A History of Until

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Abstract. Until is a notoriously difficult temporal operator as it is both existential and universal at the same time: $A \text{ U } B$ holds at the current time instant $w$ iff either $B$ holds at $w$ or there exists a time instant $w'$ in the future at which $B$ holds and such that $A$ holds in all the time instants between the current one and $w'$. This “ambivalent” nature poses a significant challenge when attempting to give deduction rules for until. In this paper, in contrast, we make explicit this duality of until by introducing a new temporal operator $\nabla$ that allows us to formalize the “history” of until, i.e., the “internal” universal quantification over the time instants between the current one and $w'$. This approach provides the basis for formalizing deduction systems for temporal logics endowed with the until operator. For concreteness, we give here a labeled natural deduction system for a linear-time logic endowed with the new history operator and show that, via a proper translation, such a system is also sound and complete with respect to the linear temporal logic $LTL$ with until.

1 Introduction

Until is a notoriously difficult temporal operator. This is because of its “ambivalent” nature of being an operator that is both existential and universal at the same time: $A \text{ U } B$ holds at the current time instant ($w$ iff either $B$ holds at $w$ or there exists a time instant $w'$ in the future at which $B$ holds and such that $A$ holds in all the time instants between the current one and $w'$. The words in emphasis highlight the dual existential and universal nature of $U$, which poses a significant challenge when attempting to give deduction rules for until, so that deduction systems for temporal logics either deliberately exclude until from the set of operators considered or devise clever ways to formalize reasoning about until. And even if one manages to give rules, these often come at the price of additional difficulties for, or even the impossibility of, proving useful metatheoretic properties, such as normalization or the subformula property. (This is even more so in the case of Hilbert-style axiomatizations, which provide axioms for until, but are not easily usable for proof construction.) See, for instance, [12,12,13,20], where techniques for formalizing suitable inference rules include introducing additional information (such as the use of a Skolem function $f(A \text{ U } B)$ to name the time
instant where $B$ begins to hold), or exploiting the standard recursive unfolding of until

$$AUB \equiv B \lor (A \land X(AUB))$$

which says that $AUB$ if either $B$ holds or $A$ holds and in the successor time instant (as expressed by the next operator $X$) we have again $AUB$.

In this paper, in contrast, we make explicit the duality of until by introducing a new temporal operator $\nabla$ that allows us to formalize the “history” of until, i.e., the fact that when we have $AUB$ the formula $A$ holds in all the time instants between the current one and the one where $B$ holds. We express this “historic” universal quantification by means of $\nabla$ with respect to the following intuitive translation:

$$AUB \equiv B \lor F(XB \land \nabla A)$$

That is: $AUB$ iff either $B$ holds or there exists a time instant $w'$ in the future (as expressed by the sometime in the future operator $F$) such that

- $B$ holds in the successor time instant, and
- $A$ holds in all the time instants between the current one and $w'$ (included).

The latter conjunct is precisely what the history operator $\nabla$ expresses. This is better seen when introducing labeling: since $\nabla$ actually quantifies over the time instants in an interval (delimited by the current instant and the one where the $B$ of the until holds), we adopt a labeling discipline that is slightly different from the more customary one of labeled deduction.

The framework of labeled deduction has been successfully employed for several non-classical, and in particular modal and temporal, logics, e.g., \[SP1,SP2\], since labeling provides a clean and effective way of dealing with modalities and gives rise to deduction systems with good proof-theoretical properties. The basic idea is that labels allow one to explicitly encode additional information, of a semantic or proof-theoretical nature, that is otherwise implicit in the logic one wants to capture. So, for instance, instead of a formula $A$, one can consider the labeled formula $b : A$, which intuitively means that $A$ holds at the time instant denoted by $b$ within the underlying Kripke semantics. One can also use labels to specify how time instants are related, e.g., the relational formula $bRc$ states that the time instant $c$ is accessible from $b$.

Considering labels that consist of a single time instant is not enough for $\nabla$, as the operator is explicitly designed to speak about a sequence of time instants (namely, the ones constituting the history of the corresponding until, if indeed $\nabla$ results from the translation of an $U$). We thus consider labels that are built out of a sequence of time instants, so that we can write $\alpha b_1 b_3 : \nabla A$ to express, intuitively, that $A$ holds in the interval between time instants $b_1$ and $b_3$, which together with the sub-sequence $\alpha$ constitute a sequence of time instants $\alpha b_1 b_3$.

\[1\] This is in contrast to the unfolding $U$. The decoupling of $U$ that we achieve with $\nabla$ is precisely what allows us to give well-behaved (in a sense made clearer below) natural deduction rules.
This allows us to give the natural deduction elimination rule

\[ \frac{\alpha b_1 b_3 : \nabla A \quad b_1 \leq b_2 \quad b_2 \leq b_3}{\alpha b_1 b_2 : A} \ \nabla E \]

that says that if \( \nabla A \) holds at time instant \( b_3 \) at the end of the sequence \( \alpha b_1 b_3 \) and if \( b_2 \) is in-between \( b_1 \) and \( b_3 \), as expressed by the relational formulas with the accessibility relation \( \leq \), then we can conclude that \( A \) holds at \( b_2 \).

Dually, we can introduce \( \nabla A \) at time instant \( b_3 \) at the end of the sequence \( \alpha b_1 b_3 \) whenever from the assumptions \( b_1 \leq b_2 \) and \( b_2 \leq b_3 \) for a fresh \( b_2 \) we can infer \( \alpha b_1 b_2 : A \), i.e.

\[ \ [ b_1 \leq b_2 \ [ b_2 \leq b_3 \] \]

\[ \frac{\alpha b_1 b_2 : A}{\alpha b_1 b_3 : \nabla A} \ \nabla I \]

The adoption of time instant sequences for labels has thus allowed us to give rules for \( \nabla \) that are well-behaved in the spirit of natural deduction [17]: there is precisely one introduction and one elimination rule for \( \nabla \), as well as for the other connectives and temporal operators (\( \supset \), \( G \), and \( X \)). This paves the way to a proof-theoretical analysis of the resulting natural deduction systems, e.g., to show proof normalization and other useful meta-theoretical analysis, which we are tackling in current work.

Moreover, the rules \( \nabla I \) and \( \nabla E \) provide a clean-cut way of reasoning about until, according to the translation [2], provided that we also give rules for \( F \) and \( X \). These operators have a local nature, in the sense that they speak not about sequences of time instants but about single time instants. Still, we can easily give natural deduction rules for them by generalizing the more standard “single-time instant” rules (e.g., [12, 16, 21, 22, 23]) using our labeling with sequences of time instants. As we will discuss in more detail below, if we collapse the sequences of time instants to consider only the final time instant in the sequence (or, equivalently, if we simply ignore all the instants in a sequence but the last), then these rules reduce to the standard ones. For instance, for the always in the future operator \( G \) (the dual of \( F \)) and \( X \), with the corresponding successor relation \( \prec \), we can give the elimination rules

\[ \frac{\alpha b_1 : GA \quad b_1 \leq b_2}{\alpha b_1 b_2 : A} \ \mathrm{GE} \quad \text{and} \quad \frac{\alpha b_1 : XA \quad b_1 \prec b_2}{\alpha b_1 b_2 : A} \ \mathrm{XE} \]

The rule \( \mathrm{GE} \) says that if \( GA \) holds at time instant \( b_1 \), which is the last in the sequence \( \alpha b_1 \) and \( b_2 \) is \( \leq \)-accessible from \( b_1 \) (i.e., \( b_1 \leq b_2 \)), then we can conclude that \( A \) holds for the sequence \( \alpha b_1 b_2 \). The rule \( \mathrm{XE} \) is justified similarly (via \( \prec \)). The corresponding introduction rules are given in Section [3] together with rules for \( \bot \) and the connective \( \supset \), as well as a rule for induction on the underlying linear ordering. As we will see, we also need rules expressing the properties of the

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\[ \text{The side condition that } b_2 \text{ is fresh means that } b_2 \text{ is different from } b_1 \text{ and } b_3, \text{ and does not occur in any assumption on which } \alpha b_1 b_2 : A \text{ depends other than the discarded assumptions } b_1 \leq b_2 \text{ and } b_2 \leq b_3. \]
relations \( \leq \) and \( \triangleleft \). Moreover, the fact that we consider sequences of time instants as labels requires us to consider some structural rules to express properties of such sequences (with respect to formulas).

This approach thus provides the basis for formalizing deduction systems for temporal logics endowed with the until operator. For concreteness, we give here a labeled natural deduction system for a linear-time logic endowed with the new history operator \( \nabla \) and show that, via a proper translation, such a system is also sound and complete with respect to the linear temporal logic \( \text{LTL} \) with until. (We do not consider past explicitly here, but adding operators and rules for it should be unproblematic, e.g., as in [23].)

We proceed as follows. In Section 2 we briefly recall the syntax and semantics of \( \text{LTL} \), and an axiomatization for it. In Section 3 we define \( \text{LTL} \nabla \), the logic that is obtained from \( \text{LTL} \) by replacing \( U \) with the history \( \nabla \), and give a validity-preserving translation, based on [2], from \( \text{LTL} \) into \( \text{LTL} \nabla \). In Section 4 we give a labeled natural deduction system \( N(\text{LTL} \nabla) \) that it is sound with respect to the semantics of \( \text{LTL} \nabla \). By focusing only on those derivations whose conclusion and open assumptions correspond to the translation of \( \text{LTL} \)-formulas, we show that \( N(\text{LTL} \nabla) \) can be used to capture reasoning in \( \text{LTL} \) and that it is in fact sound and complete with respect to the semantics of \( \text{LTL} \). In Section 5 we draw conclusions and illustrate directions of current and future work. Full proofs are given in the appendix.

2 The Linear Temporal Logic \( \text{LTL} \)

We recall the syntax and semantics of \( \text{LTL} \) and an axiomatization for it.

**Definition 1.** Given a set \( \mathcal{P} \) of propositional symbols, the set of *(well-formed)* \( \text{LTL} \)-*formulas* is defined by the grammar

\[
A ::= p \mid \bot \mid A \supset A \mid GA \midXA \mid AU A
\]

where \( p \in \mathcal{P} \). The set of \( \text{LTL} \)-*atomic formulas* is \( \mathcal{P} \cup \{ \bot \} \). The complexity of an \( \text{LTL} \)-formula is the number of occurrences of the connective \( \supset \) and of the temporal operators \( G \), \( X \), and \( U \).

The intuitive meaning of \( G \), \( X \), and \( U \) is the standard one: \( GA \) states that \( A \) holds always in the future, \( XA \) states that \( A \) holds in the next time instant, and \( AU B \) states that \( B \) holds at the current time instant or there is a time instant \( w \) in the future such that \( B \) holds in \( w \) and \( A \) holds in all the time instants between the current one and \( w \). As usual, we can introduce abbreviations and use, e.g., \( \neg \), \( \lor \) and \( \land \) for negation, disjunction, and conjunction, respectively: \( \neg A \equiv A \supset \bot \), \( A \lor B \equiv \neg A \supset B \), and \( A \land B \equiv \neg (\neg A \lor \neg B) \). We can also define other temporal operators, e.g., \( FA \equiv \neg G \neg A \) to express that \( A \) holds sometime in the future. We write \( A \) to denote a *set of \( \text{LTL} \)-formulas*.

**Definition 2.** Let \( \mathcal{N} = (\mathbb{N}, s : \mathbb{N} \to \mathbb{N}, \leq) \) be the standard structure of natural numbers, where \( s \) and \( \leq \) are respectively the successor function and the total
(reflexive) order relation. An \textit{LTL-model} is a pair \( M = \langle N, V \rangle \) where \( V : \mathbb{N} \rightarrow 2^P \). \textit{Truth} for an \textit{LTL}-formula at a point \( n \in \mathbb{N} \) in an \textit{LTL}-model \( M = \langle N, V \rangle \) is the smallest relation \( |_{LTL} \) satisfying:

\[
\begin{align*}
M, n |_{LTL} p & \text{ iff } p \in V(n) \\
M, n |_{LTL} A \supset B & \text{ iff } M, n |_{LTL} A \text{ implies } M, n |_{LTL} B \\
M, n |_{LTL} GA & \text{ iff } M, m |_{LTL} A \text{ for all } m \geq n \\
M, n |_{LTL} AXA & \text{ iff } M, n + 1 |_{LTL} A \\
M, n |_{LTL} AUB & \text{ iff } \exists n' \geq n \text{ such that } M, n' |_{LTL} B \text{ and } M, m |_{LTL} A \text{ for all } m \leq n < n'
\end{align*}
\]

Note that \( M, n \not|_{LTL} \bot \) for every \( M \) and \( n \). By extension, we write:

\[
\begin{align*}
M |_{LTL} A & \text{ iff } M, n |_{LTL} A \text{ for every natural number } n \\
M |_{LTL} A & \text{ iff } M |_{LTL} A \text{ for all } A \in A \\
A |_{LTL} A & \text{ iff } M |_{LTL} A \text{ implies } M |_{LTL} A, \text{ for every } LTL\text{-model } M
\end{align*}
\]

We now present a sound and complete Hilbert-style axiomatization, which we call \( \mathcal{H}(LTL) \), for \( LTL \) (see, e.g., [10]). \( \mathcal{H}(LTL) \) consists of the axioms

\[
\begin{align*}
(A1) \text{ Any tautology instance} & \quad (A2) \text{ } G(A \supset B) \supset (GA \supset GB) \\
(A3) \text{ } X \neg A & \leftrightarrow \negXA \\
(A4) \text{ } X(A \supset B) & \supset (XA \supset XB) \\
(A5) \text{ } GA & \supset A \wedge XGA \\
(A6) \text{ } G(A \supsetXA) & \supset (A \supset GA) \\
(A7) \text{ } AUB & \leftrightarrow (B \vee (A \wedge X(AUB))) \\
(A8) \text{ } AUB & \supset FB
\end{align*}
\]

where we denote with \( \leftrightarrow \) the double implication, and of the rules of inference

\[
\begin{align*}
(MP) \text{ If } A \text{ and } A \supset B \text{ then } B & \quad (\text{Nec}_X) \text{ If } A \text{ then } XA \\
(\text{Nec}_G) \text{ If } A \text{ then } GA
\end{align*}
\]

The set of theorems of \( \mathcal{H}(LTL) \) is the smallest set containing these axioms and closed with respect to these rules of inference.

3 \textbf{LTL}_∇: \textit{LTL} with history

In this section, we give the linear temporal logic \( \text{LTL}_\nabla \), which is obtained from \( LTL \) by replacing the operator \( \mathcal{U} \) with a new unary temporal operator \( \nabla \), called \textit{history}. The definition of the semantics of \( \text{LTL}_\nabla \) requires a notion of truth given with respect to sequences of time instants rather than just to time instants. We will then provide a translation from the language of \( LTL \) into the language of \( \text{LTL}_\nabla \) and show some properties of such a translation.
3.1 Syntax and semantics

**Definition 3.** Given a set \( \mathcal{P} \) of propositional symbols, the set of *(well-formed)* \( \textit{LTL}_\varphi \)-formulas is defined by the grammar

\[
A ::= p \mid \bot \mid A \supset A \mid GA \mid XA \mid \nabla A
\]

where \( p \in \mathcal{P} \). The set of \( \textit{LTL}_\varphi \)-atomic formulas is \( \mathcal{P} \cup \{ \bot \} \). The complexity of an \( \textit{LTL}_\varphi \)-formula is the number of occurrences of the connective \( \supset \) and of the temporal operators \( X, G, \) and \( \nabla \).

The intuitive meaning of the operators \( G \) and \( X \) is the same as for \( \textit{LTL} \), while \( \nabla A \) intuitively states that \( A \) holds at any instant of a particular time interval (but here we see that we need sequences of time instants to formalize the semantics of the history operator, as we anticipated in the introduction).

Again, we can define other connectives and operators as abbreviations, e.g., \( \neg, \lor, \land, F \) and so on. We write \( \Gamma \) to denote a *set of \( \textit{LTL}_\varphi \)-formulas*.

To define a labeled deduction system for the logic \( \textit{LTL}_\varphi \), we extend the language with a set of labels and finite sequences of labels, and introduce the notions of labeled formula and relational formula.

**Definition 4.** Let \( \mathcal{L} \) be a set of labels. A finite non-empty sequence of labels (namely, an element of \( \mathcal{L}^+ \)) is called a *sequence*. If \( A \) is an \( \textit{LTL}_\varphi \)-formula and \( \alpha \) is a sequence, then \( \alpha : A \) is a labeled *(well-formed)* formula *(lwff* for short). The set of relational *(well-formed)* formulas *(rwffs for short)* is the set of expressions of the form \( b \leq c \) or \( b < c \), where \( b \) and \( c \) are labels.

In the rest of the paper, we will assume given a fixed denumerable set \( \mathcal{L} \) of labels and we will use \( b, c, d, \ldots \) to denote labels, \( \alpha, \beta, \gamma \) to denote finite sequences of labels\(^3\) (e.g., \( bcd \ldots \) or just \( b \) in the case of a sequence consisting of only one time instant), \( \varphi \) to denote a *generic formula* (either labeled or relational) and \( \Phi \) to denote a *set of generic formulas*.

**Definition 5.** An observation sequence is a non-empty sequence \( \sigma = [n_0, \ldots, n_k] \) of natural numbers. Truth for an \( \textit{LTL}_\varphi \)-formula at an observation sequence \( \sigma \) in an \( \textit{LTL} \)-model \( \mathcal{M} = (\mathcal{N}, \mathcal{V}) \) is the smallest relation \( \models_{\mathcal{V}} \) satisfying:

\[
\begin{align*}
\mathcal{M}, [n_0, \ldots, n_k] &\models_{\mathcal{V}} p & \text{iff} & \quad p \in \mathcal{V}(n_k) \\
\mathcal{M}, [n_0, \ldots, n_k] &\models_{\mathcal{V}} A \supset B & \text{iff} & \quad \mathcal{M}, [n_0, \ldots, n_k] \models_{\mathcal{V}} A \text{ implies } \mathcal{M}, [n_0, \ldots, n_k] \models_{\mathcal{V}} B \\
\mathcal{M}, [n_0, \ldots, n_k] &\models_{\mathcal{V}} GA & \text{iff} & \quad \mathcal{M}, [n_0, \ldots, n_k, m] \models_{\mathcal{V}} A \text{ for all } m \geq n_k \\
\mathcal{M}, [n_0, \ldots, n_k] &\models_{\mathcal{V}} XA & \text{iff} & \quad \mathcal{M}, [n_0, \ldots, n_k, n_k + 1] \models_{\mathcal{V}} A \\
\mathcal{M}, [n_0, \ldots, n_k] &\models_{\mathcal{V}} \nabla A & \text{iff} & \quad \mathcal{M}, [n_0, \ldots, n_{k-1}, m] \models_{\mathcal{V}} A \text{ for all } n_{k-1} \leq m \leq n_k \text{ (if } 0 < k) 
\end{align*}
\]

\(^3\) With a slight abuse of notation, we will also use \( \alpha, \beta, \gamma \) to denote possibly empty subsequences and thus write \( \alpha b_1 \ldots b_k \) (for \( k \geq 1 \)) to denote a sequence where \( \alpha \) may be empty.
\[ M, [n_0] \models \nabla A \quad \text{iff} \quad M, [n_0] \models A \]

By extension, we write:

\[ M \models A \quad \text{iff} \quad M, \sigma \models A \text{ for every observation sequence } \sigma \]

\[ \Gamma \models A \quad \text{iff} \quad M \models A \text{ for all } A \in \Gamma \]

\[ \Gamma \models A \quad \text{iff} \quad M \models A \text{ implies } M \models A, \text{ for every LTL-model } M \]

Given an LTL-model \( M \), a structure is a pair \( S = \langle M, \mathcal{I} \rangle \) where \( \mathcal{I} : \mathcal{L} \rightarrow \mathbb{N} \). Let \( \Sigma \) be the set of observation sequences and \( \mathcal{I}^+ : \mathcal{L}^+ \rightarrow \Sigma \) the extension of \( \mathcal{I} \) to sequences, i.e., \( \mathcal{I}^+(b_0 \ldots b_n) = [\mathcal{I}(b_0), \ldots, \mathcal{I}(b_n)] \). Truth for a generic formula \( \varphi \) in a structure \( S = \langle M, \mathcal{I} \rangle \) is the smallest relation \( \models_\varphi \) satisfying:

\[ M, \mathcal{I} \models_\varphi a \leq b \quad \text{iff} \quad \mathcal{I}(a) \leq \mathcal{I}(b) \]

\[ M, \mathcal{I} \models_\varphi a < b \quad \text{iff} \quad \mathcal{I}(b) = \mathcal{I}(a) + 1 \]

\[ M, \mathcal{I} \models_\varphi \alpha : A \quad \text{iff} \quad M, \mathcal{I}^+(\alpha) \models_\varphi A \]

Note that \( M, \sigma \not\models_\varphi \bot \) and \( M, \mathcal{I} \not\models_\varphi \alpha : \bot \) for every \( M, \sigma \) and \( \mathcal{I} \).

Given a set \( \Phi \) of generic formulas and a generic formula \( \varphi \):

\[ M, \mathcal{I} \models_\varphi \Phi \quad \text{iff} \quad M, \mathcal{I} \models_\varphi \varphi \text{ for all } \varphi \in \Phi \]

\[ \Phi \models_\varphi \varphi \quad \text{iff} \quad M, \mathcal{I} \models_\varphi \Phi \text{ implies } M, \mathcal{I} \models_\varphi \varphi \text{ for all } M \text{ and } \mathcal{I} \]

### 3.2 A translation from LTL into LTL_∇

LTL and LTL_∇ are, obviously, related logics. In fact, below we will define a validity-preserving translation \( (;)^* \) from LTL into LTL_∇. Then, in Lemma \[1\], we will show that if an LTL_∇-formula corresponds to the translation of some LTL-formula, then it can be interpreted “locally”, i.e., its truth value with respect to an observation sequence depends only on the last element of the sequence. Finally, in Lemma \[2\] and Theorem \[1\] we will use this result to prove that the translation preserves the validity of formulas. This property allows us to use the deduction system for LTL_∇, which will be presented in Section \[4\] for reasoning on LTL too, as we will show in Section \[4.2\] when discussing soundness and completeness of the system.

**Definition 6.** We define the translation \( (;)^* \) from the language of LTL into the language of LTL_∇ inductively as follows:

\[
(p)^* = p, \text{ for } p \text{ atomic} \\
(GA)^* = G(A)^* \\
(\bot)^* = \bot \\
(XA)^* = X(A)^* \\
(A \supset B)^* = (A)^* \supset (B)^* \\
(AUB)^* = (B)^* \lor (F(X(B)^* \land \nabla(A)^*))
\]

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We extend $(\cdot)^*$ to sets of formulas in the obvious way: $A^* = \{B^* \mid B \in A\}$. 

**Lemma 1.** Let $\mathcal{M}$ be an LTL-model, $[n_1, \ldots, n_k]$ an observation sequence, and $A$ an LTL-formula. Then $\mathcal{M}, [n_1, \ldots, n_k] \models_{\mathcal{M}} A^*$ iff $\mathcal{M}, [n_1, \ldots, n_r, n_k] \models_{\mathcal{M}} A^*$ for every sequence $n_1, \ldots, n_r$.

**Corollary 1.** Let $\mathcal{M}$ be an LTL-model, $[n_1, \ldots, n_k]$ an observation sequence, and $A$ an LTL-formula. Then $\mathcal{M}, [n_1, \ldots, n_k] \models_{\mathcal{M}} A^*$ iff $\mathcal{M}, [n_k] \models_{\mathcal{M}} A^*$.

**Lemma 2.** Let $\mathcal{M}$ be an LTL-model, $n$ a natural number, and $A$ an LTL-formula. Then $\mathcal{M}, n \models_{\mathcal{M}} A$ iff $\mathcal{M}, [n] \models_{\mathcal{M}} A^*$.

**Theorem 1.** Let $\Lambda$ be a set of LTL-formulas, $A$ an LTL-formula and $A^* = \{B^* \mid B \in \Lambda\}$. Then $\Lambda \models_{\mathcal{LTL}} A$ iff $A^* \models_{\mathcal{M}} A^*$.

**Proof.** By Definition 2 $\Lambda \models_{\mathcal{LTL}} A$ iff $\forall \mathcal{M}, \mathcal{M} \models_{\mathcal{LTL}} A$ implies $\mathcal{M} \models_{\mathcal{LTL}} A$ iff $\forall \mathcal{M}. \forall n \mathcal{M}, n \models_{\mathcal{LTL}} B$ implies $\forall n \mathcal{M}, n \models_{\mathcal{LTL}} A$ (iff by Lemma 2) $\forall \mathcal{M}. (\forall B \in \Lambda \forall n \mathcal{M}, n \models_{\mathcal{LTL}} B^* \implies \forall n \mathcal{M}, n \models_{\mathcal{LTL}} A^*)$ (iff by Definition 5) $\forall \mathcal{M}. (\forall B \in \Lambda \forall \sigma \mathcal{M}, \sigma \models_{\mathcal{M}} B^* \implies \forall \sigma \mathcal{M}, \sigma \models_{\mathcal{M}} A^*)$ (iff by Definition 5) $\forall \mathcal{M}. (\forall B \in \Lambda \mathcal{M} \models_{\mathcal{M}} B^* \implies \mathcal{M} \models_{\mathcal{M}} A^*)$ (iff $\forall \mathcal{M}. (\mathcal{M} \models_{\mathcal{M}} A^*)$ (iff $\Lambda \models_{\mathcal{M}} A^*$).

### 4 \(\mathcal{N}(\text{LTL}_{\forall})\): a labeled natural deduction system for LTL\(_{\forall}\)

In this section, we will first define a labeled natural deduction system $\mathcal{N}(\text{LTL}_{\forall})$ that is sound with respect to the semantics of LTL\(_{\forall}\). Then, by considering a restriction of the set of $\mathcal{N}(\text{LTL}_{\forall})$-derivations and by using the translation $(\cdot)^*$ and the related results, we will show that $\mathcal{N}(\text{LTL}_{\forall})$ can be also used for reasoning on LTL; we will prove soundness with respect to the semantics of LTL and we will give a proof of weak completeness with respect to LTL, by exploiting the Hilbert-style axiomatization $\mathcal{H}(\text{LTL})$.

#### 4.1 The rules of $\mathcal{N}(\text{LTL}_{\forall})$

The rules of $\mathcal{N}(\text{LTL}_{\forall})$ are given in Figure 1. In $\mathcal{N}(\text{LTL}_{\forall})$ we do not make use of a proper relational labeling algebra (as, e.g., in [22]) that contains rules that derive rwffs from other rwffs or even lwffs. Since we are mainly interested in the derivation of logical formulas, we rather follow an approach that aims at simplifying the system: we use rwffs only as assumptions for the derivation of lwffs (as in Simpson’s system for intuitionistic modal logic [21]). Thus, in $\mathcal{N}(\text{LTL}_{\forall})$ there are no rules whose conclusion is an rwff.

The rules $\exists I$ and $\exists E$ are just the labeled version of the standard [17] natural deduction rules for implication introduction and elimination, where the notion of discharged/open assumption is also standard; e.g., $[\alpha : A]$ means that the
The rules have the following side conditions:

- In \( \text{GI} \), \( b_2 \) is fresh, i.e., it is different from \( b_1 \) and does not occur in any assumption on which \( ab_1 b_2 : A \) depends other than the discarded assumption \( b_1 \not< b_2 \) (\( b_1 \not< b_2 \)).
- In \( \nabla I \), \( b_2 \) is fresh, i.e., it is different from \( b_1 \) and \( b_3 \), and does not occur in any assumption on which \( ab_1 b_2 : A \) depends other than the discarded assumptions \( b_1 \not< b_2 \) and \( b_2 \not< b_3 \).
- In \( \text{last} \), the formula must be of the form \( A' \), as defined in [3].
- In \( \text{ser}_{\Downarrow} \), \( b_2 \) is fresh, i.e., it is different from \( b \) and does not occur in any assumption on which \( \alpha : A \) depends other than the discarded assumption \( b_1 \not< b_2 \).
- In \( \text{split}_{\Downarrow} \), \( b' \) is fresh, i.e., it is different from \( b_1 \) and \( b_2 \) and does not occur in any assumption on which \( \alpha : A \) depends other than the discarded assumptions \( b_1 \not< b' \) and \( b' \not< b_2 \).
- In \( \text{ind} \), \( b_1 \) and \( b_2 \) are fresh, i.e., they are different from each other and from \( b \) and \( b_0 \), and do not occur in any assumption on which \( ab_1 b_2 : A \) depends other than the discarded assumptions of the rule.

Fig. 1. The rules of \( \mathcal{N}(\text{LTL}_{\Downarrow}) \)
formula is discharged in $\nvdash I$. The rule $\bot E$ is a labeled version of \textit{reductio ad absurdum}, where we do not constrain the time instant sequence $(\alpha_2)$ in which we derive a contradiction to be the same $(\alpha_1)$ as in the assumption.

The rules for the introduction and the elimination of $G$ and $X$ share the same structure since they both have a “universal” formulation. Consider, for instance, $G$ and the corresponding relation $\leq$. The idea underlying the introduction rule $GI$ is that the meaning of $\alpha_1 : GA$ is given by the metalevel implication $b_1 \leq b_2 \implies \alpha b_1 b_2 : A$ for an arbitrary $b_2 \leq$-accessible from $b_1$ (where the arbitrariness of $b_2$ is ensured by the side-condition on the rule). As we remarked above, the operators $G$ and $X$ have a local nature, in that when we write $\alpha b_1 : GA$ (and similarly for $\alpha b_1 : XA$) we are stating that $GA$ holds at time instant $b_1$, which is the last in the sequence $\alpha b_1$. Hence, the elimination rule $GE$ says that if $b_2$ is $\leq$-accessible from $b_1$ (i.e., $b_1 \leq b_2$), then we can conclude that $A$ holds for the sequence $\alpha b_1 b_2$. Similar observations hold for $X$ and the corresponding relation $\prec$.

The rule $ser_{\leq}$ models the fact that every time instant has an immediate successor, while the rule $lin_{\leq}$ specifies that such a successor must be unique. $ser_{\prec}$ tells us that if assuming $b_1 \prec b_2$ we can derive $\alpha : A$, then we can discharge the assumption and conclude that indeed $\alpha : A$. $lin_{\prec}$ is slightly more complex: assume that $b_1$ had two different immediate successors $b_2$ and $b_3$ (which we know cannot be) and assume that the generic formula $\varphi$ holds; if by substituting $b_3$ for $b_2$ in $\varphi$ we obtain $\alpha : A$, then we can discharge the assumption and conclude that indeed $\alpha : A$.

Similarly, the rules $refl_{\leq}$ and $trans_{\leq}$ state the reflexivity and transitivity of $\leq$, while $eq_{\leq}$ captures substitution of equals. The rule $split_{\leq}$ states that if $b_1 \leq b_2$, then either $b_1 = b_2$ or $b_1 < b_2$. The rule thus works in the style of a disjunction elimination: if by assuming either of the two cases, we can derive a formula $\alpha : A$, then we can discharge the assumptions and conclude $\alpha : A$. Since we do not use $=$ and $<$ explicitly in our syntax, we express such relations in an indirect way: the equality of $b_1$ and $b_2$ is expressed by replacing one with the other in a generic formula $\varphi$, $\prec$ by the composition of $\prec$ and $\leq$.

The rule $base_{\leq}$ expresses the fact that $\leq$ contains $\prec$, while the rule $ind$ models the induction principle underlying the relation between $\prec$ and $\leq$. If (base case) $A$ holds in $\alpha b_0$ and if (inductive step) by assuming that $A$ holds in $\alpha b_1$ for an arbitrary $b_1 \leq$-accessible from $b_0$, we can derive that $A$ holds also in $\alpha b_j$, where $b_j$ is the immediate successor of $b_1$, then we can conclude that $A$ holds in every $\alpha b$ such that $b$ is $\leq$-accessible from $b_0$.

Finally, we have three rules that speak about the history and the label sequences: the rules $\nabla I$ and $\nabla E$, which we already described in the introduction,

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4 Recall that in this paper we use rwffs only as assumptions for the derivation of lwffs, so we do not need a more general rule that concludes $\varphi[b_2/b_1]$ from $\varphi$, $b_1 \leq b_2$ and $b_2 \leq b_1$.

5 The rule is given only in terms of relations between labels, since we restrict the treatment of operators in the system to the specific rules for their introduction and elimination.
and last. This rule expresses what we also anticipated in the introduction: the standard operators (and connectives) of LTL speak not about sequences of time instants but about single time instants, and thus if a formula $A$ whose outermost operator is not $\nabla$ holds at $\beta b$, then we can safely replace $\beta$ by any other sequence $\alpha$ and conclude that $A$ holds at $\alpha b$. To formalize this, we define the set of (well-formed) LTL$^I$-formulas (denoted by $A^I$) by means of the grammar

$$
A^I ::= p | \bot | (A^I) \supset (A^I) | G(A^{\nabla I}) | X(A^{\nabla I})
$$

and

$$
A^{\nabla I} ::= A^I | (A^{\nabla I}) \supset (A^{\nabla I}) | \nabla (A^{\nabla I})
$$

where $p$ is a propositional symbol. Hence, in a formula $A^I$, the history operator $\nabla$ can only appear in the scope of a temporal operator $G$ (and thus of $F$ as in the translation (2)) or $X$. The rule last applies to these formulas only; in fact, the “$l$” in $A^I$ stands for “last”, but it also conveniently evokes both “local” and “LTL”. For formulas $\nabla A$ whose outermost operator is the history operator $\nabla$, such a rule does not make sense (and in fact is not sound) as it would mean changing the interval over which $A$ holds.

Such considerations are formalized in the following lemma, where we prove, for LTL$^I$-formulas, a result that is the analogous of the one given in Lemma 1 with respect to the translation of LTL-formulas. At the same time, we also prove that if $A$ is a formula belonging to the syntactic category $A^{\nabla I}$ of the grammar (3) (we will call such formulas LTL$^{I \nabla}$-formulas), then the truth value of $A$ depends on at most the last two elements of an observation sequence.

**Lemma 3.** Let $M$ be an LTL-model, $[n_1, \ldots, n_k]$ an observation sequence, $A^I$ an LTL$^I$-formula and $A^{\nabla I}$ an LTL$^{I \nabla}$-formula. Then: (i) $M, [n_1, \ldots, n_k] \models_v A^I$ iff $M, [n_1, \ldots, n_k] \models_v A^{\nabla I}$ for every sequence $m_1, \ldots, m_r$ and (ii) $M, [n_1, \ldots, n_k] \models_v A^{\nabla I}$ iff $M, [m_1, \ldots, m_r, n_{k-1}, n_k] \models_v A^{\nabla I}$ for every sequence $m_1, \ldots, m_r$.

Given the rules in Fig. 1, the notions of derivation, assumption (open or discharged, as we remarked) and conclusion are the standard ones for natural deduction systems [17]. We write $\Phi \vdash_v \alpha : A$ to say that there exists a derivation of $\alpha : A$ in the system $N(LTL_\nabla)$ whose open assumptions are all contained in the set of formulas $\Phi$. A derivation of $\alpha : A$ in $N(LTL_\nabla)$ where all the assumptions are discharged is a proof of $\alpha : A$ in $N(LTL_\nabla)$ and we then say that $\alpha : A$ is a theorem of $N(LTL_\nabla)$ and write $\vdash_v \alpha : A$.

To denote that $\Pi$ is a derivation of $\alpha : A$ whose set of assumptions may contain the formulas $\varphi_1, \ldots, \varphi_n$, we write

$$
\varphi_1 \ldots \varphi_n \quad \Pi \quad \alpha : A
$$

If we are interested in LTL-reasoning, then we can restrict our attention to a subset of the $N(LTL_\nabla)$-derivations, namely, to the derivations where the conclusion and all the open assumptions correspond to the translations of LTL-formulas.

---

6 In fact, Lemma 1 is a direct consequence of Lemma 3 and of Lemma 4 below.
Definition 7. Let \( \Pi \) be a derivation in \( \mathcal{N}(LTL_\Box) \) and \( \Phi \) the set containing the conclusion and the open assumptions of \( \Pi \). We say that \( \Pi \) is an \( LTL \)-derivation iff there exists a label \( b \) such that for every \( \varphi \) in \( \Phi \) there exists an \( LTL \)-formula \( A \) such that \( \varphi = b : A^* \). We write \( A \vdash_{LTL} \) to denote that in \( \mathcal{N}(LTL_\Box) \) there exists an \( LTL \)-derivation of \( b : A^* \) from open assumptions in a set \( \Phi \), where \( A = \{ B \mid b : B^* \in \Phi \} \).

In Definition 7, we require all the open assumptions and the conclusion of an \( LTL \)-derivation to be lwffs labeled by the same single label \( b \). Note that, as a consequence of Corollary 1, we would obtain the same notion of \( LTL \)-derivation by requiring instead that such formulas were labeled by the same sequence \( \alpha \).

In Section 4.2, we will show that \( \mathcal{N}(LTL_\Box) \) is sound with respect to the semantics of \( LTL_\Box \) and, by considering the notion of \( LTL \)-derivability \( \vdash_{LTL} \), that it is sound and weakly complete with respect to \( LTL \). An investigation of completeness with respect to \( LTL_\Box \) is left for future work, together with the formalization of an axiomatization of \( LTL_\Box \).

Related to this, it is important to understand what exactly is the relationship of the class of \( LTL_\Box \)-formulas and the class of \( LTL \)-formulas, in particular with respect to the translation \(( \cdot )^* \). It is not difficult to see that the co-domain of the translation is included in \( LTL_\Box \) by construction of \(( \cdot )^* \), i.e., by induction on the formula complexity it follows that:

Lemma 4. If \( A \) is an \( LTL \)-formula, then \( A^* \) is an \( LTL_\Box \)-formula.

The other direction is trickier, as it basically amounts to defining an inverse translation. To solve this problem, we have been considering normal forms of \( LTL_\Box \)-formulas and we conjecture that the following fact indeed holds.

Conjecture 1. If \( A \) is an \( LTL_\Box \)-formula, then there exists an \( LTL \)-formula \( B \) such that \( B^* \) is semantically equivalent to \( A \).

4.2 Soundness and completeness

Theorem 2. For every set \( \Phi \) of labeled and relational formulas and every labeled formula \( \alpha : A \), if \( \Phi \vdash_\varnothing \alpha : A \), then \( \Phi \models_\varnothing \alpha : A \).

Proof. The proof proceeds by induction on the structure of the derivation of \( \alpha : A \). The base case is when \( \alpha : A \in \Phi \) and is trivial. There is one step case for every rule and we show here only the two representative cases

\[
\begin{align*}
[b_1 \leq b_2] & \quad [b_2 \leq b_3] \\
\Pi & \\
\beta b_1 b_2 : B & \quad \nabla I \\
\beta b_1 b_3 : \nabla B & \quad \nabla I \quad \text{and} \\
\Pi & \\
\beta b : A & \quad \text{last}
\end{align*}
\]

Some more cases are in Appendix A.3. First, consider the case in which the last rule application is a \( \nabla I \), where \( \alpha = \beta b_1 b_3 \), \( A = \nabla B \), and \( \Pi \) is a proof of \( \beta b_1 b_2 : B \) from hypotheses in \( \Phi' \), with \( b_2 \) fresh and with \( \Phi' = \Phi \cup \{ b_1 \leq \ldots \ldots \ldots \} \)
b_2 \} \cup \{ b_2 \leq b_3 \}. By the induction hypothesis, for every interpretation \( I \), if \( M, I \models \Phi \), then \( M, I \models b_1 b_2 : B \). We let \( I \) be any interpretation such that \( M, I \models \Phi \), and show that \( M, I \models b_1 b_2 : \nabla B \). Let \( I(b_1) = n \), \( I(b_3) = m \) and \( I^+(\beta) = [n_1, \ldots, n_k] \). Since \( b_2 \) is fresh, we can extend \( I \) to an interpretation (still called \( I \) for simplicity) such that \( I(b_2) = n + i \) for an arbitrary \( 0 \leq i \leq m \).

The induction hypothesis yields \( M, I \models b_1 b_2 : B \), i.e., \( M, [n_1, \ldots, n_k, n, n + i] \models \nabla B \), and thus, since \( i \) is an arbitrary point between 0 and \( m \), we obtain \( M, [n_1, \ldots, n_k, n, n + m] \models \nabla B \). It follows \( M, I \models b_1 b_2 : \nabla B \).

Now consider the case in which the last rule applied is \( \text{last} \). The proposed natural deduction system consists of only finitary rules; consequently, it cannot be strongly complete for \( \text{LTL} \). For every set \( M \) and every interpretation \( I \), if \( \Phi \) is a proof of \( \text{Definition 7} \), we also prove a result of soundness with respect to \( \text{LTL} \).

By exploiting the translation of Section 3.2 and the notion of \( \text{LTL-derivation} \) of Definition 7 we also prove a result of soundness with respect to \( \text{LTL} \).

**Theorem 3.** For every set \( A \) of \( \text{LTL} \)-formulas and every \( \text{LTL} \)-formula \( A \), if \( A \models_{\text{LTL}} A \), then \( A \models_{\text{LTL}} A \).

**Proof.** By definition of \( \models_{\text{LTL}} \), for a given label \( b \), there exists a derivation in \( \text{N} (\text{LTL}_{\text{c}}) \) of \( b : A^* \) from open assumptions in \( \Phi = \{ b : B^* \mid B \in A \} \). By Theorem 2 \( \Phi \models_{\text{LTL}} b : A^* \) implies \( \Phi \models_{\text{LTL}} b : A^* \). Since \( b \) is generic, we have that for every \( \text{LTL} \)-model \( M \) and every interpretation \( I \), \( M, I \models \Phi \) implies \( M, I \models b : A^* \) if for every natural number \( n \), \( M, [n] \models A^* \) implies \( M, [n] \models A^* \), where \( A^* = \{ B^* \mid B \in A \} \). By Lemma 1 we infer that for every observation sequence \( \sigma \), \( M, \sigma \models A^* \) implies \( M, \sigma \models A^* \). By Definition 5 \( A^* \models A^* \) and thus, by Theorem 1 we conclude \( A \models_{\text{LTL}} A \).

As we anticipated, an analysis of the completeness of \( \text{N} (\text{LTL}_{\text{c}}) \) with respect to \( \text{LTL}_{\text{c}} \) is left for future work. Here we discuss completeness with respect to \( \text{LTL} \). The proposed natural deduction system consists of only finitary rules; consequently, it cannot be strongly complete for \( \text{LTL} \). Nevertheless, by using the axiomatization \( \mathcal{H} (\text{LTL}) \) and the translation (\( \cdot \))^* we can give a proof of weak completeness for it; namely:

**Theorem 4.** For every \( \text{LTL} \)-formula \( A \), if \( \models_{\text{LTL}} A \), then \( \models_{\text{LTL}} A \).

**Proof.** We can prove the theorem by showing that \( \text{N} (\text{LTL}_{\text{c}}) \) is complete with respect to the axiomatization \( \mathcal{H} (\text{LTL}) \) given in Section 2 which is sound and

\[ \text{This is not a problem of our formulation: all the finitary deduction systems for temporal logics equipped with at least the operators X and G have such a defect; see, e.g., [15, Ch. 6].} \]
complete for the logic $LTL$. That is, we need to prove that: (i) the translation, via $(\cdot)^*$, of every axiom of $H(LTL)$ is provable in $N(LTL)$ by means of an $LTL$-derivation, and (ii) the notion of $\vdash_{LTL}$ is closed under the (labeled equivalent of the) rules of inference of $H(LTL)$. Showing (ii) is straightforward and we omit it here. As an example for (i), we give here a derivation of the translation of $(A6)$. The other cases are presented in Appendix A.A.

\[
\begin{array}{ll}
[b : G(A \supset XA)]^1 & [b \leq b_i]^4 \\
\overline{bb_i : A \supset XA} & GE \\
bb_i : XA & [b_i : A]^4 \\
\overline{bb_i : A} & \vdash E \\
[bb_i, b_j : A] & \text{last} \\
[bb_i : A, b_j : A] & \text{ind}^4 \\
\overline{bb_i, b_j : A} & \vdash E \\
\overline{b : G(A \supset XA) \supset (A \supset GA)} & \vdash I^1 \\
\end{array}
\]

5 Conclusions

The introduction of the operator $\nabla$ has allowed us to formalize the “history” of until and thus, via a proper translation, to give a labeled natural deduction system for a linear time logic endowed with $\nabla$ that is also sound and complete with respect to $LTL$ with until. As we remarked above, we see this work as spawning several different directions for future research. First, the “recipe” for dealing with until that we gave here is abstract and general, and thus provides the basis for formalizing deduction systems for temporal logics endowed with $U$, both linear and branching time. We are currently considering $CTL^*$ and its sublogics as in [16,18] and are also working at a formal characterization of the class of logics that can be captured with our approach.

Second, the well-behaved nature of our approach, where each connective and operator has one introduction and one elimination rule, paves the way to a proof-theoretical analysis of the resulting natural deduction systems, e.g., to show proof normalization and other useful meta-theoretical properties, which we are tackling in current work. Moreover, we are also considering different optimizations of the rules. In particular, along the lines of the discussion about the rule $\text{last}$ (and Corollary 1 and Definition 7), we are investigating to what extent we can use sequences as labels only when they are really needed, which would also simplify the proofs of normalization and other meta-properties.

---

7 As an interesting side-track, we believe that the restrictions we imposed on formulas for the rule $\text{last}$, i.e., considering $A^l$ and $A^l \nabla$, is closely related, at least in spirit, to the focus on persistent formulas when combining intuitionistic and classical logic so as to avoid the collapse of the two logics into one, see [8] but also [10]. We are, after all, considering here formulas stemming from two classes (if not two logics altogether), and it makes thus sense that they require different labeling (single instants and sequences).
This is closely related to the formalization of the relationship between the class of $LTL^l$-formulas and that of $LTL$-formulas, which in turn will allow us to reason about the completeness of $\mathcal{N}(LTL_\nabla)$ with respect to the semantics of $LTL_\nabla$ and also to provide an axiomatization of $LTL_\nabla$ (thus treating it as a full-fledged logic as opposed to as a “service” logic for $LTL$ as we did here).

Finally, it is worth observing that several works have considered *interval temporal logics*, e.g., [3, 5, 11, 14, 19]. While these works consider intervals explicitly, we have used them somehow implicitly here, as a means to formalize the dual nature of until via the history $\nabla$, and this is another reason why it is interesting to reduce the use of label sequences as much as possible. A more detailed comparison of our approach with these works is left for future work.

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A Proofs

A.1 Properties of the translation ($\cdot^*$)

Proof of Lemma 2 By induction on the complexity of $A$. The base case is when $A = p$ or $A = \perp$ and is trivial. There is one inductive step case for each connective and temporal operator.

$A = B \supset C$. Then the translation of $A$ is $A^* = B^* \supset C^*$. By Definition 5 we obtain $M, \{n_1, \ldots, n_k\} \models_{\psi} B^* \supset C^*$ if $M, \{n_1, \ldots, n_k\} \models_{\psi} B^*$ implies $M, \{n_1, \ldots, n_k\} \models_{\psi} C^*$. By the induction hypothesis, we see that this holds iff $M, \{n_1, \ldots, m_r, n_k\} \models_{\psi} B^*$ implies $M, \{n_1, \ldots, m_r, n_k\} \models_{\psi} C^*$ for every sequence $m_1, \ldots, m_r$ and thus, by Definition 6 iff for every sequence $m_1, \ldots, m_r$. $M, \{m_1, \ldots, m_r, n_k\} \models_{\psi} B^* \supset C^*$.

$A = \neg B$. Then $A^* = \neg B^*$. By Definition 6 $M, \{n_1, \ldots, n_k\} \models_{\psi} \neg B^*$ iff $\forall m \geq n_k. M, \{n_1, \ldots, n_k, m\} \models_{\psi} \neg B^*$ (by the induction hypothesis) $\forall m \geq n_k. M, \{n_1, \ldots, n_k, m\} \models_{\psi} B^*$ for every sequence $m_1, \ldots, m_r$ (by Definition 5 $M, \{m_1, \ldots, m_r, n_k\} \models_{\psi} B^*$, for every sequence $m_1, \ldots, m_r$).

$A = XB$. This case is very similar to the previous one and we omit it.

$A = B \supset C$. Then $A^* = C^* \lor (F(XC^* \land \neg B^*))$. By Definition 5 we have $M, \{n_1, \ldots, n_k\} \models_{\psi} A^*$ if $M, \{n_1, \ldots, n_k\} \models_{\psi} C^*$ or $M, \{n_1, \ldots, n_k\} \models_{\psi} F(XC^* \land \neg B^*)$ (Definition 5) (by the induction hypothesis) $\forall m \geq n_k. M, \{n_1, \ldots, n_k, m\} \models_{\psi} C^*$ or $\forall m \geq n_k. M, \{n_1, \ldots, n_k, m\} \models_{\psi} \neg B^*$ (by Definition 5) for every sequence $m_1, \ldots, m_r$. We have $M, \{m_1, \ldots, m_r, n_k\} \models_{\psi} C^*$ or $\forall m \geq n_k. M, \{m_1, \ldots, m_r, n_k, m + 1\} \models_{\psi} C^*$ and $\forall m \leq l \leq m$ implies $M, \{m_1, \ldots, m_r, n_k, l\} \models_{\psi} B^*$ (by Definition 5) $M, \{m_1, \ldots, m_r, n_k\} \models_{\psi} C^* \lor (F(XC^* \land \neg B^*))$ for every sequence $m_1, \ldots, m_r$.

Proof of Corollary 2 Immediate, by Lemma 1.

Proof of Lemma 2 By induction on the complexity of $A$. The base case is when $A = p$ or $A = \perp$ and is trivial. As inductive step, we have a case for each connective and temporal operator.

$A = B \supset C$. Then $A^* = B^* \supset C^*$. We have $M, n \models_{\text{ltl}} B \supset C$ (by Definition 2) $M, n \models_{\text{ltl}} B$ implies $M, n \models_{\text{ltl}} C$ (by the induction hypothesis) $M, [n] \models_{\psi} B^*$ implies $M, [n] \models_{\psi} C^*$ (by Definition 5 $M, [n] \models_{\psi} B^* \supset C^*$).

$A = \neg B$. Then $A^* = \neg B^*$. We have $M, n \models_{\text{ltl}} \neg B$ (by Definition 2) $\forall m \geq n. M, m \models_{\text{ltl}} B$ (by the induction hypothesis) $\forall m \geq n. M, [m] \models_{\psi} B^*$ (by Lemma 1 $\forall m \geq n. M, [m] \models_{\psi} B^*$ (by Definition 5) $M, [n] \models_{\psi} \neg B^*$).

$A = XB$. This case is very similar to the previous one and we omit it.
\[ A^* = C^* \lor (F(C^* \land \nabla B^*)) \]. We have \( M, n \models_{\text{LTL}} A \) iff (by Definition 2) \( \exists m \geq n. M, m \models_{\text{LTL}} C \) and \( \forall n'. n \leq n' < m \) implies \( M, n' \models_{\text{LTL}} B \) iff \( M, n \models_{\text{LTL}} C \) or \( (\exists m > n. M, m \models_{\text{LTL}} C \land \forall n'. n \leq n' < m \) implies \( M, n' \models_{\text{LTL}} B \) \) iff (by the induction hypothesis) \( M, [n] \models \forall \) \( C^* \) or \( (\exists m > n. M, [n, m] \models \forall \) \( C^* \) and \( \forall n'. n \leq n' < m \) implies \( M, [n, n'] \models \forall \) \( B^* \) \) iff (by Lemma 1) \( M, [n] \models \forall \) \( C^* \) or \( (\exists m > n. M, [n, m] \models \forall \) \( C^* \) and \( \forall n'. n \leq n' < m \) implies \( M, [n, n'] \models \forall \) \( B^* \) \) iff (by Definition 5) \( M, [n] \models \forall \) \( C^* \) or \( (\exists l \geq n. M, [n, l] \models \forall \) \( C^* \land \nabla B^* \) \) iff (by Definition 5) \( M, [n] \models \forall \) \( C^* \lor F(C^* \land \nabla B^*) \).

\[ A = BUC. \] Then \( A^* = C^* \lor (F(C^* \land \nabla B^*)) \). We have \( M, n \models_{\text{LTL}} A \) iff (by Definition 2) \( \exists m \geq n. M, m \models_{\text{LTL}} C \) and \( \forall n'. n \leq n' < m \) implies \( M, n' \models_{\text{LTL}} B \) iff \( M, n \models_{\text{LTL}} C \) or \( (\exists m > n. M, m \models_{\text{LTL}} C \land \forall n'. n \leq n' < m \) implies \( M, n' \models_{\text{LTL}} B \) \) iff (by the induction hypothesis) \( M, [n] \models \forall \) \( C^* \) or \( (\exists m > n. M, [n, m] \models \forall \) \( C^* \) and \( \forall n'. n \leq n' < m \) implies \( M, [n, n'] \models \forall \) \( B^* \) \) iff (by Lemma 1) \( M, [n] \models \forall \) \( C^* \) or \( (\exists m > n. M, [n, m] \models \forall \) \( C^* \) and \( \forall n'. n \leq n' < m \) implies \( M, [n, n'] \models \forall \) \( B^* \) \) iff (by Definition 5) \( M, [n] \models \forall \) \( C^* \) or \( (\exists l \geq n. M, [n, l] \models \forall \) \( C^* \land \nabla B^* \) \) iff (by Definition 5) \( M, [n] \models \forall \) \( C^* \lor F(C^* \land \nabla B^*) \).

A.2 The system \( \mathcal{N}(\text{LTL} \forall) \)

Proof of Lemma 5 The proofs of the statements (i) and (ii) proceed in parallel and are by induction on the formula complexity. The base case is when \( A^* = p \) or \( A^* = \bot \) and is trivial. There is one inductive step case for each other formation case coming from the recursive definition of the grammar \( \mathcal{K} \). Along the proof, \( A^i, B^i, C^i, \ldots \) denote LTLi-formulas while \( A^{\forall}, B^{\forall}, C^{\forall}, \ldots \) denote LTL∀-formulas.

\[ A^i = B^i \lor C^i. \] By Definition 5 we have \( M, [n_1, \ldots, n_k] \models \forall \) \( B^i \lor C^i \) iff \( M, [n_1, \ldots, n_k] \models \forall \) \( C^i \). By the induction hypothesis, we see that this holds iff \( M, [n_1, \ldots, n_k] \models \forall \) \( B^i \) implies \( M, [n_1, \ldots, m_r, n_k] \models \forall \) \( C^i \) for every sequence \( n_1, \ldots, m_r \) and thus, by Definition 5 iff for every sequence \( n_1, \ldots, m_r \), \( M, [n_1, \ldots, m_r, n_k] \models \forall \) \( B^i \lor C^i \).

\[ A^i = GB^{\forall}. \] \( M, [n_1, \ldots, n_k] \models \forall \) \( GB^{\forall} \) iff (by Definition 5) \( \forall m \geq n_k. M, [n_1, \ldots, n_k, m] \models \forall \) \( B^{\forall} \) iff (by the induction hypothesis) \( \forall m \geq n_k. M, [n_1, \ldots, m_r, n_k, m] \models \forall \) \( B^{\forall} \) for every sequence \( n_1, \ldots, m_r \) iff (by Definition 5) \( M, [n_1, \ldots, m_r, n_k] \models \forall \) \( GB^{\forall} \) for every sequence \( n_1, \ldots, m_r \).

\[ A^i = X B^{\forall}. \] This case is very similar to the previous one and we omit it.

\[ A^{\forall} = B^i. \] \( M, [n_1, \ldots, n_k] \models \forall \) \( B^i \) iff (by the induction hypothesis) \( M, [i_1, \ldots, i_s, n_k] \models \forall \) \( B^i \) for every sequence \( i_1, \ldots, i_s \) and thus also \( M, [n_1, \ldots, m_r, n_k] \models \forall \) \( B^i \) for every sequence \( n_1, \ldots, m_r \).

\[ A^{\forall} = B^{\forall} \lor C^{\forall}. \] \( M, [n_1, \ldots, n_k] \models \forall \) \( B^{\forall} \lor C^{\forall} \) iff (by Definition 5) \( M, [n_1, \ldots, n_k] \models \forall \) \( C^{\forall} \). By the induction hypothesis, this holds iff \( M, [n_1, \ldots, m_r, n_k] \models \forall \) \( B^{\forall} \) implies \( M, [n_1, \ldots, m_r, n_k] \models \forall \) \( C^{\forall} \) for every sequence \( n_1, \ldots, m_r, n_k \) and thus, by Definition 5 iff for every sequence \( n_1, \ldots, m_r \), \( M, [n_1, \ldots, m_r, n_k] \models \forall \) \( B^{\forall} \lor C^{\forall} \).

\[ A^{\forall} = \nabla B^{\forall}. \] \( M, [n_1, \ldots, n_k] \models \forall \) \( \nabla B^{\forall} \) iff (by Definition 5) \( \forall n_k \leq n \leq n_k \) implies \( M, [n_1, \ldots, n_k] \models \forall \) \( B^{\forall} \) iff (by the induction hypothesis) \( \forall n_k \leq n \leq n_k \) implies \( M, [n_1, \ldots, m_r, n_k] \models \forall \) \( B^{\forall} \) for every sequence \( n_1, \ldots, m_r \) iff (by Definition 5) \( M, [n_1, \ldots, m_r, n_k] \models \forall \) \( \nabla B^{\forall} \) for every sequence \( n_1, \ldots, m_r \).
A.3 Soundness

Proof of Theorem 2 We present here some more cases related to the proof of Theorem 2 which states the soundness of the system $\mathcal{N}(\text{LTL}_\varphi)$ with respect to the semantics of LTL.

Consider the case in which the last rule application is a GI, where $\alpha = \beta b_1$ and $A = GB$:

$$
\frac{[b_1 \leq b_2]}{\beta b_1 b_2 : B} \quad \frac{\beta b_1 b_2 : B}{\beta b_1 : GB} \quad GI
$$

where $\Pi$ is a proof of $\beta b_1 : GB$ from hypotheses in $\Phi'$, with $b_2$ fresh and with $\Phi' = \Phi \cup \{b_1 \leq b_2\}$. By the induction hypothesis, for all interpretations $I$, if $\mathcal{M}, \mathcal{I} \models \varphi'$, then $\mathcal{M}, \mathcal{I} \models \varphi \beta b_1 b_2 : B$. We let $I$ be any interpretation such that $\mathcal{M}, \mathcal{I} \models \varphi$, and show that $\mathcal{M}, \mathcal{I} \models \varphi \beta b_1 : GB$. Let $I(b_1) = n$ and $I^+(\beta) = \{n_1, \ldots, n_k\}$. Since $b_2$ is fresh, we can extend $I$ to an interpretation (still called $I$ for simplicity) such that $I(b_2) = n + m$ for an arbitrary $m > 0$. The induction hypothesis yields $\mathcal{M}, \mathcal{I} \models \varphi \beta b_1 b_2 : B$, i.e., $\mathcal{M}, [n_1, \ldots, n_k, n, n + m] \models \varphi B$, and thus, since $m$ is arbitrary, we obtain $\mathcal{M}, [n_1, \ldots, n_k, n] \models \varphi GB$. It follows $\mathcal{M}, \mathcal{I} \models \varphi \beta b_1 : GB$.

Now consider the case in which the last rule applied is GE and $\alpha = \beta b_1 b_2$:

$$
\frac{\Pi}{\beta b_1 : \text{GA}} \quad \frac{b_1 \leq b_2}{\beta b_1 b_2 : A} \quad \text{GE}
$$

where $\Pi$ is a proof of $\beta b_1 : \text{GA}$ from hypotheses in $\Phi_1$, with $\Phi = \Phi_1 \cup \{b_1 \leq b_2\}$ for some set $\Phi_1$ of formulas. By applying the induction hypothesis on $\Pi$, we have:

$$
\Phi_1 \models \varphi \beta b_1 : \text{GA}.
$$

We proceed by considering a generic LTL-model $\mathcal{M}$ and a generic interpretation $\mathcal{I}$ on it such that $\mathcal{M}, \mathcal{I} \models \varphi$ and showing that this entails

$$
\mathcal{M}, \mathcal{I} \models \varphi \beta b_1 b_2 : A.
$$

Since $\Phi_1 \subset \Phi$, we deduce $\mathcal{M}, \mathcal{I} \models \varphi \Phi_1$ and, from the induction hypothesis, $\mathcal{M}, \mathcal{I} \models \varphi \beta b_1 : \text{GA}$. Furthermore $\mathcal{M}, \mathcal{I} \models \varphi$ entails $\mathcal{M}, \mathcal{I} \models \varphi b_1 \leq b_2$. Then, by Definition 5 we obtain $\mathcal{M}, \mathcal{I} \models \varphi \beta b_1 b_2 : A$.

Now consider the case in which the last rule applied is $\nabla E$ and $\alpha = \beta b_1 b_3$:

$$
\frac{\Pi}{\beta b_1 b_3 : \nabla A} \quad \frac{b_1 \leq b_2 \quad b_2 \leq b_3}{\beta b_1 b_2 : A} \quad \nabla E
$$

where $\Pi$ is a proof of $\beta b_1 b_3 : \nabla A$ from hypotheses in $\Phi_1$, with $\Phi = \Phi_1 \cup \{b_1 \leq b_2\} \cup \{b_2 \leq b_3\}$ for some set $\Phi_1$ of formulas. By applying the induction hypothesis on $\Pi$, we have:

$$
\Phi_1 \models \varphi \beta b_1 b_3 : \nabla A.
$$
We proceed by considering a generic LTL-model $M$ and a generic interpretation $I$ on it such that $M, I \models \Phi$ and showing that this entails

$M, I \models \beta b_1 b_2 : A$.

Since $\Phi_1 \subset \Phi$, we deduce $M, I \models \Phi_1$ and, from the induction hypothesis, $M, I \models \beta b_1 b_2 : \nabla A$. Furthermore, the side-condition on the rule entails $M, I \models b_1 \leq b_2$ and $M, I \models b_2 \leq b_3$. Then, by Definition [5] we obtain $M, I \models \beta b_1 b_2 : A$.

Finally, consider the case in which the last rule applied is $\text{ind}$ and $\alpha = \beta b$:

\[
\begin{array}{c|c|c|c}
\text{II}' & b_0 \leq b & \beta b_0 : A \\
\hline
\text{ind} & \beta b : A
\end{array}
\]

where $\Pi$ is a proof of $\beta b_j : A$ from hypotheses in $\Phi_2$ and $\Pi'$ is a proof of $\beta b_0 : A$ from hypotheses in $\Phi_1$, with $\Phi = \Phi_1 \cup \{b_0 \leq b\}$ and $\Phi_2 = \Phi_1 \cup \{b_0 \leq b_1\} \cup \{b_i < b\} \cup \{b_k : A\}$ for some set $\Phi_1$ of formulas. The side-condition on $\text{ind}$ ensures that $b_i$ and $b_j$ are fresh in $\Pi$. Hence, by applying the induction hypothesis on $\Pi$ and $\Pi'$, we have:

$\Phi_2 \models \beta b_j : A$ and $\Phi_1 \models \beta b_0 : A$.

We proceed by considering a generic LTL-model $M$ and a generic interpretation $I$ on it such that $M, I \models \Phi$ and showing that this entails

$M, I \models \beta b : A$.

First, we note that $\Phi_1 \subset \Phi$ and therefore $M, I \models \Phi$ implies $M, I \models \Phi_1$ and, by the induction hypothesis on $\Pi'$, $M, I \models \beta b_0 : A$. Now let $I(b_0) = n$ for some natural number $n$. From $M, I \models \Phi$, we deduce $M, I \models b_1 \leq b$ and thus $I(b) = n + k$ for some $k \in \mathbb{N}$. We show by induction on $k$ that $M, I \models \beta b : A$.

As a base case, we have $k = 0$; it follows that $I(b) = I(b_0)$ and thus trivially that $M, I \models \beta b_0 : A$ entails $M, I \models \beta b : A$. Let us consider now the induction step. Given a label $b_{k-1}$ such that $I(b_{k-1}) = n + k - 1$, we show that the induction hypothesis $M, I \models \beta b_{k-1} : A$ entails the thesis $M, I \models \beta b : A$. We can build an interpretation $I'$ that differs from $I$ only in the points assigned to $b_i$ and $b_j$, namely, $I' = I[b_i \mapsto n + k - 1][b_j \mapsto n + k]$. It is easy to verify that the interpretation $I'$ is such that the following three conditions hold:

(i) $M, I' \models \beta b_i : A$;
(ii) $M, I' \models b_0 \leq b_i$;
(iii) $M, I' \models b_i < b_j$.

Furthermore, the side-condition on the rule $\text{ind}$ ensures that $I$ and $I'$ agree on all the labels occurring in $\Phi_1$, from which we can infer $M, I' \models \Phi_1$. It follows $M, I' \models \Phi_2$ and thus, by the induction hypothesis on $\Pi$, $M, I' \models \beta b_j : A$.

We conclude $M, I' \models \beta b : A$ by observing that $I'(b_j) = I(b)$.

□
A.4 Completeness

Proof of Theorem 4 We present here the \(N(LTL\forall)\)-derivations of the remaining axioms of \(H(LTL)\). Note that, for simplicity, we use also some rules (i.e., \(FI, FE, \lor I, \lor E, \land I\) and \(\land E\)) concerning derived operators. They can be easily derived from the set of rules in Figure 1.

(A2)

\[
\frac{[b : G(A \supset B)]^3 [b \equiv c]^3}{bc : A \supset B} \quad \frac{[b : GA]^2 [b \equiv c]^3}{bc : A} \quad \frac{[b : B]}{bc : \lor E} \quad \frac{b \equiv c}{bc : \land E} \quad \frac{b : GA \supset GB}{b : G(A \supset B) \supset (GA \supset GB) \supset I^1}
\]

(A3) \((X \neg A \leftrightarrow \neg XA)\)

\[
\frac{[b : X \neg A]^1 [b \equiv c]^2}{bc : \neg A} \quad \frac{[b : XA]^3 [b \equiv c]^2}{bc : A} \quad \frac{[b \equiv d]^4 [bc : A]^3}{bc : \land E^3} \quad \frac{b \equiv c}{bc : \lor E^2} \quad \frac{b : XA}{bc : \lor E^3} \quad \frac{b : X \neg A \supset \neg XA}{bc : \land E^1} \quad \frac{b : XA}{bc : \land E^2} \quad \frac{b : X \neg A \supset \neg XA}{bc : \land E^1}
\]

(A4) This proof is similar to the one for (A2) and we thus omit it.

(A5)

\[
\frac{[b : GA]^1 [b \equiv h]^2}{bc : A} \quad \frac{[b \equiv c]^3}{bc : \lor E} \quad \frac{bd : A}{bc : \land E} \quad \frac{bd : A}{bc : base_{\land}^c} \quad \frac{[b : GA]^1 [b \equiv d]^6}{bc : \lor E} \quad \frac{bd : A}{bc : trans_{\land}^c}
\]

(A7) Note that, for brevity, we give here a derivation of a, clearly equivalent, simplified version of the translation of (A7). Namely, we consider \(F(XB \land \nabla A) \supset (A \land X(B \lor F(XB \land \nabla A)))\) instead of \(B \lor F(XB \land \nabla A) \supset B \lor (A \land X(B \lor F(XB \land \nabla A))).\)
Left-to-right direction:

\[
\begin{align*}
& \frac{[bc : \forall b \forall A]^2}{bc : \forall A} \quad \wedge \quad E \quad [b \leq b]^2 \quad [b \leq c]^2 \quad \forall E \\
& \quad \frac{bb : A}{bb : A} \quad \text{ref}_{\leq}^5 \\
& \quad \frac{bb : A}{bb : A} \quad \text{last} \\
& \quad b : X(B \lor F(XB \land \forall A)) \quad \Pi_1 \\
& \quad \frac{b : A \land X(B \lor F(XB \land \forall A))}{b : F(XB \land \forall A)} \quad FE^2 \\
& \quad b : F(XB \land \forall A) \supset (A \land X(B \lor F(XB \land \forall A))) \quad \supset I^1
\end{align*}
\]

where \( \Pi_1 \) is the following derivation:

\[
\begin{align*}
& \frac{[bc : \forall b \forall A]^2}{bc : \forall A} \quad \wedge \quad E \quad [c \leq b]^5 \\
& \quad \frac{bb' : B}{bb' : B} \quad \text{last} \\
& \quad b \leq b' \quad b \leq b'' \quad bb'' : B \lor F(XB \land \forall A) \quad [bb' : B \lor F(XB \land \forall A)]_{\ref{lins}^6} \\
& \quad \frac{bb' : B \lor F(XB \land \forall A)}{bb' : B \lor F(XB \land \forall A)} \quad \text{split}_{\leq}^5 \\
& \quad b : X(B \lor F(XB \land \forall A)) \quad \Pi_2 \\
& \quad b : X(B \lor F(XB \land \forall A)) \quad \forall I^4
\end{align*}
\]

and \( \Pi_2 \) is the following derivation:

\[
\begin{align*}
& \frac{[bc : \forall b \forall A]^2}{bc : \forall A} \quad \wedge \quad E \quad [c \leq b']^7 \\
& \quad \frac{bc' : B}{bc' : B} \quad \text{last} \\
& \quad bb'' : B \lor F(XB \land \forall A) \quad \Pi_3 \\
& \quad bb'' : B \lor F(XB \land \forall A) \quad \forall I^7 \\
& \quad bb'' : B \lor F(XB \land \forall A) \quad \forall I
\end{align*}
\]

Right-to-left direction: in the following derivations, we denote with \( \varphi \) the formula \( b : A \land X(B \lor F(XB \land \forall A)) \).

\[
\begin{align*}
& \frac{[\varphi]_1}{b : X(B \lor F(XB \land \forall A))} \quad \wedge \quad E \quad [b \leq c]^2 \\
& \quad \frac{bc : B \lor F(XB \land \forall A)^3}{bc : B \lor F(XB \land \forall A)} \quad \Pi_1 \\
& \quad \frac{bc : B \lor F(XB \land \forall A)}{bc : B \lor F(XB \land \forall A)} \quad \Pi_2 \\
& \quad b : F(XB \land \forall A) \quad F \quad E^3 \\
& \quad b : F(XB \land \forall A) \quad \text{ser}_{\leq}^7 \\
& \quad b : X(B \lor F(XB \land \forall A)) \quad \supset I^1
\end{align*}
\]

where \( \Pi_1 \) is the following derivation:

\[
\begin{align*}
& \frac{[b \leq c]^2}{b \leq f}^5 \\
& \quad \frac{[bc : B]^3}{bc : B} \quad \Pi_1 \\
& \quad \frac{bc : B}{bc : B} \quad \text{last} \\
& \quad \frac{bc : B}{bc : B} \quad \text{last} \\
& \quad b : F(XB \land \forall A) \quad \Pi_1 \\
& \quad [\varphi]_1 \quad \wedge \quad E \\
& \quad b : A \quad \text{eq}_{\leq}^5 \\
& \quad b : A \quad \text{last} \\
& \quad b : F(XB \land \forall A) \quad \Pi_1 \\
& \quad b : F(XB \land \forall A) \quad \text{ref}_{\leq}^5 \\
& \quad b : F(XB \land \forall A) \quad \text{ref}_{\leq}^5
\end{align*}
\]
$\Pi_2$ is the following derivation:

\[
\frac{[bec : XB \land \nabla A]^8 \land E}{bec : B} \quad \frac{[c \leq f]^{11}}{XE}
\]
\[
\frac{becf : B}{\text{last}} \quad \frac{bcf : XB}{\text{I}^{11}} \quad \frac{bc : \nabla A \land I}{\Pi_3}
\]
\[
\frac{[b \leq e]^{10}}{\text{base}^9} \quad \frac{b : F(XB \land \nabla A)}{\text{F}^{10}}
\]

and $\Pi_3$ is the following derivation:

\[
\frac{[b \leq c]^2}{[b \leq e]^8} \quad \frac{[b \leq c]^8}{b : F(XB \land \nabla A)}
\]
\[
\frac{[b \leq c]^{10}}{\text{base}^9} \quad \frac{b : F(XB \land \nabla A)}{\text{F}^{10}}
\]

\[
\frac{[bec : XB \land \nabla A]^8 \land E}{bec : B} \quad \frac{[d : A]^13}{bd : A} \quad \frac{[b \leq d]^{12}}{\text{base}^9}
\]
\[
\frac{[b \leq d]^{12}}{\text{base}^9} \quad \frac{[b \leq e]^2}{[f \leq d]^{13}} \quad \frac{[f \leq d]^{13}}{\text{F}^{10}}
\]
\[
\frac{[d : A]}{\text{last}} \quad \frac{bed : A}{\text{ \text{I}^{14}}} \quad \frac{bd : A}{\text{ \text{split}^{13}}}
\]
\[
\frac{bd : A}{\text{ \text{split}^{13}}} \quad \frac{bc : \nabla A}{\text{F}^{12}}
\]
Proof of the axiom (A8)

\[
\begin{align*}
\frac{[b : B \lor (F(XB \land \nabla A))]^1}{b : F(B)} & \quad \frac{b : F(B)}{b : F(B) \lor (F(XB \land \nabla A))} \supset I^1 \\
\frac{[b : B]}{b : B} \text{ last} & \quad \frac{[b \leq b]^3 \quad [c \leq d]^6}{[c < d]^5} \quad \frac{b : F(B) \text{ refl}^5}{b : F(B) \text{ base}^6} \quad \frac{b : F(B) \text{ ser}^5}{b : F(B) \text{ E}^4} \quad \frac{b : F(B) \lor E^2}{b : F(B) \lor E^2} \\
\frac{bc : XB \land \nabla A}{} & \quad \frac{bc : XB}{} \quad \frac{[c < d]^5}{X E} \quad \frac{[c \leq d]^6}{X E} \quad \frac{b : F(B) \text{ trans}^7}{b : F(B) \supset I^1} \\
\end{align*}
\]