The THFTPTP Project – An Infrastructure for Typed Higher-order Form Automated Theorem Proving Marie Curie International Incoming Fellowship Grant Agreement PIIF-GA-2008-219982

Project Report – Implications

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1 Introduction

1.1 Project Overview

There is a well established infrastructure that supports research, development, and deployment of first-order Automated Theorem Proving (ATP) systems, stemming from the Thousands of Problems for Theorem Provers (TPTP) problem library. This infrastructure includes the TPTP itself, the TPTP language and SZS result ontology, the Thousands of Solutions from Theorem Provers (TSTP) solution library, various tools associated with the libraries, and the CADE ATP System Competition (CASC). This infrastructure has been central to the impressive progress that has been made in the development of high performance first-order ATP systems. The state of the art in higher-order ATP is not as advanced as that of first-order ATP. While there are several effective interactive systems for reasoning in higher-order logic, there has been limited automation. Critically, research and development has not been supported by a commonly accepted infrastructure that provides leverage for progress leading to effective and successful application. **The completed THFTPTP project has developed an infrastructure that supports research and development of automated theorem proving in higher-order logic.** The effect of the completed research will be to support research, development, and deployment of higher-order ATP systems, so that they can be used as effective components of academic and industrial processes.

1.2 Summary of Accomplishments

The completed THFTPTP project has developed an infrastructure that supports research and development of automated theorem proving in Church's simple type theory. The software components designed and developed are:

- A higher-order TPTP language to express problems and solutions in higher-order logic.
- A collection of higher-order test problems in the TPTP.
- A result and output ontology for higher-order ATP, extending the existing SZS ontology.
- A collection of higher-order problem solutions in the TSTP.
- Tools for preparing, processing, and analyzing higher-order ATP problems and solutions.

The completed project has been the topic of, or has contributed to, paper publications, grant proposals, presentations, and events:

- Two conference papers directly about the project.
- Two workshop papers about the project and supporting topics.

- Five other papers describing work in which the new TPTP THF infrastructure was tested and employed.
- Three grant proposals that were strongly influenced by the project.
- Seven presentations related to the project.
- Six conferences at which either the host or researcher promoted use of the TPTP and the THF format.
- The new THF division of the CADE ATP System Competition (CASC)

The completed project has had significant impact:

- Significant scientific and technical impact: efective support for the development of new and more powerful ATP systems for higher-order logic, and their application to a range of existing and new application domains.
- Seeding of multiple new research directions and projects: projects that will develop new principles and practice of automated theorem proving for higher-order logic, the use of higher-order logic for theorem proving in non-classical logics, and further development of the TPTP THF infrastructure.
- Quantifiable transfer of knowledge and expertise to Europe: to the host, researchers and students at the host university, and to eleven further institutions in Europe. Further unquantified development of expertise and knowledge follows from the interaction of the host and researcher with colleagues in Europe and beyond.

2 Impact

2.1 Development of Expertise in Europe

In Autumn 2008, Sutcliffe and Benzmüller held a one week block lecture "Working with Automated Reasoning Tools" at Saarland University. The course was attended by 10 students. The aim of this course was to teach the students to work with different automated reasoning systems for first-order and higher-order logic. The theory part of the lecture introduced the different systems and sketched their background. The focus of the lecture on practical work with the systems, and for this the TPTP infrastructure including the new higher-order TPTP THF infrastructure was introduced and exploited. The lecture attracted masters as well as PhD students, and it turned out very successful: Even long after finishing their official project course work some students actively contributed to the built-up of the TPTP THF infrastructure by submitting problem formalizations in THF for inclusion in the TPTP. An example is PhD student Georg Neis' formalization of binary relations. Another good example of mutual fertilization in this course is the input that Benzmüller received from PhD student Catalin Hritcu and which significantly fostered Benzmüller's subsequent work on automating access control logics in simple type theory [3]. The notes and other resources developed for the course are available at `http://www.cs.miami.edu/~geoff/Courses/TPTPSYS/`.

Benzmüller now has an intimate knowledge of the TPTP THF infrastructure, particularly the higher-order logic aspects. This knowledge complements his expertise in higher-order logic. Researchers at Saarland University have been directly exposed to the TPTP THF infrastructure, understand how it can be used for effective research, and are leveraging the infrastructure in their own research. High profile examples are Dr Chad Brown's use of the higher-order part of the TPTP in his development of automated higher-order ATP systems, the addition of TPTP parsing capabilities to the SPASS ATP system, and the output of TPTP format proofs from the Waldmeister ATP system.

Sutcliffe gave talks about the TPTP infrastructure, highlighting the new THF components, at eleven other European institutions. During these visits Sutcliffe also provided practical training and support for

the use of the TPTP infrastructure. European institutions at which Sutcliffe gave a talk about the TPTP infrastructure, highlighting the new THF components, are listed here. Information about other linkages between the TPTP and research at these institutions is given.

- KWARC Research Group, Jacobs University in Bremen. Code bridging THF TPTP data to OmDoc format was developed.
- Bonn Mathematical Logic Group, Mathematical Institut, University of Bonn. Their Naproche project has been modified to use the TPTP online services.
- Programming, Logics, and Semantics Group, IT University of Copenhagen. Their Twelf project was used to encode aspects of THF data, to provide an abstract logical basis for THF data.
- Theorem Proving Group, Institut für Informatik, Technische Universität München. The IsabelleP, IsabelleM, and IsabelleN ATP systems for THF problems were developed, based on their existing Isabelle interactive proof assistant.
- Working Group Beckert/Furbach, Institute for Computer Science, Universität Koblenz-Landau. Problems from their LogAnswer project were exported in TPTP format, and are now in the TPTP library.
- Laboratoire Spécification et Vérification, ENS de Cachan. This group applies automated reasoning to security analysis, and uses the TPTP format for their data.
- Faculty of Cybernetics, Kiev National Taras Shevchenko University. The SAD project has previously been used to generate problems for the TPTP library (unfortunately, the key developer of the SAD project has left their group).
- Models and Theory of Computation Group, Ecole Polytechnique Fédérale de Lausanne. Various sources of THF problems, and uses of THF ATP systems, were identified in their software verification projects. Ties were created between the European COST Action "Rich Models" and the higher-order part of the TPTP.
- Attempto Controlled English Project, Department of Informatics, University of Zurich. The logical output from their APE parser was adapted to be in TPTP format, thus providing a natural language front-end for TPTP services. This is now part of the SystemB4TPTP online service.
- Programming Methodology and Multimedia Information Systems Group, Department of Computer Science, University of Augsburg. One of their PhD students is now using THF to encode mathematical structures, and prove theorem about those structures.
- School of Electronics and Computer Science, University of Southampton. Created TPTP natural deduction format to support their proof explanation project.

2.2 Further Research

Follow-up project proposals that were strongly influenced by the THFTPTP project:

- C. Benzmüller, LEO-II im Ontologieschliessen. Forschungsstipendium proposal to the Deutsche Forschungsgemeinschaft (DFG). The proposal was granted in June 2009. In this project Benzmüller is collaborating with Articulate Software, USA, applying the higher-order automated theorem prover LEO-II to reasoning in ontologies.
- C. Benzmüller, C.P. Wirth, Effective Higher-Order Automated Theorem Proving with integrated Descente Infinie and Presburger Arithmetic LEO-III. Grant proposal submitted to the Deutsche Forschungsgemeinschaft (DFG).
- S. Autexier, EU ERC Starting Grant. Autexier has proposed a generic reasoning and proof representation framework based on assertion level proofs. This framework is planned to be TPTP THF compliant.

The combined first-order and higher-order TPTP infrastructure now supports experimentation with different logic encodings. For example, it supports the comparison of provers for first-order and higher-order logics for the same abstract problems but different logic level formalizations. Collaborative links have been established with Jens Otten's new project at Postdam University, which aims to build a problem library for multi-modal logics. A future goal is to also facilitate comparison between special purpose provers for quantified multi-modal logics and our higher-order theorem provers.

Interesting future research includes the development of an online intreface for reasoning with multi-modal logics, linked to the existing SystemOnTPTP interface. This will include automated conversion of multimodal logic problems to THF form, and the subsequent application of a higher-order ATP system to solve the problems. This interface could subsequently be extended to also support intuitionistic logics and logics for security (e.g. access control logics). Like multimodal logics, the latter logics are also fragments of THF [3].

Future work includes the development and implementation of a powerful representation, verification, and explanation framework for THF proofs. A suitable, uniform target calculus is envisaged, to which the proof outputs of the different THF provers can be translated. The THF provers will need to adapt their proof output directly to this new format, or transformation tools will have to be provided. The benefits of such a new format are obvious: (i) client systems that embed higher-order ATP system will need to support only this single format and (ii) tools for extracting information from THF proofs, for verifying them, or for explaining them, e.g., to humans, will have to support only this single format. Dr. Serge Autexier at DFKI Bremen has recently proposed a research project in this direction.

In THF0 only simple type theory is supported, and type declarations are provided. Type reconstruction is therefore not an issue. Type checking is handled with the type checking tool based on Twelf. In the richer extensions of the THF0 language, such as the THF and THFX languages, polymorphic and dependent types are allowed. Increasingly advanced type reconstruction and type checking tools will thus be required. The current type checking tool based on Twelf will be extended in our ongoing collaboration with Dr. Carsten Schürmann at IT University Copenhagen and Dr. Florian Rabe at Jacobs International University in Bremen.

3 Dissemination

3.1 Papers

The main work of the project was conducted in the funded period from July 2008 to September 2009. However, some work was done immediately after the project was granted in winter 2007/2008. This section lists all project related papers since winter 2007/2008.

Papers on the new TPTP THF infrastructure, and supporting topics: [11, 10, 8, 7, 9]

Papers in which the new TPTP THF infrastructure was tested and employed: [3, 2, 5, 4, 6, 1]

3.2 Presentations and Conferences

The THFTPTP project and the THF extension to the TPTP were resented and promoted through the following presentations and conference activities.

- C. Benzmüller, G. Sutcliffe, The 4th International Joint Conference on Automated Reasoning, Sydney, Australia, August 2008. A paper on the emerging THF syntax was presented in the main conference program. Two PAAR workshop sessions were organized, in which ten potential users of the THF syntax demonstrated their higher-order reasoning systems. A PAAR workshop panel session was held to discussing the THF extension of the TPTP. The panelists were Dr. Rob Arthan

(Lemma 1 Ltd.), Dr. Joe Hurd (Galious Inc.), and Dr. Lucas Dixon (University of Edinburgh). A separate meeting was help with Dr. Lucas Dixon to distill useful information from the panel session. The TPTP technical meeting at the conference was used to promote THF, and also obtain community feedback on a range of technical issues. In particular, Henkin semantics with extensionality was chosen as the default semantics for THF problems. This was later extended to include choice.

- C. Benzmüller, G. Sutcliffe, The Conferences on Intelligent Computer Mathematics (CICM), August 2008. Discussions were held with many potential users of the TPTP THF format, in particular Dr. Louis Dennis (University of Liverpool), Dr. Andrei Paskevitch (Paris-Sud 11 University), and Prof. Alexander Lyetski (Kiev National Taras Shevchenko University). A meeting was held with Dr. Florian Rabe from Jacobs International University, to discuss the presentation of the THF developments at future conferences.
- C. Benzmüller, "Automating Access Control Logics and Multimodal Logics in the Automatic Higher-Order Theorem Prover LEO-II", Kestrel Institute, Palo Alto, USA, October 2008.
- C. Benzmüller, "LEO-II– A Cooperative Automatic Theorem Prover for Classical Higher-Order Logic", Microsoft Research, Redmond, USA, October 2008.
- G. Sutcliffe, The 15th International Conference on Logic for Programming, Artificial Intelligence, and Reasoning, Doha, Qatar, November 2008. A paper on the SZS ontology was presented at the KEAPPA workshop. A fruitful discussion was held with Dr. Marc Bezem (Universitetet i Bergen) leading to the development of the export of THF problems to Isabelle syntax based on his Prolog code. Plans were made with Daniel Weller (Vienna University of Technology) to export THF format proofs to HandyKL for cut-elimination analysis.
- C. Benzmüller, "Automating Access Control Logics and Multimodal Logics in the Automatic Higher-Order Theorem Prover LEO-II", Pure and Applied Logic Seminar, Carnegie Mellon University, Pittsburgh, USA, November 2008. As part of this research visit, Benzmüller met with several professors and students, and introduced them to the latest developments of the THFTPTP project. This list includes Prof. Frank Pfenning, Prof. Peter Andrews, Prof. Edmund Clarke, Prof. Jeremy Avigad, Prof. Wilfried Sieg, and several PhD students of Prof. Pfenning such as Deepak Garg and Sean McLaughlin. Deepak Garg has actively contributed to the THFTPTP project by submitting example THF problems to the TPTP library.
- C. Benzmüller,"Automating Quantified Multimodal Logics in HOL – My very first Region Connection Calculus Prover", AAAI Spring Symposium on Benchmarking of Qualitative Spatial and Temporal Reasoning Systems, Stanford, USA, March 2009. During this meeting Benzmüller implemented (in only 2 days) a prototype reasoner for qualitative spatial and temporal reasoning, exploiting his embedding of modal logics into higher-order logic. He demonstrated this reasoner at the end of the symposium.
- G. Sutcliffe, "Evaluating Automated Theorem Proving Systems", AAAI Spring Symposium on Benchmarking of Qualitative Spatial and Temporal Reasoning Systems, Stanford, USA, March 2009. The possibility of encoding spatial and temporal logics in THF was discussed and is now being pursued.
- C. Benzmüller, "Automating Access Control Logics in Simple Type Theory with LE0-II", 24th IFIP International Information Security Conference, Pafos, Cyprus, May 2009. At this conference Benzmüller had discussions with Prof. Kai Rannenberg (Economics, University of Frankfurt), and pointed him to potential applications of higher-order logic in the security area. As a result Benzmüller was invited to serve on the program committee of the 25th IFIP International Information Security Conference (SEC 2010) Security & Privacy - Silver Linings in the Cloud, Brisbane, Australia, 2010.

- G. Sutcliffe, The 22nd International FLAIRS Conference, May 2009. Discussions were held regarding the export of natural language processing problems into THF syntax.
- C. Benzmüller, Handover of the Festschrift to Peter B. Andrews, CADE-22, Montreal, Canada, August 2009. In this talk Benzmüller emphasized the fact that the new TPTP THF infrastructure will particularly support better dissemination of Prof. Andrews' contributions to the field. For example, the (automated component of the) TPS system, that has been developed by Prof. Andrews and his students over the last three decades, is now easily accessible via the SystemOnTPTP interface.
- C. Benzmüller, G. Sutcliffe, The 22nd International Conference on Automated Deduction, August 2009. A paper on the work done in the project was presented in the main conference program. The THF division of the CADE ATP System Competition was run. The THF syntax was promoted in the TPTP technical meeting during the conference.

Affirmation

The work described in this report was carried out in the THFTPTP Project – An Infrastructure for Typed Higher-order Form Automated Theorem Proving, as a Marie Curie International Incoming Fellowship, Grant Agreement PIIF-GA-2008-219982.

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