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About intuitionistic public announcement logic

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Abstract

Public announcement logic (PAL) is a logic for reasoning about the dynamic of knowledge in a multi-agent system in which public announcements are made. Syntactically, public announcements are modal formulas. Semantically, they correspond to restrictions of models. There exist multifarious variants of PAL: PAL with arbitrary public announcements [1], PAL with common knowledge [7], etc. In all these variants, the construct (· → ·) is the one of classical propositional logic. In [10], Ma et al. introduce a variant of PAL in which this construct is the one of intuitionistic propositional logic ( IPL). By using the standard toolkit of duality theory in modal logic, they define an algebraic semantics for a combination of IPL and PAL into intuitionistic public announcement logic (IPAL). In this paper, grounding our approach on relational semantics rather than on algebraic semantics, we give a sound and complete axiomatization of IPAL and we consider a complete sequent calculus for the associated membership problem.

Keywords: Public announcement logic. Intuitionistic propositional logic. Axiomatization/completeness. Decidability/completeness. Sequent calculus.

1 Introduction

Public announcement logic (PAL) is a logic for reasoning about the dynamic of knowledge in a multi-agent system [16]. Syntactically, public announcements are modal formulas. Semantically, they correspond to restrictions of models. In [10], Ma et al. use the standard toolkit of duality theory in modal logic to define an algebraic semantics for a combination of IPL and PAL into intuitionistic public announcement logic (IPAL). In this paper, grounding our approach on relational semantics rather than on algebraic semantics, we give a sound and complete axiomatization of IPAL and we consider a complete sequent calculus for the associated membership problem.

Keywords: Public announcement logic. Intuitionistic propositional logic. Axiomatization/completeness. Decidability/completeness. Sequent calculus.
this paper, grounding our approach on relational semantics rather than on algebraic semantics, we provide supplementary results about IPAL. Firstly, we give a sound and complete axiomatization of IPAL and we prove its completeness. Secondly, we study the features that, according to Simpson [17], might be expected of any intuitionistic modal logic and we examine whether IPAL possesses them. Thirdly, we propose an alternative semantics for IPAL, dealing with stacks of announcements, following the approach developed in [2] for PAL, and then we derive from this semantics a new sequent calculus for IPAL that is sound and complete. Fourthly, we define a translation of IPAL’s formulas into formulas of a multimodal logic in which the construct (· → ·) is the one of classical propositional logic.

2 Syntax and semantics

Let VAR be a countable set of atomic formulas called variables (denoted p, q, etc). The set of all formulas is inductively defined as follows:

- φ ::= p | ⊥ | (φ ∨ ψ) | (φ ∧ ψ) | (φ → ψ) | □φ | ◊φ | [φ]ψ | ⟨φ⟩ψ.

⊥, (· ∨ ·), (· ∧ ·) and (· → ·) are the ordinary constructs of IPL, □ ("it is necessary that . . .") and ◊ ("it is possible that . . .") are the alethic constructs of modal logic and [·] ("if . . . then, after announcing it, . . .") and ⟨·⟩ (". . . and, after announcing it, . . .") are the announcement constructs of PAL. The IPL constructs ¬· and (· ↔ ·) are defined as usual.

- ¬φ ::= (φ → ⊥),
- (φ ↔ ψ) ::= ((φ → ψ) ∧ (ψ → φ)).

We adopt the standard rules for omission of the parentheses. Note that, following the line of reasoning suggested by [17, Chapter 3], we have added the new alethic constructs □ and ◊ and the new announcement constructs [·] and ⟨·⟩ to the ordinary language of IPL. As proved in Section 7 (see Propositions 7.4 and 7.5), the constructs □ and ◊ are independent in IPAL but [·] and ⟨·⟩ are interdefinable. For all formulas φ, let φ∗ be the formula obtained by recursively eliminating the alethic constructs and the announcement constructs occurring in φ. For all sets x of formulas, let □x = {φ; □φ ∈ x} and ◊x = {◊φ; φ ∈ x}.

Let the size of a formula φ (denoted size(φ)) be the number of occurrences of symbols φ contains. The size of a finite sequence (φ1, . . . , φn) of formulas (denoted size(φ1, . . . , φn)) is the nonnegative integer defined as follows:

- size(φ1, . . . , φn) = size(φ1) + . . . + size(φn) + n.

By ε, we will denote the empty sequence of formulas. Obviously, size(ε) = 0.

A frame is a tuple of the form F = (W, ≤, R) where W is a nonempty set (denoted x, y, etc), ≤ is a partial order on W and R is a binary relation on W. The frame F = (W, ≤, R) is said to be standard if

- R−1 ◊ ≤ □ ◊ R−1,
- RO ≤ R ◊ R.
A valuation on a frame $\mathcal{F} = (W, \leq, R)$ is a function $V: \text{VAR} \rightarrow 2^W$. The valuation $V$ on the frame $\mathcal{F} = (W, \leq, R)$ is said to be upward closed if

- for all $p \in \text{VAR}$ and for all $x \in W$, if $x \in V(p)$ then for all $y \in W$, if $x \leq y$ then $y \in V(p)$.

A model is a tuple of the form $\mathcal{M} = (W, \leq, R, V)$ where $\mathcal{F} = (W, \leq, R)$ is a frame and $V$ is a valuation on $\mathcal{F}$. We shall say that the model $\mathcal{M} = (W, \leq, R, V)$ is standard if the frame $\mathcal{F} = (W, \leq, R)$ is standard. The model $\mathcal{M} = (W, \leq, R, V)$ is said to be upward closed if the valuation $V$ on the frame $\mathcal{F} = (W, \leq, R)$ is upward closed. The satisfiability relation between a model $\mathcal{M} = (W, \leq, R, V)$, an element $x \in W$ and a formula $\phi$ (denoted $\mathcal{M} \models \phi$) is inductively defined as follows:

- $\mathcal{M}, x \models p$ iff $x \in V(p)$,
- $\mathcal{M}, x \not\models \bot$,
- $\mathcal{M}, x \models \phi \lor \psi$ iff either $\mathcal{M}, x \models \phi$, or $\mathcal{M}, x \models \psi$,
- $\mathcal{M}, x \models \phi \land \psi$ iff $\mathcal{M}, x \models \phi$ and $\mathcal{M}, x \models \psi$,
- $\mathcal{M}, x \models \phi \rightarrow \psi$ iff for all $y \in W$, if $x \leq y$ and $\mathcal{M}, y \models \phi$ then $\mathcal{M}, y \models \psi$,
- $\mathcal{M}, x \models \square \phi$ iff for all $y, z \in W$, if $x \leq y$ and $yRz$ then $\mathcal{M}, z \models \phi$,
- $\mathcal{M}, x \models \Diamond \phi$ iff there exists $y \in W$ such that $xRy$ and $\mathcal{M}, y \models \phi$,
- $\mathcal{M}, x \models [\phi] \psi$ iff for all $y \in W$, if $x \leq y$ and $\mathcal{M}, y \models \phi$ then $\mathcal{M}_{[\phi]}, y \models \psi$,
- $\mathcal{M}, x \models \langle \phi \rangle \psi$ iff $\mathcal{M}, x \models \phi$ and $\mathcal{M}_{[\phi]}, x \models \psi$.

In the above definition, $\mathcal{M}_{[\phi]} = (W_{[\phi]}, \leq_{[\phi]}, R_{[\phi]}, V_{[\phi]})$ is the model such that $W_{[\phi]} = \{x \in W: \mathcal{M}, x \models \phi\}$, $\leq_{[\phi]} = \leq \cap (W_{[\phi]} \times W_{[\phi]})$, $R_{[\phi]} = R \cap (W_{[\phi]} \times W_{[\phi]})$ and for all $p \in \text{VAR}$, $V_{[\phi]}(p) = V(p) \cap W_{[\phi]}$. Notice that the clauses concerning the modal constructs $\square$ and $\Diamond$: imitate the clauses for the quantifier $\forall$ in first-order intuitionistic logic whereas the clauses concerning $\Diamond$ and $\langle \cdot \rangle$ imitate the clauses for $\exists$. See [6, Lemma 5.3.2] for details. Obviously, in any model $\mathcal{M} = (W, \leq, R, V)$,

- $\mathcal{M}, x \models \neg \phi$ iff for all $y \in W$, if $x \leq y$ then $\mathcal{M}, y \not\models \phi$,
- $\mathcal{M}, x \models \phi \leftrightarrow \psi$ iff for all $y \in W$, if $x \leq y$ then $\mathcal{M}, y \models \phi$ iff $\mathcal{M}, y \models \psi$.

Note that if $\mathcal{M}$ is upward closed then $\mathcal{M}_{[\phi]}$ is upward closed too. The next lemma states that the set of elements satisfying a formula in an upward closed standard model is upward closed too.

**Lemma 2.1** Let $\phi$ be a formula. For all upward closed standard models $\mathcal{M} = (W, \leq, R, V)$ and for all $x \in W$, if $\mathcal{M}, x \models \phi$ then $\mathcal{M}_{[\phi]}$ is upward closed standard and for all $y \in W$, if $x \leq y$ then $\mathcal{M}, y \models \phi$.

A formula $\phi$ is said to be globally satisfied in a model $\mathcal{M} = (W, \leq, R, V)$ (denoted $\mathcal{M} \models \phi$) if for all $x \in W$, $\mathcal{M}, x \models \phi$. The following Lemma will be used in Section 7.

**Lemma 2.2** Let $\phi$ be a formula. Let $\mathcal{M} = (W, \leq, R, V)$ be a model such that
\( \leq \) is the identity relation on \( W \). If \( \phi \in \text{PAL} \) then \( \mathcal{M} \models \phi \).

There are several reasons for being interested in upward closed standard models. Following the usual paradigm for IPL saying that facts should persist in a model as we ascend its partial order, the fact that \( xRy \) in a model \( \mathcal{M} = (W, \leq, R, V) \) should persist too. Hence, the condition of being standard. Similarly, the fact that \( x \in V(p) \) in a model \( \mathcal{M} = (W, \leq, R, V) \) should persist too. Thus, the condition of being upward closed.

3 Validities

We shall say that a formula \( \phi \) is ucs-valid (denoted \( \models_{\text{ucs}} \phi \)) if for all upward closed standard models \( \mathcal{M} \), \( \mathcal{M} \models \phi \).

**Proposition 3.1** The following formulas are ucs-valid and the following inference rules are ucs-validity preserving:

\[
\begin{align*}
A1 & \text{ All instances of IPL,} \\
A2 & \Box (\phi \rightarrow \psi) \rightarrow (\Box \phi \rightarrow \Box \psi), \\
A3 & \Box (\phi \rightarrow \psi) \rightarrow (\Diamond \phi \rightarrow \Diamond \psi), \\
A4 & (\Diamond \phi \rightarrow \Box \psi) \rightarrow (\Box (\phi \rightarrow \psi), \\
A5 & \Diamond (\phi \vee \psi) \rightarrow (\Diamond \phi \vee \Diamond \psi), \\
A6 & \neg \Diamond \bot, \\
A7 & [\phi]p \leftrightarrow (\phi \rightarrow p), \\
A8 & [\phi] \bot \leftrightarrow \neg \phi, \\
A9 & [\phi]([\phi] \psi) \leftrightarrow (\phi \rightarrow ([\phi] \psi \vee [\phi] \chi)).
\end{align*}
\]

**Proof.** When restricted to announcement-free formulas, the formulas A1–A6 and the inference rules R1 and R2 have been used by Fischer Servi [8] and Simpson [17, Chapter 3] who have considered the intuitionistic analogue IK of modal logic K. The formulas A7, A8, A10, A12 and A13 have been used byMa et al. [10] as reduction axioms. Hence, leaving to the reader the proof of the proposition for the formulas A9 and A11 and the inference rule R3, we only prove the proposition for the formula A14.

Suppose \( \not\models_{\text{ucs}} (\phi) \psi \leftrightarrow (\phi \land [\phi] \psi) \). Let \( \mathcal{M} = (W, \leq, R, V) \) be an upward closed standard model and \( x \in W \) be such that \( \mathcal{M}, x \not\models (\phi) \psi \leftrightarrow (\phi \land [\phi] \psi) \). Hence, either \( \mathcal{M}, x \not\models (\phi) \psi \rightarrow (\phi \land [\phi] \psi) \), or \( \mathcal{M}, x \not\models (\phi \land [\phi] \psi) \rightarrow (\phi) \psi \). In the former case, let \( y \in W \) be such that \( x < y \), \( \mathcal{M}, y \models (\phi) \psi \) and \( \mathcal{M}, y \not\models \phi \land [\phi] \psi \). Thus, \( \mathcal{M}, y \models \phi \), \( \mathcal{M}_{[\phi]}, y \models \psi \) and \( \mathcal{M}, y \not\models [\phi] \psi \). Let \( z \in W \) be such that \( y < z \), \( \mathcal{M}, z \models \phi \) and \( \mathcal{M}_{[\phi]}, z \not\models \psi \). Since \( \mathcal{M}, y \models \phi \), therefore \( y \leq_{[\phi]} z \). Since \( \mathcal{M}_{[\phi]}, y \models \psi \), therefore by Lemma 2.1, \( \mathcal{M}_{[\phi]}, z \models \psi \) a contradiction. In the latter case, let \( y \in W \) be such that \( x < y \), \( \mathcal{M}, y \models \phi \land [\phi] \psi \) and \( \mathcal{M}, y \not\models (\phi) \psi \). Consequently, \( \mathcal{M}, y \models \phi \), \( \mathcal{M}, y \models [\phi] \psi \) and \( \mathcal{M}_{[\phi]}, y \not\models \psi \). Hence, \( \mathcal{M}_{[\phi]}, y \models \psi \) a contradiction. Thus, \( \not\models_{\text{ucs}} (\phi) \psi \leftrightarrow (\phi \land [\phi] \psi) \). \( \square \)
Proposition 3.2 The following formulas are ucs-valid and the following inference rule is ucs-validity preserving:

\begin{align*}
A15 & \quad [\phi](\psi \to \chi) \to ([\phi] \psi \to [\phi] \chi), & A18 & \quad \langle \phi \rangle (\psi \lor \chi) \to (\langle \phi \rangle \psi \lor \langle \phi \rangle \chi), \\
A16 & \quad [\phi](\psi \to \chi) \to (\langle \phi \rangle \psi \to \langle \phi \rangle \chi), & R4 & \quad \text{from } \phi \text{ infer } [\psi] \phi.
\end{align*}

\begin{proof}
Left to the reader. \qed
\end{proof}

Proposition 3.3 The following formulas are ucs-valid:

\begin{align*}
A19 & \quad [\phi] \top \leftrightarrow \top, & A25 & \quad \langle \phi \rangle (\psi \to \chi) \leftrightarrow \phi \land (\langle \phi \rangle \psi \to \langle \phi \rangle \chi), \\
A20 & \quad (\phi) \bot \leftrightarrow \bot, & A26 & \quad \langle \phi \rangle \Diamond \psi \leftrightarrow \phi \land \Diamond \langle \phi \rangle \psi, \\
A21 & \quad (\phi) \top \leftrightarrow \phi, & A27 & \quad \langle \phi \rangle p \leftrightarrow \phi \land p, \\
A22 & \quad [\phi](\psi \lor \chi) \leftrightarrow (\phi \to \langle \phi \rangle \psi \lor \langle \phi \rangle \chi), & A28 & \quad \langle \phi \rangle (\psi \land \chi) \leftrightarrow \langle \phi \rangle \psi \land \langle \phi \rangle \chi, \\
A23 & \quad (\phi)(\psi \lor \chi) \leftrightarrow (\phi) \psi \lor \langle \phi \rangle \chi, & A29 & \quad \langle \phi \rangle \Box \psi \leftrightarrow \phi \land \Box [\phi] \psi.
\end{align*}

\begin{proof}
Left to the reader. \qed
\end{proof}

Note that the set of all ucs-valid formulas is not closed under the inference rule of uniform substitution. For example, the formula \([p]p\) is ucs-valid but its instance \([q \land \Diamond \neg q](q \land \Diamond \neg q)\) is not globally satisfied in the upward closed standard model \(M = (W, \leq, R, V)\) where \(W = \{x, y\}\), \(\leq = \{(x, x), (y, y)\}\), \(R = \{(x, y)\}\) and \(V(q) = \{x\}\). Hence, we should be very careful when applying to \(IPAL\) tools and techniques designed for normal modal logic.

4 Axiomatization/completeness

Let \(IPAL\) be the least set of formulas containing the formulas A1–A14 and closed under the inference rules R1–R3. The soundness of \(IPAL\) relative to its relational semantics is straightforward, seeing that

**Proposition 4.1 (Soundness)** Let \(\phi\) be a formula. If \(\phi \in IPAL\) then \(\models_{ucs} \phi\).

**Proof.** By Proposition 3.1. \qed

Without using the standard toolkit of duality theory in modal logic and the results in [10], the completeness of \(IPAL\) relative to its relational semantics is more difficult to establish than its soundness and we defer proving that \(IPAL\) is complete with respect to the class of all upward closed standard models till the end of this section. A useful result is the following

**Proposition 4.2** Let \(\phi\) be a formula and \(\psi\) be an announcement-free formula such that \(\phi \leftrightarrow \psi \in IPAL\). Let \(\chi\) be an announcement-free formula. There exists an announcement-free formula \(\theta\) such that \([\phi] \chi \leftrightarrow \theta \in IPAL\). Moreover, if \(\psi\) and \(\chi\) are \(\Box\)-free (respectively, \(\Diamond\)-free) then \(\theta\) is \(\Box\)-free (respectively, \(\Diamond\)-free).
Proof. Let \( \text{FOR} \) be the set of all announcement-free formulas \( \chi \) such that there exists an announcement-free formula \( \theta \) such that \([\phi]\chi \leftrightarrow \theta \in \text{IPAL}\) and, moreover, if \( \psi \) and \( \chi \) are \( \Diamond \)-free (respectively, \( \Diamond \)-free) then \( \theta \) is \( \Box \)-free (respectively, \( \Diamond \)-free). Proposition 4.2 says that for all announcement-free formulas \( \chi \), \( \chi \in \text{FOR} \). We will demonstrate it by an induction on \( \chi \) based on the function \( \text{size}() \) defined in Section 2. Let \( \chi \) be an announcement-free formula such that for all announcement-free formulas \( \mu \), if \( \text{size}(\mu) < \text{size}(\chi) \) then \( \mu \in \text{FOR} \). We demonstrate \( \chi \in \text{FOR} \). We only consider the case \( \chi = \Box \mu \).

Note that \( \text{size}(\mu) < \text{size}(\chi) \). Hence, \( \mu \in \text{FOR} \). Let \( \theta \) be an announcement-free formula such that \([\phi]\mu \leftrightarrow \theta \in \text{IPAL}\). By A13, \([\phi]\Box \mu \leftrightarrow (\phi \rightarrow (\Box (\phi) \mu) \in \text{IPAL}\). Since \( \phi \leftrightarrow \psi \in \text{IPAL} \), therefore \([\phi]\Box \mu \leftrightarrow (\phi \rightarrow (\Box (\phi) \mu) \in \text{IPAL} \). By A14, \((\phi) \mu \leftrightarrow (\phi \land [\phi] \mu) \in \text{IPAL} \). Since \( \phi \leftrightarrow \psi \in \text{IPAL} \) and \([\phi] \mu \leftrightarrow \theta \in \text{IPAL} \), therefore \( (\phi) \mu \leftrightarrow (\psi \land \theta) \in \text{IPAL} \). Thus, \( (\phi) \mu \leftrightarrow (\psi \land \theta) \in \text{IPAL} \).

From Proposition 4.2, it follows that

**Proposition 4.3** For all formulas \( \phi \), there exists an announcement-free formula \( \psi \) such that \( \phi \leftrightarrow \psi \in \text{IPAL} \). Moreover, if \( \phi \) is \( \Box \)-free (respectively, \( \Diamond \)-free) then \( \psi \) is \( \Box \)-free (respectively, \( \Diamond \)-free).

Proof. Let \( \text{FOR} \) be the set of all formulas \( \phi \) such that there exists an announcement-free formula \( \psi \) such that \( \phi \leftrightarrow \psi \in \text{IPAL} \) and, moreover, if \( \phi \) is \( \Box \)-free (respectively, \( \Diamond \)-free) then \( \psi \) is \( \Box \)-free (respectively, \( \Diamond \)-free). Proposition 4.3 says that for all formulas \( \phi, \phi \in \text{FOR} \). We will demonstrate it by an induction on \( \phi \) based on the function \( \text{size}() \) defined in Section 2. Let \( \phi \) be a formula such that for all announcement-free formulas \( \psi \), if \( \text{size}(\psi) < \text{size}(\phi) \) then \( \psi \in \text{FOR} \). We demonstrate \( \phi \in \text{FOR} \). We only consider the case \( \phi = [\psi] \chi \).

Note that \( \text{size}(\psi) < \text{size}(\phi) \) and \( \text{size}(\chi) < \text{size}(\phi) \). Hence, \( \psi \in \text{FOR} \) and \( \chi \in \text{FOR} \). Let \( \theta \) be an announcement-free formula such that \( \psi \leftrightarrow \theta \in \text{IPAL} \) and \( \mu \) be an announcement-free formula such that \( \chi \leftrightarrow \mu \in \text{IPAL} \). By R3, \([\psi] \chi \leftrightarrow [\psi] \mu \in \text{IPAL} \). Let \( \nu \) be an announcement-free formula such that \( [\psi] \mu \leftrightarrow \nu \in \text{IPAL} \). Such \( \nu \) exists by Proposition 4.2 because \( \psi \leftrightarrow \theta \in \text{IPAL} \). Since \( [\psi] \chi \leftrightarrow [\psi] \mu \in \text{IPAL} \), therefore \( [\psi] \chi \leftrightarrow \nu \in \text{IPAL} \).

Now, we are ready for the proof of the completeness of \( \text{IPAL} \) relative to its relational semantics.

**Proposition 4.4 (Completeness)** Let \( \phi \) be a formula. If \( \models_{\text{ucs}} \phi \) then \( \phi \in \text{IPAL} \).

Proof. Suppose \( \models_{\text{ucs}} \phi \) and \( \phi \notin \text{IPAL} \). Let \( \psi \) be an announcement-free formula such that \( \phi \leftrightarrow \psi \in \text{IPAL} \). Such formula exists by Proposition 4.3. Since \( \phi \notin \text{IPAL} \), therefore \( \psi \notin \text{IPAL} \). By the Canonical Model Construction described in [17, Chapter 3], \( \not\models_{\text{ucs}} \psi \). Since \( \phi \leftrightarrow \psi \in \text{IPAL} \), therefore by Proposition 4.1, \( \not\models_{\text{ucs}} \phi \). Since \( \not\models_{\text{ucs}} \psi \), therefore \( \not\models_{\text{ucs}} \phi \), a contradiction. Hence, if \( \models_{\text{ucs}} \phi \) then \( \phi \in \text{IPAL} \).

In the definition of \( \text{IPAL} \), we did not use the formulas A15–A29 and the inference rule R4 considered in Propositions 3.2 and 3.3. Why not? The reason
is that neither the formulas $A15$–$A29$ nor the inference rule $R4$ are used in the proof of Propositions 4.2 and 4.3. Moreover,

**Proposition 4.5** The formulas $A15$–$A29$ are in IPAL and the inference rule $R4$ is admissible in IPAL.

**Proof.** By Propositions 3.2, 3.3, 4.1 and 4.4. □

5 **Canonical model**

Let $L$ be an extension of IPAL, i.e. $L$ is a set of formulas containing the formulas $A11$–$A14$ and closed under the inference rules $R1$–$R3$. For all sets $x, y$ of formulas, $y$ is said to be an $L$-consequence of $x$ (denoted $x \vdash_L y$) if there exists nonnegative integers $m, n$ and there exists formulas $\phi_1, \ldots, \phi_m, \psi_1, \ldots, \psi_n$ such that $\phi_1, \ldots, \phi_m \in x$, $\psi_1, \ldots, \psi_n \in y$ and $\phi_1 \land \ldots \land \phi_m \rightarrow \psi_1 \lor \ldots \lor \psi_n \in L$. In this definition, if $m = 0$ then we will consider that $\phi_1 \land \ldots \land \phi_m$ is equal to $\top$ and if $n = 0$ then we will consider that $\psi_1 \lor \ldots \lor \psi_n$ is equal to $\bot$. In the sequel, we will always assume that $\emptyset \not\vdash_L \emptyset$, i.e. we will always assume that $\top \rightarrow \bot \not\in L$.

We shall say that a set $x$ of formulas is $L$-prime if the following conditions hold:

- for all formulas $\phi$, if $x \vdash_L \{\phi\}$ then $\phi \in x$,
- $x \vdash_L \{\bot\}$,
- for all formulas $\phi, \psi$, if $\phi \lor \psi \in x$ then either $\phi \in x$, or $\psi \in x$.

**Lemma 5.1** (Prime Lemma) For all sets $x, y$ of formulas, if $x \not\vdash_L y$ then there exists an $L$-prime set $x'$ of formulas such that $x \subseteq x'$ and $x' \not\vdash_L y$.

Since $\emptyset \not\vdash_L \emptyset$, therefore the set of all $L$-prime sets of formulas is nonempty. $L$’s Canonical Model is the tuple $M_c = (W_c, \leq_c, R_c, V_c)$ where $W_c$ is the set of all $L$-prime sets of formulas, $\leq_c$ is the partial order on $W_c$ defined by $x \leq_c y$ if $x \subseteq y$, $R_c$ is the binary relation on $W_c$ defined by $xR_c y$ iff $x \leq_c y$ and $\diamond y \subseteq x$ and $V_c: \text{VAR} \rightarrow 2^{W_c}$ is the function defined by $x \in V_c(p)$ iff $p \in x$.

**Lemma 5.2** The model $M_c$ is upward closed standard.

**Lemma 5.3** (Restricted Truth Lemma) Let $\phi$ be an announcement-free formula. For all $L$-prime sets $x$ of formulas, the following conditions are equivalent: (i) $M_c, x \models \phi$, (ii) $\phi \in x$.

**Lemma 5.4** (Truth Lemma) Let $\phi$ be a formula. For all $L$-prime sets $x$ of formulas, the following conditions are equivalent: (i) $M_c, x \models \phi$, (ii) $\phi \in x$.

In Section 7, we will consider an extension of IPAL that contains all formulas of the form $\phi \lor \neg \phi$.

**Proposition 5.5** Let $L$ be an extension of IPAL that contains all formulas of the form $\phi \lor \neg \phi$. For all $L$-primes sets $x, y$ of formulas, if $x \subseteq y$ then $x = y$.

**Proof.** Let $x, y$ be $L$-primes sets of formulas. Suppose $x \subseteq y$ and $x \neq y$. Hence, $y \not\subseteq x$. Let $\psi$ be a formula such that $\psi \in y$ and $\psi \not\in x$. Since $L$ is an extension of IPAL that contains all formulas of the form $\phi \lor \neg \phi$, therefore $\psi \lor \neg \psi \in x$. Thus, either $\psi \in x$, or $\neg \psi \in x$. Since $\psi \not\in x$, therefore
\(\neg \psi \in x\). Since \(x \subseteq y\), therefore \(\neg \psi \in y\). Since \(\psi \in y\), therefore \(y \models_L \{\bot\}\): a contradiction. Consequently, if \(x \subseteq y\) then \(x = y\). □

6 Relationship with Ma et al. [10]

A formula \(\phi\) is said to be a-valid (denoted \(\models_a \phi\)) if for all algebraic models \(M = \langle A, 0_A, 1_A, +_A, \times_A, \Rightarrow_A, I_A, m_A, V\rangle\) (called Fischer Servi models in [10]),

\[\models_M \phi\]

Proposition 6.1 Let \(\phi\) be a formula. If \(\models_{ucs} \phi\) then \(\models_a \phi\).

Proof. Suppose \(\models_{ucs} \phi\) and \(\not\models_a \phi\). By Proposition 4.4, \(\phi \in IPAL\). Since the formulas considered in Proposition 3.1 are a-valid and the inference rules considered in Proposition 3.1 are a-validity preserving, therefore \(\models_a \phi\): a contradiction. □

Proposition 6.2 Let \(\phi\) be a formula. If \(\models_a \phi\) then \(\models_{ucs} \phi\).

Proof. Suppose \(\models_a \phi\) and \(\not\models_{ucs} \phi\). By [10], \(\phi\) is derivable from the axioms and the inference rules considered in [10, Section 4.1]. Obviously, these axioms are standard-valid and these inference rules are standard-validity preserving. Hence, \(\models_{ucs} \phi\): a contradiction. □

Let \(IPAL'\) be the least set of formulas containing the formulas A1–A8, A10, A13 and A19–A29 and closed under the inference rules R1 and R2. The deducibility relation between a finite set \(X\) of variables and a formula \(\phi\) (denoted \(X \models \phi\)) is inductively defined as follows:

- \(X \models p\) iff \(p \in X\),
- \(X \not\models \perp\),
- \(X \models \phi \lor \psi\) iff either \(X \models \phi\), or \(X \models \psi\),
- \(X \models \phi \land \psi\) iff \(X \models \phi\) and \(X \models \psi\),
- \(X \models \phi \rightarrow \psi\) iff \(X \models \phi\) then \(X \models \psi\),
- \(X \models \Box \phi\) iff \(X \models \phi\),
- \(X \models \Diamond \phi\) iff \(X \models \phi\),
- \(X \models [\phi] \psi\) iff \(X \models \phi\) then \(X \models \psi^*\),
- \(X \models (\phi) \psi\) iff \(X \models \phi\) and \(X \models \psi^*\).

Note that the axioms and the inference rules considered in [10, Section 4.1] do not explicitly contain the inference rule R3. Hence, they are those of \(IPAL'\). We believe that this absence of the inference rule R3 is only a careless mistake, seeing that

Lemma 6.3 Let \(X\) be a finite set of variables and \(\phi\) be a formula. If \(\phi \in IPAL'\) then \(X \models \phi\).

Lemma 6.4 Let \(X\) be a finite set of variables. If \(p \in X\), \(q \not\in X\) and \(r \in X\) then \(X \models \langle p\rangle \langle q\rangle r\) and \(X \not\models \langle p\rangle \langle q\rangle r\).

Proposition 6.5

(i) \(\langle p\rangle \langle q\rangle r \rightarrow \langle p\rangle \langle q\rangle r \in IPAL\).

(ii) \(\langle p\rangle \langle q\rangle r \not\rightarrow \langle p\rangle \langle q\rangle r \not\in IPAL'\).

Proof. (i) It suffices to use the completeness of \(IPAL\) (Proposition 4.4) and the fact that \(\langle p\rangle \langle q\rangle r \rightarrow \langle p\rangle \langle q\rangle r\) is ucs-valid.

(ii) By Lemmas 6.3 and 6.4. □
7 Other properties of IPAL

In [17], Simpson discusses what it means to combine IPL and modal logic into intuitionistic modal logic (IML) and isolates features that might be expected of an IML. In the following proposition, we examine whether IPAL complies with Simpson’s requirements.

**Proposition 7.1**

(i) IPAL is conservative over IPL.

(ii) IPAL contains all instances of IPL.

(iii) IPAL is closed under modus ponens.

(iv) The addition of the formulas of the form \( \phi \lor \neg \phi \) to IPAL yields PAL.

(v) If \( \phi \lor \psi \in IPAL \) then either \( \phi \in IPAL \), or \( \psi \in IPAL \).

**Proof.**

(i) Let \( \phi \) be a modality-free formula. To prove that \( \phi \in IPAL \) iff \( \phi \in IPL \), it suffices to use the soundness/completeness of IPAL (Propositions 4.1 and 4.4) and IPL (Theorem 2.43 in [5]).

(ii) By definition, IPAL contains all instances of IPL.

(iii) By definition, IPAL is closed under modus ponens.

(iv) Let \( \not\in IPAL^+ \) be the axiom system consisting of the addition of the formulas of the form \( \phi \lor \neg \phi \) to IPAL. Suppose IPAL \(^+\) does not yield PAL. Hence, IPAL \(^+\) \(\not\subseteq\) PAL. Obviously, IPAL \(^+\) \(\not\subseteq\) PAL. Since IPAL \(^+\) \(\not\subseteq\) PAL, therefore PAL \(\not\subseteq\) IPAL \(^+\). Let \( \psi \) be a formula such that \( \psi \in PAL \) and \( \psi \not\in IPAL^+ \). Let \( \chi \) be an announcement-free formula such that \( \psi \leftrightarrow \chi \in IPAL \). Such formula exists by Proposition 4.3. Thus, \( \psi \leftrightarrow \chi \in IPAL^+ \). Since \( \psi \not\in IPAL^+ \), therefore \( \chi \not\in IPAL^+ \). Let \( M_c = (W_c, \leq_c, R_c, V_c) \) be IPAL \(^+\)’s Canonical Model. Since \( \chi \not\in IPAL^+ \), therefore by Lemmas 5.1 and 5.4, there exists \( x \in W_c \) such that \( M_c, x \not\models \chi \). Since IPAL \(^+\) is an extension of IPAL that contains all formulas of the form \( \phi \lor \neg \phi \), therefore by Proposition 5.5, \( \leq_c \) is the identity relation on \( W_c \). Since \( M_c, x \not\models \chi \), therefore by Lemma 2.2, \( \chi \not\in PAL \). Obviously, IPAL \(\not\subseteq\) PAL. Since \( \psi \leftrightarrow \chi \in IPAL \), therefore \( \psi \not\in IPAL \). Since \( \psi \not\in IPAL \), therefore \( \psi \not\in PAL \): a contradiction. Consequently, IPAL \(^+\) yields PAL.

(v) Suppose \( \phi \lor \psi \in IPAL \), \( \phi \not\in IPAL \) and \( \psi \not\in IPAL \). By Propositions 4.1 and 4.4, \( |_{uc} \phi \lor \psi \not\models \phi \) and \( \not\models |_{uc} \psi \). Let \( M_1 = (W_1, \leq_1, R_1, V_1) \) be an upward closed standard model such that \( M_1 \not\models \phi \) and \( M_2 = (W_2, \leq_2, R_2, V_2) \) be an upward closed standard model such that \( M_2 \not\models \psi \). Let \( x \) be a new element and \( M = (W, \leq, R, V) \) be the model where \( W = W_1 \cup W_2 \cup \{ x \} \), \( \leq = \leq_1 \cup \leq_2 \cup \{ x \} \times W_1 \cup \{ \{ x \} \times W_2 \} \), \( R = R_1 \cup R_2 \) and for all \( p \in VAR \), \( V(p) = V_1(p) \cup V_2(p) \). The reader may easily verify that \( M \) is upward closed standard. Moreover, \( M_1 \) and \( M_2 \) are generated submodel of \( M \). A result similar to Proposition 2.6 in [4] would lead to the conclusion that the global satisfiability relation is invariant under generated submodels. Since \( M_1 \not\models \phi \) and \( M_2 \not\models \psi \), therefore \( M \not\models \phi \) and \( M \not\models \psi \). Since \( |_{uc} \phi \lor \psi \), therefore \( M, x \models \phi \lor \psi \). Hence, either \( M, x \models \phi \) or \( M, x \models \psi \). In the former case, let \( y \in W_1 \) be arbitrary. Thus, \( x \leq y \). Since \( M, x \models \phi \) therefore by Lemma 2.1, \( M, y \models \phi \). Consequently, \( M_1, y \models \phi \). Since \( y \) was arbitrary, therefore \( M_1 \models \phi \):
a contradiction. In the latter case, let \( y \in W_2 \) be arbitrary. Hence, \( x \leq y \). Since \( \mathcal{M}, x \models \psi \), therefore by Lemma 2.1, \( \mathcal{M}, y \models \psi \). Thus, \( \mathcal{M}_2, y \models \psi \). Since \( y \) was arbitrary, therefore \( \mathcal{M}_2 \models \psi \): a contradiction. Consequently, if \( \phi \lor \psi \in \text{IPAL} \) then either \( \phi \in \text{IPAL} \), or \( \psi \in \text{IPAL} \). □

In [17, Chapter 3], Simpson proves the following

**Proposition 7.2**

(i) For all announcement-free formulas \( \phi \), if \( \phi \in \text{IK} \) then \( \models_{\text{ucs}} \phi \).

(ii) For all announcement-free formulas \( \phi \), if \( \models_{\text{ucs}} \phi \) then \( \phi \in \text{IK} \).

(iii) There exists no \( \square \)-free announcement-free formula \( \phi \) such that \( \square \phi \leftrightarrow \phi \in \text{IK} \).

(iv) There exists no \( \Diamond \)-free announcement-free formula \( \phi \) such that \( \Diamond \phi \leftrightarrow \phi \in \text{IK} \).

From the soundness/completeness of \( \text{IPAL} \) (Propositions 4.1 and 4.4) and \( \text{IK} \) (Items 1 and 2 of Proposition 7.2), we obtain the following

**Proposition 7.3** \( \text{IPAL} \) is conservative over \( \text{IK} \).

The following propositions characterize a main difference between, on one hand, the modal constructs \( \square \) and \( \Diamond \) and, on the other hand, \( [\cdot] \) and \( \langle \cdot \rangle \).

**Proposition 7.4**

(i) There exists no \( \square \)-free formula \( \phi \) such that \( \square \phi \leftrightarrow \phi \in \text{IPAL} \).

(ii) There exists no \( \Diamond \)-free formula \( \phi \) such that \( \Diamond \phi \leftrightarrow \phi \in \text{IPAL} \).

**Proof.** (i) By Proposition 4.3, Item 3 of Proposition 7.2 and Proposition 7.3.

(ii) By Proposition 4.3, Item 4 of Proposition 7.2 and Proposition 7.3. □

**Proposition 7.5**

(i) \( [\phi] \psi \leftrightarrow (\phi \rightarrow \langle \phi \rangle \psi) \in \text{IPAL} \).

(ii) \( \langle \phi \rangle \psi \leftrightarrow (\phi \land [\phi] \psi) \in \text{IPAL} \).

**Proof.** (i) Suppose \( [\phi] \psi \leftrightarrow (\phi \rightarrow \langle \phi \rangle \psi) \notin \text{IPAL} \). By Proposition 4.4, \( \not\models_{\text{ucs}} [\phi] \psi \leftrightarrow (\phi \rightarrow \langle \phi \rangle \psi) \). Let \( \mathcal{M} = (W, \leq, R, V) \) be an upward closed standard model and \( x \in W \) be such that \( \mathcal{M}, x \not\models [\phi] \psi \leftrightarrow (\phi \rightarrow \langle \phi \rangle \psi) \). Hence, either \( \mathcal{M}, x \not\models [\phi] \psi \rightarrow (\phi \rightarrow \langle \phi \rangle \psi) \) or \( \mathcal{M}, x \not\models (\phi \rightarrow \langle \phi \rangle \psi) \rightarrow [\phi] \psi \). In the former case, let \( y \in W \) be such that \( x \leq y \). \( \mathcal{M}, y \models [\phi] \psi \) and \( \mathcal{M}, y \not\models \phi \rightarrow \langle \phi \rangle \psi \). Let \( z \in W \) be such that \( y \leq z \), \( \mathcal{M}, z \models \phi \) and \( \mathcal{M}, z \not\models \langle \phi \rangle \psi \). Since \( y \leq z \) and \( \mathcal{M}, z \models \phi \), therefore \( \mathcal{M}, y \not\models [\phi] \psi \): a contradiction. In the latter case, let \( y \in W \) be such that \( x \leq y \). \( \mathcal{M}, y \models \phi \rightarrow \langle \phi \rangle \psi \) and \( \mathcal{M}, y \not\models [\phi] \psi \). Let \( z \in W \) be such that \( y \leq z \), \( \mathcal{M}, z \models \phi \) and \( \mathcal{M}, z \not\models \langle \phi \rangle \psi \). Consequently, \( \mathcal{M}, z \not\models \langle \phi \rangle \psi \). Since \( y \leq z \) and \( \mathcal{M}, z \models \phi \), therefore \( \mathcal{M}, y \not\models \phi \rightarrow \langle \phi \rangle \psi \): a contradiction. Hence, \( [\phi] \psi \leftrightarrow (\phi \rightarrow \langle \phi \rangle \psi) \in \text{IPAL} \).

(ii) By definition, \( [\phi] \psi \leftrightarrow (\phi \land [\phi] \psi) \in \text{IPAL} \). □

### 8 An alternative semantics

A proof-theoretical analysis of \( \text{PAL} \) has been proposed in [11] in terms of a sequent calculus following the approach of [13]. Unfortunately, this sequent
calculus is not complete as it cannot prove the valid formula $[p \land p]q \leftrightarrow [p]q$. For details, see [2] where an alternative semantics for \textit{PAL} and a sequent calculus with labels that were based on a specific management of a stack of announcements have been proposed. A similar alternative semantics for \textit{IPAL} can be proposed too. Its definition necessitates the satisfiability relation between a model $M = (W, \leq, R, V)$, an element $x \in W$, a finite sequence $\varphi = (\phi_1, \ldots, \phi_n)$ of formulas and a formula $\phi$ (denoted $M, x, (\varphi) \models \phi$) inductively defined as follows:

- $M, x, \epsilon \models p$ iff $x \in V(p)$,
- $M, x, (\varphi, \phi_{n+1}) \models p$ iff $M, x, (\varphi) \models \phi_{n+1}$ and $M, x, (\varphi) \models p$,
- $M, x, (\varphi) \not\models \bot$,
- $M, x, (\varphi) \models \phi \lor \psi$ iff either $M, x, (\varphi) \models \phi$, or $M, x, (\varphi) \models \psi$,
- $M, x, (\varphi) \models \phi \land \psi$ iff $M, x, (\varphi) \models \phi$ and $M, x, (\varphi) \models \psi$,
- $M, x, \epsilon \models \phi \rightarrow \psi$ iff for all $y \in W$, if $x \leq y$ and $M, y, \epsilon \models \phi$ then $M, y, \epsilon \models \psi$,
- $M, x, (\varphi, \phi_{n+1}) \models \phi \rightarrow \psi$ iff for all $y \in W$, if $x \leq y$, $M, y, (\varphi) \models \phi_{n+1}$ and $M, y, (\varphi, \phi_{n+1}) \models \psi$,
- $M, x, \epsilon \models \square \phi$ iff for all $y, z \in W$, if $x \leq y$ and $yRz$ then $M, z, \epsilon \models \phi$,
- $M, x, (\varphi, \phi_{n+1}) \models \square \phi$ iff for all $y, z \in W$, if $x \leq y$, $yRz$, $M, y, (\varphi) \models \phi_{n+1}$ and $M, z, (\varphi) \models \phi_{n+1}$ then $M, z, (\varphi, \phi_{n+1}) \models \phi$,
- $M, x, \epsilon \models \diamond \phi$ iff there exists $y \in W$ such that $xRy$ and $M, y, \epsilon \models \phi$,
- $M, x, (\varphi, \phi_{n+1}) \models \diamond \phi$ iff there exists $y \in W$ such that $xRy$, $M, y, (\varphi) \models \phi_{n+1}$ and $M, y, (\varphi, \phi_{n+1}) \models \phi$,
- $M, x, \epsilon \models [\phi] \psi$ iff for all $y \in W$, if $x \leq y$ and $M, y, \epsilon \models \phi$ then $M, y, (\phi) \models \psi$,
- $M, x, (\varphi, \phi_{n+1}) \models [\phi] \psi$ iff for all $y \in W$, if $x \leq y$, $M, y, (\varphi) \models \phi_{n+1}$ and $M, y, (\varphi, \phi_{n+1}) \models \phi$ then $M, y, (\phi, \phi_{n+1}) \models \psi$,
- $M, x, (\varphi) \models [\phi] \psi$ iff $M, x, (\varphi, \phi_{n+1}) \models \phi$ and $M, x, (\phi, \psi) \models \psi$.

The reader may easily verify that the above definition of $M, x, (\varphi) \models \phi$ is correct decreasing on $\text{size}(\varphi, \phi)$. A similar stack-based semantics has been proposed by Balbiani \textit{et al.} [2] within the context of \textit{PAL}. The main difference with the semantics proposed by [11] lies in our interpretation of $\square$-based formulas.

Lemma 8.1 Let $(\phi_1, \ldots, \phi_n)$ be a sequence of formulas and $\phi$ be a formula. For all models $M = (W, \leq, R, V)$ and for all $x \in W$, the following conditions are equivalent: (i) $M, x \models [\phi_1] \ldots [\phi_n] \phi$, (ii) if $M, x, \epsilon \models \phi_1, \ldots, M, x, (\phi_1, \ldots, \phi_{n-1}) \models \phi_n$ then $M, x, (\phi_1, \ldots, \phi_n) \models \phi$.

9 A labelled sequent calculus

Now, we present a sequent calculus for \textit{IPAL} that is derived from the stack-based semantics given in the previous section. We propose a labelled calculus.
in which labels are defined for capturing the semantics inside the sequent calculus. This approach based on labels is a uniform approach for designing calculi in various logics like modal or intuitionistic logics [13,17] from Kripke-style semantics. We want to emphasize that starting from our stack-based semantics is central here because the similar semantics proposed for PAL allowed us to propose a new labelled calculus for PAL that corrected the deficiency about completeness of an existing labelled sequent calculus [11]. Therefore we propose a sound and complete calculus with sequents that are with multiconclusions, and with distinguished rules for dealing with empty and non-empty stacks of announcements. Let Var be a countable set of variables (denoted x, y, etc). The sequents are pairs of finite sets of expressions either of the form x(\phi) : \phi read “state x satisfies \phi with respect to the sequence (\phi)”, or of the form xRy read “state x is related to state y by means of R”. The sequent \Gamma \vdash \Delta means that the conjunction of the expressions in \Gamma implies the disjunction of the expressions in \Delta. Provability is defined as usual: formula \phi is provable iff the sequent \Gamma \vdash x(\phi) : \phi is derivable from the inference rules of the calculus presented in Figures 1 and 2. Let \mathcal{M} = (W, R, V) be a model and \gamma : Var \mapsto W. Sequents are pairs of finite sets of expressions either of the form x(\phi_1, \ldots, \phi_n) : \phi, or of the form xRy. We define the property “\mathcal{M} and \gamma satisfy the expression exp” (denoted \mathcal{M}, \gamma \vdash exp) as follows:

- \mathcal{M}, \gamma \vdash x(\phi_1, \ldots, \phi_n) : \phi \iff \mathcal{M}, \gamma(x), (\phi_1, \ldots, \phi_n) \vdash \phi,

- \mathcal{M}, \gamma \vdash xRy \iff \gamma(xR\gamma(y)).

![Inference rules for IPAL - intuitionistic rules.](image)
Let \( \phi \) be a formula. If \( \phi \) is provable then \( \phi \) is ucs-valid.

**Proof.** It suffices to demonstrate that the inference rules considered in Figures 1 and 2 are validity preserving. \( \square \)

**Proposition 9.2** Let \( \phi \) be a formula. If \( \phi \) is ucs-valid then \( \phi \) is provable.

**Proof.** By Proposition 4.4, it suffices to demonstrate that the formulas considered in Proposition 3.1 are provable and the inference rules considered in Proposition 3.1 are provability preserving. \( \square \)

In Nomura et al. [14], a labelled sequent calculus has been recently given for \( IPAL \). It is basically the same as the one for \( PAL \) [15] but with, in some rules, restrictions on labelled expressions on the right-hand side of sequents. As this calculus does not use an announcement stack discipline and has such restrictions, it cannot be directly and easily compared with our new calculus. In future work, we will try to compare them with respect, for instance, to proof-search issues and also to explore possible translations between these calculi.
10 Translation into S4PAL

By Gödel’s Translation, any formula of the IPL’s language can be translated into a formula of the S4’s language such that the resulting translation is in S4 if the translated formula is in IPL. See [5, Chapter 3] for details. Within the context of IPL, the translation of a formula \( \phi \) (denoted \( \tau(\phi) \)) is the formula inductively defined as follows:

- \( \tau(p) = \Box p \),
- \( \tau(\bot) = \bot \),
- \( \tau(\phi \lor \psi) = \tau(\phi) \lor \tau(\psi) \),
- \( \tau(\phi \land \psi) = \tau(\phi) \land \tau(\psi) \),
- \( \tau(\phi \to \psi) = \Box(\tau(\phi) \to \tau(\psi)) \),
- \( \tau(\Box \phi) = \Box \tau(\phi) \),
- \( \tau(\Diamond \phi) = \Diamond \tau(\phi) \),
- \( \tau([\phi]\psi) = \Box[\tau(\phi)]\tau(\psi) \),
- \( \tau(\langle \phi \rangle \psi) = \langle \tau(\phi) \rangle \tau(\psi) \).

The resulting translations belong to the S4PAL’s language, i.e. the set of all formulas inductively defined as follows:

- \( \phi ::= p \mid \bot \mid \neg \phi \mid (\phi \lor \psi) \mid \Box \phi \mid \Diamond \phi \mid [\phi]\psi \).

In the S4PAL’s language, the Boolean constructs (\( \cdot \land \cdot \)) and (\( \cdot \to \cdot \)), the modal constructs \( \Box \) and \( \Diamond \), and the announcement construct \( [\cdot] \) are defined as usual. Moreover, the standard rules for omission of the parentheses are adopted. The formulas of the S4PAL’s language are interpreted in models, their \( \leq \) binary relations being used to interpret \( \Box \)-based formulas and their \( R \) binary relations being used to interpret \( \Diamond \)-based formulas. More precisely, the satisfiability relation between a model \( \mathcal{M} = (W, \leq, R, V) \), an element \( x \in W \) and a formula \( \phi \) in the S4PAL’s language (denoted \( \mathcal{M}, x \models \phi \)) is inductively defined as follows:

- \( \mathcal{M}, x \models p \) iff \( x \in V(p) \),
- \( \mathcal{M}, x \not\models \bot \),
- \( \mathcal{M}, x \models \phi \lor \psi \) iff either \( \mathcal{M}, x \models \phi \), or \( \mathcal{M}, x \models \psi \),
- \( \mathcal{M}, x \models \Box \phi \) iff for all \( y \in W \), if \( x \leq y \) then \( \mathcal{M}, y \models \phi \),
- \( \mathcal{M}, x \models \Diamond \phi \) iff for all \( y \in W \), if \( xRy \) then \( \mathcal{M}, y \models \phi \),
- \( \mathcal{M}, x \models [\phi]\psi \) iff if \( \mathcal{M}, x \models \phi \) then \( \mathcal{M}_{[\phi]}, x \models \psi \).

In the above definition, \( \mathcal{M}_{[\phi]} = (W_{[\phi]}, \leq_{[\phi]}, R_{[\phi]}, V_{[\phi]}) \) is the model such that \( W_{[\phi]} = \{ x \in W : \mathcal{M}, x \models \phi \} \), \( \leq_{[\phi]} = \leq \cap (W_{[\phi]} \times W_{[\phi]}) \), \( R_{[\phi]} = R \cap (W_{[\phi]} \times W_{[\phi]}) \) and for all \( p \in VAR \), \( V_{[\phi]}(p) = V(p) \cap W_{[\phi]} \). Note that if \( \mathcal{M} \) is upward closed then \( \mathcal{M}_{[\phi]} \) is upward closed too. However, there exists a standard model \( \mathcal{M} = (W, R, V) \), there exists \( x \in W \) and there exists an announcement formula \( \phi \) in the S4PAL’s language such that \( \mathcal{M}, x \models \phi \) and \( \mathcal{M}_{[\phi]} \) is not standard. For example, in the standard model \( \mathcal{M} = (W, \leq, R, V) \) where \( W = \{ x, y, z, t, u \}, \leq = \{ (x, x), (x, t), (y, y), (y, z), (z, z), (t, t), (u, u) \} \), \( R = \{ (x, y), (t, z), (t, u) \} \) and \( V(p) = \{ y, z \} \), we have \( \mathcal{M}, x \models \Box p \), \( \mathcal{M}, y \models \Box p \), \( \mathcal{M}, z \models \Box p \), \( \mathcal{M}, t \not\models \Box p \) and \( \mathcal{M}, u \models \Box p \). Hence, \( \mathcal{M}_{[\Box p]} = (W_{\Box p}, \leq_{\Box p}, R_{\Box p}, V_{\Box p}) \) where \( W_{\Box p} = \)
Lemma 10.1 Let $\phi$ be a formula in the IPAL’s language. For all standard models $M = (W, \leq, R, V)$ and for all $x \in W$, if $M, x \models \tau(\phi)$ then $M, x \models \tau(\phi)$ is standard and for all $y \in W$, if $x \leq y$ then $M, y \models \tau(\phi)$.

Lemma 10.2 Let $\phi$ be a formula in the IPAL’s language. The formula $\tau(\phi) \rightarrow \Box \tau(\phi)$ is s-valid.

A formula $\phi$ in the S4PAL’s language is said to be globally satisfied in a model $M = (W, \leq, R, V)$ (denoted $M \models \phi$) if for all $x \in W$, $M, x \models \phi$. We shall say that a formula $\phi$ in the S4PAL’s language is s-valid (denoted $\models_s \phi$) if for all standard models $M$, $M \models \phi$.

Lemma 10.3 Let $\phi$ be a formula in the IPAL’s language. For all upward closed standard models $M = (W, \leq, R, V)$ and for all $x \in W$, the following conditions are equivalent: (i) $M, x \models \phi$, (ii) $M, x \models \tau(\phi)$.

Proposition 10.4 Let $\phi$ be a formula in the IPAL’s language. The following conditions are equivalent: (i) $\models_{ucs} \phi$, (ii) $\models_s \tau(\phi)$.

Proof. (i)$\Rightarrow$(ii): By Proposition 4.4, it suffices to demonstrate that the resulting translations of the formulas $A1$–$A14$ are s-valid and that the resulting translations of the inference rules $(R1)$–$(R3)$ are s-validity preserving.

(ii)$\Rightarrow$(i): By Lemma 10.3. □

Obviously, for all formulas $\phi$ in the IPAL’s language, $\text{size}(\tau(\phi)) \leq 2 \times \text{size}(\phi)$. Nevertheless, seeing that the complexity of the membership problem in the set of all s-valid formulas in S4PAL’s language is unknown, Proposition 10.4 does not give us any upper bound on the complexity of the membership problem in the set of all ucs-valid formulas in IPAL’s language.

11 Conclusion

In this paper, firstly, we have given a sound and complete axiomatization of IPAL and we have proved its completeness. Secondly, we have studied the features that might be expected of any intuitionistic modal logic and we have examined whether IPAL possesses them. Thirdly, we have proposed an alternative semantics for IPAL and we have designed a new sequent calculus for IPAL that is sound and complete. Fourthly, we have defined a translation of IPAL’s formulas into formulas of a multimodal logic in which the construct $(\cdot \rightarrow \cdot)$ is the one of classical propositional logic. Much remains to be done: computability of the membership problem in the set of all ucs-valid formulas in IPAL’s language; multi-agent variants with or without positive introspection, common knowledge, distributed knowledge, etc; extension of our framework to intermediate logics.
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References


Annex

Proof of Lemma 2.1: Let \( FOR \) be the set of all formulas \( \phi \) such that for all upward closed standard models \( M = (W, \leq, R, V) \) and for all \( x \in W \), if \( M, x \models \phi \) then \( M[\phi] \) is upward closed standard and for all \( y \in W \), if \( x \leq y \) then \( M, y \models \phi \). Lemma 2.1 says that for all formulas \( \phi, \phi \in FOR \).
We will demonstrate it by an induction on $\phi$ based on the function $\text{size}(\cdot)$ defined in Section 2. Let $\phi$ be a formula such that for all formulas $\psi$, if $\text{size}(\psi) < \text{size}(\phi)$ then $\psi \in \text{FOR}$. We demonstrate $\phi \in \text{FOR}$. We only consider the case $\phi = \Diamond \psi$. Note that $\text{size}(\psi) < \text{size}(\phi)$. Hence, $\psi \in \text{FOR}$. Let $M = (W, \leq, R, V)$ be an upward closed standard model and $x \in W$ be such that $M, x \models \Diamond \psi$.

Let $y, z, t \in W_{\Diamond \psi}$ be such that $y \leq_{\Diamond \psi} z$ and $yR_{\Diamond \psi} t$. We demonstrate there exists $u \in W_{\Diamond \psi}$ such that $zR_{\Diamond \psi} u$ and $t \leq_{\Diamond \psi} u$. Since $y \leq_{\Diamond \psi} z$ and $yR_{\Diamond \psi} t$, therefore $y \leq z$ and $yR t$. Let $u \in W$ be such that $zRu$ and $t \leq u$. Such $u$ exists because $M$ is standard. Since $t \in W_{\Diamond \psi}$, therefore $M, t \models \Diamond \psi$. Hence, there exists $v \in W$ such that $tRv$ and $M, v \models \psi$. Let $w \in W$ be such that $uRw$ and $v \leq w$. Such $w$ exists because $M$ is standard and $t \leq u$. Since $M$ is upward closed standard, $\psi \in \text{FOR}$ and $M, v \models \psi$, therefore $M, w \models \psi$. Since $uRw$, therefore $M, u \models \Diamond \psi$. Thus, $u \in W_{\Diamond \psi}$. Since $z, t \in W_{\Diamond \psi}$, $zR u$ and $t \leq u$, therefore $zR_{\Diamond \psi} u$ and $t \leq_{\Diamond \psi} u$.

Let $y, z, t \in W_{\Diamond \psi}$ be such that $yR_{\Diamond \psi} z$ and $z \leq_{\Diamond \psi} t$. We demonstrate there exists $u \in W_{\Diamond \psi}$ such that $y \leq_{\Diamond \psi} u$ and $uR_{\Diamond \psi} t$. Since $yR_{\Diamond \psi} z$ and $z \leq_{\Diamond \psi} t$, therefore $yRz$ and $z \leq t$. Let $u \in W$ be such that $y \leq u$ and $uR t$. Such $u$ exists because $M$ is standard. Since $z \in W_{\Diamond \psi}$, therefore $M, z \models \Diamond \psi$. Hence, there exists $v \in W$ such that $yRv$ and $M, v \models \psi$. Let $w \in W$ be such that $uRw$ and $v \leq w$. Such $w$ exists because $M$ is standard and $y \leq u$. Since $M$ is upward closed standard, $\psi \in \text{FOR}$ and $M, v \models \psi$, therefore $M, w \models \psi$. Since $uRw$, therefore $M, u \models \Diamond \psi$. Thus, $u \in W_{\Diamond \psi}$. Since $y, t \in W_{\Diamond \psi}$, $y \leq u$ and $uR t$, therefore $y \leq_{\Diamond \psi} u$ and $uR_{\Diamond \psi} t$.

Let $y \in W$ be such that $x \leq y$. We demonstrate $M, y \models \Diamond \psi$. Since $M, x \models \Diamond \psi$, therefore there exists $z \in W$ such that $xRz$ and $M, z \models \psi$. Let $t \in W$ be such that $yRt$ and $z \leq t$. Such $t$ exists because $M$ is standard and $x \leq y$. Since $M$ is upward closed standard, $\psi \in \text{FOR}$ and $M, z \models \psi$, therefore $M, t \models \psi$. Since $yRt$, therefore $M, y \models \Diamond \psi$.

**Proof of Lemma 2.2:** Suppose $\phi \in \text{PAL}$. Hence, $\phi$ is globally $\text{PAL}$-satisfied in $M$. Since $\leq$ is the identity relation on $W$, therefore one can demonstrate by an induction on $\psi$ based on the function $\text{size}(\cdot)$ defined in Section 2, that for all formulas $\psi$ and for all $x \in W$, $M, x \models \psi$ iff $\psi$ is $\text{PAL}$-satisfied at $x$ in $M$. Since $\phi$ is globally $\text{PAL}$-satisfied in $M$, therefore $M \models \phi$.

**Proof of Lemma 5.1:** The proof is similar to the proof in [17, Chapter 3].

**Proof of Lemma 5.2:** The proof is similar to the proof in [17, Chapter 3].

**Proof of Lemma 5.3:** The proof is similar to the proof in [17, Chapter 3].
Proof of Lemma 5.4: By Proposition 4.3, let ψ be an announcement-free formula such that φ ↔ ψ ∈ IPAL. Hence, the following conditions are equivalent: (i) \( M, x \models φ \), (ii) \( M, x \models ψ \), (iii) φ ∈ x, (iv) φ ∈ x. The equivalence between (i) and (ii) follows from Proposition 4.1, Lemma 5.2 and the fact that φ ↔ ψ ∈ IPAL. The equivalence between (ii) and (iii) follows from Lemma 5.3. The equivalence between (iii) and (iv) follows from the fact that L is an extension of IPAL and φ ↔ ψ ∈ IPAL.

Proof of Lemma 6.3: It suffices to demonstrate that the formulas A1–A14 are X-deducible and that the inference rules (R1) and (R2) are X-deducibility preserving.

Proof of Lemma 8.1: Let \( FOR^+ \) be the set of all nonempty sequences \((φ_1, \ldots, φ_n, φ)\) of formulas such that for all models \( M = (W, ≤, R, V) \) and for all \( x ∈ W \), \( M, x \models [φ_1][φ_2][φ_n]φ \) iff if \( M, x, φ_1, \ldots, φ_{n-1} \models φ_n \) then \( M, x, (φ_1, \ldots, φ_n) \models φ \). Lemma 8.1 says that for all nonempty sequences \((φ_1, \ldots, φ_n, φ)\) of formulas \((φ_1, \ldots, φ_n, φ) \in FOR^+ \). We will demonstrate it by an induction on \((φ_1, \ldots, φ_n, φ)\) based on the function size(·) defined in Section 2. Let \((φ_1, \ldots, φ_n, φ)\) be a nonempty sequence of formulas such that for all nonempty sequences \((φ'_1, \ldots, φ'_n, φ')\), if size(\(φ'_1, \ldots, φ'_n, φ')\) < size(\(φ_1, \ldots, φ_n, φ)\) then \((φ'_1, \ldots, φ'_n, φ') \in FOR^+ \). We demonstrate \((φ_1, \ldots, φ_n, φ) \in FOR^+ \). We only consider the case φ = ψ. Note that for all \( i = 1 \ldots n \), size(\(φ_1, \ldots, φ_{i-1}, φ_i\)) < size(\(φ_1, \ldots, φ_n, φ\)). Moreover, size(\(φ_1, \ldots, φ_n, ψ\)) < size(\(φ_1, \ldots, φ_n, φ)\). Hence, for all \( i = 1 \ldots n \), \((φ_1, \ldots, φ_{i-1}, φ_i) \in FOR^+ \). Moreover, \((φ_1, \ldots, φ_n, ψ) \in FOR^+ \). Let \( M = (W, ≤, R, V) \) be a model and let \( x ∈ W \). We assume that \( n ≥ 1 \).

Suppose \( M, x \models [φ_1][φ_2][φ_n]ψ \). Suppose \( M, x, φ_1, \ldots, φ_{n-1} \models φ_n \). Since for all \( i = 1 \ldots n \), \((φ_1, \ldots, φ_i) \in FOR^+ \), therefore for all \( i = 1 \ldots n \), \( M, x \models [φ_1][φ_2][φ_n]ψ \). Let \( y ∈ W \) be such that for all \( i = 1 \ldots n \), \( M, y \models [φ_1][φ_2][φ_n]ψ \). Each \( xRy \) and \( M, x \models [φ_1][φ_2][φ_n]ψ \). Such \( y \) exists because \( M, x \models [φ_1][φ_2][φ_n]ψ \) and for all \( i = 1 \ldots n \), \( M, x \models [φ_1][φ_2][φ_n]ψ \). Since for all \( i = 1 \ldots n \), \((φ_1, \ldots, φ_{i-1}, φ_i) \in FOR^+ \) and \((φ_1, \ldots, φ_n, ψ) \in FOR^+ \) and \( φ_1, \ldots, φ_n, ψ \models φ_n \). Hence, \( M, y \models [φ_1][φ_2][φ_n]ψ \). Since \( xRy \), therefore \( M, x \models [φ_1][φ_2][φ_n]ψ \).

Suppose if \( M, x, φ_1, \ldots, φ_{n-1} \models φ_n \) then \( M, x \models [φ_1][φ_2][φ_n]ψ \). Suppose \( M, x \not\models [φ_1][φ_2][φ_n]ψ \). Hence, for all \( i = 1 \ldots n \), \( M, x \not\models [φ_1][φ_2][φ_n]φ_1 \) and for all \( y ∈ W \), if for all \( i = 1 \ldots n \), \( M, y \not\models [φ_1][φ_2][φ_n]ψ \). Since for all \( i = 1 \ldots n \), \((φ_1, \ldots, φ_{i-1}, φ_i) \in FOR^+ \), therefore for all \( i = 1 \ldots n \), \( M, x \models [φ_1][φ_2][φ_n]ψ \). Since \( M, x, φ_1, \ldots, φ_{n-1} \models φ_n \) then \( M, x \models [φ_1][φ_2][φ_n]ψ \). Let \( y ∈ W \) be such that for all \( i = 1 \ldots n \), \( M, y \models [φ_1][φ_2][φ_n]ψ \). \( xRy \) and
Let $\mathcal{M}, y, (\phi_1, \ldots, \phi_n) \models \psi$. Since for all $i = 1 \ldots n$, $(\phi_1, \ldots, \phi_{i-1}, \phi_i) \in \text{FOR}^+$ and $(\phi_1, \ldots, \phi_n, \psi) \in \text{FOR}^+$, therefore for all $i = 1 \ldots n$, $\mathcal{M}, y \models [\phi_1] \ldots [\phi_{i-1}] \phi_i$ and $\mathcal{M}, y \models [\phi_1] \ldots [\phi_n] \psi$. Since $xRy$, therefore $\mathcal{M}, x \models [\phi_1] \ldots [\phi_n] \psi$: a contradiction.

**Proof of Lemma 10.1:** Let $\text{FOR}$ be the set of all formulas $\phi$ in the IPAL’s language such that for all standard models $\mathcal{M} = (W, \leq, R, V)$ and for all $x \in W$, if $\mathcal{M}, x \models \tau(\phi)$ then $\mathcal{M}, y \models \tau(\phi)$. Lemma 10.1 says that for all formulas $\phi$ in the IPAL’s language, $\phi \in \text{FOR}$. We will demonstrate it by an induction on $\phi$ based on the function $\text{size}(\cdot)$ defined in Section 2. Let $\phi$ be a formula such that for all formulas $\psi$, if $\text{size}(\psi) < \text{size}(\phi)$ then $\psi \in \text{FOR}$. We demonstrate $\phi \in \text{FOR}$. We only consider the case $\phi = \diamond \psi$. Note that $\text{size}(\psi) < \text{size}(\phi)$. Hence, $\psi \in \text{FOR}$. Let $\mathcal{M} = (W, \leq, R, V)$ be a standard model and $x \in W$ be such that $\mathcal{M}, x \models \diamond \psi$.

Let $y, z, t \in W_{\diamond \psi}$ be such that $y \leq_{\diamond \psi} z$ and $yR_{\diamond \psi} t$. We demonstrate there exist $u \in W_{\diamond \psi}$ such that $zRu$ and $t \leq_{\diamond \psi} u$. Since $y \leq_{\diamond \psi} z$ and $yR_{\diamond \psi} t$, therefore $y \leq z$ and $yRt$. Let $u \in W$ be such that $zRu$ and $t \leq u$. Such $u$ exists because $\mathcal{M}$ is standard. Since $t \in W_{\diamond \psi}$, therefore $\mathcal{M}, t \models \diamond \psi$. Hence, there exists $v \in W$ such that $tRv$ and $\mathcal{M}, v \models \tau(\psi)$. Let $w \in W$ be such that $uRw$ and $v \leq w$. Such $w$ exists because $\mathcal{M}$ is standard and $t \leq u$. Since $\mathcal{M}$ is standard, $\psi \in \text{FOR}$ and $\mathcal{M}, v \models \tau(\psi)$, therefore $\mathcal{M}, w \models \diamond \psi$. Thus, $u \in W_{\diamond \psi}$. Since $z, t \in W_{\diamond \psi}$, $zRu$ and $t \leq u$, therefore $zR_{\diamond \psi} u$ and $t \leq_{\diamond \psi} u$.

Let $y, z, t \in W_{\diamond \psi}$ be such that $yR_{\diamond \psi} z$ and $z \leq_{\diamond \psi} t$. We demonstrate there exist $u \in W_{\diamond \psi}$ such that $y \leq_{\diamond \psi} u$ and $uR_{\diamond \psi} t$. Since $yR_{\diamond \psi} z$ and $z \leq_{\diamond \psi} t$, therefore $yRz$ and $z \leq t$. Let $u \in W$ be such that $y \leq u$ and $uRt$. Such $u$ exists because $\mathcal{M}$ is standard. Since $y \in W_{\diamond \psi}$, therefore $\mathcal{M}, y \models \diamond \psi$. Hence, there exists $v \in W$ such that $yRv$ and $\mathcal{M}, v \models \tau(\psi)$. Let $w \in W$ be such that $uRw$ and $v \leq w$. Such $w$ exists because $\mathcal{M}$ is standard and $y \leq u$. Since $\mathcal{M}$ is standard, $\psi \in \text{FOR}$ and $\mathcal{M}, v \models \tau(\psi)$, therefore $\mathcal{M}, w \models \tau(\psi)$. Since $uRv$, therefore $\mathcal{M}, u \models \diamond \psi$. Thus, $u \in W_{\diamond \psi}$. Since $y, t \in W_{\diamond \psi}$, $y \leq u$ and $uRt$, therefore $y \leq_{\diamond \psi} u$ and $uR_{\diamond \psi} t$.

Let $y \in W$ be such that $x \leq y$. We demonstrate $\mathcal{M}, y \models \diamond \psi$. Since $\mathcal{M}, x \models \diamond \psi$, therefore there exists $z \in W$ such that $xRz$ and $\mathcal{M}, z \models \tau(\psi)$. Let $t \in W$ be such that $yRt$ and $z \leq t$. Such $t$ exists because $\mathcal{M}$ is standard and $x \leq y$. Since $\mathcal{M}$ is standard, $\psi \in \text{FOR}$ and $\mathcal{M}, z \models \tau(\psi)$, therefore $\mathcal{M}, t \models \tau(\psi)$. Since $yRt$, therefore $\mathcal{M}, y \models \diamond \psi$.

**Proof of Lemma 10.2:** Let $\text{FOR}$ be the set of all formulas $\phi$ in the IPAL’s language such that the formula $\tau(\phi) \rightarrow \square \tau(\phi)$ is s-valid. Lemma 10.2 says that for all formulas $\phi$ in the IPAL’s language, $\phi \in \text{FOR}$. We will demonstrate it by an induction on $\phi$ based on the function $\text{size}(\cdot)$ defined in Section 2. Let $\phi$ be a formula such that for all formulas $\psi$, if $\text{size}(\psi) < \text{size}(\phi)$ then $\psi \in \text{FOR}.$
We demonstrate \( \phi \in \text{FOR} \). We only consider the case \( \phi = \langle \psi \rangle \chi \). Note that \( \text{size}(\psi) < \text{size}(\phi) \) and \( \text{size}(\chi) < \text{size}(\psi) \). Hence, \( \psi \in \text{FOR} \) and \( \chi \in \text{FOR} \). Thus, the formulas \( \tau(\psi) \to \Box \tau(\psi) \) and \( \tau(\chi) \to \Box \tau(\chi) \) are s-valid. Let us consider the following formulas: (i) \( \langle \tau(\psi) \rangle \tau(\chi) \), (ii) \( \tau(\psi) \land [\tau(\psi)] \Box \tau(\chi) \), (iii) \( \lnot \Box \tau(\psi) \land [\tau(\psi)] \Box \tau(\chi) \), (iv) \( \Box \tau(\psi) \land (\tau(\psi) \to \Box \tau(\psi)) \tau(\chi) \), (v) \( \Box \tau(\psi) \land [\tau(\psi)] \Box \tau(\chi) \), (vi) \( \Box (\tau(\psi) \land [\tau(\psi)] \Box \tau(\chi)) \), (vii) \( \Box (\tau(\psi)) \tau(\chi) \).

The s-validity of the formula (i)→(ii) follows from the definition of the satisfiability of formulas in the \text{SA\textsc{pal}}'s language. The s-validity of the formula (ii)→(iii) follows from the s-validity of the formulas \( \tau(\psi) \to \Box \tau(\psi) \) and \( \tau(\chi) \to \Box \tau(\chi) \). The s-validity of the formulas (iii)→(iv), (iv)→(v), (v)→(vi) and (vi)→(vii) follows from the definition of the satisfiability of formulas in the \text{SA\textsc{pal}}'s language.

**Proof of Lemma 10.3:** Let \( \text{FOR} \) be the set of all formulas \( \phi \) in the \text{IP\textsc{al}}'s language such that for all upward closed standard models \( M = (W, \leq, R, V) \) and for all \( x \in W, M, x \models \phi \) iff \( M, x \models \tau(\phi) \). Lemma 10.3 says that for all formulas \( \phi \) in the \text{IP\textsc{al}}'s language, \( \phi \in \text{FOR} \). We will demonstrate it by an induction on \( \phi \) based on the function \( \text{size}(\cdot) \) defined in Section 2. Let \( \phi \) be a formula such that for all formulas \( \psi \), if \( \text{size}(\psi) < \text{size}(\phi) \) then \( \psi \in \text{FOR} \). We demonstrate \( \phi \in \text{FOR} \). We only consider the case \( \phi = \langle \psi \rangle \chi \). Note that \( \text{size}(\psi) < \text{size}(\phi) \) and \( \text{size}(\chi) < \text{size}(\psi) \). Hence, \( \psi \in \text{FOR} \) and \( \chi \in \text{FOR} \).

Let \( M = (W, \leq, R, V) \) be an upward closed standard model and \( x \in W \).

Suppose \( M, x \models \langle \psi \rangle \chi \). Hence, \( M, x \models \psi \) and \( M_{\{\psi\}}, x \models \chi \). Since \( \psi \in \text{FOR} \), therefore \( \{y \in W: M, y \models \psi\} = \{y \in W: M, y \models \tau(\psi)\} \) and \( M_{\{\psi\}} = M_{\{\tau(\psi)\}} \).

Moreover, since \( \chi \in \text{FOR} \), \( M, x \models \psi \) and \( M_{\{\psi\}}, x \models \chi \), therefore \( M, x \models \tau(\psi) \) and \( M_{\{\psi\}}, x \models \tau(\chi) \). Since \( M_{\{\psi\}} = M_{\{\tau(\psi)\}} \), therefore \( M_{\{\tau(\psi)\}}, x \models \tau(\chi) \). Thus, \( M, x \models \tau(\psi) \tau(\chi) \).

Suppose \( M, x \models \langle \tau(\psi) \rangle \tau(\chi) \). Hence, \( M, x \models \tau(\psi) \) and \( M_{\{\tau(\psi)\}}, x \models \tau(\chi) \).

Since \( \psi \in \text{FOR} \), therefore \( \{y \in W: M, y \models \psi\} = \{y \in W: M, y \models \tau(\psi)\} \) and \( M_{\{\psi\}} = M_{\{\tau(\psi)\}} \). Moreover, since \( \chi \in \text{FOR} \), \( M, x \models \tau(\psi) \) and \( M_{\{\tau(\psi)\}}, x \models \tau(\chi) \), therefore \( M, x \models \psi \) and \( M_{\{\tau(\psi)\}}, x \models \chi \). Since \( M_{\{\psi\}} = M_{\{\tau(\psi)\}} \), therefore \( M_{\{\psi\}}, x \models \chi \). Thus, \( M, x \models \langle \psi \rangle \chi \).