

# Towards A Hybrid Approach to Software Verification (Extended Abstract)

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*Model checking* (MC) [6] is a widely accepted *pre-deployment* verification technique that checks whether a system satisfies or violates a property by potentially analysing *all* the possible system behaviours. By contrast, *runtime verification* (RV) [10, 14] is a lightweight verification technique aimed at mitigating scalability issues such state explosion problems, typically associated with traditional verification techniques like MC. RV attempts to infer the satisfaction (or violation) of a correctness property from the analysis of the *current execution* of the system under scrutiny. It is thus performed *post-deployment* (on actual system execution), which is appealing for component-based applications (parts of which may not be available for analysis pre-deployment), as well as for dynamic settings such as mobile computing (where components are downloaded and installed at runtime). The technique has fostered a number of verification tools, e.g., [2, 3, 8, 9, 12, 13, 16], and has proved effective in various scenarios [4, 7, 17].

Despite its advantages, RV is limited when compared to MC because certain correctness properties cannot be verified at runtime [5, 10, 15]. For instance, MC makes it possible to check for both *safety* and *liveness* properties, by providing either a positive or a negative answer, according to whether the system conforms with the specifications; RV, on the other hand, can only return a positive verdict for certain liveness properties (called co-safety properties [5]) or a negative one for safety conditions. Moreover, RV induces a runtime overhead over the execution of a monitored system, which should ideally be kept to a minimum [14].

RV's limits in terms of verifiable properties is evidenced more for branching-time logics, that are able to express properties describing behaviour over multiple system executions. In recent work [11], one such branching-time logic called  $\mu$ HML [1] is studied from an RV perspective. Figure 1 outlines the logic  $\mu$ HML used and its semantics, defined over a *Labelled Transition System* (LTS), consisting of a set of *states*  $s, r \in \text{STA}$ , sets of *actions*  $\alpha \in \text{ACT}$ , and a *transition relation* between states labelled by actions,  $s \xrightarrow{\alpha} r$ ; as in [1], the semantic definition employs an *environment* from  $\mu$ HML logical variables,  $\text{VARS}$ , to sets of states,  $\rho \in (\text{VARS} \rightarrow \mathcal{P}(\text{STA}))$ . One of the main contributions of [11] is the identification of an *expressively maximal, runtime-verifiable subset* of the logic, reported in Figure 1 as the grammar for SHML and CHML; in [11] they show how these classes provide an easy syntactic check for determining whether a property satisfaction (or violation) can be determined using the RV technique.

We building on the findings of [11], with the aim of extending the applicability of RV to a larger class of  $\mu$ HML properties other than  $\text{SHML} \cup \text{CHML}$  from Figure 1. Specifically, we propose a *hybrid approach* that permits automated formal verification to be spread across the pre- and post-deployment phases of a system development, with the aim of calibrating the management of the verification burden while combining the strengths of MC with those of RV. As an illustrative example, consider the  $\mu$ HML property (1) below, describing systems that *can* perform action  $a$ , prefix  $\langle a \rangle(\dots)$ , and reach a state from where it *can either* perform action

**Syntax**

$\varphi, \phi \in \mu\text{HML} ::= \text{tt}$	(truth)	$\text{ff}$	(falsehood)
$\varphi \vee \phi$	(disjunction)	$\varphi \wedge \phi$	(conjunction)
$\langle \alpha \rangle \varphi$	(possibility)	$[\alpha] \varphi$	(necessity)
$\min X. \varphi$	(min. fixpoint)	$\max X. \varphi$	(max. fixpoint)
$X$	(rec. variable)		

**Semantics**

$\llbracket \text{tt}, \rho \rrbracket \stackrel{\text{def}}{=} \text{STA}$	$\llbracket \text{ff}, \rho \rrbracket \stackrel{\text{def}}{=} \emptyset$
$\llbracket \varphi_1 \vee \varphi_2, \rho \rrbracket \stackrel{\text{def}}{=} \llbracket \varphi_1, \rho \rrbracket \cup \llbracket \varphi_2, \rho \rrbracket$	$\llbracket \varphi_1 \wedge \varphi_2, \rho \rrbracket \stackrel{\text{def}}{=} \llbracket \varphi_1, \rho \rrbracket \cap \llbracket \varphi_2, \rho \rrbracket$
$\llbracket \langle \alpha \rangle \varphi, \rho \rrbracket \stackrel{\text{def}}{=} \{s \mid \exists r. s \xrightarrow{\alpha} r \text{ and } r \in \llbracket \varphi, \rho \rrbracket\}$	$\llbracket [\alpha] \varphi, \rho \rrbracket \stackrel{\text{def}}{=} \{s \mid \forall r. s \xrightarrow{\alpha} r \text{ implies } r \in \llbracket \varphi, \rho \rrbracket\}$
$\llbracket \min X. \varphi, \rho \rrbracket \stackrel{\text{def}}{=} \bigcap \{S \in \text{STA} \mid \llbracket \varphi, \rho[X \mapsto S] \rrbracket \subseteq S\}$	$\llbracket \max X. \varphi, \rho \rrbracket \stackrel{\text{def}}{=} \bigcup \{S \in \text{STA} \mid S \subseteq \llbracket \varphi, \rho[X \mapsto S] \rrbracket\}$
$\llbracket X, \rho \rrbracket \stackrel{\text{def}}{=} \rho(X)$	

**Monitorable Fragments**

$\theta, \vartheta \in \text{sHML} ::= \text{tt}$	$\text{ff}$	$[\alpha] \theta$	$\theta \wedge \vartheta$	$\max X. \theta$	$X$
$\pi, \varpi \in \text{cHML} ::= \text{tt}$	$\text{ff}$	$\langle \alpha \rangle \pi$	$\pi \vee \varpi$	$\min X. \pi$	$X$

Figure 1:  $\mu\text{HML}$  Syntax and Semantics

$b$ , subformula  $\langle b \rangle \text{tt}$ , or else *can never* perform action  $c$ , subformula  $[c] \text{ff}$ .

$$\langle a \rangle (\langle b \rangle \text{tt} \vee [c] \text{ff}) \quad (1)$$

According to Figure 1, (1) turns out *not* to be runtime-verifiable because of the subformula  $[c] \text{ff}$ ; intuitively, whereas a system execution exhibiting action  $a$  followed by action  $b$  suffices to prove that the system satisfies (1), an RV monitor cannot determine whether a system can never produce action  $c$  after performing action  $a$  from the observation of only a *single* system execution [11]. However, property (1) can be expressed as the (logically equivalent) formula

$$(\langle a \rangle \langle b \rangle \text{tt}) \vee (\langle a \rangle [c] \text{ff}) \quad (2)$$

whereby we note that the subformula  $\langle a \rangle \langle b \rangle \text{tt}$  is *runtime verifiable*, according to [11]. We argue that reformulations such as (2) allow for a *hybrid* compositional approach to verification, where part of the property, e.g., the subformula  $\langle a \rangle [c] \text{ff}$ , can be checked prior system deployment using MC, and the remaining part of the property, e.g.,  $\langle a \rangle \langle b \rangle \text{tt}$ , can be runtime-verified during system execution.

Preliminary investigations indicate that this decomposition approach applies to arbitrary  $\mu\text{HML}$  formulas. We therefore aim to devise *general* analysis techniques that reformulate *any*  $\mu\text{HML}$  formula into either conjunctions or disjunctions, i.e.,  $\varphi_{\text{RV}} \wedge \varphi_{\text{MC}}$  or  $\varphi_{\text{RV}} \vee \varphi_{\text{MC}}$ , where  $\varphi_{\text{RV}}$  and  $\varphi_{\text{MC}}$  denote the runtime-verifiable and model-checkable formula components, respectively. From a software engineering perspective, we envisage at least two ways how this decomposition between pre- and post-deployment verification can be fruitful:

1. The ensuing hybrid approach may be used as a means to *minimise* the verification effort required *prior to the deployment* of a system. E.g., in the case of (2), the model-checked subformula  $\varphi_{\text{MC}} = \langle a \rangle [c] \text{ff}$  is *smaller* than the full formula (1), since we would be offloading a degree of verification onto the runtime phase when runtime-verifying for

- $\varphi_{RV} = \langle a \rangle \langle b \rangle \text{tt}$ . Moreover, for disjunction decompositions such as (2), the satisfaction of  $\varphi_{MC}$  prior to deployment obviates the need for any runtime analysis, minimising runtime overheads (a dual argument applies for conjunction decompositions and  $\varphi_{MC}$  violations).
2. In settings where software correctness is desirable but not essential, a hybrid approach can be used as a means to circumvent full-blown MC. Specifically, instead of model-checking for (1), a system may be runtime-verified for  $\varphi_{RV} = \langle a \rangle \langle b \rangle \text{tt}$  during its pilot launch, acting as a *vetting phase*: if  $\varphi_{RV}$  is satisfied during RV, this means that, by (2), (1) is satisfied as well; if not, we then proceed to model-check the system offline wrt.  $\varphi_{MC} = \langle a \rangle [c] \text{ff}$ .

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