

The quest for the basic fuzzy logic

Petr Cintula, Rostislav Horčík

Institute of Computer Science
Academy of Sciences of the Czech Republic
Pod vodárenskou věží 2, 182 07 Prague, Czech Republic

Carles Noguera

Institute of Information Theory and Automation
Academy of Sciences of the Czech Republic
Pod vodárenskou věží 4, 182 00 Prague, Czech Republic
Institute of Computer Science, Academy of Sciences of the Czech Republic
Pod vodárenskou věží 2, 182 07 Prague, Czech Republic

1 Introduction

The present work intends to be both a survey and a position paper, conceived as a homage to Petr Hájek and his absolutely crucial contributions to Mathematical Fuzzy Logic (MFL). Our aim is to present some of the main developments in the area, starting with Hájek's seminal works and continuing with the contributions of many others, and we want to do it by taking the search of the basic fuzzy logic as the leitmotif. Indeed, as it will be apparent in the short historical account given later in this introduction, this search has been one of the main reasons for the development of new weaker systems of fuzzy logics and the necessary mathematical apparatus to deal with them. Hájek started the quest when he proposed his basic fuzzy logic BL, complete with respect to the semantics given by all continuous t-norms. Later weaker systems, such as MTL, UL or psMTL^r, complete with respect to broader (but still meaningful for fuzzy logics) semantics, have been introduced and disputed the throne of the basic fuzzy logic. We survey the development of these systems with a stress on how they have yielded systematical approaches to MFL. The chapter is also a position paper because we contribute to the quest with our own proposal of a basic fuzzy logic. Indeed, we put forth a very weak logic called SL^ℓ, introduced and studied in [19, 15], and propose it as a base of a new framework which allows to work in a uniform way with both propositional and first-order fuzzy logics. We present a wealth of results to illustrate the power and usefulness of this framework, which support our thesis that, from a well-defined point of view, SL^ℓ can indeed be seen as the basic fuzzy logic.¹

1.1 T-norm based fuzzy logics

Mathematical Fuzzy Logic (MFL) started as the study of logics based on particular continuous t-norms,² most prominently Łukasiewicz logic Ł, Gödel–Dummett logic G and Product logic Π. These logics are rendered in a language with the truth-constant $\bar{0}$ (falsum) and binary connectives \rightarrow (implication) and $\&$ (fusion, residuated/strong conjunction). They are complete with respect to the *standard semantics*, which has the real-unit interval $[0, 1]$ as the set of truth degrees and

¹The chapter is presented (almost) without proofs because (almost) all the claims follow from results proved in previous works. When necessary, we explain how the particular formulations used in this chapter follow from previous results in the literature.

²T-norms are commutative, associative, and monotone binary operations on the real unit interval with 1 as the neutral element; see [62] for a reference book on t-norm and [3] for a detailed survey and historical account on the role of t-norms in mathematical fuzzy logic.

interprets falsum \perp by 0, fusion $\&$ by the corresponding t-norm, and the implication \rightarrow by its residuum,³ which always exists for continuous t-norms. On the other hand, these systems are also complete with respect to an algebraic semantics (MV-algebras, Gödel algebras, and product algebras, respectively) and with respect to the subclass of their linearly ordered members, also known as (MV-/Gödel/product) *chains*. These three algebraic semantics are mutually incomparable superclasses of Boolean algebras, which amounts to say that \mathbb{L} , \mathbb{G} and \mathbb{II} are mutually incomparable subclassical logics. In fact, classical logic can be retrieved as axiomatic extension of any of these three systems obtained by adding the excluded middle axiom.

In this context, Petr Hájek introduced a natural question: is it possible to see \mathbb{L} , \mathbb{G} and \mathbb{II} (and, in general, any fuzzy logic with a continuous t-norm-based semantics) as extensions of the same fuzzy logic? In other words: is there a *basic fuzzy logic* underlying all (by then) known fuzzy logic systems? As an answer to this question, he introduced in his monograph [37, 38] a system, weaker than \mathbb{L} , \mathbb{G} and \mathbb{II} , which he named BL (for *basic logic*). This logic was given by means of a Hilbert-style calculus in the language $\mathcal{L} = \{\&, \rightarrow, \bar{0}\}$ of type $\langle 2, 2, 0 \rangle$, with the deduction rule of *modus ponens* (MP)—from φ and $\varphi \rightarrow \psi$ infer ψ —and the following axioms (taking \rightarrow as the least binding connective):

- (A1) $(\varphi \rightarrow \psi) \rightarrow ((\psi \rightarrow \chi) \rightarrow (\varphi \rightarrow \chi))$
- (A2) $\varphi \& \psi \rightarrow \varphi$
- (A3) $\varphi \& \psi \rightarrow \psi \& \varphi$
- (A4) $\varphi \& (\varphi \rightarrow \psi) \rightarrow \psi \& (\psi \rightarrow \varphi)$
- (A5a) $(\varphi \rightarrow (\psi \rightarrow \chi)) \rightarrow (\varphi \& \psi \rightarrow \chi)$
- (A5b) $(\varphi \& \psi \rightarrow \chi) \rightarrow (\varphi \rightarrow (\psi \rightarrow \chi))$
- (A6) $((\varphi \rightarrow \psi) \rightarrow \chi) \rightarrow (((\psi \rightarrow \varphi) \rightarrow \chi) \rightarrow \chi)$
- (A7) $\bar{0} \rightarrow \varphi$

Other connectives are introduced as follows:

$$\begin{aligned} \varphi \wedge \psi &= \varphi \& (\varphi \rightarrow \psi) & \neg\varphi &= \varphi \rightarrow \bar{0} \\ \varphi \vee \psi &= ((\varphi \rightarrow \psi) \rightarrow \psi) \wedge ((\psi \rightarrow \varphi) \rightarrow \varphi) & \bar{1} &= \neg\bar{0} \\ \varphi \leftrightarrow \psi &= (\varphi \rightarrow \psi) \wedge (\psi \rightarrow \varphi) \end{aligned}$$

Petr Hájek also introduced the corresponding algebraic semantics for his logic. A BL-*algebra* is an algebra $\mathbf{A} = \langle A, \wedge, \vee, \cdot, \rightarrow, 0, 1 \rangle$ such that

- $\langle A, \wedge, \vee, 0, 1 \rangle$ is a bounded lattice
- $\langle A, \cdot, 1 \rangle$ is a commutative monoid
- for each $a, b, c \in A$ we have

$$\begin{aligned} a \cdot b \leq c &\text{ iff } b \leq a \rightarrow c && \text{(residuation)} \\ (a \rightarrow b) \vee (b \rightarrow a) &= 1 && \text{(prelinearity)} \\ a \cdot (a \rightarrow b) &= b \cdot (b \rightarrow a) && \text{(divisibility)} \end{aligned}$$

We say that a BL-algebra is:

- *Linearly ordered* (or BL-chain) if its lattice order is total.
- *Standard* if its lattice reduct is the real unit interval $[0,1]$ ordered in the usual way.

Note that in a standard BL-algebra $\&$ is interpreted by a continuous t-norm and \rightarrow by its residuum; and vice versa: each continuous t-norm fully determines its corresponding standard BL-algebra.

Hájek proved completeness of BL with respect to BL-algebras and BL-chains and conjectured that BL should be also complete with respect to the standard BL-algebras (i.e., the semantics

³If $*$ is a t-norm, its residuum is defined as the binary function $x \Rightarrow y = \sup\{z \in [0, 1] \mid x * z \leq y\}$.

given by all continuous t-norms). The conjecture was later proved true: Hájek himself showed the completeness by adding two additional axioms [37] which later were shown to be derivable in BL [11]. Therefore, BL could really be seen, at that time, as a *basic fuzzy logic*. Indeed, it was a genuine *fuzzy logic* because it retained what was then seen as the defining property of fuzzy logics: completeness with respect to a semantics based on continuous t-norms. And it was also *basic* in the following two senses:

1. *it could not be made weaker without losing essential properties and*
2. *it provided a base for the study of all fuzzy logics.*

The first item followed from the completeness of BL w.r.t. the semantics given by *all* continuous t-norms; thus, in a context of continuous t-norm based logics one could not possibly take a weaker system. The second meaning relied on the fact that the three main fuzzy logics (\mathcal{L} , G, and Π) are all axiomatic extensions of BL and, in fact, the methods used by Hájek to introduce, algebraize, and study BL could be utilized for any other logic based on continuous t-norms. Actually, already in [38], Hájek developed a uniform mathematical theory for MFL. He considered all axiomatic extensions of BL (not just the three prominent ones) as fuzzy logics (he called them *schematic extensions*) and systematically studied their first-order extensions (inspired by Rasiowa's works; see [76]), extensions with modalities, complexity issues, etc.

Moreover, mainly thanks to the availability of good mathematical characterizations for continuous t-norms and BL-chains, BL has turned out to be a crucial logical system giving rise to an intense research with lots of nice results obtained by many authors (for an up-to-date survey see [8]). For these reasons, we want to take on the occasion of the present tribute volume to Petr Hájek to propose that both BL logic and BL-algebras should rightfully be renamed after their creator as *Hájek logic* and *Hájek algebras* (HL and HL-algebras, for short).

Another strong reason supporting abandoning the name 'Basic Logic' is that the development of MFL has shown that HL was actually *not basic enough*. That is, HL was indeed a good basic logic for the initial framework in which it was formulated, but the active research area that Hájek helped creating with his monograph and his weakest logical system soon expanded its horizons to broader frameworks which demanded a revision of the basic logic. Therefore, Hájek had not settled but only initiated the quest for the basic fuzzy logic. The first step towards a broader point of view was taken by Esteva and Godo, who noticed that the necessary and sufficient condition for a t-norm to have a residuum is not continuity, but left-continuity. Inspired by this fact they introduced in [23] the logic MTL (shorthand for *Monoidal T-norm based Logic*) as an attempt to axiomatize the standard semantics given by all residuated t-norms. It was introduced by means of a Hilbert-style calculus in the language $\mathcal{L} = \{\&, \rightarrow, \wedge, \bar{0}\}$ of type $\langle 2, 2, 2, 0 \rangle$, (\wedge is no longer a derived connective and has to be considered as primitive). This calculus is the same as the one for HL only axiom (A4) is replaced by the following three axioms:

- (A4a) $\varphi \wedge \psi \rightarrow \varphi$
- (A4b) $\varphi \wedge \psi \rightarrow \psi \wedge \varphi$
- (A4c) $\varphi \& (\varphi \rightarrow \psi) \rightarrow \varphi \wedge \psi$

Similarly to the previous cases, Esteva and Godo introduced a broader class of algebraic structures, MTL-algebras (defined analogously to HL-algebras but without requiring the fulfilment of the divisibility condition) and proved that MTL is complete both w.r.t. the semantics given by all MTL-algebras and w.r.t. MTL-chains. Moreover, in [60], Jenei and Montagna indeed proved MTL to be complete with respect to the semantics given by all left-continuous (i.e. residuated) t-norms. Thus it was a better candidate than HL for a basic fuzzy logic, which could be retrieved as the axiomatic extension of MTL by axiom (A4).

1.2 Core fuzzy logics

In the broader framework for MFL promoted by Esteva and Godo, i.e. that of logics based on residuated t-norms, the system MTL indeed fulfilled our requirements for a basic fuzzy logic, as

expressed in the previous subsection. It was a genuine fuzzy logic enjoying a standard completeness theorem w.r.t. a semantics based on left-continuous t-norms, it could not be made weaker without losing this property and all known fuzzy logics could be obtained as extensions of MTL, thus providing a good base for a new systematical study of MFL. In fact, Petr Hájek saluted MTL as the new basic fuzzy logic and defined (in a joint work with Petr Cintula [52]) a precise general framework taking MTL as the basic system and not restricting to its axiomatic extensions (i.e. logics in the same language as MTL) but rather to its axiomatic expansions (by allowing new additional connectives). In particular they introduced two classes of logics which, though not very broad from the general perspective of the whole logical landscape, are still large enough to cover the most studied fuzzy logics. These two classes have provided a useful framework for a general study of these logics and have been utilized in particular in the study of completeness of (propositional and first-order) fuzzy logics w.r.t. distinguished semantics in [13] and the arithmetical complexity of first-order fuzzy logics in [69]. The rough idea was to capture, by simple syntactic means, a class of logics which share many desirable properties with MTL.

Definition 1. *A logic L in a language \mathcal{L} is a core fuzzy logic if:*

1. L expands MTL.
2. For all \mathcal{L} -formulae φ, ψ, χ the following holds:⁴

$$\varphi \leftrightarrow \psi \vdash_L \chi \leftrightarrow \chi', \quad (\text{Cong})$$

where χ' is a formula resulting from χ by replacing some occurrences of its subformula φ by the formula ψ .

3. L has an axiomatic system with modus ponens as the only deduction rule.⁵

Axiom schema	Name
$\neg\neg\varphi \rightarrow \varphi$	Involution (Inv)
$\neg\varphi \vee ((\varphi \rightarrow \varphi \& \psi) \rightarrow \psi)$	Cancellation (Can)
$\neg(\varphi \& \psi) \vee ((\psi \rightarrow \varphi \& \psi) \rightarrow \varphi)$	Weak Cancellation (WCan)
$\varphi \rightarrow \varphi \& \varphi$	Contraction (C)
$\varphi^{n-1} \rightarrow \varphi^n$	n -Contraction (C_n)
$\varphi \wedge \neg\varphi \rightarrow \bar{0}$	Pseudocomplementation (PC)
$\varphi \wedge \psi \rightarrow \varphi \& (\varphi \rightarrow \psi)$	Divisibility (Div)
$(\varphi \& \psi \rightarrow \bar{0}) \vee (\varphi \wedge \psi \rightarrow \varphi \& \psi)$	Weak Nilpotent Minimum (WNM)
$\varphi \vee \neg\varphi$	Excluded Middle (EM)

Table 1: Some usual axiom schemata in fuzzy logics.

Therefore, core fuzzy logics are essentially well-behaved axiomatic expansions of MTL. Observe, that since MTL is a finitary logic⁶ and we are only considering adding axioms, not rules, all core fuzzy logics remain finitary. Table 2 collects prominent members of the family of core fuzzy logics together with the axioms one needs to add to MTL to obtain them (see the definition of axioms in Table 1). An important logic, which does not fall under the scope of the previous definition, is the expansion of MTL with the Monteiro–Baaz projection connective Δ [1, 72]. This logic, denoted as MTL_Δ , is obtained by adding the unary connective Δ to the language, the rule of Δ -Necessitation (Nec_Δ)—from φ infer $\Delta\varphi$ —and the following axioms:

⁴By \vdash_L we denote the provability relation in the logic L , see Subsection 2.1 for the formal definition.

⁵The original definition of core fuzzy logics [52, Convention 1] required the validity of a variant of deduction theorem (see Theorem 3), but is shown equivalent with our definition in [52, Proposition 3]; analogously for Δ -core fuzzy logics introduced in the next definition.

⁶This means that whenever $\Gamma \vdash_{\text{MTL}} \varphi$, there is a finite $\Gamma' \subseteq \Gamma$ such that $\Gamma' \vdash_{\text{MTL}} \varphi$.

Logic	Additional axiom schemata	References
SMTL	(PC)	[41]
IIMTL	(Can)	[41]
WCMTL	(WCan)	[70]
IMTL	(Inv)	[23]
WNM	(WNM)	[23]
NM	(Inv) and (WNM)	[23]
C_n MTL	(C_n)	[10]
C_n IMTL	(Inv) and (C_n)	[10]
HL (BL)	(Div)	[38]
SHL (SBL)	(Div) and (PC)	[25]
L	(Div) and (Inv)	[38, 64]
II	(Div) and (Can)	[53]
G	(C)	[38, 21, 36]
CPC	(EM)	

Table 2: Some axiomatic extensions of MTL obtained by adding the corresponding additional axiom schemata.

- (Δ 1) $\Delta\varphi \vee \neg\Delta\varphi$
- (Δ 2) $\Delta(\varphi \vee \psi) \rightarrow \Delta\varphi \vee \Delta\psi$
- (Δ 3) $\Delta\varphi \rightarrow \varphi$
- (Δ 4) $\Delta\varphi \rightarrow \Delta\Delta\varphi$
- (Δ 5) $\Delta(\varphi \rightarrow \psi) \rightarrow (\Delta\varphi \rightarrow \Delta\psi)$

Taking MTL_Δ as an alternative basic logic, Hájek and Cintula defined another class of fuzzy logics, now with the Δ connective:

Definition 2. *A logic L in a language \mathcal{L} is a Δ -core fuzzy logic if:*

1. L expands MTL_Δ .
2. For all \mathcal{L} -formulae φ, ψ, χ the following holds:

$$\varphi \leftrightarrow \psi \vdash_{\text{L}} \chi \leftrightarrow \chi', \quad (\text{Cong})$$

where χ' is a formula resulting from χ by replacing some occurrences of its subformula φ by the formula ψ .

3. L has an axiomatic system with modus ponens and (Nec_Δ) as the only deduction rules.

Expansions of fuzzy logics with Δ were already systematically studied by Petr Hájek already in his seminal monograph [38] and have since then been considered for most fuzzy logics, making the class of Δ -core fuzzy logics another largely populated useful class.

Other well-known fuzzy logics in expanded languages fall under the scope of the two classes we have introduced, such as logics with truth-constants for intermediate truth-values (a Petr Hájek's variant [38] of the Pavelka's extension of Łukasiewicz logic [75, 73] later studied in many works by other authors; see e.g. [78, 28] or a detailed survey in [26, Section 2]), logics L_\sim expanded with an extra involutive negation (again initiated by Petr Hájek et al [25] and followed by others; see e.g. [16, 25, 32, 56] or a detailed survey in [26, Section 4]), or logics combining conjunctions and implications corresponding to different t-norms; see e.g. [12, 58, 71, 27] or again a survey in [26, Section 5]. On the other hand there are logics expanding MTL studied in the literature which are not core or Δ -core because they need some additional deduction rules, the prominent examples being the logic PL' (the extension of Łukasiewicz logic with an additional product-like conjunction which has no zero-divisors [58]) or logics with truth-hedges [30].

Core and Δ -core fuzzy logics are all finitary and well-behaved from several points of view. In particular, for every such logic L one can define in a natural way a corresponding class of algebraic structures, L -algebras, which provide a complete semantics as in the case of MTL or the previously mentioned logics and, more importantly, the completeness theorem is preserved if we restrict ourselves to *linearly ordered* L -algebras. Moreover, these classes of algebras are always *varieties*, i.e. they can be presented in terms of equations or, equivalently, are closed under formation of homomorphic images, subalgebras and direct products. Another interesting property shared by the logics in these classes is the deduction theorem. Petr Hájek already proved deduction theorems for several fuzzy logics, including his basic logic, and also for his expansions with Δ in [38]. One can analogously obtain deduction theorems for all the logics in the classes just defined (in a local form for core fuzzy logics, global for Δ -core):⁷

Theorem 3. 1. Let L be a core fuzzy logic in a language \mathcal{L} . For every $\Gamma \cup \{\varphi, \psi\} \subseteq Fm_{\mathcal{L}}$, $\Gamma, \varphi \vdash_L \psi$ iff there is $n \geq 0$ such that $\Gamma \vdash_L \varphi^n \rightarrow \psi$.

2. Let L be a core Δ -fuzzy logic in a language \mathcal{L} . For every $\Gamma \cup \{\varphi, \psi\} \subseteq Fm_{\mathcal{L}}$, $\Gamma, \varphi \vdash_L \psi$ iff $\Gamma \vdash_L \Delta\varphi \rightarrow \psi$.

We will give more precise details both about algebraization of logics and about deduction theorems in Section 2.

1.3 Substructural logics as a framework for fuzzy logics

The quest for the basic fuzzy logic did not end with MTL (or MTL_{Δ}). Indeed, MTL has been further weakened in two different directions beyond the framework of core fuzzy logics:

- (a) by dropping commutativity of conjunction Petr Hájek obtained a system, $psMTL^r$ [43], which Jenei and Montagna proved to be complete with respect to the semantics on non-commutative residuated t-norms [61],
- (b) by removing integrality (i.e. not requiring the neutral element of conjunction to be maximum of the order) Metcalfe and Montagna proposed the logic UL which is, in turn, complete with respect to left-continuous uninorms [66].

Petr Hájek liked to describe this process of successive weakening of fuzzy logics by telling the joke of the crazy scientist that studied fleas by removing their legs one by one and checking whether they could still jump [48].⁸ Namely, if HL was the original flea, it lost the ‘divisibility leg’ when it was substituted by MTL, and then $psMTL^r$ and UL respectively lost the ‘commutativity and the integrality leg’ while retaining the ability to ‘jump’ (i.e., the completeness w.r.t. intended semantics based on reals).

These weaker fuzzy logics (and even MTL itself; see [24]) can be fruitfully studied in the context of substructural logics. Recall the bounded full Lambek logic FL,⁹ a basic substructural logic which does not satisfy any of the usual three structural rules: exchange, weakening, and contraction. Although firstly presented by means of a Gentzen calculus, it can be given a Hilbert-style presentation and shown to be an algebraizable logic in the sense of [4] whose equivalent algebraic semantics is the variety of bounded pointed lattice-ordered residuated monoids (usually

⁷We need to recall the following inductively defined notation: $\varphi^0 = \bar{1}$, $\varphi^1 = \varphi$, and $\varphi^n = \varphi^{n-1} \& \varphi$.

⁸A prominent biologist conducted a very important experiment. He trained a flea to jump upon giving her a verbal command (“Jump!”). In a first stage of the experiment he removed a flea’s leg, told her to jump, and the flea jumped. So he wrote in his scientific notebook: “Upon removing one leg all flea organs function properly.” So, he removed the second leg, asked the flea to jump, she obeyed, so he wrote again: “Upon removing the second leg all flea organs function properly.” Thereafter he removed all the legs but one, the flea jumped when ordered, so he wrote again: “Upon removing the one but last leg all flea organs function properly.” Then he removed the last leg. Told flea to jump, and nothing happened. He did not want to take a chance, so he repeated the experiment several times, and the legless flea never jumped. So he wrote the conclusion: “Upon removing the last leg the flea loses sense of hearing.”

⁹We use this notation for simplicity in this introduction, even though in the literature the symbol FL is usually used for the unbounded full Lambek logic whereas the bounded FL is denoted as FL_{\perp} .

referred to as bounded pointed *residuated lattices* or *FL-algebras*). Intuitionistic logic together with logics FL_e , FL_w , and FL_{ew} are among the most prominent extensions of FL. These logics are obtained by adding some of the structural rules and correspond to subvarieties of residuated lattices satisfying corresponding extra algebraic properties (see e.g. [34]). Actually, many fuzzy logics have been shown to be axiomatic extensions of some of these prominent substructural logics by adding some axioms that enforce completeness with respect to some class of linearly ordered residuated lattices (or *chains*). For instance, Gödel–Dummett logic is the logic of linearly ordered Heyting algebras (FL_{ewc} -chains), MTL is the logic FL_{ew}^ℓ of FL_{ew} -chains,¹⁰ UL is the logic FL_e^ℓ of FL_e -chains, and psMTL^r is the logic FL_w^ℓ of FL_w -chains.

This common feature, completeness with respect to their corresponding linearly ordered algebraic structures, has motivated the methodological paper [2] where the authors postulate that *fuzzy logics are the logics of chains*, in the sense that they are logics complete with respect to a semantics of chains. However, all the fuzzy logics mentioned so far do enjoy a stronger property: the *standard completeness theorem*, i.e. completeness with respect to a semantics of algebras defined on the real unit interval $[0, 1]$ which Petr Hájek and many others have considered to be the intended semantics for fuzzy logics. Following Hájek’s flea joke, we could say that those fleas are fuzzy logics that *jump well* provided that they satisfy standard completeness. Actually, many authors implicitly (and sometimes even explicitly, e.g. in [66]) regard standard completeness as an essential requirement for fuzzy logics. It is, thus, reasonable to expect any candidate for the basic fuzzy logic to satisfy this stronger requirement. But, although they fulfill that, neither FL_e^ℓ nor FL_w^ℓ can be taken as basic because they are not comparable and hence do not satisfy our second meaning of *basic*. A reasonable candidate could be the logic FL^ℓ of FL-chains (a common generalization of FL_e^ℓ and FL_w^ℓ). But, interestingly enough, this logic does not enjoy the standard completeness (as proved in [80]) and, therefore, we must discard it. Moreover, one can also argue that FL^ℓ is still *not basic enough* (in the first meaning) because it satisfies a remaining structural rule: associativity. Hence, in the context of substructural logics, it could still be made weaker by removing associativity.

There have actually been several studies on non-associative substructural logics, starting with the original Lambek non-associative calculus [63] (without lattice connectives), and followed (in the full language) e.g. by Buszkowski and Farulewski in [9]. Recently, a general algebraic framework to study fuzzy logics as a subfamily of (not necessarily associative) substructural logics has been developed in [19]. It is based on the logic SL, a non-associative version of the bounded Full Lambek calculus, introduced by Galatos and Ono in [35].¹¹ SL is formulated in the language $\mathcal{L}_{\text{SL}} = \{\wedge, \vee, \&, \rightarrow, \rightsquigarrow, \bar{0}, \bar{1}, \perp\}$ (we also make use of the defined connectives $\varphi \leftrightarrow \psi = (\varphi \rightarrow \psi) \wedge (\psi \rightarrow \varphi)$ and $\top = \perp \rightarrow \perp$)¹² and axiomatized by means of the Hilbert-style calculus from [35, Figure 5] presented in Table 3.

Moreover, Galatos and Ono proved that SL is an algebraizable logic whose equivalent algebraic semantics is the variety of bounded lattice-ordered residuated unital groupoids, where the monoidal structure of the previous logics has become just a groupoid on account of the lack of associativity (we will see more details in Section 2). Therefore, if we are looking for a logic complete with respect to standard chains in the non-associative context, it makes sense to consider, in a similar fashion as with FL and its extensions, the logic SL^ℓ as the logic of bounded linearly ordered residuated unital groupoids.

1.4 Goals and outline of the chapter

The main goal of this chapter is to propose SL^ℓ as a new basic fuzzy logic. The current stage of development in MFL requires a broader framework than that provided by core and Δ -core fuzzy

¹⁰As notation convention (later precisely introduced in Definition 27) given a logic L, we denote by L^ℓ the logic of L-chains.

¹¹Technically speaking, Galatos and Ono introduced an unbounded version of this logic and actually never named it. The name SL, standing for ‘substructural logic’, comes from [19].

¹²When writing formulae in this language we will assume that the increasing binding order of connectives is: first $\&$, then $\{\wedge, \vee\}$, and finally $\{\rightarrow, \rightsquigarrow, \leftrightarrow\}$.

(R)	$\varphi \rightarrow \varphi$	(R')	$\bar{1} \rightarrow (\varphi \rightarrow \varphi)$
(MP)	$\varphi, \varphi \rightarrow \psi \vdash \psi$	(Push)	$\varphi \rightarrow (\bar{1} \rightarrow \varphi)$
(Sf)	$\varphi \rightarrow \psi \vdash (\psi \rightarrow \chi) \rightarrow (\varphi \rightarrow \chi)$	($\bar{1}$)	$\bar{1}$
(Pf)	$\psi \rightarrow \chi \vdash (\varphi \rightarrow \psi) \rightarrow (\varphi \rightarrow \chi)$	(Bot)	$\perp \rightarrow \varphi$
(As)	$\varphi \vdash (\varphi \rightarrow \psi) \rightarrow \psi$	($\wedge 1$)	$\varphi \wedge \psi \rightarrow \varphi$
(As $_{\ell\ell}$)	$\varphi \rightarrow ((\varphi \rightsquigarrow \psi) \rightarrow \psi)$	($\wedge 2$)	$\varphi \wedge \psi \rightarrow \psi$
(Symm $_1$)	$\varphi \rightsquigarrow \psi \vdash \varphi \rightarrow \psi$	($\wedge 3$)	$(\chi \rightarrow \varphi) \wedge (\chi \rightarrow \psi) \rightarrow (\chi \rightarrow \varphi \wedge \psi)$
(E $_{\rightsquigarrow 1}$)	$\varphi \rightarrow (\psi \rightarrow \chi) \vdash \psi \rightarrow (\varphi \rightsquigarrow \chi)$	($\vee 1$)	$\varphi \rightarrow \varphi \vee \psi$
(Res $_1$)	$\psi \rightarrow (\varphi \rightarrow \chi) \vdash \varphi \& \psi \rightarrow \chi$	($\vee 2$)	$\psi \rightarrow \varphi \vee \psi$
(Adj $_{\&}$)	$\varphi \rightarrow (\psi \rightarrow \psi \& \varphi)$	($\vee 3$)	$(\varphi \rightarrow \chi) \wedge (\psi \rightarrow \chi) \rightarrow (\varphi \vee \psi \rightarrow \chi)$
(Adj)	$\varphi, \psi \vdash \varphi \wedge \psi$	($\vee 3_{\rightsquigarrow}$)	$(\varphi \rightsquigarrow \chi) \wedge (\psi \rightsquigarrow \chi) \rightarrow (\varphi \vee \psi \rightsquigarrow \chi)$

Table 3: Axiomatic system of SL.

logics. This is witnessed by several works (some already mentioned) dealing with fuzzy logics which either need some additional deduction rule or are weaker than MTL, e.g. [6, 30, 33, 42, 43, 44, 55, 58, 61, 65, 66, 80]. For this reason fuzzy logics have started being systematically studied in the context of (not necessarily associative) substructural logics in [19]. However, this work did not offer a basic fuzzy logic in its framework.

On the other hand, SL^ℓ has been introduced and studied as an axiomatic extension of SL in the recent paper [15] where, among others, it has been shown to enjoy standard completeness. Based on these results we will defend here the thesis that SL^ℓ can serve as a basic fuzzy logic, good enough for the current needs of MFL. We will argue that is genuinely fuzzy and basic in both senses mentioned earlier in this introduction. To this end, we introduce a new class of logics containing core and Δ -core fuzzy logics and much more: *core semilinear logics*. The adjective ‘semilinear’ in the name of this class refers to a notion introduced in [18] in order to capture the idea of fuzzy logics as logics of chains proposed in [2]. The idea is the following: if a logic has a reasonable implication \rightarrow (which is the case of SL and many of its expansions like core and Δ -core fuzzy logics) then its corresponding algebraic structures can be ordered in terms of the implication ($a \leq b$ iff $a \rightarrow b \geq 1$); the logic is said to be *semilinear* iff it is complete w.r.t. the class of algebras where the order just defined is total. Moreover, the class of core semilinear logics contains both core and Δ -core fuzzy logics and is defined in formally analogous way. Actually, the class of core semilinear logics provides a convenient intermediate level of generality, between that of core and Δ -core fuzzy logics and that of weakly implicative semilinear logics of [19], by fixing SL^ℓ (and, therefore, its language) as a common base and allowing for non-axiomatic extensions.

Outline of the chapter After this introduction that has presented the topic (historically and conceptually), the main logical systems, the classes of (Δ -)core fuzzy logics, and the motivation for the forthcoming class of core semilinear logics,¹³ Section 2 presents, in mathematical details, the necessary logical and algebraic framework for our approach, which mainly restricts to substructural logics understood as well-behaved expansions of the non-associative logic SL. Section 2.1 gives the basic notions, Section 2.2 presents the useful syntactical notion of almost (MP)-based logics, and Section 2.3 is devoted to generation of filters, algebraization, and completeness w.r.t. (finitely) subdirectly irreducible algebras. Section 3, as the central part of the paper, focuses on propositional core semilinear logics. After defining them, Section 3.1 shows several useful characterizations of semilinear logics and their axiomatizations, including a presentation of SL^ℓ as

¹³Although we have tried to make this paper reasonably self-contained, the obvious space limitations do not allow for an extensive presentation of all mentioned logical systems. For an up-to-date encyclopedical account of Mathematical Fuzzy Logic see [14].

axiomatic extension of SL; Section 3.2 is a survey on completeness properties of core semilinear logics w.r.t. significant algebraic semantics, in particular we stress the standard completeness of SL^ℓ . Finally, Section 4 is devoted to first-order predicate counterparts of core semilinear logics, including $SL^{\ell\forall}$, the first-order extension of SL^ℓ . Section 4.1 shows the axiomatization of these logics, Section 4.2 presents their semantics based on general and witnessed models, and Section 4.3 focuses again on distinguished semantics, in particular stressing that $SL^{\ell\forall}$ enjoys standard completeness too.

2 Logical framework

In order to deal with the classes of logics mentioned above, we need some flexibility as regards both propositional languages and logics. Therefore, for the sake of reference and in order to fix terminology in a convenient way for this chapter, we shall start with some standard general definitions and conventions.¹⁴

2.1 Basic syntax and semantics

In this chapter we consider logics as given by finitary Hilbert-style proof systems expanding that of SL (see Table 3 in the introduction). Following Hájek's methodology, we restrict to finitary systems as he did when proposing schematic extensions of HL as a systematic approach to MFL. This does not undermine the suitability of our proposed basic logic SL^ℓ (or its first-order counterpart) because the infinitary systems of fuzzy logic can still be retrieved as its extensions; we disregard them here for simplicity of presentation only.

A *propositional language* \mathcal{L} is a *countable* type, i.e. a function $ar: C_{\mathcal{L}} \rightarrow \mathbb{N}$, where $C_{\mathcal{L}}$ is a countable set of symbols called *connectives*, giving for each one its *arity*. Nullary connectives are also called *truth-constants*. We write $\langle c, n \rangle \in \mathcal{L}$ whenever $c \in C_{\mathcal{L}}$ and $ar(c) = n$. The basic language in this chapter is \mathcal{L}_{SL} with binary connectives $\wedge, \vee, \&, \rightarrow, \rightsquigarrow$ and truth-constants $\bar{0}, \bar{1}, \perp$ (we also make use of the defined connectives $\top = \perp \rightarrow \perp$ and $\varphi \leftrightarrow \psi = (\varphi \rightarrow \psi) \wedge (\psi \rightarrow \varphi)$). Let Var be a fixed infinite countable set of symbols called *variables*. The set $Fm_{\mathcal{L}}$ of *formulae* in a propositional language \mathcal{L} is the least set containing Var and closed under connectives of \mathcal{L} , i.e. for each $\langle c, n \rangle \in \mathcal{L}$ and every $\varphi_1, \dots, \varphi_n \in Fm_{\mathcal{L}}$, $c(\varphi_1, \dots, \varphi_n)$ is a formula. $Fm_{\mathcal{L}}$ can be seen as the domain of the absolutely free algebra $\mathbf{Fm}_{\mathcal{L}}$ of type \mathcal{L} and generators Var . An \mathcal{L} -*substitution* is an endomorphism on the algebra $\mathbf{Fm}_{\mathcal{L}}$, i.e. a mapping $\sigma: Fm_{\mathcal{L}} \rightarrow Fm_{\mathcal{L}}$, such that $\sigma(c(\varphi_1, \dots, \varphi_n)) = c(\sigma(\varphi_1), \dots, \sigma(\varphi_n))$ holds for each $\langle c, n \rangle \in \mathcal{L}$ and every $\varphi_1, \dots, \varphi_n \in Fm_{\mathcal{L}}$. Since an \mathcal{L} -substitution is a mapping whose domain is a free \mathcal{L} -algebra, it is fully determined by its values on the generators (propositional variables).

An *axiomatic system* \mathcal{AS} in a propositional language \mathcal{L} is a pair $\langle Ax, R \rangle$ where Ax is set of formulae (the *axioms*) and R is a set of pairs $\langle \Gamma, \varphi \rangle$ (the *rules*) where Γ is a *finite* non-empty set of formulae and φ is a formula.¹⁵ Moreover, both Ax and R are closed under arbitrary substitutions. Given $\Gamma \cup \{\varphi\} \subseteq Fm_{\mathcal{L}}$, we say that φ is *provable from Γ in \mathcal{AS}* , in symbols $\Gamma \vdash_{\mathcal{AS}} \varphi$, if there exists a finite sequence of formulae $\langle \varphi_0, \dots, \varphi_n \rangle$ (a *proof*) such that:

- $\varphi_n = \varphi$, and
- for every $i \leq n$, either $\varphi_i \in \Gamma \cup Ax$ or there is $\langle \Delta, \varphi_i \rangle \in R$ such that $\Delta \subseteq \{\varphi_0, \dots, \varphi_{i-1}\}$.

Observe that the provability relation $\vdash_{\mathcal{AS}}$ is finitary, i.e., if $\Gamma \vdash_{\mathcal{AS}} \varphi$, then there is a finite $\Gamma' \subseteq \Gamma$ such that $\Gamma' \vdash_{\mathcal{AS}} \varphi$.

¹⁴The interested reader can complement the upcoming short presentation by consulting reference works on (Abstract) Algebraic Logic such as [4, 7, 14]. We deviate slightly from the standard treatment of some basic notions because we are tailoring them to the particular purposes of the present chapter.

¹⁵Sometimes, especially when listing rules, we use the denotation $\Gamma \vdash \varphi$ rather than $\langle \Gamma, \varphi \rangle$. Also note that axioms could be seen as nullary rules; while this identification would simplify some of the upcoming formulations we have opted for a more conceptually illuminating separation of these two notions.

Let $\mathcal{L}_1 \subseteq \mathcal{L}_2$ be propositional languages and \mathcal{AS}_i an axiomatic system in \mathcal{L}_i . We say that \mathcal{AS}_2 is an expansion of \mathcal{AS}_1 by axioms Ax and rules R if all its axioms (rules) are \mathcal{L}_2 -substitutional instances of axioms (rules) of \mathcal{AS}_1 or formulae from Ax (rules from R).

Now we are ready to give our formal convention restricting logics to finitary expansions of SL with well-behaved connectives.

Convention 4. A logic L in a language $\mathcal{L} \supseteq \mathcal{L}_{SL}$ is the provability relation given by an axiomatic system \mathcal{AS} in \mathcal{L} which is an expansion of that of SL (see Table 3) and for all \mathcal{L} -formulae φ, ψ, χ the following holds:

$$\varphi \leftrightarrow \psi \vdash_{\mathcal{AS}} \chi \leftrightarrow \chi', \quad (\text{Cong})$$

where χ' is a formula resulting from χ by replacing some occurrences of its subformula φ by a formula ψ . In this case we say that \mathcal{AS} is a presentation of L (or that L is axiomatized by \mathcal{AS}) and write $\Gamma \vdash_L \varphi$ instead of $\Gamma \vdash_{\mathcal{AS}} \varphi$.

Remark 5. One can equivalently replace the condition (Cong) by the following:

$$\varphi \leftrightarrow \psi \vdash_{\mathcal{AS}} c(\chi_1, \dots, \chi_i, \varphi, \dots, \chi_n) \leftrightarrow c(\chi_1, \dots, \chi_i, \psi, \dots, \chi_n) \quad (\text{Cong}_c^i)$$

for each $\langle c, n \rangle \in \mathcal{L}$ and each $0 \leq i < n$. Therefore, since this condition is already satisfied in SL for all its connectives, in order to check whether a particular expansion of SL is a logic in the sense just defined, it is enough to check (Cong_c^i) for all new connectives (this statement remains true if we replace SL by any other logic).

The notion of expansion can naturally be formulated for logics. Let $\mathcal{L}_1 \subseteq \mathcal{L}_2$ be propositional languages and L_i a logic in \mathcal{L}_i . We say that

- L_2 is the *expansion* of L_1 by axioms Ax and rules R if it is axiomatized by expanding some presentation of L_1 with axioms Ax and rules R .
- L_2 is an (axiomatic) *expansion* of L_1 if it is the expansion of L_1 by some axioms and rules (or just axioms respectively).

If $\mathcal{L}_1 = \mathcal{L}_2$, we use the term ‘extension’ instead of ‘expansion’. Let \mathcal{S} be a collection of extensions of a given logic L . We define the following two axiomatic systems and two logics:

$$\begin{aligned} \bigcap \mathcal{S} &= \{ \langle \Gamma, \varphi \rangle \mid \Gamma \vdash_L \varphi \text{ for each } L \in \mathcal{S} \} & \bigwedge \mathcal{S} &= \vdash_{\bigcap \mathcal{S}} \\ \bigcup \mathcal{S} &= \{ \langle \Gamma, \varphi \rangle \mid \Gamma \vdash_L \varphi \text{ for some } L \in \mathcal{S} \} & \bigvee \mathcal{S} &= \vdash_{\bigcup \mathcal{S}} \end{aligned}$$

It is clear that $\bigwedge \mathcal{S}$ and $\bigvee \mathcal{S}$ are respectively the infimum and the supremum of \mathcal{S} in the set of extensions of L ordered by inclusion. Therefore, the set of extensions of a given logic L always forms a complete lattice. Note that $\bigvee \mathcal{S}$ can be axiomatized by taking the union of arbitrary axiomatic systems for the logics in \mathcal{S} . Thus, in particular, if all logics in \mathcal{S} are axiomatic extensions of L , then so is $\bigvee \mathcal{S}$. Therefore, the class of *axiomatic* extensions of L is a sub-join-semilattice of the lattice of all extensions of L . The axiomatization of meets is not so straightforward; at the end of Section 3.1 we will see how to deal with this problem in the restricted setting of core semilinear logics.

Some important axiomatic extensions of SL are obtained by adding the axioms a_1, a_2, e, c, i, o corresponding to structural rules (see Table 4).

Given any $S \subseteq \{a_1, a_2, e, c, i, o\}$, by SL_S we denote the axiomatic extension of SL by S . If $\{a_1, a_2\} \subseteq S$, then instead of them we write the symbol ‘a’. Analogously if $\{i, o\} \subseteq S$, instead of them we write the symbol ‘w’. Equivalent ways to formulate these axioms may be found e.g. in [19, Theorem 2.5.7]. SL_a is, in fact, the bounded full Lambek logic.

Now we introduce the basic algebraic notions that will allow to provide a semantics for our logics.

Definition 6. A bounded pointed lattice-ordered residuated unital groupoid, or *shortly just* SL-algebra, is an algebra $\mathbf{A} = \langle A, \wedge, \vee, \cdot, \backslash, /, 0, 1, \perp, \top \rangle$ such that

a ₁	$\varphi \& (\psi \& \chi) \rightarrow (\varphi \& \psi) \& \chi$	<i>re-associate to the left</i>
a ₂	$(\varphi \& \psi) \& \chi \rightarrow \varphi \& (\psi \& \chi)$	<i>re-associate to the right</i>
e	$\varphi \& \psi \rightarrow \psi \& \varphi$	<i>exchange</i>
c	$\varphi \rightarrow \varphi \& \varphi$	<i>contraction</i>
i	$\psi \rightarrow (\varphi \rightarrow \psi)$	<i>left weakening</i>
o	$\bar{0} \rightarrow \varphi$	<i>right weakening</i>

Table 4: Axioms for structural rules.

- $\langle A, \wedge, \vee, \perp, \top \rangle$ is a bounded lattice
- 1 is the unit of \cdot
- for each $a, b, c \in A$ we have

$$a \cdot b \leq c \quad \text{iff} \quad b \leq a \setminus c \quad \text{iff} \quad a \leq c / b.$$

The class of all SL-algebras is a variety and it is denoted as \mathbb{SL} . Observe that the residuation condition together with the fact that 1 is a neutral element implies that for every SL-algebra \mathbf{A} and each $a, b \in A$ we have

$$a \leq b \quad \text{iff} \quad 1 \leq a \setminus b \quad \text{iff} \quad 1 \leq b / a.$$

Given an SL-algebra $\mathbf{A} = \langle A, \wedge, \vee, \cdot, \setminus, /, 0, 1, \perp, \top \rangle$, an *A-evaluation* is a homomorphism from the algebra of formulae to \mathbf{A} such that the connectives $\wedge, \vee, \&, \rightarrow, \rightsquigarrow, \bar{0}, \bar{1}, \perp, \top$ are respectively interpreted by the functions $\wedge, \vee, \cdot, \setminus, /, 0, 1, \perp, \top$, i.e., a mapping from $Fm_{\mathcal{L}}$ to A such that $e(*) = *$ for $*$ $\in \{0, 1, \perp, \top\}$ and $e(\varphi \circ \psi) = e(\varphi) \circ' e(\psi)$, where $\circ \in \{\wedge, \vee, \&, \rightarrow, \rightsquigarrow\}$ and \circ' is the corresponding operation from $\{\wedge, \vee, \cdot, \setminus, /\}$.¹⁶ By means of this notion, we can give, more generally, the following definition for the algebraic counterpart of any logic.

Definition 7. *Let L be a logic in language \mathcal{L} which is the expansion of SL by axioms Ax and rules R . An \mathcal{L} -algebra \mathbf{A} is an L-algebra if*

- its reduct $\mathbf{A}_{\text{SL}} = \langle A, \wedge, \vee, \cdot, \setminus, /, 0, 1, \perp, \top \rangle$ is an SL-algebra,
- for every $\varphi \in Ax$ and every \mathbf{A} -evaluation e , $e(\varphi) \geq 1$,
- for every $\langle \Gamma, \varphi \rangle \in R$ and every \mathbf{A} -evaluation e , if $e(\psi) \geq 1$ for every $\psi \in \Gamma$, then $e(\varphi) \geq 1$.

\mathbf{A} is a linearly ordered (or L-chain) if its lattice order is total. The class of all (linearly ordered) L-algebras is denoted by \mathbb{L} (or \mathbb{L}_{lin} respectively).

Table 5 shows what equations have to be added to SL-algebras, to obtain, for arbitrary $S \subseteq \{a_1, a_2, e, c, i, o\}$, the class of SL_S -algebras.

The following completeness theorem follows from more general results (see Section 2.3 where we show more on the connection between logics and algebras) but can also be directly proved by means of the usual Lindenbaum–Tarski process. It shows how L-algebras really give an algebraic semantics for SL and its expansions.

Theorem 8. *Let L be a logic. Then for every set of formulae Γ and every formula φ the following are equivalent:*

1. $\Gamma \vdash_L \varphi$,
2. for every $\mathbf{A} \in \mathbb{L}$ and every \mathbf{A} -evaluation e , if $e(\psi) \geq 1$ for every $\psi \in \Gamma$, then $e(\varphi) \geq 1$.

¹⁶Here we opted for a rather nonstandard (in the context of algebraic logic) notational distinction between logical connectives and algebraic operations. The reason is that, in this case, the notational traditions on both sides, algebraic and logical, are so strong that any unification would not be advisable.

a ₁	$x \cdot (y \cdot z) \leq (x \cdot y) \cdot z$
a ₂	$(x \cdot y) \cdot z \leq x \cdot (y \cdot z)$
e	$x \cdot y = y \cdot x$
c	$x \leq x \cdot x$
i	$x \leq 1$
o	$0 \leq x$

Table 5: Equations defining important classes of SL-algebras.

2.2 Almost (MP)-based logics and deduction theorems

In the introduction we have formulated the usual deduction theorems for core and Δ -core fuzzy logics (Theorem 3). In this section we show how this can be generalized to all logics in the present framework (expansions of SL) provided that the additional rules they satisfy are of a suitable form. Technically, this corresponds to the notion of almost (MP)-based logic that, as shown in [19, 15], essentially allows to repeat Hájek’s original proof of deduction theorem now in this wide context. To this end, we introduce a few more syntactical notions. Let \star be a new propositional variable not occurring in Var , which acts as placeholder for a special kind of substitutions. The notions of formula and substitution are augmented by the prefix \star - whenever they are construed over the set of variables $Var \cup \{\star\}$ and are left as they are if construed in the original set of variables Var . If φ and δ are \star -formulae, by $\delta(\varphi)$ we denote the formula obtained from δ when one replaces the occurrences of \star by φ ; note that if φ is a formula, then so is $\delta(\varphi)$ (i.e., \star does not occur in $\delta(\varphi)$).

Definition 9. *Given a set of \star -formulae Γ , we define the sets Γ^* and $\Pi(\Gamma)$ of \star -formulae:*

- Γ^* is the smallest set containing \star and $\delta(\gamma) \in \Gamma^*$ for each $\delta \in \Gamma$ and each $\gamma \in \Gamma^*$.
- $\Pi(\Gamma)$ is the smallest set of \star -formulae containing $\Gamma \cup \{\bar{1}\}$ and closed under $\&$.

We are now ready to give the formal definition of almost (MP)-based logic.

Definition 10. *Let bDT be a set of \star -formulae closed under all \star -substitutions σ such that $\sigma(\star) = \star$. A logic L is almost (MP)-based w.r.t. the set of basic deduction terms bDT if:*

- L has a presentation where the only deduction rules are modus ponens and those of the form $\langle \varphi, \gamma(\varphi) \rangle$ for $\gamma \in \text{bDT}$, and
- for each $\beta \in \text{bDT}$ and each formulae φ, ψ , there exist $\beta_1, \beta_2 \in \text{bDT}^*$ such that:¹⁷

$$\vdash_L \beta_1(\varphi \rightarrow \psi) \rightarrow (\beta_2(\varphi) \rightarrow \beta(\psi)).$$

L is called (MP)-based if it admits the empty set as a set of basic deduction terms.

SL can be shown to be indeed an almost (MP)-based logic. For this, of course, one needs to endow it with a convenient alternative presentation. Consider the axiomatic system from Table 6 and let us introduce a convenient notation for the terms appearing on the right-hand side of the rules (α) , (α') , (β) , and (β') . Given arbitrary formulae δ, ε , we define the following \star -formulae:

$$\begin{array}{ll} \alpha_{\delta, \varepsilon} = \delta \& \varepsilon \rightarrow \delta \& (\varepsilon \& \star) & \beta_{\delta, \varepsilon} = \delta \rightarrow (\varepsilon \rightarrow (\varepsilon \& \delta) \& \star) \\ \alpha'_{\delta, \varepsilon} = \delta \& \varepsilon \rightarrow (\delta \& \star) \& \varepsilon & \beta'_{\delta, \varepsilon} = \delta \rightarrow (\varepsilon \rightsquigarrow (\delta \& \varepsilon) \& \star) \end{array}$$

¹⁷We deviate slightly from the original definition from [19], where β_1, β_2 were required to be in bDT, and follow that from [15] which has some technical advantages.

(Adj _{&}) $\varphi \rightarrow (\psi \rightarrow \psi \& \varphi)$	(Bot) $\perp \rightarrow \varphi$
(Adj _{&\rightsquigarrow}) $\varphi \rightarrow (\psi \rightsquigarrow \varphi \& \psi)$	(Push) $\varphi \rightarrow (\bar{1} \rightarrow \varphi)$
(Res') $\psi \& (\varphi \& (\varphi \rightarrow (\psi \rightarrow \chi))) \rightarrow \chi$	(Pop) $(\bar{1} \rightarrow \varphi) \rightarrow \varphi$
(Res' _{\rightsquigarrow}) $(\varphi \& (\varphi \rightarrow (\psi \rightsquigarrow \chi))) \& \psi \rightarrow \chi$	(&\wedge) $(\varphi \wedge \bar{1}) \& (\psi \wedge \bar{1}) \rightarrow \varphi \wedge \psi$
(T') $(\varphi \rightarrow (\varphi \& (\varphi \rightarrow \psi))) \& (\psi \rightarrow \chi) \rightarrow (\varphi \rightarrow \chi)$	
(T' _{\rightsquigarrow}) $(\varphi \rightsquigarrow ((\varphi \rightsquigarrow \psi) \& \varphi) \& (\psi \rightarrow \chi)) \rightarrow (\varphi \rightsquigarrow \chi)$	
(\wedge1) $\varphi \wedge \psi \rightarrow \varphi$	(\vee1) $\varphi \rightarrow \varphi \vee \psi$
(\wedge2) $\varphi \wedge \psi \rightarrow \psi$	(\vee2) $\psi \rightarrow \varphi \vee \psi$
(\wedge3) $(\chi \rightarrow \varphi) \wedge (\chi \rightarrow \psi) \rightarrow (\chi \rightarrow \varphi \wedge \psi)$	(\vee3) $(\varphi \rightarrow \chi) \wedge (\psi \rightarrow \chi) \rightarrow (\varphi \vee \psi \rightarrow \chi)$
(MP) $\varphi, \varphi \rightarrow \psi \vdash \psi$	(Adj _u) $\varphi \vdash \varphi \wedge \bar{1}$
(\alpha) $\varphi \vdash \delta \& \varepsilon \rightarrow \delta \& (\varepsilon \& \varphi)$	(\beta) $\varphi \vdash \delta \rightarrow (\varepsilon \rightarrow (\varepsilon \& \delta) \& \varphi)$
(\alpha') $\varphi \vdash \delta \& \varepsilon \rightarrow (\delta \& \varphi) \& \varepsilon$	(\beta') $\varphi \vdash \delta \rightarrow (\varepsilon \rightsquigarrow (\delta \& \varepsilon) \& \varphi)$

Table 6: New axiomatic system for SL.

Logic L	bDT _L
SL	$\{\alpha_{\delta,\varepsilon}, \alpha'_{\delta,\varepsilon}, \beta_{\delta,\varepsilon}, \beta'_{\delta,\varepsilon}, \star \wedge \bar{1} \mid \delta, \varepsilon \text{ formulae}\}$
SL _w	$\{\alpha_{\delta,\varepsilon}, \alpha'_{\delta,\varepsilon}, \beta_{\delta,\varepsilon}, \beta'_{\delta,\varepsilon} \mid \delta, \varepsilon \text{ formulae}\}$
SL _e	$\{\alpha_{\delta,\varepsilon}, \beta_{\delta,\varepsilon}, \star \wedge \bar{1} \mid \delta, \varepsilon \text{ formulae}\}$
SL _{ew}	$\{\alpha_{\delta,\varepsilon}, \beta_{\delta,\varepsilon} \mid \delta, \varepsilon \text{ formulae}\}$
SL _a	$\{\lambda_{\varepsilon}, \rho_{\varepsilon}, \star \wedge \bar{1} \mid \varepsilon \text{ a formula}\}$
SL _{aw}	$\{\lambda_{\varepsilon}, \rho_{\varepsilon} \mid \varepsilon \text{ a formula}\}$
SL _{ae}	$\{\star \wedge \bar{1}\}$
SL _{aew}	$\{\star\}$

Table 7: bDTs of prominent substructural logics.

Note that the terms in the second line generalize the well-known notions of left and right conjugates used in associative logics:¹⁸

$$\lambda_{\varepsilon} = \varepsilon \rightarrow \star \& \varepsilon \qquad \rho_{\varepsilon} = \varepsilon \rightsquigarrow \varepsilon \& \star$$

In [15] it is proved that the axiomatic system from Table 6 is indeed a presentation of SL, therefore we can obtain the following result for SL and some of its notable axiomatic extension (it also shows how the sets of basic deduction terms, and so posteriorly the axioms systems, of these extensions can be simplified).

Theorem 11 ([15, Section 3.1]). *Let $S \subseteq \{a, e, w\}$. Then any axiomatic extension of the logic SL_S is almost (MP)-based with respect to the corresponding set of basic deduction terms listed in Table 7.*

Theorem 12 (Local deduction theorem [15, Corollary 3.12]). *Let L be an almost (MP)-based logic with a set of basic deduction terms bDT. Then for each set $\Gamma \cup \{\varphi, \psi\}$ of formulae the following*

¹⁸It is usual in the literature on algebraic study of substructural logics to find these terms defined in a slightly more complicated way: $\lambda_{\varepsilon} = (\varepsilon \rightarrow \star \& \varepsilon) \wedge \bar{1}$ and $\rho_{\varepsilon} = (\varepsilon \rightsquigarrow \varepsilon \& \star) \wedge \bar{1}$, although in the usual Hilbert-style axiomatizations of Full Lambek logic the simplified terms without $\wedge \bar{1}$ are used for the *product normality* rules. The reason for this more complicated form is to give algebraic terms which simultaneously cope with product normality rules and adjunction, whereas our formalism allows for a clearer distinction of their respective rôles.

holds:

$$\Gamma, \varphi \vdash_L \psi \quad \text{iff} \quad \Gamma \vdash_L \gamma(\varphi) \rightarrow \psi \text{ for some } \gamma \in \Pi(\text{bDT}^*).$$

Therefore, we obtain a (parameterized or non-parameterized, depending on the presence of variables other than \star in the set bDT) local deduction theorem for SL and its axiomatic extensions (sometimes with a simplified set bDT ; see Table 7).

2.3 Consequences of algebraization

Given a logic L in a language \mathcal{L} and an \mathcal{L} -algebra \mathbf{A} , a set $F \subseteq A$ is an L -filter if for every set of formulae Γ and every formula φ such that $\Gamma \vdash_L \varphi$ and every \mathbf{A} -evaluation e it holds: if $e[\Gamma] \subseteq F$, then $e(\varphi) \in F$. By $\mathcal{F}i_L(\mathbf{A})$ we denote the set of all L -filters over \mathbf{A} . Since $\mathcal{F}i_L(\mathbf{A})$ is a closure system (it clearly contains A and is closed under arbitrary intersections), one can define a notion of generated filter. Given $X \subseteq A$, the L -filter generated by X , denoted as $\text{Fi}_L^{\mathbf{A}}(X)$ is the least L -filter containing X (we omit the indexes when clear from the context). With this terminology one can also prove a semantical (or transferred) version of (parameterized) local deduction theorem; Theorem 12 is the particular case in which \mathbf{A} is the algebra of formulae (observe that in this case $\varphi \in \text{Fi}(\Gamma)$ iff $\Gamma \vdash_L \varphi$). First we introduce two technical notions:

Definition 13. *Given a set of \star -formulae Γ , an SL -algebra \mathbf{A} , and a set $X \subseteq A$, we define*

- $\Gamma^{\mathbf{A}}$ as the set of unary polynomials built using terms from Γ with coefficients from A and variable \star , i.e., $\{\delta(\star, a_1, \dots, a_n) \mid \delta(\star, p_1, \dots, p_n) \in \Gamma \text{ and } a_1, \dots, a_n \in A\}$.
- $\Gamma^{\mathbf{A}}(X)$ as the set $\{\delta^{\mathbf{A}}(x) \mid \delta(\star) \in \Gamma^{\mathbf{A}} \text{ and } x \in X\}$.

Theorem 14 ([15, Theorem 3.11]). *Let L be an almost (MP)-based logic in a language \mathcal{L} with a set of basic deduction terms bDT . Let \mathbf{A} be an \mathcal{L} -algebra and $X \cup \{x\} \subseteq A$. Then*

$$y \in \text{Fi}_L^{\mathbf{A}}(X, x) \quad \text{iff} \quad \gamma^{\mathbf{A}}(x) \setminus y \in \text{Fi}_L^{\mathbf{A}}(X) \text{ for some } \gamma \in (\Pi(\text{bDT}^*))^{\mathbf{A}}.$$

On the other hand, Theorem 14 can be used to obtain a general form of the usual algebraic description of the filter generated by a set.

Corollary 15 ([15, Corollary 3.13]). *Let L be an almost (MP)-based logic with a set of basic deduction terms bDT . Let \mathbf{A} be an L -algebra and $X \subseteq A$. Then*

$$\text{Fi}_L^{\mathbf{A}}(X) = \{a \in A \mid a \geq x \text{ for some } x \in (\Pi(\text{bDT}^*))^{\mathbf{A}}(X)\}.$$

The algebraic completeness result we have seen above (Theorem 8) can be strengthened obtaining that SL is actually an algebraizable logic in the sense of [4] and \mathbb{SL} is its equivalent algebraic semantics with translations $\rho(p \approx q) = p \leftrightarrow q$ and $\tau(p) = p \wedge \bar{1} \approx \bar{1}$. Indeed, if we consider formal equations in the language \mathcal{L}_{SL} as expressions of the form $\varphi \approx \psi$ where $\varphi, \psi \in \text{Fm}_{\mathcal{L}_{\text{SL}}}$ and if \models_{SL} denotes the equational consequence with respect to the class \mathbb{SL} , it is easy to prove that:

1. $\Pi \models_{\text{SL}} \varphi \approx \psi$ iff $\rho[\Pi] \vdash_{\text{SL}} \rho(\varphi \approx \psi)$
2. $p \vdash_{\text{SL}} \rho[\tau(p)]$ and $\rho[\tau(p)] \vdash_{\text{SL}} p$

Actually, this result can be extended to every logic L and its corresponding class of algebras \mathbb{L} . If L is a logic in a language \mathcal{L} which is the expansion of SL by axioms Ax and rules R , then L -algebras can also be described as the expansions of SL -algebras satisfying:

- the equation $\tau(\varphi)$ for each $\varphi \in Ax$
- the quasiequation $\tau(\varphi_1)$ and \dots and $\tau(\varphi_n) \Rightarrow \tau(\varphi)$ for each $\langle \{\varphi_1, \dots, \varphi_n\}, \varphi \rangle \in R$.

Therefore, the class \mathbb{L} is always a quasivariety and it is a variety if $R = \emptyset$, i.e. if \mathbb{L} is an axiomatic expansion of SL (note that this condition is not necessary as demonstrated e.g. by the logic MTL_Δ). Conversely, given a quasivariety \mathbb{L} of \mathcal{L} -algebras, one can always find a quasiequational base obtained by adding a set of equations E and a set of quasiequations Q to an equational base of \mathbb{SL} . Then \mathbb{L} is the equivalent algebraic semantics of the logic obtained as the expansion of SL by

- the axiom $\rho(\varphi, \psi)$ for each $\varphi \approx \psi \in E$
- the rule $\langle \{\rho(\varphi_1, \psi_1), \dots, \rho(\varphi_n, \psi_n)\}, \rho(\varphi, \psi) \rangle$ for each $(\varphi_1 \approx \psi_1)$ and \dots and $(\varphi_n \approx \psi_n) \Rightarrow \varphi \approx \psi \in Q$.

Moreover, if we fix a language $\mathcal{L} \supseteq \mathcal{L}_{\text{SL}}$ and a logic \mathbb{L} in \mathcal{L} , the translations τ and ρ between formulae and equations give a bijective correspondence between extensions of \mathbb{L} and quasivarieties of \mathbb{L} -algebras, and a bijective correspondence (its restriction) between axiomatic extensions of \mathbb{L} and varieties of \mathbb{L} -algebras. These bijections are, actually, dual lattice isomorphisms.

A logic is called *strongly algebraizable* if its corresponding quasivariety is actually a variety. Obviously, strongly algebraizable logics in \mathcal{L}_{SL} coincide with axiomatic extensions of SL .

Algebraizability also gives a strong correspondence between filters and (relative) congruences in \mathbb{L} -algebras, which can be made explicit using the particular forms of the translations. Let $\mathbf{Con}_{\mathbb{L}}(\mathbf{A})$ denote the lattice of congruences of \mathbf{A} relative to \mathbb{L} , i.e. those giving a quotient in \mathbb{L} . If \mathbb{L} is a variety, then $\mathbf{Con}_{\mathbb{L}}(\mathbf{A})$ is precisely the lattice of all congruences of \mathbf{A} . The *Leibniz operator* $\Omega_{\mathbf{A}}$ is defined, for any $F \in \mathcal{F}_{i_{\mathbb{L}}}(\mathbf{A})$, as $\Omega_{\mathbf{A}}(F) = \{ \langle a, b \rangle \in A^2 \mid a \setminus b \in F \text{ and } b \setminus a \in F \}$. Now we can state a specific variant of a well-known theorem of abstract algebraic logic (see e.g. [20]), narrowed down to our setting.

Proposition 16. *Let \mathbb{L} be a logic and \mathbf{A} an \mathbb{L} -algebra. The Leibniz operator $\Omega_{\mathbf{A}}$ is a lattice isomorphism from $\mathcal{F}_{i_{\mathbb{L}}}(\mathbf{A})$ to $\mathbf{Con}_{\mathbb{L}}(\mathbf{A})$. Its inverse is the function that maps any $\theta \in \mathbf{Con}_{\mathbb{L}}(\mathbf{A})$ to the filter $\{a \in A \mid \langle a \wedge 1, 1 \rangle \in \theta\}$.*

Observe that the minimum filter is the one generated by the emptyset, $\text{Fi}(\emptyset)$, and it must correspond to the identity congruence $\text{Id}_{\mathbf{A}}$. Therefore, using the previous proposition, we obtain that, on any \mathbb{L} -algebra \mathbf{A} , $\text{Fi}(\emptyset) = \{a \in A \mid a \geq 1\}$. This set is, of course, contained in any other filter. It is also worth noting that Proposition 16 and Corollary 15 give a description of the relative principal congruence generated by a pair of elements of a given algebra of an almost (MP)-based logic.

Finally, we focus on a restriction of the completeness theorem (Theorem 8) to a couple of subclasses of algebraic models that will play an important rôle when characterizing semilinearity in the next section: relatively (finitely) subdirectly irreducible algebras. Given a class of algebras \mathbb{K} a algebra \mathbf{A} is (*finitely*) *subdirectly irreducible relative to* \mathbb{K} if for every (finite non-empty) subdirect representation α of \mathbf{A} with a family $\{\mathbf{A}_i \mid i \in I\} \subseteq \mathbb{K}$ there is $i \in I$ such that $\pi_i \circ \alpha$ is an isomorphism. The class of all (finitely) subdirectly irreducible algebras relative to \mathbb{K} is denoted as $\mathbb{K}_{\text{R(F)SI}}$. Of course $\mathbb{K}_{\text{RSI}} \subseteq \mathbb{K}_{\text{RFSI}}$. Observe that the trivial algebra is by definition in \mathbb{K}_{RFSI} but not in \mathbb{K}_{RSI} . Again, the next theorem is a specific variant of a well-known fact of abstract algebraic logic.

Theorem 17. *Let \mathbb{L} be a logic. Then for every set of formulae Γ and every formula φ the following are equivalent:*

1. $\Gamma \vdash_{\mathbb{L}} \varphi$,
2. for every countable $\mathbf{A} \in \mathbb{L}_{\text{RSI}}$ and every \mathbf{A} -evaluation e , if $e(\psi) \geq 1$ for every $\psi \in \Gamma$, then $e(\varphi) \geq 1$.

3 Core semilinear logics

Let us start by recalling two notions mentioned in the introduction: first we give a formal semantical definition of the logic SL^ℓ (later in Theorem 29 we present some of its natural axiomatizations).

Definition 18. *The logic SL^ℓ is defined as follows for every set Γ of formulae and every formula φ :*

1. $\Gamma \vdash_{\text{SL}^\ell} \varphi$ if and only if
2. $e(\varphi) \geq 1$ for each SL -chain \mathbf{A} and each \mathbf{A} -evaluation e such that $e(\psi) \geq 1$ for all $\psi \in \Gamma$.

Remark 19. *Clearly SL^ℓ extends SL and from [19, Propositions 3.1.15. and 3.1.16.] follows that SL^ℓ is a logic in the sense of Convention 4 and that the classes of SL^ℓ -chains and SL -chains coincide.*

The second notion is that of core fuzzy logics formally defined in Definition 1. Let us reformulate this definition using the terminology introduced in the previous section (especially Convention 4 which stipulates that all the logics considered in this paper satisfy the condition (Cong)):

Definition 20. *A logic L is a core fuzzy logic if it expands MTL by some set of axioms Ax .*

Let us now generalize this class in two aspects: first, we replace MTL by the (much) weaker logic SL^ℓ and, second, we include logics axiomatized by using extra rules provided that they satisfy a certain stability condition involving disjunction. As we shall soon see (in Theorem 22), these conditions are sufficient and necessary for an expansion of SL^ℓ to remain complete w.r.t. chains.

Definition 21. *A logic L is a core semilinear logic if it expands SL^ℓ by some sets of axioms Ax and rules R such that for each $\langle \Gamma, \varphi \rangle \in R$ and every formula ψ we have:*

$$\Gamma \vee \psi \vdash_L \varphi \vee \psi,$$

where by $\Gamma \vee \psi$ we denote the set $\{\chi \vee \psi \mid \chi \in \Gamma\}$.

Observe that if L is an expansion of a core semilinear logic by axioms Ax and rules R , then L is itself a core semilinear logic iff for each $\langle \Gamma, \varphi \rangle \in R$ we have $\Gamma \vee \psi \vdash_L \varphi \vee \psi$. Thus in particular:

- Any *axiomatic* expansion of a core semilinear logic is a core semilinear logic.
- Any axiomatic expansion of SL is a core semilinear logic iff it expands SL^ℓ .

The first item justifies why Hájek considered all axiomatic extensions (*schematic extensions*) of HL in his framework for fuzzy logics, since they were all complete with respect to chains. Moreover, one can check that MTL is an extension of SL^ℓ ; therefore MTL and all core fuzzy logics are core semilinear logics. Similarly, it is easy to show that Δ -core fuzzy logics are core semilinear (note that we are adding only one rule $\langle \varphi, \Delta\varphi \rangle$ and we can easily prove that $\varphi \vee \psi \vdash_L \Delta\varphi \vee \psi$ using axioms of MTL_Δ).

By restricting and re-elaborating results from the general theory presented in [19] (and by using some new results from [15, 17]), in this section we present several characterizations of core semilinear logics, some general methods to obtain their Hilbert-style axiomatizations, and a survey of their completeness results.

3.1 Characterizations and properties of core semilinear logics

The first characterization justifies the usage of the adjective ‘semilinear’. This terminology comes from the theory of residuated lattices [74] where it denotes classes of algebras such that in all (relatively) subdirectly irreducible members the lattice order is linear.¹⁹ Such property characterizes core semilinear logics as shown by conditions 3 and 4 of the following theorem. Moreover, as stated in condition 2, this is also equivalent with what we consider the main property of our logics: completeness with respect to the semantics given by chains.

¹⁹This follows the tradition of Universal Algebra of calling a class of algebras ‘semiX’ whenever its subdirectly irreducible members have the property X ; e.g. as in ‘semisimple’.

Theorem 22 (Semilinearity). *Let L be a logic. Then the following are equivalent:*

1. L is a core semilinear logic.
2. L is complete w.r.t. L -chains, i.e. the following are equivalent for any set of formulae $\Gamma \cup \{\varphi\}$:
 - (a) $\Gamma \vdash_L \varphi$
 - (b) $e(\varphi) \geq 1$ for each L -chain \mathbf{A} and each \mathbf{A} -evaluation e such that $e(\psi) \geq 1$ for all $\psi \in \Gamma$.
3. $\mathbb{L}_{\text{RFSI}} = \mathbb{L}_{\text{lin}}$.
4. $\mathbb{L}_{\text{RSI}} \subseteq \mathbb{L}_{\text{lin}}$.

Proof. Logics satisfying condition 2 are, in particular, *weakly implicative semilinear logics* in the sense of [19]; thus we can use [19, Corollary 3.2.14.] to prove the equivalence of the first two properties (for L_1 being SL^ℓ and L_2 being L ; we need to check the validity of three premises of that corollary: (a) SL^ℓ is a weakly implicative semilinear logic: directly from Definition 18 and its following remark, (b) \vee is a protodisjunction: trivially satisfied, and (c) L proves (MP_\vee) : established in [19, Proposition 3.2.2.]).

The equivalence of the latter three claim follows from [19, Theorem 3.1.8]. \square

Thus, as established in the proof of the theorem above, core semilinear logic are weakly implicative semilinear logics in the sense of [18, 19]. In fact, in the terminology of those papers, they are exactly algebraically implicative semilinear finitary expansions of SL^ℓ .

In order to formulate the syntactic characterization theorem for core semilinear logics (in terms of syntactic properties) we need to make use of special kinds of theories. Recall that a theory is a deductively closed set of formulae, i.e., $T \vdash \varphi$ implies that $\varphi \in T$. We say that a theory T is

- *maximally consistent w.r.t. a formula φ* if $\varphi \notin T$ and for every $\psi \notin T$ we have $T, \psi \vdash \varphi$
- *saturated* if it is maximally consistent w.r.t. some formula φ
- *linear*²⁰ if for each formulae φ and ψ we have $\varphi \rightarrow \psi \in T$ or $\psi \rightarrow \varphi \in T$
- *prime* if for each formulae φ and ψ we have $\varphi \in T$ or $\psi \in T$ whenever $\varphi \vee \psi \in T$.

We also need a special formula $(\varphi \rightarrow \psi) \vee (\psi \rightarrow \varphi)$, called *prelinearity* and usually denoted by (P_\vee) , which could be equivalently replaced in the formulation of the syntactic characterization theorem by any of the following two theorems of SL^ℓ (as shown in [19, Lemma 3.2.8]):

$$\begin{aligned} (\text{lin}_\wedge) \quad & (\varphi \wedge \psi \rightarrow \chi) \rightarrow (\varphi \rightarrow \chi) \vee (\psi \rightarrow \chi) \\ (\text{lin}_\vee) \quad & (\chi \rightarrow \varphi \vee \psi) \rightarrow (\chi \rightarrow \varphi) \vee (\chi \rightarrow \psi). \end{aligned}$$

Theorem 23 (Syntactic characterization theorem). *Let L be a logic. Then the following are equivalent:*

1. L is a core semilinear logic.
2. L has the Semilinearity Property, SLP, i.e. for every set of formulae $\Gamma \cup \{\varphi, \psi, \chi\}$ the following rule holds

$$\frac{\Gamma, \varphi \rightarrow \psi \vdash_L \chi \quad \Gamma, \psi \rightarrow \varphi \vdash_L \chi}{\Gamma \vdash_L \chi}.$$

3. L has the Linear Extension Property, LEP, i.e. for every theory T and a formula φ such that $\varphi \notin T$, there is a linear theory $T' \supseteq T$ such that $\varphi \notin T'$.
4. Saturated theories are linear.

²⁰Petr Hájek in [38] called this kind of theories ‘complete’. However, after recent developments (see e.g. [19]) we prefer the more descriptive terminology used here.

5. L proves (P_{\vee}) and has the Proof by Cases Property, PCP, i.e. for every set of formulae $\Gamma \cup \{\varphi, \psi, \chi\}$ holds

$$\frac{\Gamma, \varphi \vdash_L \chi \quad \Gamma, \psi \vdash_L \chi}{\Gamma, \varphi \vee \psi \vdash_L \chi}.$$

6. L proves (P_{\vee}) and has an axiomatic system $\langle Ax, R \rangle$ such that for each $\langle \Gamma, \varphi \rangle \in R$ we have:

$$\Gamma \vee \psi \vdash_L \varphi \vee \psi.$$

7. L proves (P_{\vee}) and has the Prime Extension Property, PEP, i.e. for every theory T and a formula φ such that $\varphi \notin T$, there is a prime theory $T' \supseteq T$ such that $\varphi \notin T'$.

8. L proves (P_{\vee}) and its saturated theories are prime.

Proof. The equivalence of the first three claims follows from [19, Theorem 3.1.8.]. To prove 1 implies 4 observe that saturated theories are finitely \cap -irreducible (by [19, Proposition 2.3.7.]) and so by [19, Theorem 3.1.8.] such theories are linear. Conversely, if saturated theories are linear, then the Abstract Lindenbaum Lemma ([19, Lemma 2.3.8.]) clearly implies LEP (i.e. claim 3).

The equivalence of 1 and 5 is established using [19, Theorem 3.2.4.] (after observing that any logic L proves (MP_{\vee}) as established in [19, Proposition 3.2.2.]); the equivalence of 5 and 6 follows from [19, Theorem 2.7.15.]. We use [19, Theorem 2.7.23.] to directly prove that 5 is equivalent with 7 and 7 implies 8. Finally, by using a similar reasoning as in the proof of 4 implies 3, we complete the whole proof by showing that 8 implies 7. \square

Remark 24. *Most of these characterizations are inspired by the original ideas behind Hájek's proof of completeness of HL and its schematic extensions in [38]: actually in Lemma 2.3.15. he gives a direct proof of transferred PEP (the third line of the following theorem) and in Lemma 2.4.2 he proves LEP by proving SLP first (without giving names to any of these properties).*

Observe that while claim 6 is a just minor reformulation of Definition 21 of core semilinear logics, it provides an easy way to check whether a logic is core semilinear without having to prove that it extends SL^{ℓ} .

Note that theories are exactly the filters on the term algebra $\mathbf{Fm}_{\mathcal{L}}$. Thus it makes sense to generalize the classes of theories we introduced above to filters with ' $\Gamma \vdash \varphi$ ' replaced by ' $x \in \text{Fi}(X)$ ', e.g. a filter F in an L -algebra \mathbf{A} is maximally consistent (algebraist would say 'maximal non-trivial') w.r.t. an element $a \in A$ if $a \notin F$ and for every $b \notin F$ we have $a \in \text{Fi}(F \cup \{b\})$. This allows us not only to see the conditions appearing in the syntactic characterization theorem as claims about filters on the term algebra $\mathbf{Fm}_{\mathcal{L}}$, but mainly to formulate their the so-called *transferred* variants which speak about all L -algebras. We collect these results in the next theorem together with some other useful algebraic properties L -algebras.

Theorem 25. *Let L be a core semilinear logic and \mathbf{A} an L -algebra. Then:*

1. *For each set $X \cup \{a, b\} \subseteq A$ the following holds:*

$$\text{Fi}(X, a) \cap \text{Fi}(X, b) = \text{Fi}(X, a \vee b) \quad \text{Fi}(X, a \rightarrow b) \cap \text{Fi}(X, b \rightarrow a) = \text{Fi}(X).$$

2. *Linear and prime filters coincide and contain the set of saturated filters.*
3. *For each filter $F \in \mathcal{F}i_L(\mathbf{A})$ and each $a \in A$ such that $a \notin F$, there is a linear/prime filter $F' \supseteq F$ such that $a \notin F'$.*
4. *The lattice of L -filters is distributive.*
5. *The lattice of relative L -congruences is distributive.*
6. *The $\{\vee, \wedge\}$ -reduct of \mathbf{A} is a distributive lattice.*

Proof. We will freely use all equivalent characterizations of core semilinear logics established before.

1. [19, Theorems 2.7.18. and 3.1.8.].
2. [19, Theorems 2.7.23. and 3.1.8.] and [19, Proposition 2.3.7.].
3. [19, Theorem 2.7.23.] and claim 2.
4. [19, Theorem 2.7.20.].
5. Claim 4 and Proposition 16.
6. [19, Theorem 3.2.12.]. □

The following proposition is, among others, important to establish the soundness of the upcoming crucial definition of L^ℓ .

Proposition 26. *The intersection of a family of core semilinear logics in the same language is a core semilinear logic.*

Proof. First we need to observe that the intersection is a logic in the sense of Convention 4. This is established by [19, Proposition 3.1.16.]. Then, the fact that it is core semilinear is a simple corollary of the syntactic characterization theorem (e.g. of the Semilinearity Property). □

Definition 27. *For a logic L we define the logic L^ℓ as the least core semilinear logic extending L .*

The following two theorems give useful, semantical and syntactical, descriptions of L^ℓ . The first one is very general and, besides providing a semantical characterization of L^ℓ as the logic of L -chains, it shows how to extend any axiomatization of L into an axiomatization of L^ℓ . Roughly speaking, it adds prelinearity and the \vee -form of all rules (cf. the syntactic characterization theorem 23). Note that Petr Hájek also obtained some logics in these ways: e.g. he showed that G was in fact the logic of linearly ordered Heyting algebras or defined psMTL^r in [43] as the logic psMTL -chains.

Theorem 28. *Let L be a logic. Then:*

- L^ℓ -chains coincide with L -chains and the class \mathbb{L}^ℓ of L^ℓ -algebras is exactly the quasivariety generated by \mathbb{L}_{lin} .
- If L is axiomatized by axioms Ax and rules R , then L^ℓ is the extension of L by the axiom (P_\vee) and the set of rules $\{\langle \Gamma \vee \psi, \varphi \vee \psi \rangle \mid \langle \Gamma, \varphi \rangle \in R\}$.
- If L is obtained as the expansion of some core semilinear logic by axioms Ax and rules R , then L^ℓ is the extension of L by the rules $\{\langle \Gamma \vee \psi, \varphi \vee \psi \rangle \mid \langle \Gamma, \varphi \rangle \in R\}$.

Proof. The first claim follows from [19, Proposition 3.1.15.]; the second follows from [19, Proposition 3.2.9.] and [19, Theorem 2.7.27.]. The third one is an obvious corollary of already established facts. □

The problem of the axiomatizations provided by this theorem is that they require additional new rules. We show that if L is almost (MP)-based we can do better: L^ℓ is then actually an *axiomatic* extension of L by *variations* of the prelinearity axiom. We present two variants, B and C , of this axiomatization because they generalize two different usual formulations appearing in the literature; for comparison we also add a presentation A resulting from the direct application of the previous theorem. Note that this theorem can be used to axiomatize the two logics mentioned above and studied by Petr Hájek: G and psMTL^r .

Theorem 29. *Let L be an almost (MP)-based logic with a set bDT of basic deductive terms. Then L^ℓ is axiomatized by adding to L any of the following:*

- A $(\varphi \rightarrow \psi) \vee (\psi \rightarrow \varphi)$
 $(\varphi \rightarrow \psi) \vee \chi, \varphi \vee \chi \vdash \psi \vee \chi$
 $\varphi \vee \psi \vdash \gamma(\varphi) \vee \psi$, for every $\gamma \in \text{bDT}$
- B $((\varphi \rightarrow \psi) \wedge \bar{1}) \vee \gamma((\psi \rightarrow \varphi) \wedge \bar{1})$, for every $\gamma \in \text{bDT} \cup \{\star\}$
- C $(\varphi \vee \psi \rightarrow \psi) \vee \gamma(\varphi \vee \psi \rightarrow \varphi)$, for every $\gamma \in \text{bDT} \cup \{\star \wedge \bar{1}\}$.

Proof. A weaker claim, for *extensions* of SL^ℓ , is proved in [15, Theorem 4.29]. One can easily see, by inspecting the proof, that the theorem remains valid in our framework of *expansions* of SL^ℓ . \square

Table 8 collects axiomatizations of important semilinear substructural logics obtained as axiomatization *B* from Theorem 29. We present them in the form of axiom schemata, sometimes altered a little (in an equivalent way) for simplicity or to obtain some form known from the literature (see [15] for details).

Logic L	additional axioms needed to axiomatize L^ℓ
SL	$((\varphi \rightarrow \psi) \wedge \bar{1}) \vee \gamma((\psi \rightarrow \varphi) \wedge \bar{1})$, for every $\gamma \in \{\alpha_{\delta,\varepsilon}, \alpha'_{\delta,\varepsilon}, \beta_{\delta,\varepsilon}, \beta'_{\delta,\varepsilon}\}$
SL _w	$(\varphi \rightarrow \psi) \vee \gamma(\psi \rightarrow \varphi)$, for every $\gamma \in \{\alpha_{\delta,\varepsilon}, \alpha'_{\delta,\varepsilon}, \beta_{\delta,\varepsilon}, \beta'_{\delta,\varepsilon}\}$
SL _e	$\alpha_{\delta,\varepsilon}((\varphi \rightarrow \psi) \wedge \bar{1}) \vee \beta_{\delta',\varepsilon'}((\psi \rightarrow \varphi) \wedge \bar{1})$
SL _{ew}	$\alpha_{\delta,\varepsilon}(\varphi \rightarrow \psi) \vee \beta_{\delta',\varepsilon'}(\psi \rightarrow \varphi)$
SL _a	$(\lambda_\varepsilon(\varphi \rightarrow \psi) \wedge \bar{1}) \vee (\rho_{\varepsilon'}(\psi \rightarrow \varphi) \wedge \bar{1})$
SL _{ae}	$((\varphi \rightarrow \psi) \wedge \bar{1}) \vee ((\psi \rightarrow \varphi) \wedge \bar{1})$
SL _{aew}	$(\varphi \rightarrow \psi) \vee (\psi \rightarrow \varphi)$

Table 8: Axiomatization of L^ℓ for prominent substructural logics.

As mentioned in Section 2.2, finding nice Hilbert-style presentations for meets in the lattice of extensions of a given logic (in particular, showing that the meet of axiomatic extensions is itself an axiomatic extension of the base logic) is not straightforward. The following theorem gives a presentation for meets of extensions of a given core semilinear logic by capitalizing on the fact that \vee enjoys PCP in all core semilinear logics.

Theorem 30. *Let L_1 and L_2 be semilinear extensions of a core semilinear logic L defined by the sets of axioms Ax_i and rules R_i . Then $L_1 \cap L_2$ is the extension of L obtained by adding*

- the set of axioms $\{\varphi \vee \psi \mid \varphi \in Ax_1 \text{ and } \psi \in Ax_2\}$ and
- the union of the following three sets of rules:
 - $\langle \Gamma \vee \chi, \varphi \vee \psi \vee \chi \mid \langle \Gamma, \varphi \rangle \in R_1, \psi \in Ax_2, \text{ and } \chi \text{ a formula} \rangle$
 - $\langle \Gamma \vee \chi, \varphi \vee \psi \vee \chi \mid \langle \Gamma, \varphi \rangle \in R_2, \psi \in Ax_1, \text{ and } \chi \text{ a formula} \rangle$
 - $\langle (\Gamma_1 \cup \Gamma_2) \vee \chi, \varphi_1 \vee \varphi_2 \vee \chi \mid \langle \Gamma_1, \varphi_1 \rangle \in R_1, \langle \Gamma_2, \varphi_2 \rangle \in R_2, \text{ and } \chi \text{ a formula} \rangle$

Proof. It follows from [17, Theorem 5.10.]. \square

To close the subsection we clarify the position of core semilinear (axiomatic) extensions of given logic in the lattice of all its (axiomatic) extensions.

Corollary 31. *Let L be a logic. Then the class of core semilinear extensions of L is a sublattice of the lattice of extensions of L^ℓ . Furthermore, the class of core semilinear axiomatic extensions of L is a principal filter in the lattice of axiomatic extensions of L^ℓ .*

3.2 Completeness results

We devote this subsection to completeness theorems for core semilinear logics. As discussed in the introduction, a crucial guideline for Petr Hájek and others when studying new fuzzy logics was to find logical systems complete with respect to a semantics of algebras defined on the real unit interval $[0, 1]$. This kind of completeness results have been known as *standard completeness theorems*, although this terminology is not univocally defined. Indeed, by *standard* semantics one means the semantics that, due to some design choices, is considered to be the *intended* one for the logic. In some cases it consists of all algebras defined over $[0, 1]$ (e.g. for HL, SHL, MTL, SMTL, or IMTL); in other cases it consists of algebras with a fixed interpretation using particular operations (e.g. for \mathbb{L} , \mathbb{G} or Π where one interprets $\&$ as the corresponding t-norm [38], or for logics with an additional involutive negation \sim where one interprets it as $1 - x$ [25]). In all the examples taken from (Δ -)core fuzzy logics, the standard semantics is based on left-continuous t-norms and their residua. Later on, the introduction of weaker systems brought forth an analogous relaxation for the corresponding algebraic structures on $[0, 1]$, such as residuated uninorms (for UL) or residuated non-commutative t-norms (for psMTL r). Recently, when considering a standard semantics for SL^ℓ in [15], even associativity has been dropped giving rise to residuated unital groupoids on $[0, 1]$.

Some other works have however focused on other kinds of semantics for fuzzy logics, besides the real-valued one. It is the case of rational-chain semantics, hyperreal-chain semantics or finite-chain semantics (see e.g. [13, 29, 31, 69]) where instead of $[0, 1]$ one respectively takes the rational unit interval, any hyperreal interval or any finite linearly ordered set as the domain for the intended models. A systematical study of the corresponding completeness properties is better presented in the following general formulation.

Definition 32. *Let L be a core semilinear logic and $\mathbb{K} \subseteq \mathbb{L}_{lin}$. We say that L has the Strong \mathbb{K} -Completeness, SKC for short, when the following are equivalent for every set of formulae $\Gamma \cup \{\varphi\}$:*

1. $\Gamma \vdash_L \varphi$,
2. for every $\mathbf{A} \in \mathbb{K}$ and every \mathbf{A} -evaluation e , if $e(\psi) \geq 1$ for every $\psi \in \Gamma$, then $e(\varphi) \geq 1$.

If the equivalence above holds for finite Γ (or only for $\Gamma = \emptyset$) we speak about Finite Strong \mathbb{K} -Completeness (or just \mathbb{K} -Completeness, respectively). The Finite Strong \mathbb{K} -Completeness is denoted by FSKC whereas the \mathbb{K} -Completeness is denoted by \mathbb{KC} .

It is easy to show that the failure of completeness properties is inherited by conservative expansions (recall that a logic L_2 in a language \mathcal{L}_2 is a *conservative* expansion of a logic L_1 in a language \mathcal{L}_1 if $\mathcal{L}_1 \subseteq \mathcal{L}_2$ and for each set of \mathcal{L}_1 -formulae $\Gamma \cup \{\varphi\}$ we have that $\Gamma \vdash_{L_2} \varphi$ iff $\Gamma \vdash_{L_1} \varphi$).

Proposition 33 ([19, Proposition 3.4.14.]). *Let L' be a conservative expansion of L , \mathbb{K}' a class of L' -chains and \mathbb{K} the class of their L -reducts. If L' enjoys the $\mathbb{K}'C$, then L enjoys the $\mathbb{K}C$. The analogous claim holds for $\text{FSK}'C$ and $\text{SK}'C$.*

We recall now several algebraic characterizations of completeness properties from [13, 19]. In what follows we will use the following operators on classes of algebras of the same type:

- $\mathbf{S}(\mathbb{K})$ is the class of subalgebras of members in \mathbb{K} ,
- $\mathbf{I}(\mathbb{K})$ is the class of algebras isomorphic to a member in \mathbb{K} ,
- $\mathbf{H}(\mathbb{K})$ is the class of homomorphic images of members in \mathbb{K} ,
- $\mathbf{P}(\mathbb{K})$ is the class of direct products of members in \mathbb{K} ,
- $\mathbf{P}_{fin}(\mathbb{K})$ is the class of finite direct products of members in \mathbb{K} ,
- $\mathbf{P}_U(\mathbb{K})$ is the class of ultraproducts of members in \mathbb{K} ,
- $\mathbf{P}_{\sigma-f}(\mathbb{K})$ is the class of reduced products of members in \mathbb{K} over countably complete filters (i.e. filters closed under countable intersections),

- $\mathbf{V}(\mathbb{K})$ is the variety generated by \mathbb{K} , i.e., $\mathbf{V}(\mathbb{K}) = \mathbf{HSP}(\mathbb{K})$,
- $\mathbf{Q}(\mathbb{K})$ is the quasivariety generated by \mathbb{K} , i.e., $\mathbf{Q}(\mathbb{K}) = \mathbf{ISPP}_U(\mathbb{K})$.

Let us fix a core semilinear logic L and a class of L -chains \mathbb{K} . We present several characterizations of the general completeness properties. The first one relates them respectively with generation of the class of algebras as a variety, a quasivariety and a generalized quasivariety, respectively.

Theorem 34 ([19, Theorem 3.4.3.]).

1. L has the $\mathbb{K}C$ if, and only if, $\mathbf{H}(L) = \mathbf{V}(\mathbb{K})$.
2. L has the \mathbf{FSKC} if, and only if, $L = \mathbf{Q}(\mathbb{K})$.
3. L has the \mathbf{SKC} if, and only if, $L = \mathbf{ISP}_{\sigma-f}(\mathbb{K})$.

The completeness properties of L can be also characterized in terms of (finitely) subdirectly irreducible algebras relative to L . Recall that, by Theorem 22, finitely subdirectly irreducible L -algebras relative to L coincide with the class of L -chains, i.e., we have $L_{\text{RSI}} \subseteq L_{\text{RFSI}} = L_{\text{lin}}$. Given a class of algebras \mathbb{M} , the class of its nontrivial members is denoted \mathbb{M}^+ . Similarly, \mathbb{M}^σ stands for countable members of \mathbb{M} .

Theorem 35. *We have the following chains of equivalences:*

1. L has the $\mathbb{K}C$ iff $L_{\text{lin}} \subseteq \mathbf{HSP}_U(\mathbb{K})$ iff $L_{\text{RSI}}^\sigma \subseteq \mathbf{HSP}_U(\mathbb{K})$.
2. L has the \mathbf{FSKC} iff $L_{\text{lin}}^+ \subseteq \mathbf{ISP}_U(\mathbb{K})$ iff $L_{\text{RSI}}^\sigma \subseteq \mathbf{ISP}_U(\mathbb{K})$.
3. L has the \mathbf{SKC} iff $L_{\text{lin}}^{\sigma+} \subseteq \mathbf{IS}(\mathbb{K})$ iff $L_{\text{RSI}}^\sigma \subseteq \mathbf{IS}(\mathbb{K})$.

Proof. To prove the first claim we use Dziobiak's result [22] showing that for a congruence distributive quasivariety \mathbb{Q} and a class $\mathbb{M} \subseteq \mathbb{Q}$ we have $\mathbf{V}(\mathbb{M}) \cap \mathbb{Q}_{\text{RFSI}} \subseteq \mathbf{HSP}_U(\mathbb{M})$. Indeed from Theorem 25 we know that the quasivariety L is congruence distributive and thus by setting $\mathbb{Q} = L$ and $\mathbb{M} = \mathbb{K}$ we obtain

$$\mathbf{V}(\mathbb{K}) \cap L_{\text{lin}} = \mathbf{V}(\mathbb{K}) \cap L_{\text{RFSI}} \subseteq \mathbf{HSP}_U(\mathbb{K}).$$

Now assume that L has the $\mathbb{K}C$. Then by Theorem 34 we have $\mathbf{H}(L) = \mathbf{V}(\mathbb{K})$. Consequently, $L_{\text{lin}} \subseteq \mathbf{HSP}_U(\mathbb{K})$ because $L_{\text{lin}} \subseteq \mathbf{H}(L)$. Further, it is obvious that $L_{\text{lin}} \subseteq \mathbf{HSP}_U(\mathbb{K})$ implies $L_{\text{RSI}}^\sigma \subseteq \mathbf{HSP}_U(\mathbb{K})$ since $L_{\text{RSI}}^\sigma \subseteq L_{\text{lin}}$. Finally, suppose that $L_{\text{RSI}}^\sigma \subseteq \mathbf{HSP}_U(\mathbb{K})$. By Theorem 34 it is sufficient to show that $\mathbf{H}(L) = \mathbf{V}(\mathbb{K})$. Since $\mathbf{V}(L) = \mathbf{H}(L)$ and $\mathbb{K} \subseteq L$, we always have $\mathbf{V}(\mathbb{K}) \subseteq \mathbf{H}(L)$. Conversely, L is strongly complete w.r.t. L_{RSI}^σ by Theorem 17. Thus by Theorem 34 we have $\mathbf{H}(L) = \mathbf{V}(L_{\text{RSI}}^\sigma)$. Consequently, by our assumption we obtain

The first equivalence of the second claim is proved in [19, Theorem 3.4.11.]. To prove the remaining one, one can argue similarly as above. Since $L_{\text{RSI}}^\sigma \subseteq L_{\text{lin}}^+$, $L_{\text{lin}}^+ \subseteq \mathbf{ISP}_U(\mathbb{K})$ implies $L_{\text{RSI}}^\sigma \subseteq \mathbf{ISP}_U(\mathbb{K})$. Conversely, assume that $L_{\text{RSI}}^\sigma \subseteq \mathbf{ISP}_U(\mathbb{K})$. Again using Theorems 17 and 34, we obtain

$$L = \mathbf{Q}(L_{\text{RSI}}^\sigma) \subseteq \mathbf{Q}(\mathbf{ISP}_U(\mathbb{K})) = \mathbf{Q}(\mathbb{K}) \subseteq L.$$

Thus L enjoys \mathbf{FSKC} by Theorem 34.

The last claim is proved in [19, Theorem 3.4.6.]. □

Corollary 36. *If L enjoys \mathbf{FSKC} , then it enjoys the $\mathbf{SP}_U(\mathbb{K})C$ as well.*

Alternatively, for logics with finitely many propositional connectives, an algebraic property equivalent to finite strong \mathbb{K} -completeness is expressed in terms of partial embeddings. This was, in fact, the property used by Hájek and others to prove standard completeness of \mathbf{HL} .

Definition 37. Given two algebras \mathbf{A} and \mathbf{B} of the same language \mathcal{L} , we say that a finite subset X of \mathbf{A} is partially embeddable into \mathbf{B} if there is a one-to-one mapping $f: X \rightarrow B$ such that for each $\langle c, n \rangle \in \mathcal{L}$ and each $a_1, \dots, a_n \in X$ satisfying $c^{\mathbf{A}}(a_1, \dots, a_n) \in X$, $f(c^{\mathbf{A}}(a_1, \dots, a_n)) = c^{\mathbf{B}}(f(a_1), \dots, f(a_n))$.

A class \mathbb{K} of algebras is partially embeddable into a class \mathbb{K}' if every finite subset of every member of \mathbb{K} is partially embeddable into a member of \mathbb{K}' .

Theorem 38. Assume that the language of L is finite. Then the following are equivalent:

1. L has the FSKC.
2. The class $\mathbb{L}_{\text{RSI}}^\sigma$ is partially embeddable into \mathbb{K} .
3. The class $\mathbb{L}_{\text{lin}}^+$ is partially embeddable into \mathbb{K} .
4. L is partially embeddable into $\mathbf{P}_{\text{fin}}(\mathbb{K})$.

Proof. The equivalence of the first three claims is proved in [19, Theorem 3.4.8].

(3) \Rightarrow (4): Let $\mathbf{A} \in \mathbb{L}$ and $X \subseteq A$ a finite subset. By a well-known fact from universal algebra, every algebra \mathbf{C} in a quasivariety \mathbb{Q} is a subdirect product of subdirectly irreducible algebras relative to \mathbb{Q} . Since \mathbb{L} is a quasivariety, it follows that \mathbf{A} can be viewed as a subdirect product of a family $\{\mathbf{A}_i \in \mathbb{L}_{\text{RSI}} \mid i \in I\}$. Since X is finite, it suffices to consider only finitely many \mathbf{A}_i 's in order to separate elements of X . Thus X is partially embeddable into a finite direct product of some subdirectly irreducible algebras relative to \mathbb{L} . Since $\mathbb{L}_{\text{RSI}} \subseteq \mathbb{L}_{\text{lin}}$ by Theorem 22, X is partially embeddable into $\mathbf{P}_{\text{fin}}(\mathbb{K})$ by (3).

(4) \Rightarrow (1): Assume that $\Gamma \not\vdash_L \varphi$ for a finite set Γ of formulae. By Theorem 17 there is a counter-model $\mathbf{A} \in \mathbb{L}_{\text{RSI}}$. By (4) we have also a counter-model $\mathbf{B} \in \mathbf{P}_{\text{fin}}(\mathbb{K})$. Since \mathbf{B} is a direct product of members from \mathbb{K} , one of them actually has to be a counter-model as well. \square

Remark 39. Notice that the implications from 2, 3, or 4 to 1 hold also for infinite languages, whereas the converse ones do not (as shown in [13, Example 3.10]).

Let us now deal with particular notable semantics. We consider first the class of all finite L -chains, denoted by \mathcal{F} .

Theorem 40 ([19, Theorems 3.4.16.]). *The following are equivalent:*

1. L enjoys the SFC.
2. All L -chains are finite.
3. There exists $n \in \mathbb{N}$ such each L -chain has at most n elements.
4. There exists $n \in \mathbb{N}$ such that $\vdash_L \bigvee_{i < n} (x_i \rightarrow x_{i+1})$.

Corollary 41. *For any core semilinear logic L and a natural number n , the axiomatic extension $L_{\leq n}$ obtained by adding the schema $\bigvee_{i < n} (x_i \rightarrow x_{i+1})$ is a semilinear logic which is strongly complete with respect the L -chains of length less than or equal to n .*

Next we show that the properties of FSC and \mathcal{F} have purely algebraic characterizations in terms of basic notions studied in universal algebra. We say that a class of algebras \mathbb{M} has:

- the *finite embeddability property* (FEP) if \mathbb{M} is partially embeddable into the class of its finite members,
- the *(strong) finite model property* ((S)FMP) if every (quasi-)identity that fails to hold in \mathbb{M} can be refuted in a finite member of \mathbb{M} .

The next theorem follows from Theorem 38 but can be also seen as an instance of a purely universal-algebraic result from [5] (after replacing the first claim by an equivalent algebraic formulation using Theorem 34).

Theorem 42. *The following are equivalent:*

1. \mathbb{L} enjoys the FSFC.
2. \mathbb{L} enjoys the SFMP.
3. \mathbb{L} enjoys the FEP.

Finally, the algebraic characterization of \mathcal{FC} is not much of use because it involves free algebras whose structure is usually quite complex, but we include it for the sake of completeness.

Theorem 43. *The following are equivalent:*

1. \mathbb{L} enjoys the \mathcal{FC} .
2. \mathbb{L} enjoys the FMP.
3. *The class of finitely generated \mathbb{L} -free algebras is partially embeddable into the class of finite members of \mathbb{L} .*

Proof. (1) \Rightarrow (2): The first claim clearly implies the second one due to algebraizability of \mathbb{L} .

(2) \Rightarrow (3): Assume that \mathbb{L} has the FMP. Let \mathbf{F} be a finitely generated \mathbb{L} -free algebra and $X \subseteq F$ a finite subset. We will construct a partial embedding

$$f: X \rightarrow \prod_{\substack{x, y \in X \\ x \neq y}} A_{x, y},$$

where $A_{x, y}$ are going to be finite members of \mathbb{L} . Let $x, y \in X$ such that $x \neq y$. Since \mathbf{F} is free, x, y can be viewed as equivalence classes of terms. Consider any term t_x belonging to x and similarly any term t_y from y . Then the identity $t_x \approx t_y$ does not hold in \mathbb{L} because $x \neq y$. By FMP there is a finite algebra $A_{x, y} \in \mathbb{L}$ where $t_x \approx t_y$ can be refuted. Since \mathbf{F} is free, we have a surjective homomorphism $f_{x, y}: F \rightarrow A_{x, y}$ such that $f_{x, y}(x) \neq f_{x, y}(y)$. The collection of homomorphisms $f_{x, y}$ induces a homomorphism

$$g: F \rightarrow \prod_{\substack{x, y \in X \\ x \neq y}} A_{x, y}$$

defined by $g(z) = \langle f_{x, y}(z) \rangle_{x, y \in X, x \neq y}$ whose restriction to X gives the desired partial embedding f .

(3) \Rightarrow (1): Let φ be a formula which is not a theorem of \mathbb{L} , i.e., $\not\vdash_{\mathbb{L}} \varphi$. By algebraizability the identity $\bar{1} \approx \bar{1} \wedge \varphi$ does not hold in \mathbb{L} . Consequently, $\bar{1} \approx \bar{1} \wedge \varphi$ does not hold in a finitely generated \mathbb{L} -free algebra \mathbf{F} . Since \mathbf{F} is partially embeddable into a finite member $\mathbf{A} \in \mathbb{L}$, $\bar{1} \approx \bar{1} \wedge \varphi$ does not hold in \mathbf{A} . By a well-known fact from universal algebra, every algebra \mathbf{C} in a quasivariety \mathbb{Q} is a subdirect product of subdirectly irreducible algebras relative to \mathbb{Q} which are homomorphic images of \mathbf{C} . Since $\mathbb{L}_{\text{RSI}} \subseteq \mathbb{L}_{\text{fin}}$, \mathbf{A} is a subdirect product of chains \mathbf{B}_i , $i \in I$, which are homomorphic images of \mathbf{A} . Thus \mathbf{B}_i 's have to be finite as well. Consequently, $\bar{1} \approx \bar{1} \wedge \varphi$ does not hold in $\prod_{i \in I} \mathbf{B}_i$ and therefore $\bar{1} \approx \bar{1} \wedge \varphi$ can be refuted in one of the components \mathbf{B}_i 's. \square

The completeness properties w.r.t. the class \mathcal{F} of finite L-chains are usually used in order to show decidability of theorems and finite consequence of \mathbb{L} . More precisely, if \mathbb{L} is finitely axiomatizable then \mathcal{FC} implies decidability of the set $\{\varphi \mid \vdash_{\mathbb{L}} \varphi\}$ and FSFC implies decidability of $\{(\Gamma, \varphi) \mid \Gamma \vdash_{\mathbb{L}} \varphi, \Gamma \text{ finite}\}$. Table 9 lists several known results on completeness properties w.r.t. \mathcal{F} (see [57, 81] and references thereof).

We now consider the semantics given by chains defined over the rational and the real unit interval. We present both notions together because their completeness properties are much related.²¹

²¹Another closely related semantics is that of hyperreal or non-standard reals proposed as a semantics for fuzzy logics in [31]. See [13] for results linking hyperreal completeness with real and rational completeness.

Logic	SFC	FSFC	FC
SL_S^ℓ , for each $S \subseteq \{e, c, i, o\}$	No	Yes	Yes
SL_{aw}^ℓ	No	Yes	Yes
MTL, IMTL, SMTL	No	Yes	Yes
UL, WCMTL, IIMTL, II	No	No	No
HL, SHL, L	No	Yes	Yes
G, WNM, NM, C_n MTL, C_n IMTL	No	Yes	Yes
CPC	Yes	Yes	Yes

Table 9: Finite strong completeness w.r.t. \mathcal{F} for some core semilinear logics.

Definition 44. The class $\mathcal{R} \subseteq \mathbb{L}_{lin}$ is defined as: $\mathbf{A} \in \mathcal{R}$ if the domain of \mathbf{A} is the real unit interval $[0, 1]$ and $\leq_{\mathbf{A}}$ is the usual order on reals. The class $\mathcal{Q} \subseteq \mathbb{L}_{lin}$ is analogously defined requiring the rational unit interval as domain.

Theorem 45 ([19, Theorem 3.4.19.]).

1. L has the FSQC iff it has the SQC.
2. If L has the RC, then it has the QC.
3. If L has the FSRC, then it has the SQC.

Observe that the completeness properties with respect to \mathcal{Q} are, in fact, equivalent to completeness properties with respect to the whole class of densely ordered chains. Indeed, when we have an evaluation over a densely ordered linear model providing a counterexample to some derivation, we can apply the downward Löwenheim–Skolem Theorem to the (countable) subalgebra generated by the image of all formulae by the evaluation and obtain a rational countermodel.

Strong rational completeness also admits a proof-theoretic characterization in terms of the Density Property:²²

Theorem 46. The following are equivalent:

1. L has the SQC.
2. L has the Density Property DP, i.e. if for any set of formulae $\Gamma \cup \{\varphi, \psi, \chi\}$ and any variable p not occurring in $\Gamma \cup \{\varphi, \psi, \chi\}$ the following meta-rule holds:

$$\frac{\Gamma \vdash_L (\varphi \rightarrow p) \vee (p \rightarrow \psi) \vee \chi}{\Gamma \vdash_L (\varphi \rightarrow \psi) \vee \chi}.$$

3. L is the intersection of all its extensions satisfying the DP.

Proof. The equivalence of 1 and 2 follows from [19, Theorem 3.3.8.]. The equivalence with 3 follows from [19, Theorem 3.3.13.]. \square

The last claim gives some insight into an approach used in the fuzzy logic literature to prove completeness w.r.t. the semantics of densely ordered chains (e.g. in [66] for the logic UL). Indeed, in this approach one starts from a suitable proof-theoretic description of a logic L, which then is extended into a proof-system for the intersection of all extensions of L satisfying the DP just by adding DP as a rule (in the proof-theoretic sense, not as we understand rules here). This rule is then shown to be eliminable (using analogs of the well-known cut-elimination techniques), i.e., the condition 3 is met and hence the original logic is complete w.r.t. its densely ordered chains (of

²²This property originally appeared in [79] in a much more specific context, then was generalized to a wide class of fuzzy logics in [66].

course, our general theory is not helpful in this last step, because here one needs to use specific properties of the logic in question).

Many works in the literature of MFL focus on the study of these completeness properties. Besides the historical papers devoted to particular logical systems, there are more systematic approaches dealing with the study of these properties such as [13, 57]. Table 10 collects the results for some prominent core semilinear logics. Unlike FL^ℓ , the weakest core semilinear logic SL^ℓ does enjoy all these completeness properties, as proved in [15]. In particular, if one considers residuated groupoids defined over $[0, 1]$ as its intended semantics, then SL^ℓ enjoys standard completeness in the strong version, and hence, can be regarded as a genuine fuzzy logic as much as HL, MTL or UL. On the other hand, it can arguably be seen as a basic logic in the meanings described in the introduction. Indeed, the class of core semilinear logics is based in this logic and provides a useful framework covering virtually all the work done nowadays in MFL; moreover in the context of substructural logics complete w.r.t. chains could not be made weaker. We have therefore defended the role of SL^ℓ as basic fuzzy logic in the framework of propositional logics. In the last part of the chapter we argue that this is also the case at the first-order level.

Logic	\mathcal{RC}	FSRC	SRC	\mathcal{QC}	$\text{FSQC} = \text{SQC}$
SL_S^ℓ , for each $S \subseteq \{e, c, i, o\}$	Yes	Yes	Yes	Yes	Yes
$\text{SL}_a^\ell, \text{SL}_{ac}^\ell$	No	No	No	No	No
$\text{UL} = \text{SL}_{ae}^\ell, \text{SL}_{aw}^\ell$	Yes	Yes	Yes	Yes	Yes
$\text{MTL} = \text{SL}_{aew}^\ell, \text{IMTL}, \text{SMTL}$	Yes	Yes	Yes	Yes	Yes
$\text{WCMTL}, \text{IMTL}$	Yes	Yes	No	Yes	Yes
$\text{HL}, \text{SHL}, \text{L}, \text{II}$	Yes	Yes	No	Yes	Yes
$\text{G}, \text{WNM}, \text{NM}, \text{C}_n\text{MTL}, \text{C}_n\text{IMTL}$	Yes	Yes	Yes	Yes	Yes
CPC	No	No	No	No	No

Table 10: Real and rational completeness for some core semilinear logics.

4 First-order core semilinear logics

In this section we present the theory of first-order core semilinear logics. The presentation, definitions, and results of the first two subsections closely follow the fifth section of [19] simplified to our setting of core semilinear logics. The third subsection generalizes results of [13] (proved there for core *fuzzy* logics) and shortly surveys the undecidability results treated in detail in [54].

4.1 Syntax

In the following let L be a fixed core semilinear logic in a propositional language \mathcal{L} . The language of a first-order extension of L is defined in the same way as in classical first-order logic. In order to fix the notation and terminology we give an explicit definition:

Definition 47. A predicate language \mathcal{P} is a triple $\langle \text{Pred}_{\mathcal{P}}, \text{Func}_{\mathcal{P}}, \text{Ar}_{\mathcal{P}} \rangle$, where $\text{Pred}_{\mathcal{P}}$ is a non-empty set of predicate symbols, $\text{Func}_{\mathcal{P}}$ is a set (disjoint with $\text{Pred}_{\mathcal{P}}$) of function symbols, and $\text{Ar}_{\mathcal{P}}$ is the arity function, assigning to each predicate or function symbol a natural number called the arity of the symbol. The function symbols F with $\text{Ar}_{\mathcal{P}}(F) = 0$ are called object or individual constants. The predicates symbols P for which $\text{Ar}_{\mathcal{P}}(P) = 0$ are called truth constants.²³

\mathcal{P} -terms and (atomic) \mathcal{P} -formulae of a given predicate language are defined as in classical logic (note that the notion of formula also depends on propositional connectives in \mathcal{L}). A \mathcal{P} -theory is

²³The roles of nullary predicates of \mathcal{P} and nullary connectives of \mathcal{L} are analogous, even though the values of the former are only fixed under a given interpretation of the predicate language, while the values of the latter are fixed under all such interpretations. The ambiguity of the term *truth constant* is thus a harmless abuse of language.

a set of \mathcal{P} -formulae. The notions of free occurrence of a variable, substitutability, open formula, and closed formula (or, synonymously, *sentence*) are defined in the same way as in classical logic. Unlike in classical logic, in fuzzy logics without involutive negation the quantifiers \forall and \exists are not mutually definable, so the primitive language of $L\forall$ has to contain both of them.

There are several variants of the first-order extension of a propositional fuzzy logic L that can be defined. Following Hájek's original approach in [38] and his developments in [49, 50, 51], here we restrict ourselves to logics of models over linearly ordered algebras (see Subsection 4.2) and introduce the first-order logics $L\forall$ and $L\forall^w$ (respectively, complete w.r.t. all models or w.r.t. witnessed models). The axiomatic systems of the logics $L\forall$ and $L\forall^w$ are defined as follows:

Definition 48. *Let \mathcal{P} be a predicate language. The logic $L\forall$ in language \mathcal{P} has the following axioms:²⁴*

- (P) The axioms of L
- ($\forall 1$) $(\forall x)\varphi(x) \rightarrow \varphi(t)$, where the \mathcal{P} -term t is substitutable for x in φ
- ($\exists 1$) $\varphi(t) \rightarrow (\exists x)\varphi(x)$, where the \mathcal{P} -term t is substitutable for x in φ
- ($\forall 2$) $(\forall x)(\chi \rightarrow \varphi) \rightarrow (\chi \rightarrow (\forall x)\varphi)$, where x is not free in χ
- ($\exists 2$) $(\forall x)(\varphi \rightarrow \chi) \rightarrow ((\exists x)\varphi \rightarrow \chi)$, where x is not free in χ
- ($\forall 3$) $(\forall x)(\chi \vee \varphi) \rightarrow \chi \vee (\forall x)\varphi$, where x is not free in χ .

The deduction rules of $L\forall$ are those of L plus the rule of generalization:

- (Gen) $\langle \varphi, (\forall x)\varphi \rangle$.

The logic $L\forall^w$ is the extension of $L\forall$ by the axioms:

- ($C\forall$) $(\exists x)(\varphi(x) \rightarrow (\forall y)\varphi(y))$
- ($C\exists$) $(\exists x)((\exists y)\varphi(y) \rightarrow \varphi(x))$.

The notions of proof and provability are defined for first-order core semilinear logics in the same way as in first-order classical logic. The fact that the formula φ is provable in $L\forall$ from a theory T will be denoted by $T \vdash_{L\forall} \varphi$, and analogously for $L\forall^w$; in a fixed context we can write just $T \vdash \varphi$.

Helena Rasiowa gave a first general theory of first-order non-classical logics in [76] based on her notion of propositional implicative logic. The presentation of her first-order logics, which we denote $L\forall^m$, omitted the axiom ($\forall 3$).²⁵ The superscript 'm' stands for 'minimal', because $L\forall^m$ is, in a sense, the weakest first-order extension of L . Indeed, $L\forall^m$ is sound and complete w.r.t. first-order models built over *arbitrary* L -algebras. However, the axioms of $L\forall^m$ are not strong enough to ensure the completeness w.r.t. first-order models (see the next subsection for technical details) over *linearly ordered* L -algebras —i.e., the usual chain completeness theorem, which we have presented as an essential common trait of all core semilinear logics. That is the reason why Hájek needed to add the axiom ($\forall 3$) in his presentation of first-order fuzzy logics. This axiom is valid in all models over L -chains (though not generally in models over arbitrary L -algebras, see e.g. [19, Example 4.1.18]) and ensures the chain completeness theorem for the resulting logic $L\forall$.²⁶ This makes $L\forall$ a natural choice for *the* first-order extension of a given core *semilinear* logic L . Consequently, we denote this first-order logic as $L\forall$ with no superscript (though in some works the more systematic denotation $L\forall^\ell$ is used). Finally let us note that in the context of MFL, the logics $L\forall^m$ were rediscovered by Petr Hájek in [39], where he denoted them by $L\forall^-$.

Let us list some important theorems that are provable in all logics $L\forall$. For their proofs in MTL or HL see [23, 38]; their proofs in a weaker setting can be found in [19].

²⁴When we speak about axioms or deduction rules of a propositional logic, we actually consider them with \mathcal{P} -formulae substituted for propositional variables.

²⁵Actually her axiomatization omitted also the generalization rule, and the axioms ($\forall 2$) and ($\exists 2$) were replaced by the corresponding rules. However it can be shown that in the context of core semilinear logics her axiomatization and ours (without ($\forall 3$)) are equivalent.

²⁶This fact was first observed for Gödel logic by Horn in [59].

Theorem 49 ([19, Propositions 4.2.5. and 4.3.2]). *Let \mathcal{P} be a predicate language, φ, ψ, χ \mathcal{P} -formulae, x a variable not free in χ , and x' a variable not occurring in φ . The following \mathcal{P} -formulae are theorems of $\mathbb{L}\forall$:*

(T \forall 1) $\chi \leftrightarrow (\forall x)\chi$	(T \forall 11) $(\exists x)(\chi \rightarrow \varphi) \rightarrow (\chi \rightarrow (\exists x)\varphi)$
(T \forall 2) $(\exists x)\chi \leftrightarrow \chi$	(T \forall 12) $(\exists x)(\varphi \rightarrow \chi) \rightarrow ((\forall x)\varphi \rightarrow \chi)$
(T \forall 3) $(\forall x)\varphi(x) \leftrightarrow (\forall x')\varphi(x')$	(T \forall 13) $(\forall x)(\varphi \wedge \psi) \leftrightarrow (\forall x)\varphi \wedge (\forall x)\psi$
(T \forall 4) $(\exists x)\varphi(x) \leftrightarrow (\exists x')\varphi(x')$	(T \forall 14) $(\exists x)(\varphi \vee \psi) \leftrightarrow (\exists x)\varphi \vee (\exists x)\psi$
(T \forall 5) $(\forall x)(\forall y)\varphi \leftrightarrow (\forall y)(\forall x)\varphi$	(T \forall 15) $(\forall x)(\varphi \vee \chi) \leftrightarrow (\forall x)\varphi \vee \chi$
(T \forall 6) $(\exists x)(\exists y)\varphi \leftrightarrow (\exists y)(\exists x)\varphi$	(T \forall 16) $(\exists x)(\varphi \wedge \chi) \leftrightarrow (\exists x)\varphi \wedge \chi$
(T \forall 7) $(\forall x)(\varphi \rightarrow \psi) \rightarrow ((\forall x)\varphi \rightarrow (\forall x)\psi)$	(T \forall 17) $(\exists x)(\varphi \& \chi) \leftrightarrow (\exists x)\varphi \& \chi$
(T \forall 8) $(\forall x)(\varphi \rightarrow \psi) \rightarrow ((\exists x)\varphi \rightarrow (\exists x)\psi)$	(T \forall 18) $(\exists x)(\varphi^n) \leftrightarrow ((\exists x)\varphi)^n$
(T \forall 9) $(\chi \rightarrow (\forall x)\varphi) \leftrightarrow (\forall x)(\chi \rightarrow \varphi)$	(T \forall 19) $(\exists x)\varphi \rightarrow \neg(\forall x)\neg\varphi$
(T \forall 10) $((\exists x)\varphi \rightarrow \chi) \leftrightarrow (\forall x)(\varphi \rightarrow \chi)$	(T \forall 20) $\neg(\exists x)\varphi \leftrightarrow (\forall x)\neg\varphi$.

Remark 50. The converse implication of (T \forall 19) is provable in $\mathbb{L}\forall$, $\text{IMTL}\forall$, or $\text{NM}\forall$, i.e., in logics where \neg is involutive (i.e. proves $\neg\neg\varphi \rightarrow \varphi$). Thus in such logics the existential quantifier is definable and the axioms (\exists 1) and (\exists 2) become redundant. Actually, for this claim to hold, the presence of an arbitrary unary connective \sim such that $\varphi \rightarrow \psi \vdash_{\mathbb{L}} \sim\psi \rightarrow \sim\varphi$ and $\vdash_{\mathbb{L}} \varphi \leftrightarrow \sim\sim\varphi$. is sufficient (which could be either the ‘natural’ logical negation given by implication, or a new primitive connective added in logics \mathbb{L}_{\sim}).

The provability of the converse implications of (T \forall 11) or (T \forall 12) is equivalent to provability of (C \exists) or (C \forall) resp., i.e., if $\mathbb{L}\forall$ proves them, then $\mathbb{L}\forall = \mathbb{L}\forall^w$. This is the case of Łukasiewicz logic; product logic proves (C \exists) (and so the converse of (T \forall 11)) but not (C \forall), and Gödel logic proves neither. Finally it is worth noting that the axiom (\forall 3) is redundant in the axiomatization of $\mathbb{L}\forall$ and therefore $\mathbb{L}\forall^m = \mathbb{L}\forall = \mathbb{L}\forall^w$.

Some syntactic metatheorems valid in propositional core semilinear logics hold analogously for their first-order logics:

Theorem 51 ([19, Theorems 4.2.6. and 4.2.8., Corollary 4.2.11., and Theorem 4.3.9.]). *Let \mathbb{L} be a core semilinear logic, \vdash be either $\vdash_{\mathbb{L}\forall}$ or $\vdash_{\mathbb{L}\forall^w}$, and \mathcal{P} be a predicate language. Then the following holds for each \mathcal{P} -theory T , \mathcal{P} -sentences φ, ψ , and \mathcal{P} -formula χ :*

1. *The intersubstitutability:*

$$\varphi \leftrightarrow \psi \vdash \chi \leftrightarrow \chi',$$

where χ' is a \mathcal{P} -formula obtained from χ by replacing some occurrences of φ by ψ .

2. *The constants theorem:*

$$T \vdash \chi(c) \quad \text{iff} \quad T \vdash \chi(x),$$

for any constant c not occurring in $T \cup \{\chi\}$.

3. *The proof by cases property:*

$$\frac{T, \varphi \vdash \chi \quad T, \psi \vdash \chi}{T, \varphi \vee \psi \vdash \chi}$$

4. *The semilinearity property:*

$$\frac{T, \varphi \rightarrow \psi \vdash \chi \quad T, \psi \rightarrow \varphi \vdash \chi}{T \vdash \chi}$$

If, furthermore, \mathbb{L} is almost (MP)-based with a set of basic deductive terms bDT , we can add:

5. The local deduction theorem:

$$T, \varphi \vdash \chi \quad \text{iff} \quad T \vdash \delta(\varphi) \rightarrow \chi \quad \text{for some } \delta \in \Pi(\text{bDT}^*)_{\mathcal{P}},$$

where by $\Pi(\text{bDT}^*)_{\mathcal{P}}$ we denote the set of formulae resulting from any \star -formula from $\Pi(\text{bDT}^*)$ by replacing all its propositional variables other than \star by arbitrary \mathcal{P} -sentences.

Petr Hájek in [38] (or in [52]) used the local deduction theorems for schematic extensions of HL (for (Δ) -core fuzzy logics resp.) to show the semilinearity property (even though only in [52] it is formulated explicitly), which in turn is a crucial prerequisite for proving the completeness theorem.

4.2 General and witnessed semantics

In this subsection we shall introduce the (witnessed) semantics of predicate fuzzy logics, corresponding to the axiomatic systems $L\forall$ and $L\forall^w$ respectively. To simplify the formulation of upcoming definitions let us fix: a core semilinear logic L in a propositional language \mathcal{L} , a predicate language $\mathcal{P} = \langle \text{Pred}, \text{Func}, \text{Ar} \rangle$, and an L -chain \mathbf{B} .

Definition 52. A \mathbf{B} -structure \mathbf{M} for the predicate language \mathcal{P} has the form: $\mathbf{M} = \langle M, (P_{\mathbf{M}})_{P \in \text{Pred}}, (F_{\mathbf{M}})_{F \in \text{Func}} \rangle$, where M is a non-empty domain; for each n -ary predicate symbol $P \in \text{Pred}$, $P_{\mathbf{M}}$ is an n -ary fuzzy relation on M , i.e., a function $M^n \rightarrow \mathbf{B}$ (identified with an element of \mathbf{B} if $n = 0$); for each n -ary function symbol $F \in \text{Func}$, $F_{\mathbf{M}}$ is a function $M^n \rightarrow M$ (identified with an element of M if $n = 0$).

Let \mathbf{M} be a \mathbf{B} -structure for \mathcal{P} . An \mathbf{M} -evaluation of the object variables is a mapping v which assigns an element from M to each object variable. Let v be an \mathbf{M} -evaluation, x a variable, and $a \in M$. Then by $v[x \mapsto a]$ we denote the \mathbf{M} -evaluation such that $v[x \mapsto a](x) = a$ and $v[x \mapsto a](y) = v(y)$ for each object variable y different from x .

Let \mathbf{M} be a \mathbf{B} -structure for \mathcal{P} and v an \mathbf{M} -evaluation. We define the values of terms and the truth values of formulae in \mathbf{M} for an evaluation v recursively as follows noting that in the last two clauses, if the infimum or supremum does not exist, then the corresponding value is taken to be undefined, and in all clauses, if one of the arguments is undefined, then the result is undefined:

$$\begin{aligned} \|x\|_{\mathbf{M},v}^{\mathbf{B}} &= v(x) \\ \|F(t_1, \dots, t_n)\|_{\mathbf{M},v}^{\mathbf{B}} &= F_{\mathbf{M}}(\|t_1\|_{\mathbf{M},v}^{\mathbf{B}}, \dots, \|t_n\|_{\mathbf{M},v}^{\mathbf{B}}) \quad \text{for } F \in \text{Func} \\ \|P(t_1, \dots, t_n)\|_{\mathbf{M},v}^{\mathbf{B}} &= P_{\mathbf{M}}(\|t_1\|_{\mathbf{M},v}^{\mathbf{B}}, \dots, \|t_n\|_{\mathbf{M},v}^{\mathbf{B}}) \quad \text{for } P \in \text{Pred} \\ \|c(\varphi_1, \dots, \varphi_n)\|_{\mathbf{M},v}^{\mathbf{B}} &= c_{\mathbf{B}}(\|\varphi_1\|_{\mathbf{M},v}^{\mathbf{B}}, \dots, \|\varphi_n\|_{\mathbf{M},v}^{\mathbf{B}}) \quad \text{for } c \in \mathcal{L} \\ \|(\forall x)\varphi\|_{\mathbf{M},v}^{\mathbf{B}} &= \inf\{\|\varphi\|_{\mathbf{M},v[x \mapsto a]}^{\mathbf{B}} \mid a \in M\} \\ \|(\exists x)\varphi\|_{\mathbf{M},v}^{\mathbf{B}} &= \sup\{\|\varphi\|_{\mathbf{M},v[x \mapsto a]}^{\mathbf{B}} \mid a \in M\}. \end{aligned}$$

We say that the \mathbf{B} -structure \mathbf{M} is

- safe if $\|\varphi\|_{\mathbf{M},v}^{\mathbf{B}}$ is defined for each \mathcal{P} -formula φ and each \mathbf{M} -evaluation v ,
- witnessed if for each \mathcal{P} -formula φ we have:

$$\begin{aligned} \|(\forall x)\varphi\|_{\mathbf{M},v}^{\mathbf{B}} &= \min\{\|\varphi\|_{\mathbf{M},v[x \mapsto a]}^{\mathbf{B}} \mid a \in M\} \\ \|(\exists x)\varphi\|_{\mathbf{M},v}^{\mathbf{B}} &= \max\{\|\varphi\|_{\mathbf{M},v[x \mapsto a]}^{\mathbf{B}} \mid a \in M\}. \end{aligned}$$

Note that each witnessed structure is safe. To simplify the upcoming definitions and theorems we write $\langle \mathbf{B}, \mathbf{M} \rangle \models \varphi$ if $\|\varphi\|_{\mathbf{M},v}^{\mathbf{B}} \geq_{\mathbf{B}} 1$ for each \mathbf{M} -evaluation v .

Definition 53. Let \mathbf{M} be a \mathbf{B} -structure for \mathcal{P} and T a \mathcal{P} -theory. Then \mathbf{M} is called a \mathbf{B} -model of T if it is safe and $\langle \mathbf{B}, \mathbf{M} \rangle \models \varphi$ for each $\varphi \in T$.

Observe that models are safe structures by definition. As obviously each safe \mathbf{B} -structure is a \mathbf{B} -model of the empty theory, we shall use the term *model* for both models and safe structures in the rest of the text.²⁷ By a slight abuse of language we use the term model also for the pair $\langle \mathbf{B}, \mathbf{M} \rangle$.

The following completeness theorems show that the syntactic presentations introduced above succeed in capturing the intended general chain-semantics for first-order fuzzy logics.²⁸

Theorem 54 ([19, Theorems 4.4.10 and 4.3.5.]). *Let L be a core semilinear logic, \mathcal{P} a predicate language, T a \mathcal{P} -theory, and φ a \mathcal{P} -formula. Then the following are equivalent:*

- $T \vdash_{L\forall} \varphi$.
- $\langle \mathbf{B}, \mathbf{M} \rangle \models \varphi$ for each L -chain \mathbf{B} and each model $\langle \mathbf{B}, \mathbf{M} \rangle$ of the theory T .

Theorem 55 ([19, Theorem 4.5.12. and Example 4.5.3.]). *Let L be an axiomatic expansion of SL_{ae}^l , \mathcal{P} a predicate language, T a \mathcal{P} -theory, and φ a \mathcal{P} -formula. Then the following are equivalent:*

- $T \vdash_{L\forall^w} \varphi$.
- $\langle \mathbf{B}, \mathbf{M} \rangle \models \varphi$ for each L -chain \mathbf{B} and each witnessed model $\langle \mathbf{B}, \mathbf{M} \rangle$ of the theory T .

4.3 Standard semantics

Already in the pioneering works of Petr Hájek, as in the case of propositional fuzzy logics, the general chain completeness we have just seen was not considered sufficient and, in fact, a crucial item in his agenda was again the search for standard completeness theorems with respect to distinguished classes of models. In order to survey the corresponding results in our framework, in this section we restrict ourselves to *countable* predicate languages. We shall say that $\langle \mathbf{B}, \mathbf{M} \rangle$ is a \mathbb{K} -model (of T) for some $\mathbb{K} \subseteq \mathbb{L}_{lin}$ if $\langle \mathbf{B}, \mathbf{M} \rangle$ is a model (of T) and $\mathbf{B} \in \mathbb{K}$.

Definition 56. *Let L be a core semilinear logic and $\mathbb{K} \subseteq \mathbb{L}_{lin}$. We say that $L\forall$ enjoys (finite) strong \mathbb{K} -completeness SKC (FSKC resp.) if for each countable predicate language \mathcal{P} , \mathcal{P} -formula φ , and (finite) \mathcal{P} -theory T holds:*

$$T \vdash_{L\forall} \varphi \quad \text{iff} \quad \langle \mathbf{B}, \mathbf{M} \rangle \models \varphi \text{ for each } \mathbb{K}\text{-model } \langle \mathbf{B}, \mathbf{M} \rangle \text{ of the theory } T$$

We say that $L\forall$ enjoys \mathbb{K} -completeness $\mathbb{K}C$ if the equivalence holds for $T = \emptyset$.

All these properties are stronger than their corresponding ones for propositional logics:

Theorem 57. *Let L be a core semilinear logic and \mathbb{K} a class of L -chains. If $L\forall$ has the SKC (FSKC or $\mathbb{K}C$ respectively), then L has the SKC (FSKC or $\mathbb{K}C$ respectively).*

As in the propositional case (Theorem 35), strong \mathbb{K} -completeness is related to an embedding property, although it is a stronger one requiring preservation of existing suprema and infima:

Definition 58. *Let \mathbf{A} and \mathbf{B} be two algebras of the same type with (defined) lattice operations. We say that an embedding $f: \mathbf{A} \rightarrow \mathbf{B}$ is a σ -embedding if $f(\sup C) = \sup f[C]$ (whenever $\sup C$ exists) and $f(\inf D) = \inf f[D]$ (whenever $\inf D$ exists) for each countable $C, D \subseteq A$.*

Theorem 59. *Let L be a core semilinear logic. If every countable L -chain \mathbf{A} can be σ -embedded into some L -chain $\mathbf{B} \in \mathbb{K}$, then $L\forall$ enjoys SKC.*

The proof of this theorem is almost straightforward. Unlike in the propositional case, the existence of σ -embeddings is not a necessary condition, as shown in [13, Theorem 5.38], but nevertheless it is the usual method for proving these results. It also has an interesting corollary for completeness w.r.t. finite chains (recall the characterizations of SFC in Theorem 40).

²⁷In the literature the term ‘ ℓ -model’ is sometimes used instead to stress that \mathbf{B} is linearly ordered.

²⁸For the proofs of Theorems 54 and 55 for core and Δ -core fuzzy logics see [52]. Instances of Theorem 54 for various core semilinear logics were originally proved separately (usually for countable predicate languages only): the proofs for prominent core fuzzy logics can be found in [23, 38].

Corollary 60. *Let L be a core semilinear logic. Then L enjoys the SFC iff $L\forall$ enjoys the SFC.*

It is obvious that every \mathbf{B} -structure over a finite L -chain is necessarily witnessed. Thus we have the following proposition which can be used in order to disprove the \mathcal{FC} for many logics.

Proposition 61. *Let L be a core semilinear logic such that $L\forall$ enjoys \mathcal{FC} . Then $L\forall = L\forall^w$.*

For instance, the examples in [38, Lemma 5.3.6] can be used to show that $(C\exists)$ is unprovable in $G\forall$ and $(C\forall)$ is unprovable both in $G\forall$ and in $\Pi\forall$. We can also easily show that $\not\vdash_{\text{NM}\forall} (C\forall)$. Thus these logics do not enjoy \mathcal{FC} .

Logic	\mathcal{RC}	FSRC, SRC	$\mathcal{QC}, \text{FSQC}, \text{SQC}$	$\mathcal{FC}, \text{FSFC}, \text{SFC}$
$\text{SL}_S^\ell\forall$, for each $S \subseteq \{e, c, i, o\}$	Yes	Yes	Yes	No
$\text{SL}_a^\ell\forall$	No	No	No	No
$\text{SL}_{\text{aw}}^\ell\forall$	Yes	Yes	Yes	No
$\text{MTL}\forall, \text{IMTL}\forall, \text{SMTL}\forall$	Yes	Yes	Yes	No
$\text{WCMTL}\forall, \text{IMTL}\forall$?	No	?	No
$\text{HL}\forall, \text{SHL}\forall$	No	No	No	No
$\mathbb{L}\forall, \Pi\forall$	No	No	Yes	No
$G\forall, \text{WNM}\forall, \text{NM}\forall$	Yes	Yes	Yes	No
$C_n\text{MTL}\forall, C_n\text{IMTL}\forall$	Yes	Yes	Yes	No
$\text{CPC}\forall$	No	No	No	Yes

Table 11: Completeness properties for some first-order core semilinear logics.

Table 11 collects results on real, rational and finite-chain completeness of prominent core semilinear logics. Their proofs are scattered in the literature; see [38, 23] for the proofs for the main core fuzzy logics, and [13] for more information and detailed references. For logics weaker than $\text{MTL}\forall$ the negative results are derived from the corresponding failure of completeness at the propositional level, while the positive ones are justified by observing that the embeddings built to prove completeness for the underlying propositional logic are actually σ -embeddings. Observe that the family of logics in the first row of the table include $\text{SL}^\ell\forall$, which enjoys both strong rational and real (i.e. standard) completeness. This fact was not stated before in the literature because the only paper dealing with SL^ℓ [15] concentrated only on propositional logics, but it is not difficult to check that for SL^ℓ the obtained embedding is also actually a σ -embedding, i.e., we obtain:

Theorem 62. *Let $S \subseteq \{e, c, i, o\}$. Then for each countable predicate language \mathcal{P} , \mathcal{P} -formula φ , and \mathcal{P} -theory T holds:*

$$T \vdash_{\text{SL}_S^\ell\forall} \varphi \quad \text{iff} \quad \langle \mathbf{B}, \mathbf{M} \rangle \models \varphi \text{ for each } \mathcal{R}\text{-model } \langle \mathbf{B}, \mathbf{M} \rangle \text{ of the theory } T.$$

It is worth adding that for all core fuzzy logics appearing in the table the same results hold for their expansions with Δ ; moreover G_\sim behaves like G , while SHL_\sim and $\mathbb{L}\Pi$ behave like HL . Observe the rather surprising behavior of continuous t-norm based logics regarding the rational-chain semantics: while $\mathbb{L}\forall$, $\Pi\forall$, and $G\forall$ enjoy the SQC , the logics $\text{HL}\forall$ and $\text{SHL}\forall$ do not even have \mathcal{QC} (see [13] for the proofs of these facts). Petr Hájek already gave in [38] an important hint towards the failure of rational completeness in $\text{HL}\forall$ and $\text{SHL}\forall$: he found a formula, $(\forall x)(\chi \& \varphi) \rightarrow (\chi \& (\forall x)\varphi)$, which holds in every model on a densely ordered HL -chain but (as shown later in [23]) it is not a tautology of any of those two logics; therefore it makes sense to extend them with this axiom and, by doing so, one obtains new first-order logics complete with respect to all models over rational HL -chains or, respectively, SHL -chains (again, see [13]).

Finding particular examples of formulae witnessing failure of \mathcal{RC} of a given logic is not in easy task. Even though some examples were found by Petr Hájek for some particular cases [46], a usual method of proving this is to show that the set of standard tautologies (see next definition) is not

	$G\forall$	$L\forall$	$\Pi\forall$	$HL\forall$
stTAUT	$\Sigma_1\text{-c}$	$\Pi_2\text{-c}$	NA	NA
stSAT	$\Pi_1\text{-c}$	$\Pi_1\text{-c}$	NA	NA

Table 12: Arithmetical complexity of standard semantics.

recursively enumerable, and therefore it cannot coincide with the set of its theorems. Determining the position in the arithmetical hierarchy (see e.g. [77]) of prominent sets of formulae (such as the tautologies of a given logic) is an important field of study in mathematical logic with major contributions done by Petr Hájek. Here we just briefly mention a few results related to fuzzy logics: for a full treatment of the arithmetical complexity of first-order (Δ -)fuzzy logics see [54]. Other references on the topic are [47, 40, 45, 67, 68, 69].

First let us introduce some prominent sets of formulae given by a core semilinear logic L :

Definition 63. *We say that a sentence φ is*

- A general (*resp.*, standard) tautology of $L\forall$ if $\langle \mathbf{B}, \mathbf{M} \rangle \models \varphi$ for each (\mathcal{R} -)model $\langle \mathbf{B}, \mathbf{M} \rangle$.
- Generally (*resp.*, standardly) satisfiable in $L\forall$ if $\langle \mathbf{B}, \mathbf{M} \rangle \models \varphi$ for some (\mathcal{R} -)model $\langle \mathbf{B}, \mathbf{M} \rangle$.

The sets of general and standard tautologies and generally and standardly satisfiable sentences are denoted, respectively, by genTAUT , stTAUT , genSAT , and stSAT .

For illustration, let us state the results for four predicate logics: $HL\forall$, $L\forall$, $G\forall$, and $\Pi\forall$. For each of them, the set of general tautologies is Σ_1 -complete (thus they are recursively axiomatizable, but undecidable) and the set of generally satisfiable formulae is Π_1 -complete. For the arithmetical complexity of their standard semantics see Table 12 (where “-c” stands for “-complete” and “NA” for “non-arithmetical”). It can be seen that as far as standard semantics is concerned, the four logics differ drastically with respect to their degree of undecidability.

5 Conclusions

In this paper we have presented a general approach to fuzzy logics based on the logic SL^ℓ . We have introduced a broad class of, both propositional and predicate, core semilinear logics and shown their axiomatizations and completeness with respect to models over chains. Moreover, we have surveyed their completeness results with respect to distinguished semantics and obtained, in particular, that the weakest predicate fuzzy logic of our framework, $SL^\ell\forall$, enjoys the standard completeness theorem. Therefore, our flea still jumps (and jumps very well, even in the first-order case!) and we can arguably say that the quest for the basic fuzzy logic initiated by Petr Hájek so far seems to culminate with SL^ℓ . Indeed, both for propositional and first-order predicate logics, SL^ℓ provides a good ground level to build broad families of logics containing all the important particular systems of fuzzy logic: propositional fuzzy logics are captured inside the class of core semilinear logics, while first-order fuzzy logics are obtained as extensions of the logic $L\forall$ built over a core semilinear logic L . Moreover, SL^ℓ is the weakest possible logic one could take in the context of substructural logics in a language with lattice connectives, a conjunction which is not required to satisfy any property corresponding to the usual structural rules and its left and right residua. We do not know whether Mathematical Fuzzy Logic will require an even weaker system to serve as the basic fuzzy logic in the future. Only time will tell. What we can say is that, at the moment, we do not see any remaining legs to be pulled.

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