Interactive Runtime Verification

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Monitoring is the study of a system at runtime, looking for input and output events to discover, check or enforce behavioral properties. Interactive debugging is the study of a system at runtime in order to discover and understand its bugs and fix them, inspecting interactively its internal state.

Interactive Runtime Verification (i-RV) combines monitoring and interactive debugging. We define an efficient and convenient way to check behavioral properties automatically on a program using a debugger. We aim at helping bug discovery while keeping the classical debugging techniques and interactivity, which allow understanding and fixing bugs.

CCS Concepts: • Software and its engineering → Software testing and debugging;
Additional Key Words and Phrases: runtime verification, property, monitoring, debugging

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1 INTRODUCTION

When developing software, detecting and fixing bugs as early as possible is important. This can be difficult: an error does not systematically lead to a crash, it can remain undetected during the development cycle. Besides, when detected, a bug can be hard to understand, especially if the method of detection does not provide methods to study the bug.

Interactive debugging. A widespread way to fixing bugs consists in observing a bad behavior and starting a debugging session to find the cause. A debugging session generally consists in repeating the following steps: executing the program in a debugger, setting breakpoints before the expected cause of the bug, finding the point in the execution where it starts being erratic and inspecting the internal state (callstack, values of variables) to determine the cause of the problem. The program is seen as a white box and its execution as a sequence of program states that the developer inspects step by step using a debugger in order to understand the cause of a misbehavior. The execution is seen at a low level (assembly code, often mapped to the source code) while one would ideally want it be abstracted. The debugger links the binary code to the programming language. The state of the program can be modified at runtime: variables can be edited, functions can be called, the execution can be restored to a previous state. This lets the developer test hypotheses on a bug without having to modify the code, recompile and rerun the whole program, which would be time consuming. However, this process can be tedious and prone to a lot of trials and errors. Moreover, observing a bug does not guarantee that this bug will appear during the debugging session, especially if the misbehavior is caused by a race condition or a special input that was not recorded when the bug was observed. Interactive debugging does not target bug discovery: usually, a developer already knows the bug existence and tries to understand it.
Monitoring. Runtime verification (aka monitoring) [20, 28, 35] aims at detecting bugs. The execution is abstracted into a sequence of events of program-state updates. Monitoring aims at detecting misbehaviors of a black-box system: its internal behavior is not accessible and its internal state generally cannot be altered. Information on the internal state can be retrieved by instrumenting the execution of the program. The execution trace can be analyzed offline (i.e. after the termination of the program) as well as online (i.e. during the execution) and constitutes a convenient abstraction on which it is possible to express runtime properties.

We aim at easing bug discovery, bug understanding as well as their combination. We introduce Interactive Runtime Verification (i-RV), a method that brings bug discovery and bug understanding together by combining interactive debugging and monitoring, augmenting debuggers with runtime verification techniques. Using i-RV, one can discover a bug and start getting insight on its cause at the same time. i-RV aims at automating debugging. For instance, it is possible to automatically stop the execution when a misbehavior is detected or to automate checkpointing at the right times. We define an expressive property model that allows flexibility when writing properties. We give a formal description of our execution model using high-level pseudo-code which serves as a basis for a solid implementation and reasoning and to ensure correctness of our approach. End-users are however not required to have a full understanding of this description. i-RV takes advantage of checkpoints. Checkpoints allow saving and restoring the program state. They are a powerful tool to explore the behavior of programs by trying different execution paths. i-RV introduces the notion of Scenarios. They allow defining actions that are triggered depending on the current state of the property verification. We provide a full-featured tool for i-RV, Verde, written in Python as a GDB extension, facilitating its integration to developers’ traditional environment. Verde also provides an optional animated view of the current state of the monitor. We give a detailed evaluation of
i-RV using Verde. This evaluation validates the usefulness of i-RV and its applicability in terms of performance.

Organization of this paper. In Sec. 2, we give a general picture of our approach. In Sec. 3, we describe our approach more precisely. In Sec. 5, we present our proof-of-concept implementation of this approach, Verde. In Sec. 6, we evaluate our approach. In Sec. 7, we present existing techniques for finding and studying bugs and compare them to our work. In Sec. 8, we conclude by presenting our future works.

2 APPROACH OVERVIEW

In i-RV (Fig. 1), the developer provides a property to check against the execution trace of a program to debug. The property can be written according to its specification or the Application Programming Interface (API) of the libraries it uses. An example of a property is pictured in Figure 2 and gives the verdict false as soon as a queue overflows. The program is run with a debugger which provides tools to instrument its execution, mainly breakpoints and watchpoints, and let us generate events to build the trace, including function calls and variable accesses. An extension of the debugger provides a monitor that checks this property in real time. Breakpoints and watchpoints are automatically set at relevant locations as the evaluation of a property requires monitoring function calls and memory accesses. When an event stops influencing the evaluation of any property, the corresponding instrumentation (breakpoints, watchpoints) becomes useless and is therefore removed: the instrumentation is dynamic. The user-provided scenario defines what actions should be taken during the execution according to the evaluation of the property. Examples of scenarios are: when the verdict given by the monitor becomes false (e.g. when the queue overflows), the execution is suspended to let the developer inspect and debug the program in the usual way, interactively; save the current state of the program (e.g. using a checkpoint, a feature provided by the debugger) while the property holds (e.g. while the queue has not overflowed) and restore this state later, when the property does not hold anymore (e.g. at the moment the queue overflows). When an event is generated — when a breakpoint or a watchpoint is reached — at runtime, the monitor updates its state. Monitor updates are seen as input events for the scenario. Examples of these events are “the monitor enters state X”, “the state X has been left”, “an accepting state has been entered”, “a non-accepting state has been left”.

3 JOINT EXECUTION OF THE DEBUGGER, THE MONITOR AND THE PROGRAM

i-RV relies on the joint execution of different components: the program, the debugger, the monitor and the scenario. We formally describe the Interactively Runtime Verified program (i-RV-program) composed of these components as a Labeled Transition System (LTS). We first present each component and our property model based on an extension of finite-state machines in Sec. 3.2. Events play the role of symbols of the LTS. Events are defined in Sec. 3.1. We then describe the evolution
of the i-RV-program in Sec. 3.3 using pseudo-code. This formalization is not needed to adopt the approach. However, it offers a solid basis for implementation and for reasoning and expressing properties over the concepts behind i-RV.

Notations. We define some notations used in this paper. We denote the set of booleans by $\mathbb{B} = \{\text{true}, \text{false}\}$. Given two sets $E$ and $F$, $E \rightarrow F$ denotes the set of functions from $E$ to $F$. By $f : E \rightarrow F$ or $f \in [E \rightarrow F]$, we denote that $f \in E \rightarrow F$. Let $f : E \rightarrow F$, function $f' = f[x_1 \mapsto v]$ is such that $f'(x) = f(x)$ for any $x \neq x_1$, and $f'(x_1) = v$. The domain of function $f$ is denoted by $\mathcal{D}(f)$.

Let us consider a non-empty set of elements $E$. The powerset of $E$ is denoted $\mathcal{P}(E)$. Moreover, $\epsilon_E$ is the empty sequence (over $E$), noted $\epsilon$ when clear from the context. $E^*$ denotes the set of finite sequences over $E$. Given two sequences $s$ and $s'$, the sequence obtained by concatenating $s'$ to $s$ is denoted $s \cdot s'$. We denote by $\text{Name}$ the set of valid function and variable names in a program.

We define the transitive relation "$f'$ is more specific than $f" : f \sqsubseteq f' \overset{\text{def}}{=} \mathcal{D}(f) \subseteq \mathcal{D}(f') \land \forall p \in \mathcal{D}(f) : f(p) = f'(p)." Likewise, "$f'$ is strictly more specific than $f" : f \sqsubseteq f' \overset{\text{def}}{=} \mathcal{D}(f) \subset \mathcal{D}(f') \land \forall p \in \mathcal{D}(f) : f(p) = f'(p)."

### 3.1 Events

i-RV is based on capturing events from the program execution with the debugger.

**Definition 3.1 (Event).** An event is a tuple $e = (t, n, p, i, b) \in \text{EventTypes} \times \text{Names} \times \text{ParamNames} \times \text{Values}_p \times \mathbb{B}$ where $\text{EventTypes} = \{\text{Call}, \text{ValueWrite}, \text{ValueRead}, \text{UpdateExpr}\}$. The event name $n \in \text{Names}$ is denoted $\text{name}(e)$. A grammar describing the set of valid parameter names $\text{ParamNames}$ is given in Figure 3. A parameter can be the name of a variable defined in the program, the value pointed by a pointer, the address of a variable, an argument of the current function or a return value.

**Remark 1.** The parameter $\text{arg} i$ is not necessarily the value that was passed to the function when it was called. The parameter can be modified between the function call and when the event is triggered.

If $e$ is a symbolic event, its parameters are uninstantiated, i.e., $i = \emptyset$. If $e$ is a runtime event, $i$ is a list of parameter instances and $\text{values}(e)$ is the function that maps parameters to their values:

$$\text{values}(e) : \text{Names} \rightarrow \text{Values}$$

$$p_k \mapsto i_k$$

Symbolic events are used to describe properties. Runtime event are matched with symbolic events if all its components, except values, are identical to the components of the symbolic event.

**Example 3.2 (Event).** (FunctionCall, push, $(q, v), \emptyset, \text{true}$) is an event that is triggered before the call to function push. Parameters $q$ and $v$ are retrieved when producing the event.
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Definition 3.3 (Event matching). A runtime event $e_i$ matches a symbolic event $e_f$ if $\text{name}(e_i) = \text{name}(e_f)$ and $\text{type}(e_i) = \text{type}(e_f)$ and $\text{isBefore}(e_i) = \text{isBefore}(e_f)$ and $\text{params}(e_i) = \text{params}(e_f)$.

Example 3.4 (Event matching). "Before push(q, 5)" is a runtime event matching the symbolic event "Before a call to function (type) push (name) that takes a queue and an element in parameters (list of parameters)".

The type $t \in \text{EventTypes}$ of event $e$ is denoted $\text{type}(e)$. If $b = \text{true}$ (resp. $\text{false}$), $e$ is a before (resp. after) event and $\text{isBefore}(e) = \text{true}$ (resp. $\text{false}$). We describe the different event types. A FunctionCall event is generated by a function call. A before event is triggered before the first instruction of the function and after the jump to the function body. An after event fires after the last instruction of the function and before the jump to the caller. The parameter ret then corresponds to the return value of the call. A ValueWrite event is generated by an assignment. A before (resp. after) event fires before (resp. after) the assignment instruction and parameter ret refers to the old (resp. new) value of the variable. A ValueRead event is generated by a variable read. A before event fires before (resp. after) the instruction that reads the variable and parameter ret refers to the value of the variable. An UpdateExpr event is generated whenever the value of an expression is changed. A before (resp. after) event $e$ is fired before (resp. after) the update. For a before (resp. after) UpdateExpr event, parameter ret refers to the old (resp. new) value of the expression.

Remark 2. In practice, FunctionCall events are captured using breakpoints and ValueWrite, ValueRead and UpdateExpr events are captured using watchpoints. An UpdateExpr event requires as many watchpoints as variables in the expression. Current debuggers hide this requirement by allowing setting watchpoints on expressions.

3.2 Modeling the Components of i-RV

We model the components of i-RV and their behaviors by giving their configurations. Our execution model is a composition of these configurations.

3.2.1 The Program. For the sake of generality, we define a platform-independent and language-independent abstraction of a program that is loaded in memory, which allows us to apply the runtime techniques used in i-RV. The memory is abstracted as a function that maps addresses to values.

Definition 3.5 (Memory). A memory $m$ is a function in $\text{Mem} = [\text{Address} \to \text{Values}]$. Some addresses correspond to variables of the program and are therefore linked to symbol names by the symbol table built during the compilation of the program.

Remark 3. The actual type of the elements of Address does not matter. They can be seen as integers like in a real memory. Elements of Values are machine words. They are either data (values of variables) or program instructions. They can also be seen as integers.

Definition 3.6 (Program). A program is a 4-tuple $(\text{Sym}, m_0^p, \text{start}, \text{runInstr})$ where:

- $\text{Sym} : \text{Names} \to \text{Address}$ is a symbol table
- $m_0^p \in \text{Mem}$ is the initial memory,
- $\text{start} \in \text{Address}$ is an address that points to the first instruction to run in the memory, and
- $\text{runInstr} : (\text{Mem} \times \text{Address}) \to (\text{Mem} \times \text{Address} \times (\text{Address} \times \mathcal{B} \times \mathcal{B})^*)$ is a function that abstracts the operational semantics of the program\(^1\).

\(^1\)The actual semantics usually depends on the instruction set of the architecture.
Function runInstr takes the current memory and Program Counter (PC) (in Address) and executes the instruction at PC: it returns a (possibly new) memory, a new PC and a list of 3-tuples made of an address, and two booleans, representing the accesses to the memory. In an access, the two booleans hold true if the value at the given address was read and written (respectively), false otherwise. Memory accesses are used by the debugger to trigger watchpoints (see Sec. 3.2.3).

Example 3.7 (Program). In the remainder of this section, we will use program $P$ given by the following source code to illustrate the concepts:

\[ a := 0 ; b := 1 ; a := a + b \]

Definition 3.8 (Configuration of the program). A configuration is a pair $(m_p, pc) \in \text{Mem} \times \text{Address}$ where $m_p$ is the memory and $pc$ is the current PC (an address in the program memory), i.e. the address of the next instruction.

Example 3.9 (Configuration of the program). For program $P$ given in Ex. 3.7, just after the execution of the second instruction, the configuration of the program is $(m_p, pc_3)$ where $pc_3$ is the address of the code that corresponds to the third instruction of $P$, $m_p[\text{Sym}(a)] = 0$ and $m_p[\text{Sym}(b)] = 1$.

3.2.2 The Monitor. The monitor evaluates a property against a trace, giving a verdict upon the reception of each event. The verdict corresponding to the last event of the execution trace is called the final verdict [18].

Property model. We describe properties in a model based on finite-state machines. It is composed of states, transitions and an environment and it recognizes sequences of events. Transitions have guards that are expressions of event parameters and the memory and a function that can update the environment. Properties can be expressed on the whole set of events that can be retrieved from the debugger. Events are parameterized, i.e. values are linked to events. For instance, a function call generates an event parameterized with the values of arguments passed during this call, as well as values that are accessible at this time (global variables for example).

Trace slicing. Some properties should hold on each instance of an object or a set of objects rather than on the global state of the program. For example, a property on good file usage must be checked on each file that is manipulated by the program. For these properties, the execution trace is sliced in a way that is similar to what is achieved by trace slicing in [8, 21]. Each slice of the trace concerns a specific instance of an object or a set of objects on which the property holds. When trace slicing is used, a monitor does not correspond to a single finite state machine but to a set of finite state machines, one for each particular instance of an object.

Definition 3.10 (Monitor). A monitor is a 7-tuple $(Q, \Sigma, \text{init}, \text{env}_0, \Delta, \nu, S)$ where $Q$ is a set of states, $\Sigma$ is the set of symbolic events, $\text{env}_0 \in \text{Env}$ is the initial environment ($\text{Env} = \text{Names} \rightarrow \text{Values}$, where Names is the set of variable names and Values is the set of values that can be stored in a variable), $\Delta : \mathcal{P}(\text{Names} \times \text{Names}) \times Q \times \Sigma \times (\text{Env} \times \text{Env} \rightarrow \text{B}) \times (\text{Env} \times \text{Env} \rightarrow \text{Env}) \times Q$ is the transition relation, $\nu \in [Q \rightarrow \mathcal{V}]$ is the function that maps states to verdicts and $S \subseteq \text{Names}$ is a set of parameter names on which the slicing applies.

A transition is a 6-tuple $(sb, q_s, e_f, g, upd, q_d)$ where $sb$ is the slice binding of the transition, $q_s$ is the start state, $e_f$ is the symbolic event, $g$ is the guard, $upd$ is the “updater” and $q_d$ is the destination state. The slice binding $sb$ is a set of pairs $(p, s)$ where $p$ is a name of the parameter of the function on which the slicing applies and $s \in S$ is the name of the slice parameter at the level of the property.

Remark 4. In practice, in most cases, $p$ and $s$ are equal. However, it is possible that a particular object is named differently in different functions. This is the reason why a slice binding is used
instead of a simple parameter name: an object is uniquely identified in $S$ (at the level of the property), and then each actual function parameter name is bound to this unique identifier.

The guard $g : \text{Env} \times \text{Env} \rightarrow \mathbb{B}$ takes the environment built from the parameters of the runtime event, the environment of the monitor and returns a boolean. If it returns true (resp. false), the transition is taken (resp. not taken). The updater $\text{upd} : \text{Env} \times \text{Env} \rightarrow \text{Env}$ returns an environment from the environment built from the parameters of the runtime event and the environment of the monitor. This function is used to update the environment of the property.

A monitor is given in Ex. 3.11.

**Example 3.11 (Monitor).** The property illustrated in Fig. 2 is a tuple $(Q, \Sigma, \text{init}, \text{env}_0, \Delta, \nu, S)$ where:

- $Q = \{\text{Init, ready, sink}\}$,
- $\Sigma = \{e_{f}^\text{before}(\text{queue\_new}), e_{f}^\text{before}(\text{push}), e_{f}^\text{before}(\text{pop})\}$,
- $\text{init} = \text{Init}$,
- $\text{env}_0 = [N \mapsto 0, \text{Max} \mapsto 0]$,
- $\nu = [\text{Init} \mapsto \text{true}, \text{ready} \mapsto \text{true}, \text{sink} = \text{false}]$,
- $S = \{q\}$,
- the transition $\Delta$ is defined as $\Delta = \{(q, q), \text{init}, e_{f}^\text{before}(\text{new}), [\text{any} \mapsto \text{true}], ([\text{size}], \text{env}) \mapsto \text{env}([\text{max} := \text{size} - 1], \text{ready})\}$,
- $\{(q, q), \text{ready}, e_{f}^\text{before}(\text{push}), [[\text{N}], \text{Max}] \mapsto \text{N} < \text{Max}], (\text{any}, \text{env}) \mapsto \text{env}([\text{N}+ = 1], \text{ready})\}$,
- $\{(q, q), \text{ready}, e_{f}^\text{before}(\text{pop}), [[\text{N}], \text{Max}] \mapsto \text{N} > 0], (\text{any}, \text{env}) \mapsto \text{env}([\text{N} = = 1], \text{ready})\}$,
- $\{(q, q), \text{ready}, e_{f}^\text{before}(\text{pop}), [[\text{N}], \text{Max}] \mapsto \text{N} >= \text{Max}], (\text{any}, \text{env}) \mapsto \text{env}(\text{sink})\}$,
- $\{(q, q), \text{ready}, e_{f}^\text{before}(\text{pop}), [[\text{N}], \text{Max}] \mapsto \text{N} <= 0], (\text{any}, \text{env}) \mapsto \text{env}(\text{sink})\}$.

The first transition makes the property transition from Init to ready when queue\_new is called. The guard always returns true so the transition is taken unconditionally. The updater stores the maximum number of elements in the queue in the environment of the monitor. This maximum is computed from the size parameter of the event new. The two next transitions make the monitor stay on the state ready when it is correct to add or (resp. remove) elements from the queue. In each case, the updater updates the number of elements in the queue in the environment of the monitor. The two last transitions detect that an element is added (resp. removed) though the queue is full (resp. empty) and makes the property transition from ready to sink. Each time a new value of the parameter $q$ is encountered, a new instance of the property is created.

We define the configuration of monitors.

**Definition 3.12 (Configuration of the monitor).** A configuration of the monitor is a set of 4-tuples $M = \{(q^0_m, m^0_m, s^0_m, sp^0_m), \ldots (q^n_m, m^n_m, s^n_m, sp^n_m)\} \in \mathcal{P}(\text{Q}_m \times (\text{Names} \rightarrow \text{Values}) \times (S \rightarrow \text{Values} \cup \{\gamma\}) \times (S \rightarrow \text{Values} \cup \{\gamma\}))$ where $\gamma$ corresponds to an uninstantiated value.

In a configuration of a monitor, each 4-tuple $(q^k_m, m^k_m, s^k_m, sp^k_m) \in M$ represents an instance of the extended automaton that corresponds to a slice of the trace. $q^k_m$ is its current state, $m^k_m$ its current environment, $s^k_m$ a mapping that gives which instance of the parameters this slice corresponds to (the slice instance) and $sp^k_m$ the parent slice instance of this slice, that is, the slice instance of the slice $sp$ from which this slice was created (because an event with parameters more specific than the parameter instance of $sp$ happened). We denote by $C_m$ the set of configurations of a monitor and by enabled($M$) the set of symbolic events to which the monitor is “sensitive” in $M$: For all
A breakpoint stops the execution at a given address. Example 3.15 illustrates the notion of breakpoint. A breakpoint set by the user on the second instruction of the program gives in the program memory. This breakpoint is triggered when the instruction is to be executed. Example 3.15 illustrates the notion of breakpoint.

Example 3.15 (Breakpoint). A breakpoint set by the user on the second instruction of the program given in Ex. 3.7 is \((pc_2, b := 1, true)\) where \(pc_2\) is the memory address at which the second instruction is loaded. The instruction of the second instruction is stored as the second component of the tuple and the third component indicates that this breakpoint is set by the user.

Definition 3.16 (Watchpoint). A watchpoint is a 4-tuple \((addr, read, write, isUserWP) \in \mathcal{W}p\) where:

- \(addr\) is the address of the watchpoint in the program memory,
- \(read\) (resp. \(write\)) is a Boolean that holds true if this watchpoint should be triggered when the memory is read (resp. written),
- \(isUserWP\) is a Boolean that holds true if the watchpoint was set by the user, and false if it was set by the monitor.

The set of watchpoints is defined by \(\mathcal{W}p = \text{Address} \times \mathbb{B} \times \mathbb{B} \times \mathbb{B}\).

Example 3.17 illustrates the notion of watchpoint.

Example 3.17 (Watchpoint). A watchpoint set by the user on variable \(b\) in the program given in Ex. 3.7 is \((\&b, \text{false, true})\) where \(\&b\) denotes the address of variable \(b\) in the program memory. This watchpoint is triggered whenever variable \(b\) is written (but not when it is only read).
\[a ::= v := e \text{ (assignment)}\]

\[v ::= \text{checkpoint (saving a checkpoint)}\]

\[a ; a \text{ (sequential composition)}\]

\[\text{if } e \text{ then Action else Action (conditional statement)}\]

\[\text{while } e \text{ then Action else Action (loop)}\]

\[\text{restore-checkpoint checkpoint (restart a checkpoint)}\]

\[\text{setWatchpoint } w t \text{ (set a watchpoint. } t \in \{r, w, rw\})\]

\[\text{setBreakpoint } b \text{ (set a breakpoint)}\]

\[\text{unsetWatchpoint } w \text{ (remove a watchpoint)}\]

\[\text{unsetBreakpoint } b \text{ (remove a breakpoint)}\]

with \(e\) a usual expression in a programming language and \(v \in \text{Names}\).

Fig. 4. Grammar of Scenario actions

**Checkpoint.** When debugging, it can be useful to save the state of the program (e.g., before the occurrence of a misbehavior to determine its cause or to try alternative executions). A checkpoint can be set by the user as well as by the scenario. There is not syntactical element in the definition of a checkpoint as it only depends on runtime elements. The states of the monitor and of the program are both saved, allowing coherent states after restoration.

**Definition 3.18 (Checkpoint).** A checkpoint is a 2-tuple \((c_p, c_m) \in C_p\) where:

- \(c_p\) is a configuration of the program (as per Definition 3.6), and
- \(c_m\) is a configuration of the monitor (as per Definition 3.10).

The set of all possible checkpoints is defined by \(C_p = (\text{Mem} \times \text{Address}) \times C_m\).

Example 3.19 illustrates the notion of checkpoint.

**Example 3.19 (Checkpoint).** For the program given in Ex. 3.7, the checkpoint \(((a \mapsto 0, b \mapsto 1), pc_3), M)\), when the third instruction is about to be executed, is such that:

- \([a \mapsto 0, b \mapsto 1]\) is the program memory,
- \(pc_3\) is the memory address at which the third instruction is loaded, and
- \(M\) is the configuration of the monitor when the checkpoint is set.

**Configuration of the debugger.** The debugger can be either interactive, waiting for the user to issue commands and execute them, or passive, with the program executing normally until a breakpoint or a watchpoint is triggered or the user interrupts the execution. The debugger keeps track of the current breakpoints, watchpoints and of user’s checkpoints.

**Definition 3.20 (Configuration of the debugger).** A configuration of the debugger is a 4-tuple \((q_d, \mathcal{B}, \mathcal{W}, \mathcal{C}) \in \{i, p\} \times \mathcal{P}(\mathcal{B}p) \times \mathcal{P}(\mathcal{W}p) \times C_p^*\) where:

- \(q_d\) is the current mode of the debugger, either \(i\) (interactive) or \(p\) (passive),
- \(\mathcal{B}\) and \(\mathcal{W}\) are the sequences of breakpoints and watchpoints handled by the debugger,
- \(\mathcal{C}\) is the sequence of checkpoints set by the user.

Sequences are used for \(\mathcal{C}, \mathcal{W}\) and \(\mathcal{B}\) in order to allow the user manipulate checkpoints, watchpoints and breakpoints by their index.

3.2.4 The Scenario. The scenario reacts to monitor events by executing actions that update the state of the program, of the debugger and of the scenario itself. We define actions, then reactions, and finally the scenario itself. Actions are executed when monitor events are received according to the notion of scenario reactions.
Definition 3.21 (Scenario action). The set of possible actions, Actions, is defined by the grammar in Figure 4. The set of possible actions, Actions, is constructed like the set of statements in a classical programming language in which it is also possible to set and remove breakpoints, watchpoints and checkpoints.

Definition 3.22 (Scenario reaction). A scenario reaction is a 3-tuple \((lt, q_m, a)\) ∈ \{entering, leaving\} × \(Q_m\) × Actions, where \(lt\) determines the "moment of the reaction", \(q_m\) is the state of the monitor to which the reaction is attached, and \(a\) is an action to be executed. The set of scenario reactions is denoted \(SR\).

The scenario reaction \((lt, q_m, a)\) is triggered when entering (resp.) leaving state \(q_m\) in the monitor when \(lt =\) entering (resp. \(lt =\) leaving. When \((lt, q_m, a)\) is triggered, action \(a\) is executed. A scenario is specified by giving a list of reactions and an environment \(m_s\) used by actions. If a transition starting from a given state and leading to the same state is taken by the monitor, this state is both left and entered.

Definition 3.23 (Scenario). A scenario is a pair \((m_s^0, S)\) ∈ \((\text{Names} \to \text{Values}) \times SR^*\) where \(m_s^0\) is an initial environment and \(S\) a list of scenario reactions.

Remark 5. \(S\) is a list (and not a set) because if a state-update in the monitor triggers more than one scenario reactions, these reactions are handled in order in \(S\).

Ex. 3.24 illustrates the notion of scenario.

Example 3.24 (Scenario). Assuming that \(a_1\) and \(a_2\) are two scenario actions and \(x\) a monitor state, the following listing describes a scenario:

```plaintext
accesses := 0
on entering state x do
    accesses := accesses + 1
if accesses = 2 then
    [do something]
else
    [do something else]
```

This listing defines the scenario \([[\text{accesses} \mapsto 0], ([\text{entering, } x, a])\]) where action \(a\) increments variable accesses and its behavior depends on the value of variable accesses, the environment \([\text{accesses} \mapsto 0]\) is the initial memory of the scenario and \((\text{entering, } x, a)\) is its only reaction.

3.3 Gathering the Components

In this section, we give the representation of the state of the i-RV-program at each execution step (i.e. its configuration). We then describe its evolution by means of pseudo-code, precisely explaining how it transitions from one configuration to another. The i-RV-program is depicted in Figure 5. Let \(P = (\text{Sym}, m_s^0, \text{start}, \text{runInstr})\) be a program, \(M = (Q_m, q_m^0, m_s^0, \Sigma_m, \Delta_m)\) a monitor and \(S = (m_s^0, S)\) a scenario. The i-RV-program, denoted by i-RV\((P, M, S)\), is defined as the composition of \(P, M\) and \(S\) synchronized on events. We first define the configurations of the i-RV-program in Sec. 3.3.1 and the evolution of its configurations in Sec. 3.3.3 driven by the instrumentation functions of debugger defined in Sec. 3.3.2.

3.3.1 Configuration of the Composition. We define the configurations of the i-RV-program.

Definition 3.25 (Configuration of the i-RV-program). A configuration of i-RV\((P, M, S)\) is a 4-tuple \(c_{iRV} = (c_P, c_{\text{dbg}}, c_M, c_S)\) ∈ \((\text{Mem} \times \text{Address}) \times ((\mathcal{I}, \mathcal{P}) \times \mathcal{B}p^* \times \mathcal{W}p^* \times \mathcal{C}p^*) \times C_m \times \text{Mem}_s\). The initial configuration of i-RV\((P, M, S)\) is \(c_{iRV}^0 = ((m_P^0, p_{c_0}^0), (\mathcal{I}, \mathcal{E}, \mathcal{E}, \mathcal{E}), \{((\text{init}, m_m^0, \mathcal{E} \mapsto \emptyset, \emptyset)\}, m_s^0)\).

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A configuration is composed of the initial program memory, the start address of the program as the PC, the debugger is interactive and does not manage any breakpoint, watchpoint or checkpoint, the monitor has one slice instance of the property that is in its initial state and in its initial environment and all parameters of the slice are uninstantiated and the memory of scenario is its initial memory.

3.3.2 Instrumentation Functions of the Debugger.

setBP, unsetBP. Breakpoints and watchpoints are used to monitor function calls. We define the following functions: setBP (sets a breakpoint), unsetBP (find a breakpoint by its address and remove it from the memories of the program and the debugger), setWP (sets a watchpoint) and unsetWP (unsets a watchpoint).

To set a breakpoint, we need to write a special instruction in the program memory. When this instruction is encountered during the execution, the execution is suspended and the debugger takes control over it. We also need to keep the word we replace in memory, so when the execution is resumed from this breakpoint or when the breakpoint is removed, the special breakpoint instruction is replaced by the stored instruction in the program memory.

Several breakpoints can be set at the same address. For instance, the monitor and the user might want to set a breakpoint on the same function. Breakpoints have to be stored in order in the structures of the debugger. We therefore use a list to save them.

We define setBP, a function that sets a breakpoint and register it in the configuration of the debugger. We indicate if the breakpoint was set by the user or by the monitor, so that breakpoints set by the user do not call the monitor and breakpoint set by the monitor are not seen by the user.

We define setInstrBp : Env × Address → Env, a function replacing the word at a given address in the program memory by a breakpoint instruction (denoted by B). setInstrBp(m_p, addr)[addr] = B and ∀a ∈ Address : a ≠ addr, setInstrBp(m_p, a)[a] = m_k[a]. Function setBP : Mem × Bp × Address × B sets a breakpoint and saves it in the memory of the debugger: setBP(m_p, B, addr,.isUserBP) = (B ′, m_p ′) with m_p ′ = setInstrBp(m_p, addr) and B ′ = (addr, m_p[addr], isUserBP) :: B. In the same way, we define setWP : Wp × Address × B × B × B that adds a watchpoint in the memory of the
We also define watchpoints. The list of watchpoint to set for an expression is returned by function \(1:12\) Raphaël Jakse, Yliès Falcone, Jean-François Méhaut, and Kevin Pouget

\[\text{match}(\cdot, \text{ Vol. 1, No. 1, Article 1. Publication date: May 2017.}\]

initialized (command load monitor, Alg. 3, Line 4): breakpoints and watchpoints relevant to the new state. It takes the old program memory, the new state and the symbol table and returns a new memory and a new list of breakpoints. Function \(\text{unInstrument}\) unsets breakpoints that are not needed anymore.

#### Remark 7. Instrumenting to monitor value changes for an expression may require setting several watchpoints. The list of watchpoint to set for an expression is returned by function \(\text{variablesAccesses} : \text{Events} \rightarrow \mathcal{P}(\mathcal{Wp})\) which is not defined formally here for the sake of simplicity.

\(\text{removeAllBPs}\). In a checkpoint, the saved program memory must not contain any instruction \(\mathcal{B}\). A function to remove all breakpoints from the memory is therefore needed. We define \(\text{removeAllBPs}\), a function which iterates over the list of breakpoints of the debugger and replaces each instruction \(\mathcal{B}\) by the original instruction. \(\text{removeAllBPs}(m_p, \varepsilon) = m_p\) and \(\forall \mathcal{B} \in \mathcal{Bp} : \mathcal{B} \neq \varepsilon, \text{removeAllBPs}(m_p, \mathcal{B}) = \text{removeAllBPs}(m_p', \mathcal{B'})\) where \(\mathcal{B} = (\text{addr}, \text{instr}, b) \cdot \mathcal{B}'\) and \(m_p' = m_p[\text{addr} \mapsto \text{instr}].\) When a checkpoint is restored, current breakpoints must be set in the memory. We therefore define the function \(\text{restoreBPs}\) which iterates over the list of breakpoints and sets the instruction \(\mathcal{B}\) at the relevant addresses. \(\text{restoreBPs}(m_p, \mathcal{B}) = m_p'\) with

\[
\forall a \in \text{Address}, m_p'[a] = \begin{cases} 
\mathcal{B} & \text{if } \exists (\text{addr}, \text{instr}, b) \in \mathcal{B} : \text{addr} = a \\
\text{m}_p[a] & \text{otherwise} 
\end{cases}
\]

#### 3.3.3 Evolution of the i-RV-program. In this section, we describe the precise behavior of the i-RV-program. The algorithm describing the general behavior of the i-RV-program is given in Alg. 2 and explained right after. The initial configuration of the i-RV-program is \(((m_p, \text{pc}), (q_d, \mathcal{B}, \mathcal{W}, \mathcal{C}), M, m_s) = ((m_0^{p}, \text{pc}_0), (t, \epsilon, \epsilon, \epsilon), \{(\text{init}, m_0^{m_s}, \ast \mapsto \emptyset, \emptyset)\}, m_0^{s}).\) In this configuration, the debugger is in interactive mode, meaning it is waiting for commands from the user (Line 3)

First step of the execution. When starting the execution of the i-RV-program, the monitor is initialized (command load monitor, Alg. 3, Line 4): breakpoints and watchpoints relevant to the initial state of the property are set.
**Algorithm 1** INSTRUMENT, UNINSTRUMENT

1: function needsBreakpoint(e)  
   return type(e) = FunctionCall  
2: function needsWatchpoint(e)  
   return type(e) ∈ \{ValueWrite, ValueRead, UpdateExpr\}
3: function evtToWatchpoints(e, Sym)
   res ← ∅  
   for all \((n, r, w) \in \text{variablesAccesses}(e)\) do  
      \(res \leftarrow res \cup \{(\text{Sym}[n], r, w)\}\)
4: function uninstrument\((m_p, \mathcal{B}, \mathcal{W}, M, \text{Sym})\)
   let \(m_p' \leftarrow m_p\)  
5: function instrument\((m_p, \mathcal{B}, \mathcal{W}, \text{Sym})\)
   let \((m_p', \mathcal{B}', \mathcal{W}') \leftarrow (m_p, \mathcal{B}, \mathcal{W})\)

**Algorithm 2** Behavior of the System

1: let cont ← true
2: while cont do
3:   if \(q_d = 1\) then  
   \(\text{interactive execution}\)  
4:   \((\text{cont}, ((m_p, pc), c_1\_RV)) \leftarrow \text{handleUserCMD}(c_1\_RV)\)
5:   else if User stops the execution or \(m_p[pc] = \text{stop}\) then  
   \(\text{interruption}\)  
6:   \(q_d \leftarrow 1\)
7:   else if \(m_p[pc] \neq \text{B} \land m_p[pc] \neq \text{stop}\) then  
   \(\text{normal execution}\)  
8:   \(c_1\_RV \leftarrow \text{normalStep}(c_1\_RV)\)
9:   else if \(m_p[pc] = \text{B}\) then  
   \(\text{a breakpoint is reached}\)  
10:  \(c_1\_RV \leftarrow \text{handleBP}(c_1\_RV)\)

**Normal execution.** If the debugger is passive and the instruction about to be executed is not an instruction B, the program executes normally as if there were no debugger and no monitor (Alg. 2), Line 7. In function normalStep (Alg. 7, Line 17), the PC and the program memory are updated by function runInstr which runs the instruction to be executed. Watchpoints relevant to memory accesses made by this execution are handled. The instruction stop ends the execution (Alg. 2, Line 5).
Algorithm 3 Behavior when the debugger is Interactive

1: \textbf{function} HANDLEUserCMD(c_{i-RV})
2: \hspace{.5em} \textbf{let} cont \leftarrow \text{true}
3: \textbf{switch} getUserCMD() \textbf{do}
4: \hspace{1em} \textbf{case} load monitor \textbf{do}
5: \hspace{1.5em} \langle m_p, B, W \rangle \leftarrow \text{INSTRUMENT}(m_p, B, W, M, Sym) \\text{\textcopyright{Loading the monitor}}
6: \hspace{1em} \textbf{case} restart \textbf{do}
7: \hspace{1.5em} \langle m_p^{tmp}, B, W \rangle \leftarrow \text{UNINSTRUMENT}(m_p^{tmp}, B, W, M, Sym) \\text{\textcopyright{Restarting from a checkpoint}}
8: \hspace{1em} \langle m_p^{tmp}, pc, M \rangle \leftarrow C
9: \hspace{1em} \langle m_p^{tmp}, B, W \rangle \leftarrow \text{INSTRUMENT}(restoreBPs(m_p^{tmp}, B), M, Sym) \\text{\textcopyright{Continuing the execution}}
10: \hspace{1em} \textbf{case} continue \textbf{do}
11: \hspace{1.5em} c_{i-RV} \leftarrow \text{INTERACTIVEStep}(c_{i-RV}) \\text{\textcopyright{Setting a breakpoint}}
12: \hspace{1.5em} q_d \leftarrow p
13: \hspace{1em} \textbf{case} break a \textbf{do}
14: \hspace{1.5em} \textbf{if} a \in \text{Address} \textbf{then}
15: \hspace{2em} \langle m_p, B \rangle \leftarrow \text{setBP}(m_p, a, B, \text{true}) \\text{\textcopyright{Setting a watchpoint}}
16: \hspace{1.5em} \textbf{else}
17: \hspace{2em} \langle m_p, B \rangle \leftarrow \text{setBP}(m_p, \text{Sym(name)}, B, \text{true})
18: \hspace{1em} \textbf{case} watch mode a, a \in \text{Address} \textbf{do}
19: \hspace{1.5em} W \leftarrow W \cdot (a, r \in \text{mode}, w \in \text{mode}, \text{true}) \\text{\textcopyright{Setting a checkpoint}}
20: \hspace{1em} \textbf{case} checkpoint \textbf{do}
21: \hspace{1.5em} \langle n, C_N \rangle \leftarrow (\min N, \bot) \\text{\textcopyright{Setting a checkpoint}}
22: \hspace{1.5em} \forall k \in \mathbb{N}, C_k \leftarrow \begin{cases} C_k & k \neq n \\text{(removeAllBPs(m_p, B), M, pc)} & k = n \end{cases}
23: \hspace{1em} \textbf{case} step \textbf{do}
24: \hspace{1.5em} c_{i-RV} \leftarrow \text{INTERACTIVEStep}(c_{i-RV}) \\text{\textcopyright{Executing a step}}
25: \hspace{1em} \textbf{case} exit \textbf{do}
26: \hspace{1.5em} cont \leftarrow \text{false} \\text{\textcopyright{Stopping the i-RV-program}}
27: \hspace{1em} \textbf{case} other \textbf{do}
28: \hspace{1em} print "Illegal Command"
29: \hspace{1em} \textbf{return} (cont, c_{i-RV})
30: \end{algorithm}

Handling a watchpoint. In Alg. 4, we define HANDLEWP. If the watchpoint was set by the user, the state of the i-RV-program is returned as is, except for the state of the debugger, which becomes interactive. If the watchpoint belongs to the monitor, the corresponding events are applied using the function \textsc{APPLYEVENTS} defined in Alg. 5, updating the monitor and executing the scenario.

The user sets a breakpoint. When the debugger is interactive (i), the user can set a breakpoint (Alg. 3, Line 14) by giving either an address in the program memory or a symbol (function) name transformed into an address using the symbol table \text{Sym}, part of the definition of the program.

The user sets a watchpoint. In interactive mode (i), the user can set a watchpoint by giving the address in the program memory where it should be set (Alg. 3, Line 19).

The user sets a checkpoint. In interactive mode, the user can set a checkpoint (Alg. 3, Line 21). Several objects are saved: the program memory (without the breakpoints instructions), the PC and
Algorithm 4 Handling Instrumentation (generating events)

1: function HANDLEBP(c1_RV)
2:   if ∃ instr : (addr, instr, true) ∈ B then  
3:     return (mp, pc), (t, B, W, C, M, ms)  
4:     return APPLYEVENTS(bpToEvts(mp, pc, M, Sym), c1_RV)  
5: function watchpointsMatching(W, (addr, r, w))  
6:   Wₛ ← ∅  
7:   for all (addr′, r′, w′, isUserWP) ∈ W do  
8:     if addr = addr′ ∧ (r = r′ ∨ w = w′) then  
9:       Wₛ ← Wₛ ∪ {(addr′, r′, w′, isUserWP)}  
10:  return Wₛ  
11: return APPLYEVENTS(wpsToEvts(Wₛ, P, M, Sym), c1_RV)  

The state of the monitor. The least identifier n that is not used for a checkpoint is used as an index for the new checkpoint. The checkpoint is stored in Cn.

The user restarts a checkpoint. In interactive mode (I), the user can restore a checkpoint (Alg. 3, Line 6). The current program memory, the current PC, the current configuration of the monitor and its current memory are restored from the checkpoint. Current breakpoints are set in the newly restored program memory (this behavior matches the behavior of GDB and LLDB).

A breakpoint instruction is encountered. When encountering a breakpoint instruction, the debugger has to check if it matches a breakpoint of the user or a breakpoint of the monitor. In the first case, the i-RV-program transitions to the I state. In the second case, the event is applied.

Remark 8. In real systems, the breakpoint instruction triggers a trap caught by the operating system which suspends the execution and informs the debugger of the trap. Traps are not described in our model because we do not model the OS. The behavior of our model is otherwise close to the reality.

Handling a breakpoint. In Alg. 4, we define HANDLEBP. If the breakpoint belongs to the user, the i-RV-program becomes interactive but is not otherwise modified. If the breakpoint belongs to the monitor, breakpoints are removed from the program memory, a corresponding before event is applied using the function APPLYEVENT defined in Alg. 5, the original instruction is run and an after event is applied using the function APPLYEVENT that updates the state of the i-RV-program. It first updates each slice of the configuration of the monitor according to the event and the transition relation, retrieving the set of transitions involved. It then applies the scenario using the function $\lambda_{sc}$ (applyScenario) defined in Alg. 6. The scenario can update the whole state of the i-RV-program. It is applied only if the current state has been updated (Line 19) of Alg. 5). For each entry of the scenario, if the event corresponds to the entry, the corresponding action is run with function runAction. For the sake of conciseness, function runAction is not defined precisely here. See Alg. 2, Line 9. Breakpoints are restored and the instrumentation needed for the new current state is added.
Algorithm 5 Handling events

1: function UPDATE_MON(M, e):
2:     \( M' \leftarrow \emptyset \)
3:     \( \text{trans} \leftarrow \emptyset \)
4:     \textbf{for all} \( (q, m, s, sp) \in M \) \textbf{do}
5:          \textbf{for all} \( (sb, q_s, e_t, g, \text{upd}, q_d) \in \Delta_m \) \textbf{do}
6:              \( \text{instance} \leftarrow [s \mapsto (\text{values}(e))(p) \mid \exists (p, s) \in sb] \)
7:              \textbf{if} \( q = q_s \land s \subseteq \text{instance} \land \exists (q', m', s', sp') \in M : s \subseteq s' \land s' \subseteq \text{instance} \) \textbf{then}
8:                  \( M' \leftarrow M'U(q_d, \text{upd}(\text{values}(e), m), \text{instance}, s) \)
9:              \textbf{else}
10:         \textbf{end if}
11:         \( \text{trans} \leftarrow \text{trans} \cup (q_s, q_d) \)
12:     \textbf{end for all}
13:     \textbf{end for all}
14:     \textbf{return} \( (M', \text{trans}) \)

15: function APPLY_EVENT(c_{i-RV}, e) \quad \triangleright \text{We apply one before or after event}
16:     \( (M', \text{trans}) \leftarrow \text{UPDATE_MON}(M, e) \)
17:     \textbf{return} \( \lambda_{sc}(S, c_{i-RV}, M', \text{trans}) \) \quad \triangleright \text{We apply the scenario}
18: function APPLY_EVENTS(evList, c_{i-RV}) \quad \triangleright \text{For a list of generated events}
19:     \( m'_p \leftarrow \text{removeAllBPs}(m_p, B) \) \quad \triangleright \text{Step 1: remove all instrumentation}
20:     \( (B', Wp') \leftarrow \text{UNINSTRUMENT}(B, W', M, \text{Sym}) \)
21:     \( (pc', q'_d, e', M', m'_s) \leftarrow (pc, q_d, e, M, m_s) \)
22:     \textbf{for all} \( e \in \text{evList} \) \text{ s.t. isBefore}(e) \textbf{do} \quad \triangleright \text{Step 2: apply before events}
23:         c'_{i-RV} \leftarrow \text{APPLY_EVENT}(c'_{i-RV}, e) \quad \triangleright \text{Step 3: run the instruction}
24:     \textbf{end for all}
25:     \( m'_p, pc' \leftarrow \text{runInstr}(m'_p, pc') \) \quad \triangleright \text{Step 4: apply after events}
26:     \textbf{for all} \( e \in \text{evList} \) \text{ s.t. not isBefore}(e) \textbf{do} \quad \triangleright \text{Step 5: restore / update instrumentation}
27:         c_{i-RV} \leftarrow \text{APPLY_EVENT}(c_{i-RV}, m'_s, e)
28:     \textbf{end for all}
29:     \( m'^{\text{imp}} \leftarrow \text{restoreBPs}(m'_p, B') \)
30:     \( (m'^{\text{imp}}, B', W') \leftarrow \text{INSTRUMENT}(m'^{\text{imp}}, B', W', M', \text{Sym}) \)
31: \textbf{return} \( c'_{i-RV} \)

Function bpToEvts generates a list of events from a breakpoint. The type, the name, the parameters and the values of each event from the list is determined by the current PC, the symbol table and the program memory and is given by the instruction set of the program. If the PC is at the first (resp. last) instruction of a function, a before (resp after) event of type FunctionCall is generated. The function bpToEvts specifies for each generated event whether the event is a before event or an after event.

The execution of the program is done step by step. In interactive mode, function interactiveStep (Alg. 7) is executed when the command step is issued. The instruction at the current address is run normally and possible watchpoints are handled (Lines 21 and Line 23). If the instruction is a breakpoint, the breakpoint is handled if it is set by the monitor or ignored otherwise, and the original instruction is executed.

The execution of the program is interrupted by the user. The debugger switches from passive (p) to interactive (i) mode (Line 5).
Algorithm 6 APPLYSCENARIO

1: function SRMATCHESEVENT(lt, q_m, q_s, q_m')
2: return (lt = leaving ∧ q_m = q_s) ∨ (lt = entering ∧ q_m' = q_s)
3: function λ_sc(s, P, D, M^i, m_s, M^f)
4: ((m_p', pc'), D', m_s') ← (P, D, m_s)
5: if s = ε then
6: return (m_p', pc'), D', m_s' ▶ End of scenario reached (or empty scenario)
7: for all (q_m', m_m', s', sp') ∈ M' do ▶ For each slice in the monitor
8: let (q_m, m_m, s) be such that ▶ We get the previous state of the slice
9: s = s' ∧ (q_m, m_m, s', sp') ∈ M or else ▶ The previous state may not exist
10: s = sp' ∧ ∃sp : (q_m, m_m, sp', sp) ∈ M or else
11: (q_m, m_m, s) = (∅, ∅, ∅) ▶ If the state of the slice changed
12: if q_m ≠ q_m' then
13: (lt, q_s, a) ← head(s) ▶ We apply the current scenario reaction
14: if SRMATCHESEVENT(lt, q_m, q_s, q_m') then
15: (P', D', m_s') ← runAction(P, D, a) ▶ If relevant to the current states
16: (P', D', m_s') ← λ_sc(tail(s), P', D', M^i, m_s, M^f) ▶ Recursive call

Remark 9. This mechanism is meaningful if a step in the algorithm is assumed to take a non-zero amount of time.

The execution of the program is resumed. This mechanism is the inverse of the previous one. If the execution is continued (e.g. by issuing the command continue, see Line 11), a step is executed (in case the execution was interrupted by a breakpoint or a watchpoint) and the i-RV-program transitions from I to P.

4 PRESERVING THE INITIAL PROGRAM EXECUTIONS

In this section, intuitively we show that instrumenting the program for interactive runtime verification does not interfere with the program. That is, we show that there is some relation between the execution of the program instrumented for interactive runtime verification and the initial execution of the program. Such a relation serves the purpose of ensuring that one observes and studies bugs that are present only in an execution of the original program. This ensures soundness when finding bugs and reporting verdicts with a monitor.

In the following, we formalize and prove this relation.

We consider the execution of a program P (Definition 3.6) and the execution of iRV(P, M, S) (Definition 3.25) composed of the same program P, the debugger, a monitor M (Definition 3.10) and the empty scenario S (Definition 3.23). We denote by run(P) the execution of P that is a sequence of its configurations. We prove a relation between the executions under the following conditions:

Condition 1. The execution of the program terminates, i.e. it eventually reaches instruction stop.

Condition 2. The set of commands of the debugger that can be used is restricted to:
(1) load monitor (run once, at the very beginning)
(2) continue n
(3) break a
(4) watch mode a, a ∈ Address
(5) checkpoint
(6) step
Algorithm 7 Handling a step

1: function HANDLESTEPWP(accesses, \((m_p^{imp}, pc^{imp}), c_{i-RV}\))
2:     \(\mathcal{W}_s \leftarrow \emptyset\) \hfill \(\triangleright\) Watchpoint during an interactive step
3:     for all access \(\in\) accesses do \hfill \(\triangleright\) We retain each known watchpoint corresponding to
4:         \(\mathcal{W}_s \leftarrow \mathcal{W}_s \cup \{\text{watchpointsMatching(}\mathcal{W}, \text{access)}\}\) \hfill \(\triangleright\) an access returned by runInstr
5:     \(\mathcal{W}_s \leftarrow \{\text{addr, r, w, isUserWP} \in \mathcal{W}_s \mid \text{isUserWP} = \text{false}\}\) \hfill \(\triangleright\) We ignore user’s watchpoints
6:     if \(\mathcal{W}_s = \emptyset\) then
7:         return \((m_p^{imp}, pc^{imp}), (P, \mathcal{B}, \mathcal{C}), M, m_s)\)
8:     return APPLYEVENTS(wpsToEvts(\(\mathcal{W}_s, m_p, pc, M, \text{Sym}\), \(c_{i-RV}\) \)) \hfill \(\triangleright\) We update the monitor and run the scenario

9: function HANDLESTEPBP(((\(m_p, pc\), D, M, m_s))) \hfill \(\triangleright\) Breakpoint during an interactive step
10:     if \(\exists\text{instr} : (pc, \text{instr}, \text{false}) \in \mathcal{R}\) then \hfill \(\triangleright\) If a breakpoint belongs to the monitor
11:         return APPLYEVENTS(bpToEvts((\(m_p', pc, M, \text{Sym}\), \(c_{i-RV}\) \)) \) \hfill \(\triangleright\) We update the monitor and run the scenario
12:     let instr : (pc, instr, \_) \(\in\) \(\mathcal{R}\) such that instr \(\neq\) B \hfill \(\triangleright\) We remove it from the memory
13:     \(c_{i-RV}' \leftarrow\) NORMALSTEP(\(c_{i-RV}\) \) \hfill \(\triangleright\) Execution step
14:     if \(\exists\text{instr} : (pc, \text{instr}, \text{true}) \in \mathcal{R}'\) then \hfill \(\triangleright\) We restore the breakpoint if still present
15:         return ((\(m_p'[pc \mapsto B], pc', D', M', m_s'\) \) \) \hfill \(\triangleright\) Otherwise, the breakpoint belongs to the user
16:     return ((\(m_p', pc', (q_d', \mathcal{B}', \mathcal{W}', \mathcal{C}'), M', m_s'\) \) \) \hfill \(\triangleright\) One step of normal execution
17: function NORMALSTEP(\(c_{i-RV}\) \) \hfill \(\triangleright\) The current instruction is run
18:     \((m_p^{imp}, pc^{imp}, \text{accesses}) \leftarrow \text{runInstr}(m_p, pc)\) \hfill \(\triangleright\) A watchpoint may be reached
19:     return HANDLEWP(accesses, \(c_{i-RV}\) \) \hfill \(\triangleright\) We make an interactive step
20: function INTERACTIVESTEP(\(c_{i-RV}\) \) \hfill \(\triangleright\) We make an interactive step
21:     if \(m_p[pc] = B\) then
22:         return HANDLESTEPBP(\(c_{i-RV}\) \) \hfill \(\triangleright\) We handle it
23:     if \(m_p[pc] \neq \text{stop}\) then \hfill \(\triangleright\) Otherwise, we execute one step normally
24:         return NORMALSTEP((\(m_p, pc\), (P, \(\mathcal{B}, \mathcal{C}\), M, m_s) \) \) \hfill \(\triangleright\) Making a step when at the end of the program is forbidden
25:         print “Illegal Command”

Combined together, Conditions 1 and 2 ensure that the execution is not altered. Specifically, the user cannot restore any checkpoint (see Def. 3.18) using the restart n and the command exit is used exactly once: when the execution of the program reaches the instruction stop (the user cannot abort the execution of the program).

The relation between the program executions is defined as a relation between a configuration of the i-RV-program and a configuration of the program.

Definition 4.1 (Relation \(\rightsquigarrow\) (corresponds to)). Let \(c_{i-RV} = ((m_p', pc'), (q_d, \mathcal{B}, \mathcal{W}, \mathcal{C}), M, m_s)\) be a configuration of i-RV(\(P, M, S\)) and \(c_P = (m_p, pc)\) a configuration of \(P\). A configuration \(c_{i-RV}\) is said to correspond to a configuration \(c_P\), denoted by \(c_{i-RV} \rightsquigarrow c_P\), if removeAllBPs(\(m_p', \mathcal{B}\)) = \(m_p\) and if \(pc' = pc\).

That is, \(c_{i-RV}\) corresponds to \(c_P\) when the memory of the program in the system \(m_p'\) is the same as the memory of the initial program \(m_p\) when instrumentation is removed from \(m_p'\) and the current address is the same in both configurations (\(pc' = pc\)).

In addition, we need a last condition on function runInstr, the transition function that updates the state of the program.
Condition 3. Function runInstr does not access to the executable portion of the memory (the instructions of the program); except for reading the cell at the current address (pc).

The evolution of system i-RV(P, M, S) is driven by functions implemented in the debugger. Some of these functions are used by the restricted set of commands of the debugger given in Conditions 1 and 2. These functions update (a part of) the state of the system. Let Upd = \{INSTRUMENT, APPLYEVENTS, NORMALSTEP, setBP, INTERACTIVESTEP\} be the set of these functions. These functions can take (a part of) a configuration of the system and possibly other parameters, and return (a part of) a new configuration. Let $c_{i,RV}$ be a configuration of the system. For any $f \in \text{Upd}$, we allow the following (abusive) notation for readability: $c'_{i,RV} = f(c_{i,RV}, \ldots)$, where $c'_{i,RV}$ is the new configuration of the system after a call to $f$ and $c_{i,RV}$ is the configuration of the system before the call.

The preservation of the executions of the initial program is stated in Theo. 4.2:

Theorem 4.2. Let $c_{i,RV}^{\text{init}}$ and $c_{P}^{\text{init}} = (m_{P}^{0}, pc^{0})$ be the initial configurations of i-RV(P, M, S) and P, respectively. Let $c_{i,RV}$ and $c_{P}$ be configurations of i-RV(P, M, S) and P. Let $f \in \text{Upd}$ be a function updating the configuration of i-RV(P, M, S). Under Conditions 1, 2, and 3, the following assertions hold:

1. $c_{i,RV} \Rightarrow c_{P}^{\text{init}}$.
2. If $c_{i,RV} \Rightarrow c_{P}$, then $f(c_{i,RV}) \Rightarrow c_{P}$ or $f(c_{i,RV}) \Rightarrow \text{runInstr}(c_{P})$.

The first assertion holds true by construction: it is a direct consequence of Def. 3.25.

To prove the second assertion, we shall use three intermediate predicates on the configurations of i-RV(P, M, S).

- Predicate INSTR\textsc{Orig} holds on a configuration $c_{i,RV}$ when, in the memory, the instructions are either breakpoints or instructions of the original program:

  $\forall a \in \text{InstrAddress}(P), m_{P}^{\text{IRV}}[a] = \text{B} \lor m_{P}^{\text{IRV}}[a] = m_{P}^{0}[a]$

  (InstrAddress(P) is the set of addresses at which program instructions are found).

- Predicate BP\textsc{Consistent} holds when, if there is a breakpoint instruction at a memory address, then the debugger is aware of this breakpoint, and the instruction associated to this breakpoint is the instruction in the original program:

  $\forall a \in \text{InstrAddress}(P), m_{P}^{\text{IRV}}[a] = \text{B} \implies \exists (a, instr) \in \mathcal{B} : \text{instr} = m_{P}^{0}[a]$.

- Predicate IRV\textsc{CorrespToPrgm} holds when one can associate a configuration of the i-RV-program to a configuration of the initial program:

  $\exists c_{P} \in \text{run}(P) : c_{i,RV} \Rightarrow c_{P}$.

These predicates are tools for proving the second point of Theo. 4.2.

The proof is organized as follow. We first prove that each relevant function in the pseudo code behaves correctly, that is, after the call to the function with a configuration that satisfies the three predicates, the returned configuration $c'_{i,RV}$ also satisfies the three predicates and $c'_{i,RV}$ satisfies point two of Theo. 4.2. We then prove that each command of the debugger in the restricted set described in Condition 2, by using these functions, behaves correctly.

4.1 By function

We first prove that functions called when the user issues a command in the debugger do not prevent the system from simulating the original program.
4.1.1 Function setBP. Function setBP sets a breakpoint.

Let \( c_{i-RV} \) be the configuration of the system before the call to function setBP such that \( c_{i-RV} \) satisfies the three predicates. Let \( c'_{i-RV} \) be the configuration of the system after the call to function setBP.

A call to setBP, defined in Section 3.3.2, replaces an instruction in the memory of the program by an instruction \( B \) at the given address \( a \in \text{InstrAddress}(P) \) and adds a breakpoint in the breakpoint list containing \( a \) and the instruction that is replaced.

Because we have \( \text{INSTRORIG}(c_{i-RV}) \), this instruction is either \( B \) or the original instruction at address \( a \) in \( P \). In the first case, \( BP\text{CONSISTENT}(c_{i-RV}) \) ensures that the original instruction is already kept in the list of breakpoints so \( BP\text{CONSISTENT}(c'_{i-RV}) \) is satisfied. In the second case, the original instruction is stored and \( BP\text{CONSISTENT}(c'_{i-RV}) \) is satisfied. \( \text{INSTRORIG}(c'_{i-RV}) \) is also verified as the memory of the program has been modified so that at each address, the value is either the same as before or is \( B \).

Because we have \( \text{IRVCORRESPToPRGM}(c_{i-RV}) \), \( \text{INSTRORIG}(c'_{i-RV}) \), \( BP\text{CONSISTENT}(c'_{i-RV}) \) are verified and values in the memory have not been modified, \( c'_{i-RV} \leadsto cp \) and \( c'_{i-RV} \) satisfies point two of Theo. 4.2.

Since \( \forall c_{i-RV}, c_{i-RV} \leadsto cp \implies \text{setBP}(c_{i-RV}) \leadsto cp \) and \( \text{setBP}(c_{i-RV}) \) satisfies the three predicates, The configuration obtained after several calls to setBP verifies point 2 of Theo. 4.2.

4.1.2 Function instrument. Let \( c_{i-RV} = ((m^i_{p-RV}, p^i_{c-RV}), (q_d, \mathcal{B}, \mathcal{W}, \mathcal{C}), M, m_s) \) be the configuration of the system before the call to function instrument such that \( c_{i-RV} \) satisfies the three predicates. Let \( cp \) be such that \( c_{i-RV} \leadsto cp \) (possible because \( \text{IRVCORRESPToPRGM}(c_{i-RV}) \)). Let \( c'_{i-RV} = ((m^i_{p-RV}, p^i_{c-RV}), (q'_d, \mathcal{B}', \mathcal{W}', \mathcal{C}'), M', m'_s) \) be the configuration of the system after the call to function instrument. Function instrument makes one or more calls to setBP on Line 23. \( c'_{i-RV} \) satisfies the three predicates and because \( c'_{i-RV} \leadsto cp, c'_{i-RV} \) satisfies point two of Theo. 4.2. See Sec. 4.1.1.

4.1.3 Function normalStep. Function normalStep executes one instruction of the program, when there is no breakpoint at the current instruction.

Let \( c_{i-RV} = ((m^i_{p-RV}, p^i_{c-RV}), (q_d, \mathcal{B}, \mathcal{W}, \mathcal{C}), M, m_s) \) be the configuration of the system before the call to function normalStep such that \( c_{i-RV} \) satisfies the three predicates. Let \( c'_{i-RV} = ((m^i_{p-RV}, p^i_{c-RV}), (q'_d, \mathcal{B}', \mathcal{W}', \mathcal{C}'), M', m'_s) \) be the configuration of the system after the call to function normalStep.

Function runInstr is run, we obtain the new state: \( c'^{\text{run}}_{i-RV} = ((m^{\text{run}}_{p-RV}, p^{\text{run}}_{c-RV}), (q_d, \mathcal{B}^{\text{run}}, \mathcal{W}, \mathcal{C}), M, m_s) \). Because of Assumption 3, \( \text{INSTRORIG}(c'^{\text{run}}_{i-RV}) \) and \( BP\text{CONSISTENT}(c'^{\text{run}}_{i-RV}) \) hold and because there exists \( k \in \mathbb{N} \) such that \( c_{i-RV} \leadsto cp, c'^{\text{run}}_{i-RV} \leadsto \text{runInstr}(cp) \).

Function handleWP (Line 19) either does not change the state of the system except for the state of the debugger which becomes interactive, so \( c'_{i-RV} = ((m'^i_{p-RV}, p'^i_{c-RV}), (1, \mathcal{B}, \mathcal{W}, \mathcal{C}), M, m_s) \), or calls applyEvents with state \( c_{i-RV} \) (See Sec. 4.1.4). In both cases, \( c'_{i-RV} \) satisfies the three predicates and \( c'_{i-RV} \) satisfies point two of Theo. 4.2 (see Sec. 4.1.4).

4.1.4 Function applyEvents. Function applyEvents removes all breakpoints from the memory (1), removes the breakpoints related to the current state of the property in the configuration of the debugger (2), applies before events that are related to the current breakpoint (3), runs the current instruction (4), applies after events that are related to the current breakpoint (5) and adds the instrumentation related to the new state of the property (6).

Let \( c_{i-RV} = ((m^i_{p-RV}, p^i_{c-RV}), (q_d, \mathcal{B}, \mathcal{W}, \mathcal{C}), M, m_s) \) be the configuration of the system before the call to function applyEvents such that \( c_{i-RV} \) satisfies the three predicates.
Let $c_p$ be such that $c_{i-RV} \rightsquigarrow c_p$ (possible because $\text{irvCorrespToPrgm}(c_{i-RV})$). Let $c'_{i-RV} = ((m^{|RV}_p, p_{c^{|RV}}), (q'_d, B', W', C'), M', m'_s)$ be the configuration of the system after the call to function \textsc{applyEvents}.

1. First, all breakpoints are removed from $m^{|RV}_p$ (Line 21). Let $m^{tmp, 1}_p$ be the result of this process and $c^{tmp, 1}_{i-RV} = ((m^{tmp, 1}_p, p_{c^{tmp, 1}}), (q_d, B, W', C), M, m_s)$. As there are no more addresses at which there is a B instruction in $m^{tmp, 1}_p$, $\text{instrOrig}(c^{tmp, 1}_{i-RV})$ and $\text{bpcConsistent}(c^{tmp, 1}_{i-RV})$ are verified. $c^{tmp, 1}_{i-RV} \rightsquigarrow c_p$.

2. The function \textsc{uninstrument}, defined in Alg. 1, is called (Line 22). This function removes some breakpoints from the list of breakpoints. Let $B^{tmp, 2}$ this new list of breakpoints and $c^{tmp, 2}_{i-RV} = ((m^{tmp, 1}_p, p_{c^{tmp, 1}}), (q_d, B^{tmp, 2}, W', C), M, m_s)$.

\text{instrOrig}(c^{tmp, 2}_{i-RV})$ and $\text{bpcConsistent}(c^{tmp, 2}_{i-RV})$ are verified and $c^{tmp, 2}_{i-RV} \rightsquigarrow c_p$.

As we assume an empty scenario, the memory and the list of breakpoints are not modified and the state remains unchanged.

3. The function \textsc{runInstr} is run (Line 26), we obtain the new state $c^{tmp, 3}_{i-RV} = ((m^{tmp, 3}_p, p_{c^{tmp, 4}}), (q_d, B^{tmp, 2}, W', C), M, m_s)$. Because of Assumption 3, $\text{instrOrig}(c^{tmp, 3}_{i-RV})$ and $\text{bpcConsistent}(c^{tmp, 3}_{i-RV})$ hold and because $c^{tmp, 2}_{i-RV} \rightsquigarrow c_p$, $c^{tmp, 3}_{i-RV} \rightsquigarrow \text{runInstr}(c_p)$.

4. While applying after events (Line 29), \textsc{applyEvent} updates the memory and the list of breakpoints only if a scenario element to be executed. As we assume an empty scenario, the memory and the list of breakpoints are not modified. By construction of $\text{restoreBPs}$, the new memory $m^{tmp, 4}_p$ contains instructions B only at addresses that have corresponding breakpoints in the list of breakpoints. $c^{tmp, 4}_{i-RV}$ satisfies the three predicates with $c^{tmp, 4}_{i-RV} = ((m^{tmp, 4}_p, p_{c^{tmp, 4}}), (q_d, B^{tmp, 2}, W', C), M, m_s)$.

5. The function \textsc{instrument}, is called on Line 30 with state $c^{tmp, 4}_{i-RV}$. The new state $c'_{i-RV}$ satisfies the three predicates (see Sec. 4.1.2) and $c'_{i-RV} \rightsquigarrow \text{runInstr}(P)$, so $c'_{i-RV}$ satisfies point two of Theo. 4.2.

4.1.5 Function \textsc{handleStepBp}. Function \textsc{handleStepBp} handles the case when a step needs to be executed, but there is a breakpoint at the current instruction.

Let $c_{i-RV} = ((m^{|RV}_p, p_{c^{|RV}}), (q_d, B, W', C), M, m_s)$ be the configuration of the system before the call to function \textsc{handleStepBp} such that $c_{i-RV}$ satisfies the three predicates. Let $c_p$ be such that $c_{i-RV} \rightsquigarrow c_p$ (possible because $\text{irvCorrespToPrgm}(c_{i-RV})$). Let $c'_{i-RV} = ((m^{tmp, 1}_p, p_{c^{tmp, 1}}), (q'_d, B', W', C'), M', m'_s)$ be the configuration of the system after the call to function \textsc{handleStepBp}.

Function \textsc{handleStepBp} has two cases:

1. A breakpoint is set by the monitor at the current address (Line 10).

Function \textsc{applyEvents}, defined in Alg. 5, is called. See Sec. 4.1.4.

2. A breakpoint is not set by the monitor, but by the user, at the current address (Line 11).

The breakpoint is replaced by the original instruction in the memory: $m^{tmp, 1}_p = m^{|RV}_p[p_{c^{|RV}}] \leftrightarrow m^{tmp, 1}_p[p_{c^{|RV}}]$. Let $c^{tmp, 1}_{i-RV} = ((m^{tmp, 1}_p, p_{c^{tmp, 1}}), (q_d, B, W', C), M, m_s)$ be the state of the system at this point. $\text{instrOrig}(tmp, 1)$ and $\text{bpcConsistent}(tmp, 1)$ are verified because the set of addresses at which an instruction B is present in this new memory $m^{tmp, 1}_p$ is the set of addresses at which an instruction B is present in $m^{tmp, 1}_p$, without $p_{c^{|RV}}$. Because values in $m^{tmp, 1}_p$ are the same as in $m^{tmp, 1}_p$, $c^{tmp, 1}_{i-RV} \rightsquigarrow c_p$.
We now prove that each command the user can issue does not prevent the system from simulating the memory of the program and the list of breakpoints, or calls the function \texttt{setBP} if a breakpoint is encountered. Function \texttt{HANDLEBP} either does not modify the memory of the program and the list of breakpoints, or calls the function \texttt{APPLYEVENTS}. See Sec. 4.1.4.

4.2 Commands of the Debugger

We now prove that each command the user can issue does not prevent the system from simulating the program. The behavior of the system for each command is described in Alg. 2.

4.2.1 The user issues the command \texttt{load} monitor.. When this command is issued in Alg. 3 on Line 4, the memory of the program and the list of breakpoints are modified by the function \texttt{INSTRUMENT} defined in Alg. 1. See Sec. 4.1.2.

4.2.2 The user issues the command \texttt{continue}.. When the user issues the command \texttt{continue} in Alg. 3 on Line 11, the function \texttt{INTERACTIVESTEP} is called. See Sec. 4.1.6. The mode of the debugger becomes \texttt{p}, making the system run function \texttt{NORMALSTEP} a number of times (see Sec. 4.1.3), and run function \texttt{HANDLEBP} if a breakpoint is encountered. Function \texttt{HANDLEBP} either does not modify the memory of the program and the list of breakpoints, or calls the function \texttt{APPLYEVENTS}. See Sec. 4.1.4.

4.2.3 \texttt{break}. When the user issues the command \texttt{break} in Alg. 3 on Line 14, the function \texttt{setBP}. See Sec. 4.1.1.

4.2.4 \texttt{step}. When the user issues the command \texttt{continue} in Alg. 3 on Line 11, the function \texttt{INTERACTIVESTEP} is called. See Sec. 4.1.1.

4.2.5 \texttt{watch}, \texttt{checkpoint} or the user interrupts the execution. These commands (in Alg. 3, Lines 19, 21 and 5) do not affect the list of breakpoints nor the memory of the program, so simulation is unaffected.

4.2.6 Normal execution. During a normal execution (Alg. 2, Line 7), the function \texttt{NORMALSTEP} is called. See Sec. 4.1.3.

4.2.7 A breakpoint is reached. When a breakpoint is reached (Alg. 2, Line 9), function \texttt{HANDLEBP} is called. This function either does not modify the memory of the program and the list of breakpoints, or calls the function \texttt{APPLYEVENTS}. See Sec. 4.1.4.
Interactive Runtime Verification

GDB Process

Verde (inside Python)

Monitor 1

...

Monitor n

set breakpoints

event

Monitored Process

Breakpoint reached

Breakpoint reached

Program execution

Fig. 6. Instrumentation in Verde

Fig. 7. During the execution of the property given in Figure 10, the following graphs can be seen respectively before initialization of the property initialization, on initialization, while the property is verified and when the property becomes falsified. Light red, red, brown and gray respectively correspond to non accepting state, a current non accepting state, a transition taken during the last state change and a state which was current before the last state change. Graphs are automatically drawn using Graphviz and colors animated during the execution.

5 IMPLEMENTATION: VERDE

To validate and evaluate i-RV in terms of usefulness and performance, we implemented it in a tool called Verde. We overview Verde and give some details about its architecture in Sec. 5.1. In Sec. 5.3, we describe the syntax used in Verde to write properties. We explain how to use Verde in Sec. 5.5.
5.1 Overview
Verde is written in Python and works seamlessly as a GDB plugin by extending GDB Python interface. Verde can be used with any program written in a programming language supported by GDB. Verde supports the verification of several properties by means of monitors working independently. Each monitor sets and deletes breakpoints according to the events that are relevant to its current state. Verde provides a graphical and animated view of the properties being checked at runtime. The view facilitates understanding the current evaluation of the property and, as a consequence, the program. Verde also lets the developer control the monitors and access their internal state (property instances, current states, environments). Verde is called by GDB when GDB handles breakpoints in the monitored program. When a breakpoint is reached, the state of the property is updated and the execution is resumed. Figure 6 depicts the execution of a program with Verde.

5.2 Architecture of Verde
The organization of the code is depicted in Figure 8. The central part of Verde is the Monitor class. A Monitor object is instantiated for each property checked at runtime. When the developer’s properties and scenarios are read from files, the result is stored in instances of classes Property and Scenario. These instances are used to build monitors.

Verde and its monitors are controlled with the GDB command line interface using commands defined in the module GDB Commands. This module defines the interface between the GDB user and Verde. Theses commands expose a part of the interface defined in the module Monitor Interface. This interface is meant to remain a stable interface to access monitors. It does not give access to the internal structures that are exposed by the Monitor class and that are not relevant for the end user. This interface is given in Appendix B. Module Breakpoint defines the interface between the monitors and GDB. It defines debugger-independent methods to handle breakpoints. Module Graph Displayer defines the graphical view of running monitors. If the view is enabled, Verde shows the property as a graph using Graphviz. As the current state of the monitor changes, the graphical view is updated: the current state is shown in green if it is accepting, in red if it is not accepting. Taken transitions are represented in brown. Module Property handles the property model used in Verde and trace slicing.
Interactive Runtime Verification

\[
\text{slice on } [\text{param}, +]?
\]

\[
\text{initialization } \{
\begin{align*}
\text{Python code}
\end{align*}
\}\]

\[
\text{state state\_name} [\text{non-accepting}]? [\text{action\_name()}]? [\text{transition } \{
\begin{align*}
\text{before | after}\? \text{event event\_name([param, \*])}\? \{
\text{Python code returning True False or None}
\}\? \text{success } \{
\begin{align*}
\text{Python code}
\end{align*}
\}\? \text{state\_name}\}
\text{failure } \{
\begin{align*}
\text{Python code}
\end{align*}
\}\? \text{state\_name}\}
\}
\}
\]
\]

Fig. 9. Informal grammar for the automaton-based property description language in Verde

### 5.3 Syntax of Properties

Verde provides a custom syntax for writing properties in the model presented in Sec. 3.2.2 with slight modifications to allow more conciseness. An informal grammar is given in Fig. 9. Fig. 10 gives a property used to check whether an overflow happens in a multi-threaded producer-consumer program.

First, the optional keyword \text{slice on} gives the list of slicing parameters. Then, an optional Python code block initializes the environment of the monitor. Then, states are listed, including the mandatory state \text{init}. A state has a name, an optional annotation indicating whether it is accepting, an optional action name attached to the state and its transitions. Transitions can be written with two destination states: a success (resp. failure) state used when the guard returns success (resp. failure). The guard can also return \text{not relevant} meaning that the transition will not be taken. Each transition comprises the monitored event, the parameters of the event used in the guard, the guard (optional), the success block and the failure block (optional). Success and failure blocks comprise an optional Python code block, an optional action name and the name of a destination state. The guard is Python block code without any side effect that returns \text{True} (resp. \text{False}) if the guard succeeds (resp. fails) and \text{None} if the transition should not be taken.

### 5.4 Checkpointing

Verde features two process checkpointing techniques on Linux-based systems. The first uses the native \text{checkpoint} command of GDB. This method is based on \text{fork()} to save the program state in a new process, which is efficient, as \text{fork} is implemented using Copy on Write. A major drawback of this technique is that multithreaded programming is not supported since \text{fork()} keeps only

\footnote{Verde can be downloaded at https://gitlab.inria.fr/monitoring/verde.}

\footnote{We did not use pre-existing syntax in order to allow us flexibility as we experiment. Interfacing with existing monitoring tool is planned.}
one thread in the new process. The second technique uses CRIU\textsuperscript{4}, which supports multithreaded processes and trees of processes. CRIU uses the ptrace API to attach the (tree of) process to be checkpointed and saves its state in a set of files. CRIU supports incremental checkpointing by computing a differential between an existing checkpoint and a checkpoint to create. It can make the system track memory changes in the process to speed this computation.

\textsuperscript{4}Checkpoint/Restore In Userspace

\textit{Fig. 10. Verde version of the property in Figure 2}
5.5 Using Verde

A typical usage session begins by launching gdb and Verde (which can be automatically loaded by configuring GDB appropriately). Then, the user loads one or several properties. Additional python functions, used in properties, can be loaded at the same time. A scenario can also be loaded. Then, the user starts the execution. It is also possible to display the graph of the property with the show-graph subcommand (see Fig. 7).

$ gdb ./my-application
(gdb) verde load -property correct-behavior.prop \ functions.py
(gdb) verde load -scenario default -scenario.sc
(gdb) verde show -graph
(gdb) verde run -with -program
...
[verde] Initialization: N = 0
[verde] Current state: init (N = 0)
queue.c: push!
[verde] Current state: init
...
queue.c: push!
[verde] GUARD: nb push: 63
[verde] Overflow detected!
[verde] Current state: sink (N = 63)
[Execution stopped.]
(gdb)

Verde provides more fine-tuned commands to handle cases when properties and functions need to be loaded separately, or when properties and the program need to be run at different times. A list of commands is given in Appendix A.

6 EVALUATION

We report on six experiments carried out with Verde to measure its usefulness in finding and correcting bugs and its efficiency from a performance point of view. We discuss the objective and possible limitations (threat to validity) of each experiment. These experiments also illustrate how a developer uses Verde in practice.

6.1 Correcting a Bug in zsh

In zsh, a widely-used UNIX shell, a segmentation fault happened when trying to auto-complete some inputs like !> . by hitting the tab key right after character >. We ran zsh in GDB, triggered the bug and asked for a backtrace that leads to a long and complicated function, get_comp_string, calling another function with a null parameter itype_end, and then making zsh crash. Instead of trying to read and understand the code or doing step by step debugging from the beginning of this function, we wrote a property to monitor the writes to the variable passed to function itype_end and a scenario that prints the backtrace each time the state of the property changes. This lets us see that the last write to this variable nulls it. We were able to prevent the crash by adding a null check before a piece of code that seems to assume that the variable is not null and that contains

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5A video and the source codes needed for reproducing the benchmarks are available at http://gitlab.inria.fr/monitoring/verde.
the call to `type_end` that lead to the crash. While Verde was not used to discover the bug, it helped us determining its source in the code of `zsh` and fixing it. A fix has since been released.

### 6.2 Multi-Threaded Producer-Consumers

This experiment is purposed to check whether our approach is realistic in terms of usability. We considered the following use-case: a developer works on a multi-threaded application in which a queue is filled by 5 threads and emptied by 20 threads and a segmentation fault happens in several cases. We wrote a program deliberately introducing a synchronization error, as well as a property (see Fig. 2) on the number of additions in a queue in order to detect an overflow. The size of the queue is a parameter of the event `queue_new`. The function `push` adds an element into the queue. A call to this function is awaited by the transition defined at line 15 of Fig. 10. We ran the program with Verde. The execution stopped in the state `sink` (defined at line 39 of Fig. 10). In the debugger, we had access to the precise line in the source code from which the function is called, as well as the complete call stack. Under certain conditions (that we artificially triggered), a mutex was not locked, resulting in a queue overflow. After fixing this, the program behaved properly. In this experiment, we intentionally introduced a bug (and thus already knew its location). However this experiments validates the usefulness of Verde in helping the programmer locate the bug: the moment the verdict given by the monitor becomes false can correspond to the exact place the error is located in the code of the misbehaving program.

### 6.3 Micro-benchmark

In this experiment, we evaluated the overhead of the instrumentation in function of the temporal gap between events. We wrote a C program calling a NOP function in a loop. To measure the minimal gap between two monitored events for which the overhead is acceptable, we simulated this gap by a loop of a configurable duration. The results of this benchmark using a Core i7-3770 @ 3.40 GHz (with a quantum time (process time slice) around 20 ms), under Ubuntu 14.04 and Linux 3.13.0, are presented in Fig. 11. The curve `verde-arg` corresponds to the evaluation of a property which retrieves an argument from calls to the monitored function. With 0.5 ms between

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6 The code of the property is in Appendix C. We worked on commit 85ba685 of `zsh`.  
7 The bug was reported at https://sourceforge.net/p/zsh/bugs/87/

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two events, we measured a slowdown factor of 2. Under 0.5 ms, the overhead can be significant. From 3 ms, the slowdown is under 20% and from 10 ms, the slowdown is under 5%. We noticed that the overhead is dominated by breakpoint hits. The absolute overhead by monitored event, in the manner of the overhead of an argument retrieval, is constant. We measured the mean cost of encountering a breakpoint during the execution. We obtained 95 μs on the same machine and around 300 μs on a slower machine (i3-4030U CPU @ 1.90 GHz). While this experiment does not give a realistic measure of the overhead added by the instrumentation, it is still useful to estimate the overhead in more realistic scenarios.

6.4 User-Perceived Performance Impact

Multimedia Players and Video Games. We evaluated our approach on widespread multimedia applications: the VLC and MPlayer video players and the SuperTux 2D platform video game. A property made the monitor set a breakpoint on the function that draws each frame to the screen for these applications, respectively ThreadDisplayPicture, update_video and DrawingContext::do_drawing. For SuperTux, the function was called around 60 times per second. For the video players, it was called 24 times per second. In each case, the number of frames per second was not affected and the CPU usage remains moderated: we got an overhead of less than 10% for the GDB process. These results correspond to our measurements in Sec. 6.3: there is a gap of 16 ms between two function calls which is executed 60 times per second. Thus, our approach does not lead to a significant overhead for multimedia applications when the events occur at fixed frequency.

Opening and Closing Files, Iterators. We evaluated the user-perceived overhead with widespread applications. We ensured that all open files are closed with the Dolphin file manager, the NetSurf Web browser, the Kate text editor and the Gimp image editor. Despite some slowdowns, caused by frequent disk accesses, they remained usable. Likewise, we checked that no iterator over hash tables of the GLib library (GHashTableIter) that is invalidated was used. Simplest applications like the Gnome calculator remained usable but strong slowdowns were observed during the evaluation of this property, even for mere mouse movements. In Sec. 8, we present possible ways to mitigate these limitations.

6.5 Dynamic Instrumentation on a Stack

We measured the effects of the dynamic instrumentation on the performance. A program adds and removes, alternatively, the first 100 natural integers in a stack. We checked that the integer 42 is taken out of the stack after being added. A first version of this property leverage the dynamic instrumentation. With this version, the call to the remove function was watched only when the monitor knew that 42 is in the stack. A second version of the property made the monitor watch every event unconditionally. The execution was 2.2 times faster than with the first version. While this experiment used artificial properties, it shows that dynamic instrumentation has a positive impact on the overhead in that it improves performance.

6.6 Performance Impact of Checkpointing

In this experiment, we measured the cost of checkpointing a process running in GDB with CRIU. We wrote a C program that allocates an amount of memory given in parameter. We set a checkpoint and restarted it ten times for different sizes, once using the memory as storage for checkpoints, once using a regular hard drive (see Table 1). We noticed that checkpointing leads to acceptable costs for debugging purposes, ranging from 0.02 seconds for a 1 MB process to 0.3 seconds for a 1 GB process when storing checkpoints in RAM. We also noticed that the impact of checkpointing and restoring when using a hard drive as storage for saved checkpoints, as compared to a storage
Table 1. Average time to checkpoint and restore in function of the size of the process, when checkpoints are saved on a Hard Disk Drive or in RAM.

| Process size (MB) | RAM         | HDD         |
|------------------|-------------|-------------|
|                  | Checkpoint Avg (s) | ± | Restore Avg (s) | ± | Checkpoint Avg (s) | ± | Restore Avg (s) | ± |
| 1                | 0.0205      | 0.0026      | 0.0469      | 0.0134 | 0.0215      | 0.0048      | 0.0441      | 0.0129  |
| 5                | 0.0243      | 0.0048      | 0.0490      | 0.0216 | 0.0238      | 0.0033      | 0.0447      | 0.0220  |
| 10               | 0.0237      | 0.1005      | 0.0438      | 0.0106 | 0.0250      | 0.0021      | 0.0527      | 0.0260  |
| 25               | 0.0274      | 0.0008      | 0.0524      | 0.0230 | 0.0337      | 0.0167      | 0.0505      | 0.0141  |
| 50               | 0.0348      | 0.0046      | 0.0556      | 0.0107 | 0.0435      | 0.0031      | 0.0593      | 0.0151  |
| 75               | 0.0433      | 0.0057      | 0.0678      | 0.0267 | 0.0545      | 0.0054      | 0.0626      | 0.0117  |
| 100              | 0.0494      | 0.0067      | 0.0766      | 0.0173 | 0.0674      | 0.0101      | 0.0685      | 0.0123  |
| 250              | 0.0918      | 0.0063      | 0.1086      | 0.0216 | 0.1370      | 0.0236      | 0.1101      | 0.0229  |
| 500              | 0.1732      | 0.0688      | 0.1796      | 0.0191 | 0.2508      | 0.0475      | 0.1716      | 0.0107  |
| 750              | 0.2347      | 0.0197      | 0.2454      | 0.0220 | 0.3645      | 0.0749      | 0.2360      | 0.0206  |
| 1000             | 0.3018      | 0.0132      | 0.3098      | 0.0805 | 0.4839      | 0.1323      | 0.3018      | 0.0431  |

in RAM, is higher but remains in the same order of magnitude\(^8\). The incremental checkpointing feature of CRIU improves performance when checkpointing a process several times.

6.7 Automatic Checkpointing to Debug a Sudoku Solver

We evaluated i-RV by mutating the code of a backtracking Sudoku solver\(^9\). This experiment illustrates the use of scenarios to automatically set checkpoints and add instrumentation at relevant points of the execution. Sudoku is a game where the player fills a 9x9 board such that each row, each column and each 3x3 box contains every number between 1 and 9. The solver reads a board with some already filled cells and prints the resulting board. During the execution, several instances of the board are created and unsolvable instances are discarded. We wrote a property describing its expected global behavior after skimming the structure of the code, ignoring its internal details. No values should be written on a board deemed unsolvable or that break the rules of Sudoku (putting two same numbers in a row, a column or a box). Loading a valid board should succeed. We then wrote a scenario that creates checkpoints whenever the property enters an accepting state. Entering a non-accepting state makes the scenario restore the last checkpoint and add watchpoints on each cells of the concerned board instance. When watchpoints are reached, checkpoints are set, allowing us to get a more fine-grained view of the execution close to the misbehavior and choose the moment of the execution we want to debug. This scenario allows a first execution that is not slowed down by heavy instrumentation, and precise instrumentation for a relevant part of it. The solver is bundled with several example boards that it solves correctly. We mutated its code using \texttt{mutate.py}\(^10\) to artificially introduce a bug without us knowing where the change is. When ran, the mutated program outputs "bad board". We ran it with i-RV. The property enters the state failure_load. When restoring a checkpoint and running the code step by step in the function that loads a board, the execution seems correct. The code first runs one loop reading the board using scanf by chunks of 9 cells, and then a second loop iterates over the 81 cells to convert them to the representation used by the solver. Setting breakpoints and displaying values during the first loop exhibits a seemingly correct behavior. During the second loop, the last line of the board holds incorrect values. Since we observed correct behavior for the first loop and the 72 first iterations of the second loop, and since both loops do not access the board in the same way, we suspected

\(^8\)This is probably due to caching mechanisms provided by the operating system.

\(^9\)https://github.com/jakub-m/sudoku-solver

\(^10\)https://github.com/arun-babu/mutate.py
a problem with the array containing the board. We checked the code and saw that the mutation happened in the type definition of the board, giving it 10 cells by line instead of 9. A caveat of this experiment is that we had to choose the mutated version of the code such that the code violates the property. We also introduced a bug artificially rather than working on a bug produced by a human. However, the example can be generalized and illustrates how scenarios can be used for other programs, where checkpoints are set on a regular basis and execution is restarted from the last one and heavy instrumentation like watchpoints is used, restricting slowness to a small part of the execution.

7 RELATED WORK

i-RV is related to several families of techniques for finding and fixing bugs. Interactive and reverse debugging. Tools used in interactive debugging are mainly debuggers such as GDB, LLDB and the Visual Studio debugger. GDB is a cross-platform free debugger from the Free Software Foundation. LLDB is the cross-platform free debugger of the LLVM project, started by the University of Illinois, now backed by various firms like Apple and Google. The Visual Studio debugger is Microsoft’s debugger. Reverse debugging [16, 19, 34] is a complementary debugging technique. A first execution of the program showing the bug is recorded. Then, the execution can be replayed and reversed in a deterministic way, guaranteeing that the bug is observed and the same behavior is reproduced in each replay. UndoDB and rr are GDB-based tools allowing record and replay and reverse debugging with a small overhead. i-RV also allows to restore the execution in a previous state using checkpoints, with the help of the monitor and the scenario, adding a level of automation.

Manual testing. Beta testing is a widespread way of testing. Most obvious bugs can easily be spotted this way during the development of the software. Modifications to the code are manually tested, possibly by a team responsible for testing the software [23]. Bugs are also spotted by final users of the software, which, depending on the development model, the kind of software and the severity of the bug, is more or less undesirable.

Automatic testing. Unit tests ensure that already-fixed bugs do not show again, to limit regressions and to check the correctness of the code for a restricted set of inputs [22]. Unit testing is a way to apply automatic testing. Many unit testing frameworks exist. JUnit and CppUnit are two examples of such frameworks. Some research efforts have been carried out on the automatic generation of unit tests. For instance, [9] defines a way to generate test oracles from formal specifications of the expected behavior of a Java method or class.

Debugging. A debugger has been written to type check program written in C [29] by tagging memory cells with types and break when an inconsistency is detected (e.g., when a double is stored in a cell pointed by an int* pointer).

7.1 Heavyweight Verification

Static Analysis and Abstract Interpretation. With heavyweight verification techniques [13], the source code of the software is analyzed without being run. The goal is to find errors and chunks of code that can cause maintenance difficulties that raise the risk of introducing bugs during subsequent modifications. Properties can also be proven over the behavior of the software. Unfortunately, these approaches can be slow, limited to certain classes of bugs or safety properties and can produce false positives and false negatives. SLAM is based on static analysis and aims at checking good API usage. SLAM is restricted to system code, mainly Windows [1, 2] drivers.
Model-Checking. Model checking is an automatic verification technique for finite-state reactive systems. Model checking consists in checking that a model of the system verifies temporal properties [10].

While static analysis and abstract interpretation and model checking can provide certain guarantees by proving properties over the program or a model of the program, proving correction of a software statically is undecidable in general [27].

7.2 Monitoring
Monitoring consists in property checking at runtime. Checks are performed on event produced during the execution. Production of events requires instrumentation. Different instrumentation techniques exist. In this section, we give some of the most important ones.

Compile-Time Instrumentation. RiTHM [32] is an implementation of a time-triggered monitor, i.e. a monitor ensuring predictable and evenly distributed monitoring overhead by handling monitoring at predictable moments. Instrumentation is added to the code of the program to monitor. In our approach, the code of the program is not modified and not recompilation is required.

Dynamic Binary Instrumentation. DBI makes it possible to detect cache-related performance and memory usage related problems. The monitored program is instrumented by dynamically adding instructions to its binary code at runtime and run in an virtual machine-like environment. Valgrind [33] is a tool that leverages DBI and can interface with GDB. It provides a way to detect memory-related defects. Dr. Memory [4] is another similar tool based on DynamoRIO [5]. DynamoRIO and Intel Pin [30] are both DBI frameworks that allow to write dynamic instrumentation-based analysis tools. DBI provides a more comprehensive detection of memory-related defects than using the instrumentation tools provided by the debugger. However, it is also less efficient and implies greater overheads when looking for particular defects like memory leaks caused by the lack of a call to the function free.

Instrumentation Based on the VM of the Language. For some languages like Java, the Virtual Machine provides introspection and features like aspects [25, 26] used to capture events. The Jassda framework [3], which uses CSP-like specifications, LARVA [11, 12] and JavaMOP [7] are monitoring tools for virtual machine based programming languages (mainly Java). This is different from our model which rather depends on the features of the debugger. JavaMOP [24] is a tool that allows monitoring Java programs. However, it is not designed for inspecting their internal state. JavaMOP also implements trace slicing as described in [8]. In our work, events are dispatched in slices in a similar way, We do not implement all the concepts defined by [8] but this is sufficient for our purpose. In monitoring, the execution of the program can also be affected by modifying the sequence of input or output events to make it comply with some properties [17]. This is different from our approach which applies earlier in the development cycle. In our approach, we modify the execution from the inside and aim at fixing the program rather than its observable behavior.

Debugger-Based Instrumentation. Morphine, Opium and Coca [15] are three automated trace analyzers. The analyzed program is run in another process than the monitor, like in our approach. The monitor is connected to a tracer. Like in our approach, this work relies on the debugger to generate events. Focus is set on trace analysis: interactivity is not targeted and the execution remains unaffected.

Frama-C [14]. Frama-C is a modular platform aiming at analyzing source code written in C and provides plugins for static analysis, abstract interpretation, deductive verification, testing and monitoring programs. It is a comprehensive platform for verification. It does not support interactive debugging nor programs written in other programming languages.
Conclusions. Current approaches to finding and studying bugs have their own drawbacks and benefits and are suitable for discovering different sorts of bugs in different situations. Their relevance is also related to a phase of the program life cycle. None of them gather bug discovery and understanding.

8 CONCLUSION AND FUTURE WORK

8.1 Conclusion

This report presents an approach combining monitoring and debugging as two complementary approaches to program correctness.

In monitoring, the program receives and outputs events. Properties on these events are verified or enforced. Detecting a bug is possible: if a property on the correctness of the program breaks at runtime, a bug is present in the program. However, a limitation of monitoring is that it does not provide a way to understand bugs.

In debugging, the program has an internal state that can be studied and modified. Interactive debugging is a way to understand a bug and find its cause. However, debugging has no support for bug discovery: a programmer uses a debugger at a time when the bug is already known.

Our approach aims at taking the best of both techniques by seeing the program as a system that can be monitored to find bugs and, at the same time, as a system that can be debugged interactively to understand the bugs that were found. When a bug is found using monitoring, the debugger can be used in a traditional way to understand it.

In this report, we described this approach in details, we provided a theoretical framework that eases the reasoning about the notion of joint execution of the monitor, the debugger and the program. We also presented Verde, an implementation of this approach and its evaluation. Our experiments showed that even though the property checker can slow down the execution of the program considerably when events are temporally close to each other, performance are acceptable beyond a reasonable threshold (Sec. 6.3). We demonstrated that this approach is applicable in realistic use-cases with software such as video games and video players 6.4. Our current implementation shows limitations in terms of performance under other use-cases. In the next section, we present ideas to mitigate this issue.

8.2 Future Work

In this section, we present some perspectives opened by this work: diversifying the supported event types, exploring other ways of instrumenting the execution, possibilities opened by checkpoints and further validating our approach.

Event Types. Our main event types are the function call and variable accesses. A way to make our approach more powerful is to find and include other kinds of events in our model. System calls are an example of event type we have not taken in account yet for technical reasons. They might be of interest for checking properties on drivers or programs dealing with hardware.

Instrumentation. Handling breakpoints is costly [6] and handling watchpoints even more. Code injection could provide better efficiency [31, 32] by limiting round trips between the debugger and the program would to the bare minimum (for example, when the scenario requires the execution to be suspended to let the user interact with the debugger) while keeping the current flexibility of the approach.

Checkpointing the File System. We plan to explore the possibility of capturing the environment of the developer in addition to the process being debugged when checkpointing. More specifically, we shall look at the atomic snapshotting capabilities of modern file systems like Brfs and ZFS.
We aim to augment i-RV with reverse debugging and RR techniques. Record and Replay and Reverse Execution. RR is a powerful technique for finding bugs. Once a buggy execution is recorded, the bug can be studied and observed again by running the recording. We aim to augment i-RV with reverse debugging and RR techniques.

Validation of the Approach. Our approach has been evaluated on small, simple examples. Next step is to validate it in more concrete situations, find more cases of real bugs in widespread applications and show that it indeed eases both discovery and understanding of the bug with a solid user study.

Another idea that is yet to be explored is verifying good practice rules and good API usage at runtime. We think that API designers and library writers could leverage our approach by providing properties with their APIs and their libraries. This would provide a means to check that their APIs are used correctly and make their usage safer. This would also be a means to document these APIs and these libraries.

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A  VERDE COMMAND LIST

verde activate  Activates all the commands monitor related commands
verde checkpoint  Sets a checkpoint for the program and each managed monitor
verde checkpoint-restart  Restores a checkpoint
verde cmd-group-begin  Begins a group of commands
verde cmd-group-end  Ends a group of command
verde delete  Deletes a monitor
verde exec  Executes an action in the current monitor. Can be used to call methods of the interface of the current monitor defined in Appendix B
verde get-current  Prints the name of the current monitor
verde load-functions  Loads a user defined functions file
verde load-property  Loads a property file and possibly a function file in the given monitor
verde load-scenario  Loads a property file and possibly a function file in the given monitor
verde new  Creates a monitor that will also become the current monitor
verde run  Runs the monitor
verde run-with-program  Running the monitor and the program at the same time
verde set-current  Sets the current monitor
verde show-graph  Shows the graph of the monitor in a window and animates it at runtime

B  INTERFACE OF THE VERDE MONITORS

The following is the documentation of the MonitorInterface class. Its methods can be used programmatically, some of them can be used from the shell of GDB using the verde exec command. For instance, verde exec get_current_states prints the current states of the current monitor.
debugger_shell(self)
    Raises an exception making the monitor drop to the shell of the debugger.

get_current_states(self)
    Returns the set of the current states of the property.

get_env(self, s=None)
    Returns the environment dictionary of the property.

get_env_keys(self, s, as_iterator=True)
    Returns the keys of the environment of the property, as an iterator or a list, whether as_iterator is True or False, respectively.

get_env_value(self, s, key)
    Returns the value of the given variable in the environment of the property environment. Raises if the key is not present in the environment.

get_slice_bindings(self)

get_slices(self)

get_states(self)
    Returns the set of the states of the property.

print_monitor_state(self)
    Prints current state of the monitor.

register_event(self, event_type, callback)
    Register a callback for this event type.

    Possible events:
    - state_changed(new_states)
        new_states is the set of the new current states
    - transition_taken(transition, point)
        transition is the object representing the transition
        point is either "success" or "failure"
    - event_applied

    The event type is given by its name and the parameters passed to the callback is what is given in parenthesis.

set_current_state(self, state)
    Sets the current state of (the root slice of) the property.

set_env_dict(self, s, new_env)
    Sets the environment of the property.
set_env_value(self, s, key, value)
    Sets the value of the given variable in the environment of the property.

setGlobals(self, g)
    Sets the dictionary in which functions will be found, if needed, when e.g. calling (un)register_event.

set_quiet(self, b='True')
    Sets the monitor quiet or not.

set_transition_debug_function(self, fun_name=None)
    Specifies a user’s function to call whenever a monitored action not taken in account in the current states of the property is called. no argument means the default: no user function is called when it happens.

step_by_step(self, b='True')
    Set step by step monitor

stop_execution(self)
    Raises an exception making the execution of the monitor stop the execution of the program and the monitor.

unregister_event(self, event_type, callback)
    Unregister a callback for this event type.
    See also register_event.

Some commands are not accessible from verde exec: get_env_dict, set_globals, get_env_keys, stop_execution, set_current_states, debugger_shell, set_env_dict.

C PROPERTY ON VALUE CHANGES OF S IN GET_COMP_STRING IN ZSH
In this appendix, we present a property written in Verde property format that is used to find the cause of a segfault in zsh; see Figures 12 and 13. In this property, we are in an accepting state while the state of zsh seems consistent. That is, no null pointer is going to be used. In state init, we track a call to the function get_comp_string. When the call happens, the state becomes in_get_cmp_str_init. In this state, several things can happen. Destination states in the state in_get_cmp_str_init correspond to the different continuations we imagined as possible after this state by taking a quick look at the code. We did not aim at exactly understanding the meaning of these different possibilities. Rather, we aimed at seeking where the pointer was nulled in the code.

Note that for the sake of readability, we omit importing gdb with the command import gdb in the failure handlers.
state init accepting {
    transition {
        before event get_comp_string()
        success in_get_cmp_str_init
    }
}

state in_get_cmp_str_init accepting {
    transition {
        after event write s(s) { return s != None and s != 0 }
        success { print("s = " + str(s)) } in_get_cmp_str_init_s_not_null
        failure { gdb.execute("backtrace") } in_get_cmp_str_init_s_null
    }
    transition {
        before event itype_end(ptr) { return ptr == None or ptr == 0 }
        success calling_itype_end_with_null_ptr
    }
    transition {
        before event get_comp_string()
        success in_get_cmp_str_init
    }
}

state in_get_cmp_str_init_s_null accepting {
    transition {
        after event write s(s) { return s != None and s != 0 }
        success { print("s = " + str(s)) } in_get_cmp_str_init_s_not_null
        failure { gdb.execute("backtrace") } in_get_cmp_str_init_s_null
    }
    transition {
        before event itype_end(ptr) { return ptr == None or ptr == 0 }
        success calling_itype_end_with_null_ptr
    }
    transition {
        before event get_comp_string()
        success in_get_cmp_str_init_s_null
    }
}

Fig. 12. Verde property to find the cause of the segfault in zsh - Part 1)
Fig. 13. Verde property to find the cause of the segfault in zsh - Part 2)