An Extensible Logic Embedding Tool for Lightweight Non-Classical Reasoning (system description)

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Abstract. The logic embedding tool provides a procedural encoding for non-classical reasoning problems into classical higher-order logic. It is extensible and can support an increasing number of different non-classical logics as reasoning targets. When used as a pre-processor or library for higher-order theorem provers, the tool admits off-the-shelf automation for logics for which otherwise few to none provers are currently available.

Keywords: Non-Classical Logic · Logic Encoding · Higher-Order Logic

1 Introduction

Non-classical logics (NCLs) deviate from various principles of classical logics such as bivalence, truth-functionality, idempotency of entailment, etc. NCLs have numerous topical applications in artificial intelligence, mathematics, computer science, philosophy and other fields; and increasingly many domain-specific NCLs are being introduced. Despite the relevance of NCL reasoning, for many formalisms automated theorem proving (ATP) systems do not exist. One major reason is that the development of ATP systems requires not only suitable theoretical foundations, but it also requires considerable resources for software development and related aspects. It is not surprising that these efforts are only rarely made for logics that are still the subject of active research and discussion (i.e., moving targets), and might be superseded with novel formalisms in the near future. This situation impedes the deployment of methods in practical AI research, and it also hampers the systematic evaluation of available formalisms. Of course, there are notable exceptions of well-established NCLs for which ATP systems do exist, such as linear logics [14,21], intuitionistic logics [29,27,32,44] and modal logics [30,29,28,45,13,22].

Orthogonal to the development of special-purpose provers for individual NCLs is the use of logic translations that encode the logic under consideration (the source logic) into another logic formalism (the target logic) for which there exist means of automation [25,26]. In this setting, improvements to ATP systems for the target logic inherently benefit reasoning in the source logic. A special type of logic translation is shallow embedding [18], in which the source logic’s semantics is directly encoded in the target logic.
The logic embedding tool (LET) provides a library of shallow embeddings of NCLs into higher-order logic, and an executable for applying these embeddings on input problems. Special attention is paid to the extensibility of the tool's underlying library of embeddings. LET is implemented in Scala and freely available as open-source software (BSD-3 license) via Zenodo [33] and GitHub[1]. The input format is a non-classical TPTP syntax extension [36] that allows non-classical reasoning problems to be written within the common TPTP framework [39], see Sect. 2 for an overview. LET can be used as library or as external pre-processor to higher-order ATP systems, effectively enabling automated reasoning for various NCLs. Currently, the following logics are supported:

- Many quantified normal multi-modal logics
- Various hybrid logics
- Public announcement logic
- Carmo and Jones’ dyadic deontic logic
- Åqvist’s dyadic deontic logic E

2 Problem Representation Format

As input syntax LET accepts the TFN and THN languages [36], recent non-classical extensions of the well-established TPTP syntax standard for ATP systems. The TPTP syntax is part of the TPTP World infrastructure [39], and defines several languages for representing reasoning problems and solutions, including languages for untyped first-order logic (FOF) [38], typed first order logic (TFF) [42,10], typed first-order logic extended with Boolean terms and variables (TXF, formerly TFX) [41], and higher-order logic (THF) [40,23]. A comprehensive survey of these languages and their usage is available in the literature [39].

The TXN and THN languages extend TXF and THF, respectively, with new generic non-classical operators of the form \{connective.name\} that are applied like function symbols. For some operators there are also short forms available (not discussed here). Although TXN is a typed language, it may also represent untyped formalisms. Following the conventions from TFF and TXF, any predicate symbol and function symbol in the problem with undeclared type implicitly defaults to a canonical n-ary predicate type or n-ary function type.

Additionally, TXN and THN introduce so-called logic specifications, special kinds of TPTP annotated formulas with the role logic, which specify the logic being used within the problem file. In TXN they are of form ...

\[\text{tff(name,logic,logic_name == properties).}\]

where logic_name is some TPTP or user defined name for a logic (or logic family), and properties is a list of key-value parameters that optionally further specify the intended NCL. In THN the format is the same, only that the THF formula identifier thf is used instead.

A detailed introduction of non-classical connectives and logic specifications is presented in the respective TPTP proposal [21,36], and they are informally illustrated via the application examples below.

[1] github.com/leoprover/logic-embedding
3 Architecture

The components of LET and their relationship are displayed in Fig. 1. It is structured into two main modules:

1. The library module defines a common embedding interface, and constitutes the collection of shallow embeddings for different NCLs.
2. The application module implements a stand-alone executable on top of the library module. It finds and applies the correct shallow embedding on a given input problem.

Note that the library module is independent from the application module, and can be included in existing ATP systems via a simple API. The application module, in contrast, can be employed as external pre-processor executable.

The general procedure implemented by the application module is as follows:

1. The input problem is parsed and scanned for a logic specification (an annotated TPTP formula with the role logic),
2. the logic name and the parameters are extracted from the logic specification,
3. the database of supported logics is queried for the given logic and, if supported, the respective embedding procedure is provided, and finally,
4. the embedding procedure is invoked on the input problem and the result is returned as classical TPTP THF problem.

If the problem does not contain any logic specification, the original problem is returned. If the logic specified in the input problem is malformed or not supported by LET an error is reported. The separation of library and application facilitates LET’s extensibility, as the library can be easily extended with new embeddings of further NCLs while the application module remains unchanged.

Note that the output of the tool is a classical higher-order problem represented in THF syntax. Hence every higher-order ATP system that supports reasoning in THF can be employed for reasoning in the respective NCL. Additionally, LET supports TSTP-compatible result reporting for seamless integration into TPTP/TSTP tool chains.
4 Overview of Supported NCLs

The NCLs currently supported by LET are the following:

**Modal logics.** The logic name $\textit{modal}$ represents the family of propositional and first-order quantified normal multi-modal logics [9][11]. The modal operators $\Box$ and $\Diamond$ are represented by the non-classical connectives $\texttt{box}$ and $\texttt{dia}$, respectively. In the case of multiple modalities, the connectives are indexed with uninterpreted user constants, prefixed with a # (hash sign) as, e.g., in $\texttt{box(#i)}$ and $\texttt{dia(#i)}$. Global assumptions via the role axiom, and local assumptions are expressed via annotated formulas of role hypothesis [17]. Relevant embeddings are described in [6][20].

**Hybrid logics.** Hybrid logics, referred to as $\textit{hybrid}$, extend the modal logic family $\textit{modal}$ with the notion of nominals, a special kind of atomic formula symbol that is true only in a specific world [2]. The logics represented by $\textit{hybrid}$ are first-order variants of $\mathcal{H}(E, @, \downarrow)$ [2][11]. A nominal symbol $n$ is represented as $\texttt{nominal}(n)$, the shift operator $@$, as $\texttt{shift(#s)}$, and the bind operator $\downarrow x$ as $\texttt{bind(#X)}$. All other aspects are analogous to the modal logic representation above. Preliminary shallow embeddings results are reported in [46]. The embedding implemented in LET simplifies and extends these.

**Public announcement logic.** Public announcement logic (PAL), $\textit{pal}$, is a propositional epistemic logic that allows for reasoning about knowledge. In contrast to $\textit{modal}$, PAL is a dynamic logic that supports updating the knowledge of agents via so-called announcement operators [16]. The knowledge operator $K_i$ is given by $\texttt{knows(#i)}$, the common knowledge operator $C_A$, with $A$ a set of agents, by $\texttt{common($$group := \ldots))}$, and the announcement $[!\phi]$ is represented as $\texttt{announce($$formula := \phi)}$. An embedding of PAL is presented in [8].

**Dyadic deontic logics.** Deontic logics are formalisms for reasoning over norms, obligations, permissions and prohibitions. In contrast to modal logics used for this purpose (e.g., modal logic $\textit{D}$), dyadic deontic logics (DDLs), named $\textit{ddl}$, offer a more sophisticated representation of conditional norms using a dyadic obligation operator $\odot(\varphi/\psi)$. They address paradoxes of other deontic logics in the context of so-called contrary-to-duty (CTD) situations [15]. The concrete DDLs supported by LET are the propositional system by Carmo and Jones [12] and Åqvist’s propositional system $\textit{E}$ [1]. The dyadic deontic operator $\odot$ is represented by $\texttt{obl}$ (short for obligatory). An embedding of the above DDL is studied in [7][5].

Note that the name $\textit{modal}$ of modal logics and that of its connective names are given by TPTP defined names (starting with a single dollar sign) since it is the first non-classical logic standardized by the TPTP [21][36]. All further logics are LET-specific logic representations that have not (yet) been included in the collection of TPTP curated NCLs; following the TPTP naming convention, their identifiers hence start with two dollar signs (system defined names).
Table 1. Overview of the parameters of the different NCLs supported by LET

| Logic | Parameter | Description |
|-------|-----------|-------------|
| $modal$ | $quantification$ | Selects whether quantification semantics is varying domains, constant domains, cumulative domains or decreasing domains. Accepted values: $varying, $constant, $cumulative, $decreasing |
| $constants$ | | Selects whether constant and functions symbols are interpreted as rigid or flexible. Accepted values: $rigid, $flexible† |
| $modalities$ | | Selects the properties for the modal operators. Accepted values, for each modality: $modal_system_X$ where $X \in \{K, KB, K4, K5, KB5, D, DB, D4, D5, D45, T, B, S4, S5, SSU\}$ or a list of axiom schemes $[$$modal_axiom_X1, ..., modal_axiom_Xn$] $X_i \in \{K, T, B, D, 4, 5, CD, C4\}$ |
| $hybrid$ | see $modal$ | |
| $pal$ | none | |
| $ddl$ | $system$ | Selects which DDL logic system is employed: Carmo and Jones or Áqvist’s system E. Accepted values: $$carmoJones or $$aqvistE |

Non-classical logic languages quite commonly admit different concrete logics using the same syntax. In order to choose the exact logic intended for the input problem, suitable parameters are given as properties to the logic specification as introduced in Sect. 2. For the above NCLs supported by LET, Table 1 gives an overview of the individual parameters and their meaning. We refer to Fitting and Mendelsohn [17] for an explanation of the modal logic properties.

5 Application Examples

The functionality of LET is illustrated by a number of examples. Exemplary ATP system results are produced by the higher-order prover Leo-III [35], version 1.6.8, in which LET is integrated as a library and accessed via its API. Leo-III parses the problems, invokes the embedding API, and then applies standard proof search on the resultant THF problem.

Example 1: Modal logic reasoning. The Barcan formula [3], given by

$$\forall x. \Box p(x) \Rightarrow \Box(\forall x. p(x))$$

in a first-order variant, is a modal logic formula that is valid if and only if the quantification domain of the underlying first-order modal logic model is non-cumulative [17]. This is written in TXN as ...
This specifies a modal logic with rigid function symbols, decreasing quantification domains and box operators satisfying modal axiom schemes $K$ and 5. As expected, Leo-III returns ...

However, when the parameter $quantification$ is changed to $cumulative$ or $varying$ the problem becomes countersatisfiable.

### Example 2: Hybrid logic reasoning.

Hybrid logics can talk about the satisfaction relation of the modal logic at the object language level. Up to the author’s knowledge, Leo-III is the first ATP system to support reasoning in many different first-order hybrid logics. An example tautology is given by

$$\forall X. \Box \@ n (\downarrow Y. (Y \land p(X)) \iff (n \land p(X)))$$

that is encoded as ...

### Example 3: CTD reasoning in deontic logics.

In deontic logics, CTD situations arise when reasoning with obligations that prescribe what to do if other (primary) obligations are violated. Simple approaches, e.g., using modal logic $\mathbf{D}$, lead to inconsistencies that allow arbitrary conclusions to be inferred. This is addressed by dyadic deontic logics that encode conditional norms using a special operator $\Box (\psi, \varphi)$ (read: it ought to be $\psi$, given $\varphi$). An example is ...

```prolog
tff(spec_e, logic, $$ddl == [ $$system == $$aqvistE ] ).
tff(a1, axiom, {$$obl}(go,$true)).
tff(a2, axiom, {$$obl}(tell, go)).
tff(a3, axiom, {$$obl}(t’tell, ”go)).
tff(situation, axiom, ”go).
tff(c, conjecture, {$$obl}(t’tell,$true)).
```
This example encodes that (a1) you ought to go and help your neighbors, (a2) if you go then you ought to tell them that you are coming, and (a3) if you don’t go, then you ought not tell them. It can consistently be inferred that if you actually don’t go, then you ought not tell them; Leo-III confirms this. Up to the author’s knowledge, Leo-III is the first ATP system to support system E and the system of Carmo and Jones.

6 Summary

LET is a library and pre-processing tool for encoding non-classical reasoning problems into classical higher-order logic, by means of shallow embeddings. The output of the tool is TPTP THF, and any compatible ATP system can be used in conjunction with it, offering of-the-shelf automation for non-classical logics. Although the range of supported logic families is still quite limited, already at this point LET allows for the automation of more than 60 different first-order modal logics (including all logics from the modal cube), 60 different hybrid logics, dynamic epistemic logic (PAL), and different dyadic deontic logics.\(^2\) For some of these logics there exist no other ATP systems to date. The tool is designed to be easily extensible with new embeddings of further logics. Shallow semantical embeddings into HOL have also been studied for various other purposes [4].

Shallow embeddings and hence LET target rapid logic prototyping, but might not be as effective as ATP systems specifically designed for the respective NCL. The embedding approach allows for the automation of logics that otherwise would have no automation at all. LET aims at closing automation gaps for interesting NCLs, rather than challenging available ATP systems. Nevertheless, previous studies indicate that embeddings perform quite competitively in the context of quantified benchmarks [37]. However, for many of the logics currently covered by LET, in particular for quantified logics, there are no benchmark sets or competitors available, and comparisons are not possible. Automation via embeddings can also be employed in an educational context for low-threshold student experiments.

LET generalizes and extends previous work on modal logic embedding tools [20, 19], and offers more encoding variants for modal logics, including embedding into polymorphic THF (not discussed in detail here). LET makes use of the novel non-classical TPTP format and is seamlessly included into the Leo-III prover so that no extra steps are necessary for non-classical reasoning.

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\(^2\) The number of modal logics is at least 15 (modality axiomatizations) × 4 (quantification semantics) = 60. Many more modal logics are supported since LET allows arbitrary combinations of different modalities. Also, quantification semantics can be controlled on a per-type basis.
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