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Learning from experts to aid the automation of proof search

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Most formal methods give rise to proof obligations which are putative lemmas that need proof. Discharging these POs can become a bottleneck in the use of formal methods in practical applications. Some techniques for reducing this bottleneck are known — it is our aim to increase the repertoire of techniques by tackling learning from proof attempts. Even after obvious fixed heuristics are used, there remains the problem of what to do with POs that are *not* discharged automatically. In many cases where a correct PO has not been discharged, an expert can easily see how to complete a proof. We believe that it would be acceptable to rely on such expert intervention to do one proof if this would enable a system to kill off others “of the same form”.¹

Our objective is to significantly decrease the human effort in doing top-down formal development. We believe this can be achieved by increasing the proportion of POs that are discharged by the system.

Without questioning the value of any other approach to improving software development, we wish to be precise about the setting to which we hope to contribute. We are interested in helping engineers discharge POs that arise in the development process from a (formal) specification to a completed design.

Experience also tells us that change is of the essence and the impact of this gives another insight into the advantages of learning. When a change is made, a user has to redo proofs. The Rodin Toolset is already good at tracing the impact of changes and reducing the proof rework. But it would be a bonus if the system could learn enough from hand proof attempts at pre-change POs to discharge automatically similar proof obligations after a change. Of course, there will always be differences that defeat this strategy.

The main hypothesis to be addressed is: *enough information can be automatically extracted from a hand proof that examples of the same class can be proved automatically.*

We believe that it is possible to build a system that will learn enough from one proof attempt to significantly improve the chances of proving “similar” results automatically. By “proof attempt” we include things like the order of the steps explored by the user (not just the finished chain in the final proof). Thus it is central to our goal that we find *high-level* strategies capable of cutting down the search space in proofs. What we are looking for is at a much higher level than LCF-style tactic languages — such tactics are programs to construct proofs and are brittle in the sense that they behave differently for similar POs.

We believe that by separating information about data structures and approaches to different patterns of POs, a taxonomy begins to evolve. A PO approach might be seen to use “generalise induction hypothesis” in a specific proof about, say, sequences; a future use of this PO might involve a more complicated tree data structure — but if it has an extended induction rule (e.g. by adding an argument to accumulate values), the same strategy might work.

¹ To see how useful such a facility could be, note that at the first review of DEPLOY, one of the industrial partners reported an application that gave rise to some 300 POs; of these, about 200 were discharged automatically; five really difficult proofs were done by hand; although the remaining 95 “followed the pattern” of the five, they also had to be done slowly and manually.

So our hypothesis can be recast as: *we believe that it is possible to (devise a high-level strategy language for proofs and) extract strategies from successful proofs that will facilitate automatic proofs of related POs.*

Designing the strategy language is a part of a proposed project but it might be useful to give some indications of what we expect it to look like. Our strategy language will combine a high-level proof strategy with a “vocabulary” of terms that might be instantiated in the separate theories of data structures stored in the system. The meta-language employed in our rippling/induction proof-planning work provides an existence proof for such a strategy language. Items that we expect to play a major part include:

- *Some ‘standard’ proof plans and known deviations from and patches to them.* [BBHI05] uses rippling to describe a ‘standard’ proof plan for inductive proofs and shows how each different pattern of failure in rippling suggests a different way of patching a failed proof attempt. We hypothesise that expert-provided proofs of undischarged POs will typically exhibit either a new proof plan or a new patch to an existing plan.
- *Choices of unusual induction rules and variables, choices of loop invariants.* Choosing an alternative non-standard induction rule is one of the patches to the standard induction proof plan which is described in [BBHI05]; patching a failed loop invariant is the patch described in [SI98].
- *Choices of intermediate lemmas.* Designing, constructing and proving a key intermediate lemma is one of the patches to the standard induction proof plan described in [BBHI05].
- *Generalisation of the PO.* [BBHI05] also describes a couple of ways of generalising the PO or the current goal to patch a failed proof.

Lemmas, case splits, loop invariants, generalisations and their points of application all need to be described in an abstract form if they are to apply to all members of a family of proofs. This is because the details will vary from proof to proof, but there may be a level of abstraction at which their descriptions coincide. Rippling, for instance, provides an exemplar abstract language, since it can describe ‘missing’ intermediate lemmas in terms of subexpressions that must match with different parts of the current goal. We will also make use of generic taxonomies, for instance, types of induction rule, types of generalisation, etc. to support the abstraction of proofs and their subsequent application to new conjectures. For instance, the use of a two-step induction on a recursive data-structure in the source proof must first be abstracted in order to be applied to a different data-structure in the target proof. We expect to develop and use additional kinds of abstraction during the course of the project.

The major challenge is to design a sufficiently general-purpose and robust strategy language so that it can deal with unanticipated proof plans and patches that experts will devise. If we knew in advance what these plans and patches would be, we could include them in the theorem prover, so that the problematic POs would be discharged and would not require expert attention.

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