a theory* Γ *is said to be an* equilibrium model *iff it is total and there is no other HT-model* $\mathcal{I}'$ *of* Γ *s.t.* $\mathcal{I}' < \mathcal{I}$*.* □

[1] We denote by $\sim S \stackrel{\text{def}}{=} \{ \sim\varphi \mid \varphi \in S \}$ the set strongly negated formulas given some set S. Similarly, we also define $\neg S \stackrel{\text{def}}{=} \{ \neg\varphi \mid \varphi \in S \}$.

Interestingly, consistent equilibrium models precisely capture the answer set of a logic program (Pearce 1996). More in general, it has been shown in (Odintsov and Pearce 2005) that the (possible non-consistent) equilibrium models of a logic program capture its paraconsistent answer sets (Sakama and Inoue 1995).

The following proposition characterises some interesting properties of intuitionistic and strong negation that will be useful through the paper:

Proposition 1. *Given any HT-interpretation* $\mathcal{I}$*, formula* φ *and world* $w \in \{h, t\}$*, the following hold:*

i) $\mathcal{I}, w \models^+ \neg\varphi$ *iff* $\mathcal{I}, t \not\models^+ \varphi$*, and*

ii) $\mathcal{I}, w \models^+ \neg\neg\varphi$ *iff* $\mathcal{I}, t \models^+ \varphi$*, and*

iii) $\mathcal{I}, w \models^+ \neg\neg\neg\varphi$ *iff* $\mathcal{I}, w \models^+ \neg\varphi$*, and*

iv) $\mathcal{I}, w \models^- \neg\varphi$ *iff* $\mathcal{I}, w \models^- \sim\varphi$*.* □

Abstract Argumentation Frameworks

Since their introduction, the syntax of AFs have been extended in different ways. One of these extensions, usually called SETAFs, consists in generalising the notion of binary attacks to collective attacks such that a set of arguments B attacks some argument a (Nielsen and Parsons 2007). Another such extension, usually called Bipolar AFs (BAFs), consists on considering frameworks with a second positive relation called *support* (Amgoud, Cayrol, and Lagasquie-Schiex 2004). In particular, Verheij (2003) introduced the idea that, in AFs, arguments are considered as *prima-facie* justified statements which can be considered true until proved otherwise, that is, until they are defeated. This allows to introduce a second class of *ordinary arguments*, which cannot be considered true unless get supported by the prima-facie ones. Latter, Polberg and Oren (2014) developed this idea by introducing Evidence-Based AFs (EBAFs), an extension of SETAFs (and, this, of AFs) which incorporates the notions of support and prima-facie arguments. Next we introduce an equivalent definition from (Cayrol et al. 2018) which is closer to the logic formulation we pursue here.

Definition 3 (Evidence-Based Argumentation framework)**.** *An Evidence-Based Argumentation framework is a* 4*-tuple* $\mathbf{EF} = \langle \mathbf{A}, \mathbf{R}_a, \mathbf{R}_s, \mathbf{P} \rangle$ *where* $\mathbf{A}$ *represents a (possible infinite) set of arguments,* $\mathbf{R}_a \subseteq 2^{\mathbf{A}} \times \mathbf{A}$ *is an attack relation,* $\mathbf{R}_s \subseteq 2^{\mathbf{A}} \times \mathbf{A}$ *is a support relation and* $\mathbf{P} \subseteq \mathbf{A}$ *is a set of distinguished* prima-facie *arguments. We say that an* $\mathbf{EF}$ *is* finitary *iff* B *is finite for every attack or support* $(B, a) \in \mathbf{R}_a \cup \mathbf{R}_s$*.* □

The notion of acceptability is extended by requiring not only defence against all attacking arguments, but also support from some prima-facie arguments. Furthermore, defence can be provided not only by defeating all attacking sets of arguments, but also by denying the necessary support for some of their non-prima-facie arguments.

Definition 4 (Defeat/Acceptability)**.** *Given some argument* $a \in \mathbf{A}$ *and set of arguments* $E \subseteq \mathbf{A}$*, we say*

1. a *is* defeated *w.r.t.* E *iff* $\exists B \subseteq E$ *s.t.* $(B, a) \in \mathbf{R}_a$*,*

$Def(E)$ will denote the set of arguments that are defeated w.r.t. E.

2. *a is* supported *w.r.t. E iff either $a \in \mathbf{P}$ or there is some $B \subseteq E \setminus \{a\}$ whose elements are supported w.r.t. $E \setminus \{a\}$ and such that $(B, a) \in \mathbf{R}_s$,*
3. *a is* supportable *w.r.t. E iff it is supported w.r.t. $\mathbf{A} \setminus Def(E)$,*
4. *a is* unacceptable *w.r.t. E iff it is either defeated or not supportable,*
5. *a is* acceptable *w.r.t. E iff it is supported and, for every $(B, a) \in \mathbf{R}_a$, there is $b \in B$ such that b is unacceptable w.r.t. E*

$Sup(E)$ (resp. $UnAcc(E)$ and $Acc(E)$) will denote the set of arguments that are supported (resp. unacceptable and acceptable) w.r.t. E. □

Then, semantics are defined as follows:

Definition 5. *A set of arguments $E \subseteq \mathbf{A}$ is said to be:*

1. self-supporting *iff $E \subseteq Sup(E)$,*
2. conflict-free *iff $E \cap Def(E) = \varnothing$,*
3. admissible *iff it is conflict-free and $E \subseteq Acc(E)$,*
4. complete *iff it is conflict-free and $E = Acc(E)$,*
5. preferred *iff it is a $\subseteq$-maximal admissible set,*
6. stable *iff $E = \mathbf{A} \setminus UnAcc(E)$.* □

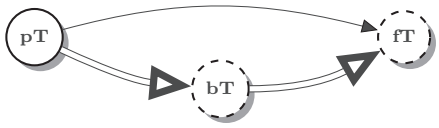
SETAFs can be seen as a special cases where the set of supports is empty and all arguments are prima-facie. In this sense, we write $\mathbf{SF} = \langle \mathbf{A}, \mathbf{R}_a \rangle$ instead $\mathbf{EF} = \langle \mathbf{A}, \mathbf{R}_a, \varnothing, \mathbf{A} \rangle$. Furthermore, in their turn, AFs can be seen as a special case of SETAFs where all attacks have singleton sources. In such case, we write $\mathbf{AF} = \langle \mathbf{A}, \mathbf{R} \rangle$ with $\mathbf{R} = \{ (b, a) \mid (\{b\}, a) \in \mathbf{R}_a \}$ instead $\mathbf{SF} = \langle \mathbf{A}, \mathbf{R}_a \rangle$. For this kind of frameworks, the respective notions of conflict-free (resp. admissible, complete, preferred or stable) coincide with those being defined in (Nielsen and Parsons 2007) and (Dung 1995).

To illustrate the notions support and prima-facie arguments, consider the well-known Tweety example:

Example 1. *Suppose we have the knowledge base that includes the following statements:*

1. *birds (normally) can fly,*
2. *penguins are birds,*
3. *penguins cannot fly and*
4. *Tweety is a penguin.*

We can formalise this by the following graph:



where pT, bT and fT respectively stand for "Tweety is a penguin", "Tweety is a bird" and "Tweetry can fly." Double arrows represent support while simple ones represent attacks. Furthermore, circles with solid border represent prima-facie arguments while dashed border ones represent ordinary ones. That is, "Tweety is a penguin" is considered a prima-facie argument that supports that "Tweety is a bird" which, in its turn, supports that "Tweety can fly." The latter is then considered also prima-facie, that is, true unless proven otherwise. Note that "Tweety is a penguin" also attacks that "Tweety can fly", so the latter cannot be accepted as true. Formally, this corresponds to the framework $\mathbf{EF}_1 = \langle \mathbf{A}, \mathbf{R}_a, \mathbf{R}_s, \mathbf{P} \rangle$ with $\mathbf{R}_a = \{(\{pT\}, fT)\}$ and $\mathbf{R}_s = \{(\{pT\}, bT), (\{bT\}, fT)\}$ and $\mathbf{P} = \{pT\}$ whose unique admissible, complete, preferred and stable extension is $\{pT, bT\}$. In other words, we conclude that "Tweety cannot fly." Note that "Tweety is a penguin" provides conflicting evidence for whether it can fly or not. In EBAFs, this is solved by given priority to the attack relation, so "Tweety cannot fly" is inferred. □

Reasoning with Contradictory Evidence in Equilibrium Logic

In this section we formalise principles **NC** and **CW** in constructive logic, obtaining as a result formalism which is a conservative extension of logic programming under the answer set semantics (see Theorem 1 and Corollary 1 below) and which is capable of reasoning with contradictory evidence. We start by defining a new implication connective that captures **NC** in terms of intuitionistic implication and strong negation:

$$\varphi_1 \Rightarrow \varphi_2 \quad \stackrel{\text{def}}{=} \quad (\neg{\sim}\varphi_1 \wedge \varphi_1) \rightarrow \varphi_2 \qquad (1)$$

Recall that intuitionistic implication $\varphi_1 \rightarrow \varphi_2$ can be informally understood as a means to construct a proof of the truth of the consequent φ_2 in terms of a proof of truth or the antecedent φ_1. In this sense, (1) can be understood as a means to construct a proof of the truth of the consequent φ_2 in terms of proof of the truth of the antecedent φ_1 and the absence of a proof of its falsity, or in other words, in terms of a *consistent proof* of the antecedent φ_1. It is easy to see that (1) is weaker than intuitionistic implication:

$$\varphi_1 \rightarrow \varphi_2 \ \models^+ \ \varphi_1 \Rightarrow \varphi_2$$

holds for every pair of formulas φ_1, φ_2. We can use the following simple example to illustrate the difference between intuitionistic implication and (1):

Example 2. *Let Γ_2 be the following set of formulas:*

$$a \qquad b \qquad {\sim}b \qquad a \Rightarrow c \qquad b \Rightarrow d$$

and let Γ_2' be the theory obtained by replacing each occurrence of $\Rightarrow$ by $\rightarrow$. □

On the one hand, we have that both, Γ_2 and Γ_2', entail atoms a and c while, on the other hand, we have: $\Gamma_2' \models^+ d$ but $\Gamma_2 \not\models^+ d$. This is in accordance with **NC**, since the only way to obtain a proof of d is in terms of b, for which we have contradictory evidence. Note also that an alternative proof of d could be obtained if new consistent evidence becomes available: for the theory $\Gamma_3 = \Gamma_2 \cup \{a \Rightarrow d\}$ we have that $\Gamma_3 \models^+ d$. It is also worth to highlight that, in contrast with intuitionistic implication, (1) is not monotonic: for $\Gamma_4 = \{b,\ b \Rightarrow d\}$ we have that $\Gamma_4 \models^+ d$ and $\Gamma_4 \cup \{{\sim}b\} \not\models^+ d$. Obviously, it is not antimonotonic either: $\Gamma_4 \setminus \{b\} \not\models^+ d$.

The following result shows that, when dealing with consistent evidence, these differences disappear and (1) collapses into intuitionistic implication:

Proposition 2. *Let $\mathcal{I}$ be a consistent N-interpretation and let φ_1, φ_2 be any pair of formulas. Then, we have: $\mathcal{I} \models^+ \varphi_1 \Rightarrow \varphi_2$ iff $\mathcal{I} \models^+ \varphi_1 \rightarrow \varphi_2$.* □

Let us now formalise the **CW** assumption. As usual non-monotonicity is obtained by considering equilibrium models (Definition 2). However, to capture **CW**, we need to restrict the consequences of these models to those that are consistent. We do so by introducing a new *cw-inference* relation which, precisely, restricts the consequences of $\models^+$ to those which are consistent:

$$\mathcal{I}, w \models \varphi \quad \text{iff} \quad \mathcal{I}, w \models^+ \neg{\sim}\varphi \wedge \varphi \tag{2}$$

Furthermore, as usual, we will write $\mathcal{I} \models \varphi$ iff $\mathcal{I}, w \models \varphi$ for all $w \in W$. We will also write $\Gamma \models \varphi$ iff we have that $\mathcal{I} \models \varphi$ for every equilibrium model $\mathcal{I}$ of Γ. It is easy to see, for instance, that $\Gamma_2 \models^+ b$ and $\Gamma_2 \models^+ {\sim}b$, but $\Gamma_2 \not\models b$ and $\Gamma_2 \not\models {\sim}b$ because the unique equilibrium model of Γ_2 contains contradictory evidence for b. On the other hand, as may be expected, when we deal with non-contradictory evidence cw-inference $\models$ just collapses to the regular inference relation $\models^+$ (see Proposition 3 below).

To finalise the formalisation of **CW**, we also need to define *default negation*. This is accomplished by introducing a new connective not and adding the following two items to the Nelson's forcing relations:

$$\mathcal{I}, w \models^+ not\ \varphi \text{ iff } \mathcal{I}, w \models^+ \neg\varphi \vee (\varphi \wedge {\sim}\varphi)$$
$$\mathcal{I}, w \models^- not\ \varphi \text{ iff } \mathcal{I}, w \models^+ \varphi \text{ and } \mathcal{I}, w \not\models^- \varphi$$

Then, an *extended formula* φ is defined using the following grammar:

$$\varphi ::= \bot \mid a \mid {\sim}\varphi \mid not\ \varphi \mid \varphi \wedge \varphi \mid \varphi \vee \varphi \mid \varphi \rightarrow \varphi$$

with $a \in At$ an atom. The following result shows that cw-inference and default negation are conservative extensions of the satisfaction relation $\models^+$ and intuitionistic negation $\neg$ when restricted to consistent knowledge.

Proposition 3. *Let $\mathcal{I}$ be a consistent N-interpretation and φ be any extended formula. Then, the following condition hold:*

i) $\mathcal{I} \models \varphi$ iff $\mathcal{I} \models^+ \varphi$
ii) $\mathcal{I} \models not\ \varphi$ iff $\mathcal{I} \models \neg\varphi$. □

More in general, the following result shows the relation between default negation, implication and cw-inference.

Proposition 4. *Let $\mathcal{I}$ be any N-interpretation and φ be any formula. Then,*

i) $\mathcal{I} \models \varphi$ and $\mathcal{I} \models^+ \varphi \Rightarrow \psi$ implies $\mathcal{I} \models^+ \psi$,
ii) $\mathcal{I} \models not\ \varphi$ implies $\mathcal{I} \not\models \varphi$.

Furthermore, if $\mathcal{I}$ is a total HT-interpretation, then

iii) $\mathcal{I} \models not\ \varphi$ iff $\mathcal{I} \not\models \varphi$. □

Condition i) formalises a kind of *modus pones* for $\Rightarrow$ in the sense that if the we have a consistent proof of the antecedent we a least have a (possibly inconsistent) proof of the consequent. It is clear that this statement cannot be strengthened to provide a consistent proof of the consequent because any other formula could provide the contradictory evidence to make it inconsistent. Condition iii) formalises **CW** assumption, that is, $not\ \varphi$ holds whenever φ is not known to be true or we have contradictory evidence for it. Note that, according to this, the default negation of an inconsistent formula is true and, therefore, the evaluation of default negation itself is always consistent (even if the formula is inconsistent): that is, $\mathcal{I}, w \not\models^+ \varphi$ or $\mathcal{I}, w \not\models^- \varphi$ holds for any extended formula. Furthermore, on the contrary that implication $\Rightarrow$, default negation not cannot be straightforwardly defined[2] in terms of Nelson's connectives. In particular, the following result shows the difference between $not\ \varphi$ and $\neg\varphi \vee (\varphi \wedge {\sim}\varphi)$ in terms of cw-inference.

Proposition 5. *Let $\mathcal{I}$ be any N-interpretation and φ be any formula. Then, $\mathcal{I} \models \neg\varphi \vee (\varphi \wedge {\sim}\varphi)$ iff $\mathcal{I} \models \neg\varphi$.* □

That is, in terms of cw-inference, $\neg\varphi \vee (\varphi \wedge {\sim}\varphi)$ is equivalent to intuitionistic negation and, it is easy to check that, if default negation were defined as intuitionistic negation, condition iii) in Proposition 4 would not hold. The following example illustrates this difference:

Example 3. *Let Γ_5 be the following theory:*

$$a \qquad {\sim}a \qquad not\ {\sim}a \Rightarrow b$$

This theory has a unique equilibrium model $\mathcal{I} = \langle \mathbf{T}, \mathbf{T} \rangle$ with $\mathbf{T} = \{a, {\sim}a, b\}$. Note that, every model $\mathcal{J}$ of Γ_5 must satisfy $\mathcal{J} \models^+ a \wedge {\sim}a$ and, thus, it must also satisfy $\mathcal{J} \models not\ {\sim}a$ and $\mathcal{J} \models^+ b$ follows (Proposition 4). Hence, $\mathcal{I}$ is a $\leq$-minimal model and, thus, an equilibrium model. On the other hand, let Γ_6 be the theory:

$$a \qquad {\sim}a \qquad \neg{\sim}a \Rightarrow b$$

In this case, we can check that $\mathcal{J} = \langle \mathbf{H}, \mathbf{T} \rangle$ with $\mathbf{H} = \{a, {\sim}a\}$ is a model of Γ_6 because $\mathcal{J} \not\models \neg{\sim}a$ and, thus, now $\mathcal{I}$ is not an equilibrium model. In fact, $\langle \mathbf{H}, \mathbf{H} \rangle$ is the unique equilibrium model of Γ_6. □

The following example illustrates that, though default negation allows to derive new knowledge from contradictory information, it does not allow to self justify a contradiction.

Example 4. *Let Γ_7 be a logic program containing the following single rule:*

$$not\ {\sim}a \Rightarrow a \tag{3}$$

stating, as usual, that a holds by default. As expected this theory has a unique equilibrium model $\mathcal{I}$ which satisfies $\mathcal{I} \models a$ and $\mathcal{I} \not\models {\sim}a$. Let now $\Gamma_8 = \Gamma_7 \cup \{{\sim}a\}$. This second theory also has a unique equilibrium model $\mathcal{I}$ which now satisfies $\mathcal{I} \models {\sim}a$ and $\mathcal{I} \not\models a$. To see that $\mathcal{J} = \langle \mathbf{T}, \mathbf{T} \rangle$ with $\mathbf{T} = \{a, {\sim}a\}$ is not an equilibrium model of Γ_8, let $\mathcal{J}' = \langle \mathbf{H}, \mathbf{T} \rangle$ with $\mathbf{H} = \{{\sim}a\}$ be an interpretation. Since $\mathcal{J}'$ satisfies $\mathcal{J}' < \mathcal{J}$ and it is a model of ${\sim}a$, it only remains to be shown that $\mathcal{J}'$ is a model of (3)*. For that, just note $\mathcal{J} \models {\sim}a \vee ({\sim}a \wedge {\sim}{\sim}a)$ and, thus, $\mathcal{J} \not\models not\ {\sim}a$ follows by definition. This implies that $\mathcal{J}'$ satisfies* (3) *and, consequently, that $\mathcal{J}$ is not an equilibrium model. In fact, $\langle \mathbf{H}, \mathbf{H} \rangle$ is the unique equilibrium model of Γ_8.* □

[2] It is still an open question whether it is definable in terms of Nelson's connectives or not.

A Conservative Extension of Logic Programming

Let us now consider the language formed with the set of logical connectives $\mathcal{C}_{LP} \stackrel{\text{def}}{=} \{\bot, \sim, \wedge, \vee, \Rightarrow, not\}$. In other words, a $\mathcal{C}_{LP}$*-formula* φ is defined using the following grammar:

$$\varphi ::= \bot \mid a \mid \sim\varphi \mid not\ \varphi \mid \varphi \wedge \varphi \mid \varphi \vee \varphi \mid \varphi \Rightarrow \varphi$$

with $a \in At$ being an atom. A $\mathcal{C}_{LP}$-literal is either an explicit literal l or is default negation $not\ l$. A $\mathcal{C}_{LP}$-rule is a formula of the form $H \Leftarrow B$ where H is a disjunction of atoms and B is a conjunction of $\mathcal{C}_{LP}$-literals. $\mathcal{C}_{LP}$*-theories* and $\mathcal{C}_{LP}$*-programs* are respectively defined as sets of $\mathcal{C}_{LP}$-formulas and $\mathcal{C}_{LP}$-rules. The definition of an answer set is applied straightforwardly as in Definition 1. Given any theory $\mathcal{C}_{LP}$-theory Γ, by $\mathcal{C}_N(\Gamma)$ we denote the result of

1. replacing every occurrence of $\Rightarrow$ by $\rightarrow$ and
2. and every occurrence of not by $\neg$.

Then, the following results follow directly from Propositions 2 and 3:

Theorem 1. *Let Γ be any $\mathcal{C}_{LP}$-theory and $\mathcal{I}$ be any consistent interpretation. Then, $\mathcal{I}$ is an equilibrium model of Γ iff $\mathcal{I}$ is an equilibrium model of $\mathcal{C}_N(\Gamma)$.* □

Corollary 1. *Let P be a $\mathcal{C}_{LP}$-program and $\mathbf{T}$ be any consistent set of explicit literals. Then, $\mathcal{I} = \langle \mathbf{T}, \mathbf{T} \rangle$ is an equilibrium model of P iff $\mathbf{T}$ is an answer set of P.* □

In other words, the equilibrium models semantics are a conservative extension of the answer set semantics. The following example shows the usual representation of the Tweety scenario in this logic (an alternative representation using contradictory evidence will be discussed in Discussion section).

Example 5 (Ex. 1 continued)**.** *Consider now the Tweety scenario. The following logic program P_9 is a usual way of representing this scenario in LP:*

$$flyTweety \Leftarrow birdTweety \wedge not \sim flyTweety \quad (4)$$
$$birdTweety \Leftarrow penguinTweety \quad (5)$$
$$\sim flyTweety \Leftarrow penguinTweety \quad (6)$$
$$penguinTweety$$

where rule (4) *formalises the "birds normally can fly" statement by considering $\sim flyTweety$ as an exception to this rule. It can be checked that P_9 has a unique equilibrium model $\mathcal{I}_9$, which is consistent, and which satisfies $\mathcal{I}_9 \not\models flyTweety$ and $\mathcal{I}_9 \models not\ flyTweety$. In other words, Tweety cannot fly.* □

Example 6 (Ex. 2 continued)**.** *Consider now the theory obtained by replacing formulas $a \Rightarrow c$ and $b \Rightarrow d$ in Γ_2 by the following two formulas:*

$$not\ e \wedge a \Rightarrow c \qquad not\ e \wedge b \Rightarrow d$$

Let Γ_{10} be such theory. □

It is easy to see that neither Γ_{10} nor $\mathcal{C}_N(\Gamma_{10})$ monotonically entail c nor d. This is due to the fact that the negation of e is not monotonically entailed: $\Gamma_{10} \not\models^+ not\ e$ and $\mathcal{C}_N(\Gamma_{10}) \not\models^+ \neg e$. On the other hand, the negation of e is non-monotonically entailed in both cases: $\Gamma_{10} \models not\ e$ and $\mathcal{C}_N(\Gamma_{10}) \models \neg e$. Note that both Γ_{10} and $\mathcal{C}_N(\Gamma_{10})$ have a unique equilibrium model, $\mathcal{I}_{10} = \langle \mathbf{T}, \mathbf{T} \rangle$ and $\mathcal{I}'_{10} = \langle \mathbf{T}', \mathbf{T}' \rangle$ with $\mathbf{T} = \{a, b, \sim b, c\}$ and $\mathbf{T} = \{a, b, \sim b, c, d\}$, respectively, and in both cases we have $\mathcal{I}_{10} \models not\ e$ and $\mathcal{I}'_{10} \models \neg e$. As a result, we have that both theories cautiously entail c. However, as happened in Example 2, only $\mathcal{C}_N(\Gamma_{10})$ cautiously entails d, because the unique evidence for d comes from b for which we have inconsistent evidence. This behaviour is different from paraconsistent answer sets (Sakama and Inoue 1995; Odintsov and Pearce 2005). As pointed out in (Sakama and Inoue 1995), the truth of d is less credible than the truth of c, since d is derived through the contradictory fact b. In order to distinguish such two facts (Sakama and Inoue 1995) also define *suspicious answer sets* which do not consider d as true.[3]

Example 6 also helps us to illustrate the strengthened closed world assumption principle **CW**. On the one hand, we have that $\Gamma_{10} \models not\ e$ holds because there is no evidence for e. On the other hand, we have that $\Gamma_{10} \models not\ b$ holds because we have contradictory evidence for b. Moreover, we have that $\Gamma_{10} \models not\ d$ holds because the only evidence we have for d is based on the contradictory evidence for b.

Argumentation Frameworks in Equilibrium Logic

In this section, we show how AFs, SETAFs and EBAFs can be translated in this logic in a modular way and using only the object language. This translation is a formalisation of the intuition of an attack stated in **AT**. Theorems 2, 3 and 4 show that the equilibrium models of this translation precisely characterise the stable extension of the corresponding framework.

Dung's Argumentation Frameworks

Now, let us formalise the notion of attack introduced in **AT**, by defining the following connective:

$$\varphi_1 \quad \varphi_2 \stackrel{\text{def}}{=} \varphi_1 \Rightarrow \sim\varphi_2 \quad (7)$$

Here we identify the acceptability of φ_1 with having a consistent proof of it, or in other words, as having a proof of the truth of φ_1 and not having a proof of its falsity. Then, (7) states that the acceptability of φ_1 allows to construct a proof of the falsity of φ_2. In this sense, we identify a proof of the falsity of φ_2 with φ_2 being defeated.

Using the language $\mathcal{C}_{AF} = \{\rightsquigarrow\}$, we can translate any AF as follows:

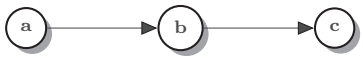
[3] Suspicious answer sets are based on a 6-value lattice which add the values *suspiciously true* and *suspiciously false* to the four values of **N4**. In the unique suspicious answer set of Γ_{10}, atom d gets assigned the suspiciously true value instead the true value. A formal comparison with suspicious answer sets is left for future work.

Definition 6. *Given some framework* $\mathbf{AF} = \langle \mathbf{A}, \mathbf{R} \rangle$*, we define the theory:*

$$\mathcal{C}_{AF}(\mathbf{AF}) \stackrel{\text{def}}{=} \mathbf{A} \cup \{\, a \quad b \mid (a,b) \in \mathbf{R}_a \,\} \qquad (8)$$

In addition, we assign a corresponding set of arguments $E_{\mathcal{I}} \stackrel{\text{def}}{=} \{\, a \in \mathbf{A} \mid \mathcal{I} \models a \,\}$ *to every interpretation* $\mathcal{I}$*.*

Example 7. *To illustrate this translation, let* $\mathbf{AF}_{11}$ *be the framework corresponding to the following graph:*



Then, we have that $\mathcal{C}_{AF}(\mathbf{AF}_{11})$ *is the theory containing the following two attacks:*

$$a \rightsquigarrow b \qquad\qquad b \quad c$$

plus the facts $\{a, b, c\}$*.* □

Proposition 6. *Let* $\mathbf{AF}$ *be some framework and* $\mathcal{I}$ *be some HT-model of* $\mathcal{C}_{AF}(\mathbf{AF})$*. Then, the following hold:*

i) if a *is defeated w.r.t.* $E_{\mathcal{I}}$*, then* $\mathcal{I} \models^{+} \sim a$

ii) $E_{\mathcal{I}}$ *is conflict-free.*

If, in addition, $\mathcal{I}$ *is an* $\leq$*-minimal model, then*

iii) a *is defeated w.r.t.* $E_{\mathcal{I}}$ *iff* $\mathcal{I} \models^{+} \sim a$*.* □

Continuing with our running example (Example 7), let $\mathcal{I}_{11} = \langle \mathbf{T}_{11}, \mathbf{T}_{11} \rangle$ and $\mathcal{J}_{11} = \langle \mathbf{T}'_{11}, \mathbf{T}'_{11} \rangle$ be two total models of $\Gamma_{\mathbf{AF}_{11}}$ with $\mathbf{T}_{11} = \{a, b, c, \sim b\}$ and $\mathbf{T}'_{11} = \{a, b, c, \sim a, \sim c\}$. Then, we have that both $S_{\mathcal{I}_{11}} = \{a, c\}$ and $S_{\mathcal{J}_{11}} = \{b\}$ are conflict-free (though only $S_{\mathcal{I}_{11}}$ is stable). Furthermore, we also have that b is the unique defeated argument w.r.t. $S_{\mathcal{I}_{11}}$ and the unique atom for which $\mathcal{I}_{11} \models \sim b$ holds. On the other hand, we have c is the unique defeated argument w.r.t. $E_{\mathcal{J}}$, but we have that both $\mathcal{I}_{11} \models \sim a$ and $\mathcal{I}_{11} \models \sim c$ hold. Note that, as stated by iii) in Proposition 6, this implies that only $S_{\mathcal{I}_{11}}$ can be an equilibrium model. Let us show that it is indeed the case that $\mathcal{J}_{11}$ is not an equilibrium model and let us define, for that purpose, an interpretation $\mathcal{J}'_{11} = \langle \mathbf{H}'_{11}, \mathbf{T}'_{11} \rangle$ with $\mathbf{H}'_{11} = \mathbf{T}'_{11} \setminus \{\sim a\} = \{a, b, c, \sim c\}$. In other words, interpretation $\mathcal{J}'_{11}$ is as $\mathcal{J}_{11}$, but removing the non-defeated argument a as a negated conclusion $\sim a$. It is easy to check that $\mathcal{J}'_{11} \models b \rightsquigarrow c$ because $\sim c \in \mathbf{H}'_{11}$ holds. Besides, since $\sim a \in \mathbf{T}'_{11}$, we have that $\mathcal{J}'_{11} \not\models a$ and, therefore, that $\mathcal{J}'_{11} \models a \quad b$ and, thus, that $\mathcal{J}'_{11}$ is a model of $\Gamma_{\mathbf{AF}_{11}}$. Since $\mathcal{J}'_{11} < \mathcal{J}_{11}$, this implies that $\mathcal{J}_{11}$ is not an equilibrium model. In fact, we can generalise this correspondence between the stable extensions of and the equilibrium models to any argumentation framework as stated by the following theorem:

Theorem 2. *Given some* $\mathbf{AF} = \langle \mathbf{A}, \mathbf{R} \rangle$*, there is a one-to-one correspondence between its stable extensions and the equilibrium models of* $\mathcal{C}_{AF}(\mathbf{AF})$ *such that*

i) if $\mathcal{I}$ *is an equilibrium model of* $\mathcal{C}_{AF}(\mathbf{AF})$*, then* $E_{\mathcal{I}}$ *is a stable extension of* $\mathbf{AF}$*,*

ii) if E *is a stable extension of* $\mathbf{AF}$ *and* $\mathcal{I}$ *is a total interpretation such that* $T^{+}_{\mathcal{I}} = \mathbf{A}$ *and* $T^{-}_{\mathcal{I}} = Def(E)$*, then* $\mathcal{I}$ *is an equilibrium model of* $\mathcal{C}_{AF}(\mathbf{AF})$*.* □

Proof (sketch). First, note that condition i) follows directly from iii) in Proposition 6 and the facts that (a) equilibrium models are $\leq$-minimal models and (b) $E_{\mathcal{I}}$ is a stable extension iff $E_{\mathcal{I}}$ are exactly the non-defeated arguments w.r.t. $E_{\mathcal{I}}$. To show ii), it is easy to see that $E_{\mathcal{I}}$ being a stable extension implies that $\mathcal{I}$ is a model of $\mathcal{C}_{AF}(\mathbf{AF})$. Hence, to show that $\mathcal{I}$ is an equilibrium model what remains is to prove that any $\mathcal{J} < \mathcal{I}$ is not a model of $\mathcal{C}_{AF}(\mathbf{AF})$. Any such $\mathcal{J}$ must satisfy $H^{+}_{\mathcal{J}} = H^{+}_{\mathcal{I}} = \mathbf{A}$ and $H^{-}_{\mathcal{J}} \subset H^{-}_{\mathcal{I}} = T^{-}_{\mathcal{I}} = Def(E)$. Therefore, there is some defeated argument such that $a \notin H^{-}_{\mathcal{J}}$ and some defeating attack $(b, a) \in \mathbf{R}_a$ such that $b \in E = H^{+}_{\mathcal{I}} \setminus T^{-}_{\mathcal{I}} = H^{+}_{\mathcal{J}} \setminus T^{-}_{\mathcal{J}}$. This implies that $b \quad a \in \mathcal{C}_{AF}(\mathbf{AF})$ and $\mathcal{J} \models b$ which, in its turn, implies that $a \in H^{-}_{\mathcal{J}}$. This is a contradiction and, consequently, $\mathcal{I}$ is an equilibrium model. □

Set Attack Argumentation Frameworks

We may also extend the results of the previous section to SETAFs using the language $\mathcal{C}_{SF} = \{\rightsquigarrow, \wedge\}$ and a similar translation.

Definition 7. *Given some finitary set attack framework* $\mathbf{SF} = \langle \mathbf{A}, \mathbf{R}_a \rangle$*, we define*

$$\Gamma_{\mathbf{R}_a} \stackrel{\text{def}}{=} \left\{ \bigwedge A \rightsquigarrow b \;\middle|\; (A, b) \in \mathbf{R}_a \right\} \qquad (9)$$

and $\mathcal{C}_{SF}(\mathbf{SF}) \stackrel{\text{def}}{=} \mathbf{A} \cup \Gamma_{\mathbf{R}_a}$*.* □

Theorem 3. *Given some finitary* $\mathbf{SF}$ *there is a one-to-one correspondence between its stable extensions and the equilibrium models of* $\mathcal{C}_{SF}(\mathbf{SF})$ *such that*

i) if $\mathcal{I}$ *is an equilibrium model of* $\mathcal{C}_{SF}(\mathbf{SF})$*, then* $E_{\mathcal{I}}$ *is a stable extension of* $\mathbf{SF}$*,*

ii) if E *is a stable extension of* $\mathbf{SF}$ *and* $\mathcal{I}$ *is a total interpretation such that* $T^{+}_{\mathcal{I}} = \mathbf{A}$ *and* $T^{-}_{\mathcal{I}} = Def(E)$*, then* $\mathcal{I}$ *is an equilibrium model of* $\mathcal{C}_{SF}(\mathbf{SF})$*.* □

Proof (sketch). The proof follows as in Theorem 2 by noting that any interpretation $\mathcal{I}$ and set of arguments B satisfy: $B \subseteq E_{\mathcal{I}}$ iff $\mathcal{I} \models b$ for all $b \in B$ iff $\mathcal{I} \models \bigwedge B$. □

Argumentation Frameworks with Evidence-Based Support

Let us now extend the language of SETAFs with the LP implication (1), in other words, we consider the language possessing the following set of connectives $\mathcal{C}_{EF} = \{\rightsquigarrow, \wedge, \Rightarrow\}$, so that we can translate any EBAF as follows:

Definition 8. *Given any finitary evidence-based framework* $\mathbf{EF} = \langle \mathbf{A}, \mathbf{R}_a, \mathbf{R}_s, \mathbf{P} \rangle$*, we define its corresponding theory as:* $\mathcal{C}_{EF}(\mathbf{EF}) \stackrel{\text{def}}{=} \mathbf{P} \cup \Gamma_{\mathbf{R}_a} \cup \Gamma_{\mathbf{R}_s}$ *with*

$$\Gamma_{\mathbf{R}_s} \stackrel{\text{def}}{=} \left\{ \bigwedge A \Rightarrow b \;\middle|\; (A, b) \in \mathbf{R}_s \right\} \qquad (10)$$

and $\Gamma_{\mathbf{R}_a}$ *as stated in* (9)*.* □

Note that, in contrast with AFs and SETAFs, the theory corresponding to an EBAFs do not contain all arguments as atoms, but only those that are prima-facie $\mathbf{P}$. This reflects the fact that in EBAFs not all arguments can be accepted,

but only those that are prima-facie or are supported by those prima facie. Supports are represented using the LP implication $\Rightarrow$ and supported arguments are captured by the positive evaluation of each interpretation $H^+_{\mathcal{I}}$. The following result extends Proposition 6 to EBAFs including the relation between supported arguments and models.

Proposition 7. *Let* **EF** *be some framework and* $\mathcal{I}$ *be some HT-model of* $\mathcal{C}_{EF}(\mathbf{EF})$*. Then, the following hold:*

i) if a *is supported w.r.t.* $E_{\mathcal{I}}$*, then* $\mathcal{I} \models^+ a$*,*

ii) if a *is defeated w.r.t.* $E_{\mathcal{I}}$*, then* $\mathcal{I} \models^+ \sim a$*,*

iii) $E_{\mathcal{I}}$ *is conflict-free.*

If, in addition, $\mathcal{I}$ *is an* $\leq$*-minimal HT-model, then*

iii) a *is supported w.r.t.* $E_{\mathcal{I}}$ *iff* $\mathcal{I} \models^+ a$*,*

iv) a *is defeated w.r.t.* $E_{\mathcal{I}}$ *iff* $\mathcal{I} \models^+ \sim a$*,*

v) $E_{\mathcal{I}}$ *is self-supporting.* □

Example 8 (Ex. 1 continued)**.** *Consider now framework* **EF** *representing the Tweety scenario.*

$$birdTweety \Rightarrow flyTweety \quad (11)$$
$$penguinTweety \Rightarrow birdTweety \quad (12)$$
$$penguinTweety \quad flyTweety \quad (13)$$
$$penguinTweety$$ □

As mentioned in Example 1, framework $\mathbf{EF}_1$ has a unique stable extension $\{penguinTweety,\ birdTweety\}$ which does not include the argument $flyTweety$. In other words, Tweety cannot fly. Interestingly, $\mathcal{C}_{SF}(\mathbf{EF}_1)$ has also a unique equilibrium model $\mathcal{I}_{12} = \langle \mathbf{T}_{12}, \mathbf{T}_{12} \rangle$ where $\mathbf{T}_{12}$ stands for the set:

$$\{penguinTweety,\ birdTweety,\ flyTweety,\ \sim flyTweety\}$$

This equilibrium model precisely satisfies the two arguments in that stable extension: $\mathcal{I}_{12} \models penguinTweety$ and $\mathcal{I}_{12} \models birdTweety$. Note that $\mathcal{I}_{12} \not\models flyTweety$ follows from the fact that $\mathcal{I}_{12} \models^+ \sim flyTweety$. In fact, this correspondence holds for any EBAF as shown by the Theorem 4 below. Though more technically complex, the proof of Theorem 4 is similar that those of Theorems 2 and 3. In particular, it is necessary to prove the following relation between equilibrium models and supportable arguments:

Proposition 8. *Let* **EF** *be some framework and* $\mathcal{I}$ *be some equilibrium model of* $\mathcal{C}_{EF}(\mathbf{EF})$*. Then, the following statement holds:*

i) a *is supportable w.r.t.* $E_{\mathcal{I}}$ *iff* $\mathcal{I} \models^+ a$*.* □

In contrast with the results for supported arguments stated in Proposition 7, this property does not hold for arbitrary $\leq$-minimal models. This fact can be illustrated by considering a simple $\mathbf{EF}_{13}$ such that $\mathcal{C}_{EF}(\mathbf{EF}_{13}) = \{a,\ a \Rightarrow b\}$. Let $\mathcal{I}_{13} = \langle \mathbf{H}_{13}, \mathbf{T}_{13} \rangle$ be some interpretation with $\mathbf{H}_{13} = \{a\}$ and $\mathbf{T}_{13} = \{a, \sim a\}$. It is easy to see that $\mathcal{I}_{13}$ is a $\leq$-minimal model of $\mathcal{C}_{EF}(\mathbf{EF}_{13})$, though it is not an equilibrium model (because it is not a total interpretation). It can also be checked that a is not defeated and, consequently, that b is supportable w.r.t. $E_{\mathcal{I}_{13}} = \varnothing$. On the other hand, the unique equilibrium model of $\mathcal{C}_{EF}(\mathbf{EF}_{13})$ is $\mathcal{J}_{13} = \langle \mathbf{H}'_{13}, \mathbf{T}'_{13} \rangle$ with $\mathbf{H}'_{13} = \{a, b\}$ and $\mathbf{T}'_{13} = \{a, b\}$. Here, both a and b are supportable (and supported) w.r.t. $E_{\mathcal{J}_{13}} = \{a, b\}$.

The following result shows that, indeed, this correspondence holds for any EBAF:

Theorem 4. *Given some finitary* **EF***, there is a one-to-one correspondence between its stable extensions and the equilibrium models of* $\mathcal{C}_{EF}(\mathbf{EF})$ *such that*

i) if $\mathcal{I}$ *is an equilibrium model of* $\mathcal{C}_{EF}(\mathbf{EF})$*, then* $E_{\mathcal{I}}$ *is a stable extension of* **EF***,*

ii) if E *is a stable extension of* **EF** *and* $\mathcal{I}$ *is a total interpretation such that* $T^+_{\mathcal{I}} = Sup(E)$ *and* $T^-_{\mathcal{I}} = Def(E)$*, then* $\mathcal{I}$ *is an equilibrium model of* $\mathcal{C}_{EF}(\mathbf{EF})$*.* □

Discussion

LP and AFs are two well-established KRR formalisms for dealing with nonmonotonic reasoning (NMR). In particular, Answer Set Programming (ASP) is an LP paradigm, based on the stable model semantics, which has raised as a preeminent tool for practical NMR with applications in diverse areas of AI including planning, reasoning about actions, diagnosis, abduction and beyond (Baral 2003; Brewka, Eiter, and Truszczynski 2011). On the other hand, one of the major reasons for the success of AFs is their ability to handle conflicts due to inconsistent information.

Here, we have shown that both formalisms can be successfully accommodated in Nelson's constructive logic. In fact, it is easy to see that by rewriting attacks using definition (7), the translation of any AF becomes a normal $\mathcal{C}_{LP}$-program. For instance, by rewriting the attack (13), we obtain the equivalent formula:

$$penguinTweety \Rightarrow \sim flyTweety \quad (14)$$

which is a $\mathcal{C}_{LP}$-rule. In fact, we can consider $\mathcal{C}_{SF}(\mathbf{EF}_1)$ in Example 8 as an alternative representation of the Tweety scenario in LP. Note that both the unique equilibrium model $\mathcal{I}_9$ of program P_9 (Example 5) and the unique equilibrium model $\mathcal{I}_{12}$ of this program satisfy:

$$\mathcal{I}_9 \not\models flyTweety \qquad \mathcal{I}_{12} \not\models flyTweety$$
$$\mathcal{I}_9 \models not\ flyTweety \qquad \mathcal{I}_{12} \models not\ flyTweety$$

In other words, in both programs we conclude that Tweety cannot fly. However, there are a couple of differences between these two representations. First, in contrast with $\mathcal{I}_9$, we have that $\mathcal{I}_{12}$ is not consistent: $\mathcal{I}_{12} \models^+ flyTweety$ and $\mathcal{I}_{12} \models^+ \sim flyTweety$. Second and perhaps more interestingly, in $\mathcal{C}_{SF}(\mathbf{EF}_1)$, the "normality" of the statement "birds can fly" does not need to be explicitly represented. Instead, this normality is implicitly handled by the strong closed word assumption **CW**, which resolves the contradictory evidence for $flyTweety$ by regarding it as false. In this sense, $\mathcal{C}_{LP}$-programs and AFs can be seen as two different syntaxes of a same formalism based in the principles **NC** and **CW** highlighted in the introduction. In addition, another such a principle of this formalism is the fact that evidence must be founded or justified: this clearly shows up in normal LP and EBAFs where true literals can be computed by some recursive procedure, but also in Dung's AFs where, as we have seen, defeat can be understood as a proof of falsity.

Regarding practical aspects, we can use $\mathcal{C}_{LP}$-programs as a unifying formalism to deal with both logic programs and AFs. This directly allows to introduce variables in AFs through the use of grounding. Going further, full first order characterisations of AFs can be provided by applying the same principles to first order constructive logic (full first order characterisation of consistent logic programs has been already provided by Pearce and Valverde (2004)). Besides, constructive logic immediately provides an interpretation for other richer syntaxes like the use of disjunctive targets in Collective Argumentation (Bochman 2003) or the use of arbitrary propositional formulas to represent attacks in Abstract Dialectical Frameworks (Brewka et al. 2013).

Another important practical aspect is that current state-of-the-art ASP solvers (Faber et al. 2008; Gebser, Kaufmann, and Schaub 2012) can be applied to $\mathcal{C}_{LP}$-programs by applying a simple transformation:

Definition 9. *Given a $\mathcal{C}_{LP}$-program P, by by $\mathcal{C}_S(P)$ we denote the result of*

1. *replace every positive literal a in the body of a rule by $a \wedge \neg\sim a$*
2. *replace every negative literal $not\ a$ in the body of a rule by $\neg a \vee (a \wedge \sim a)$, and*
3. *add rules $a'' \leftarrow \neg a$ and $a'' \leftarrow a \wedge a'$ for each atom $a \in At$ with a'' a fresh atom*
4. *replace each occurrence of $\neg a \vee (a \wedge a')$ in the body of any rule by a''.*
5. *replace $\Leftarrow$ by $\leftarrow$.*

Furthermore, given a total interpretation $\mathcal{I}$, we also denote by $\mathcal{C}_S(\mathcal{I})$ an interpretation that, for all $a \in At$, satisfies:

1. $\mathcal{C}_S(\mathcal{I}) \not\models^- a$
2. $\mathcal{C}_S(\mathcal{I}) \models^+ a$ *iff* $\mathcal{I} \models^+ a$
3. $\mathcal{C}_S(\mathcal{I}) \models^+ a'$ *iff* $\mathcal{I} \models^- a$
4. $\mathcal{C}_S(\mathcal{I}) \models^+ a''$ *iff either* $\mathcal{I} \not\models^+ a$ *or both* $\mathcal{I} \models^+ a$ *and* $\mathcal{I} \models^- a$. □

Theorem 5. *Given a $\mathcal{C}_{LP}$-program P and a total interpretation $\mathcal{I}$, we have that $\mathcal{I}$ is an equilibrium model of P iff $\mathcal{C}_S(I)$ an equilibrium model of $\mathcal{C}_S(P)$.* □

Another immediate consequence of this translation is deciding whether there exists any stable extension of some $\mathcal{C}_{LP}$-program is Σ_2^{P}-complete in general and NP-complete for normal $\mathcal{C}_{LP}$-program (Dantsin et al. 2001). Furthermore, this result directly applies to EBAFs so that deciding whether there exists any stable extension is NP-complete.

Conclusion and future work

We have formalised the principles **NC** and **CW** in Nelson's constructive logic and shown that this is a conservative extension of logic programs which allow us to reason with contradictory evidence. Furthermore, this allows us to translate argumentation frameworks in a modular way and using the object language such that attacks and supports become connectives in the logic. As a consequence, we can combine both formalisms in an unifying one and use proof methods from the logic or answer set solver to reason about it.

Regarding future work, an obvious open topic is to explore how other argumentation semantics can be translated into the logic. Another important open questions are studying how the principles **NC** and **CW** stand in the context of paraconsistent logics (da Costa 1974) and paraconsistent logic programming (Blair and Subrahmanian 1989); and study ing the notion of strong equivalence (Lifschitz, Pearce, and Valverde 2001; Oikarinen and Woltran 2011) in this logic and evidence-based frameworks.

Acknowledgements. We are thankful to Seiki Akama, Pedro Cabalar, Marcelo Coniglio, Newton Peron, David Pearce and Agustín Valverde for their suggestions and comments on earlier versions of this work. We also thank the anonymous reviewers for their help to improve the paper.

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