Implementing Separation Logic using an SMT-backed Frame Rule

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Abstract

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Symbolic execution is a technique frequently used to reason about code. In symbolic execution, an analyzer keeps track of the program using a representation of the logical state, and validates that state transitions are valid. This verification is often discharged to SMT solvers as queries to the logical state.

Separation Logic is frequently used to express and verify the properties of programs with pointers or references. However, most SMT solvers (like the popular z3 [6]) do not support Separation Logic natively. Recently, the CVC5 SMT Solver has introduced partial support for separation logic, which has not yet been integrated into more high-level tools.

This work aims to address this gap, by providing a proof of concept for implementing the Frame Rule using SMT queries in the Symbolic Heap fragment of Separation Logic, as supported by CVC5. We conclude that this encoding can simplify the machinery dealing with separation logic, such as that present in Smallfoot or Verifast.

CCS Concepts: • **Computer systems organization → Embedded systems**; *Redundancy*; Robotics; • **Networks →** Network reliability.

ACM Reference Format:
Kirill Golubev and Alcides Fonseca. 2018. Implementing Separation Logic using an SMT-backed Frame Rule. In *Proceedings of Make sure to enter the correct conference title from your rights confirmation emai (Conference acronym 'XX)*. ACM, New York, NY, USA, 3 pages. https://doi.org/XXXXXXX.XXXXXXX

Conference acronym 'XX, June 03–05, 2018, Woodstock, NY

ACM ISBN 978-1-4503-XXXX-X/18/06…$15.00
https://doi.org/XXXXXXX.XXXXXXX

$$\frac{\texttt{\{pre\} code \{post\}}}{\texttt{\{pre}\ \star\ \texttt{frame\} code \{post}\ \star\ \texttt{frame\}}}\ \text{Frame rule}$$

Figure 1. The general definition of the Frame Rule.

1 Introduction

Formal verification is one of the few known ways to ensure that a computer program has the least amount of errors. The idea is to prove that a given program satisfies a specification provided in advance. The language of program specification is usually some logic that fits to describe program behavior. There are many ways to achieve this with varying resource requirements and automation degrees.

One technique employed to verify imperative programs is symbolic execution [3]. Usually, the engine for it is implemented separately for each tool [2, 7]. SMT solvers are used as oracles to verify that each step of the symbolic execution engine is correct.

Most programs in imperative languages are written in terms of heap manipulation. Separation Logic [11] is an extension of Hoare Logic [9], frequently used to reason about these types of programs. It introduces some new operations and constants to it alongside a new inference rule called *Frame Rule*. In general, Separation Logic is proved to be undecidable [5], but there are decidable subsets.

In this work, we focus on the *Symbolic Heap* fragment [2], as it enables a significant degree of automation by being supported in the CVC5 SMT Solver [1]. A simplified Symbolic Heap requires the logical context to be split into a pure boolean part ($BCtx$) and a pure spatial part ($H = emp * h_0 * \cdots * h_n$), made of disjoint heaplets ($h_i = p \mapsto v$)

$$\mathrm{BCtx} \wedge \mathrm{emp} * h_0 * \cdots * h_n$$

This simplified version significantly restricts the expressive power of Separation Logic but still permits encoding of some interesting program properties. Thus, we chose it as a starting point, but CVC5 actually supports a larger fragment called GRASS [12]. In contrast, Z3 does not have any support for separation logic. [1]

[1]But it was once prototyped: https://github.com/Z3Prover/z3/issues/811.

The goal of this work is to show evidence of the opportunity to shift some heavy lifting related to separation logic from a symbolic execution engine to an SMT solver. For this, we present an algorithm to encode the Frame Rule of Separation Logic (Figure 1) through SMT Solver queries.

2 Frame Rule

Preliminaries. To prove that a formula with universally free variables holds, we query the SMT solver whether the negation of the query, using existentially quantified free variables, is unsatisfiable (`unsat`). We denote this verification as isUNSAT(¬query).

Algorithm. The algorithm to check the Frame Rule is split into two phases:

- Check if the current context satisfies the precondition
- Apply postcondition to the larger context

The first step focus on verifying whether the precondition is guaranteed by the context. The context is composed of the boolean context, including pointer equivalente (e.g., $a = b$) and the heap (e.g., $a \mapsto x, b \mapsto y$). The requirement is composed of the boolean pre-condition (pre), together with any heap (pre $*$ true).

$$\text{BCtx} \wedge H \Vdash \text{pre} \iff \text{isUNSAT}(\neg(\text{BCtx} \wedge H \implies \text{pre} * \text{true}))$$

The second step selects the relevant parts of the frame to be kept in the outgoing context, by discarding all heaplets that invalidates the precondition. In particular, for the incoming context $S_{in} = \text{BCtx} \wedge H_{in}$, we will generate the outgoing context $S_{out} = (\text{BCtx} \wedge \text{post}) \wedge H_{out}$.

$$H_{out} = \{h_i \mid h_i \in H_{in}, \text{BCtx} \wedge H \Vdash \text{pre} * h_i * \text{true}\}$$

H_{out} is the separating conjunction of all the heaplets from the incoming context that are not invalidated by the precondition. From this heap reconstruction, we can build the complete outgoing context S_{out}. The heap reconstruction process can be used in other contexts, such as merging heaps after branches.

When compared to other SMT-based Separation Logic approach, such as Implicit Dynamic Frames, our approach takes `O(size(H))` queries from decidable logics, instead of the `O(1)` queries in undecidable logics. This approach presents another alternative in the design space between guarantee of results versus performance.

Evaluation. We validated the feasibility of this approach by implementing it in the Liquid Java compiler, supporting function calls, conditional branching, and assignments. The performance degradation for synthetic benchmarks is around 30% relative to the pure boolean version of Liquid Java.

3 Conclusions

The big advantage of this approach is that the SMT solver algorithm for separation logic is decidable. This is different than other approaches, such as Viper [10], which have their own internal infrastructure for implementing the frame rule.

The simplicity and decidability come with the cost of features that are possible to support. Viper is a much more mature and rich backend for the language, while the presented approach is capped by the capabilities of separation logic support in SMT solver. Said capabilities are defined by GRASS fragment of separation logic which looks like "propositional" separation logic. The main features that are kept unreachable by this limitation are recursive predicates and fractional permissions [4].

While our validation was in the specific context of Liquid Java [8], but it is general enough to be used in other projects relying on SMT solvers to verify symbolic execution steps. The primary benefit of this algorithm is simplicity and delegation of responsibility for separation logic handling to the SMT solver instead of a symbolic execution engine which is usually implemented separately for each tool.

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Received 20 February 2007; revised 12 March 2009; accepted 5 June 2009