Debugging Program Verification Proof Scripts
– Tool Paper –

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Abstract. Interactive program verification is characterized by iterations of unfinished proof attempts. To support the process of constructing a complete proof, many interactive program verification systems offer a proof scripting language as a text-based way to describe the non-automatic steps in a proof. Such scripting languages are beneficial, but users spent a lot of effort on inspecting proof scripts and the proofs they construct to detect the cause when a proof attempt is unsuccessful and leads to unintended proof states. We present an offline and replay debugger to support the user in analyzing proof attempts performed with proof scripts. This debugger adapts successful concepts from software debugging to the area of proof script debugging. The tool is built on top of KeY, a system for deductive verification of Java programs. The debugger and its graphical user interface are designed to support program verification in particular, the underlying concepts and the implementation, however, are adaptable to other provers and proof tasks.

1 Introduction

Motivation. Proving complex properties of programs requires user guidance, which can come in the form of program annotations as well as user interaction during proof construction. Providing the right guiding information that allows a verification system to find a proof is, in general, an iterative process of repeated failed attempts. Also, the characteristics of program verification proofs are considerably different from proofs of mathematical theorems (such as properties of algebraic structures). Proofs in program verification consist of many structurally and/or semantically similar cases that are syntactically large, but usually of low intrinsic complexity. The mechanism for providing user guidance needs to reflect this peculiarity of proofs in the program verification domain and provide appropriate means for interaction. To support the iterative process of constructing proofs, many interactive program verification systems offer a proof scripting language as a text-based way to describe the non-automatic steps in a proof. Such scripting languages are beneficial, but users spent a lot of effort on inspecting proof scripts and the proofs they construct to detect the cause when a proof attempt is unsuccessful and leads to unintended proof states.

Contribution. In this paper, we describe our tool psdbg, an offline and replay debugger adapting successful concepts from software debugging to the area
of proof script debugging. It implements our interaction concept for interactive program verification described in [1]. PDBG combines point-and-click with text-based interaction based on a scripting language for proofs, KPS (Sect. 2). The replay functionalities offered by our tool allow the user to analyze unfinished proof attempts by using functionalities known from software debugging like forward stepping, breakpoints, and the visualization of the proof script state and proof. Furthermore, step-back and replay of proof commands are supported. Partial proof scripts can be extended by either appending new script commands (text-based) or by point-and-click selection of proof rules and commands. Additionally, PDBG contains aids for writing proof scripts such as the generation of a case-distinction expressions for goal selection and a visualization of the result of term matching expressions.

PDBG is available at formal.iti.kit.edu/psdbg together with a video of its usage.

Underlying verification system. We have chosen to built PDBG on top of the KeY system, which is an interactive theorem prover for the verification of Java programs at source code level [2]. KeY is based on a sequent calculus for Java Dynamic Logic. It was successfully applied to verify real world Java programs, e.g., implementations of Timsort [3] and Dual-Pivot Quicksort [4]. KeY constructs an explicit proof object, i.e., all proof steps and rule applications are available to the user at any time in addition to the current open goals. This enables a more fine-grained stepping functionality down to the level of single calculus rule applications. KeY offers point-and-click interaction for prover guidance. Combining KeY with a script component allows to automate user actions without losing the advantages of point-and-click interaction. Also, this combination provides more stable guidance in situations where the proof problem evolves. PDBG is designed to support program verification in particular, the underlying concepts and the implementation, however, are adaptable to other provers and proof tasks (Sect. 4).

Related work. The need to analyze failed proof attempts in interactive theorem proving has lead to different mechanisms for gaining insight into proof construction. The interactive theorem provers Isabelle [5] and Coq [6] both provide text-based interaction, and the way in which proofs are constructed allows to step over tactics, to revert a tactic application, and to add tactic invocations iteratively. The user can inspect the proof states between tactic applications. To get a deeper insight into tactics, both tools allow for the use of debuggers for the language in which the tactics and the tools are implemented (Standard ML respectively OCaml). While tactics implement generic proof strategies independent from the concrete proof problem, proof scripts are usually tailored to the current verification task. This difference manifests itself when debugging proof scripts in contrast to debugging tactics. Additionally, Hupel proposes an interactive tracing of Isabelle’s simplification tactic [7]. Lean’s metaframework [8] – an API to the theorem prover Lean – provides support for classical program debuggers to step through the execution of the declarative language of Lean.
Fig. 1. A proof script for proving correctness of the split method of Quicksort (see Appendix A line 76). The first lines perform a pre-processing. After application of simplification steps and a rule specific for the data type sequence (seqPermFromSwap), user guidance in the form of quantifier instantiations is required (lines 8–9). The match expression in line 7 matches sequents that contain a formula which consists of at least two nested existential quantifiers and binds the concrete terms of the quantified variables to the schema variables $?X$ resp. $?Y$ to be used in in lines 8 and 9 where they are parameters for the proof command instantiate.

2 Language for Proof Scripts

In this section, we introduce the basic concepts of the KEY PROOF SCRIPT (kps) language. As an example, we use a script constructing a proof for the correctness of the pivotal split in a Quicksort implementation (see Fig. 1).

State. A proof state consists of a set of proof goals of which at most one is selected. The main part of a proof goal is an open verification condition. In addition, it assigns values to variables. These variables are goal-local, i.e., changing the value of a variable has only local effect. When a new goal is created, it inherits its parent goal’s assignment. The configuration of the underlying theorem prover (e.g., the particular heuristic used for proof search) is accessible and can be changed via a special subset of these variables.

Mutators. As proof construction is characterized by selecting and manipulating goals, KPS provides goal selectors and mutators. Mutators are commands which modify a single proof goal by either manipulating the verification condition or changing the variable assignment. Mutators for verification conditions are either calls to sub-scripts (to construct sub-proofs) or commands from the underlying theorem prover. In the example in Fig. 1 one of the mutators is autopilot_prep (line 2), an internal prover strategy of KeY, that performs symbolic execution of the program to be verified with intermediate simplification steps. Another mutator in the example is instantiate (lines 8 and 9), which is a rule with parameters var and with. This rule instantiates the quantified variable var with a term. If a proof state contains more than one goal, before applying mutators a single goal has to be selected, as described in the following.

Goal selectors. With goal selectors one picks goals from the current state for mutator application. KPS provides the following selectors: foreach, theonly,
cases. With `foreach`, a mutator is applied to all proof goals (lines 3 and 4 in Fig. 1). The `cases` selector is used to make case distinctions over proof goals based on matching pattern expressions (in lines 5 to 10 there are two cases). In addition to syntactical patterns, matching expressions can be semantic, and they can refer to local goal variables; see [1] for more details. This kind of selection statement allows to mutate similar goals in the same way. After the evaluation of a matching expression, the state is updated by variable bindings.

3 Tool Features and Their Use

Program verification is an iterative process of unsuccessful proof attempts. The user needs to find the reason why proof construction failed. In the case of proof debugging, the user investigates whether the last state of the proof script, including the remaining verification conditions, matches his or her mental model of the proof, and how this state was reached. To support the user, our tool makes use of the analogy between writing programs and writing proof scripts presented in [1]. This analogy enables us to adopt mechanisms from software debugging systems to the analysis of failed proof attempts.

Visualization. Like software debuggers, `psdbg` offers different views on the proof states as shown in Fig. 2: (1) The source code of the proof script, with the next command to be executed being highlighted. (2) A list of the current proof goals and the; the currently selected proof goal is highlighted. This window pane allows different representations of the goals to be used, e.g., branching labels which are introduced by the underlying verification system to identify certain proof branches like induction base, step and use case. (3) Below, the selected proof goal is shown in full textual representation; this view supports the application of rules on selected terms in the interactive mode. (4) The lower left pane shows the source code of the Java program being verified. The highlighted lines are the executed Java statements corresponding to the selected proof goal. (5) The proof tree, i.e., the explicit proof object constructed by KeY is displayed. Note that, only a small portion of the proof tree can be seen, showing the beginning of the proof, where no branching has occurred yet. (6) The toolbar contains the buttons that are used for stepping through the proof script’s execution. Not shown in the screenshot of Figure 2 is the editor for writing and evaluating match expressions and the window with proof command documentation. Note that not all views are open all the time – rather the user may choose which views to see.

Breakpoints and stepping. For the analysis of proof script executions, `psdbg` allows to set breakpoints and to use stepping functionalities. The tool supports line breakpoints with and without a boolean condition. Script execution pauses when a breakpoint is reached and – in case a condition is provided – if moreover the state reached satisfies the breakpoint’s condition.

When script execution is paused, the user can use the stepping functionalities (by using the respective buttons in the toolbar).

For stepping, statements can either be compound (blocks or prover strategies) or atomic (e.g., single rule applications or variable assignments). The functions
Fig. 2. The user interface of psdbg

*step into* and *step over* have the usual behavior known from software debugging: *step over* executes until the end of the compound statement, while *step into* allows the user to inspect the execution of the constituents of a compound statements in more detail (e.g., if invoked before a block or a call to a sub-script). If *step into* is invoked for a native command of the underlying proof system, there are two possibilities: if the proof command is a prover strategy, the user is presented with the partial proof tree that corresponds to the execution of the that strategy. Stepping into a single (atomic) calculus rule behaves like *step over*.

In addition to *step over* and *step into*, two more stepping functions are available to inspect script execution in reverse: *step over reverse* and *step into reverse*. These allow the user to inspect proofs from end to start. This reverse inspection of proof states is possible due to the (partial) explicit proof object provided by the underlying verification system.

**Interactive manipulation of proof goals.** When the execution of a script is completed with some open proof goals remaining, the user has the possibility to interactively manipulate these open goals (e.g., using point-and-click interaction provided by the underlying verification system). Our tool allows to make these user interactions persistent automatically by recording and appending them to the end of the proof script upon leaving the interactive mode.
4 System Architecture

PSDBG consists of three main components (Fig. 3), which are built on top of an underlying theorem prover. (1) The user interface needs direct access to the theorem prover to allow interactive execution of goal mutators and to extract information for visualization, e.g., the executed Java source code lines. Integration of new additional views and state projection is supported by the use of a docking framework and full access to the underlying stack. (2) Execution control is a layer that provides the debugging logic to the UI, e.g., stepping, state tracing and breakpoints. (3) The interpreter is the heart of the architecture. It executes the proof script and performs the calls to the goal mutators of the theorem prover.

The debugging logic is separated from the interpreter core and the user interface. The UI is in parts dependent on the underlying theorem prover, i.e., the shape of the goals and the prover’s user interaction style (in KeY the goals are sequents, and KeY uses a point-and-click style for interaction).

For the adaption to a different theorem prover, the interpreter provides well-defined extension points—so the execution control and interpreter core are independent to the kind of proof goals. The extensions points are the handler of goal mutators, and special variables (prover settings) and the evaluation of matchings against verification conditions. The matching mechanism supports a special language for pattern matching of proof goals. The current pattern language is optimized for KeY’s sequents and needs to be adapted when using other types of proof goals.

5 Future Work

For future work, we will explore the usability of PSDBG and KPS on larger and more complex verification tasks, where script modularization becomes necessary. We plan to better visualise relations between different views, e.g., showing the relation between the proof script and the program to be verified. Also, better support for proof exploration is planned, so that less manual effort is required.

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A  QuickSort.java

    /* This example formalizes and verifies the wellknown quicksort algorithm for int-arrays algorithm. It shows that the array is sorted in the end and that it contains a permutation of the original input.
    * The proofs for the main method sort(int[]) runs automatically while the other two methods require interaction. You can load the files "sort.key" and "split.key" from the example's directory to execute the according proof scripts.
    * The permutation property requires some interaction: The idea is that the only actual modification on the array are swaps within the "split" method. The sort method body contains three method invocations which each maintain the permutation property. By a repeated appeal to the transitivity of the permutation property, the entire algorithm can be proved to only permute the array.
    * To establish monotonicity, the key is to specify that the currently handled block contains only numbers which are between the two pivot values array[from-1] and array[to]. The first and last block are exempt from one of these conditions since they have only one neighbouring block.
    */
    /*
    * The example has been added to show the power of proof scripts.
    * @author Mattias Ulbrich, 2015
    */

    class Quicksort {
        public void sort(int[] array) {
            if (array.length > 0) {
                sort(array, 0, array.length-1);
            }
        }
    }

    class Quicksort {
        private void sort(int[] array, int from, int to) { /*
            /*
        
        }
if(from < to) {
    int splitPoint = split(array, from, to);
    sort(array, from, splitPoint-1);
    sort(array, splitPoint+1, to);
}

/*@
public normal behaviour
requires 0 <= from && from < to && to <= array.length-1;
requires from > 0 ==> (\forall int x; from<=x && x<=to; array[from-1] < array[x]);
requires to < array.length-1 ==> (\forall int y; from<y && y<=to; array[y] <= array[to+1]);
ensures \dl_seqPerm(array);
ensures from <= \result && \result <= to;
ensures (\forall int m; from <= m && m <= \result; array[m] <= array[\result]);
ensures to < array.length-1 ==> (\forall int y; from<y && y<=to; array[y] <= array[to+1]);
ensurable array[from..to];
@*/
private int split(int[] array, int from, int to) {
    int i = from;
    int pivot = array[to];
    /*@
    loop_invariant from <= i && i <= to;
    loop_invariant \dl_seqPerm(array);
    loop_invariant (\forall int k; from <= k && k < i; array[k] <= pivot);
    loop_invariant (\forall int l; i <= l && l < to; array[l] > pivot);
    loop_invariant (\forall int x; from <= x && x<=to; array[from-1] < array[x]);
    loop_invariant to < array.length-1 ==>
    (\forall int y; from<y && y<=to; array[y] <= array[to+1]);
    assignable array[from..to-1];
    @*/
    for(int j = from; j < to; j++) {
        if(array[j] <= pivot) {
            int t = array[i];
            array[i] = array[j];
            array[j] = t;
            i++;
        }
    }
    array[to] = array[i];
    array[i] = pivot;
    return i;
