Tool Integration for Reasoned Programming*

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Abstract. We argue for the importance of tool integration in achieving the Program Verifier Grand Challenge. In particular, we argue for what we call *strong integration*, *i.e.* a co-operative style of interaction between tools. We propose the use of an existing planning technique, called *proof planning*, as a possible basis for achieving strong integration.

1 Introduction

The renewed interest in the mechanical verification of software, we believe, can be attributed in part to the following three factors:

- A focus on property based verification, rather than full functional verification.
- Progress in terms of mechanizing abstractions.
- Greater integration of tools.

Below we highlight some software verification projects in which these factors played a key role:

- SLAM [1] provides an integrated toolkit for checking safety properties of software interfaces written in C. SLAM has been applied very successfully to the validation of device driver software. Predicate abstraction and model checking are used to identify potential defects. Using a theorem prover, the potential defects are then refined to identify true defects.
- ESC/Java [12] is a tool for identifying defects in Java programs. Using a theorem prover, ESC/Java can verify that a program is free of run-time exceptions. In general, annotations are required in order to support the theorem proving. In order to address this annotation burden, ESC/Java has been integrated with the Houdini [11] *annotation assistant*. Houdini is based upon predicate abstraction, and uses refutations to refine candidate annotations.
- Caveat [3] is a static analysis tool for software written in C, and was used during the development of the flight-control software for the Airbus A380. Caveat includes a theorem prover that supports the verification of annotated C programs. A tool called Cristal supports the automatic generation of annotations (preconditions) for run-time exception freedom proofs. Currently, abstract interpretation [26] is being explored as a basis for generating loop invariants [25].
- NuSPADE[1] [9, 10, 20] builds upon the SPARK approach to high integrity software development [2]. The SPARK approach has been used extensively on safety [22] and security [15] critical applications. The NuSPADE project developed an integrated approach to program reasoning, based upon the use of proof-failure analysis to constrain the generation of program annotations. NuSPADE focused in particular on automation for run-time exception freedom proofs.

[1] More details can be found at `http://www.macs.hw.ac.uk/nuspade`

The above list is by no means complete. The aim is simply to highlight the role of property-based verification, mechanized abstract and tool integration within current software verification projects. The remainder of this position paper focuses on the importance of tool integration for software verification.

2 Tool integration

The importance of tool integration for software verification is not a new observation. For instance, the potential benefits of having a close relationship between heuristic guidance, *i.e.* annotation generation, and theorem proving were anticipated by Wegbreit in his early work on program verification [31]. Achieving a "close relationship", what we will refer to as *strong integration*, requires a co-operative style of interaction between tools. Note that strong integration is closely related to the notion of *tightly coupled integration* presented in [8]. The use of counterexamples in guiding the search for program annotations is an example of strong integration. As an aside, the importance of counterexamples within the context of software verification is discussed in more detail in [30]. This is in contrast to a black box style of integration, or *weak integration*, where interaction between tools is minimal, *e.g.* success and failure.

In terms of automated reasoning, the benefits of strong integration are illustrated in [4] where Boyer and Moore report on the experimental integration of their theorem prover with a decision procedure for linear arithmetic. They found that the decision procedure was directly applicable to very few subgoals generated by the theorem prover – so weak integration gave poor performance. In contrast, strong integration, *i.e.* allowing the theorem prover and decision procedure to interact co-operatively, gave significant performance improvements. However, the customization associated with such strong integration is costly. Boyer and Moore reported that implementing strong integration was time-consuming, involving extensive and complex changes to both the theorem prover and decision procedure. An in-depth discussion of the trade-offs that need to be considered when addressing the challenge of tool integration can be found in [8].

If one accepts strong integration as an important factor in addressing the task of software verification, then alleviating the costs associated with strong integration is an important milestone on the road to meeting the Program Verifier Challenge. We believe that approaches that support the kind of "customization" outlined above will play a vital role in alleviating such costs. We propose planning, and in particular *proof planning* [5], as a possible approach to achieving the level of customization that is required in order reduce the cost of strong integration.

Proof planning is a computer-based technique for automating the search for proofs. At the core of the technique are high-level proof outlines, known as *proof plans*. Proof planning builds upon tactic-based reasoning [14]. Starting with a set of general purpose tactics, plan formation techniques are used to construct a customized tactic for a given conjecture. A key feature of proof planning is that it separates proof search from proof checking. This gives greater flexibility in the strategies that can be used in guiding proof search as compared to conventional proof development environments. An example of this greater flexibility is the *proof critics* mechanism [16, 18] that supports the automatic analysis and patching of proof planning failures. Proof critics have been very successful in automating the generation of auxiliary lemmas, conjecture generalizations and loop invariants [17–19, 29, 21].

Inspired by [4], the value of proof planning as a basis for strong integration was first observed in [6], where part of a decision procedure was rationally reconstructed as a proof plan. The modularity imposed by the proof plan enabled flexibility in

the application of the decision procedure, *e.g.* auxiliary information such as lemmas, could be easily incorporated. In terms of tool integration, the value of proof planning as a basis for a co-operative style reasoning has been demonstrated through the Clam-HOL [28] and NuSPADE projects, the details of which are outlined below.

In the case of Clam-HOL, the Clam proof planner [7] was integrated with the Cambridge HOL interactive theorem prover [13]. The Boyer and Moore integration example, highlighted above, was re-implemented within the Clam-HOL framework with positives results [27].

Within the NuSPADE project, proof plans were used to increase the level of proof automation available via the SPARK toolset. Part of this effort involved the development of new proof plans, as well as the reuse of existing proof plans, *i.e.* proof plans developed for mathematical induction. The NuSPADE project also broadened the role of proof plans, *i.e.* proof patching was extended to incorporate light-weight program analysis. That is, common patterns of proof-failure were identified with constraints on missing properties. These constraints were used by our program analyzer to guide the introduction of auxiliary program annotations, *e.g.* loop invariants. It should be noted that the program analyzer also initiated interactions with the proof planner, *i.e.* the program analyzer called upon the proof planner to discharge simple equational reasoning goals. In terms of automation for run-time exception freedom proofs, NuSPADE was evaluated on a number of industrial applications, including SHOLIS [22], the first system developed to meet the UK Ministry of Defence Interim Defence Standards 00-55 [24] and 00-56 [23]. Our techniques are aimed at verification conditions that arise in loop-based code. While industrial strength critical software systems are engineered to minimize the number and complexity of loops, we found 80% of the loops that we encountered were provable using our techniques. That is, our program analysis, guided by proof-failure analysis, automatically generated auxiliary program annotations that enabled subsequent proof planning and proof checking attempts to succeed.

3 Conclusion

Tool integration is prevalent within current software verification projects. We have argued for the value of strong integration, *i.e.* a co-operative style of tool interaction, within the context of software verification. To achieve strong integration, we have proposed the use of proof planning, an approach which has a track-record in the development of reasoning systems which embody a co-operative style of interaction. We believe that strong integration will accelerate the development and sharing of tools and techniques on the road to achieving the Program Verifier Grand Challenge.

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