Iltis: Learning Logic in the Web

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Abstract. The ILTIS project provides an interactive, web-based system for teaching the foundations of formal methods. It is designed with the objective to allow for simple inclusion of new educational tasks; to pipeline such tasks into more complex exercises; and to allow simple inclusion and cascading of feedback mechanisms. Currently, exercises for many typical automated reasoning workflows for propositional logic, modal logic, and some parts of first-order logic are covered. Recently, ILTIS has reached a level of maturity where large parts of introductory logic courses can be supplemented with interactive exercises. Sample interactive course material has been designed and used in courses over the last years, many of them with more than 300 students. We invite all readers to try out ILTIS: https://iltis.cs.tu-dortmund.de

Keywords: teaching support system, formal methods, propositional logic, modal logic, first-order logic

1 Introduction and motivation

Formal, logical foundations are a cornerstone for many applications of computer science, including formal verification, artificial intelligence and database systems. For this reason, recommendations for Bachelor computer science curricula include logical foundations as an integral part (see, e.g., [14,9]).

Teaching formal foundations of computer science is a challenge for instructors as it is one of the harder topics for many students. Handling diverse backgrounds for a rapidly increasing number of students enrolled in computer science courses [4] is problematic and providing individual human tutoring for so many students not always possible, in particular in online teaching scenarios, e.g., under COVID-19 conditions or in freely accessible online courses (MOOCs). A general approach for increasing learning outcomes across STEM disciplines is provided by the National Research Council of the US which advocates, among others, to "Leverage technologies to make the most effective use of students' time, shifting from information delivery to sense-making and practice in class" [18,2].

The ILTIS project aims at implementing this objective for the foundations of formal methods [8,7]. The project offers a web-based teaching support system for the logic domain, with a flexible, modular framework for designing and combining

educational tasks. A variety of educational tasks for typical workflows in formal methods have already been implemented (see Section 2). For instance, standard reasoning workflows — modeling scenarios with logical formulas, transforming formulas into suitable normal forms, and inferring new knowledge — are covered for propositional logic and modal logic, and partially for first-order logic. For each task, automated feedback is given which can be declaratively configured by combining predefined feedback generators (see Section 3). The ability to combine small educational tasks into more complex exercises and workflows is a core aspect of ILTIS.

Contribution The objective of this article is to announce that the ILTIS teaching support system has reached maturity for broad use in introductory courses for formal methods.

As a proof-of-concept, extensive interactive material has been designed for an introductory course *Logic for computer scientists* aimed at introducing basic concepts, algorithms, and theoretical foundations for propositional logic, modal logic and first-order logic to 2nd year computer science students. The interactive material includes exercises for practicing concepts, multiple choice quizzes, and interactive tutorials for each chapter of the course.

The focus of development since the initial announcement of the ILTIS project [8] has been on the following aspects:

- Broadening the portfolio of educational tasks: A focus has been on supporting more standard workflows from formal methods. The available portfolio of tasks can be used flexibly to cover a multitude of typical workflows for propositional logic, modal logic, and first-order logic. This includes, for instance, reasoning workflows for propositional and modal logic (modeling scenarios by logical means; transformation into normal forms; drawing inferences with the tableau calculus, resolution, or other calculi; and with intermediate testing of understanding via multiple choice questions) as well as workflows for deciding equivalence of formulas (formulating decision hypotheses;
- Improving the quality and flexibility of feedback: The feedback system has been re-implemented from scratch to allow instructors to specify how feedback is provided in a flexible, yet simple declarative language.
- Increasing usability and user experience: The graphical user interface
 has been re-designed from scratch, taking didactical and usability aspects
 into account.

Related work A large variety of teaching support systems for the foundations of formal methods have been developed over the years. As most of these systems were developed ad-hoc by instructors for helping their students, a common theme is that they only cover a small set of topics (typically: only one) and are abandoned and/or become technologically outdated rather quickly. For instance, of the 26 tools described by Huertas [1], at least 13 are not available anymore (as

of November 2021) and many of the remaining tools use outdated technology. There are only few modern, web-based tools:

- For teaching the foundations of logic: Modeling for propositional logic is supported by the DiMo tool [13]. The LogEX system supports transformation of propositional formulas [16,15]. The focus of the Logic₄Fun project is on modeling scenarios and puzzles by logical means [19]. AELL [12] offers tasks for natural deduction, truth tables, and resolution but is not publicly available. Modal logic semantics can be explored with Hintikka's World [3].
- For teaching the foundations of formal languages: Constructing models for formal languages such as regular expressions, automata, and formal grammars can be practiced with a variety of tools. In FLACI [11], students can convert between these models. The AutomataTutor [6,5] offers elaborate feedback on finite automata construction tasks. JFLAP [10,17] features many algorithms on automata, but is not web-based.

2 Designing educational content in Iltis

Instructors can design educational content flexibly by using the broad portfolio of educational tasks available and the compositionality of such tasks.

Compositional task model Exercises in ILTIS are built from small, easily composable, educational tasks. Each educational task is configured by inputs — either given explicitly or as the output of prior tasks — and provides the objects created by students in this task as outputs, which can then be used by subsequent educational tasks. For instance, a task for transforming a formula into conjunctive normal (CNF) form receives a formula as input and provides the student-constructed, equivalent formula in CNF as output. Two typical multi-step exercises — a reasoning workflow for propositional logic as well as a satisfiability workflow for modal formulas — are illustrated in Figures 1 and 2 (instantiations of these workflows can be found in the course material³).

Educational tasks ILTIS supports a variety of educational tasks for propositional logic, modal logic, and first-order logic (see Table 1 for a high-level summary):

- Evaluating formulas: Students can evaluate formulas for a given interpretation. For propositional logic, students can construct truth tables; for modal logic, students can construct evaluation tables for a given Kripke structure.
- Constructing models: Students can construct models (i.e. satisfying interpretations) for formulas. For propositional logic, models are specified by valuations of all variables, for modal logic by Kripke structures. For first-order logic, students can construct models for formulas describing properties of (colored) graphs.

³ The course material is accessible at https://iltis.cs.tu-dortmund.de.

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Task	Propositional logic	Modal logic	First-order logic	General
Evaluating formulas	å	å	*	
Constructing models	å	✓•	(√) [•]	
Constructing formulas	✓	✓•	(√)•	
Transforming	✓	å	*	
Testing satisfiability	√°	✓•	(√) [•]	
Task variants & further tasks	Satisfiability tests with - truth tables - HornSat algorithm - tableau calculus - resolution Choosing propositional variables	Satisfiability test with tableau calculus Calculating bisimulations Proving non-bisimilarity of worlds	Satisfiability test with resolution Proving non-equivalence of formulas	Multiple choice Messaging

Table 1: A summary of educational tasks that are supported (\checkmark) , supported with limitations $((\checkmark))$, and in development (\clubsuit) . Functionality that has been added $(^{\bullet})$ or substantially extended $(^{\circ})$ compared to [8] is indicated.

- Constructing formulas: Students can construct formulas for the respective logics. For propositional and modal logic, formulas are checked for correctness and, if they are not, underlying misconceptions are determined and used to provide adequate feedback (see Section 3). For first-order logic, another approach is taken due to the intractability of equivalence tests: instructors provide a textual description of a unary graph query as well as a sample graph, and students are asked to provide a first-order formula that selects the same nodes as the graph query on this sample graph (see Figure 4).
- Applying equivalence transformations: Students can transform formulas step
 by step either into an equivalent target formula or into an equivalent formula
 in a normal form such as conjunctive, disjunctive, or negation normal form.
 Currently, this educational task is available for propositional and modal logic.
- Testing satisfiability: Students can test formulas for satisfiability using several methods. For propositional logic, students can a) construct truth tables, b) construct tableaux according to the tableau calculus, c) apply the algorithm for testing satisfiability of Horn formulas (HornSat), or d) construct a resolution graph. For modal logic, students can apply the tableau calculus. For first-order logic, students can construct a resolution graph.
- Determining (non-)bisimilar worlds of Kripke structures: Students can prove the (non-)bisimilarity by interactively calculating the maximal bisimulation between two Kripke structures using the standard algorithm. Additionally, students can prove non-bisimilarity of two worlds by providing a modal formula that distinguishes them.

Further educational tasks for smoothing complex exercise workflows (such as a multiple choice task) and for specific content (such as providing witnesses for non-equivalence) are also available.

3 Feedback in Iltis

One of the core objectives of ILTIS is to provide immediate and comprehensive feedback, as this is one of the most important factors for learning success.

Compositional feedback model In the feedback framework of ILTIS, each educational task type comes with multiple feedback generators, each one responsible for one kind of feedback. Individual feedback generators can be composed to feedback strategies by simple rule-based programs. Such programs determine the order of feedback with the invocation of certain rules possibly depending on the success of previous rules.

When specifying interactive exercises, instructors can state which feedback strategy to use (or define a custom one). In this way, the progress of students can be taken into account, e.g., a strategy that provides a lot of feedback can be used for beginners, while a strategy that provides almost no feedback can be used for exam preparation. As an example, each section in the feedback box (indicated by thin red lines) in Step 1 of Figure 1 is provided by a different feedback generator. By step-wise uncovering the feedback of the different generators, students can choose how much of the provided feedback they want to use.

Sample feedback strategies and generators Designing feedback strategies and generators is a subtle and challenging task as algorithmic feasibility as well as didactical aspects have to be taken into account. We sketch two sample strategies and their feedback generators that are currently provided out-of-the-box for instructors.

A feedback strategy for providing feedback for the construction of propositional formulas can look like this (it is partially illustrated in Step 1 of Figure 1):

- (1) Correctness: Is the constructed formula correct or not correct?
- (2) Misconceptions: Typical misconceptions (e.g., mixing up the premise and the conclusion of an implication, especially in "only if"-statements) are identified using an abstract rule framework (see [8]). They are the basis for multiple feedback generators:
 - (a) Hint at the misconception (e.g., "Do you remember how 'if'- and 'only if'-statements can be expressed in propositional logic?")
 - (b) State the misconception explicitly (e.g., "You might have mixed up 'if' and 'only if'.")
 - (c) Point out the precise mistake position
- (3) Distinguishing model: A valuation that distinguishes the constructed formula from a correct formula.

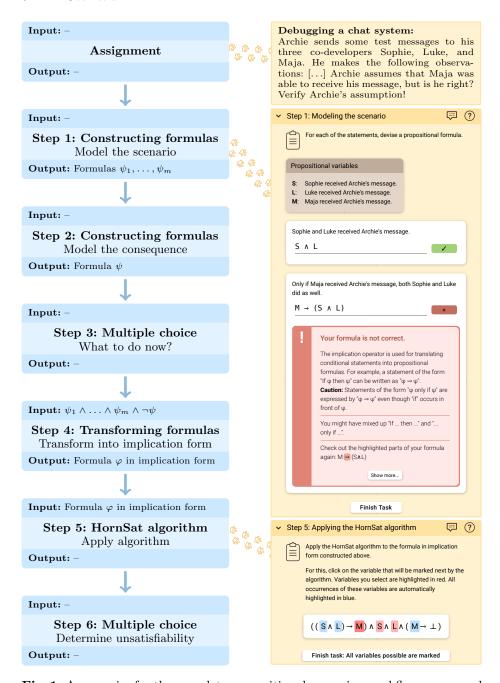


Fig. 1: An exercise for the complete propositional reasoning workflow, composed of smaller educational tasks. For this sample scenario, the instructor chose the HornSat satisfiability test as Horn formulas are sufficiently expressive. For general propositional formulas, also truth tables, propositional resolution, and the propositional tableau calculus can be used.

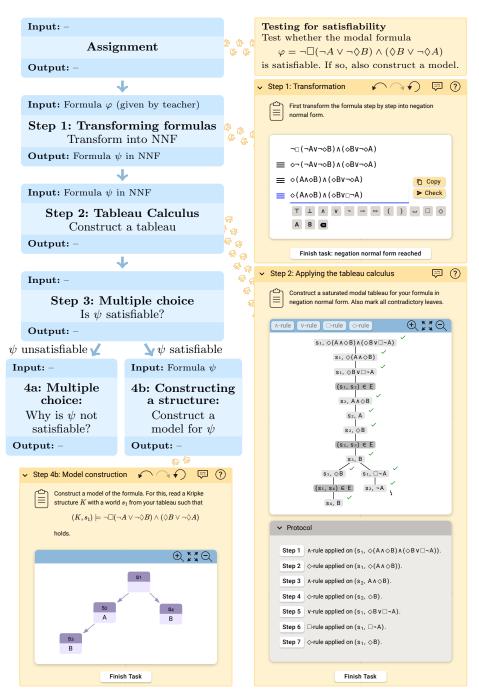


Fig. 2: An exercise for solving the satisfiability problem for modal formulas, composed of smaller educational tasks. For satisfiable and unsatisfiable formulas, different workflows can be used.

For providing feedback for the construction of first-order formulas for graph queries, the following feedback strategy can be used. It is shown in action in Figure 4.

- (1) Correctness: Is the set of nodes selected by the student-constructed formula correct or not correct?
- (2) Subset feedback: Is the set of nodes selected by the student-constructed formula a subset or superset of the correct set?
- (3) Visual feedback: The difference between the nodes selected by the student-constructed formula and the correct set are highlighted.

Besides construction tasks like the ones explained above, Iltis also supports tasks for training specific step-by-step algorithms. In these learning situations, feedback is not only given at the end of the task, but after each step of the algorithm. This helps students to recognize at which specific step they did not adhere to the algorithm and, thus, to correct their error. For example, in the task for constructing resolution graphs, every resolution (and possibly substitution) step is checked immediately and feedback is given via a feedback generator dedicated to this step (see Figure 5). The other algorithmic tasks (HornSat, Tableau Calculus, Bisimulation, etc.) follow the same principle.

4 Evaluation of the system

Interactive course material in ILTIS has been used in an introductory course "Logic for computer scientists" at TU Dortmund University in the winter terms 2019/2020, 2020/2021, and 2021/2022 as well as at Ruhr University Bochum in the summer terms 2020 and 2021. The use of the material was *voluntary*.

The usage statistics indicate that students rely on ILTIS a lot, in particular for preparing their solutions to biweekly exercise sheets and for their exams (see sample data in Figure 3). Additionally, the courses and also the Iltis system itself were evaluated by the students using non-mandatory questionnaires. Many students stated that ILTIS was very useful for understanding the contents of the lecture and in particular for training methods and algorithms.

We highlight that a controlled empirical study of the effectiveness of ILTIS is far beyond the scope of this paper. Due to fairness required by law, it is hard to set-up such a study with limited resources.

5 Future work and (shameless) call for help

In this demonstration, we have described ILTIS, a web-based system offering interactive exercises for learning propositional logic, modal logic, and first-order logic. It is used as e-learning tool accompanying an introductory course on logic covering most of its major topics and can be freely tested at https://iltis.cs.tu-dortmund.de. In the future, we plan to complete the portfolio of ILTIS and extend it to other foundational areas of computer science.

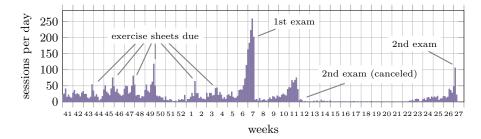
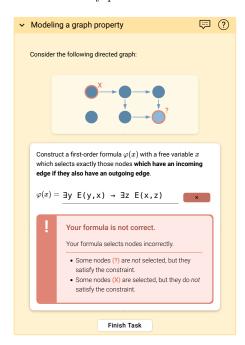


Fig. 3: Access numbers of the ILTIS course website for the logic course at TU Dortmund University in the winter term 2019/2020. These numbers represent the number of sessions per day, with a session starting when a student accesses ILTIS in their browser and ending when this student is inactive for at least 30 minutes. A total of about 380 students actively participated until the end of the course. The deadlines for handing in the biweekly exercise sheets and the exams are reflected by peaks in the access numbers.



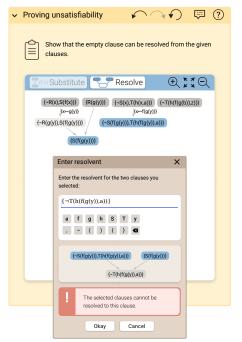


Fig. 4: An example task for constructing first-order formulas for graph properties. The feedback highlights which nodes of the given graph are erroneously (not) selected by the student-constructed formula.

Fig. 5: An example task for proving unsatisfiability of first-order formulas by constructing a resolution graph. Students can freely apply substitutions and resolution steps until they reach the empty clause.

Our vision for ILTIS is to provide opportunities to re-think approaches for teaching formal foundations. As an example, a technology-assisted introduction to first-order logic as modeling language could look as follows:

After providing intuition by modeling a sample scenario in first-order logic, an instructor asks students to model statements in the same application context in a web system on their mobile devices. The web system analyzes the student attempts and provides the instructor with learning analytics on the distribution of types of mistakes in graphical form, which they can discuss in-class. Afterwards the instructor presents formal syntax and semantics of first-order logic. Before the tutorial sessions, each student individually trains modeling with first-order formulas in different application contexts in the web system, which provides immediate feedback ensuring early correction of misconceptions. At the beginning of the tutorial sessions, most students are able to model with first-order logic and thus larger, more realistic and open-ended modeling tasks can be tackled.

To implement this vision, we are looking for:

- Instructors who want to use Iltis in their courses and thereby provide helpful feedback for future directions.
- Interested students, PhD students, and PostDocs for helping us to a) lay the theoretical foundations for ILTIS (e.g. the development of suitable feedback mechanisms in algorithmically hard domains) and to b) drive forward the coverage of topics by ILTIS.
- Experts in natural language processing for help in building educational tasks for bridging the gap between natural languages and formal modeling.

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