

Report on the outcomes of a Short-Term Scientific Mission¹

Action number: CA20111

Grantee name: Daniele Nantes Sobrinho

Details of the STSM

Title: Higher-Order Equational Unification and Anti-Unification for Program Verification

Start and end date: 17/03/2025 to 27/03/2025

Description of the work carried out during the STSM

Description of the activities carried out during the STSM. Any deviations from the initial working plan shall also be described in this section.

During the visit, we divided our work into two main problems: (i) anti-unification for general equational theories and (ii) schematic unification for program verification.

In the first week, we held daily meetings to focus on problem (i), during which we identified a hierarchy of theories that exhibit different behaviors when linear least general generalizations (LLGG) are considered, compared to non-linear ones (nLGG). The theories investigated included the semi-regular, ground, semi-ground, collapse-free and permutative theories. The goal was to identify whether the existence of minimal complete set of LLGG implied the existence of a minimal complete set of nLGG for each theory. We proved some correspondence results and identified the exact conditions to ensure the existence of the latter.

The second week was dedicated to exploring unification with recursive operators, using the technique of *schematic unification*. This problem has direct applications in program verification, particularly as it addresses critical open questions in the field. The problem of schematic unification is very complex and we identified a subproblem “recursive matching” that is enough for the first applications in symbolic execution using separation logic.

On the final day of my visit, I gave a talk to the Computational Logic group titled “Compositional Symbolic Execution for Correctness and Incorrectness Reasoning.”

¹ This report is submitted by the grantee to the Action MC for approval and for claiming payment of the awarded grant. The Grant Awarding Coordinator coordinates the evaluation of this report on behalf of the Action MC and instructs the GH for payment of the Grant.

Description of the STSM main achievements and planned follow-up activities

Description and assessment of whether the STSM achieved its planned goals and expected outcomes, including specific contribution to Action objective and deliverables, or publications resulting from the STSM. Agreed plans for future follow-up collaborations shall also be described in this section.

The goals of the STSM project were partially achieved. While we were unable to complete the extension of nominal equational unification in the context of equational theories, primarily due to the need for further development of the first-order approach, we focused on finalizing the latter and left the extension to the nominal framework as future work. The second goal of the project, start a collaboration on Schematic Unification, was successfully addressed during the visit. The contributions are detailed below, organized by problem (i) and (ii):

For Problem (i):

- We proved that the existence of LLGG for semi-ground equational theories implies the existence of a minimal complete set of nLGG. This result involved several technical concepts, such as merging substitutions and frozen variables, as well as a strategy for analyzing symbols from the root to the position where two equivalent terms diverge.
- We identified a ground equational theory where a minimal complete set of LLGG exists, but no minimal complete set of nLGG can be found.
- We established correspondence results between semi-ground, collapse-free, and permutative semi-ground equational theories, and constructed a hierarchy among these theories.

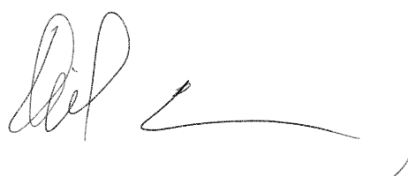
For Problem (ii):

- We identified a subproblem of schematic unification, termed “recursive matching,” which simplifies the general problem and can be applied to solve the frame problem in symbolic execution when dealing with recursive predicates.
- We are currently collaborating on the paper *Schematic Unification*, which is in draft form but requires further refinement, particularly regarding the unification algorithm. A preliminary toy implementation exists but needs to be evaluated using examples.

Expected Outcomes:

- We have completed a first draft of the paper detailing the results for problem (i), which we plan to polish and submit to a journal such as *TOCL* or *JACM*.
- We have a preliminary draft for a paper on Schematic Unification (problem ii), though it requires more formalism and evaluation with examples. We intend to submit this paper to a conference after the submission of the work on problem (i).

Future Plans: We plan to continue collaborating on the refinement and submission of both papers. Future work will also include the extension of nominal equational unification and further exploration of schematic unification, particularly with respect to recursive predicates in symbolic execution.

Def , Prague 18.04.2025
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